POLITECNICO DI TORINO

Master's Degree in Energy and Nuclear Engineering

Master's Degree Thesis

Estimation and analysis of offshore renewable energy potential for Mediterranean Sea.

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Summary

In order to satisfy the need to increase renewable sources, in the future it will be necessary to focus also on the offshore ones. To date, this term refers substantially to offshore wind, in its two forms bottom-fixed and floating wind turbines, and ocean energy, which has among its resources wave energy as the most promising. Without their use it would be impossible to achieve the reliability and flexibility that renewable sources need.

Given their importance, in this study a methodology has been designed to analyse data of wind and waves in the Mediterranean Sea, in order to obtain an estimate and evaluation of its potential.The study used eleven years of hourly weather data downloaded from the ERA5 site, from 2010 to 2020, while the writing is done using the MATLAB platform.

The first part of the methodology uses wind (speed and direction) and wave data (period, significant height, direction) to create maps of resources power density and technology potential.These data are interpolated, using the MATLAB function *interp2*, to increase the accuracy of the grid (it is possible to choose it), then the following constraints are set: bathymetry, protected areas, exclusive economic zones, distance from the coast and technological restrictions. These limits depend on the type of technology and are the main factors that influence the results of the analysis.

The second part of the study, instead, carries out a metocean time series analysis of a precise location, always inside of the Mediterranean Sea, obtaining therefore the average values and the fluctuations of the resources and the technologies. In this case it is possible to choose the location of the study, but there is no possibility to interpolate the data as a time analysis is carried out. In this part is also added an evaluation of the extreme cases of the location.

The results show that the technology with the highest potential is floating wind, with a value of about 18,500 TWh/year and a capacity of 3,290 GW. Values totally different from the bottom-fixed wind turbine that has about 2,410 TWh/year of energy potential and 224 GW for the capacity. This huge difference is mainly due to the difference in area available for the two technologies, because the Mediterranean seabed is very deep and it is impossible to install a bottom-fixed turbine over a

maximum of 50-60 m.Wave energy has similar potential to the latter, but still higher, in fact it is about 4,670 TWh/year and 533 GW.

Main limit for this source is the technological one, because the Mediterranean does not have a particularly high power density.These results highlight how in the Mediterranean it is necessary to focus on floating wind, although there is also the possibility to install some bottom -fixed wind turbine. While, regarding wave energy, there is need to continue with the research to design new devices, as however, although there is a considerable potential, with the modern technologies it is not exploitable.

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Chapter 1

Introduction

Nowadays everybody knows the importance of renewable sources. It is almost impossible to think of a future without environmental and climatic change in the absence of their use. Every day we hear news of the need to stop the exploitation of fossil fuels, to find new solutions for the production of energy because global warming and climate change caused by sources such as coal or oil have become unsustainable for our planet. Over the years this has become increasingly evident, there are many articles demonstrating how the average temperature of the planet has increased, especially from 1981[1], how heat waves have never been higher[2] and how at this rate millions of people around the world will be forced to abandon their homes due to rising seas[3].

For these reasons, since the beginning of the 90s the United Nations have started talking about climate change, reaching the summit with the Kyoto protocol, which in 1997 (it came into force only in 2005) laid the foundations for the first limits for greenhouse gas emissions. In recent years, however, a new, much more stringent agreement has been stipulated, that of Paris (2015). Its primary objective is to prevent the average temperature of the planet from rising by 2° in the coming decades[4].To make this possible, it will be necessary to reach as soon as possible the global peak of greenhouse gas emissions, and then go to achieve neutrality in the second half of this century.

These aspects are only from a climatic and environmental point of view. The Russia-Ukraine war is enough to make everyone understand that depending on fossil fuels, because of their strong regionality and political power, involves enormous energy and economic risks, and every country should be able to produce the necessary energy for itself,or at least a considerable part without depending on external states.

To respect the constraints imposed by the United Nations and the European Union, and to avoid depending on energy from other countries, a massive expansion of the exploitation of renewable sources will be necessary.Between 2021 and 2026, a quantity of renewable sources equal to 50% more than those installed between 2015 and 2020 should be installed, in order to exceed the capacity of 4800 GW in 2026[5].

To achieve these objectives, however, it will not be enough to simply increase the number of the most common RES, like solar photovoltaic and onshore wind energy, because, although they are reliable and competitive sources in the market, they have their limits. The first and most important is related to their inability to provide continuous production. In fact, depending on the sun cycle and wind fluctuations, it is not possible to produce a purely base load from these resources. The second reason is linked to the exploitation of the land. To reach a sufficient capacity, considering also that the demand for electricity every year increases, a huge amount of acres will have to be used. These problems can not be solved with the simple increase in capacity and therefore in size of the plants,therefore,it will be necessary to exploit also those RES that are less widespread today, such as all those offshore renewable sources.

In this group of RES,to date, essentially there are three technologies: fixed and floating offshore wind turbine and ocean energy. They will be explained in detail in the second chapter,for now, it is enough to know that offshore wind turbine, for now, is the only technology capable of producing substantial quantities of electricity in the open sea,and not only that, almost all of offshore wind farm consists of bottom-fixed turbines.

This type of RES is more widespread because it is substantially the same as the onshore one,therefore the step to install a wind turbine on the seabed is certainly complex, but not to the point of stopping the research or to avoid its exploitation.

Floating wind turbines are less widespread due to the fact that the creation and installation of a turbine that must work in the open sea without being fixed to the seabed is much more complex,and requires to find new types of foundations that can keep wind turbines to the surface.

However, even bottom-fix wind turbine is a technology not spread enough, in fact,in 2021, were installed worldwide 830 GW of wind capacity, only about 7% of total production was from offshore wind[6].

Most wind farm, from both technology, are built in the North sea, between Great Britain, Germany,Norway and Denmark, where, in 1991 in Vindeby the first offshore wind farm has been built[7].

In the picture 1.1 it is possible to observe Hornsea 2, with its 165 turbines and 1.3 GW is the largest offshore wind farm in the world, located 89 km off the Yorkshire Coast, in the North Sea.

Thanks to a very rapid expansion in recent years, now China is the country with the largest installed capacity, equal to 24.9 GW[8]. However, other countries,

Figure 1.1: Hornsea 2 wind farm photo.

such as France, Spain, Portugal, but especially the U.S.A and Japan are rapidly increasing their capacity too.

As with onshore wind, offshore also depends heavily on the wind. But it changes considerably when moving from land to open sea, it tends to be stronger and more constant, in fact the potential of offshore wind in some areas of the world, such as in Europe, is greater than the equivalent on land. For this reason, however, it needs different analyses, which take into consideration factors and constrains different than onshore wind turbines.

On the other hand, the purpose of ocean energy is to transform the energy contained in the oceans and seas into usable power. Exploiting resources such as waves, currents or tides, is not a modern concept, indeed the researchers have conceived it well before many sources that today are widespread renewable. Unfortunately, this type of technology is far behind other RES, there are only few devices on the market, but mostly are still at a research stage.There are however several projects and prototypes in operation,such as the OPT Power Buoy, one of the wave energy converter to date at the most advanced stage.

Figure 1.2: OPT PB3 PowerBuoy photo.[9]

In recent years, interest in offshore renewable sources has significantly increased because their potential is immense. First of all because on Earth there is much more surface covered by water masses (70%) than uncovered,and therefore the space from arrangement is considerably larger. Secondly, they are technologies that are based on resources and factors that have not yet been exploited, and therefore their use would be fundamental to increase the flexibility and reliability that RES currently need.

The European Union itself in 2021 published a report entitled "EU strategy on offshore renewable energy", in which it sets targets to satisfy the objectives set for renewable sources for 2030 and 2050. In particular, the plan would be to achieve in 2030 at least 60 GW of offshore wind and 1 GW of ocean energy, while for 2050 the objectives would be 300 GW for the former and 40 GW for the latter[10]. The objectives regarding offshore wind, thanks to the future plants already commissioned, seem to be achievable, while, those related to wave energy are more complex to meet.

Offshore renewable depend very much on the climatic and meteorological conditions in which they are located,in order to decide whether it is possible to install one in a given area, there is a need before carrying out careful assessments of the potential of resources and technologies. To perform these analyses, platforms and database are usually used to provide useful information to the study. These can simply be resource data, or real preliminary analyses.

Given their importance, in this study, a methodology (divided in two parts) that can evaluate the power density of offshore resources in the Mediterranean Sea has been produced , moreover it integrate the results with different technologies, to obtain their energy potential.

The first part, has the task of illustrating through geographical maps the resources power density and the potential of technologies in selected areas of the Mediterranean Sea, in order to provide a first visual evaluation of the quality of the resources.

To do this a Matlab script has been created, it uses the data of winds and waves downloaded from the ERA5 database. They are interpolated in order to increase their accuracy, and then are integrated with limits of a geographical nature (bathymetry, distance from the coast, protected areas) and technical nature (wind speed and power density). It will be explained in detail in the third chapter, together with its results.

The second part of the study has the task of making a metocean time series analysis of a precise location. Indicating a site, it is possible to obtain as result the average value and fluctuations of wind and waves in that place,over a period of eleven years, from 2010 to 2020. This section will be described in the fourth chapter, using an example result as a demonstration.

However, firstly, in the first chapter, most famous institutions and their methodology for wind and wave analysis will be illustrated,in order to understand what their goals are, how they treat data and how they return results.

In the second chapter instead,will be described in detail the three sources mentioned above, therefore their operation, their structure, their limits and constraints, in order to understand on which principles they are based, and why different constraints have been chosen within the study.

Chapter 2

Methodology State of Art

In this chapter, the state of the art of the most important methods for the study and the analysis of the offshore resources will be illustrated.These can be websites, databases or platforms, what unites them is the dissemination of data and assessments, to encourage and facilitate scholars and private entities to invest time and money in the seas or oceans resources.

As mentioned above, the use of these services is essential for the correct and efficient conduct of a study or research. In addition to providing the necessary data simply and accurately, they are also useful for carrying out analyzes both at a preliminary level and at more specific levels.

2.1 Global Wind Atlas

The Global Wind Atlas is a web-based application, able to indicate with high precision the wind power potential of many areas around the world, mainly the mainland and areas not too far from the coast. Completely free, it allows to download continuously updated data obtained with the newest modeling methodologies.

Its main purpose is to support wind energy development during resource exploration and initial assessment prior to the installation of on-site weather stations. It can also serve as a useful tool for better understand the potential of wind resources in particular areas.

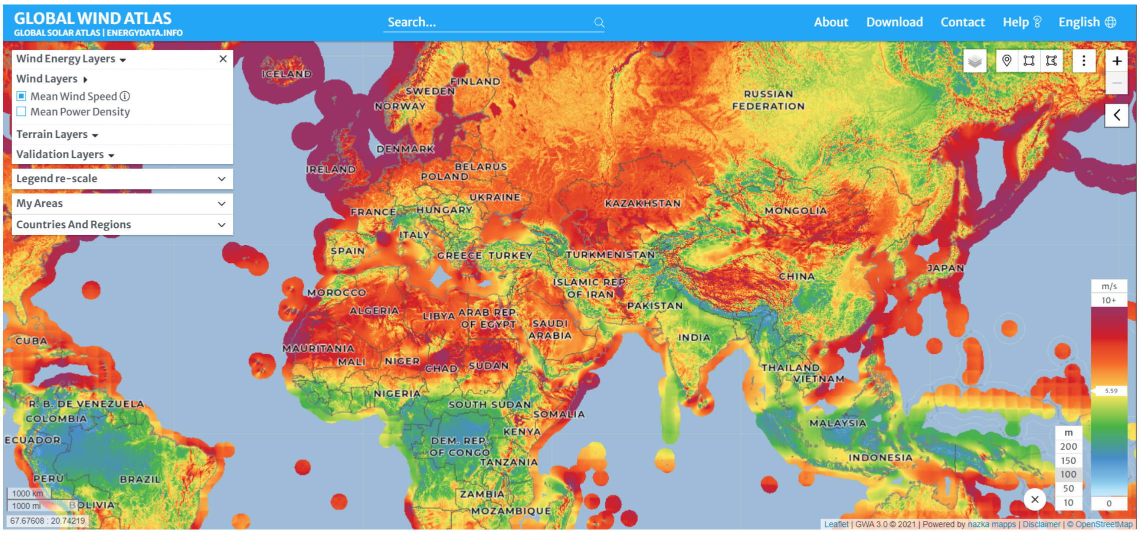

Figure 2.1: Global Wind Atlas main page.

This present version of the Global Wind Atlas (GWA 3.1) is the result of a collaboration between the Department of Wind Energy at the Technical University of Denmark (DTU Wind Energy) and the World Bank Group. It is part of the global ESMAP initiative to map renewable energy resources, including biomass, small hydro and solar.

Its most important features are:

- Wind Coverage of all global onshore land and also of 200 km from the coastline.
- Wind potential mapping at 250 m for horizontal grid spacing and at:10,50,100, 150 and 200 m above ground and sea level.

Furthermore ,it is also able to provide data for preliminary analyses, as it is possible to download data for certain areas, such as provinces or states, but also to see their variation over time, through hourly, monthly and annual data. GWA gives also the opportunity to download GIS data and WAsP LIB files.

It is also able to provide the user with high-resolution maps, in order to show mean wind speed, wind power density, capacity factor, orthography and roughness length. Thanks to the energy yield calculator tool it is also possible to obtain, for a generic or a precise wind turbine, the energy yield creating the GIS-data.

