DEPARTMENT OF ELECTRICAL
AND COMPUTER ENGINEERING

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Master in Aerospace Engineering

UNFOLDING OCEAN POWER SOLUTIONS POTENTIAL FOR ELECTRICITY GENERATION USING PROJECT DRAWDOWN FRAMEWORK

MASTER IN RENEWABLE ENERGY ENGINEERING

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NOVA SCHOOL OF
SCIENCE & TECHNOLOGY

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Acknowledgements

In addition to acknowledging different contributions to this thesis, I would like to use this section to make a small overview of these two years of my life I spent studying to become a renewable energy engineer.

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As I stated, I feel fortunate for the experiences I had, the people I met and the moments I lived over the past two years. It has been quite a journey.

"Choose life.
Choose a job.
Choose a career.
Choose a family. (...)
Choose your future.
Choose Life."

John Hodge,
based on the novel by Irvine Welsh,
Trainspotting.

Abstract

This thesis addresses the potential of ocean power to reduce greenhouse gas emissions, considering its total net costs and operational savings at a European Union level. Such emissions are the leading cause of global warming. A significant shift in policies is therefore needed if countries are to comply with the emissions reduction targets defined in the meantime. A powerful tool to help tackle this endeavor is modeling future energy scenarios. Project Drawdown organization assesses multiple climate solutions and presents a methodology allowing researchers to compare new electricity generation technologies with conventional ones along various parameters. The present work displays projections regarding the future of the electricity generation market and the adoption of ocean power technologies. These ocean power adoption projections are based on peer-reviewed publications and institutional reports and refer to the period 2021-2050. Using Project Drawdown's framework, these projections are coupled with emissions, financial and technical data to model the potential of ocean power solutions for electricity generation and for reducing greenhouse gas emissions in the European Union up to 2050. Finally, sensitivity analyses are carried out to understand how the financial variables' behaviour may affect the results.

The results obtained in this work show that ocean energy may generate 33 to 170 TWh by 2050 while replacing conventional electricity generation technologies. These figures account for 0.59%-3.05% of the total generation of the European Union electricity system by 2050. In terms of financial competitiveness, the results obtained show marginal costs to vary from 19.1 to 60.8 Billion €, net operating savings to vary from -17.2 to -84.0 Billion €, and lifetime operating savings vary from -42.0 to -214.5 Billion €. The total emissions reduction for the period under analysis is expected to range from 0.16 to 0.81 Gt $CO_{2\text{-eq}}$ well below the potential of other renewable energy sources as solar or wind power.

Keywords: Ocean Power, Electricity Generation, Greenhouse Gas Emissions, Project Drawdown

Resumo

Esta tese debruça-se sobre o potencial da energia oceânica para reduzir as emissões de gases com efeito de estufa, considerando os custos líquidos totais da sua exploração e as poupanças operacionais da sua adoção na União Europeia. Estas emissões são a principal causa do aquecimento global. É por isso necessária uma mudança significativa nas políticas adotadas caso os países pretendam respeitar os objetivos de redução de emissões entretanto definidos. Uma ferramenta poderosa para ajudar neste empreendimento é a modelação de cenários energéticos futuros. A organização Project Drawdown avalia múltiplas soluções climáticas e apresenta uma metodologia que permite aos investigadores comparar as novas tecnologias de produção de eletricidade com as convencionais no âmbito de vários parâmetros. Este trabalho formula projeções a respeito do futuro mercado de produção de eletricidade e da adoção futura de tecnologias de energia oceânica. Estas projeções baseiam-se em publicações revistas pelos pares e relatórios institucionais e referem-se ao período 2021-2050. Usando a metodologia do Project Drawdown, estas projeções são combinadas com dados de emissões, financeiros e técnicos com vista à previsão do potencial das soluções de energia oceânica para a produção de eletricidade e para a redução das emissões de gases com efeito de estufa na União Europeia. Por último, efetuam-se análises de sensibilidade com vista a compreender como é que o comportamento das variáveis financeiras pode afetar os resultados.

Os resultados obtidos neste trabalho mostram que a energia oceânica poderá gerar entre 33 a 170 TWh em 2050. Estes valores representam 0.59%-3.05% da produção total do sistema elétrico da União Europeia em 2050. Em termos financeiros os resultados obtidos mostram que os custos marginais variam entre 19.1 e 60.8 mil milhões de € e que as poupanças operacionais líquidas e totais variam entre -17.2 e -84.0 mil milhões de €, e -42.0 to -214.5 mil milhões de €, respetivamente. É expetável que a redução total de emissões se situe entre 0.16 e 0.81 Gt $CO_{2\text{-eq}}$, muito menor que a potencial redução de emissões de outras fontes de energia renovável como a energia solar ou eólica.

Palavras-chave: Energia Oceânica, Produção de Eletricidade, Emissões de Gases com Efeito de Estufa, Project Drawdown

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Glossary

Adoption	Predicted shape of adoption growth of ocean power technologies for electricity generation for the period under analysis 2021 to 2050.
Average Annual Use	The average number of functional units that a single implementation unit typically provides in one year.
First Costs	The investment costs per implementation unit which is essentially the full cost of establishing or implementing the solution.
Functional Unit	Measurement unit that represents the value, provided to the world, of the function that the solution performs.
Implementation Unit	A measurement unit that represents how the solution approach or technology will be installed/setup and priced.
Indirect Emissions	Emissions caused by the production or delivery or setup or establishment of the solution in a specified area.
Lifetime Capacity	This is the total average functional units that one implementation unit of the solution or conventional technology can provide before replacement is needed.
Total Addressable Market	Represents the total potential market of functional demand provided by the technologies and practices under investigation, adjusting for estimated economic and population growth.

Variable Meta-Analysis Represents emissions, financial and technical input variables used for comparing solution and conventional technologies.

Acronyms

CCUS Carbon Capture Utilisation and Storage
CDR Carbon Dioxide Removal
COP26 Conference of the Parties
CWF ClimateWorks Foundation

DERA Drawdown Europe Research Association

EC European Commission
ECF Europe Climate Foundation
EU European Union

FOM Fixed Operation and Maintenance

GHG Greenhouse Gas

IEA International Energy Agency
IEEJ Institute of Energy Economics, Japan
IPCC Intergovernmental Panel On Climate Change
IRENA International Renewable Energy Agency

JRC Joint Research Centre

LCOE Levelized Cost of Electricity
LTS Long-Term Strategy

NDC Nationally Determined Contributions
NECP National Energy and Climate Plans

OB Oscillating Bodies
OD Overtopping Devices
OEE Ocean Energy Europe
OES Ocean Energy Systems
OM Operation and Maintenance
OWC Oscillating Water Columns

PDS Project Drawdown Solution
PV Photovoltaic

REF Reference
RRS Reduction and Replacement Solutions

TAM Total Addressable Market
TRL Technology Readiness Level

UK United Kingdom
UN United Nations

VMA Variable Meta-Analysis
VOM Variable Operation and Maintenance

WEO World Energy Outlook

1

Introduction

One of our generation's most daring challenges is the fight against global warming. Trying to develop and improve societies while fighting climate change is, without a doubt, a tremendously difficult problem for policymakers worldwide. Embracing an energy transition scenario from fossil fuels to renewable energies, to massively reduce Greenhouse Gas (GHG) emissions, involves undertaking big changes in the power sector, industry, transport and building. All these sectors need to be aware of this urgent agenda. But this means they need to substantially increase the electricity share in their final energy consumption. Renewable energies must in turn source this electricity with zero GHG emissions upon production. The energy sector is therefore on the forefront of this challenge.

Most of the major technical difficulties involved in this challenge were already overcome - the levelized cost of electricity for renewable sources, one of the most common indicators of technology readiness, is already more attractive than the cost of electricity from fossil fuels [1]. And, contrary to fossil fuels, these renewable sources are limitless, at least on a human-life period. The main shift is now in the hands of policymakers, implementers and final users.

In August 2021 the United Nations (UN) Intergovernmental Panel On Climate Change (IPCC) presented the first study contained in its sixth assessment report [2]. There it states that the climate crisis is, without a doubt, caused by human activities and that its effects are already being felt worldwide. The IPCC report also shows that only an immediate and drastic reduction in GHG emissions will prevent an irreversible temperature rise and its excessively costly and unpredictable consequences. Given such conclusions, the scientific community was looking forward to the outcome of the UN Climate Change Conference, where the parties met in November 2021. The Glasgow Climate Pact was signed there. Countries agreed to the progressive elimination of inefficient subsidies for fossil fuels, elaborated a global methane pledge and committed themselves to reversing deforestation. They also agreed to "phase down"(rather than "phase out") coal. This last-minute choice of words shows how difficult it is for policymakers to address the fight against global warming in a united and resolute way. 2021 was a year in which strong commitments were also made at a European level: the European Climate Law [3] was enacted, binding Europe's economy and society to the pledge of becoming climate-neutral by 2050. This law also set a more ambitious European Union (EU) target: reducing net GHG emissions by at least 55% by 2030, compared to 1990 levels. In line with this ambition, several European countries submitted updates on their Nationally Determined Contributions (NDC)s, which have been defined as a follow-up to 2015's Paris Agreement.

Modeling future energy scenarios is a powerful tool in energy and climate debates. Different organizations within the energy sector community publish their updates for the future on a yearly basis. In particular, energy agencies, utilities and academia regularly release their publications containing updated information and statistics concerning energy. Within this context, the non-profit organization Project Drawdown continuously resources and assesses multiple climate solutions. In its most widespread publication [4], this global organization put forth an energy model combining several dimensions; it encompasses emissions reduction, financial analysis, total addressable market and current implementation of each of distinct solutions.

If a carbon-neutral energy system becomes a reality, more renewable energy sources need to be included in the electricity generation mix. Due to their characteristics, wind and solar energies are subject to variability; thus, they must be supplemented with other renewable sources or storage systems. Ocean energy is a possible solution for balancing electricity systems. It is predictable, since tides and ocean currents can be predicted accurately and with many years in advance; it is constantly available, due to its infinite power source; and it is secure, because ocean energy can reduce the reliance on fuel imports for many countries, helping them in the pursuit of energy independence. It thus has much potential for many regions in the world. On the other hand, the levelized cost of electricity from ocean power technologies does not yet allow the offer of competitive prices. This is due to the relatively early life-cycle stage of ocean power technologies. Further technology deployment and technical improvements are necessary to fully attest the maturity of these technologies and the potential for the electricity generation systems of the future.

This work will use Project Drawdown Reduction and Replacement Solutions (RRS) Model to parametrically analyze the adoption of ocean power technologies for electricity generation in the forthcoming decades. A developed dataset is taken as input. It combines electricity generation historical data with different future scenarios for the power sector; the latter are based on current policy settings, climate commitments announced by governments and net-zero emissions perspectives. Its main goal is to assess the potential of ocean power to reduce GHG emissions, considering its total net costs and operational savings.

1.1 Global Energy Transition

The energy sector accounts for almost 75% of global GHG emissions [5], and if it is true that energy transition trends are in place, as well as strategies to bring down GHG emissions, it is a fact that the world is still a long way to go in the fight against global warming. The latest evidence shows that society's partial recovery from the Covid-19 pandemic was enough to bring back the demand for all energy sources and technologies, resulting in an abrupt increase in prices and CO_2 emissions. This can be easily perceived by Figure 1.1 below.

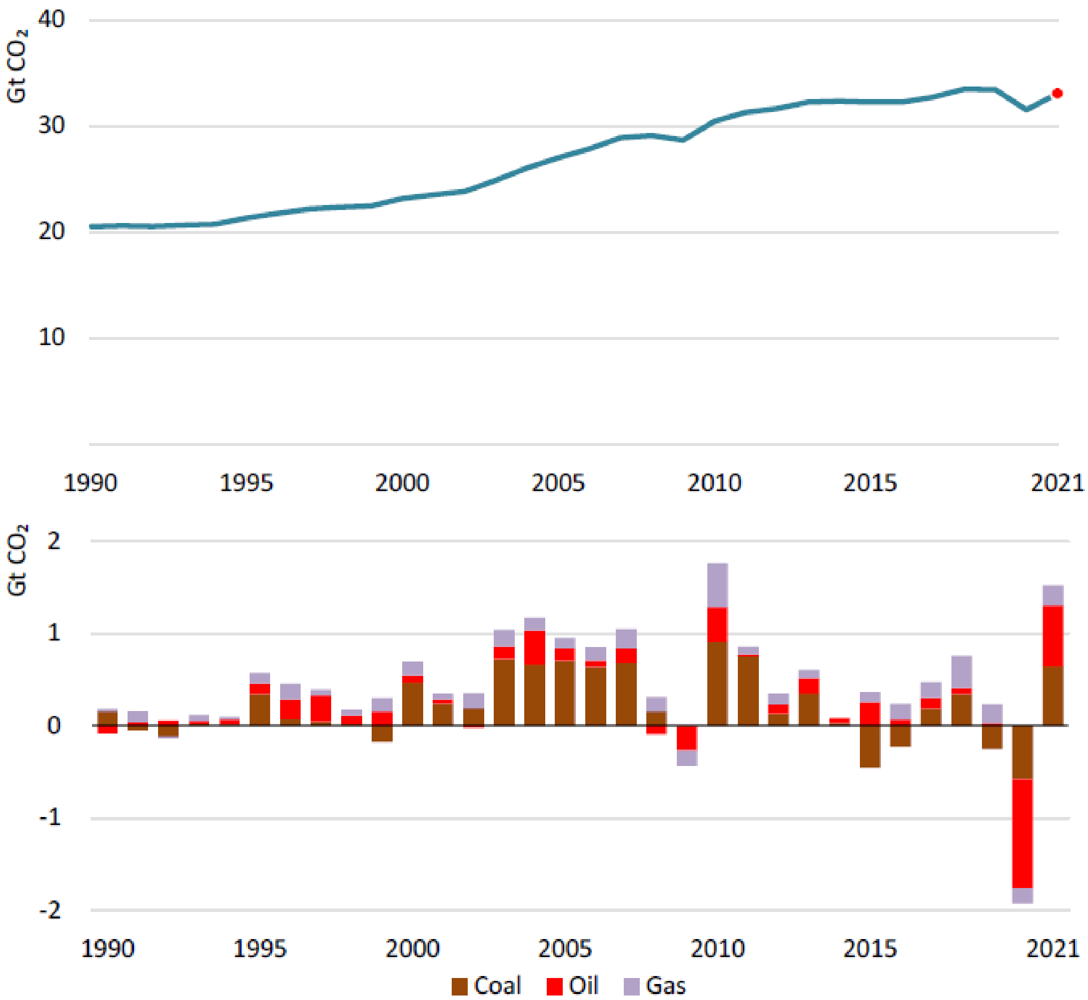

Figure 1.1: Global energy-related CO_2 emissions; and change in CO_2 emissions by fuel, 1990-2021 [6]

Despite being another record year for renewables in 2021, that was not enough to cover the rise in electricity demand. In the last year, it is expected to have increased over 1000 TWh after declining in 2020, meaning that consumption is well above pre-pandemic levels. This led to an increase in coal-fired generation in some geographies, bringing along higher emissions. Global energy-related CO_2 emissions are expected to exceed 1.2 billion tonnes in 2021 [5]. This corroborates the hypothesis that most of the government's plans and targets will not do more than stabilize global emissions, instead of drastically reducing them: the only way to address climate change. The truth is that despite all evidence and widespread support in the last years, energy-related CO_2 emissions have averaged increased by 1.3% annually, between 2014 and 2019 [7].

Unprecedent actions must be put in place. To achieve rapid decarbonization, policy initiatives and investments for clean energy deployment must continue in the coming years. Although the timeframe for a 1.5 ºC future may remain in reach, it is up to human society now to fulfil its commitments from the Paris Agreement and the UN Sustainable Development Goals. Figure 1.2 shows how far away world society is from a decarbonized electrical system: in 2020, more than 60% of the electricity generated was sourced from fossil fuels.

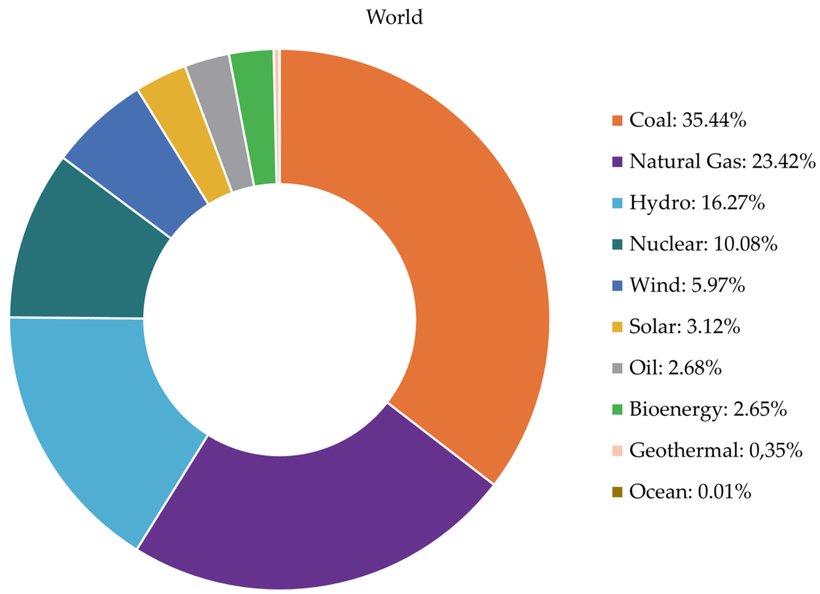

Figure 1.2: Electricity generation by source, World, 2020; based on [5]

1.2 Project Drawdown

In 2017, an international group of researchers, professionals and scientists published "Drawdown: The Most Comprehensive Plan Ever Proposed to Reverse Global Warming". This book tackles climate change from three angles: to bring pollutant emissions to zero; to improve Earth's natural capability to capture carbon; and improve society through education and environmental awareness. One hundred substantive solutions to revert global warming are there presented. 'Drawdown' is defined as "the future point in time when levels of greenhouse gases in the atmosphere stop climbing and start to steadily decline. This is the point in time when we begin stopping further climate change and averting potentially catastrophic warming. It is a critical turning point for life on Earth" [4]. Figure 1.3 illustrates Project Drawdown solutions framework.

The publication of this book turned out to be a commercial success, bringing the public's attention to Project Drawdown, a non-profit organization founded in 2014, thus enhancing its visibility. The goal of Project Drawdown is to help the world to reach drawdown. In addition to the publication of the book in 2017, this organization established partnerships with multiple institutions, cities, universities, communities and policymakers to continuously resource and assess multiple climate solutions. A reviewed version of the book's conclusions [8], containing data from 2018-2019, shows how climate solutions can best adapt to some of the world's latest events. That is, besides global assessment, and to make Drawdown methodology meaningful and understandable for all implementers and users, the specific scientific knowledge there provided is presented at a more drill-down level with applications to regions, sectors and specific locations. It is within this context that Drawdown Europe Research Association (DERA) was founded.

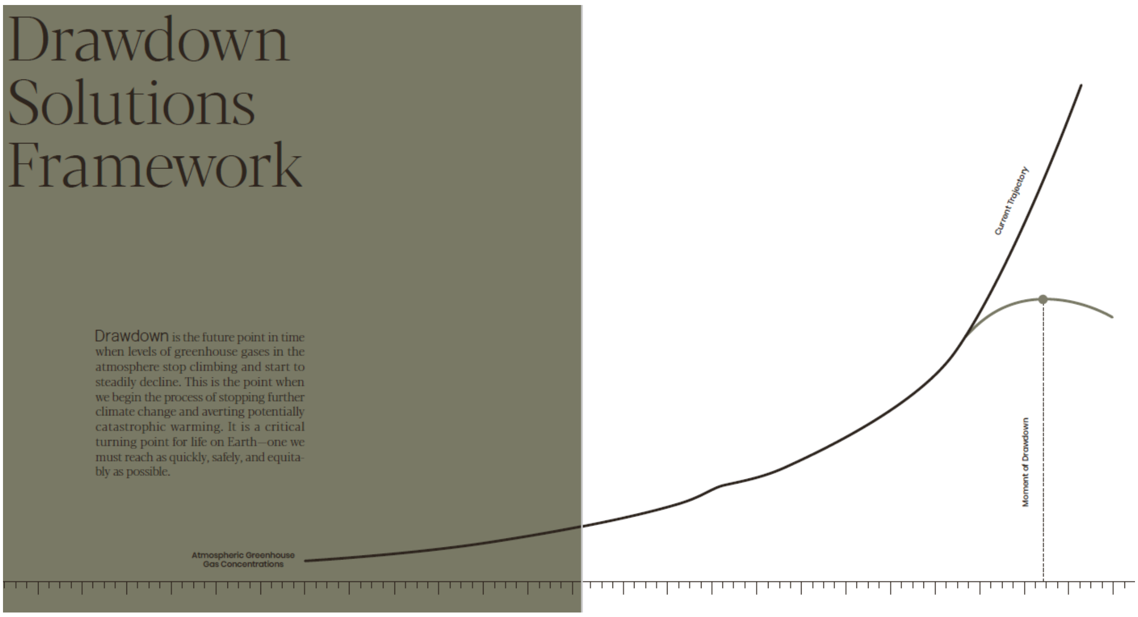

Figure 1.3: Drawdown Solutions Framework [8]

DERA aims to bring Project Drawdown to the European level using several projects and publications [9]. Several studies were conducted within this framework to assess the potential of the European power sector technologies (solar, wind and hydropower) to help achieve Drawdown [10–12]. The aim with the present work is to assess the potential of oceanic power for reverting global warming.

As explained in [4], solutions to reverse global warming admit being ranked according to three main quantitative parameters: total atmospheric $CO_{2\text{-eq}}$ reduction, either by avoiding GHG emissions or by sequestering CO_2 from the atmosphere; total net cost of each solution, considering the purchase, installation and operation for at least thirty years; and total net savings, revealing the cost-effectiveness of the solution. These results were computed with Project Drawdown RRS Model. The model combines several dimensions; it is sensitive to emissions reduction, financial analysis, total addressable market and current implementation of each solution. As mentioned above, this model was used in [4] by Project Drawdown in the context of a global approach, setting no specific differences according to each geography or sector. In [10–12] the same model was used, aiming to analyze only the energy sector, specifically, different technologies usable at a European level for electricity generation.

The present work will also use Project Drawdown RRS Model to focus on the oceanic power potential for electricity generation at a European Union level. Wave and tidal energy represent an enormous source of renewable energy that remains practically unused; even if it is not yet economically competitive, compared with more mature renewable energy technologies, it could play an important role in mitigating global warming. In the last decades, wind and solar energy technologies have achieved a levelized cost of electricity that makes it very difficult to compete with [1]; however, with current targets for renewable energy penetration in the electricity generation mix, more technologies must step up. Oceanic power can be a powerful solution to help accomplish Drawdown.

1.3 Thesis Structure

1.3.1 Objectives

The main goal of this work is to assess the potential of ocean power to reduce GHG emissions up to 2050, taking into consideration its total net costs and operational savings at a European Union level. To do so, several intermediate objectives need to be met.

First, a data collection process for the future of the electricity generation system must be conducted. It will allow us to understand the future addressable market for the different electricity generating technologies - particularly, ocean power technologies. This dataset should include electricity generation historical data and different future scenarios for the power sector based on current policies, climate commitments announced by governments and net-zero emissions perspectives. Variable meta-analysis data will also be included in the dataset in order to address economic and technical contexts.

Second, choosing, within the available literature, the appropriate data to use as inputs for the Project Drawdown RRS Model. The model will compute ocean power adoption, financial and emissions results, by comparison with a reference adoption scenario and different technical and financial variables of conventional electricity generation technologies (coal, natural gas, oil).

Finally, drawing some conclusions concerning the potential of ocean power within the EU's future electricity generation system. Such findings need to take different desiderata into account: not only achieving an effective reduction in GHG emissions, but also doing so at an affordable economic cost and reaching operational savings.

1.3.2 Contribution

To achieve countries goals regarding climate change mitigation and energy transition, all renewable energy sources must be considered as a means to reduce pollutant emissions. The oceans are, by far, the world's largest untapped renewable energy source. Despite technological advances still being needed for ocean power technologies to compete with more mainstream renewable energy technologies, oceanic energy can complement the energy mix by balancing electricity systems with its predictability and abundance.

The oceanic energy sector will also catapult a new industry worldwide, creating new opportunities for maritime industries and coastal regions, with all corresponding economic benefits attached. Therefore, it is essential, not only to explore the potential contribution of ocean power to bring pollutant emissions to zero, but also to understand its real economic potential. This is the context within this work needs to be understood.

1.3.3 Outline

The next chapter contains the literature review on ocean energy and ocean power technologies carried out for the present work and the future energy system scenarios publications. Chapter 3 includes a presentation of the methodology used, by presenting the Project Drawdown RRS Model, the data collection process and the variables inputs of the model. Chapter 4 reveals the results from the literature review for Total Addressable Market data, Adoption data and Variable-Meta Analysis data; the proposed solution adoption, financial and emissions results obtained with the Project Drawdown RRS Model. Chapter 5 presents the discussion of the results, considering the assumptions, limitations and benchmarks considered. Finally, chapter 6 presents the conclusions arrived at in this thesis work.

2

Literature Review

This work addresses ocean power's potential to reduce greenhouse gas emissions. It does so by predicting and modelling the importance of ocean power in the electricity generation mix in the near future. Oceanic energy is a vastly unused resource for electricity generation; it is therefore of the utmost importance to understand which strategies might be implemented to make the most out of this renewable energy source.

Several ocean power technologies for electricity generation are currently available, displaying different maturity levels. The more mature ones are those aimed at harnessing tidal energy. Some of these have already achieved a Technology Readiness Level (TRL), closer to reaching a commercialization stage. In contrast, wave energy technologies are less mature. Most projects implemented worldwide are still in a prototype or demonstration stage. Considering these different readiness levels, Project Drawdown focuses its analysis on three types of ocean power technology: wave energy converters, tidal stream and tidal barrage. Since this work is being written within the framework of Project Drawdown, it will limit its discussion to these three types of ocean power technology.

As stated in the previous chapter, the analysis to be developed within Project Drawdown RRS Model is built on top of a dataset containing electricity generation historical data as well as different scenarios concerning the future evolution of the energy sector (based on current policy settings, climate commitments announced by governments and net-zero emissions perspectives). The data, which will encompass all sources of electricity generation, including renewable energy sources and oceanic energy sources, are to be collected from publications issued by different agents (e.g., energy agencies, utilities or academia).

In this chapter, both the potential displayed by different ocean energy resources and current strategies for generating renewable energy offshore will be described. Different technologies for harvesting oceanic energy will also be described, as well as some of the most prominent energy projects currently being implemented in the ocean. The prospects for the evolution in the coming years of the levelized cost of electricity associated with these technologies will also be discussed. Finally, key scenarios describing future energy systems will also be addressed; in particular, their importance for the viewpoint underlying this work will be made apparent.

2.1 Ocean Energy

If our society's ambitious decarbonization goals are to be met, the use of all renewable energy sources must be contemplated. The ocean is an enormous source of energy that cannot be ignored. It is a resource that may help deliver a prosperous and just transition by complementing other renewables and balancing energy systems [13]. According to several publications [14], its environmental impact is limited. Further investigation is, however, needed to thoroughly understand the effects of full-scale commercial projects.

2.1.1 Resource potential

Earth is largely covered by oceanic water; roughly three billion people live within 200 km of the coast [15], which is increasing yearly due to migration phenomena. Ocean energy resources can thus offer a convenient solution to sustainably provide energy to many millions of households. According to several ocean energy assessments, the ocean has an enormous resource potential for electricity generation, well above the current global demand for electricity [16].

There are many oceanic energy resources that can be used to generate electricity. Current research and analysis focus mostly on four energy sources: tides and currents, ocean waves, ocean thermal energy and salinity gradient. These are illustrated in Figure 2.1 below.

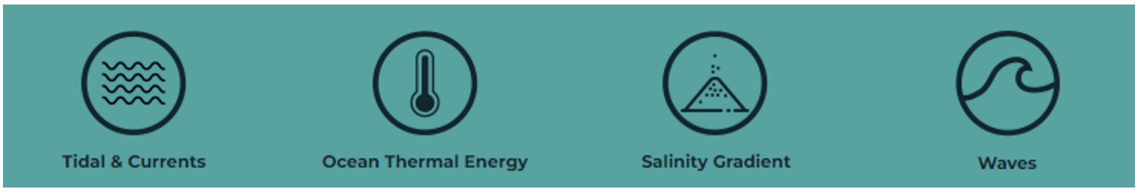

Figure 2.1: Ocean energy resources ([17], adapted)

Tidal energy has a theoretical power of around 1 200 TWh/year [18]. The goal is to harness the potential energy generated by height changes in sea level due to the movement of ocean water volumes caused by tides. In this respect, a distinction must be drawn between tidal range, tidal currents and ocean currents resources. Even though it displays a minimal resource potential when compared with other renewable energy sources, tidal energy has a significant comparative advantage: it is both entirely predictable and weather independent. Tides can be predicted for the short and long term, even decades ahead. Tides are caused by the gravitational attraction of the moon, the sun and other astronomical bodies on oceanic water bodies [19]. In order to trap potential energy from ebb and flow (range), barrages or fences can be built to trap high tide water mass and then exhaust its potential before the next tidal cycle. Tides also generate kinetic energy, creating tidal currents. These currents are found on particular spots near the coast, mainly on locations exhibiting topography constraints such as passes, islands and straits [16]. Ocean surface currents are driven both by wind energy and latitudinal distribution. The power generated by these currents can be harnessed only at shallow depths; although they are generally slower than tidal currents, they tend to be more continuous.

The potential of wave energy is tremendous. According to [20], wave energy can produce 29 500 TWh/year; this means that it could meet the global energy demand by itself [5]. To do so, kinetic and potential wave energy must be harnessed. This type of energy, probably due to its often-spectacular visual effects, has been arousing the curiosity of scientists and academics for centuries in their search to convert wave energy into usable energy [21, 22]. Different types of modular technologies have been developed to meet this challenge. The power of waves, when compared to tidal energy, is more spatially distributed, being more prevalent in mid-latitudes, given the fact that it is influenced by water density, wavelength, wave speed and wave height [16].

An even greater technical potential is to be found in ocean thermal energy. The largest of all ocean energy sources can provide around 44 000 TWh/year [23]. The conversion of ocean thermal energy into electricity makes use of the temperature gradient between the sea surface and deep-water. This temperature gradient, which must be around 20ºC, is converted into a thermal cycle; the latter admits be turned into electricity. It must be said, however, that these temperature gradient conditions are to be found in tropical regions only; as a matter of fact, only there can the following three necessary circumstances be simultaneously met: warm surface water temperatures, large ocean depths and stable air temperatures. The energy potential that is generated there derives from ocean thermal energy's high capacity factor and its capability to produce energy uninterruptedly [16, 19].

Finally, the energy generated by salinity gradients can be harnessed by making use of the pressure potential originated by differences in salt concentration, particularly there where a mix between fresh and saltwater is to be found. The amount of energy produced is proportional to the difference in salt concentration. This makes estuaries the ideal location for the placement of systems capable of transforming salinity gradient into usable energy. These systems use membranes and operate under two main principles: pressure retarded osmosis and reverser electro dialyses [24].

2.1.2 Offshore renewable energy strategies

After the Paris Agreement (2015), the Parties agreed to present 5-years NDCs to tackle GHG emissions up to 2030 and long-term strategies looking forward to 2050. Although all Parties promised to increase the production of electricity from renewable sources, very few of them have included oceanic energy in their agenda, in spite of the fact that many of these Parties are located close to oceans [25]. Within the EU, National Energy and Climate Plans (NECP) [26] exhibit the same pattern; however, an exception regarding some targets is to be found in the NECP from Ireland, Portugal and Spain [27–29].

It was not before November 2020 that the European Commission (EC) published the European Offshore Renewable Energy Strategy [30], which points out the relevance of oceanic energy for achieving an economy with net-zero GHG emissions in 2050. This document set concrete targets for offshore wind capacity; but its major innovation was the introduction of oceanic energy capacity targets for the first time - the EC aims to reach a target of 40 GW of marine energy together with other emerging technologies (e.g., floating wind and solar devices) by 2050. In the meantime, some intermediate goals were fixed: to achieve a total capacity of 100 MW across the EU by 2025 and of around 1 GW by 2030. These targets have to be integrated into National Maritime Spatial Plans. Setting such ambitious targets reflects the global leadership position EU companies have in this sector. Across the world, some other countries have also developed specific plans for harvesting energy from the oceans [31, 32], namely, the members of Ocean Energy Systems - an International Energy Agency technology collaboration program.

2.2 Ocean Power Technologies

2.2.1 Tidal barrage

As its name indicates, tidal barrage technology uses the tides' potential energy by placing a dam or other barrier to harvest power from the height difference between high and low tides. This technology is a commercially feasible and represents more than 90% of the total ocean energy combined capacity currently operational. This capacity is mainly distributed across three projects: 254 MW in Sihwa Lake Tidal Power Station in Korea (2011), 240 MW in La Rance Tidal Power Station in France (1966) and 20 MW in Annapolis Tidal Station in Canada (1984). However, it must be said that Annapolis is currently going through a dismantling process, after it stopped generating electricity in 2019 due to equipment failure. The remaining capacity is installed in smaller projects in China and Russia. The total installed capacity of tidal barrage technology sums up to 494 MW.

In tidal barrages, power is generated in tidal turbines (usually bulb turbines) similar to those used in hydropower power stations. The main principle is the following: water enters an enclosed tidal basin when the tide is high and it is released from there when the tide is low; the water released drives the turbines that generate electricity. There are one-way power generation tidal barrages and two-way power generation tidal barrages. The former can produce energy either only at ebb or only at flood but not at both. The latter can produce energy at both ebb and flood. One-way power generation allows for only a short period of electricity production, and the generation of electricity at flood induces ecological collateral damage, as the water level in the impoundment is kept low for a long time. Two-way power generation allows power generation for a longer period but requires reversible turbines. (See references [16, 19, 33] for a detailed description of tidal barrage technology).

Despite having a TRL 9, tidal barrage technology reveals the following disadvantages: i) considerable environmental impact in the bays or estuaries where it is implemented; ii) high capital investment costs [33]. Another problem associated with tidal barrage costs is that these may vary considerably from one site to another; important variables to take into account in this respect are: i) the size of the barrage (both in length as well in height) and ii) the difference in height between high and low tide. Last but not least, the resource potential to be explored in tidal barrages, is low compared to other ocean power technologies. Given these disadvantages, no tidal barrage power plants of scale have been developed over the last decade.

2.2.2 Tidal stream

Among ocean power technologies, the tidal stream was probably the one that made more technological advances in the last years; it is close to reaching a commercialization stage. This technology is very close to maturity; expectations are that it will become more widespread than tidal barrage technology in the near future. A global installed capacity of 10.6 MW is already operational, and a significant number of projects, at different levels of readiness, are being tested; it is expected that tidal stream technology will have 2.4 GW of installed capacity in the next decade only in Europe [16, 34]. The 10.6 MW mentioned above of installed capacity refers to subscale test plants, full-scale demonstration plants, smaller completed commercial projects and, the last step before full-scale commercialization, some first-stage projects of larger commercial tidal farms. The United Kingdom (UK) is a frontrunner in tidal energy globally, but other countries such as Australia, Canada, France and Korea also have large tidal energy ambitions.

Tidal stream technologies convert the kinetic energy caused by the changing tides into usable energy. The process follows: sea water is driven into tidal stream turbines to generate power. Several concepts of tidal stream turbines have been proposed and tested in recent years. Still, the last decade has observed a strong convergence toward horizontal axis turbines (TRL 8). This is similar to what happened with wind turbine generators. Vertical axis turbines, crossflow turbines and other concepts (e.g., oscillating hydrofoil, helical screw devices and tidal kites) are among other extensively tested tidal stream technologies. The main differences between the several concepts involve the number of blades, the control of blades pitch and the method of securing the turbine. Typically, tidal current devices are generally modular and intended for deployment in multi-unit arrays for a utility-scale generation. (See references [16, 18, 19] for a detailed description of tidal stream technology). Figure 2.2 display three types of tidal energy technologies.

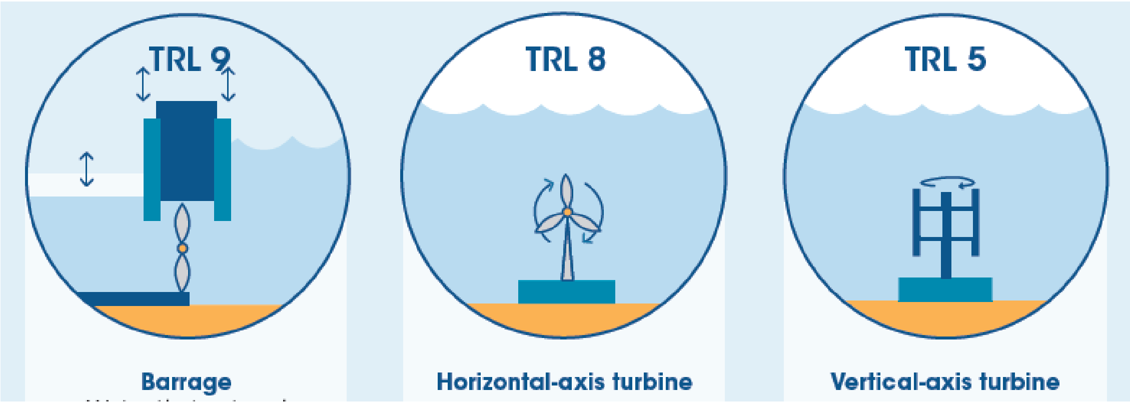

Figure 2.2: Tidal energy technologies ([16], adapted)

As mentioned above, recent advances in tidal energy technologies have been made. Some of the projects at the forefront of this endeavour are the following. Minesto®, a tidal developer, signed a power purchase agreement in 2020 with the Faroe Islands, after successfully testing their large-scale tidal kite device [35]. Simec Atlantis Energy® deployed a 500 kW tidal project in China and secured a 12 MW tidal project in France, while its flagship MeyGen tidal stream project in Scotland remains one of the largest tidal power installations in the world with four 1.5 MW turbines; for the next stage of development, expected for 2024, forty-nine more turbines will be deployed with a total capacity of 73.5 MW [36, 37]. In Nova Scotia, Canada, feed-in-tariffs of around 350€/MWh, and government grants have created conditions for tidal projects to emerge; Big Moon Power® was granted a license and signed a power purchase agreement for a 4 MW tidal project [37].

2.2.3 Wave energy converters

Most wave energy projects worldwide are still in the prototype and demonstration stages. Thus, no specific type of design has yet gained the upper hand. By 2020 the global installed capacity of wave energy was of only 2.3 MW and only one project above 1 MW was being deployed (in Hawaii). Most other locations where electricity is generated from wave energy are in Europe (France, Italy, Portugal, Spain and the UK) [19, 38].

Wave energy converters capture the energy contained in ocean waves to use it to generate electricity. It is possible to divide these technologies into three main categories: Oscillating Water Columns (OWC), Oscillating Bodies (OB) and Overtopping Devices (OD). OWC use trapped air pockets in a water column to drive a turbine; OB, either floating or submerged, use the wave motion (from side to side, forwards/backwards, up/down) to produce electricity; OD use water potential energy in closed reservoirs to drive hydraulic turbines subsequently. These technologies are also classified in function of water depth (shallow, deep, intermediate), motion (pitching, surging, heaving), mode of conversion (translation, rotation), power take-off system (hydraulic engines, hydraulic turbines, air turbines), mooring and foundation structures (submerged, floating, fixed) and location (offshore, nearshore, shoreline). According to [39], the combination of characteristics from this set has resulted in over 50 different technology types. As of today, the technologies better suited for commercialization are of the OWC type, (TRL 8 already) and of the OB type (such attenuators - TRL 8 -, point absorbers and oscillating water surge converters - TRL 7). An attenuator consists of several connected segments or of a unique long flexible part that extracts energy from the waves by following their parallel motion. Point absorbers may be floating or submerged devices and generate energy thanks to a buoy's movement in all directions relative to its anchor point. Oscillating water surge converters are structures using the surging movement of the waves (the back-and-forth motion) in order to capture energy in the oscillating arm. (See references [16, 18, 38] for a detailed description of wave energy converters technology). Figure 2.3 display four types of wave energy technologies.

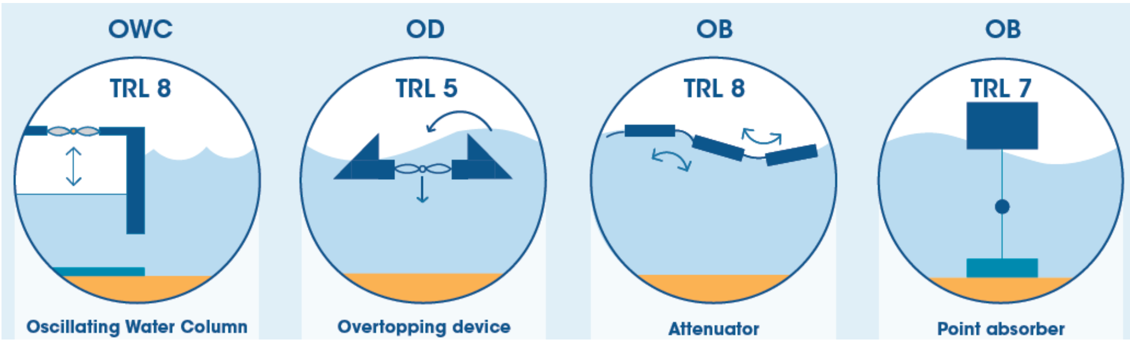

Figure 2.3: Wave energy technologies ([16], adapted)

OWC's three main projects dominate global total installed capacity: Ocean Energy Ltd's® OE35 device in Hawaii, the largest wave energy device ever operated so far (1.25 MW capacity) [40]; Mutriku wave plant in Spain (296 kW capacity) [41]; and REWEC3® project in Italy [42]. However, major advances have been made recently in OB devices, such as the ones performed by Ocean Technologies® [43] and Carnegie Wave® [44] (point absorbers). Promising new oscillating water surge converters have also been released recently by AW-Energy's WaveRoller® 0.3 MW. An ongoing project in Portugal may lead to the introduction there of WaveRoller® farms (with up to 24 integrated units) in the near future [45].

2.2.4 Levelized cost of electricity

One of the most important metrics to assess economic readiness of an electricity generating technology is the Levelized Cost of Electricity (LCOE). This is a very useful economic measure for comparing the lifetime costs of generating electricity within several generation technologies. The lifetime costs that should be considered are among the following groups: capital costs, operation and maintenance costs and disposition costs. Financing costs are internalized in the LCOE calculation, which by considering tax benefits, includes depreciation that may provide a tax shield. The LCOE can be viewed as a tool for comparison of different electricity generation technologies [46].

In the last years, the LCOE for renewable energy technologies has been falling (see Figure 2.4) and it is becoming increasingly below the costs of conventional fossil fuel generation. This is even more obvious, when considering CO_2 emission certificate costs [1]. The latest data regarding 2020 [47] shows that, despite costs varying strongly from country to country, global weighted-average LCOE from new capacity additions of onshore wind declined 13%, utility-scale solar Photovoltaic (PV) declined 7% and offshore wind declined 9% compared with 2019. This sets the corresponding LCOE at 35 €/MWh for onshore wind, 51 €/MWh for solar PV and 74 €/MWh for offshore wind in 2020. Even more impressive is comparing actual LCOE for these renewable energy technologies with 2010 figures: there was a price reduction of 56% (onshore wind), 85% (solar PV) and 48% (offshore wind). This was possible due to the steadily improving technologies, economies of scale, competitive supply chains and improving developer experience.

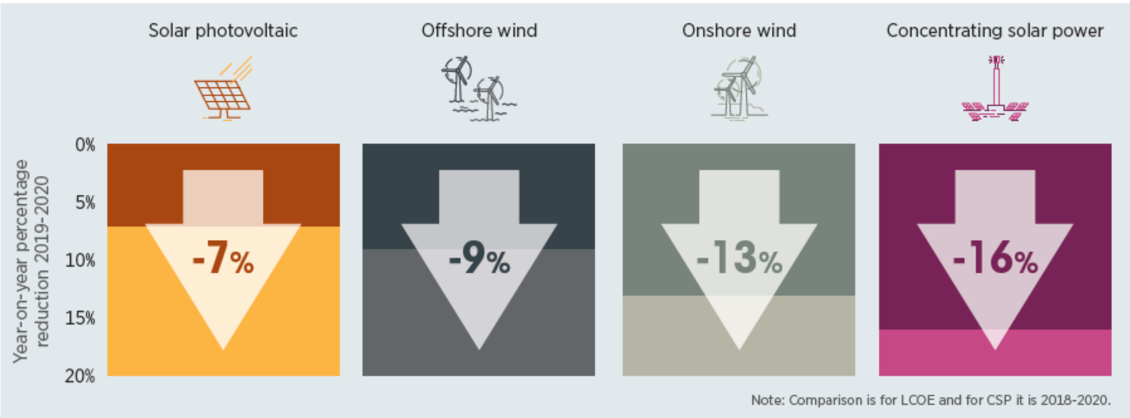

Figure 2.4: Global weighted-average LCOE from newly commissioned utility-scale solar and wind power technologies, 2019-2020 [47]

In ocean power technologies, as previously mentioned, the LCOE is still uncertain due its early lifecycle stage, and future projections are difficult to make. In 2015 the EC proposed targets for the LCOE for ocean power technologies: 150 €/MWh by 2025 and 100 €/MWh by 2030 for tidal energy technologies, with wave energy technologies reaching the same targets but with a five-year delay (150 €/MWh by 2030 and 100 €/MWh by 2035). For achieving such targets, technology costs must reduce by about 75% from 2016 values [48].

Data from current European demonstration projects (FloTec, Meygen) and the latest publications [48–50], assess that the current LCOE of tidal stream is 350 €/MWh. Still, the costs will drop substantially when volumes increase, with the LCOE expected to decrease for 180 €/MWh at 100 MW of installed capacity, to 110 €/MWh at 1 GW, and to 97 €/MWh at 2 GW. In [50], the cost reduction can occur through initial accelerated reductions (economies of scale, turbine size, volume and accelerated learning), industry learning and innovation. In [13], now regarding wave energy technology, considering a high-growth industry scenario, it would be possible to anticipate EC targets and achieve an LCOE of 110 €/MWh in 2030, with 494 MW installed. However, despite larger capacity development means a significant cost reduction, with still so low capacity deployment made so far, assumptions of cost reduction can be too optimistic and need to be viewed with caution. Besides, these projections, based on increases in deployment, can only be achieved with sufficient financial support mechanisms. While even the most optimistic scenario is considerably higher than cost projections for other renewables, the extra charge could be justified, if this ocean power technology provided additional benefits, such as predictability and steady energy supply. Also, niche markets could be seriously competitive, such as islands, which depend on costly fossil fuel imports [16].

2.3 Future Energy System Scenarios Projections

As previously mentioned, the present work will use a developed dataset of electricity generation historical data and future scenarios for the electricity generation sector. To develop it, updated energy publications were reviewed. In this section, it will be described the main sources of data for the present work. The publications reviewed have multiple sources: energy agencies, academia, utilities, non-profit organizations, and others. The main results of the future scenarios modelled in the literature concern energy-related CO_2 emissions, energy demand, fossil fuels use, renewable energy share both in total final energy consumption and in electricity generation, electrification share of final energy and many other energy metrics. The electricity generation system is also modeled, so one might understand how much capacity must be installed to fulfill future energy needs.

For obvious reasons, energy agencies publications were reviewed first. Every year, the International Energy Agency (IEA) publishes a World Energy Outlook (WEO) report analyzing energy demand and supply trends and providing valuable insights. Other key subjects usually discussed in these reports are emissions, environmental protection, energy security and economic development. 2021 WEO is dedicated to the emerging new global energy economy. It highlights how this new economy managed to thrive despite the heavy blows inflicted on economies in general by Covid-19 lock-downs. However, it reminds us that still a lot needs to be done. In particular, it points out how conservative the status quo is. As an illustration, it remarks that despite the current availability of highly cost-effective solutions to the problem of reducing emissions, so that the 1.5 ºC target may be reached, today's pledges will enable us to reach by 2030 only 20% of the necessary emissions reduction. But incentives exist; as a matter of fact, the authors of the report consider that there is a huge potential prize awaiting those who will be able to leap to the new energy economy. On the other hand, 2021 extreme weather events highlighted the enormous costs of inaction. This report was published a few weeks before the UN Conference of the Parties (COP26) in Glasgow; ironically, one of its conclusions was that if we are to make this decade the decade of massive clean energy deployment, then COP26 conclusions would need to contain unmistakably clear commitments of the parties regarding future energy policies [5].

As usual, besides the latest energy data, the report sketches four scenarios for the development of the global energy system: net zero emissions by 2050, sustainable development, the announced pledges and stated policies scenarios. The net zero emissions by 2050 scenario assume, obviously, that the global energy sector will reach the net zero emissions target; the sustainable development scenario assumes the implementation of further clean energy policies and investments; the announced pledges scenario assumes that all of the climate commitments made by governments around the world will be met fully; and stated policies scenario holds a more conservative vision for the future, assuming that not all governments will achieve the announced goals. All these scenarios use as inputs economic and population assumptions, energy and carbon prices, and technology innovation, deployment and costs [5]. Other relevant IEA publications address future energy technology perspectives [51], forecast and analyze renewable energy technologies [52] and draw road maps for achieving net zero emissions by 2050 [53].