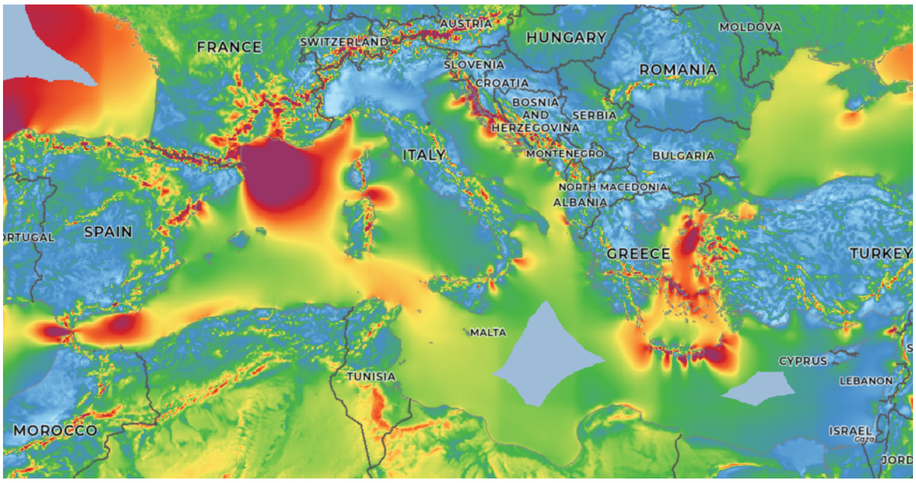

Figure 2.2: Global Wind Atlas Mediterranean Sea Mean Power Density.

The data used by Global Wind Atlas are of different nature and origin.

For the topography they have been divided into surface elevation and surface use or class. This kind of data is one of the simplest, it is now in the public domain and also it has elevate precision.

Regarding orography, elevation data taken by the NASA Shuttle Radar Topography Mission (SRTM) with the digital elevation model (DEM) from Viewfinder Panoramas are combined. The former are precise and reliable data and they have been used to cover the area from 60° N and 60 S°, while the latter from 60°N onward,in order to consider also the areas of Russia, Scandinavia and Canada. This last database possesses empty numbers and is less precise, however the hole are filled with a cubic interpolation in the y-dimension of the raster.

Roughness length data are derived from the European Space Agency's Climate Change Initiative Land Cover (CCI-LC) dataset v2.0.7. It has a resolution of 10 arc-second, equal to 300 m, and the data have been converted for GWA using a nearest-neighbor interpolation, while maintaining the same resolution. To fill void areas (again above 60°N), the MODIS-based 0.5 km global land cover climatology has been used.

As latest sources of information, those relating to the bathymetry of both land and seabed, the GEBCO_2020 dataset has been used.

Talking about Gloabl Wind Atlas methodology, it basically uses a downscaling model to process its data. The starting meteorological information are taken from ERA5 database, a platform provided by the European Center for Medium-Range Weather Forecasts (ECMWF). These are large-scale reanalysis data, positioned on a grid of about 30 kilometers, will be shown below, in the paragraph dedicated to ERA5 its methodology.

They are taken and, using the Weather Research and Forecasting (WRF) mesoscale model, they are forced into a new grid, this time with a precision of 3 kilometers, in order to obtain a new set of data with a 10 times greater precision. The WRF is one of the best mesoscale numerical weather prediction model. It consists of two dynamic parts, the first one the assimilation of data, while the second is a support software for parallel calculations and system extensibility. Subsequently, a microscale modeling system designed by DTU Wind Energy is applied.The final result is a dataset with a spatial arrangement of 250 meters at five different heights: 10,20,50,100 and 250 m. The concept behind the methodology formulated by DTU wind energy is the generalized wind climate. Essentially, the conformation and roughness of the soil is used to calculate wind speed at different heights, as things are directly related.

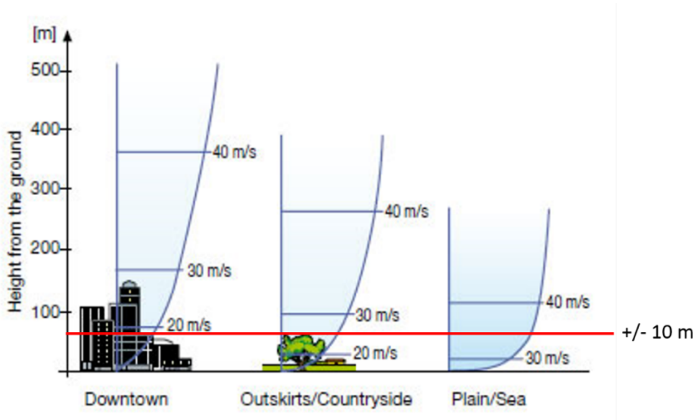

Figure 2.3: General Wind speed profile due to terrain roughness.[11]

2.2 The European Marine Observation and Data Network

The European Marine Observation and Data Network (EMODnet) is a network that aims to provide the user with a large amount of data about marine life and conditions. The platform is supported by the EU's integrated maritime policy, and thanks to this it is free. Its functionality is based on the connection and interpolation of various data layers and products.

The great quality of EMODnet is that it has a gateway to access a large amount of data, starting from local data, ending with those managed by national and international entities. The data collected are manipulated in such a way as to obtain detailed maps of the seas and oceans that bathe the European continent.

This network follows a few simple principles:

- Get data from archives only once, but use it several times. Afterwards develop standards in each characteristic covered and also across them.
- Use, as starting point of work, where the organizations have already started to process the data. Then, exploit and validate them at all levels, if they are missing, like the European one, create it.
- The creation of a decision-making process for priorities that is user-driven and the data that are provided must always possess information regarding the their origin, accuracy and precision.
- Maximize the efforts of EU member states by providing EU level funding and raise awareness among public organizations that marine data is a good that should be free for the population.

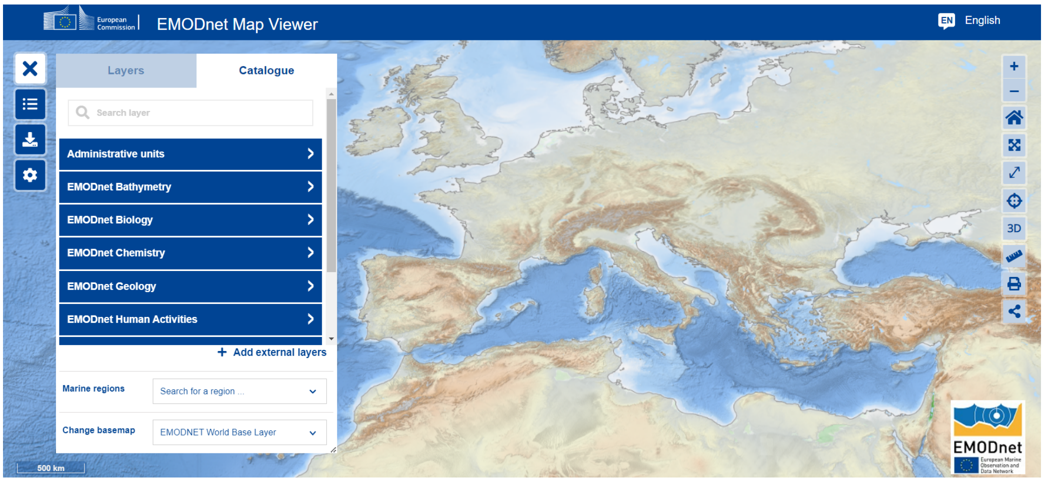

Figure 2.4: EMODnet main page.[12]

EMODnet is able to provide information and evaluation for seven different marine characteristics:

- Bathymetry

  In this section EMODnet allows to store and download one of the best Digital Terrain Models in European waters. Its accuracy is very high and the dataset is periodically checked and updated by himself[13].

- Biology

  EMODnet Biology provides more than 670 different biodiversity dataset. These are interpolated data,both temporally and spatially, for most marine species, from fish to zooplankton[14].

- Chemistry

  According to the Marine Strategy Framework Directive, the use of data on the chemical conditions of the seas and oceans is crucial for the proper assessment of the marine ecosystem. For this reason EMODnet Chemistry provides a great variety of information concerning the substances present in European seas, especially those that need special stains and subsequent analysis in the laboratory to be identified[15].

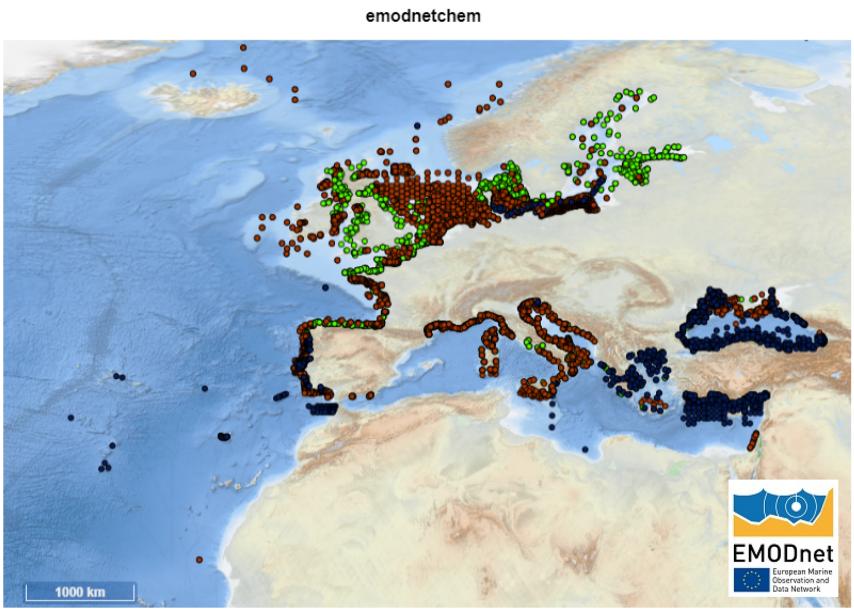

Figure 2.5: EMODnet Cadmium,Mercury, Fluoranthene and Anthracene map.[12]

- Geology

  EMODnet Geology is specialized in the collection and representation of data related to: seabed substrates and geology, seismic events and their probability and finally mineral resources[16].

- Human activities

  This function is different from the others, EMODnet Human Activities does not provide information directly related to the marine environment, but to the structures and works that have been done or will be done. This aspect is not to be underestimated, as with the future increase of works that will have to be done in the European seas, especially those related to the offshore RES, to have a knowledge of the sites already occupied is fundamental[17].

- Physics

  Here there is access to information related to the physical state of European seas. In some ways, especially those relating to the evaluation of the energy potential of a zone, it is the most important section. Main information are about wind(speed and direction) and wave(height and period).There are also data related sea temperature, salinity and currents.[18]

- Seabed habitats

  EMODnet broad-scale seabed habitat gives access to information on seabed habitat in Europe.[19]

Providing such a database and making it public domain reduces uncertainties in research,improves and speeds up scientific research, makes the market more competitive.

2.3 The European Center for Medium-Range Weather Forecasts

The European Center for Medium-Range Weather Forecasts (ECMWF) is one the main meteorological dataset and provision institutions in the world. Both a research institute and an operational service, it has one of the largest meteorological archives in the world[20]. Its main objectives are to produce a global meteorological archive, and to improve or create techniques for data collection and processing[21]. ECMWF is able to provide data of different kinds: from wind to air quality, from climatic conditions to marine data, even information regarding areas at risk of fire[21].

2.3.1 ERA5

In the great variety of services that ECMWF is able to provide, there is ERA5,a the database in which the meteorological data are taken for the creation of the methodologies that will be illustrated in chapters 4 and 5.

ERA5 is the fifth generation atmospheric reanalysis of the global climate, produced by the Copernicus Climate Change Service (C3S) at ECMWF. This database provide the possibility to download hourly global data concerning the wind, the waves, the land-surface, and in general atmospheric characteristics, from 1950 to today.

Reanalysis is the process by which physical laws are used to collect and process data across the world. The base concept is called data assimilation that, practically, take data that are recorded (the time between one survey and the next depends on the monitoring station) to combine them with old forecast , in order to form a new, more accurate evaluation of the weather forecasts[22].

Reanalysis takes the time to formulate past forecasts, integrating improved original forecasts when the time comes. In this way, although the initial resolution is lower than a normal meteorological analysis (having to go back over the years), the final quality of the reanalysis itself can be improved[22].

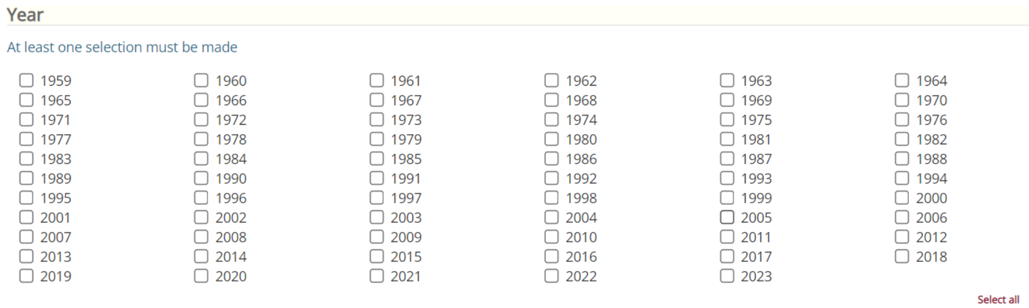

Figure 2.6: ERA5 interface page.