International Renewable Energy Agency (IRENA) also releases periodic publications dealing with the energy and climate agenda. IRENA's most recent reports [7, 54] present road maps for the 2050 energy sector analyzing future global socioeconomic consequences and assessing regional techno-economic performances. Starting from the baseline energy scenario (Paris Agreement 2015 policies), IRENA forecasts three different scenarios: 1. planned energy scenario, based on current energy plans; 2. transforming energy scenario, based on renewable energy sources and improved energy efficiency; 3. 1.5ºC scenario, limiting global average temperature increase to this value by the end of the century. A deeper decarbonization perspective is also sketched according to which energy is reduced and process-related CO_2 emissions are brought down to zero by 2050-2060. IRENA also publishes yearly reports containing updated renewable energy production and capacity statistics [55, 56]. A 2022 report on NDCs and the renewable energy targets in 2021 attests that, in spite of the recent increase in ambition, many more changes need to be undertaken if the world is to be put on a path enabling us to keep the rise in global temperature below 1.5 ºC [57].

Several reports from different energy companies are also available; all of them are highly relevant for the discussion concerning the future of energy. BP® describes business-as-usual, rapid and net zero scenarios [58]; Shell® analysis compares waves, islands and sky 1.5 scenarios until 2100 [59]; DNV® details its energy transition outlook [60]; Total Energies® presents momentum and rupture scenarios [61] and Equinor® focuses in reform, rebalance and rivalry scenarios [62]. Moreover, they bring to the fore the private sector's perspective regarding the possible evolution of the global energy industry. All models in these scenarios consider the socioeconomic consequences of the covid-19 pandemic. Distinct networks of professional services related to energy business areas also present periodic reports displaying their views on energy's future [63–65]. Figure

2.5 below present examples of several future energy system scenarios publications.

Figure 2.5: Future energy system scenarios publications [7, 16, 25, 34, 37, 59]

The UN also issues publications containing the modeling of energy scenarios. In 2019, the IPCC issued a report focusing on the impacts associated with a global warming of 1.5 ºC above pre-industrial levels and related global GHG emissions [66]. This report defines two pathway groups (1.5 ºC and 2 ºC), and divides them further into classes (bellow 1.5 ºC, 1.5 ºC-low-OS, 1.5 ºC-high-OS, lower-2 ºC, higher-2 ºC). Within these classes, multiple scenarios are then portrayed, reaching a total of 222 hypotheses for the future. UN documentation also displays the NDCs defined by different countries, and their long-term strategies for energy and climate change.

Within the EU, EC's Joint Research Centre (JRC) publishes science reports in order to prepare and assist policymakers. After the publication of an EU reference scenario [67], in JRC's latest energy outlook [25], four different scenarios regarding the future of energy were put forth: CurPol, NDC-LTS, 1.5 ºC-Uniform, 1.5 ºC-Differentiated. The first, assumes a world where currently existing GHG emissions policies, renewables deployment and energy efficiency policies are implemented; the second, considers NDCs policies in the medium term and longer-term strategies in the long term; the third, represents an economically efficient pathway to the 1.5 ºC climate target, assuming a single global carbon price; the last, is consistent with the same temperature target, but assumes a different regional and temporal allocation of the mitigation efforts. There are analyses and results for all G20 countries. It is also possible to find the NECPs within EU documentation, where EU countries state their ambitions for the 2021-2030 period. Outside the EU, several countries also make public their vision regarding the future of energy. Canada, Japan and the United States of America issued very complete reports on this topic [68–70]. Greenpeace also issued a very insightful publication referring to three possible energy scenarios: reference, energy revolution and advanced energy revolution scenarios [71]. Another respected reference on potential climate change outcomes that is often quoted is [72]. Three scenarios are there modeled: 5 ºC, 2 ºC and 1.5 ºC scenarios. Finally, Eurelectric also discusses periodic decarbonization targets for 2050 (models in which 80%, 90% and 95% reductions in emissions are reached [73]).

Projections regarding the future of ocean energy are not abundant in the reports referred to above. This is mainly due to current limited technology development and deployment worldwide. Nevertheless, some of these reports give us insights regarding both ocean energy capacity in the future and its share in the future electricity generation system [5, 59, 71, 72] (see Figure 2.6 and Figure 2.7). In particular, [59] details tidal and wave technologies. As it may, specific ocean power reports were reviewed, in which it was possible to find current projections for ocean energy deployment. Ocean Energy Systems (OES) is an intergovernmental collaboration project associating countries under the IEA framework that aims to connect individuals and organizations working in the ocean energy systems sector to accelerate its economic viability in an environmentally acceptable manner and therefore promote its social acceptance [74]. OES publishes annual reports describing yearly achievements and international activities [75]. It put forth a strategic plan for 2022-2026 containing well-defined objectives for the ocean energy sector [76]. IRENA and the EC JRC also produced several publications addressing the potential for electricity generation in the coming decades of ocean power technologies [16, 19, 38]. The latest of these publications [34, 48, 77] show the impact ocean energy can have on the European electricity generation system and its economy in the forthcoming years. Another good source of information on this topic is Ocean Energy Europe (OEE), a non-profit organization, which claims to be the largest ocean energy professionals network. OEE edits mainly annual key trends and statistics covering tidal and wave technologies in Europe but it also develops global outlooks [37]. For the future, OEE foresees two different 2030 deployment projections: one is a high growth scenario, picturing a European recovery fully driven by decarbonization; the other is a low growth scenario, according to which Europe simply delivers the Strategic Energy Technology Plan targets [13, 49].

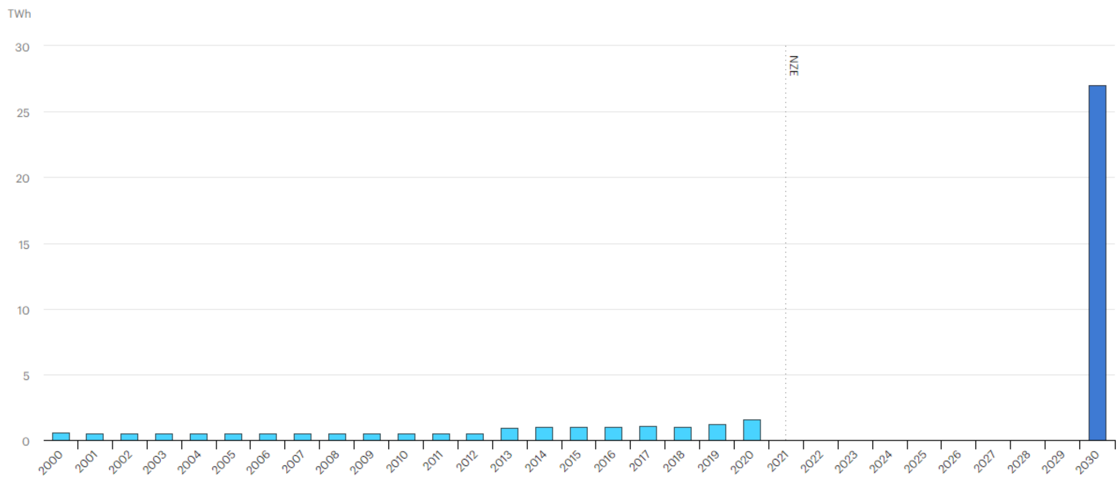

Figure 2.6: Global ocean power generation in the IEA net zero emissions scenario, 2000-2030 [78]

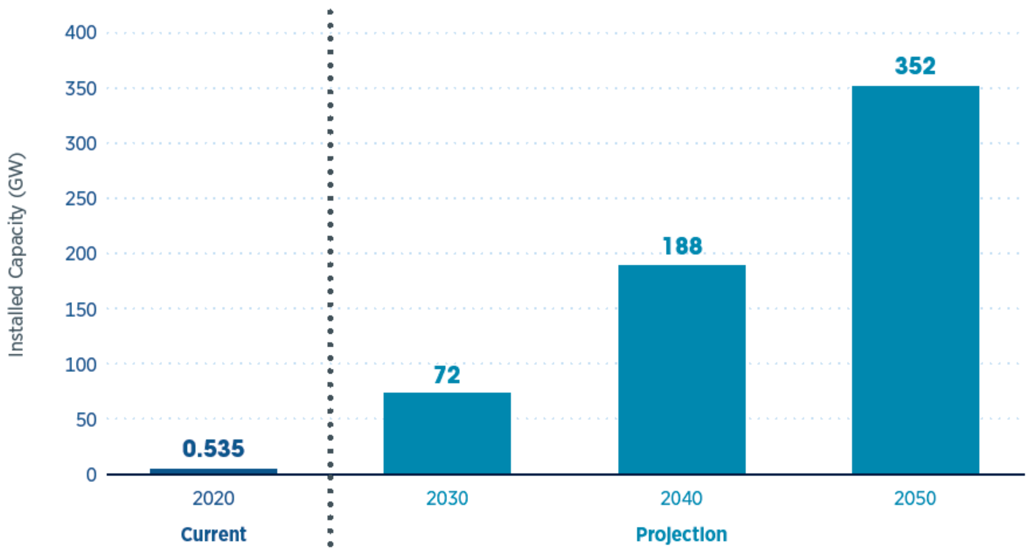

Figure 2.7: Global ocean current and projected capacity according to IRENA 1.5-S, 2020-2050 [7]

3

Methodology

This chapter is dedicated to describing the methodology underlying this work. It begins with a review of a sample of the relevant literature originating in a variety of sources. This review is guided by the purpose of studying different future scenarios regarding the energy system. Next, in order to perform a meta-analysis using the RRS Model, a dataset needed to be gathered. It turns out that the model developed by Project Drawdown is an "Excel workbook that contains all of the data necessary to calculate the greenhouse-gas reductions and financial implications associated with a solution and allows users to change important inputs and see how the results are impacted" [79]. It thus admits being used as a tool in order to study how conventional electricity generation technologies (coal, natural gas, oil), and their respective emissions, may be replaced by alternative solutions. In particular, by the adoption of ocean power systems at a European Union level.

Below, the Project Drawdown Excel-based model will be described. Its underlying parameters and inputs will be detailed and the data collection process will be explained (namely, which assumptions were made and which criteria were used in selecting future energy scenarios). This process focused on three main types of input: Total Addressable Market (TAM) data, Adoption data and Variable Meta-Analysis (VMA) data. These data comprise emissions, financial and technical variables; distinct sensitivity analyses were carried out in order to understand how the behaviour of financial variables can affect the results.

3.1 Project Drawdown Reduction and Replacement Solutions Model

As mentioned above, Project Drawdown RRS Model was used in [4] to compare and rank the different climate solutions assessed within the electricity sector. This Model evaluates the proposed technological solutions for electricity generation and models the possibilities such technologies display for replacing conventional ones (coal, natural gas, oil). The model is divided into four sections, each of them comprising several Excel workbook sheets, which account for the following:

- Basic sheets
- Advanced sheets
- Developer sheets
- Additional sheets

The period analyzed in the RRS Model is the period 2021-2050; the currency unit used there is the 2014 USD; and the Functional Unit of measure for electricity generation is TWh. To update financial inputs, an inflation adjustment factor was used to convert historic USD to 2014 USD [80]. However, for this work context, results will be presented in 2022 €. Regarding the functional unit of measure, it represents the output produced by the solution, or, as described in [79], the 'function' of the solution. This unit is not to be confused with the Implementation Unit of measure, represented by the number of installations, or 'implementations', of the solution. The two units are, however, interconnected: the implementation unit creates the function that is in demand. The implementation unit of measure for capacity installed for the electricity sector is TW.

In this section, a brief overview of the model's content will be offered focusing specially on the sheets carrying more impact to the present work.

3.1.1 Basic sheets

There are nine different sheets to be found in the Basic sheets section. It is important to highlight four of them. The first of these is the Welcome sheet, where the model and the most important of its sheets are presented, together with a brief explanation of their contents (see Figure 3.1). The second one is the Basic Controls sheet, where the most commonly used parameters of the model are available for editing. The main outputs of the model are also displayed here, namely the overall financial and GHG reduction results. The third one is a Data Interpolator sheet, a fundamental tool for the usability of the model. It allows users to interpolate and extrapolate data for the model inputs, namely for TAM and Adoption data. In the literature reviewed, it is not always possible to find TAM and Adoption projections for every year of the analysis; however, yearly data are a mandatory input for the RRS Model. Thanks to this interpolator sheet, users can cope with this specification. The model allows users to choose from a predefined set of options for the interpolation in order to get the best trend line: linear trend, 2nd order polynomial, 3rd order polynomial, exponential trend and S-Curve (logistic function).

Finally, there is the Total Addressable Market Datasheet, which contains one of the main inputs for the model. It is where users can insert a set of future growth scenarios for the electricity generation market for the period under analysis. The RRS Model allows the upload of fifteen different future energy scenarios, displaying yearly data for electricity generation for the period 2021-2050, and of historic data for the period 2012-2020.

Within the context of this sheet, the model also computes annual values for high, medium and low market growth scenarios using multiple regression fits. The above-mentioned fifteen different market growth scenarios are ranked in four categories: Modest TAM Growth (four scenarios), Intermediate TAM Growth (five scenarios), Ambitious TAM Growth (five scenarios) and Very Ambitious TAM Growth (one scenario). TAM data includes all technologies for electricity generation - fossil fuels and renewable sources - that offer the same function.

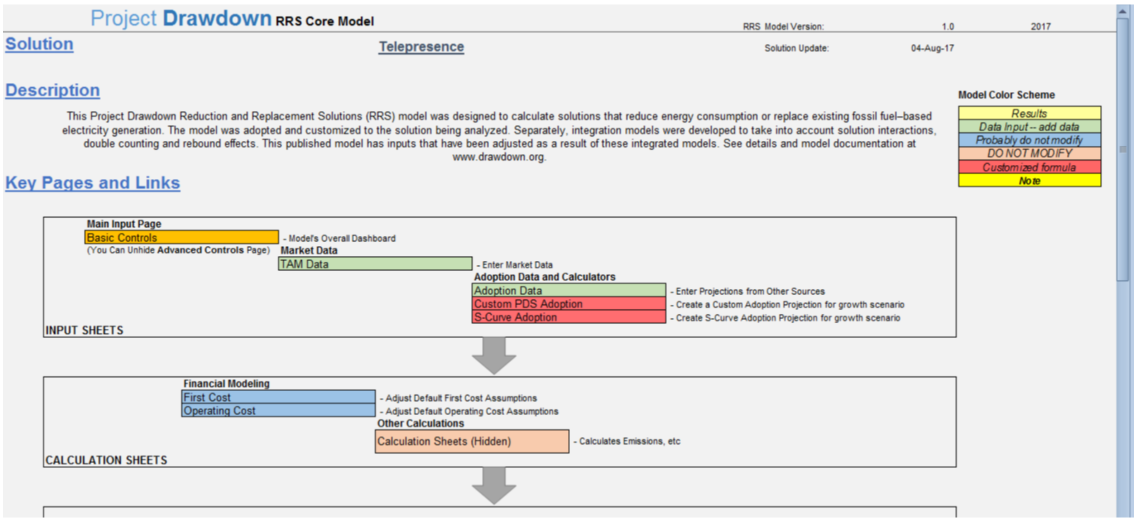

Figure 3.1: RRS Model Welcome sheet [79]

3.1.2 Advanced sheets

The Advanced sheets section comprises also nine sheets; three of them will be detailed. These are the following. First, there is the Adoption Datasheet, another major input for the RRS model. It is here that the user can insert a set of future adoption scenarios associated with the proposed solution for the period under analysis. It is very similar in shape to the TAM Datasheet. It allows, for each solution, the upload of sixteen different adoption scenarios with yearly data for electricity generation for the period 2021-2050, and historical data for 2012-2020. The model also estimates here annual values for high, medium and low adoption scenarios. The sixteen different adoption scenarios are ranked into four categories: Modest Growth (four scenarios), Intermediate Growth (five scenarios), Ambitious Growth (six scenarios) and Very Ambitious Growth (one scenario). Adoption data are the data of electricity generation by ocean power technologies.

The second of these sheets is the Variable Meta-Analysis sheet. It plays a key part in model inputs. This sheet is to be used for collecting data on the various key assumptions used to calculate the model outputs. It is here that the emissions, financial and technical inputs are uploaded. In order to provide the model with these variables, data from both ocean power technologies and conventional fossil fuels (coal, natural gas, oil) are used, since the latter are the current solutions to be replaced. At least thirty-three emissions, financial and technical different variables can be used in the model. For each variable, several data points can be collected from the literature, and the model organizes the data by source, world region and specific geographic location, year and original units. It is however necessary to convert the original units to the functional/implementation units of the model or the currency unit for some financial variables. In this sheet, the model performs a sensitivity analysis for each variable based on standard deviations around the mean of all data points collected. The standard deviation value defined by the model is the value 1. The results are expressed as Mean, High and Low and appear on the Advanced Controls sheet.

The Advanced Controls sheet can be described as the main output of the model. Similarly to the Basic Controls sheet, one can find here the model outputs and the adjustable parameters of the model. However, one finds here a much higher level of detail; thus, this sheet is the appropriate one to use in order to perform sensitivity analyses and to get a very clear understanding of the model's results. The key results are divided into three categories: Adoption results, Financial results and Emission results.

In terms of Adoption results, the model presents the increase by 2050 of the implementation unit adoption (TW) and the functional unit adoption (TWh) by comparing several Project Drawdown Solution (PDS) Adoption scenarios with a Reference (REF) Adoption Scenario. The REF Adoption Scenario is where the Adoption of the proposed technology remains a fixed percentage value of the TAM until 2050; the PDS Adoption scenarios are those used as inputs in the Adoption Datasheet, both individually or aggregated in the respective categories.

Regarding the Financial results, the model computes marginal first costs, net operating savings and lifetime operating savings (Billion €). The marginal first costs represent the increase in first costs for the emissions reduction calculated for the period under analysis; the operating savings represent the savings obtained by all implementation units for the period of study; and the lifetime operating savings relate to the savings for the entire lifetime of all implementation units. The Financial results displayed in this work will show whether replacing the existing fossil fuel solutions for electricity generation by ocean power technologies incurs in additional costs or in desired net savings.

For the Emission results, the model calculates the sum of all emissions (Gt $CO_{2\text{-eq}}$) reduced by comparing the PDS Adoption scenarios with the REF Adoption Scenario over the period under analysis. The Emission results displayed in this work will exhibit the amount of emissions that can be avoided by using ocean power technologies for electricity generation during the period under analysis.

As previously explained, along with the TAM and Adoption data, the model outputs rely on the emissions, financial and technical variables collected in the literature. These variables, provided in the VMA sheet, can be chosen and edited in the Advanced Control sheet, in order to understand their impact on the final results.

3.1.3 Developer and Additional sheets

The model contains a set of seven different Developer sheets that are locked for editing in order to protect the integrity of the model. It is in these sheets that the financial modeling necessary to compute the financial results is performed. This modeling adjusts both the default first costs and operating costs assumptions. It is also here that the calculations for emissions reduction are performed; the latter take into account the emission factors related to electricity generation (kg $CO_{2\text{-eq}}$/kWh).

For some models additional sheets may be used, containing specific data for the solutions studied in relation with custom calculations. These custom calculations may not conform easily with the RRS Model, so it is important to be in possession of the sheets necessary to perform them. In the case of the present work, these sheets were used mainly as an auxiliary to upload all raw data points from the literature before inserting them in the corresponding sheets.

3.2 Data Collection

In the previous section, it was possible to understand the three main inputs for the Project Drawdown RRS Model: Total Addressable Market data, Adoption data and Variable Meta-Analysis data (which include emissions, financial and technical variables). These inputs were compiled through literature search having as its objective the assessment of the potential of ocean power to reduce GHG emissions (taking into consideration also its total net costs and potential operational savings at a European Union level). As previously explained in [4, 8], the Project Drawdown RRS Model was used in all solutions put forth in order to revert global warming with a global perspective, including the ocean power technology solution. The aim is now to conduct a similar approach on a drill-down regional level focused on the European Union.

The primary data sources used in the research undertaken for writing this work were already presented in section 2.3. The aim of this research was to collect data from the largest possible number of different stakeholders. It is true that all such publications address the same subject - modeling future energy scenarios. However, their models are different (e.g. Integrated Assessment Models, Energy-Environment-Economy Models, Energy System Models) and are based on a disparate set of complex and multidisciplinary variables (e.g. population and economic growth, gross domestic product, pollutant emissions).

Depending on the nature and format of such publications, the data collection process was performed in different ways: some publications provided free access to the results contained in their model databases [5, 7, 25, 62]; others chose to insert the data in tables within the published reports [69, 71]; in a few cases, however, the data had to be collected by visual inspection from figures and charts [72, 73]. It is also interesting to highlight that for the TAM and Adoption most of the publications provide data points with five or ten years intervals: in order to cope with the model, the interpolation sheet was used to obtain yearly data values. Another important topic to address was the geographic definition of the data. The present work aims to access ocean power potential in the European Union, which, in the most recent publications, is defined as a political and economic union of twenty-seven member states. However, since the withdrawal of the UK from the EU took place only very recently, in many of the publications the EU is taken to be a union of twenty-eight member states. Some other publications define the region targeted in their study either as OECD Europe or as Europe *simpliciter*. The way this issue was addressed with TAM and Adoption data is explained in the following sections.

The data collection process was performed in order to include the most updated publications; the number of reviewed publications issued in 2022 reflects this. Between TAM, Adoption and VMA data collection, more than 200 publications were consulted and 72 future energy scenarios were identified. An extensive list of these publications as well as of the different scenarios contained in them may be found in Appendix A.

3.3 Total Addressable Market

As already discussed, the Total Addressable Market data to be used in the Project Drawdown RRS Model must include the future growth scenarios for the EU electricity generation market for the period under analysis 2021-2050, as well as the historical data for the period 2012-2020. The historical data are important for the model for two reasons: on the one hand, when interpolations are performed, they provide a strong foundation for future projections made from few data points; on the other hand, they allow the user to understand the coherence of future projections.

TAM historical data were elicited from two different sources: data concerning electricity generation from conventional sources (coal, natural gas, nuclear and oil) were obtained from the IEA; data concerning electricity generation from renewable sources (bioenergy, geothermal, hydro, ocean, solar, wind) were obtained from the IRENA. However, since the data concerning electricity generation from renewable sources for 2020 were not yet available in IRENA, both conventional and renewables data for 2020 were obtained from IEA. It has to be reminded though that the historical data for the EU include the electricity generation data from the UK. In order to obtain TAM historical data from the EU-27, UK values, as indicated by the IEA and by the IRENA, were subtracted from them.

Figure 3.2 shows the electricity generation by source for 2020 in the EU, the last year used for the historical data. Although renewable sources already accounted for almost 40% of the electricity generated in 2020, the two primary sources are still nuclear energy and natural gas.

In the case of the future growth scenarios for the EU electricity generation market for the period under analysis (2021-2050), data from several different publications were used. Among the 72 future electricity generation scenarios reviewed, thirty scenarios were chosen to undergo the interpolation process, for yearly data. The main criterion underlying the choice of these thirty scenarios was the one of selecting as much diversity as possible. As a matter of fact, many of the scenarios available, usually originating in the same source, displayed very similar data, sometimes only differing in one or two data points; most of these scenarios were not selected to undergo the interpolation process. Among the thirty chosen scenarios, there were one hundred and three data points, usually distributed in intervals of five to ten years in the period under analysis.

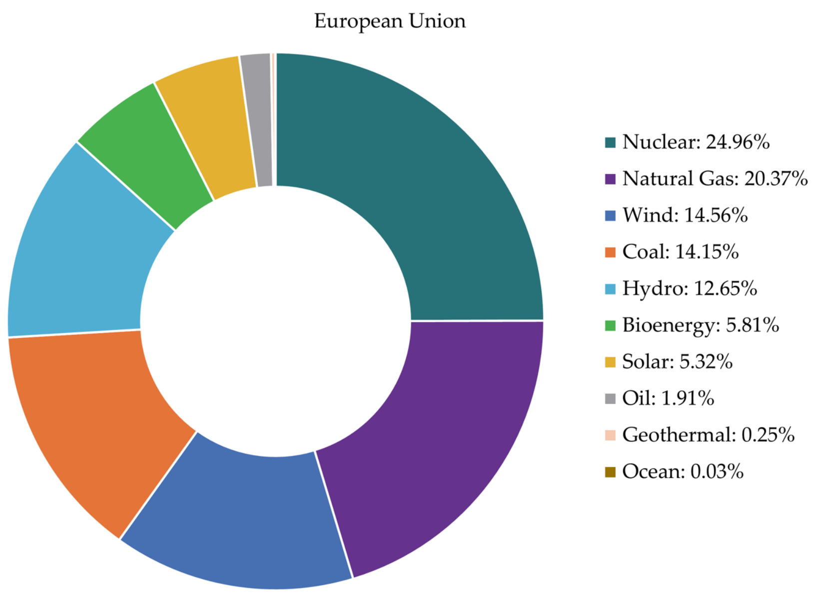

Figure 3.2: Electricity generation by source, EU, 2020; based on [5, 52]

Once the thirty selected scenarios underwent the interpolation process, it was necessary to select the fifteen final scenarios to be used as the TAM data for the model (this is the maximum number of scenarios it allows). The criteria for selecting the TAM future scenarios were as follows, by order of relevance:

- The publishing date of the data source: in general, the latest socioeconomic and technological trends are to be found in more recent publications; thus, the future energy projections contained in the latter tend to be more trustworthy
- Data sources diversity: the selected scenarios should reflect the diversity of approaches and inputs characterizing the energy sector community (e.g. energy agencies, utilities and academia) and therefore take into account their respective contributions
- Diversity of scenarios: the scenarios chosen should also be intrinsically diverse; this means that both scenarios reflecting current policies, as well as scenarios assuming disruptive technological advances or events needed to be included in the final lot;

similarly, scenarios more focused on increasing electricity generation from renewable sources ought to be included alongside scenarios focusing on carbon dioxide removal or on achieving higher rates of energy efficiency

- Geographic definition: EU-27 TAM future scenarios

As explained in subsection 3.1.1, it was necessary to group the fifteen different market growth scenarios into four categories. The criterion for grouping the scenarios was the size of the electricity generation market in the EU by 2050. The Modest Growth category comprises scenarios in which the size of the market is smaller than 3600 TWh; the Intermediate Growth category comprises scenarios in which the size of the market lies between 3600 TWh and 4800 TWh; the Ambitious Growth category comprises scenarios in which the market size lies between 4800 TWh and 7000 TWh; and Very Ambitious Growth category consists of the highest value for electricity generation in 2050.

3.4 Adoption

The Adoption data to be used in the Project Drawdown RRS Model needed to include the future adoption scenarios for ocean power technologies for the period under analysis (2021-2050), and historical data for 2012-2020. For the historical data, the procedure followed in the case of TAM historical data was followed in this case also; the source for the historical data 2012-2019 was IRENA; however, the data of electricity generation from renewable sources from 2020 were not available in IRENA yet; thus, the data for the last year of the historical ocean power data was mined from IEA. Figure 3.2 shows that, in 2020, ocean energy accounted for only 0.03% of the electricity generated in the EU.

In the case of the adoption scenarios for ocean power technologies for the period under analysis (2021-2050), data from several different publications were used. Due to their limited development and deployment, ocean power technologies have a very small share in current electricity generation; as a consequence, future projections regarding ocean energy are not abundant in the main publications reviewed (see section 2.3). However, it is possible to find other scenarios in specific ocean power technical reports. For the case of ocean energy, it was possible to collect twenty-one scenarios from the literature reviewed. There were eighty-four data points in the twenty-one scenarios selected, usually distributed in intervals of five to ten years in the period under analysis. All of these twenty-one scenarios underwent the interpolation process, in order to provide us with yearly data.

Once the interpolation process was over, it was necessary to select the sixteen final scenarios to be used as Adoption data for the model (again, this is the maximum number it allows). The criteria for selecting the Adoption future scenarios were the same as those used for selecting the TAM future scenarios (this time with only five scenarios to be excluded). An important consideration regarding adoption data is that, due to the very early stages of ocean technology development and the unpredictability of the market, no distinction was made between the adoption of wave or tidal technologies.

As explained in subsection 3.1.2, the sixteen different market growth scenarios were grouped into four categories. As in section 3.3, the criterion for grouping the scenarios was the electricity generation market in the EU by 2050 (here for ocean power technologies): Modest Growth category comprises scenarios in which the market size is smaller than 50 TWh; Intermediate Growth category comprises scenarios in which market size lies between 50 TWh and 100 TWh; Ambitious Growth category comprises scenarios in which market size lies between 100 TWh and 165 TWh; and the Very Ambitious Growth category exhibiting the highest value for electricity generation from ocean energy by 2050.

3.4.1 Reference adoption scenario

As explained in subsection 3.1.2, to compute Adoption results, it was necessary to define a Reference Adoption scenario. Thus, the REF Adoption scenario was fixed at the current adoption contained in the TAM: in 2020, the last year used for historical data, ocean energy accounted for 0.03% of the electricity generated in the EU. This value will remain constant in the REF Adoption scenario, assuming that the total number of ocean energy power plants adopted grows at the same pace so that the percent adoption is maintained at its starting value in 2020.

3.5 Variable Meta-Analysis

Having defined the scenarios for the TAM and Adoption data to be used in the Project Drawdown RRS Model, it was necessary to provide the Variable Meta-Analysis data to the model. As referred in subsection 3.1.2, this data includes emissions, financial and technical input variables. Emissions variables are related to the direct and Indirect Emissions for the proposed solution; financial variables represent all costs associated with the lifetime of conventional and ocean technological power plants, as well as proposed learning rates; technical variables are the ones concerning lifetime capacity and average annual use for both conventional and innovative technologies. Also other input variables can be used in the model associated with the creation of jobs and materials used for the proposed solution:

- Emissions input variables: Direct and Indirect CO_2 Emissions
- Financial input variables: First Costs, Fixed Operation and Maintenance (FOM) Costs, Variable Operation and Maintenance (VOM) Costs, Fuel Prices, Learning Rate Factor
- Technical input variables: Lifetime Capacity, Average Annual Use
- Jobs and Materials input variables

Among the VMA data collected were data from conventional technologies, since the model uses these data for computing final results. Since these technologies are those that need to be replaced, VMA conventional data were compared in the model with the VMA data from ocean power solutions. However, since the conventional data include inputs from different types of technology (coal, natural gas, oil), it was necessary to weigh in each of these technologies, so that their share in the actual EU electricity generation mix could be reflected. Thus, Figure 3.2 shows the weights given for conventional technologies in the VMA data.

Table 3.1 and Table 3.2 show the diversity of sources and data points collected for the main emissions, financial, technical and jobs and materials input variables:

Table 3.1: VMA data points and sources for conventional technologies

Input Variable	Units	Data Points (#)	Number of Sources (#)
First Costs	US$2014/kW	201	13
FOM Costs	US$2014/kW	110	5
VOM Costs	US$2014/kWh	62	5
Fuel Prices	US$2014/kWh	183	13
Lifetime Capacity	hours	32	7
Average Annual Use	hours	68	5

Table 3.2: VMA data points and sources for solution

Input Variable	Units	Data Points (#)	Number of Sources (#)
Indirect CO_2 Emissions	t $CO_{2\text{-eq}}$/TWh	45	6
First Costs	US$2014/kW	204	16
FOM Costs	US$2014/kW	60	6
VOM Costs	US$2014/kWh	18	3
Learning Rate Factor	%	40	4
Lifetime Capacity	hours	15	11
Average Annual Use	hours	69	13
Jobs Creation	Jobs/TW	19	9
Materials Use	t/TW	16	1

Regarding the VMA data points listed above, it is important to say that there was a selection criteria for the financial input variables related to costs. In the VMA sheet of the Project Drawdown RRS Model, it is possible to choose which variables to include in the analysis and scenarios modelling, by excluding some inputs. An option is embedded in the model. As a matter of fact, the criterion for excluding such VMA data is the following: future projections values are to be excluded both for conventional and ocean energy technologies. In the case of conventional technologies costs, only recent data, posterior to 2015, were used; and for both technologies, EU data were preferred. This means that in some variables with many data points, all non-EU data were excluded from consideration; however, in the case of other variables with less data points, EU and non-EU data were included in the model; this happened frequently in the innovative solutions VMA data. Considering what was done with the Adoption data, where no distinction was applied to wave and tidal technologies for the future scenarios, in the VMA sheet all variables for ocean technologies were included together in the calculations of Mean, High and Low values, despite their intrinsic differences. In fact, although tidal and wave energy technologies are both in an early stage of development, wave energy technology presents higher costs because it is a less mature technology.

3.6 Sensitivity Analyses

A series of sensitivity analyses were performed to assess how the different VMA data inputs impact the results. As explained in the previous section, the model computes Mean, High and Low values of the different VMA variables. In the Advanced Controls sheet, it is possible to select from within the different VMA variables, which of these three values (Mean, High, Low) to use in order to arrive at results. The sensitivity analyses focus on financial variables related to both conventional and ocean power technologies. The first set of results (the most important one) was obtained with all VMA financial variables set to their Mean values, while comparing the REF Adoption Scenario with the selected sixteen Adoption scenarios until 2050. The average of each Adoption category (Modest, Intermediate and Ambitious Growth) was also compared with the REF Adoption Scenario.

Four different sensitivity analyses were performed. In all of them the High value for the learning rate factor of the alternative solution was considered, as well as future projections of costs values for ocean energy technologies. In the first sensitivity analysis, the remainder of the financial variables was set to their Mean values for both conventional and solution technologies.

The second sensitivity analysis was performed considering, for conventional technologies, the High value for First, FOM and VOM Costs, and the High value for Fuel Prices; and maintaining the financial variables set to their Mean values for the alternative solution.

The third sensitivity analysis was performed considering the Low value for First, FOM and VOM Costs for alternative solution technologies; and maintaining the financial variables set to their Mean values for conventional technologies.

The fourth and last sensitivity analysis was performed considering the Low value for First, FOM and VOM Costs for alternative solution technologies; the High value for First, FOM and VOM Costs for conventional technologies, and the High value for Fuel Prices.

4

Results

In this chapter, the results obtained throughout this work are presented. As previously mentioned (see chapter 3), in order to assess the benefits of increasingly adopting ocean power technologies for electricity generation, a comparison with conventional technologies needs to be made. To do this, the Project Drawdown RRS Model required to be fed with different input types. These inputs resulted from the data collection process described above, including TAM, Adoption and VMA data. The data collection results are the first results to be presented in this chapter, together with the data sources their based on, and the interpolation processes that needed to be implemented. The results presented next are those that were obtained by using the Project Drawdown RRS Model, from now on mentioned as RRS Model EU Ocean Power. These results include Adoption, Financial and Emission results for the period under analysis (2021-2050). The sensitivity analyses that are also presented display the impact financial variables may have in future scenarios in which ocean power technologies are adopted.

4.1 Total Addressable Market

As explained above (see section 3.3), a wide variety of future electricity generation market scenarios was reviewed. Thirty of these were chosen to undergo the interpolation process. These thirty scenarios were then subject to a second and final selection. As a result, fifteen scenarios were selected. The criteria underlying this selection were also described above. These fifteen scenarios were then used as TAM data for the model. They are all presented in Table 4.1. This table also indicates wherefrom they were collected, year of publication, and the TAM Growth category of each scenario (Modest, Intermediate, Ambitious, Very Ambitious).

The scenarios selected were sourced from different types of institutions. They display a wide range of projections for the EU electricity generation market. The Modest TAM Growth category consists of four scenarios. The first one, Climate Analytics High Carbon Dioxide Removal (CDR) scenario, displays an illustrative pathway based on a world of sustainability-focused growth and equality. This scenario assumes a rapid technical development in the energy sector, with a special focus on CDR technologies and low CO_2 prices [81]. The Reform scenario developed by Equinor®, the Norwegian state-owned energy company, assumes that climate policies continue to tighten, but that not all stated policy targets are met. It assumes, more in particular, that governments will continue to prioritize short-economic growth over long-term climate goals, and that there will be a limited penetration of new solutions such as Carbon Capture Utilisation and Storage (CCUS) and hydrogen, which will remain too costly when compared to moderate CO_2 prices [62]. The Institute of Energy Economics, Japan (IEEJ) Advanced Technologies scenario is, in turn, very skeptical regarding carbon neutrality targets. This scenario points out that maximum reduction measures for CO_2 emissions are expected based on social opportunities and acceptability [69]. IEA's Stated Policies scenario also assumes a conservative pathway for the power sector, considering that not all announced goals for emissions reduction will be met [5].

The Intermediate TAM Growth category contains five scenarios. The Planned Energy scenario by IRENA is the primary reference case in [7], based on current energy plans, planned targets and policies, such as the countries NDCs under the Paris Agreement subscribed to. From JRC's latest energy outlook, two scenarios were selected: CurPol and NDC-LTS scenarios. CurPol considers that no new policies besides those that were subject to legislation by 2019 will be implemented; NDC-LTS assumes that NDCs objectives will be reached in the course of the 2025-2030 period, and that beyond 2030 long term strategies will be actively pursued [25]. Within the 2050 Roadmap Tool project - a collaboration between ClimateWorks Foundation (CWF) and Europe Climate Foundation (ECF) that analyzes possible pathways to reach net-zero GHG emissions - the Shared Efforts scenario can be found. It assumes that a comparable level of effort will be maintained across sectors and levels, putting no emphasis on any specific mitigation option [82]. The last of the scenarios included is the 80% Decarbonisation scenario by Eurelectric. This scenario assumes that a significant shift in present policies will occur that will remove the barriers that presently hinder the promotion of effective actions towards the decarbonization and electrification of the energy system; according to this scenario, the achievement of an 80% reduction in emissions by 2050 cannot be foreseen without the occurrence of such a shift [73].

Ambitious TAM Growth scenarios reveal bolder perspectives concerning the future of the power sector. The following scenarios fall under this category: i) the Transforming Energy scenario by IRENA, which, if realized, would set the energy system on the path to keeping the rise in global temperature to well below 2 ºC and to 1.5 ºC in the course of this century [7]; ii) the IEA's Announced Pledges scenario that assumes that NDCs and long term strategies will be met in full and on time by the corresponding countries [5]; iii) the Advanced Energy Revolution scenario, developed by Greenpeace, which defines an ambitious pathway towards a full decarbonized energy system by 2050 [71]; iv) the 1.5 ºC scenario from [72] which is mainly technical - it models technically possible measures and options only, not taking into account any of the potential societal risks or resistances the latter might originate; the options envisaged by this scenario would require immediate action; v) the 95% Decarbonisation scenario developed by Eurelectric, which assumes the early onset of technological breakthroughs and their large scale deployment made possible through the achievement of a robust global coordination [73]. Finally, another Climate Analytics scenario was selected to fulfill the role of Very Ambitious TAM Growth: the High Energy Demand scenario, based on an energy-economic general equilibrium model named REMIND, which links a macro-economic growth model with a bottom-up engineering-based energy system model [81].

Table 4.1: Publication scenarios in which TAM results are based on

Scenarios	Source	Publication Year	TAM Growth
High CDR	Climate Analytics	2022	Modest
Reform	Equinor	2021	Modest
Advanced Technologies	IEEJ	2021	Modest
Stated Policies	IEA	2021	Modest
Planned Energy	IRENA	2022	Intermediate
CurPol	JRC-EU	2021	Intermediate
Shared Efforts	CWF-ECF	2018	Intermediate
NDC-LTS	JRC-EU	2021	Intermediate
80% Decarbonisation	Eureletric	2018	Intermediate
Transforming	IRENA	2022	Ambitious
Announced Pledges	IEA	2021	Ambitious
Advanced Energy Revolution	Greenpeace	2015	Ambitious
1.5 °C	Teske	2019	Ambitious
95% Decarbonization	Eurelectric	2018	Ambitious
High Energy Demand	Climate Analytics	2022	Very Ambitious

All fifteen scenarios referred to above had multiple energy variable projections; however, and as previously explained, the data points collected from them were those concerning EU electricity generation market projections for the period under analysis (2021-2050). Regarding the interpolation process, the trend line that turned out to be most suitable for all scenarios was the 3rd order polynomial. However, it is necessary to refer that, at the end of the interpolation process, some data outliers remained in some projections; thus, an extra, step-wise, interpolation needed to be performed. Consequently, one or more of these outlier data points ended up being removed to smooth out the data trend and complete the data for some missing years.

Figure 4.1 exhibits the resulting projections for the evolution of TAM in the European Union until 2050. It is possible to elicit distinct behaviours from the projections obtained. REMIND scenario clearly projects an evolution of the electricity generation market in the EU well above any other projection, with a TAM value higher than 7 500 TWh by 2050. In contrast, High CDR scenario presents a curious trend: TAM size diminishes until 2035, and it reaches 2020 values again only around 2050. This is most likely associated with the fact that this model assumes sustainability-focused growth and equality. In between these extremes, the 2050 projections follow two tiers: 95% Decarbonisation, and 1.5 °C and Advanced Energy Revolution scenarios with a TAM size around 6 000 TWh. The other ten scenarios present results ranging from 3 000 TWh to 5 000 TWh market sizes. This may indicate that the results obtained in this tier might reflect deployments that are most likely. As a matter of fact, these projections are based on the more realistic and more prudent perspectives. Figure 4.2 compares the projection average values of electricity generation for 2025 and 2050 for each of the four categories discussed - Modest, Intermediate, Ambitious and Very Ambitious. The growth in TAM size is proportional to the different categories, ranging from a 17% increase in Modest TAM Growth category to a 125% increase in Very Ambitious TAM Growth category.

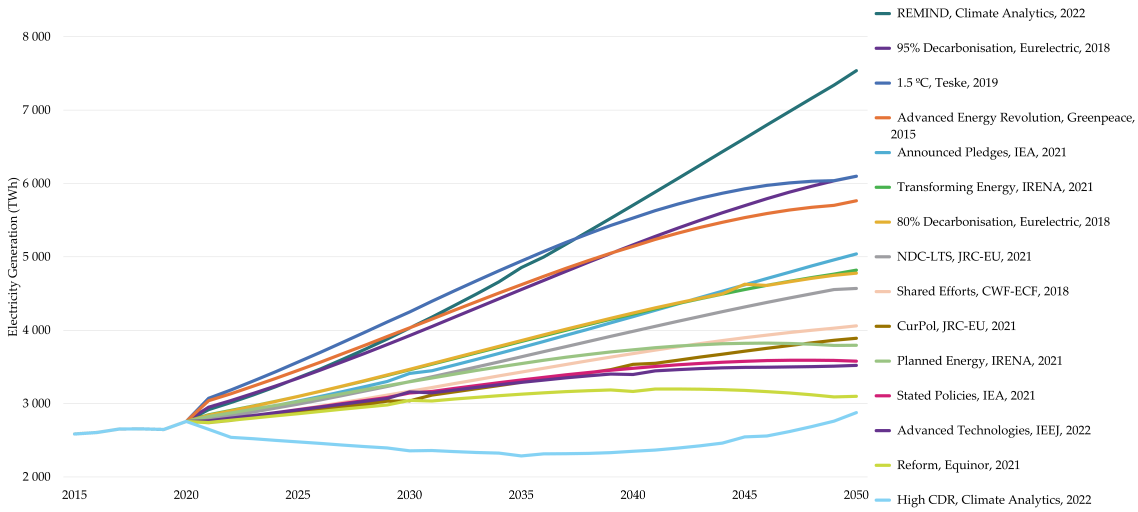

Figure 4.1: TAM projections results for the EU electricity generation market until 2050, based on fifteen literature scenarios

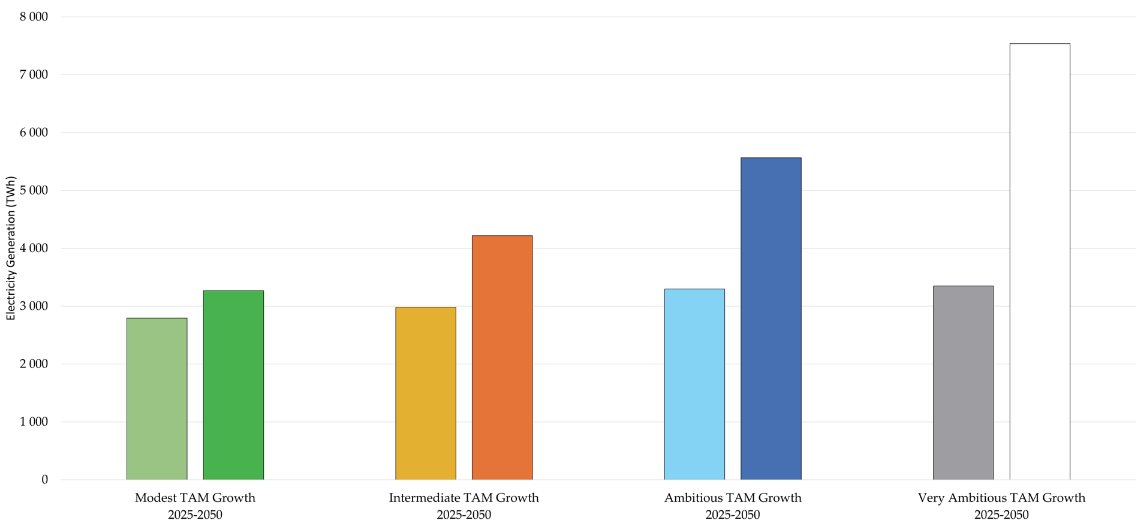

Figure 4.2: TAM categories results for the EU electricity generation market in 2025 and 2050

4.2 Ocean Power Technologies Adoption

Regarding the adoption of ocean power technologies, twenty-one scenarios were chosen to undergo the interpolation process (see section 3.4). Sixteen of these were selected for use as Adoption data for the model. Selection criteria were also described above. Table 4.2 exhibits the sixteen scenarios selected, detailing the organizations that authored them, the year of the publication, and the Adoption category (Modest, Intermediate, Ambitious, Very Ambitious) they were grouped in.

Most of the scenarios falling under this heading were collected from technical reports within the EU framework. The Modest Growth category contains four scenarios. From an EC Market Study on Ocean Energy two scenarios were selected: one having a Pessimistic outlook, assuming that pipelined projects are delayed and some of them are even cancelled; and a Medium forecast, considering that all pipelined projects are deployed, but with some delay [77]. The Low Growth scenario was obtained from OEE reports. According to this scenario, European ocean energy projects will only deliver the Strategic Energy Technology Plan targets defined, without going further in terms of technology deployment [13]. The High Nuclear scenario, developed by JRC, also pertains to this category: it addresses the impacts on technology and total system costs of a larger social acceptance of the nuclear option. It is one of the multiple scenarios sketched by JRC with its linear optimisation bottom-up technology model JRC-EU-TIMES. This model views ocean energy technologies as solutions for achieving a decarbonized EU in 2050. The definition of the scenarios was done for the first time in [83], but they were updated with new data in [84, 85].

There are five scenarios featuring in the Intermediate Growth category. One of them is The High Growth scenario. OEE admits in this scenario that the European recovery post-Covid-19 pandemic will be driven mainly by decarbonization efforts, which will strongly impact the ocean energy industry. This scenario reflects a specific political, economic, social and technological analysis [13]. Another one is the Optimistic scenario, developed by the above-mentioned Market Study on Ocean Energy. It assumes that all ocean energy planned projects are deployed and start at the proposed start date [77]. A third scenario was picked out from the EC policies documents. It is based upon the European Offshore Renewable Energy Strategy; there, the ocean energy capacity targets are set by the EC [30]. The two remaining scenarios are, first, IEA's Stated Policies scenario and, second, the JRC-EU-TIMES High Renewables scenario. The former was retrieved from the 2020 WEO edition (the edition that made EU ocean energy data available [86]); the latter explores the impacts a larger social acceptance and corresponding easiness of licensing of plants operating with renewable energy sources would have [85].

Finally, the Ambitious Growth category contains the six most enthusiastic scenarios regarding the adoption of ocean power technologies described in the literature. Two of them are Greenpeace's Energy Revolution and Advanced Energy Revolution scenarios.

The first was designed as a means to achieve a set of environmental policy targets resulting in an optimistic, but still feasible, pathway towards a widely decarbonized energy system by 2050. The second was described in the previous section, since it was already used in TAM Growth scenarios [71]. Similarly, the 1.5 ºC scenario developed by [72] was also included within the ocean energy adoption scenarios. Two further scenarios were selected for this category from JRC-EU-TIMES. One of them is the Delayed Carbon Capture scenario exploring the impacts of delayed penetration of CCUS options on technology. The other is the Low Biomass scenario investigating the impacts of lower biomass availability on the energy system [83]. Finally, the sixth scenario is the IEA's Sustainable Development scenario retrieved from the 2020 WEO edition. In it, clean energy policies and investments are put in place to achieve sustainable energy objectives, including the Paris Agreement goals [86]. Another JRC-EU-TIMES model scenario was selected to be the Adoption Very Ambitious Growth. It is the Low Solar and Wind scenario. In this scenario, the model explores the impacts concerns related to the reliability of transmission and distribution might have by the share of variable solar and wind electricity generation technologies in the total power system. Consequently, other reliable sources of renewable energy, such as ocean energy, would need to step up and augment their share in the total power system to achieve decarbonization [83].