ERA5 also allows the user to change the coordinates of the area for which you want to have data.

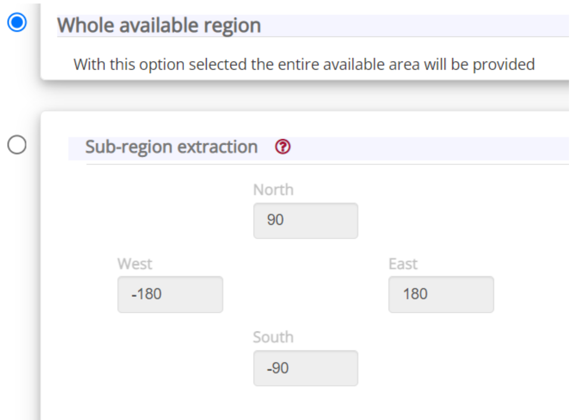

Figure 2.7: ERA5 coordinates interface.

2.4 New European Wind Atlas

The New European Wind Atlas is a platform capable of accurately providing wind atlas data. Its most important feature is the display of wind condition maps, with different depth layers.It is also able to produce analyses, show graphs and finally allows the download of data. Obviously it is possible to take advantage of the data by choosing certain European zones and changing periods of time. An interesting aspect is the possibility of selecting the type of user, in such a way as to arrange the data and analyses more appropriately according to who wishes to use them. There are five types of profiles available: Educator, Researcher, Wind Farm Developer, Electricity System Operator and Policy Maker.

For what concern the methodology, as for Global Wind Atlas, it can be divided into mesoscale modeling and microscale modeling, depending on the map layer and dataset to be obtained.

In this case, the first model totally covers the European Union, Turkey, and up to 100 kilometers off the coast. Here the WRF model, in the modified version v3.8.1 (PBL, icing),includes 10 regions, and it has an adaptive time step and its grid spacing transition is from 27 km, to 9 km and finally to 3 km[23].

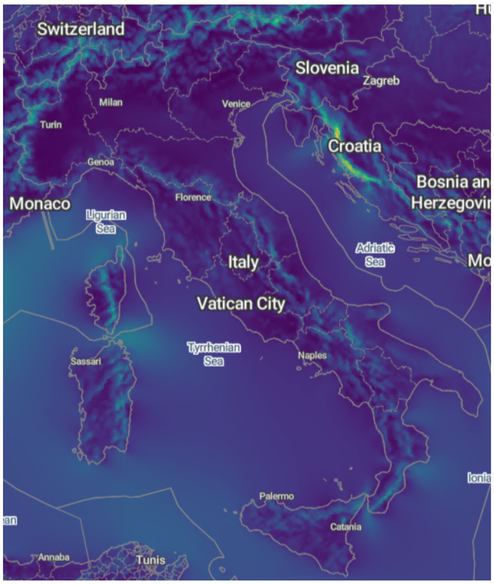

Figure 2.8: Italy mesoscale modelling of Wind Power Density at 100 m.

Microscale modeling is practically identical to that used for the Global Wind Atlas, in fact it is created by the DTU, in particular by their Cluster WAsP, which has the peculiarity of working with linux clusters. The substantial difference is that, in this way, the model has used a finer grid spacing, equal to 50 m[23].

Figure 2.9: Italy microsclae modelling of Wind Power Density at 100 m.

In this case, the orthography data are Taken by SRTM version 3 dataset, integrated with viewfinder for over 60° N, while those related to the roughness are taken from the Corine Land Cover (CLC) 2018, with a 100 m resolution.

2.5 ORECCA

The term ORECCA stands for Offshore Renewable Energy Conversion Platform Coordination Action. Its aim is to collect and merge information regarding offshore RES in Europe, in order to spur researchers and organizations to focus on this energy sector. To do so, the project brings together a multitude of experts from around the world, from multinational corporations to researchers and developers.

The focus of the project are in particular three types of renewable sources: Offshore Wind, Wave energy and Tidal Stream. Therefore between the illustrated methodology until now, is the most dedicated to the study and exploitation of ocean energy.

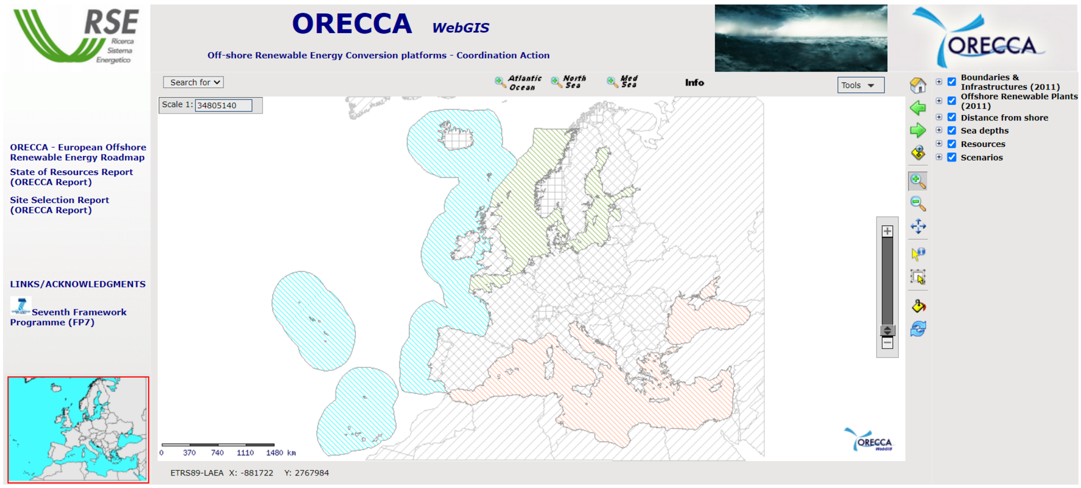

Figure 2.10: ORECCA main website page.

As can be seen from the figure2.10, the site directly divides European waters into three zones, the Mediterranean Sea, the Baltic Sea and the Atlantic Ocean, making it possible to easily select one of the three zones. Furthermore, the platform allows to choose six different layers:Boundaries Infrastructures (2011);Offshore Renewable Plants (2011);Distance from shore;Sea depths;Resources ;Scenarios; Each with their own sublevels.

ORECCA is essentially divided into two parts, one relating to data collection and assessment, and one relating to projects. In fact, differently from the other projects, ORECCA not only sets itself the task of collecting and supplying data, above all its objective is the identification of the most suitable areas for the installation of an offshore RES.

2.5.1 Resource Data

Each renewable source has different data sources and analysis methodologies. The process by which the wind data have been evaluated is composed substantially in two phases: a first analysis carried out through long-term local data and a second more detailed, focused on the location of interest, in which masts are often installed in such a way as to make an annual local survey. In the end, in the vast multitude of data available, the QuikSCAT were used for the ORECCA projects. They cover 11 years of time (1999-2010),and coming from the SeaWinds scatterometer aboard the NASA satellite also named it QuikSCAT , are able to confer accurate wind data statistics. Unfortunately, this type of data presents high uncertainties (even 2 m/s) when it comes to measurements carried out in narrow and closed basins such as those in Europe. Especially as we approach the coast, this growth increases, precisely in the areas of greatest interest for the installation of plants.

For wave data, the data used have been collected in two ways, either directly or indirectly. The first is intended to be a local, in situ measurement using buoys and sensors. It is obviously the most accurate, but measurement sites of this type are not very widespread. The second is data collected remotely, with the use of satellite, or data derived from numerical models. The numerical models, instead, work with wind data (oceanic or even global) and formulate directional spectra on a grid concerning the aquatic body under the wind itself. The main advantages of using wind-wave models are: the vastness of areas they can cover and the low cost compared to local measurements. The best thing is to use the models for a first general evaluation , however quite accurate, and then improve the accuracy calibrating these results with data measured in situ or satellite.

The data that have been used by the ORECCA project are the Fugro-OCEANOR wave data, these are taken from and ECMWF WAM model archive and have been calibrated and corrected through the use a global buoy and Topex satellite altimeter database. These data were chosen as they are among the most accurate and consistent in all three European maritime regions studied.

The latest data to consider, which are even more difficult to find, are those related to tidal current. In fact, as far as these currents are known, generally are of no use and therefore lack concrete data. What is used as a starting point are the Tidal diamond dataset, obtained using a boat anchored at a point and every hour, for twelve hours, the measurement of the sea current is made just below the surface. ORECCA project for the construction of tidal Currents, data from 105 different sites, resulting in turn from several studies. The result is shown on GIS-data layer For the processing and visualization of data ORECCA is based on GIS (Geographical Information Systems). GIS is used by many platforms and organizations for offshore RES Assessing.

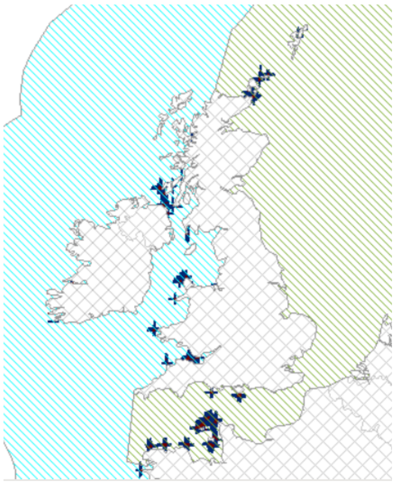

Figure 2.11: ORECCA tidal stream sites in North sea and Atlantic Ocean.

2.5.2 Site Selection Analysis

The second task performed by ORECCA is the study of possible areas for the installation of offshore renewable sources. The methodology chosen by this project for the identification of sites is based on that of Nobre A. et al (2009), or a multi-criteria geospatial analysis for wave energy converters. Its main characteristic is flexibility, as it is able to work with different areas and different RES. Unfortunately, however, it requires a basic GIS database of advanced level, so this method has been completed following the indications given in the Site Selection Methodology Reports of the European project WavePlam.

The methodology begins with the division of the data into two groups, the one related to the places prohibited in the areas of interest and the one containing the resources of the area to be studied. The second step is to choose, for when you can do, a unit that can represent all the factors of the analysis. In ORECCA this unit is money, because every aspect of a study, from the use of the resource to the distance from the coast can be reduced to the gain or the expenses. After assigning to each criteria a judicious weighting and deciding the scale with which to give the final votes (in this case 0-100), the last step is to divide the area of interest into a grid. However, its size is not fixed, it must vary depending on location and technology.

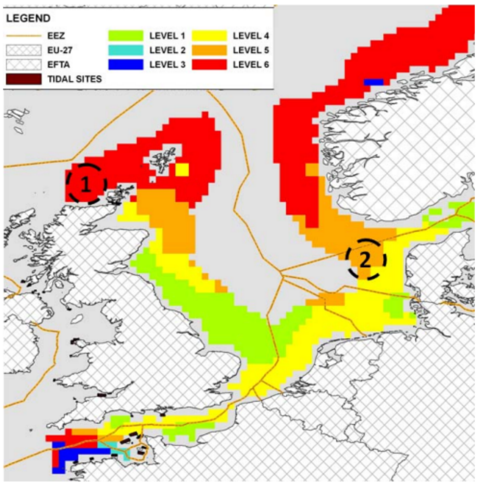

Figure 2.12: ORECCA site selection for floating resource area.

An important aspect when producing a methodology is the comparison of the first results. In fact, it is necessary to check the initial evaluations by making comparisons with other studies and methodology, also carefully observe the results for evaluations clearly inconsistent with what is expected.

Chapter 3

Offshore Wind Turbine and Ocean Energy

In this chapter, the three most common offshore renewable sources will be described more specifically, which as previously mentioned are: bottom fixed wind turbine, floating wind turbine and wave energy converter. Firstly, to understand how they work, and secondly, what are their differences and their limits, in order to understand successively the considerations and constrains that have been made for the methodology.

3.1 Bottom-Fixed wind Turbine

Bottom-fixed wind turbines are very similar to those that are installed on land. On average, however, they are higher and larger, because the wind is a resource that blows more intensely and constantly in the open sea,furthermore there are no obstacles. In this way the turbines have a higher power density. Basically, inside a wind turbine, the rotational motion of the blades, due to the incident wind, is converted into electricity.

In the figure 3.1 it is possible to observe the basic structure of a wind turbine:

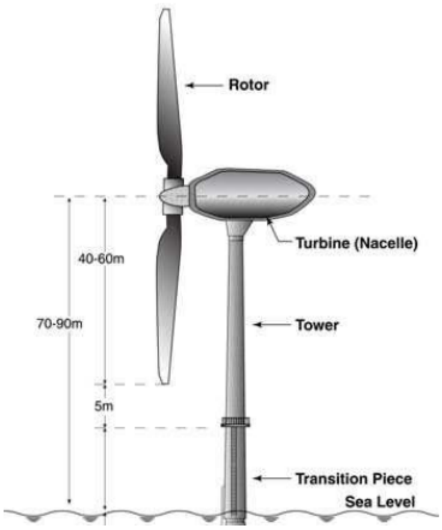

Figure 3.1: Offshore wind turbine main components [24].

Once the foundations and a few other elements have been removed, it design has always the same key components, whether onshore or offshore, these are:

3.1.1 Three blade system

The blades have the fundamental task of opposing resistance to the incident wind,they are directed against him and in this way the blades begin to rotate converting the intrinsic energy in the wind into kinetic energy. Most wind turbines have three blades,because, after several studies, this number was chosen as a compromise between energy yield and turbine stability.