Table 4.2: Publication scenarios in which Adoption results are based on

Scenarios	Source	Publication Year	Growth
Pessimistic Ocean Market	EC	2018	Modest
Low Growth	OEE	2020	Modest
Medium Ocean Market	EC	2021	Modest
High Nuclear	JRC-EU	2018	Modest
High Growth	OEE	2020	Intermediate
Optimistic Ocean Market	EC	2018	Intermediate
Stated Policies	IEA	2020	Intermediate
High Renewables	JRC-EU	2018	Intermediate
EU Offshore Renewable Strategy	EC	2020	Intermediate
Sustainable Development	IEA	2020	Ambitious
1.5 ºC	Teske	2019	Ambitious
Energy Revolution	Greenpeace	2015	Ambitious
Delayed Carbon Capture	JRC-EU	2018	Ambitious
Low Biomass	JRC-EU	2018	Ambitious
Advanced Energy Revolution	Greenpeace	2015	Ambitious
Low Solar and Wind	JRC-EU	2018	Very Ambitious

It is important to state that, as similar as it was explained in section 3.3 for TAM results, all sixteen scenarios referred above had multiple energy variable projections, but the data points collected from them, were the ones concerning EU electricity generation sourced by ocean energy for the period under analysis (2021-2050). Once again, upon the interpolation process, the trend line that turned out to be most suitable for all scenarios was the 3rd order polynomial. After performing the interpolation process, again in projections where some data outliers were present, an extra step-wise interpolation was performed. As so, one or more of these outlier data points ended up being removed in order to smooth the data trend and also to complete the data for missing years. This was particularly noted in the JRC-EU-TIMES model scenarios, since several of them only admitted electricity generation from ocean energy from 2030 onwards.

Figure 4.3 shows the resulting projections for the evolution of ocean energy technologies adoption in the European Union until 2050. Since the current share of ocean energy in the EU electricity generation system is residual (2020 historical data shows a 0.03% market share, which is equivalent of 0.7 TWh of electricity produced by ocean energy), most of the projections present exponential growths for the period under analysis. This is an expected behaviour due to the early stage of ocean energy technologies. The most ambitious projections comprise three JRC-EU-TIMES based on scenarios (Low Solar and Wind, Low Biomass and Delayed Carbon Capture scenarios) and the one based on Greenpeace's Advanced Energy Revolution scenario; these projections considered more than 150 TWh of electricity production in 2050. More conservatives are the projections based on IEA's or EC's scenarios: for instance, the Optimistic scenario from [77] admits ocean energy can power no more than 70 TWh of electricity in 2050. Interesting is also the projections based on OEE vision for EU ocean power market, ranging from 30 TWh (Low Growth scenario) to 60 TWh of electricity generated in 2050 (High Growth scenario).

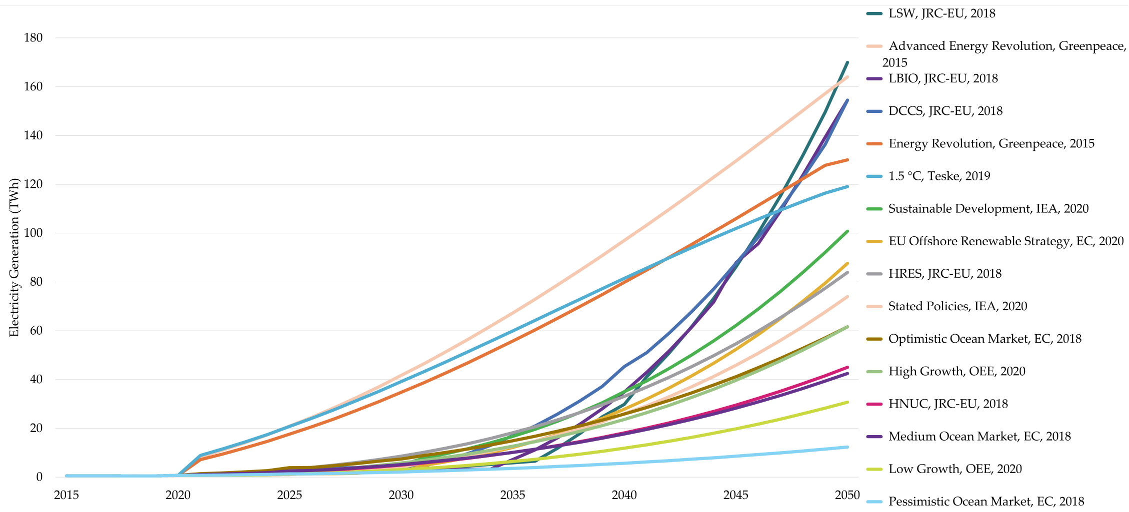

Figure 4.3: Ocean Power Adoption projections results for the EU until 2050, based on sixteen literature scenarios

Figure 4.4 represents a comparison between average projection values of electricity generation by ocean energy in 2025 and 2050 for each of the four categories discussed - Modest, Intermediate, Ambitious and Very Ambitious. The exponential growth in ocean technologies adoption is very clear here: even in the Modest Growth category the market size increases by a factor of 18; for the Very Ambitious Growth category, the difference is drastic: market size increases by a factor of 120.

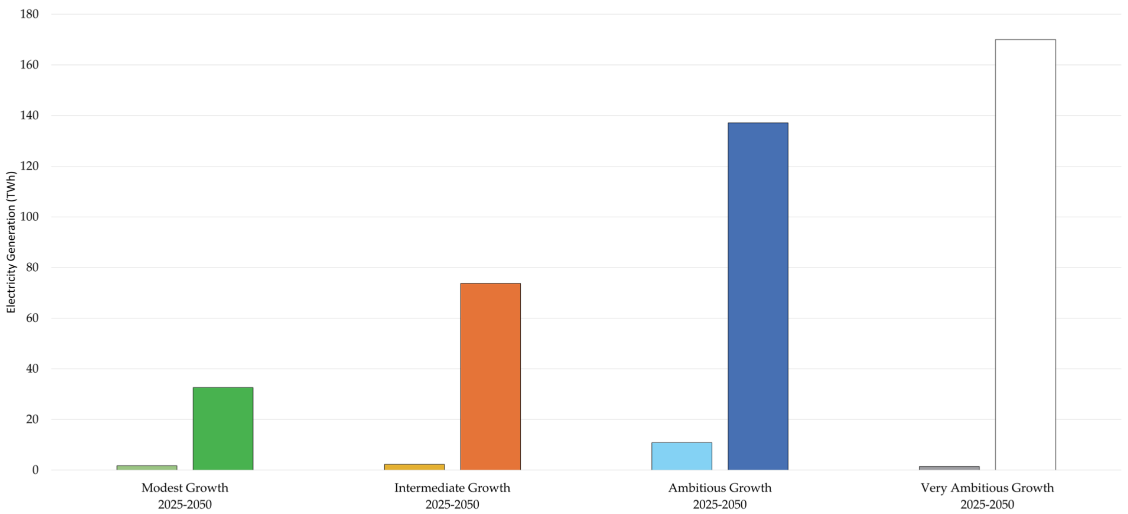

Figure 4.4: Adoption of ocean power categories results for EU in 2025 and 2050

4.3 Variable Meta-Analysis

The third and final key input for the RRS Model EU Ocean Power were VMA data, with its emissions, financial and technical input variables. After applying the criterion discussed to the financial variables among the VMA data collected in the literature review (see section 3.5), the complete sets of data used in the RRS Model EU Ocean Power for conventional technologies and the proposed solution are detailed in Table 4.3 and Table 4.4, respectively. In these tables, it is possible to see the different input variables collected, their units, number of data points used in the model, and three calculated values for each variable: Mean, High and Low values. For some cases, due to standard deviation method applied in the VMA sheet, the low boundary was negative for a given variable, that can only have positive values. In these cases the lowest collected data point was used as the Low value.

For conventional VMA data, financial and technical input variables were collected. Some of the sources for these variables were already mentioned, since these data is present in many of the future energy system scenarios publications. A very useful reference for investment and Operation and Maintenance (OM) costs for coal and natural gas power plants was [1], with the latest data from IEA. Regarding oil power plants costs, the main sources used were DNV® report [60], Teske's book [72], and a Handbook of International Energy Economics [87]. The main sources for the technical variables, including lifetime capacity and average annual use, were EC technology studies [83, 88, 89]. Regarding fuel prices, data collected only contains data points posterior to 2015, with the latest data from 2022 [90].

Table 4.3: VMA results for conventional technologies used as input data for the RRS Model EU Ocean Power

Input Variable	Units	Data Points	Mean	High	Low
First Costs	US$2014/kW	60	2 136	3 838	435
FOM Costs	US$2014/kW	35	49	79	20
VOM Costs	US$2014/kWh	14	0.005	0.012	0.002
Fuel Prices	US$2014/kWh	72	0.036	0.075	0.01
Lifetime Capacity	hours	32	130 671	154 302	107 040
Average Annual Use	hours	43	3 860	5 248	2 473

Table 4.4: VMA results for solution technologies used as input data for the RRS Model EU Ocean Power

Input Variable	Units	Data Points	Mean	High	Low
Indirect Emissions	t $CO_{2\text{-eq}}$/TWh	45	29 250	55 101	3 399
First Costs	US$2014/kW	82	7 296	11 476	3 115
FOM Costs	US$2014/kW	16	298	493	103
VOM Costs	US$2014/kWh	5	0.002	0.006	0.001
Learning Rate Factor	%	40	11	15	6
Lifetime Capacity	hours	14	71 119	85 727	56 511
Average Annual Use	hours	34	3 141	3 554	2 186
Jobs Creation	Jobs/TW	19	6M	11M	805 818
Materials Use	t/TW	16	2B	3B	790M

Concerning solution VMA data: emissions, financial, technical and jobs and materials input variables were collected. Since the solution does not account for CO_2 emissions upon electricity generation, emissions input is related to indirect CO_2 emissions through its life cycle. For ocean power technologies, such accounts mainly for manufacturing, transport, installation and other associated activities. To retrieve this information from the literature, several life cycle assessment studies on wave and tidal energy systems were reviewed [91–93], exhibiting indirect emission values between 2 and 126 g $CO_{2\text{-eq}}$/kWh. First and OM costs were gathered from multiple data sources [19, 38, 71, 72, 84, 85, 88, 89, 94], portraying the early stage of development for ocean power technologies with a wide range of values for these financial variables. The learning rate factor present values between 6% to 15% [84, 89, 95], but the expectation is that, in the future, it continues to lower ocean power solutions costs.

The technical data for ocean energy systems currently presents lower values when compared with conventional power plants: according to the literature, the solution systems have a lifetime capacity ranging from 15 to 80 years and a capacity factor between 22% to 51% (which is converted in Average Annual Use in Table 4.4) [38, 71, 84, 88, 89, 94]. In terms of jobs and materials variable inputs, there is huge uncertainty regarding the impact on jobs creation and the usage of materials for ocean energy systems. Current and future projections consider that ocean energy can have a substantial impact in the labor market depending on the solution adoption [13, 71, 72, 96–98]. For materials use, there are great variations in weight/power ratios, with specific device weights varying from 470 to 3897 kg/kW: ocean energy devices seem to demand quite a high input of materials per installed capacity [91, 93].

4.4 RRS Model EU Ocean Power results

Having gathered all the necessary inputs, all conditions required were fulfilled for running the RRS Model EU Ocean Power. As explained above (see chapter 3), the model presents results by comparing the REF Adoption Scenario with the selected sixteen Adoption scenarios until 2050, and also the comparison with the average of each Adoption category (Modest, Intermediate and Ambitious Growth). This means that a total of nineteen runs of the RRS Model EU Ocean Power were performed. In each run, VMA data points both from conventional and ocean power technologies were set to their Mean values. In this section, selected adoption, financial, emission and jobs and materials results are exhibited, assessing ocean power solutions' potential for electricity generation when compared with the use of conventional technologies (coal, natural gas, oil): results will be presented here for the average of each Adoption category, and they will be referred as Moderate Growth, Intermediate Growth, Ambitious Growth and Very Ambitious Growth aggregated scenarios. The complete set of results obtained can be found in Appendix B.

4.4.1 Adoption results

Starting with the ocean power Adoption (TWh), it is interesting to compare the results obtained with the REF Adoption scenario. It is this comparison that is on the basis of the RRS Model EU Ocean Power adoption results between 2021 and 2050 period. The Modest Growth scenario forecasts that 0.59% of the total EU electricity generation market will be sourced by ocean energy technologies by 2050. The more disruptive scenarios, Ambitious Growth and Very Ambitious Growth scenarios, present market shares of 2.46% and 3.05%, respectively. A considerable growth trajectory having in mind the starting point of the REF Adoption scenario, that accounts for 0.03% of the 2020 EU market share. Table 4.5 exhibits the EU adoption of ocean power solutions by 2050 in terms of functional unit and market share. Figure 4.5 shows the projections for the four aggregated scenarios for the period under analysis 2021-2050.

Table 4.5: EU Adoption of ocean power solutions by 2050

Scenario	Generation (TWh)	Market Size (%)
REF 2020	0.7	0.03
Modest	33	0.59
Intermediate	74	1.33
Ambitious	137	2.46
Very Ambitious	170	3.05

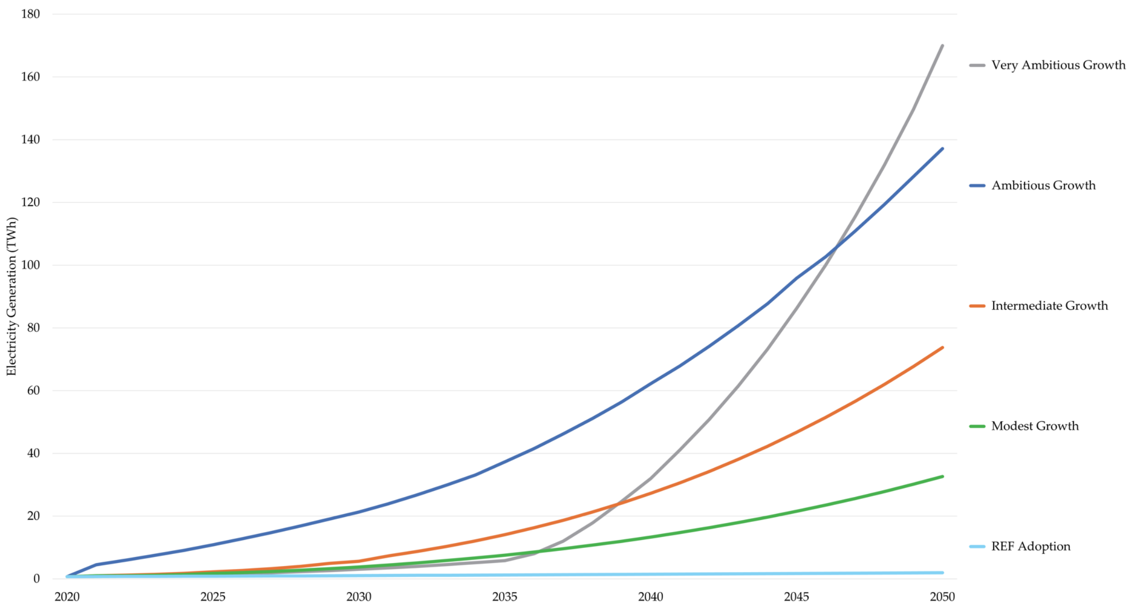

Figure 4.5: Ocean Power Adoption projections results for the EU until 2050, for the four categories defined

4.4.2 Financial results

Regarding the Financial results, based on the replacement of conventional technologies, it is possible to verify that the projections for ocean energy solutions will incur in significant additional costs. All four aggregated scenarios present negative values for net and lifetime operating savings. Marginal first cost, which is calculated by subtracting the cumulative first cost of the REF adoption scenario to the cumulative first cost of the Adoption scenario, also displays more investment needed. For the period under analysis, Modest Growth scenario presents a marginal first cost of 19.1 Billion € and negative net and lifetime operating savings of 17.2 and 42.0 Billion €, respectively. On the other end of the Adoption spectrum, Ambitious Growth and Very Ambitious Growth scenarios project similar marginal first costs of 60.5 and 60.8 Billion €, respectively. The Ambitious Growth scenario presents -84.0 Billion € of net operating savings, a higher cost than the Very Ambitious Growth scenario. This one projects -214.5 Billion € of lifetime operating savings. Table 4.6 displays the EU financial results for the period under analysis of the adoption of ocean power solutions, according to the four aggregated scenarios.

Table 4.6: EU Financial results for the period under analysis 2021-2050

Scenario	Marginal First Cost	Net Operating Savings	Lifetime Operating Savings
	Billion €	**Billion €**	**Billion €**
Modest	19.1	-17.2	-42.0
Intermediate	35.0	-37.1	-94.9
Ambitious	60.5	-84.0	-189.3
Very Ambitious	60.8	-60.3	-214.5

4.4.3 GHG Emissions

In terms of emissions results, Table 4.7 presents total emissions reduction for the next three decades, and Figure 4.6 projects EU annual emissions reduction for the four aggregated categories. As expected, for the scenarios with higher penetration of ocean power solutions, the reduction on emissions increases. The Intermediate Growth scenario presents a total emissions reduction of 0.36 Gt $CO_{2\text{-eq}}$, while the Ambitious Growth scenario more than doubles that amount of emissions reduction. For the period under analysis, it displays a total emissions reduction of 0.81 Gt $CO_{2\text{-eq}}$. This value is higher than the one projected for the Very Ambitious Growth scenario (0.58 Gt $CO_{2\text{-eq}}$). The explanation for this apparent incoherence is the exponential behaviour of the Very Ambitious Growth adoption scenario. Until 2035, this scenario presents the lower value of electricity generation from ocean energy, but from that year on, it has an exponential growth that leads this scenario to be the one with highest adoption in 2050. However, the Ambitious Growth scenario produces more electricity for the whole period; hence, it is the scenario with a higher emissions reduction result.

Table 4.7: EU Total Emissions Reduction for the period under analysis 2021-2050

Scenario	Total Emissions Reduction (Gt $CO_{2\text{-eq}}$)
Modest	0.17
Intermediate	0.36
Ambitious	0.81
Very Ambitious	0.58

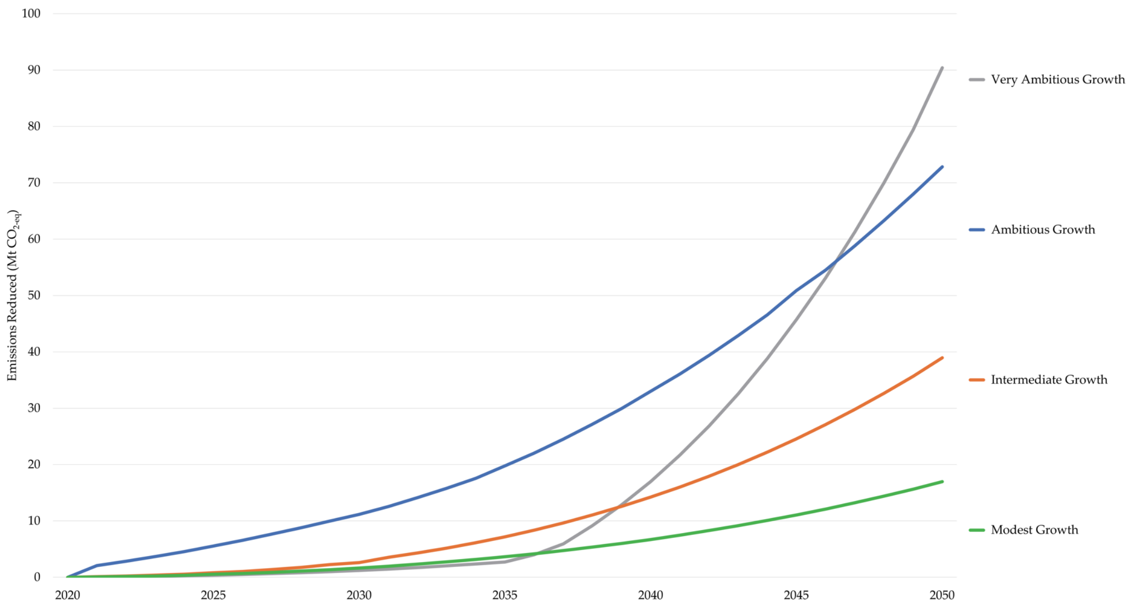

Figure 4.6: EU annual emissions reduction for the period under analysis 2021-2050, for the four categories defined

4.4.4 Jobs and Materials results

Finally, the last results computed by the RRS Model EU Ocean Power are jobs and materials results. These display the potential for job creation in the ocean energy industry and how intensively ocean power technology uses materials. These are relevant parameters; they can decisively impact policymakers and final users in their decision-making regarding the development and implementation of ocean energy technology. A significant part of the jobs created by this industry are highly skilled; this will presumably have a largely beneficial socioeconomic effect on the labor market of several EU countries. According to the four aggregated scenarios depicted below, Table 4.8 anticipates the number of jobs created over the next decades. It also displays the level of material resources needed to build ocean power plants capable to produce the amount of electricity indicated in each scenario. Job creation figures vary across a wide range of results: from 62 710 jobs (Modest Growth scenario) to 326 805 jobs (Very Ambitious Growth scenario). In any case, these figures are bound to have a considerable impact on several EU labor markets.

The results concerning the amount of material resources that will be needed in the next decades vary also across a vast spectrum of values. The intermediate values are to be found in the Intermediate Growth scenario (44 940 kt) and in the Ambitious Growth scenario (83 570 kt). According to several life cycle assessment studies of ocean energy technologies [91–93] the main materials used in manufacturing and implementation of ocean energy systems are steel, other metals, electronics, plastics, concrete, sand and water. Table 4.9 exhibits again the amount of material resources needed to implement each of the four aggregate scenarios, now divided by type. The share corresponding to each material indicated in the table was based on [91], where most of the more promising ocean energy devices are studied in terms of their specific weight. It is possible to conclude that steel predominates, concrete is an important material, followed by other metals and plastics, and electronics account for the smallest share among all materials used.

Table 4.8: EU jobs and materials impact of ocean power solutions by 2050

Scenario	Jobs (#)	Materials (kt)
Modest	62 710	19 875
Intermediate	141 780	44 940
Ambitious	263 650	83 570
Very Ambitious	326 805	103 590

Table 4.9: Materials used to produce ocean power solutions by 2050

Material (kt)	Modest	Intermediate	Ambitious	Very Ambitious
Steel	11 931	26 975	50 163	62 179
Other Metals	1 069	2 417	4 495	5 572
Electronics	225	509	947	1 173
Plastics	1 474	3 333	6 199	7 683
Concrete	3 866	8 740	16 253	20 146
Sand	358	808	1 503	1 863
Water	953	2 155	4 007	4 967

4.5 Sensitivity Analyses

In this section the sensitivity analyses results are presented. As explained in section 3.6, four different analyses were performed in order to highlight the financial conditions under which ocean power technologies may outperform conventional technologies. Bearing this goal in mind, the RRS Model EU Ocean Power was rerun and both the conventional and the solution VMA financial variables were adjusted accordingly. As in the previous section, the model was run for all nineteen solution adoption scenarios: the selected sixteen scenarios and the average of each growth category. In this section results will be presented for the average of each Adoption category, and they will be referred as Moderate Growth, Intermediate Growth, Ambitious Growth and Very Ambitious Growth aggregated scenarios. The full set of results obtained can be found in Appendix B.

Table 4.10 shows the results obtained in the first sensitivity analysis. On this first run, the High value for the learning rate factor of the solution was considered, as well as future costs for ocean energy technologies. These two parameters were maintained in the subsequent analyses. As the table shows, net operating savings are not yet to be gotten; however the additional costs are lower than those obtained in the first set of results (see Table 4.6).

Table 4.10: Sensitivity analyses - round #1 for the period 2021-2050

Scenario	Marginal First Cost	Net Operating Savings	Lifetime Operating Savings
	Billion €	**Billion €**	**Billion €**
Modest	7.3	-10.5	-25.6
Intermediate	9.4	-22.7	-58.1
Ambitious	11.5	-51.4	-115.8
Very Ambitious	5.4	-36.9	-131.2

Table 4.11 displays the results for the second sensitivity analysis. On this second run, the High value for First, FOM and VOM Costs associated with conventional technologies was taken into account, as well as the High value for fuel prices. In this case, marginal first costs favor the solution over conventional technologies: even the Modest Growth scenario would allow savings in the amount of 2.5 Billion €; obviously, the Very Ambitious Growth scenario would allow far greater savings in this parameter (46.9 Billion €).