A single blade or two, would be the best choice if only the ability to exploit and capture the energy from the wind was considered, in both cases, however, there would be problems related to the instability of the structure, and therefore to the emergence of greater stress which would put in greater danger the life of the turbine [25]. On the other hand, as the number of blades increases, i.e. thinking of producing a turbine with four or five blades, the costs would increase too much in the production phase, and the productivity and stability benefits that would be obtained would not be sufficient to cover this cost[26].

3.1.2 The nacelle

Inside the nacelle there are the fundamental components for an effective conversion of the rotary motion of the blades, namely: generator, gearbox, brake, low and high speed shaft and controller. As is possible to observe in the figure 3.2, in addition to the components mentioned above, there may be others, mainly linked to the measurement of local meteorological conditions, such as the anemometer.

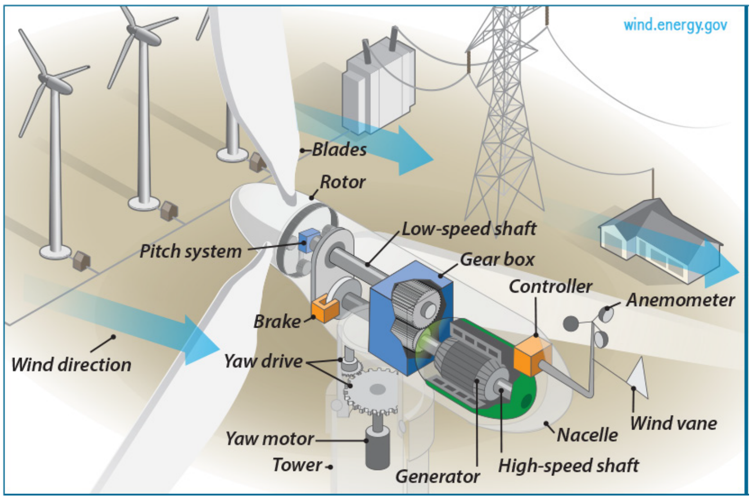

Figure 3.2: General Wind Turbine Nacelle composition[27].

The task of the gearbox is to convert the 30-60 rpm of the low-speed shaft to the 1200-1800 rpm of the high-speed shaft, which is the speed necessary for the generator to produce electricity[28]. The combination of shafts, bearings, gearboxes and a brake is called drive train. Since it, in its entirety, is very thoughtful and expensive, in recent years there has been an attempt to build turbines that work with direct drive, in order to eliminate the gearbox and consequently increase efficiency, reliability and reduce the weight that weighs on the to tower. This, however, at a cost that is currently higher than the standard.

The control system has the task of collecting all data related to wind speed and direction, temperature, conditions inside the nacelle, rotor speed and generator operating conditions, in such a way as to, together with the yaw systems, maximize electricity generation. This because the latter, which is located below the nacelle, has the task of rotating the turbine in the direction of the wind. The nacelle is pre-assembled in the factory and then is installed and very gently attached to the tower and blades. Being of fundamental importance and having many components inside, it is possible to access it for simple maintenance or repairs[29].

3.1.3 The tower

The primary task of the tower is obviously to support the weight of the blades and nacelle, and to unload it to the foundations. It must resist the strong thrusts and oscillations that can occur given the high height, in fact on average a tower is 80 meters high, but the tallest in the world also reach around 130 meters. Its second task is to allow access to the nacelle and therefore inside it there are ladders and platforms at different levels,in some of the newest and highest there an elevator.

Most are made of tubular steel, especially the larger ones, in fact there are old wind turbines, small or for which you can not invest much, which are made of concrete, latex or hybrid.

3.1.4 The transformer

The task of the transformer is to increase the voltage level coming from the wind turbine up to that of the distribution network. Contrary to what it may seem, it is not a trivial action, in fact due to the variable speed of the wind and therefore the continuous fluctuation of the voltage value at the turbine output, this step is considered one of the most delicate. Furthermore, a wind turbine transformer is subject to more mechanical, electrical or chemical (corrosion) problems than other transformers used in standard situations. For this reason their design must be modified to be in accordance with the type of wind turbine and other external factors[30].

3.1.5 The foundation

As has already been said, the foundation is the biggest difference between bottom fixed and floating wind turbine. As can be easily guessed from the name, the former are fixed to the seabed, while the latter are not, in fact they float. For this reason the foundations between them are completely different, starting from the idea behind them. While at the beginning it was difficult to think of being able to install and fix wind turbines at sea, it is even more difficult and complex to try to install them without any direct connection to the land.

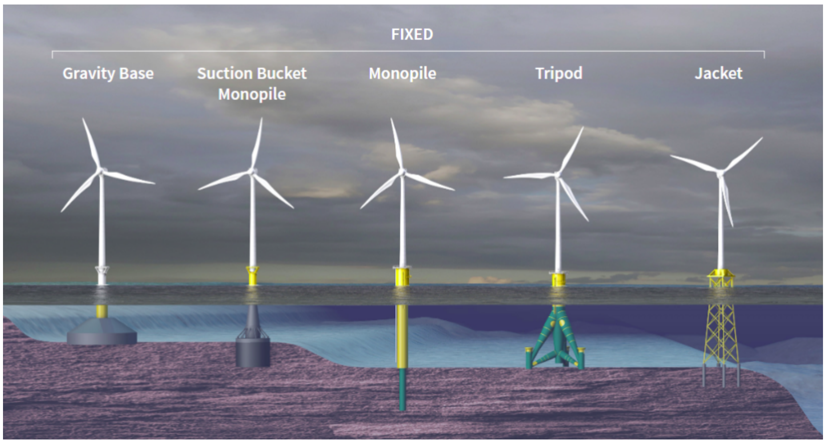

Figure 3.3: Main foundation for bottom fixed wind turbine.

In the figure 3.3 it possible to observe the five main foundations used for bottom-fixed wind turbines,but most common ones are the following three:

- Monopile

  Given its simplicity, Monopile foundation is among the most used in the world, not only for wind turbines but also in general for other shallow water installations. Its main qualities are simplicity and adaptability. Its classic design allows it to be produced without the need for particular processes and technologies. Furthermore, the design is able to adapt to considerable load and external variations, without however going to distort its nature, therefore it makes the calculation engineering problem easier to solve[31]. However it has limitations,in fact her biggest flaw is that she can only be used up to a depth of 35 meters.

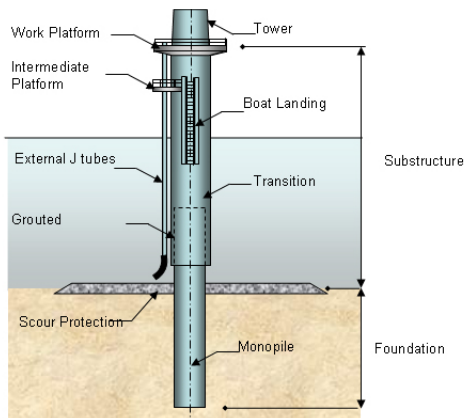

Figure 3.4: Monopile foundation detailed structure[32].

- Jacket

  The term jacket indicates a steel lattice-type structure composed of four legs connected to each other with braces.Each leg is fixed to the seabed by small foundation piles, called pinpiles.

  Its main advantages are the possibility of being used up to a depth of 60 meters and the possibility of being installed in particularly difficult seabeds, with stiff clays and medium-to-dense sand. However, these are not the only ones: in fact, the cost of material and labor is low and no scour protection is necessary. However, the structure is complex, both in its manufacture and in its assembly[33].

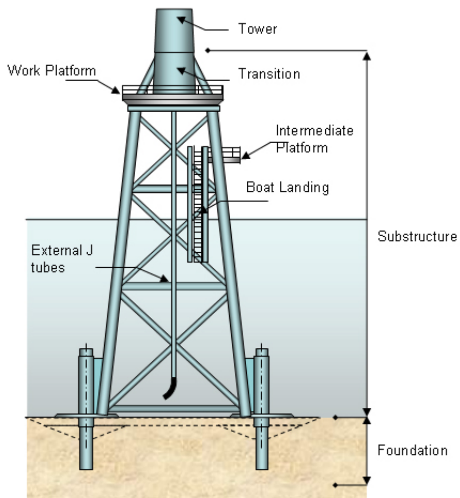

Figure 3.5: Jacket foundation detailed structure[32].

- Gravity based

  This type of foundation is also well known, in fact it has been used for offshore oil and gas platforms for many decades, however it is not yet very widespread among wind turbine solutions, despite its potential. The basic concept is simple, with the term Gravity based structure (GBS), we mean huge bodies which, given their high mass, are able to support both the weight of the wind turbine and the lateral thrusts exerted by the waves and currents[34]. They are usually formed by an external reinforcement of concrete which is then filled with sand and water.

  Its main advantages are the low environmental impact as there is no drilling for installation and there is reduced fatigue sensitivity compared to other types. Furthermore there is the possibility of having the internal J-tube and a long lifetime[33]. Unfortunately, however, it has several disadvantages, the most important being the need to prepare the seabed before installation[35] and the high weight, which leads to limits in transport and installations, and therefore to increase costs even though those of the material are not elevated.

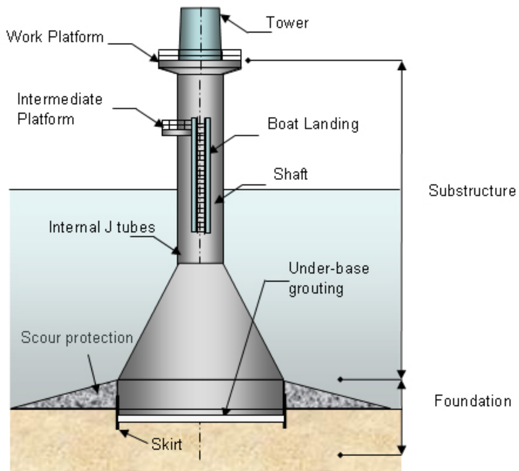

Figure 3.6: Gravity based foundation detailed structure[32].

An aspect not to be underestimated when considering the foundations is the scour. It has already been mentioned previously, without however explaining what it is. This term indicates the continuous erosion of the neighboring sediments[36],therefore the lowering of the sea bed in the area surrounding the base of the foundation, due to the hydrodynamic bottom shear stress. This could reduce the support of the wind turbine, and therefore affect its stability. The most effective method of avoiding or reducing scour is to surround the base of the foundation with a layer of rock[37].

Another properties that generally characterizes this type of turbine is how to access it. Every wind turbine must have the possibility to be checked, repaired, and to seek a normal and periodical maintenance. For this reason there are essentially three ways to access it.

The first is also the simplest, the boat landing, that means reach the base of the structure at sea level whit a ship or a boat, and then use the stairs outside the tower to reach the first outdoor platform that allows access to the inside of the structure.

The second method is similar to the first, but it is its evolution. It allows to reach directly the access platform of the tower, generally located between 15 and

20 meters above sea level. This is to speed up and make the procedure safer. To do this, however, there is a need for special equipment and techniques that are able to compensate the relative motion between the ship from which is lit the operator and the tower. In particular, the methods can be either active (sensors and control system) or passive (mechanical linkage).

The last way to access a turbine is to get directly to the platform of the nacelle through the use of a helicopter. As much as this method is the fastest and most effective , it requires first of all the platform itself, and also to the equipment and people that can be brought simultaneously are reduced compared to the classic use of a ship.

3.2 Floating Wind Turbine

Over the years the need arose to develop this typology as it has a much higher potential than the other. Considering that those fixed to the seabed have a depth limit of 50-60 metres, it is easy to understand how a very limited part of the seas and oceans can be exploited with this technology. Even floating wind turbines have a limit, i.e. 1000 meters, which greatly expands the potential of the offshore wind. In fact, considering the two technologies together, the technical potential of offshore wind is 120 TW, with an electricity production potential of 420,000 TWh per year[6].

As can be seen from the image 3.7, produced using Global Wind Atlas, substantially all northern Europe has a potential elevation, with most areas with values around or above 1000 W/m^2. Starting from all the coasts of Ireland and Great Britain, up to all the North Sea, giving potential also to Estonia Latvia and Lithuania.

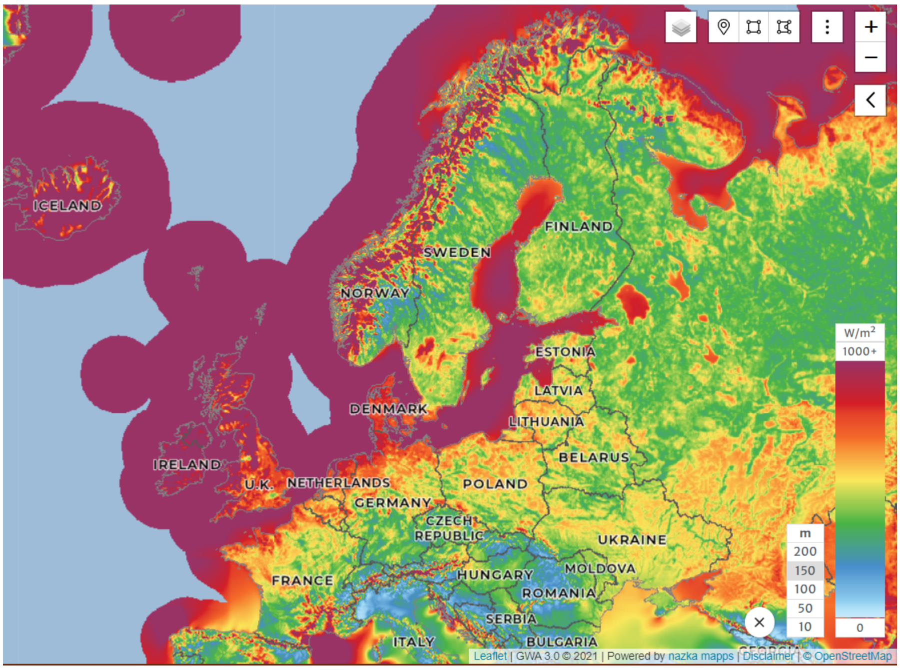

Figure 3.7: North Europe Wind Offshore Focus.

If Europe could make the best use of these two resources, it could even export electricity to neighbouring countries.

Furthermore, it should also be considered that floating turbine, once a suitable technology has been developed, would not have a minimum depth and therefore could also be chosen instead of a bottom fixed one. There are already full-scale prototypes in operation,also pilot farm like HyWind Scotland, a wind farm with an installed capacity of 30 MW, located in Buchan Deep in the North Sea[38].However companies are continuing their research and testing to broaden the market.

As was mentioned earlier, their basic structure is practically identical to any wind turbine, for this reason now will be illustrated only their foundations. In the following picture it is possible to observe the three main types:Spar-buoy,Semi-submersible and Tension Leg Platform.

Figure 3.8: Main foundations for floating offshore wind [39].

- Spar-buoy

  This first type of solution consists of a simple cylindrical Spar-buoy, stabilized with ballast in order to keep the center of gravity under the buoyancy one. Its main advantages are the simple design, which allows it to be mass produced, and a mooring system composed only of chains, which further simplifies and reduces costs. It also has good stability. However, it has several negative aspects, in fact, due to the large size and weight that the structure must have, it can only be installed from a depth of one hundred meters onward and large quantities of concrete and steel are required for its production. Furthermore, all aspects of assembly and installation are also very complex, as it can only be mounted offshore, with sufficient depth, and expensive heavy machinery is required[40].

  To date, one of the most established prototypes of this type is the Hywind spar-bouy of Equinor. Its 6 MW turbines with a draft of 70-90m and a 3-line catenary mooring system make up the wind farm mentioned above.

Figure 3.9: Hywind spar-buoy concept.

- Semi-submersible

  This second foundation concept is based on the connection of columns connected to each other via submerged poontos. The union of these bodies confers stability to the whole structure, obtained through buoyancy forces. In this case there are no simple chains as a mooring system, drag or suction anchors can also be found. Nevertheless, the low cost of the mooring system remains one of its main advantages. However, unlike the spar-buoy, this is a more adaptable structure, as it does not need a minimum depth, and can also be installed onshore. Unfortunately, however, it is more complex to build and in any case the problem of the high mass remains[40].

  For this concept, however, one of the most mature prototype is the WindFloat of Pricipale Power. The turbine, of 2 MW, was positioned on the coast of Portugal and its structure consists of a semi-submersible hull with three columns.

Figure 3.10: WindFloat operation photo.

- Tension Leg Platform

  This last type of floating foundation is based on the stabilization of the structure across the tensors, which once connected to the base, an anchor, give the necessary stability to the structure. This only eliminates the foundation mass issues, and is still more versatile than the spar-buoy. As disadvantages we can find that it is difficult to install, together with a high cost of mooring systems[40].

  Here an example is the Bluewater Floating Wind TLP (Tension Leg Platform). This prototype is however at a much lower ripeness than the others.

Figure 3.11: Bluewater TLP conceptual design.

3.3 Ocean Energy

The third type of offshore renewable source is completely different from the two previously explained. In fact, the term ocean energy indicates the exploitation of the sea and oceans for the production of energy. First of all, it is necessary to understand with how many methods it is possible to harness the seas and oceans.

Sources of Energy	World Potential (TWh/year) Source IEA	Location	TRL
Wave Energy	29.500	Mainly West Cost at middle latitude	6
Tidal range and currents	7.800	Costiline and tidal streams	9-8
Ocean Currents	-	-	5
Salinity Gradient	1,650	Estuary	4
Ocean Thermal Energy Conversion	44,000	Equator	6
Marine biomass	-	-	4
Offshore Geothermal	-	High geothermal zones	4

3.3.1 Wave Energy

Wave motion is the first source that we can find in seas or oceans. We are talking about a renewable source with a theoretical potential per year of 29,500 TWh/year and technical between 2000-4000 TWh/year[41].

Its base concept is very simple, it to sue the energy that is contained in waves to produce electricity. This energy is closely linked to the wind, as it generate the waves by blowing on the surface of the water, and they store both its kinetic and potential energy. Unfortunately, although there are oceans and seas everywhere on the globe, this source is not homogeneous. In fact, having to submit to the intensity and direction of the wind, it is concentrated in medium latitudes and on the west coasts of the continents, because it blows with the greatest intensity at these coordinates and, following the global circulation, it goes from West to Est.

The concept behind all the prototypes designed so far,called Wave Energy Converter (WEC), is to use a prime mover (a body in water) to transfer energy to a hydraulic fluid or directly to a hydraulic turbine, in motion such as to transform the rotary mechanical motion into electricity through a generator. To reduce losses, some prototypes are trying to work in direct drive, with the transformation directly from the prime mover to the generator.

Like all other sources concerning ocean energy it is still at research stage, their first division can be created considering where they can be installed, if only on the coast, then considered onshore, if nearshore, and then up to the depth of the seabed of about 25 meters, or offshore, when placed at a distance of more than 40 meters.

The main concepts developed so far are:

- Oscillating Water column (OWC)

  These prototypes are found predominantly on the coast, though none are missing near shore or offshore. The principle behind the Oscillating Water Column is to exploit the heave motion of the sea surface to push the air confined in a chamber through a turbine. In fact, the structure is formed by a chamber that on one side is open to the outside through a turbine, on the other side it is semi-submerged by the water and the sea level inside continues to vary. Following this movement, the air column is pushed through the turbine as the surface level rises, and back in when it drops.The velocity of the air in the duct is increased by making the cross-sectional area of the duct much smaller than that of the column. The peculiarity of the installation lies in the shape of the turbine, type Wells, able to rotate continuously in the same direction, regardless of the wind orientation[42]. It is a technology that is very suitable to be positioned on the coast, even integrated on existing breakwater. Unfortunately, there are problems with sound pollution.

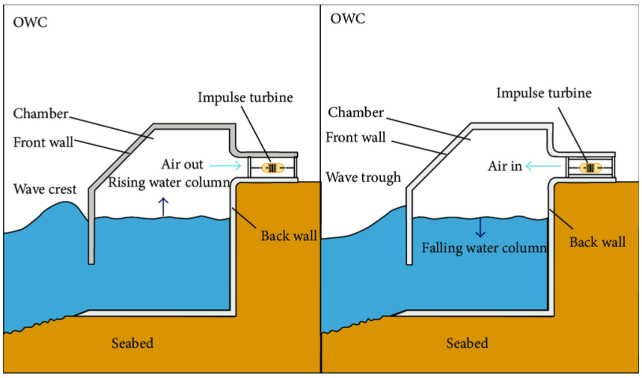

Figure 3.12: Oscillating Water Column scheme [43].

- Point Absorber

  Point absorber are devices that can harness energy from any direction. They are floating bodies, simply anchored, composed of a part that is on the sea surface and a base. The waves move the buoy on the surface and there is the conversion of the relative motion between it and the base into electricity. Given their simple structure and easy adaptability[44], there are several prototypes, such as Corpower 3.13 and CETO 3.14.

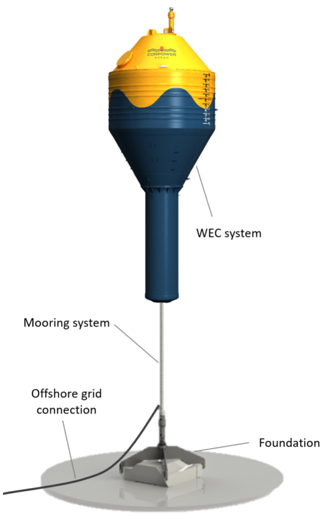

Figure 3.13: Corpower structure.

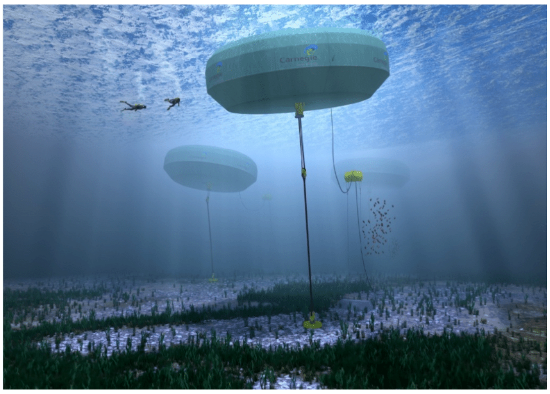

Figure 3.14: CETO design photo[45].

To date, one of the prototype of point absorber at the most advanced level is the Powerbuoy. Its peculiarity is that the motion includes three components.

In fact, the PowerBuoy is composed by a float body, a spar and a heave plate.The float, following the movement of the waves, moves vertically and is connected to the spar that is kept stationary by the heave plat. The relative motion that is thus created puts into operation a mechanical mechanism within the spar that converts the vertical motion of the float in rotary. Finally, it is from this rotary motion that electricity is produced.

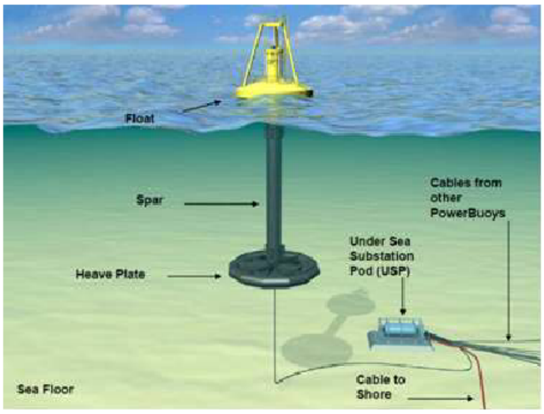

Figure 3.15: Powerbuoy structure.[46].

- Overtopping Devices

  This type of WEC is completely different from those described above. His goal is to create a water reservoir, breaking the waves crashing on his walls. In this way, the head of water generated can be successively used in a hydraulic turbine and generate electricity. The biggest disadvantage of this technology is its non-linearity, in fact it is the only case where waves cannot be simplify and described through their pivotal theory, the linear water wave theory.

Figure 3.16: Wave Dragon illustration.

3.3.2 Tides

The second source we can find are the tides. The tidal currents are easily predictable (hundreds of years), as they are due to the continuous oscillations of the gravitational forces exerted by the Sun and the Moon on the water masses. This aspect, combined with the fact that they are not affected by climatic conditions, makes this technology one of the most reliable,although it is the ocean energy source with the lowest theoretical potential, equal to 8,760 TWh/year[47]. Not only can the currents generated by the tides be exploited, but also the rise and fall of the water level itself. The prototypes that have been designed up to now are based on the idea of simple turbines, what changes are the operating environment and the dimensions[48].

Figure 3.17: Picture of Orbital O2, the most powerful tidal turbine in the world.[49]

Here we can find the only concept of ocean energy that is not at the research and development stage, the tidal barrage. This is because they essentially function as an hydraulic turbine. It is sufficient to construct a dam or to limit through some barriers a water course in proximity of the mouth of a river, better if the zone is particular subject to the tides. The production of electricity takes place by exploiting the movement of tides back and forth in a two-way turbine.

To understand the level difference between this and other o cean technologies just know that the largest tidal barrage plant in the world is the Sihwa LAke Tidal Power Station with a capacity of 254 MW, while the second, named La Rance Tidal Power Plant, 240 MW. The first is located in Sihwa LAke in the Gyeonggi Province of South Korea, the other in Brittany, France.

Figure 3.18: Sihwa Lake Tidal Power photo.

3.3.3 Ocean Currents

Sea currents are generated by various factors, in particular by: wind, the Coriolis effect and temperature and salinity gradients of the water masses. In open tides there are real continuous flows, with little variability, which carry large quantities of energy. As with the methods listed above, it is therefore possible to install one or more turbines along the direction of the current to produce electricity[50]. Unfortunately, unlike tidal currents these are located further away from the coast.

Figure 3.19: Ocean current turbine prototype.[51]

3.3.4 Salinity Gradient

This last type of source is also based on a completely different principle than the others. In this case the salinity gradient that occurs when different waters merge is exploited. This system can essentially only be used at river mouths. However, this does not diminish its exploitation, in fact being on the coast it is certainly closer to inhabited or industrial centers than other sources, furthermore its theoretical potential is in any case much more, or 15,000 TWh/yr[52], a value equal to the three-quarters if the global electricity need. The two main methods to exploit this resource are:

- Pressure Retarded Osmosis

  The term osmosis refers to the process in which pure water passes from a soul with a lower osmotic pressure to a higher one, through a semi-permeable membrane. In this case the passage occurs from the water with a lower salt contraction to that with a higher concentration[53].

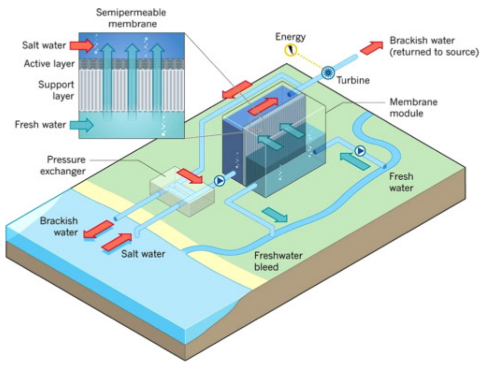

Figure 3.20: Pressure Retarded Osmosis scheme[53].