Table 4.11: Sensitivity analyses - round #2 for the period 2021-2050

Scenario	Marginal First Cost	Net Operating Savings	Lifetime Operating Savings
	Billion €	**Billion €**	**Billion €**
Modest	-2.5	-7.5	-18.2
Intermediate	-13.2	-16.1	-41.2
Ambitious	-30.7	-36.5	-82.1
Very Ambitious	-46.9	-26.2	-93.1

Table 4.12 exhibits the results for the third sensitivity analysis. On this third run, the Low value for First, FOM and VOM Costs associated with ocean technologies was considered. It is possible to observe that also in this analysis, marginal first costs favor the solution over conventional technologies; although still negative, operating savings are however much closer to the point of breakeven. The Modest Growth scenario presents net and lifetime operating savings of -0.8 and -1.9 Billion €, respectively.

Table 4.12: Sensitivity analyses - round #3 for the period 2021-2050

Scenario	Marginal First Cost	Net Operating Savings	Lifetime Operating Savings
	Billion €	**Billion €**	**Billion €**
Modest	-3.5	-0.8	-1.9
Intermediate	-11.4	-1.7	-4.3
Ambitious	-24.0	-3.8	-8.6
Very Ambitious	-33.7	-2.8	-9.7

Table 4.13 presents the results obtained in the fourth sensitivity analysis. On this fourth run, the Low value for First, FOM and VOM Costs associated with ocean technologies was taken into account; at the same time, conventional technologies were associated

with the High value for First, FOM and VOM Costs. In this final analysis, all scenarios favor in all considered parameters the ocean power solution over conventional technologies. The maximum net and lifetime operating savings could reach 11.1 and 28.4 Billion €, respectively.

Table 4.13: Sensitivity analyses - round #4 for the period 2021-2050

Scenario	**Marginal First Cost**	**Net Operating Savings**	**Lifetime Operating Savings**
	Billion €	**Billion €**	**Billion €**
Modest	-13.4	2.3	5.5
Intermediate	-34.0	4.9	12.6
Ambitious	-66.3	11.1	25.0
Very Ambitious	-86.1	8.0	28.4

5

Discussion

As previously stated, the main goal of this thesis is to assess ocean power potential to reduce GHG emissions, projecting the adoption of these technologies by the EU power system up to 2050. This is done by using the RRS Model EU Ocean Power and evaluating its results, as well as the results obtained by the literature review for TAM, Adoption and VMA data. In this chapter each set of results will be discussed, to better understand their findings and conclusions.

Despite the different policies and technological assumptions they are based on, TAM projections clearly align in a considerable future growth of the power system in the EU. Most of the scenarios present steadily increasing trajectories until 2050, although some of them include faster growth tracks. The exception is the Climate Analytics High CDR scenario, where a different path is presented. Another important common conclusion is that all of them consider that the EU power system will necessarily increase its share of renewable energy sources. This will be enabled either by technology development, which will continue to lower renewable energy technologies LCOE, and by the urge of facing climate change disasters. Every year new unprecedented climate events remind policymakers the urge to commit with a fast decarbonization of the electricity generation system.

Regarding the adoption scenarios presented, it is possible to affirm that ocean power technologies will not have a major role in the EU power system for the next decades. Currently, ocean technology is still being tested, with the majority of actual installed capacity concerning different readiness level projects. No utility-scale projects are already deployed, which is the phase when technology costs start to drop substantially, due to volume increase. It is true that all adoption scenarios results show exponential growth for the period under analysis, but this is an expected trend due to a very limited adoption starting point. According to the results obtained, ocean energy could reach a maximum of 3.05% of the EU electricity market system, with the most conservative projection pointing out to a 0.59% market share by 2050. In any case, it is clear that for the next three decades ocean energy technologies will aim at most to be a support to other renewable major energy sources (as wind and solar) for EU energy transition.

For VMA data, the early stage of ocean energy devices is also highlighted: the wide spectrum of values for costs, indirect emissions, and technical variables clearly indicates this. It shows that the industry is not mature, proving the uncertainty related to the technology implementation costs present values in the literature ranging from 2 201 €/kW to 8 107 €/kW. These values compare with the conventional technologies current costs which present significant lower values, with a maximum first cost of 2 711 €/kW. These comparison decisively impact RRS Model EU Ocean Power financial results.

For the next decades, the financial results obtained by the model clearly reflect that implementing ocean power technologies will result in additional costs when compared with the current situation based on conventional technologies. No operating savings were obtained for the period 2021-2050, considering the main set of results for all adoption scenarios modelled, and where all VMA variables were set to their Mean values. These scenarios analysis assume a conservative approach of no technological and financial improvements, which is aimed to reduce the level of uncertainty of the results based on predictions of multiple parameters.

Regarding emission results, RRS Model EU Ocean Power predicts the avoidance of 0.16 to 0.81 Gt $CO_{2\text{-eq}}$ emissions. These include the difference between grid, fuel and direct emissions by conventional technologies, and the indirect emissions associated with the solution. Also here, one can conclude that the impact of ocean power solutions to emissions reduction is residual, especially when compared with other renewable energy sources, as previously explored for solar, wind and hydro for EU, following the same methodological framework [10–12]. However due to the urge of energy transition and necessity to reach Drawdown, all renewable energy sources must be put at disposal for this effort, and these emission reduction results should not be neglected.

The last parameters studied with the model were jobs creation and the total amount of materials resources need for an increased adoption of ocean power technologies. The most ambitious scenarios project over 300 000 jobs created by 2050, which can provide new opportunities for traditional maritime industries as well as revitalising coastal regions across the EU. In relation to the amount of materials resources needed to implement ocean power solutions, the results show that this is still a very intensive industry (470 to 3860 kg/kW), demanding quite a high input of materials per installed capacity, especially when compared with other renewable energy technologies (PV systems weigh 330 to 360 kg/kW and wind turbines about 340 to 770 kg/kW) [91].

Following the computation of the first set of results, several sensitivity analyses were conducted in order to understand if, by varying some of the model's financial input variables, savings could be reached by replacing conventional technologies with ocean power solutions by 2050. The definition of the assumptions behind each analysis had to due with plausible outcomes for the next decades. The actual learning rate factor of the solution, as per any early stage technology, is prompt to rapidly increase; hence the High value for this variable was selected. Also, accordingly with Project Drawdown RRS climate solutions methodology, costs are assumed constant over the period of study and should reflect the latest current data. However, due to the same reason referred above, ocean energy technology costs should decrease strongly, and that will most certainly impact ocean power solutions adoption. As so, future solution costs were included for these analyses. With this parameters fixed for all sensitivity analyses, cost input values for conventional and ocean energy technologies were adjusted based on the assumption of an EU future energy system on track for full decarbonization. On this anticipated future scenario, the costs associated with all renewable energy sources will continue to decrease and the costs related to conventional technologies will become less and less competitive, specially the conventional fuel prices. This was the rationale behind the different sensitivity analyses performed. On the last analysis, where the High value for conventional costs was selected as the same time as the Low value for ocean power technologies costs, the breakeven point was achieved, where ocean power solutions start to be more cost efficient for the period of study.

5.1 Benchmarks

For validating purposes, it is important to compare the RRS Model EU Ocean Power results with similar projections from the literature. Table 5.1 below exhibits a benchmark of this thesis results for 2050 on the four aggregated scenarios described in other relevant publications. The results compared are for EU electricity generation from ocean energy in 2050.

Table 5.1: Benchmarks

Scenario	Generation (TWh)	Market Size (%)
Modest	33	0.59
Intermediate	74	1.33
Ambitious	137	2.46
Very Ambitious	170	3.05
IEA Stated Policies	74	2.07
IEA Sustainable Development	101	2.00
Greenpeace Reference	48	0.93
Greenpeace Energy Revolution	130	2.95
Greenpeace Advanced Energy Revolution	160	2.78
Teske 5 ºC	18	0.38
Teske 1.5 ºC	116	1.93
JRC-EU HRES	84	2.16
JRC-EU LBIO	155	3.39
JRC-EU LSW	170	3.78

It is possible to see that the Modest Growth scenario presents results comparable to the ones projected by Greenpeace Reference and Teske 5 ºC scenarios. IEA's scenarios can relate more with those obtained with the Intermediate Growth scenario. In contrast, the Very Ambitious scenario agrees more with Greenpeace Energy Revolution and JRC-EU

LBIO scenarios.

Related to other type of results, OEE projects 400 000 jobs created in Europe by 2050 for the ocean energy industry, and 234 Mt $CO_{2\text{-eq}}$ emissions avoided [37]. While in [97, 98], results show the possibility 127 000-260 000 jobs being created. The results obtained by the model relate with this range of values, both for jobs and materials and emission results.

6 Conclusions

In this chapter a description of the work conducted to write this thesis will be presented, as well as the most significant conclusions drawn. This work may be useful for further developments in ocean power potential assessments for electricity generation. Therefore, a number of suggestions for future work making use of this approach will also be included.

6.1 Achievements

Bearing in mind the objectives mentioned in subsection 1.3.1 a literature review was performed to understand how different publications foresee the future of the EU energy system in the following decades. The electricity generation system was specifically focused on. The contribution ocean power technology might make to this system is still very uncertain. However, what is certain is that it needs to increase its renewable energy share. A literature review on ocean energy resources, technologies and policies was also performed to check the latest trends and possible future adoption scenarios.

The ultimate goal of the review was to collect three types of input for the RRS Model EU Ocean Power: TAM, Adoption and VMA data. TAM data were mainly gathered from institutional reports addressing the EU power system, ocean power solutions adoption scenarios were retrieved from several ocean energy technical reports and peer-reviewed publications, and VMA data were primarily collected from technological studies and assessments. To achieve compliance with the requirements of the RRS Model EU Ocean Power, these data were cleansed according to the assumptions made above.

The RRS Model EU Ocean Power was then used to compute adoption, financial, emission and jobs and materials results. These results were obtained by setting VMA data to their Mean values and by comparing the REF scenario with the nineteen solution adoption scenarios selected (see chapter 4). Sensitivity analyses were also conducted in order to further investigate whether financial savings could be reached by 2050 as a consequence of replacing conventional technologies with ocean power solutions.

The results show that it is implausible that ocean power technologies will play a major role in the EU power system in the course of the next decades due to their early levels of development and the competitiveness of mature and cheaper technologies as solar PV and wind onshore. They also show that further technological improvements need to happen if ocean power technologies are to become financially competitive. Finally, these results also show that the impact of the introduction of these technologies on reducing emissions, when compared to the impact of introducing other renewable energy technologies, is tenuous. However, it is to be expected that the situation might change with further technological research development and increased funding. Nevertheless, it should be noted that ocean energy, due to its predictability and abundance, might play a non-neglectable role in future power systems by being complementary to variable renewable energy sources.

6.2 Future Work

There are several suggestions that can be made for future developments. As explained, ocean power solutions are not yet mature, which is reflected in the current TRLs and deployment. However, the prospects for technological development and cost reduction, as per the latest data on ocean energy but also taking into consideration the route already paved by other renewable sources technologies, is auspicious for future adoption. As so, more data will become available for these technologies, and complementary assessments could be performed: to study ocean energy technologies independently (tidal and wave) or even for specific ocean energy devices (e.g.: horizontal axis turbines, oscillating water converters).

New and even more trustful power sector scenarios projections could be obtained from the literature, since these are regularly updated, in order to incorporate the impact of the major disruptions from 2020-2022: Covid-19 pandemic, the war in Ukraine and the consequent crisis created in the world's economy and resources availability. One of the most impacted sectors from these events is the power sector, and despite the current uncertainty, newer projections for the EU total addressable market including these variables could provide more insights for the future decades.

Further developments could also be implemented to the Project Drawdown RRS Model. In fact, it is under development an open source Python-based platform for deploying and executing the climate solution models to any context, region or scale. It will be a tool with real time data integration and equipped with decision support tools, which expects to allow further findings and more complete results.

References

[1] International Energy Agency and Nuclear Energy Agency. *Projected Costs of Generating Electricity, 2020 Edition*. 2020.

[2] Intergovernmental Panel on Climate Change. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, 2021.

[3] European Commission. *Europe Climate Law: establishing the framework for achieving climate neutrality and amending Regulation (EU) 2018/1999*. 2020.

[4] Hawken, P., Wilkinson, K., Frischmann, C., Allard, R., Bayuk, K., Gouveia, J. P., Mehra, M., Toensmeier, E., Chissel, C. *Drawdown The Most Comprehensive Plan Ever Proposed to Reverse Global Warming*. 2017.

[5] International Energy Agency. *World Energy Outlook 2021*. 2021.

[6] International Energy Agency. *Global Energy Review 2021: Assessing the effects of economic recoveries on global energy demand and CO_2 emissions in 2021*. 2021.

[7] International Renewable Energy Agency. *World Energy Transitions Outlook: 1.5°C Pathway*. Abu Dhabi, 2022.

[8] Foley, J., Frischmann, C., Wilkinson, K., Allard, R., Gouveia, J.P., Mehra, M., Bayuk, K. et al. *Drawdown Review 2020*. 2020.

[9] Link, J., Grobben, I., Slob, W., Duijvestein, P., Straver, R., Janssen, R. *Preliminary Climate Solution Assessment - Provincie Gelderlan*. Drawdown Europe Research Association, 2021.

[10] Silveira, L. *European Potential of Solar Technologies for Electricity Generation under Project Drawdown Framework*. [Master's Thesis, Instituto Superior Técnico, Universidade de Lisboa], 2021.

[11] Freitas, D. *European Potential of Wind Technologies for Electricity Generation under Project Drawdown Framework*. [Master's Thesis, NOVA School of Science Technology, Universidade Nova de Lisboa], 2022.

[12] Vieira, F. *Analysis of the Future of Hydropower Technologies in the European Union under Project Draw-down Framework*. [Master's Thesis, NOVA School of Science Technology, Universidade Nova de Lisboa], 2022.

[13] Ocean Energy Europe. *2030 Ocean Energy Vision: Industry analysis of future deployments, costs and supply chains*. 2020.

[14] Copping, A. E., Hemery, L.G. *OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewa-ble Energy Development Around the World*. Ocean Energy Systems, 2020.

[15] United Nations Department of Economic and Social Affairs, Population Division. *Global Population Growth and Sustainable Development*. UN DESA/POP/2021/TR/NO. 2, 2021.

[16] International Renewable Energy Agency. *Innovation outlook: Ocean energy technologies*. Abu Dhabi, 2021.

[17] Ocean Energy Systems. "What is Ocean Energy". In: URL: https://www.ocean-energy-systems.org/ocean-energy/what-is-ocean-energy/ (visited on 08/20/2022).

[18] Ocean Energy Systems. *An international vision for ocean energy*. 2017.

[19] Kempener, R., Neumann, F. *Tidal Energy: Technology Brief*. International Renewable Energy Agency, 2014.

[20] Mørk, G., Barstwo, S., Kabuth, A. K., Pontes, M. T. "Assessing the global wave energy potential". In: *Proceedings of the 29th International Conference on Ocean, Offshore Mechanics and Arctic Engineering, Shanghai, China*. 2010.

[21] Masuda, Y., Miyazaki, T. "Tests on the wave power generator 'Kaimei'". In: *Proceedings of the offshore technology conference*. 1975.

[22] Masuda, Y., McCormick, M. E. "Experiences in pneumatic wave energy conversion in Japan". In: *Utilization of Ocean Wave - Wave to energy Conversion*. New York: American Society of Civil Engineers, 1986, pp. 1–33.

[23] Nihous, G. C. "A preliminary assessment of ocean thermal energy conversion resources". In: *Journal of Energy Resources Technology*. Vol. 129/1, American Society of Mechanical Engineers, New York, 2007, pp. 10–17.

[24] Skråmestø, Ø. S., Skilhagen, S. E., Nielsen, W. K. *Power production based on osmotic pressure*. Washington, 2009.

[25] Keramidas, K., Fosse, F., Díaz Vázquez, A., Dowling, P., Garaffa, R., Després, J., Russ, P., Schade, B., Schmitz, A., Soria Ramirez, A., Vandyck, T., Weitzel, M., Tchung-Ming, S., Diaz Rincon, A., Rey Los Santos. L., Wojtowicz, K. *Global Energy and Climate Outlook 2021: Advancing towards climate neutrality*. EUR 30861 EN, Publications Office of the European Union, Luxembourg, 2021.

[26] European Commission. *An EU-wide assessment of National Energy and Climate Plans: Driving forward the green transition and promoting economic recovery through integrated energy and climate planning*. 2020.

[27] Ireland Department of Communications, Climate Action Environment. *National Energy Climate Plan 2021-2030*. 2019.

[28] Portugal Ministry of Environment and Climate Action. *National Energy and Climate Plan 2021-2030 (NECP 2030)*. 2019.

[29] Spain Ministry for the Ecological Transition and the Demographic Challenge. *Hoja de Ruta para el desarrollo de la Eólica Marina y de las Energías del Mar en España*. 2021.

[30] European Commission. *An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future*. 2020.

[31] Province of Nova Scotia, Canada. *Marine Renewable Energy Strategy*. 2012.

[32] Marine Scotland Directorate. *Sectoral Marine Plan for Offshore Wind Energy*. 2020.

[33] Etemandi, A., Emami, Y., AsefAfshar, O., Emdadi, A. *Electricity Generation by the Tidal Barrages*. Urmia University of Technology, IGSGCE 2011, Chengdu, China, 2011.

[34] European Commission. *The EU Blue Economy Report 2021*. Publications Office of the European Union, Luxembourg, 2021.

[35] Minesto. "Faroe Islands - tidal energy to reach 100% renewable by 2030". In: URL: `https://minesto.com/projects/faroe-islands` (visited on 08/14/2022).

[36] Simec Atlantis Energy. "Tidal Streams Projects Meygen". In: URL: `https://simecatlantis.com/projects/meygen/` (visited on 08/16/2022).

[37] Ocean Energy Europe. *Key trends and statistics 2020*. 2021.

[38] Kempener, R., Neumann, F. *Wave Energy: Technology Brief*. International Renewable Energy Agency, 2014.

[39] Lewis, A. et al., "Ocean Energy", in O. Edenhofer et al., eds. *IPCC special report on renewable energy sources and climate change mitigation*. Cambridge, UK and New York, US, 2011.

[40] Ocean Energy. "Ocean Energy A World of Power". In: URL: `https://oceanenergy.ie/` (visited on 08/18/2022).

[41] BiMEP Biscay Marine Energy Platform. "Nuestra mar Nuestra energía". In: URL: `https://www.bimep.com/` (visited on 08/20/2022).

[42] Wavenergy.it. "Wavenergy". In: URL: `https://www.wavenergy.it/` (visited on 08/22/2022).

[43] Ocean Power Technologies. "OPT Ocean Power Technologies". In: URL: `https://oceanpowertechnologies.com/` (visited on 08/24/2022).

[44] Carnegie Clean Energy. "CETO Technology". In: URL: https://www.carnegiece.com/ceto-technology/ (visited on 08/24/2022).

[45] AW-Energy. "Waveroller Solution". In: URL: https://aw-energy.com/waveroller/ (visited on 08/24/2022).

[46] Raikar, S., Adamson, S. *Renewable Energy Finance: Theory and Practice*. Academic Press, 2019.

[47] International Renewable Energy Agency. *Renewable Power Generation Costs in 2020*. Abu Dhabi, 2021.

[48] Magagna, D. *Ocean Energy Technology Development Report 2020*. EUR 30509 EN, Publications Office of the European Union, Luxembourg, 2020.

[49] European Commission. *SET Plan - Declaration of Intent on Strategic Targets in the context of an Initiative for Global Leadership in Ocean Energy*. Brussels, 2021.

[50] ORE Catapult. *Tidal stream and wave energy cost reduction and industrial benefit*. Offshore Renewable Energy Catapult, Glasgow, 2018.

[51] International Energy Agency. *Energy Technology Perspectives 2020*. 2021.

[52] International Energy Agency. *Renewables 2021: Analysis and forecast to 2026*. 2021.

[53] International Energy Agency. *Net Zero by 2050: A Roadmap for the Global Energy Sector*. 2021.

[54] International Renewable Energy Agency. *Global Renewables Outlook: Energy transformation 2050*. Abu Dhabi, 2020.

[55] International Renewable Energy Agency. *Renewable Energy Statistics 2022*. Abu Dhabi, 2022.

[56] International Renewable Energy Agency. *Renewable Capacity Statistics 2022*. Abu Dhabi, 2022.

[57] International Renewable Energy Agency. *NDCs and renewable energy targets in 2021: Are we on the right path to a climate-safe future?* Abu Dhabi, 2022.

[58] BP. *Energy Outlook 2022 edition*. 2022.

[59] Shell. *The Energy Transformation Scenarios*. 2021.

[60] DNV. *Energy Transition Outlook 2021: A global and regional forecast to 2050*. 2021.

[61] Total Energies. *TotalEnergies Energy Outlook 2021*. 2021.

[62] Equinor. *Energy Perspectives 2021: Long-term macro and market outlook*. 2021.

[63] McKinsey Company. *Global Energy Perspective 2021*. 2021.

[64] Bain Company. *Global Energy and Natural Resources Report 2021: Navigating the Energy Trasition*. 2021.

[65] Boston Consulting Group. *Energy Transitions: Adapting to the New Normal of the Changing World*. 2019.

[66] Intergovernmental Panel on Climate Change. *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. 2019.

[67] European Commission. *EU Reference Scenario 2020: Energy, transport and GHG emissions - Trends to 2050*. Publications Office of the European Union, Luxembourg, 2021.

[68] Canada Energy Regulator. *Canada's Energy Future 2021: Energy Supply and Demand Projections to 2040*. 2021.

[69] The Institute of Energy Economics, Japan. *IEEJ Outlook 2022*. 2021.

[70] U.S. Energy Information Administration. *Annual Energy Outlook 2022*. 2022.

[71] Greenpeace, Global Wind Energy Council, SolarPower Europe. *energy [r]evolution: a sustainable world energy outlook 2015*. 2015.

[72] Teske, S., ed. *Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5°C and +2°C*. Springer, 2019.

[73] Eurelectric. *Decarbonisation pathways: European economy and European power sector*. 2018.

[74] Ocean Energy Systems. "Who is OES?" In: URL: https://www.ocean-energy-systems.org/about-us/who-is-oes-/ (visited on 08/20/2022).

[75] Ocean Energy Systems. *Annual Report: An Overview of Ocean Energy Activities in 2020*. 2021.

[76] Ocean Energy Systems. *Strategic Plan 2022 - 2026*. 2021.

[77] European Commission. *Market Study on Ocean Energy - Final Report*. Publications Office of the European Union, Luxembourg, 2018.

[78] International Energy Agency. "Ocean power generation in the Net Zero Scenario, 2000-2030". In: URL: https://www.iea.org/data-and-statistics/charts/ocean-power-generation-in-the-net-zero-scenario-2000-2030 (visited on 09/01/2022).

[79] Project Drawdown. *Drawdown Reduction and Replacement Solutions (RRS) Model Framework and Guide*, 2019.

[80] OFX. "Historical exchange rates". In: URL: https://www.ofx.com/en-us/forex-news/historical-exchange-rates/ (visited on 08/30/2022).

[81] Climate Analytics. “1.5 ºC national pathway explorer”. In: URL: http://1p5ndc-pathways.climateanalytics.org/methodology/ (visited on 09/20/2022).

[82] ClimateWorks Foundation & European Climate Foundation. “The CTI 2050 Roadmap Tool project”. In: URL: https://stakeholder.netzero2050.eu/ (visited on 09/20/2022).

[83] European Commission. *The JRC-EU-TIMES model. Assessing the long-term role of the SET Plan Energy technologies*. Publications Office of the European Union, Luxembourg, 2013.

[84] European Commission. *Cost development of low carbon energy technologies: scenario-based cost trajectories to 2050*. Publications Office of the European Union, Luxembourg, 2018.

[85] European Commission. *Deployment Scenarios for Low Carbon Energy Technologies*. Publications Office of the European Union, Luxembourg, 2018.

[86] International Energy Agency. *World Energy Outlook 2020*. 2020.

[87] Hafner, M., Luciani, G. *The Palgrave Handbook of International Energy Economics*. Palgrave Macmillan, 2022.

[88] European Commission. *ASSET Study on Technology pathways in decarbonisation scenarios*. Publications Office of the European Union, Luxembourg, 2020.

[89] European Commission. *ETRI 2014: Energy Technology Reference Indicator projections for 2010-2050*. Publications Office of the European Union, Luxembourg, 2014.

[90] European Commission. *Quarterly report On European electricity markets, Volume 15, issue 1*. Market Observatory for Energy, 2022.

[91] Uihlein, A. “Life cycle assessment of ocean energy technologies”. In: *LCA for Enegy Systems and Food Products*. 2016.