- Reverse Electrodialysis

  This process instead takes advantage of a direct electrical current. In fact, the passage of ions between membranes is exploited, which occurs when two fluids of different salinity are placed along a series of permselective membranes.

3.3.5 Ocean thermal energy conversion

This type of technology is completely different from the previous ones,it exploits the natural temperature gradient of the oceans. Electricity is produced through a Rankine cycle in which it exploits the warm water on the surface and the cold one below[54].

It among the ocean energy sources, is the one with the greatest potential, equal to 30 TW the theoretical one, and up to 7 TW the technical one with no sea temperature affection[55].

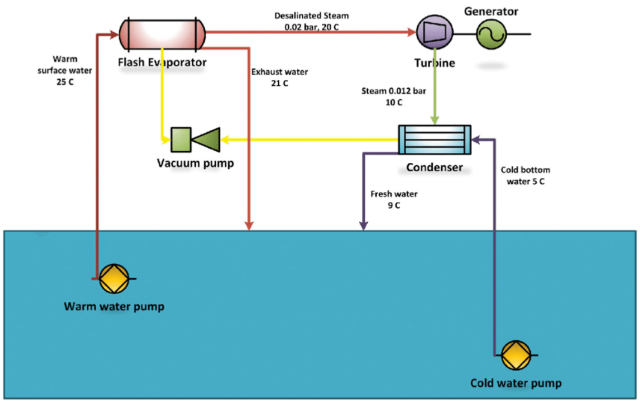

Figure 3.21: OTEC open cycle scheme.[56]

One aspect to consider in this case is that this type of resource is in a substantially opposite position to those of the waves. This is because the absorption of heat from the sun is concentrated almost entirely in the equatorial area, where on the contrary there is few wind and therefore little waves. In this area it is possible to have the maximum exploitation and efficiency of this technology, as the temperature difference between surface and deep water is the biggest one, approximately constant at 20 °C.

Figure 3.22: Makai OTEC located in Kailua-Kona, Hawaii[57].

Chapter 4

Methodology to estimate Mediterranean offshore renewable energy potential

This chapter will describe the methodology that has been created for the identification of areas in the Mediterranean Sea suitable for the different types of offshore renewable sources. This function arises from the need to have, in just a few steps, a function that is able to carry out a preliminary analysis that allows the user to make an initial visual assessment of the maritime area to be studied.

To create this methodology, the MATLAB® programming platform was chosen. In order to take advantage of the ease with which it allows to process the data and the accuracy of the maps that can be created.

The script then, after having picked data indicated by the user, through a series of steps, is able to return a maps concerning a precise characteristic of the wind or waves of an area of the Sea.

4.1 Data manipulation

The first aspect that must be observed is the data that has been used. They come from different sources and are in different formats, each with a very different purpose.

4.1.1 Wind and Waves

As it was said before, the meteorological data used have been downloaded from the ERA5 database. These are large netCDF format files that need specific MATLAB®

functions to be handled, such as ncfile and nread.

To characterize the offshore sources, five types of data are chosen, two for wind and three for waves.The two for the wind are the speed components at 100 meters above sea level, denominated U100 and V100. While for the waves their mean period,significant height and mean direction have been downloaded.

Inside the ERA5 file there are: three vectors and three-dimensional matrices. The first two vectors represent the spatial discretization of the data, therefore their latitude and longitude, while the third represents the temporal discretization, and therefore the hours in a year.The matrices contain the parameter mentioned above, one for each of them. They have $LongitudexlLtitudexTime$ size and are divided into different rows depending on the resource, even if they belong to the same year.

From the data relating to the wind, its speed its been calculated with the formula:

$$\alpha = sqrt(Un \cdot 100^2 + V \cdot 100^2) \qquad [m/s] \tag{4.1}$$

The wind direction was also calculated with the same components:

$$\beta = |\frac{(270 - arctan2(U100, V100)180}{\pi},360| \qquad [deg] \tag{4.2}$$

Afterwards, using the wind speed, it is calculated the wind energy flux, more commonly known as the Wind Power Density (WPD) (Letcher,2017)[58] :

$$WPD = \frac{1}{2} \cdot \rho \cdot \alpha^3 \qquad [\mathrm{W/m^2}] \tag{4.3}$$

Where rho is the air density, choose equal to 1.225 Kg/m^3. In this way the study is carried out by normalizing the wind power.

subsequently, the resource technical potential is evaluated. Wind speed data were used as input to calculate *Full Load Hour* (Held, 2010) ,that is equal to the number of hours resulting from the division of the output produced by the wind turbine over the year by its rated power:

$$FLH = 728 \cdot v - 2{,}368 \qquad [hours/year] \tag{4.4}$$

The technical potential was then evaluated using the formula:

$$\Omega = Wd \cdot FLH \cdot A \cdot \eta \qquad [GWh/year] \tag{4.5}$$

Where η,equal to 81%, represents overall efficiency between operational and array efficiency,both equal to 90%. The first takes into account the times when turbines are offline for maintenance reasons. The second, takes into account the losses due to the presence of more turbines that interact with each other.

Wd is the wind power density, chosen equal to 6 MW/km^2.This value is selected observing a study of European Maritime Spatial Planning Platform (European MSP Platform, 2018a) that shows the trends of the densities of power of the current wind farms. It shows that in general the average is around 7 MW/km^2 but, being these farms all in the North Sea, was considered to reduce this value slightly ,in order to adapt the capacity to a more appropriate value in the Mediterranean Sea
The term A is more complex. Being possible to decide in the methodology the spatial discretization, at each point of the map, depending on the different grid spacing, corresponds in kilometers a different area. A coincides precisely with the dimensions in km^2 of the points of the map, in this way the each time the power density is calculated referring to the precision chosen.

As a last step, to better characterize the technology, the potential capacity has been calculated. The equation is similar to 4.5, in fact it is equal to:

$$\sum \Psi = Wd \cdot \eta \cdot A \qquad [GW] \tag{4.6}$$

The only difference is that there is no use of the Full Load Hour parameter.

On the other hand, with the data relating to the waves, the theoretical power density of the Mediterranean Sea was immediately calculated, following the formula (Falcão, António FO,2014)[59]:

$$P = \frac{\rho \cdot g^2}{64 \cdot \pi} \cdot H_s^2 \cdot T_e \qquad [kW/m] \tag{4.7}$$

Where Hs and Te are the significant wave height and the wave period, and ρ is the density of the water, set to 1.025 g/m^3.

As for the evaluation of the wave resource technical potential, first the *capacity factor* has been calculated through the formula 4.8,provided by the Ocean Energy Systems/International Energy Agency LCOE report (OES IEA, 2015) :

$$CF = 0.0445 \cdot P^{0.552} \tag{4.8}$$

Where P represents the power density calculated in the formula 4.7. This capacity factor was then inserted into the formula:

$$\Omega = 8760 \cdot A \cdot Wd \cdot \eta \cdot CF \qquad [GWh/year] \tag{4.9}$$

8760 represents how many hours there are in a year and as wave power density *(Wd)* is assumed a value of (12.5 MW/km^2)[60].The last two factors coincide with those mentioned above, but in this case η is equal to 95% as only operational efficiency is considered.

Also in this case the potential capacity of the resource is calculated. The formula used in this case is, similarly to 4.9:

$$\sum \Psi = A \cdot Wd \cdot \eta \cdot CF \qquad [GW] \tag{4.10}$$

The difference now is that the capacity factor is used directly in the formula.

A very interesting aspect to consider is the different discretization with which ERA5 supplies the data relating to the wind with respect those of the waves.

Measurements of the former are more common than the latter, easier to perform,and also useful in more fields.Therefore, in general all over the world, there are more wind measurements station and device respect the one of the waves.

Each database or platform that has been listed in Chapter 2 is affected by this difference in data capture, also ERA5, which in fact provide wind data with a discretization twice as precise as waves data. In fact for the first one, two points are given at 0.25° from each other, for the second the value of Hs,Te or Wd are provided every 0.50°. Successively, will be shown how this different definition of the grids has influenced the methodology.

Another aspect to consider is that these,as already said, are hourly data ,with size 87x35x8760 for waves data and 173x69x8760 for wind (if the year is leap the place 8784 replaces the last term).This makes the data heavy, difficult to manipulate and cumbersome for the PC RAM.

For these reasons, to facilitate the methodology and to make the results visible to the user on the map, the analysis is performed making the annual average of each characteristic for each coordinate,in order two work with just a two-dimensional matrix.

Not only this, here the evaluations is carried out considering the years divided,unlike the methodology that will be illustrated in chapter five. This because it would impossible to perform particular functions and manipulation, especially visual ones, with a volume of data greater than a few years.

4.1.2 Bathymetry and Zone delimitation

In order to create the methodology, data relating to the bathymetry of the Mediterranean Sea and those relating to zone delimitation are needed. Bathymetry is essential to understand the depth of the sea bed, and therefore to immediately set limits to the different offshore renewable sources.

On the other hand, knowledge of zone delimitation, like protected areas or exclusive economic zone is also essential, in order to better divide the Mediterranean and eliminate areas in which, regardless of the source, there cannot be installations.

To understand its importance of protected areas it is enough to think that,in 2020, about 8.33% of the Mediterranean Sea was classified as Marine Protected Area (MPA), and almost all of these zones are situated in European waters (97.33%) [61]. Furthermore, every year the number of MPAs grows continuously,so this source should always be updated.

This aspect should not be underestimated, although the issue of environmental change from renewable sources offshore is still open. Surely the impact is not zero, especially from a visual and acoustic point of view. As regards the interference with the migratory routes of birds or with the marine habitat there are several studies that are dealing with the issue.

As bathymetry sources, GEBCO 2022 Grid dataset is utilized. It is a terrain model with elevation value in meters of global land and oceans. Like resources file, it is in the netCDF format, however it has a much finer spatial discretization than them. In fact, it is equal to 15 arc second, that means a spatial distribution equal to 0.0041667°,in both latitude and longitude. Unfortunately, due to this difference, this accuracy has not been exploited and has been reduced to match wind and wave data.

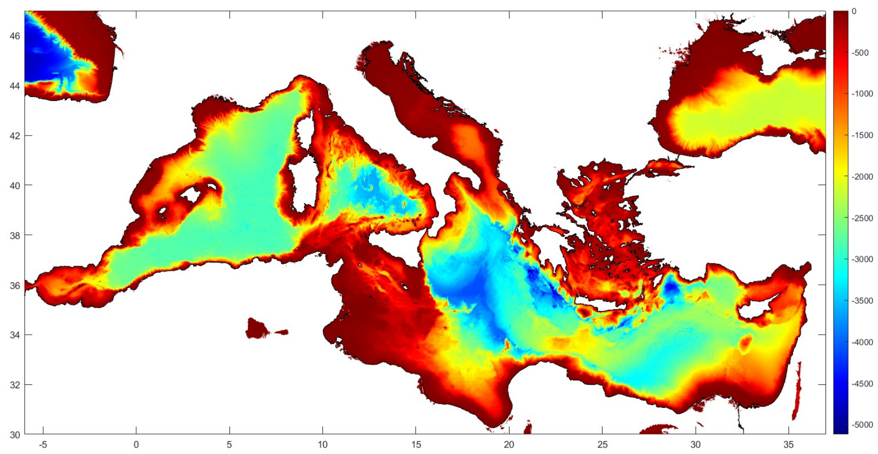

Figure 4.1: Mediterranean Sea Bathymetry [m].

Within the methodology it has not only been used to envelop the depth of the seabed, but also to delimit the mainland. In fact, ERA5 wind data provides information for both onshore and offshore resource, but there is no distinction between them. Those related to waves obviously do not have numbers values in correspondence to the mainland, only NaN indication, however, the coordinates of the emerged lands are not indicated. Without data processing, therefore, it would be impossible to analyse only offshore resources.

To solve this problem has been used the GEBCO file, because, being in netCDF format is compatible with those of ERA5. In particular were its data corresponded to the mainland, therefore those indicating elevation positive (above sea level).

In the script, firstly they are marked as NaN, and then are used to mark as NaN the matrices containing the characteristics of the resources, in order to obtain the shape of the Mediterranean Sea.

As regard zone delimitation, three files are actually used,all are Shapefile format and are downloaded from the European Environment Agency database.

The first is downloaded from the European Environment Agency database and contains simply the European and African coastline,as can be seen in the figure 4.2:

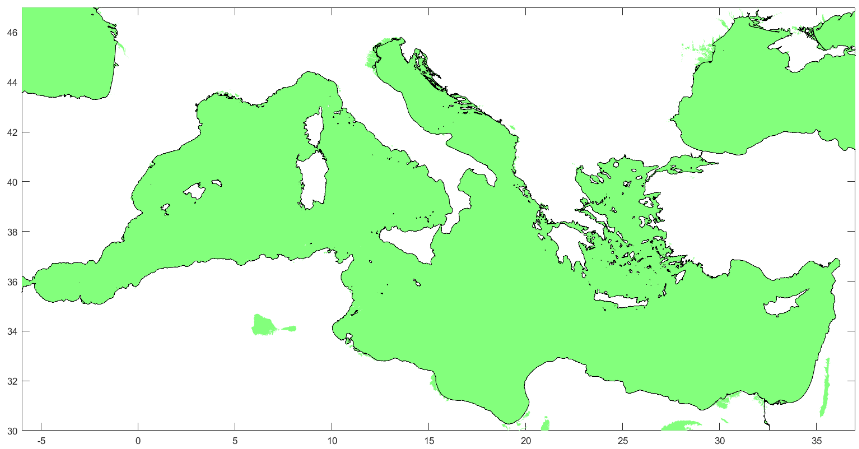

Figure 4.2: Europe Coastline.