[92] Paredes, M. G., Padilla-Rivera, A., Guereca, L. P. “Life Cycle Assessment of Ocean Energy Technologies: A Systematic Review”. In: *Jornal of Marine Science and Engineering*. 2019.

[93] Apolónia, M., Simas, T. “Life Cycle Assessment of an Oscillating Wave Surge Energy Converter”. In: *Jornal of Marine Science and Engineering*. 2021.

[94] Ocean Energy Systems. *International Levelised Cost of Energy for Ocean Energy Technologies*. 2015.

[95] Pennock, S., Garcia-Teruel, A., Noble, D. R., Roberts, O., Andres, A., Cochrane, C., Jeffrey, H. “Deriving Current Cost Requirements from Future Targets: Case Studies for Emerging Offshore Renewable Energy Technologies”. In: *Multidisciplinary Digital Publishing Institute*. 2022.

[96] International Renewable Energy Agency and International Labour Organization. *Renewable Energy and Jobs – Annual Review 2021*. Abu Dhabi, Geneva, 2021.

[97] ETIP OCEAN. *A study into the potential social value offered to Europe from the development and deployment of wave and tidal energy to 2050.* 2022.

[98] ETIP OCEAN. *A European Ocean Energy Industry - the €140bn Economic Opportunity: The industrial payoff from the EU Offshore Strategy.* 2021.

A

List of Publications Reviewed

The complete list of publications reviewed for this thesis work will be presented in this appendix. Due to its nature, this work encompassed an extensive literature review. Future energy scenarios publications, ocean energy technical reports and EU policy documents are among the main data sources. Regarding future energy scenarios publications, it will be enumerated the number and name of scenarios included in each publication.

1. International Energy Agency

    - *World Energy Outlook 2021*, 2021
        a) Stated Policies scenario
        b) Announced Pledges scenario
        c) Sustainable Development scenario
        d) Net Zero Emissions by 2050 scenario
    - *World Energy Outlook 2020*, 2020
        a) Stated Policies scenario
        b) Delayed Recovery scenario
        c) Sustainable Development scenario
        d) Net Zero Emissions by 2050 scenario
    - *World Energy Outlook 2019*, 2019
        a) Current Policies scenario
        b) Stated Policies scenario
        c) Sustainable Development scenario
    - *Renewables 2021: Analysis and forecast to 2026*, 2021
    - *Net Zero by 2050: A Roadmap for the Global Energy Sector*, 2021
    - *Global Energy Review 2021: Assessing the effects of economic recoveries on global energy demand and CO_2 emissions in 2021*, 2021
    - *Energy Technology Perspectives 2020*, 2021

- *Electricity Market Report 2022*, 2022
- *Projected Costs of Generating Electricity*, IEA-NEA, 2020
- *Energy Prices and Taxes - Second Quarter 2022*, 2022

2. International Renewable Energy Agency

- *Electrification with Renewables, Driving the transformation of energy services*, 2019
- *Fostering a blue economy: Offshore renewable energy*, 2020
- *Offshore renewables: An action agenda for deployment*, 2021
- *Global energy transformation: A roadmap to 2050*, 2019
- *Global Renewables Outlook: Energy transformation 2050*, 2020
- *Innovation outlook: Ocean energy technologies*, 2020
- *NDCs and renewable energy targets in 2021: Are we on the right path to a climate-safe future?*, 2022
- *Renewable capacity Statistics 2017*, 2017
- *Renewable capacity statistics 2021*, 2021
- *Renewable capacity statistics 2022*, 2022
- *Renewable Energy and Jobs – Annual Review 2021*, 2021
- *Renewable Energy Statistics 2017*, 2017
- *Renewable Energy Statistics 2021*, 2021
- *Renewable Energy Statistics 2022*, 2022
- *Renewable Power Generation Costs in 2020*, 2021
- *Renewable Power Generation Costs in 2021*, 2022
- *Renewable Technology Innovation Indicators: Mapping progress in costs, patents and standards*, 2022
- *Smart Electrification with Renewables, Driving the transformation of energy services*, 2022
- *Tidal Energy: Technology Brief*, 2014
- *Wave Energy: Technology Brief*, 2014
- *World Energy Transitions Outlook: 1.5°C Pathway*, 2021
    a) Planned Energy scenario
    b) Transforming Energy scenario
    c) 1.5 ºC scenario
- *World Energy Transitions Outlook 2022: 1.5°C Pathway*, 2022

3. United Nations

   - *IPCC Climate Change 2021: The Physical Science Basis*, 2021
   - *IPCC Climate Change 2022: Mitigation of Climate Change*, 2022
   - *IPCC Global warming of 1.5°C*, 2018
     a) Bellow 1.5 ºC (LO) scenario
     b) Above 1.5 ºC (HO) scenario
     c) Two Above Classes Combined scenario
   - *Long-Term Strategy (LTS) Canada*
   - *LTS European Union*
   - *LTS France*
   - *LTS Germany*
   - *LTS Japan*
   - *LTS Portugal*
   - *LTS Spain*
   - *LTS United Kingdom*
   - *LTS United States of America*
   - *NDC Australia*
   - *NDC Canada*
   - *NDC China*
   - *NDC European Union*
   - *NDC India*
   - *NDC Japan*
   - *NDC Korea*
   - *NDC New Zealand*
   - *NDC Russia*
   - *NDC United Kingdom*
   - *NDC United States of America*
   - *UN Climate Change Annual Report 2020*

4. European Commission

   - *Asset study on Technology pathways in decarbonisation scenarios*, 2018
   - *DTOcean+ Advanced Design Tools for Ocean Energy Systems Innovation, Development and Deployment*, 2020

- *The EU Blue Economy Report 2021*
- *Boosting Offshore Renewable Energy for a Climate Neutral Europe*, EC Press Release 2020
- *State of the Energy Union 2021: Renewables overtake fossil fuels as the EU's main power source*, EC Press Release 2021
- *Blue Energy: Action needed to deliver on the potential of ocean energy in European seas and oceans by 2020 and beyond*, 2014
- *State of the Energy Union 2021 – Contributing to the European Green Deal and the Union's recovery*, 2021
- *An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future*, 2020
  a) EU Offshore Strategy scenario
- JRC - *Cost development of low carbon energy technologies: Scenario-based cost trajectories to 2050*, 2017 edition
- JRC - *Deployment Scenarios for Low Carbon Energy Technologies, Deliverable D4.7 for the Low Carbon Energy Observatory*, 2018
- JRC - *Ocean Energy: Technology development report, Low Carbon Energy Observatory 2020*
- JRC - *Global Energy and Climate Outlook 2021: Advancing towards climate neutrality*
  a) CurPol scenario
  b) NDC-LTS scenario
  c) 1.5 ºC Uniform scenario
  d) 1.5 ºC Differentiated scenario
- JRC - *Energy Technology Reference Indicator projections for 2010-2050*, 2014
- JRC - *The POTEnCIA Central scenario, an EU energy outlook to 2050*, 2019
- JRC - *The JRC-EU-TIMES model: Assessing the long-term role of the SET Plan Energy technologies*, 2013
  a) Current Policies scenario
  b) Current Policies with CAP scenario
  c) Delayed CCS scenario
  d) High Renewables scenario
  e) High Nuclear scenario
  f) Low Energy scenario
  g) Low Biomass scenario
  h) Low Solar & Wind scenario

- *ETIP Ocean - Deliverable 3.3: A study into the potential economic value offered to Europe from the development and deployment of wave and tidal energy to 2050*, 2022
- *ETIP Ocean - Deliverable 3.4: A study into the potential social value offered to Europe from the development and deployment of wave and tidal energy to 2050*, 2022
- *ETIP Ocean - Strategic Research and Innovation Agenda for Ocean Energy*, 2020
- *ETIP Ocean - A European Ocean Energy Industry: the €140bn Economic Opportunity, Industrial Roadmap for Ocean Energy*, 2022
- *Blue Energy: Action needed to deliver on the potential of ocean energy in European seas and oceans by 2020 and beyond*, 2014
- *Market study on ocean energy*, 2018
  a) Initial scenario
  b) Pessimistic scenario
  c) Medium scenario
  d) Optimistic scenario
- *EU energy in figures - statistical pocketbook 2021*
- *EU Reference Scenario 2020: Energy, transport and GHG emissions - Trends to 2050*, 2020
- *Ocean Energy Barometer*, 2019
- *CORDIS Results Pack on ocean energy: Promising new technologies to help Europe achieve its ambitious climate goals*, 2021
- *Quarterly report on European electricity markets, volume 14, issue 1*, 2021
- *Quarterly report on European electricity markets, volume 14, issue 2*, 2021
- *Quarterly report on European electricity markets, volume 14, issue 3*, 2021
- *Quarterly report on European electricity markets, volume 14, issue 4*, 2021
- *Quarterly report on European electricity markets, volume 15, issue 1*, 2022
- *National Energy and Climate Plans*: Belgium, Bulgaria, Croatia, Cyprus, Denmark, Estonia, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Latvia, Lithuania, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovenia, Spain, Sweden, United Kingdom
- *Marine Spatial Plans*: Belgium, Germany, Ireland, Portugal, Spain, Sweden
- *Hoja de Ruta para el desarrollo de la Eólica Marina y de las Energías del Mar en España*, 2021

5. Ocean Energy Europe

   - *2030 Ocean Energy Vision: Industry analysis of future deployments, costs and supply chains*, 2020
     a) Low Growth scenario
     b) High Growth scenario
   - *Key trends and statistics 2018*
   - *Key trends and statistics 2019*
   - *Key trends and statistics 2020*
   - *Key trends and statistics 2021*
   - *Last stop to 2025: A 2022 Action Plan to deliver on the Offshore Strategy's Ocean Energy Target*, 2022
     a) Potential Installed Capacity by 2025 scenario
   - *Ocean energy: The next big thing in energy - brochure*, 2020

6. Ocean Energy Systems - IEA

   - *An International Evaluation and Guidance Framework for Ocean Energy Technology*, 2021
   - *OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World*, 2020
   - *Annual Report: An Overview of Ocean Energy Activities in 2020*, 2020
   - *Strategic Plan 2022 – 2026*, 2021
   - *Alternative Markets for Ocean Energy*, 2021
   - *International levelised cost of energy for ocean energy technologies: An analysis of the development pathway and Levelised Cost Of Energy trajectories of wave, tidal and OTEC technologies*, 2015

7. Utilities

   - NextEra, *Energy Annual Report 2020*, 2021
   - Endesa, *Carbon Footprint 2020*, 2021
   - Duke, *Energy 2020 Annual Report*, 2021
   - TotalEnergies, *TotalEnergies energy Outlook 2021*, 2021
     a) Momentum scenario
     b) Rupture scenario
   - RWE, *Powering Ahead - Annual Report 2020*, 2021
   - Dominion, *Energy Climate Report 2021*, 2021

- Eletrobras, *Plano Diretor de Negócios e Gestão 2022-2026*, 2021
- Orsted, *Annual Report 2020*, 2021
- BP, *Energy Outlook 2020 edition*, 2020
- BP, *Statistical Review of World Energy 2021*, 2021
- BP, *Energy Outlook 2022 edition*, 2022
  a) New Momentum scenario
  b) Accelerated scenario
  c) Net Zero scenario
- DNV, *Energy Transition Outlook 2021*, 2021
  a) DNV Energy Transition Outlook scenario
- EDP, *EDP Strategic Update 2021-2025*, 2021
- EDP, *EDP Energy Outlook 2017*, 2017
- E-ON, *Annual Report 2020*, 2020
- Iberdrola, *Iberdrola Integrated Report 2021*, 2021
- ING, *Energy Outlook 2022: Powering ahead*, 2022
- Veolia, *Veolia: Integrated Report 2020-2021*, 2021
- BloombergNEF, *New Energy Outlook 2020*, 2020
- BloombergNEF, *New Energy Outlook 2021*, 2021
- Exelon, *Exelon Annual Report 2020*, 2020
- Southern Company, *Southern Company 2020 Annual Report*, 2020
- Enel, *Enel X - Energy Market Outlook: What to Expect in 2021 and Beyond*, 2021
- Engie, *Engie - 2021 Integrated Report*, 2021
- Shell, *Shell Energy Scenarios to 2050: An era of volatile transitions*, 2019
- Shell, *Shell: The energy transformation scenarios*, 2021
  a) Waves scenario
  b) Islands scenario
  c) Sky 1.5 scenario
- Tepco, *Tepco: Integrated Report 2020-2021*, 2021
- Equinor, *Energy Perspectives 2021: Long-term and market outlook*, 2021
  a) Reform scenario
  b) Rebalance scenario
  c) Rivalry scenario

8. Professional services networks

    - Bain & Company, *Global Energy and Natural Resources, Report 2021: Navigating the Energy Transition*, 2021
    - BCG, *Energy Transitions: adapting to the new normal of the changing world*, 2019
    - McKinsey & Company, *Global Energy Perspective 2021*, 2021
    - KPMG, *Hindsight is 2050 vision*, 2021
    - PWC, *State of climate 2021: scaling breakthroughs for net zero*, 2021
    - Deloitte, *2022 renewable energy industry outlook*, 2022
    - Poyry, *Portuguese market outlook up to 2040, a report to APREN*, 2020

9. Books, scientific papers and industry reports

    - Hafner, M., Luciani, G., *The Palgrave Handbook of International Energy Economics*. Palgrave Macmillan, 2022.
    - Teske, S., ed., *Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5ºC and +2ºC*, Springer, 2019.
        a) 5 ºC scenario
        b) 2 ºC scenario
        c) 1.5 ºC scenario
    - Chang, G., Jones, C. A., Roberts, J. D., Neary, V. S., "A comprehensive evaluation of factors affecting the levelized cost of wave energy conversion projects". In: *Renewable Energy Journal*, 2018
    - Douziech, M., Hellweg, S., Verones, F., "Are Wave and Tidal Energy Plants New Green Technologies?". In: *Environmental Science & Technology*, 2016
    - Andres, A., MacGillivray, A., Roberts, O., Guanche, R., Jeffrey, H., "Beyond LCOE: A study of ocean energy technology development and deployment attractiveness". In: *Sustainable Energy Technologies and Assessments*, 2016
    - Castro-Santos, L., Silva, D., Bento, A. R., Salvação, N., Soares, C. G., "Economic Feasibility of Wave Energy Farms in Portugal". In: *Energies: Multidisciplinary Digital Publishing Institute*, 2018
    - Etemadi, A., Emami, Y., AsefAshar, O., Emdadi, A., "Electricity Generation by the Tidal Barrages", 2011
    - Astariz, S., Vazquez, A., Iglesias, G., "Evaluation and comparison of the levelized cost of tidal, wave, and offshore wind energy". In: *Journal of Renewable and Sustainable Energy*, 2015
    - Rourke, F. O., Boyle, F., Reynolds, A., "Tidal energy update", 2009

- Das, T. K., Halder, P., Samad, A., "Optimal design of air turbines for oscillating water column wave energy systems: A review". In: *International Journal of Ocean and Climate Systems*, 2017
- Astariz, A., Iglesias, G., "The economics of wave energy: A review", 2015
- Zhang, X., Zhang, L., Yuan, Y., Zhai, Q., "Life Cycle Assessment on Wave and Tidal Energy Systems: A Review of Current Methodological Practice". In: *International Journal of Environmental Research and Public Health*, 2020
- Uihlein, A., "Life cycle assessment of ocean energy technologies". In: *LCA for Energy Systems and Food Products*, 2016
- Paredes, M. G., Padilla-Rivera, A., Guereca, L. P., "Life Cycle Assessment of Ocean Energy Technologies: A Systematic Review". In : *Journal of Marine Science and Engineering*, 2019
- Apolonia, M., Simas, T., "Life Cycle Assessment of an Oscillating Wave Surge Energy Converter". In : *Journal of Marine Science and Engineering*, 2021
- Rodrigues, N., Pintassilgo, P., González-Gorbeña, E., Pacheco, A., "Cost-benefit analysis of tidal energy production in a coastal lagoon: The case of Ria Formosa - Portugal", 2021
- Pennock, S., Garcia-Turel, A., Noble, D. R., Roberts, O., Andres, A., Cochrane, C., Jeffrey, H., "Deriving Current Cost Requirements from Future Targets: Case Studies for Emerging Offshore Renewable Energy Technologies". In: *Energies: Multidisciplinary Digital Publishing Institute*, 2022
- Sgobbi, A., Simões, S. G., Magagna, D., Nijs, W., "Assessing the impacts of technology improvements on the deployment of marine energy in Europe with an energy system perspective". In: *Renewable Energy Journal*, 2015
- Falcão, A. F. O., "Development of Wave Energy Technology Exploitation in Portugal in the International Context". In: *Seminar - Testing and Demonstration Infrastructures for the Development of the Blue Economy*. 2017
- MeyGen, *MeyGen Lessons Learnt Summary Report*, 2020
- Bombora Wave Power, *Invisibly powering our world - cost effective electricity from the ocean*, 2016

10. Project Drawdown Publications

- Hawken, P., Wilkinson, K., Frischmann, C., Allard, R., Bayuk, K., Gouveia, J. P., Mehra, M., Toensmeier, E., Chissel, C. *Drawdown The Most Comprehensive Plan Ever Proposed to Reverse Global Warming*. 2017.
- Foley, J., Frischmann, C., Wilkinson, K., Allard, R., Gouveia, J.P., Mehra, M., Bayuk, K. et al. *Drawdown Review 2020*. 2020.

- Project Drawdown: Drawdown Reduction and Replacement Solutions Model Framework and Guide, 2019
- Frischmann C.J., Mehra M., Allard R., Bayuk K., Gouveia J.P., Gorman M.R., "Drawdown's "System of Solutions" Helps to Achieve the SDGs". In: Leal Filho W., Azul A., Brandli L., Lange Salvia A., Wall T. (eds) *Partnerships for the Goals. Encyclopedia of the UN Sustainable Development Goals*. Springer, 2020.

11. Energy and Environment Agencies

- European Climate Foundation, *Net Zero by 2050: From whether to how*, 2018
  a) EU-REF16 scenario
  b) Shared Efforts scenario
  c) Demand-Focus scenario
  d) Technology scenario
- Climate Analytics, "1.5°C national pathway explorer", In: http://1p5ndc- pathways.climateanalytics.org/methodology/ (visited on 09/20/2022).
  a) Low Carbon Dioxide Removal scenario
  b) High Carbon Dioxide Removal scenario
  c) Low Energy Demand scenario
  d) High Energy Demand scenario
- Climate Analytics, *1.5°C pathways for Europe, Achieving the highest plausible climate ambition*, 2021
- Climate Action Tracker, *Warming Projections Global Update*, 2021
- Canada Energy Regulator, *Canada Energy Future*, 2021
  a) Current Policies scenario
  b) Evolving Policies scenario
- EIA U.S. Energy Information Administration, *Annual Energy Outlook*, 2022
  a) AEO20222 Reference Case scenario
  b) High Economic Growth scenario
  c) Low Economic Growth scenario
  d) High Oil Price scenario
  e) Low Oil Price scenario
  f) High Oil and Gas Supply scenario
  g) Low Oil and Gas Supply scenario
  h) High Renewables Cost scenario
  i) Low Renewables Cost scenario

- CSIRO, *Ocean renewable energy 2015-2050, An analysis of ocean energy in Australia*, 2012
- Eurelectric, *Decarbonisation pathways: European Economy and European power secotr*, 2018
  a) 80% Decarbonisation scenario
  b) 90% Decarbonisation scenario
  c) 95% Decarbonisation scenario
- Greenpeace, Global Wind Energy Council, SolarPower Europe, *energy [r]evolution: a sustainable world energy outlook 2015*, 2015
  a) Reference scenario
  b) Energy Revolution scenario
  c) Advanced Energy Revolution scenario
- Greenpeace, *Filling the Energy gap: Building a secure renewable energy system to meet UK climate targets after the collapse of Wylfa and Moorside nuclear power plants*, 2019
- Greenpeace, *A green recovery, how we get there*, 2020
- LUT University & Energy Watch Group, *Global Energy System based on 100% Renewable Energy – Power, Heat, Transport and Desalination Sectors*, 2019
  a) Best Policy scenario
- LUT University & Energy Watch Group, *Global Energy System based on 100% Renewable Energy – Energy Transition in Europe Across Power, Heat, Transport and Desalination Sectors*, 2018
  a) Best Policy scenario
- Institute of Energy Economics of Japan, *IEEJ Outlook 2022*, 2021
  a) Reference scenario
  b) Advanced Technologies scenario
  c) Circular Carbon Economy/4Rs scenario
- European Environment Agency, *Trends and projections in Europe 2021*
- United Kingdom Department of Energy and Climate Change, *Review of Renewable Electricity Generation Cost and Technical Assumptions*, 2016
- EIA U.S. Energy Information Administration, *Capital Cost and Performance Characteristic Estimates for Utility Scale Electric Power Generating Technologies*, 2020
- World Energy Council, *World Energy Scenarios*, 2019

B

TAM, Adoption, RRS Model EU Ocean Power results

In this appendix the complete set of results obtained from the RRS Model EU Ocean Power are exhibit. The figures were retrieved directly by the Excel-based model and they are important to understand the complete framework of this work.

	Modest TAM Growth				Intermediate TAM Growth					Ambitious TAM Growth					mbitious TAM Growth	
	Based on High CDR Scenario, Climate Analytics, 2022	Based on Reform Scenario, Equinor, 2021	Based on Advanced Technologies Scenario, IEEJ, 2022	Based on Stated Policies Scenario, IEA, 2021	Based on Planned Energy Scenario, IRENA, 2021	Based on CurPol Scenario, JRC-EU, 2021	Based on Shared Efforts Scenario, CWF-ECF, 2018	Based on NDC-LTS Scenario, JRC-EU, 2021	Based on 80% Decarbonisation Scenario, Eurelectric, 2018	Based on Transforming Energy Scenario, IRENA, 2021	Based on Announced Pledges Scenario, IEA, 2021	Based on Advanced Energy Revolution Scenario, Greenpeace,	Based on 1.5 °C Scenario, Teske, 2019	Based on 95% Decarbonisation Scenario, Eurelectric, 2018	Based on REMIND Scenario, Climate Analytics, 2022	Functional Unit
2012	2550	2550	2550	2550	2550	2550	2550	2550	2550	2550	2550	2550	2550	2550	2550	TWh
2013	2548	2548	2548	2548	2548	2548	2548	2548	2548	2548	2548	2548	2548	2548	2548	TWh
2014	2520	2520	2520	2520	2520	2520	2520	2520	2520	2520	2520	2520	2520	2520	2520	TWh
2015	2585	2585	2585	2585	2585	2585	2585	2585	2585	2585	2585	2585	2585	2585	2585	TWh
2016	2605	2605	2605	2605	2605	2605	2605	2605	2605	2605	2605	2605	2605	2605	2605	TWh
2017	2654	2654	2654	2654	2654	2654	2654	2654	2654	2654	2654	2654	2654	2654	2654	TWh
2018	2655	2655	2655	2655	2655	2655	2655	2655	2655	2655	2655	2655	2655	2655	2655	TWh
2019	2647	2647	2647	2647	2647	2647	2647	2647	2647	2647	2647	2647	2647	2647	2647	TWh
2020	2757	2757	2757	2757	2757	2757	2757	2757	2757	2757	2757	2757	2757	2757	2757	TWh
2021	2649	2743	2766	2763	2825	2740	2747	2787	2841	2848	2810	3039	3072	2951	2918	TWh
2022	2541	2772	2801	2799	2873	2772	2787	2834	2901	2907	2862	3135	3186	3042	3014	TWh
2023	2520	2802	2838	2838	2923	2805	2829	2884	2963	2968	2916	3237	3307	3138	3118	TWh
2024	2500	2832	2876	2877	2975	2840	2873	2937	3029	3032	2974	3342	3433	3240	3229	TWh
2025	2478	2863	2914	2917	3028	2876	2919	2993	3097	3098	3034	3453	3565	3346	3351	TWh
2026	2457	2893	2953	2958	3081	2914	2966	3050	3168	3167	3097	3564	3697	3456	3472	TWh
2027	2435	2923	2992	2999	3135	2953	3015	3110	3240	3238	3163	3679	3834	3570	3602	TWh
2028	2415	2953	3031	3041	3190	2992	3065	3171	3315	3311	3231	3796	3973	3686	3739	TWh
2029	2395	2981	3070	3083	3244	3033	3115	3235	3391	3385	3302	3914	4114	3806	3881	TWh
2030	2356	3044	3159	3145	3297	3038	3167	3300	3468	3461	3411	4033	4250	3928	4030	TWh
2031	2360	3036	3147	3165	3350	3116	3219	3365	3545	3537	3449	4153	4396	4051	4179	TWh
2032	2346	3062	3184	3206	3401	3159	3272	3432	3624	3614	3526	4272	4536	4176	4335	TWh
2033	2334	3086	3221	3246	3452	3202	3325	3500	3702	3691	3604	4390	4674	4302	4496	TWh
2034	2324	3108	3256	3284	3500	3245	3377	3569	3781	3769	3684	4507	4810	4428	4660	TWh
2035	2286	3129	3289	3322	3546	3289	3430	3638	3859	3846	3765	4622	4943	4554	4854	TWh
2036	2315	3147	3321	3357	3590	3332	3482	3707	3937	3923	3847	4734	5072	4679	4998	TWh
2037	2316	3163	3351	3392	3631	3376	3533	3777	4013	4000	3930	4843	5196	4803	5171	TWh
2038	2322	3176	3378	3424	3669	3420	3584	3847	4089	4075	4015	4949	5315	4926	5347	TWh
2039	2332	3186	3404	3454	3704	3463	3633	3916	4162	4149	4100	5050	5427	5047	5524	TWh
2040	2349	3166	3396	3482	3733	3534	3681	3985	4234	4221	4186	5143	5529	5165	5705	TWh
2041	2367	3198	3446	3507	3762	3549	3728	4053	4304	4293	4272	5237	5630	5280	5885	TWh
2042	2393	3199	3463	3529	3784	3592	3774	4121	4371	4362	4358	5322	5719	5391	6067	TWh
2043	2424	3196	3477	3548	3802	3633	3817	4187	4436	4428	4445	5401	5799	5499	6249	TWh
2044	2462	3190	3487	3564	3815	3674	3858	4252	4497	4493	4532	5472	5868	5602	6432	TWh
2045	2546	3179	3493	3577	3823	3714	3897	4316	4626	4554	4618	5536	5927	5698	6616	TWh
2046	2559	3164	3496	3586	3825	3753	3934	4379	4610	4612	4705	5591	5974	5794	6798	TWh
2047	2619	3145	3500	3591	3821	3791	3968	4439	4660	4667	4791	5638	6009	5881	6980	TWh
2048	2686	3121	3505	3591	3810	3828	3999	4498	4707	4718	4876	5676	6031	5962	7161	TWh
2049	2761	3092	3510	3588	3794	3863	4028	4554	4748	4765	4960	5703	6038	6036	7341	TWh
2050	2876	3100	3520	3577	3796	3890	4060	4570	4778	4820	5040	5764	6100	6100	7537	TWh

Figure B.1: TAM projections used in the Excel-based model

	Modest Growth				Intermediate Growth					Ambitious Growth						ly Ambitious Growth	
	Based on Pessimistic Scenario, Market Study on Ocean Energy by EC,	Based on Low Growth Scenario, OEE 2030 Ocean Energy Vision, 2020	Based on Medium Scenario, Market Study on Ocean Energy by EC, 2018	Based on HNUC Scenario, JRC, 2018	Based on High Growth Scenario, OEE 2030 Ocean Energy Vision,	Based on Optimistic Scenario, Market Study on	Based on Stated Policies Scenario, IEA, 2020	Based on HRES Scenario, JRC, 2018	Based on EU Offshore Renewable Energy Strategy, EC,	Based on Sustainable Development Scenario, IEA, 2020	Based on 1.5 ºC Scenario, Teske, 2019	Based on Energy Revolution Scenario, Greenpeace,	Based on DCCS Scenario, JRC, 2018	Based on LBIO Scenario, JRC, 2018	Based on Advance d Energy Revolutio n	Based on LSW Scenario, JRC, 2018	Functional Unit
2012	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	TWh
2013	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	0,4	TWh
2014	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	TWh
2015	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	TWh
2016	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	TWh
2017	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	TWh
2018	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	TWh
2019	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	TWh
2020	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	0,7	TWh
2021	0,8	0,7	1,0	0,9	0,8	1,4	0,8	1,1	0,8	0,8	8,9	7,2	1,0	0,9	8,4	0,8	TWh
2022	0,8	0,8	1,2	1,1	0,9	1,7	0,8	1,5	0,9	0,8	11,5	9,5	1,5	1,3	11,1	0,9	TWh
2023	0,9	0,8	1,5	1,3	1,2	2,1	0,9	1,9	1,0	0,9	14,4	11,9	2,0	1,5	14,1	1,0	TWh
2024	1,1	1,0	1,9	1,7	1,6	2,6	0,9	2,5	1,1	0,9	17,5	14,6	2,5	1,7	17,3	1,2	TWh
2025	1,3	1,2	2,5	2,0	2,0	3,9	1,0	3,2	1,2	1,0	20,8	17,6	3,0	1,9	20,9	1,4	TWh
2026	1,3	1,4	2,7	2,5	2,6	3,9	1,5	4,0	1,3	1,7	24,1	20,6	3,5	2,1	24,5	1,7	TWh
2027	1,5	1,7	3,2	3,0	3,2	4,7	2,1	4,9	1,4	2,5	27,7	23,9	3,7	2,4	28,5	1,9	TWh
2028	1,7	2,1	3,8	3,5	3,9	5,5	2,9	6,0	1,5	3,5	31,3	27,3	3,9	2,5	32,6	2,3	TWh
2029	1,9	2,5	4,4	4,2	4,8	6,5	3,8	7,2	2,4	4,7	35,2	30,9	4,1	2,7	37,0	2,6	TWh
2030	2,1	3,0	5,1	4,9	5,8	7,4	4,0	8,6	2,2	5,0	39,1	34,8	4,3	2,9	41,7	3,0	TWh
2031	2,4	3,5	6,0	5,8	6,8	8,8	6,0	10,1	4,8	7,7	43,1	38,6	4,5	3,0	46,4	3,5	TWh
2032	2,6	4,1	6,9	6,7	8,1	10,1	7,3	11,8	6,3	9,5	47,2	42,7	6,9	3,1	51,3	4,0	TWh
2033	2,9	4,8	7,9	7,7	9,5	11,6	8,9	13,7	8,0	11,6	51,4	46,9	9,7	3,2	56,5	4,5	TWh
2034	3,2	5,6	8,9	8,9	11,0	13,2	10,6	15,8	10,0	14,0	55,7	51,3	13,0	3,3	61,8	5,2	TWh
2035	3,6	6,4	10,1	10,1	12,7	14,9	12,6	18,2	12,2	16,7	59,9	55,8	17,0	7,2	67,3	5,8	TWh
2036	4,0	7,3	11,4	11,5	14,5	16,8	14,7	20,7	14,7	19,6	64,2	60,4	21,0	11,2	72,9	6,5	TWh
2037	4,3	8,3	12,8	12,9	16,5	18,8	17,1	23,4	17,5	22,9	68,6	65,1	25,8	16,1	78,7	11,8	TWh
2038	4,8	9,4	14,3	14,5	18,7	21,0	19,8	26,4	20,6	26,5	72,9	69,9	31,2	21,7	84,7	17,8	TWh
2039	5,2	10,6	15,9	16,2	21,1	23,3	22,7	29,6	24,1	30,4	77,2	74,8	37,1	28,0	90,8	24,7	TWh
2040	5,7	11,8	17,6	18,1	23,6	25,8	26,0	33,1	27,9	35,0	81,4	79,8	45,3	34,9	97,0	29,8	TWh
2041	6,2	13,2	19,5	20,1	26,4	28,5	29,2	36,9	32,0	39,4	85,7	84,9	51,0	42,9	103,3	41,1	TWh
2042	6,7	14,7	21,5	22,2	29,4	31,4	32,9	40,9	36,5	44,5	89,9	90,1	59,0	51,7	109,7	50,8	TWh
2043	7,3	16,3	23,6	24,5	32,6	34,5	36,9	45,2	41,4	49,9	94,0	95,3	67,6	61,3	116,2	61,5	TWh
2044	7,9	18,0	25,9	26,9	36,0	37,7	41,2	49,8	46,6	55,8	98,0	100,6	77,0	71,8	122,9	73,2	TWh
2045	8,6	19,8	28,3	29,5	39,7	41,2	45,8	54,6	52,3	62,1	101,9	105,9	87,6	87,9	129,6	86,2	TWh
2046	9,2	21,7	30,8	32,3	43,5	44,8	50,8	59,8	58,5	68,9	105,7	111,4	98,2	95,7	136,4	100,1	TWh
2047	9,9	23,8	33,5	35,2	47,7	48,7	56,1	65,4	65,0	76,2	109,4	116,8	110,0	109,2	143,3	115,3	TWh
2048	10,7	25,9	36,3	38,3	52,1	52,8	61,7	71,2	72,0	83,9	113,0	122,3	122,7	123,7	150,2	131,8	TWh
2049	11,5	28,3	39,3	41,5	56,7	57,1	67,7	77,4	79,5	92,1	116,4	127,8	136,3	139,3	157,2	149,6	TWh
2050	12,3	30,7	42,5	45,0	61,6	61,6	74,0	83,9	87,6	100,8	119,1	130,0	154,5	154,5	164,0	170,0	TWh

Figure B.2: Adoption projections used in the Excel-based model

	Key Adoption Results		Key Financial Results			Key Emissions Results
ADOPTION	Implementation Unit Adoption Increase in (PDS vs REF) TW	Functional Unit Adoption Increase in (PDS vs REF) TWh	Marginal First Cost 2020-2050 Billion USD	Net Operating Savings 2020-2050 Billion USD	Lifetime Operating Savings 2020-2050 Billion USD	Total Emissions Reduction Gt CO2 (2020-2050)
Modest Growth	0,01	31,71	27,10	-24,32	-59,35	0,17
Intermediate Growth	0,02	72,84	49,64	-52,49	-134,30	0,36
Ambitious Growth	0,04	136,24	85,58	-118,91	-267,86	0,81
Extremely Ambitious Growth	0,05	169,09	86,12	-85,44	-303,55	0,58
All Sources	0,03	92,45	61,62	-72,23	-175,34	0,49
Based on Pessimistic Scenario, Market Study on Ocean Energy by EC, 2018	0,00	11,38	12,23	-9,27	-21,60	0,06
Based on Low Growth Scenario, OEE 2030 Ocean Energy Vision, 2020	0,01	29,79	25,22	-21,62	-54,85	0,15
Based on Medium Scenario, Market Study on Ocean Energy by EC, 2018	0,01	41,58	33,71	-32,71	-78,46	0,22
Based on HNUC Scenario, JRC, 2018	0,01	44,09	34,85	-33,70	-82,52	0,23
Based on High Growth Scenario, OEE 2030 Ocean Energy Vision, 2020	0,02	60,70	43,64	-44,87	-112,53	0,31
Based on Optimistic Scenario, Market Study on Ocean Energy by EC, 2018	0,02	60,72	45,15	-48,61	-115,21	0,33
Based on Stated Policies Scenario, IEA, 2020	0,02	73,11	48,47	-50,05	-132,79	0,34
Based on HRES Scenario, JRC, 2018	0,03	82,99	55,72	-63,28	-155,32	0,43
Based on EU Offshore Renewable Energy Strategy, EC, 2020	0,03	86,69	54,57	-55,63	-155,68	0,38
Based on Sustainable Development Scenario, IEA, 2020	0,03	99,91	60,58	-68,06	-181,28	0,46
Based on 1.5 ºC Scenario, Teske, 2019	0,04	118,16	88,74	-146,39	-258,59	1,00
Based on Energy Revolution Scenario, Greenpeace, 2015	0,04	129,09	89,80	-145,09	-271,36	0,99
Based on DCCS Scenario, JRC, 2018	0,05	153,59	82,98	-92,93	-279,05	0,63
Based on LBIO Scenario, JRC, 2018	0,05	153,59	81,14	-83,82	-276,74	0,57
Based on Advanced Energy Revolution Scenario, Greenpeace, 2015	0,05	163,09	105,17	-177,16	-340,14	1,21
Based on LSW Scenario, JRC, 2018	0,05	169,09	86,12	-85,44	-303,55	0,58

Figure B.3: RRS Model EU Ocean Power results with VMA data set to Mean values

Sensitivity Analysis #1						
Learning Rate - Max	14,82%					
Include financial values for SOLUTION in the FUTURE						
Using MEAN values for SOLUTION financial variables						
Using MEAN values for CONVENTIONAL financial variables						

	Key Adoption Results		Key Financial Results			Key Emissions Results
ADOPTION	Implementation Unit Adoption Increase in (PDS vs REF) TW	Functional Unit Adoption Increase in (PDS vs REF) TWh	Marginal First Cost 2020-2050 Billion USD	Net Operating Savings 2020-2050 Billion USD	Lifetime Operating Savings 2020-2050 Billion USD	Total Emissions Reduction Gt CO2 (2020-2050)
Modest Growth	0,01	31,71	10,41	-14,88	-36,32	0,17
Intermediate Growth	0,02	72,84	13,28	-32,12	-82,18	0,36
Ambitious Growth	0,04	136,24	16,29	-72,76	-163,90	0,81
Extremely Ambitious Growth	0,05	169,09	7,77	-52,28	-185,74	0,58
All Sources	0,03	92,45	15,04	-44,20	-107,29	0,49
Based on Pessimistic Scenario, Market Study on Ocean Energy by EC, 201	0,00	11,38	5,95	-5,67	-13,22	0,06
Based on Low Growth Scenario, OEE 2030 Ocean Energy Vision, 2020	0,01	29,79	9,73	-13,23	-33,56	0,15
Based on Medium Scenario, Market Study on Ocean Energy by EC, 2018	0,01	41,58	11,93	-20,01	-48,01	0,22
Based on HNUC Scenario, JRC, 2018	0,01	44,09	11,98	-20,62	-50,49	0,23
Based on High Growth Scenario, OEE 2030 Ocean Energy Vision, 2020	0,02	60,70	12,94	-27,46	-68,85	0,31
Based on Optimistic Scenario, Market Study on Ocean Energy by EC, 2018	0,02	60,72	13,78	-29,75	-70,50	0,33
Based on Stated Policies Scenario, IEA, 2020	0,02	73,11	12,52	-30,62	-81,25	0,34
Based on HRES Scenario, JRC, 2018	0,03	82,99	14,10	-38,72	-95,04	0,43
Based on EU Offshore Renewable Energy Strategy, EC, 2020	0,03	86,69	12,42	-34,04	-95,26	0,38
Based on Sustainable Development Scenario, IEA, 2020	0,03	99,91	12,38	-41,64	-110,93	0,46
Based on 1.5 ºC Scenario, Teske, 2019	0,04	118,16	22,36	-89,58	-158,23	1,00
Based on Energy Revolution Scenario, Greenpeace, 2015	0,04	129,09	20,17	-88,78	-166,04	0,99
Based on DCCS Scenario, JRC, 2018	0,05	153,59	10,39	-56,86	-170,75	0,63
Based on LBIO Scenario, JRC, 2018	0,05	153,59	9,24	-51,29	-169,33	0,57
Based on Advanced Energy Revolution Scenario, Greenpeace, 2015	0,05	163,09	19,16	-108,41	-208,13	1,21
Based on LSW Scenario, JRC, 2018	0,05	169,09	7,77	-52,28	-185,74	0,58

Figure B.4: RRS Model EU Ocean Power sensitivity analysis - round #1 results

Sensitivity Analysis #2						
Learning Rate - Max	14,82%					
Include financial values for SOLUTION in the future						
Using MEAN values for SOLUTION financial variables						
Using HIGH values for CONVENTIONAL financial variables						

	Key Adoption Results		**Key Financial Results**			**Key Emissions Results**
ADOPTION	**Implementation Unit Adoption Increase in (PDS vs REF) TW**	**Functional Unit Adoption Increase in (PDS vs REF) TWh**	**Marginal First Cost 2020-2050 Billion USD**	**Net Operating Savings 2020-2050 Billion USD**	**Lifetime Operating Savings 2020-2050 Billion USD**	**Total Emissions Reduction Gt CO2 (2020-2050)**
Modest Growth	0,01	31,71	-3,60	-10,56	-25,76	0,17
Intermediate Growth	0,02	72,84	-18,74	-22,78	-58,28	0,36
Ambitious Growth	0,04	136,24	-43,51	-51,60	-116,24	0,81
Extremely Ambitious Growth	0,05	169,09	-66,38	-37,08	-131,73	0,58
All Sources	0,03	92,45	-25,46	-31,34	-76,09	0,49
Based on Pessimistic Scenario, Market Study on Ocean Energy by EC, 201	0,00	11,38	0,86	-4,02	-9,37	0,06
Based on Low Growth Scenario, OEE 2030 Ocean Energy Vision, 2020	0,01	29,79	-3,43	-9,38	-23,80	0,15
Based on Medium Scenario, Market Study on Ocean Energy by EC, 2018	0,01	41,58	-6,40	-14,19	-34,05	0,22
Based on HNUC Scenario, JRC, 2018	0,01	44,09	-7,44	-14,63	-35,81	0,23
Based on High Growth Scenario, OEE 2030 Ocean Energy Vision, 2020	0,02	60,70	-13,76	-19,47	-48,83	0,31
Based on Optimistic Scenario, Market Study on Ocean Energy by EC, 2018	0,02	60,72	-12,93	-21,10	-50,00	0,33
Based on Stated Policies Scenario, IEA, 2020	0,02	73,11	-19,61	-21,72	-57,62	0,34
Based on HRES Scenario, JRC, 2018	0,03	82,99	-22,37	-27,46	-67,40	0,43
Based on EU Offshore Renewable Energy Strategy, EC, 2020	0,03	86,69	-25,76	-24,14	-67,56	0,38
Based on Sustainable Development Scenario, IEA, 2020	0,03	99,91	-31,49	-29,53	-78,67	0,46
Based on 1.5 ºC Scenario, Teske, 2019	0,04	118,16	-29,57	-63,53	-112,22	1,00
Based on Energy Revolution Scenario, Greenpeace, 2015	0,04	129,09	-36,53	-62,96	-117,76	0,99
Based on DCCS Scenario, JRC, 2018	0,05	153,59	-56,98	-40,33	-121,10	0,63
Based on LBIO Scenario, JRC, 2018	0,05	153,59	-58,13	-36,38	-120,09	0,57
Based on Advanced Energy Revolution Scenario, Greenpeace, 2015	0,05	163,09	-52,45	-76,88	-147,61	1,21
Based on LSW Scenario, JRC, 2018	0,05	169,09	-66,38	-37,08	-131,73	0,58

Figure B.5: RRS Model EU Ocean Power sensitivity analysis - round #2 results

Sensitivity Analysis #3						
Learning Rate - Max	14,82%					
Include financial values for SOLUTION in the future						
Using LOW values for SOLUTION financial variables						
Using MEAN values for CONVENTIONAL financial variables						
	Key Adoption Results		**Key Financial Results**			**Key Emissions Results**
ADOPTION	**Implementation Unit Adoption Increase in (PDS vs REF) TW**	**Functional Unit Adoption Increase in (PDS vs REF) TWh**	**Marginal First Cost 2020-2050 Billion USD**	**Net Operating Savings 2020-2050 Billion USD**	**Lifetime Operating Savings 2020-2050 Billion USD**	**Total Emissions Reduction Gt CO2 (2020-2050)**
Modest Growth	0,01	31,71	-4,99	-1,11	-2,71	0,17
Intermediate Growth	0,02	72,84	-16,14	-2,39	-6,13	0,36
Ambitious Growth	0,04	136,24	-33,98	-5,42	-12,22	0,81
Extremely Ambitious Growth	0,05	169,09	-47,72	-3,90	-13,85	0,58
All Sources	0,03	92,45	-21,21	-3,29	-8,00	0,49
Based on Pessimistic Scenario, Market Study on Ocean Energy by EC, 201	0,00	11,38	-0,84	-0,42	-0,99	0,06
Based on Low Growth Scenario, OEE 2030 Ocean Energy Vision, 2020	0,01	29,79	-4,71	-0,99	-2,50	0,15
Based on Medium Scenario, Market Study on Ocean Energy by EC, 2018	0,01	41,58	-7,29	-1,49	-3,58	0,22
Based on HNUC Scenario, JRC, 2018	0,01	44,09	-8,03	-1,54	-3,76	0,23
Based on High Growth Scenario, OEE 2030 Ocean Energy Vision, 2020	0,02	60,70	-12,62	-2,05	-5,13	0,31
Based on Optimistic Scenario, Market Study on Ocean Energy by EC, 2018	0,02	60,72	-12,25	-2,22	-5,26	0,33
Based on Stated Policies Scenario, IEA, 2020	0,02	73,11	-16,56	-2,28	-6,06	0,34
Based on HRES Scenario, JRC, 2018	0,03	82,99	-18,84	-2,89	-7,09	0,43
Based on EU Offshore Renewable Energy Strategy, EC, 2020	0,03	86,69	-20,79	-2,54	-7,10	0,38
Based on Sustainable Development Scenario, IEA, 2020	0,03	99,91	-24,73	-3,10	-8,27	0,46
Based on 1.5 ºC Scenario, Teske, 2019	0,04	118,16	-25,81	-6,68	-11,80	1,00
Based on Energy Revolution Scenario, Greenpeace, 2015	0,04	129,09	-30,09	-6,62	-12,38	0,99
Based on DCCS Scenario, JRC, 2018	0,05	153,59	-41,86	-4,24	-12,73	0,63
Based on LBIO Scenario, JRC, 2018	0,05	153,59	-42,37	-3,82	-12,62	0,57
Based on Advanced Energy Revolution Scenario, Greenpeace, 2015	0,05	163,09	-40,84	-8,08	-15,52	1,21
Based on LSW Scenario, JRC, 2018	0,05	169,09	-47,72	-3,90	-13,85	0,58

Figure B.6: RRS Model EU Ocean Power sensitivity analysis - round #3 results

Sensitivity Analysis #4							
Learning Rate - Max	14,82%						
Include financial values for SOLUTION in the future							
Using LOW values for SOLUTION financial variables							
Using HIGH values for CONVENTIONAL financial variables							

	Key Adoption Results		Key Financial Results			Key Emissions Results
ADOPTION	Implementation Unit Adoption Increase in (PDS vs REF) TW	Functional Unit Adoption Increase in (PDS vs REF) TWh	Marginal First Cost 2020-2050 Billion USD	Net Operating Savings 2020-2050 Billion USD	Lifetime Operating Savings 2020-2050 Billion USD	Total Emissions Reduction Gt CO2 (2020-2050)
Modest Growth	0,01	31,71	-18,99	3,22	7,85	0,17
Intermediate Growth	0,02	72,84	-48,16	6,95	17,77	0,36
Ambitious Growth	0,04	136,24	-93,79	15,73	35,44	0,81
Extremely Ambitious Growth	0,05	169,09	-121,86	11,31	40,17	0,58
All Sources	0,03	92,45	-61,71	9,56	23,20	0,49
Based on Pessimistic Scenario, Market Study on Ocean Energy by EC, 201	0,00	11,38	-5,94	1,23	2,86	0,06
Based on Low Growth Scenario, OEE 2030 Ocean Energy Vision, 2020	0,01	29,79	-17,87	2,86	7,26	0,15
Based on Medium Scenario, Market Study on Ocean Energy by EC, 2018	0,01	41,58	-25,62	4,33	10,38	0,22
Based on HNUC Scenario, JRC, 2018	0,01	44,09	-27,45	4,46	10,92	0,23
Based on High Growth Scenario, OEE 2030 Ocean Energy Vision, 2020	0,02	60,70	-39,32	5,94	14,89	0,31
Based on Optimistic Scenario, Market Study on Ocean Energy by EC, 2018	0,02	60,72	-38,96	6,43	15,25	0,33
Based on Stated Policies Scenario, IEA, 2020	0,02	73,11	-48,69	6,62	17,57	0,34
Based on HRES Scenario, JRC, 2018	0,03	82,99	-55,31	8,37	20,55	0,43
Based on EU Offshore Renewable Energy Strategy, EC, 2020	0,03	86,69	-58,97	7,36	20,60	0,38
Based on Sustainable Development Scenario, IEA, 2020	0,03	99,91	-68,60	9,01	23,99	0,46
Based on 1.5 ºC Scenario, Teske, 2019	0,04	118,16	-77,74	19,37	34,22	1,00
Based on Energy Revolution Scenario, Greenpeace, 2015	0,04	129,09	-86,80	19,20	35,91	0,99
Based on DCCS Scenario, JRC, 2018	0,05	153,59	-109,23	12,30	36,93	0,63
Based on LBIO Scenario, JRC, 2018	0,05	153,59	-109,74	11,09	36,62	0,57
Based on Advanced Energy Revolution Scenario, Greenpeace, 2015	0,05	163,09	-112,45	23,44	45,01	1,21
Based on LSW Scenario, JRC, 2018	0,05	169,09	-121,86	11,31	40,17	0,58

Figure B.7: RRS Model EU Ocean Power sensitivity analysis - round #4 results

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