The second has the same origin as the previous one but is much more complex. Named Nature 2000, it is made up of the union of protected sites under the control of the Birds Directive (Special Protection Areas or SPAs) and the Habitats Directive (Sites of Community Importance or SCIs, and Special Areas of Conservation or SACs) . Every single descriptive data for each single site contained is submitted through a specific data form. Furthermore, the spatial data are validated by the EEA itself.

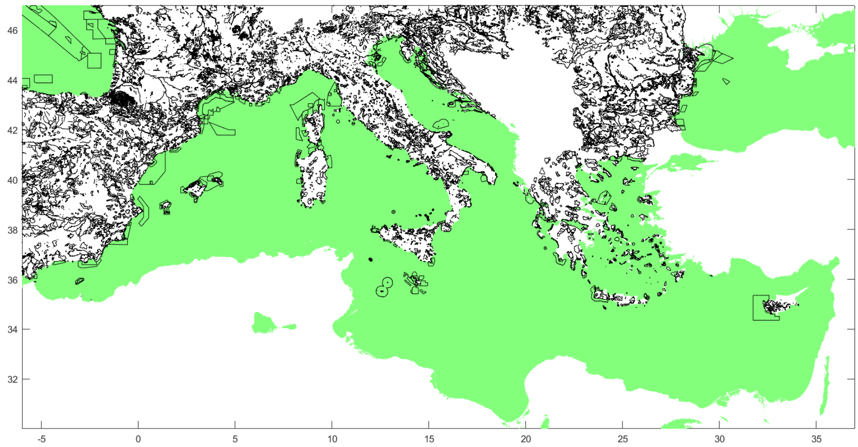

Figure 4.3: Europe Nature Site Location.

From figure 4.3 it can be seen that all European protected areas are present, not just the maritime ones. Furthermore, there is no trace of the coastlines, that is the reason why the first file was used. Lastly, it can be noted that, unfortunately, there is no information regarding any natural sites on the African coast.

The latest shapefile is related to exclusive economic zones, and was downloaded from the Marine Region database.

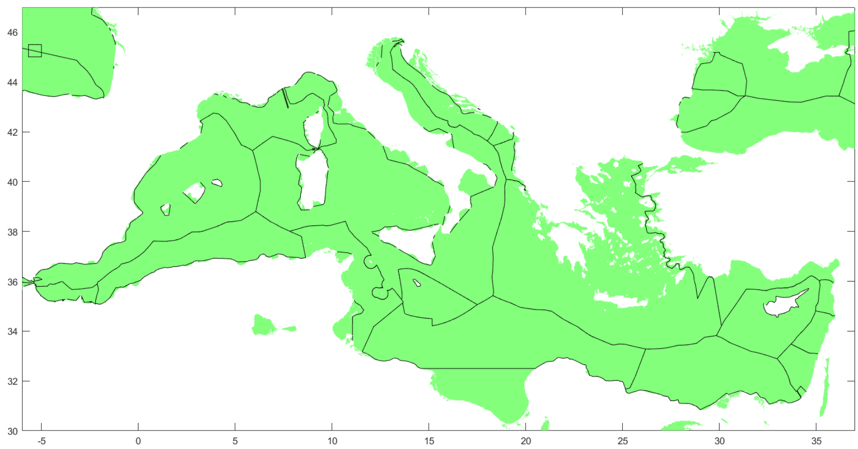

Figure 4.4: Exclusive Economic Zone.

Also in this case, all files have the accuracy of the data higher than those of

ERA5, anyway there was no impact on the assessment because ,unlike the GEBCO file, since these three files are different in nature from those of ERA5, in the methodology they interact differently with the wind or waves values. They do not directly affect their matrices,as happens for bathymetry, their attribute is only visual,as they limit zones by intervening on the resulting map and not on resources data.

4.1.3 Area selection

As regards the region taken into consideration, it ranges from 30°to 47°of latitude, and from -6° to 37° degrees of longitude, in such a way as to be able to enclose the whole Mediterranean Sea, also the African and Turkish coasts.

One of the features of the methodology is the ability to decide the area to be observed. By inserting four coordinates, the formation of a rectangle is obtained which delimits the zone of interest for the study. The only limits on these coordinates are those of the whole map, so -6° and 37° for longitude, and 30° and 47° for latitude. The script will check these limits, together with the correct order of data entry.

If the user wrongly inserted the coordinates , he would see the message written:

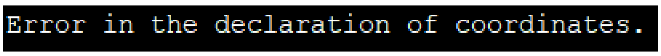

Figure 4.5: Error message coordinates selection.

Here is an example, produced by limiting the area to that of Sicily.

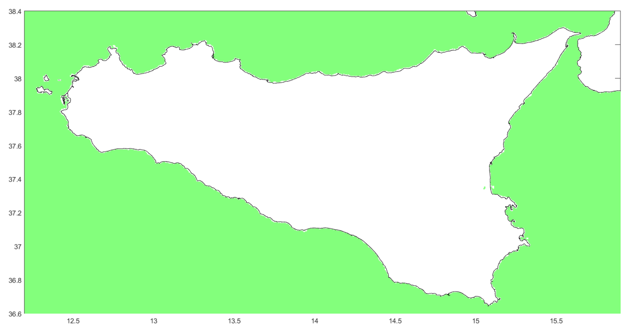

Figure 4.6: Sicily focus example.

The functioning of the methodology is very simple, it captures the coordinates set as input by the user and cuts the files containing the data in the corresponding points. It is not necessary to insert points equal to those of longitude and latitude present in ERA5 vectors, therefore multiples of 0.25 for wind and 0.50 for waves, because a total new grid is generated, with the limits imposed by the user as extreme coordinates,and in between points with the desired spacing.

4.2 Data interpolation

One of the key points of the methodology is data interpolation. As mentioned earlier, spatial dicretization of bathymetry, wind and waves file is different. The one of the last two is so large that it does not allow an adequate visual analysis of the resources, for this reason there was a need to reduce the grid spacing by interpolating the data. In the script, it presents a section where this new spacing can be chosen. Starting with a jump of 0.2500° between one point and another, it is possible to arrive at a spacing of 0.0100°. The limits are not imposed by the study, but by the performance of the computer and the size of the area to be studied. In fact, taking as an example the case limit of 0.0100, the matrix inherent to the resources would have dimensions 4301x1701. Exceeding this threshold is possible, at the cost of computational time and RAM permitting. Reducing the area is allowed to decrease the spacing grid,without compromising the evaluation performance, it all depends on the size of the zone to study and therefore to the amount of data that are cut.

The only real limit is imposed by the spacing of the bathymetry (0.0041667°). In fact, while the wave and wind data increase their precision, the opposite happens to data relating to the depth of the seabed,as this must be reduced to mach the one of the resources. Going beyond this limit would cause problems for the amount of data processed (slowness of the code, insufficient space for the data) and would still have an unnecessary precision.

The interpolation takes place by means of the MATLAB® *interp2* function, that allows to carry it out simultaneously along both directions of the matrix.Its syntax is as follows:

$$Vq = interp2(X, Y, V, Xq, Yq) \tag{4.11}$$

It directly outputs the new matrix, Vq. X and Y instead represent the vectors of the starting matrix, V.Xq and Yq are the new vectors. Furthermore, the function allows you to choose different methods of interpolation, such as cubic or nearest. In this case, the default one, i.e. the linear one, was chosen,as it is the most suitable for meteorological data.

4.2.1 Wave Data Missing Question

As has been mentioned previously, the wave data has generated a separate problem. In fact, not only are they discretized in a different way, but it has some holes since, quite rightly, there is no wave data on land. This lack of data has been a problem for interpolation, as it is not possible to interpolate non-existent data.

In the next two pictures it is possible to observe concretely the difference between original wind and wave data,only coastal lines were added to facilitate understanding.

As is possible to see from the figure 4.7, the wind data do not have any gaps, moreover their accuracy is already at a good level.

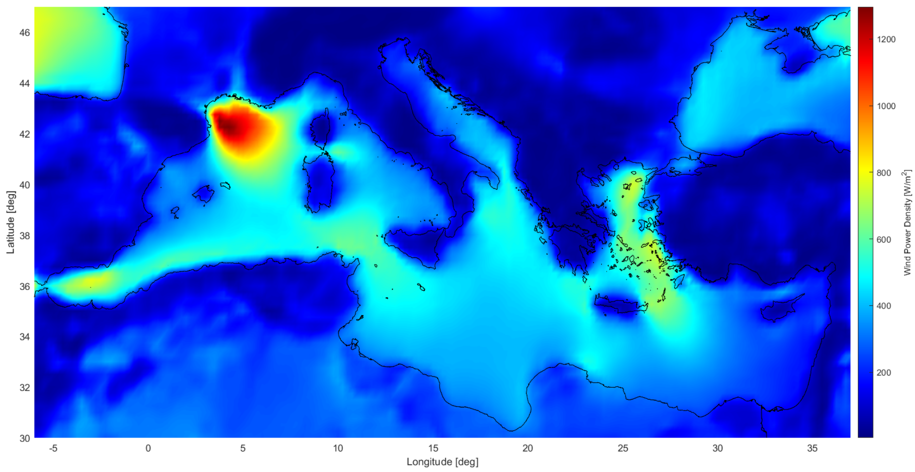

Figure 4.7: Original wind data shape [W/m^2].

Instead, looking at the map4.8 inherent to the waves,is possible to notice that the land emerged are not properly defined, there are real holes around what should be the shape of the coasts.

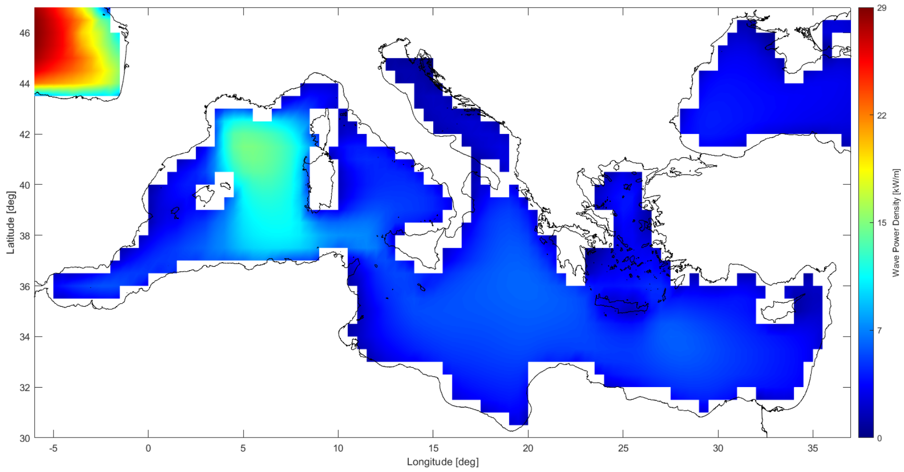

Figure 4.8: Original wave data shape [kW/m].

To solve this problem,these data were then first interpolated like the others, and then a Matlab function was used, called *inpanit-nans*, which has the task of interpolating the missing data in a matrix. Its syntax is :

$$B = inpaint\_nans(A, method)[62] \tag{4.12}$$

Where B is the output matrix with the filled gaps, while A in the input source matrix whit data missing. To fill the holes this function allows to use different interpolation methods. For this analysis, the number four was used, a method in which each element is calculated trying to be similar to its neighbors, both diagonally, vertically and horizontally.

This characteristic brings the inherent analysis to the wave energy less precise regarding that of the offshore wind, in fact not only the original data receive an interpolation but successively undergo the substitution of the gaps on the coast. However, this methodology is mainly based on a visual analysis and identification, so this aspect does not especially influence it.

4.3 Constraints imposition

The last and one of the most important section of the methodology is related to the constraints.

Despite its great theoretical potential, the Mediterranean Sea has multiple production limits, mainly due to natural and technological limits. Protected areas have already been considered and those apply equally to all offshore renewable sources.They are found predominantly on the coast, although cases can be found several kilometers from the coast.

However, geographical and technological constraints still need to be considered. In this evaluation are taken into account the bathymetry (for this reason the file is needed), the distance from the coast and the technological limitation.

The constraints relating to fishing grounds, to those in which oil and gas platforms are present, and to maritime routes have not been taken into account.

Each resource has its limits, which is why three different assessments are done.

4.3.1 Geographical constrains

As previously mentioned, there are mainly two types geographical limits, one related to the bathymetry and one related to the distance from the coast. As can be seen from the figure4.1 , the Mediterranean Sea, despite being a closed sea, is deep, and not only, this depth increases rapidly away from the coast, reaching hundreds of meters a few kilometers from the coast.

Unfortunately, this implies that most of the Mediterranean is not suitable to the installation of bottom-fixed type. In fact, in the current state of technology, as explained in more detail in the paragraph 3.1,this type of turbine can be positioned at a maximum depth of 50-60 metres. For deeper depth installation of a wind turbine it is necessary to switch to floating type, but they also have a limit, which is at a depth of 1000 metres. With a greater depth it is no longer possible to position any installation. In the following table it is possible to observe what are the limits imposed in this study.

Constrains	Bottom Wind	Floating Wind	Wave Power
Minimum distance from cost [km]	20	20	-
Maximum distance from cost [km]	200	200	200
Minimum depth [m]	-	50	-
Maximum depth [m]	50	1000	1000

The limits concerning the depth are the general ones for the technologies, therefore no lower limit and 50 m as maximum for fixed turbines, while instead the range for those floating goes from 50 m to 1000 m.

Even wave energy converters do not have a minimum limit, but only maximum, equal to 1000 m.

The upper limit was chosen not so much for technological reasons, but rather for monetary and logistical reasons. In fact, the lower the bottom of the seabed the more the mooring system is expensive and complex, and therefore it is a factor that must be taken into consideration.

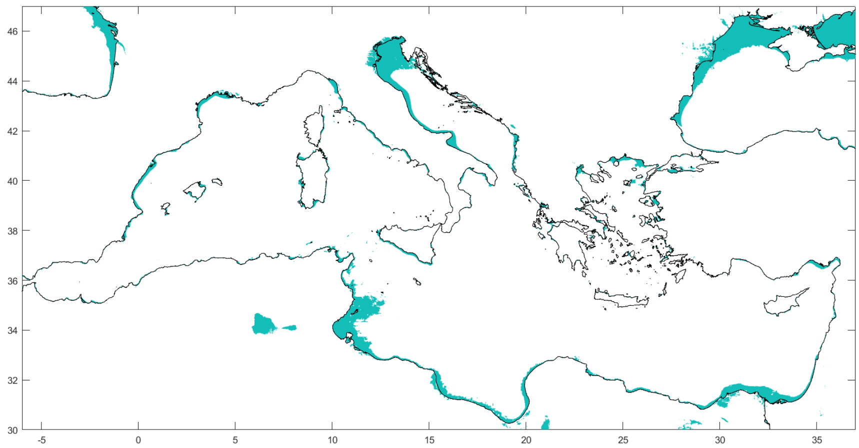

Figure 4.9: Fixed wind turbine area considering bathymetry constraints.

Comparing the two figures 4.9 and 4.10 is possible to observe how big the difference is between the areas suited for fixed wind turbine and areas where floating installation are allowed, just consider the depth of the seabed. This immediately shows how much, within the Mediterranean Sea, we need to take advantage of floating turbines to exploit wind resource.

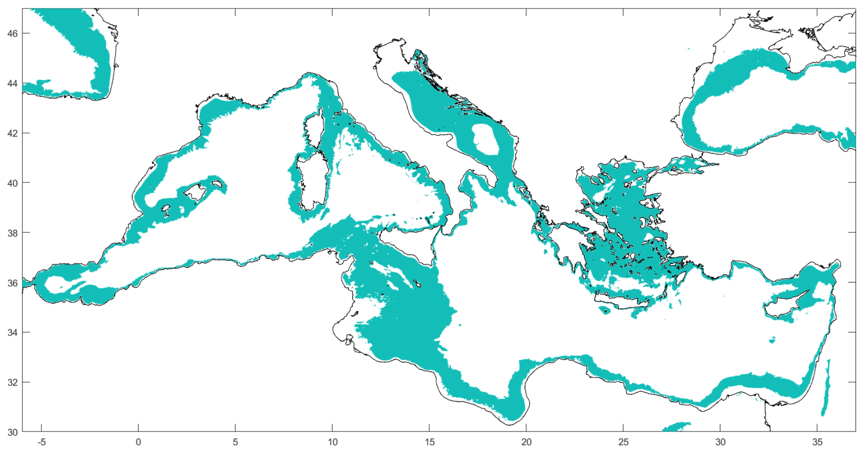

Figure 4.10: Floating wind turbine area considering bathymetry constraints.

Image 4.11 shows how the total area for the installation of WEC is bigger then the previous two, because it is their sum.

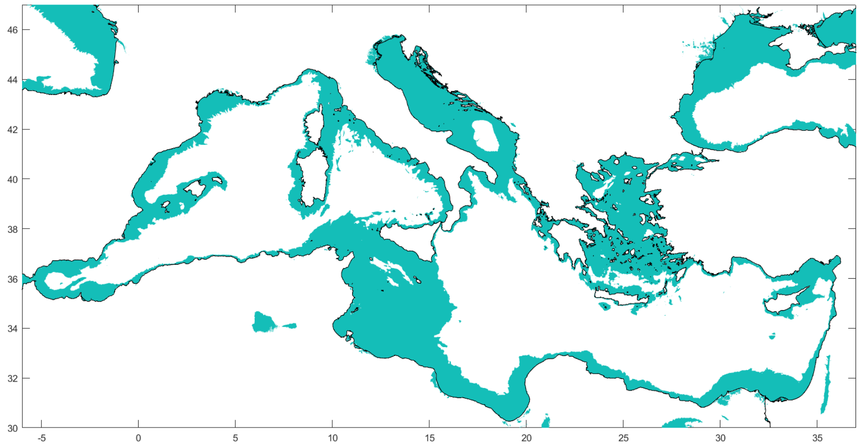

Figure 4.11: Wave energy converter area considering bathymetry constraints.

As regards the distance from the coast, they are equal for both types of wind turbines, therefore 20 km as minimum and 200 km as maximum. The lower limit is mainly related to safety, environmental, acoustic and visual pollution.

This is because installing a wind farm near the coast involves an environmental disturbance both visually and from the noise that can make the blades. Moreover so close to the coast we must consider other factors like a greater number of protected areas and the intensification of the number of boats, both civil and fishermen. For these reasons it is appropriate to distance the wind farms from the coast.

The upper limit was selected for logistical and monetary reasons, similar to bathymetry one. Moving too far from the mainland would mean too much expense for submarine cables, given their high price to date. In addition, the costs of maintenance and operation would be greater having to reach the wind farm constantly.

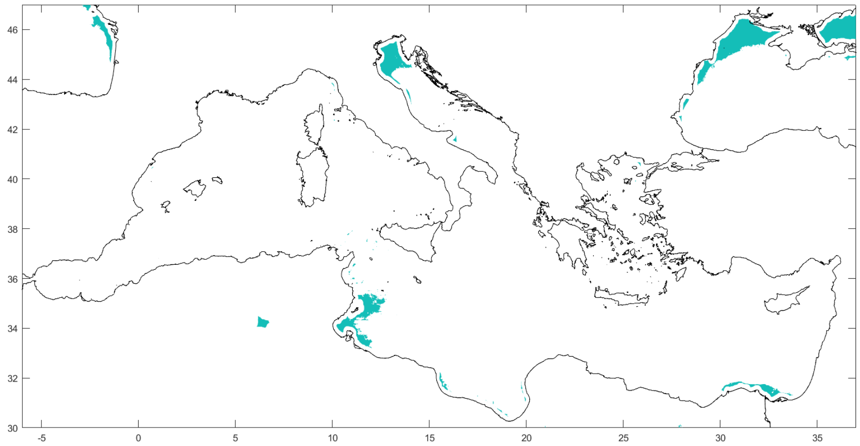

Figure 4.12: Fixed wind turbine area considering also distance from coastline.

Although this limit is the same for both technologies, it has a more negative effect on fixed turbine,already the most limited one,because the areas with a shallow water are the closest to the coast.

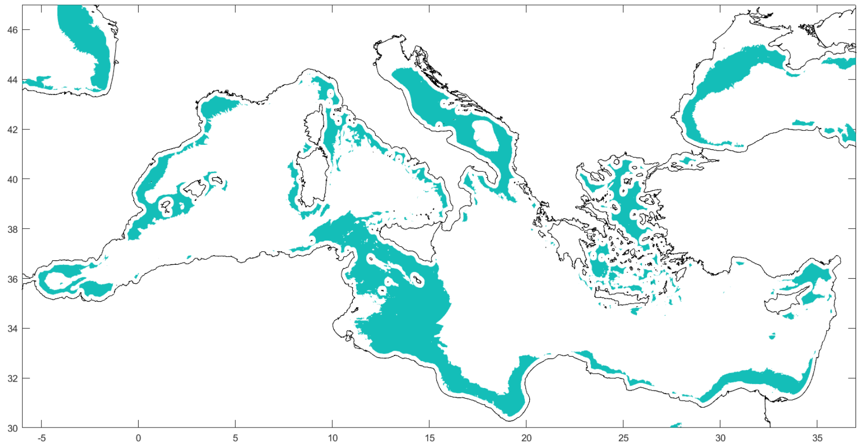

Figure 4.13: Floating wind turbine area considering also distance from coastline.

To wave energy source instead has not been placed any constraint of minimum distance, there is only the maximum distance from the coast, pairs to 200 km, for the same reasons explained above.

As for the lower limit, it was not chosen because in general these devices have less environmental impact than wind turbines, sticking out of the water only few meters and being more silent, they also take up less space. If, in the future, WEC of a different nature will be designed, this limit should also rightly be considered.

For what can be seen from the figure 4.14 this limit does not particularly affect the availability of zones.

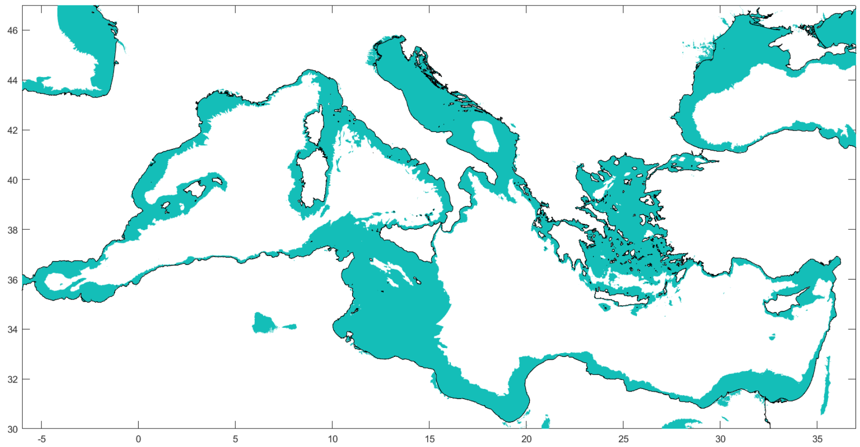

Figure 4.14: Wave energy area considering distance from coastline.

The imposition of these constraints within the methodology is not a simple step. Unlike the others, which through a simple passage is possible to impose limits on bathymetry or technical specifications, this requires to calculate the distance between a point in the sea and a the points of the coast.

What is done, is a comparison between the NaN values present in the bathymetry file at the coordinates of the coast with the values inside of wind or waves matrix. Once for each point at sea, the distance between this point and all the coastal points is calculated at the same time using the formula:

$$distances = sqrt((X - Xs).^2 + (Y - Ys).^2); \tag{4.13}$$

Where X and Y are the vectors with coastline coordinates and Xs and Ys in the one of the point in the sea. As a final step the scrip transforms distances into kilometers,utilizing *deg2km* function, in order to check if the distances are within the limits.

This section is what mostly slow down the methodology, given the size of the matrices and the numbers of iteration. But all again depends on the chosen grid spacing and the size of the area that the user wants to analyze.

4.3.2 Technical Constrains

This type of limit is linked to the technology developed for each of these RES. Even in the case where natural constraints are respected, it is not said that an offshore plants can be installed in an area, since special conditions must be verified for each resource. This applies to any type of renewable source.In this case, the valuation was carried out considering two technical limits, one for the wind power and one for wave energy.

As has already been seen, the power of a wind turbine is cubic proportional to the wind speed. So below a minimum speed threshold, the installation of one or the construction of a wind farm would be too risky, because even if in case of power production this would not be enough to cover the investment. This limit is set at 4 m/s [63], a value already at the limit, suitable only for small turbines. In case of the need to increase their size, a higher minimum speed should also be considered.

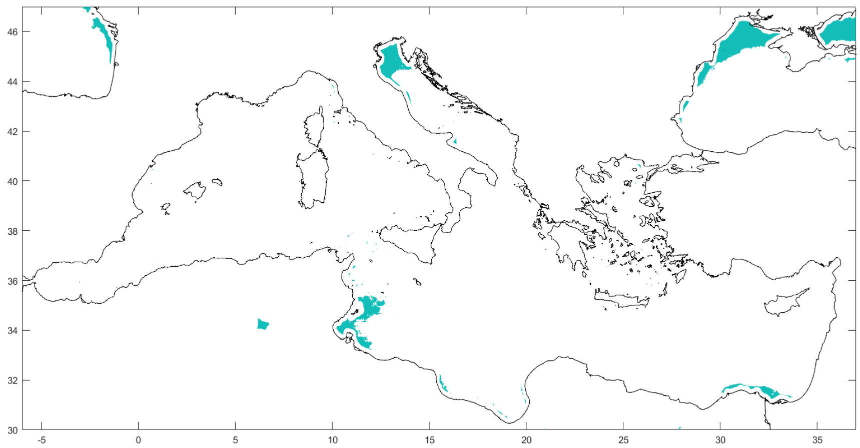

Figure 4.15: Fixed wind turbine area considering also wind speed limit.

In both cases, this particular limit does not particularly affects these two resources, because the remaining areas already have a moderate average wind speed. If this limit were raised even slightly, to 6-7 m/s to try to install larger turbines with greater capacity, the areas would be reduced considerably.

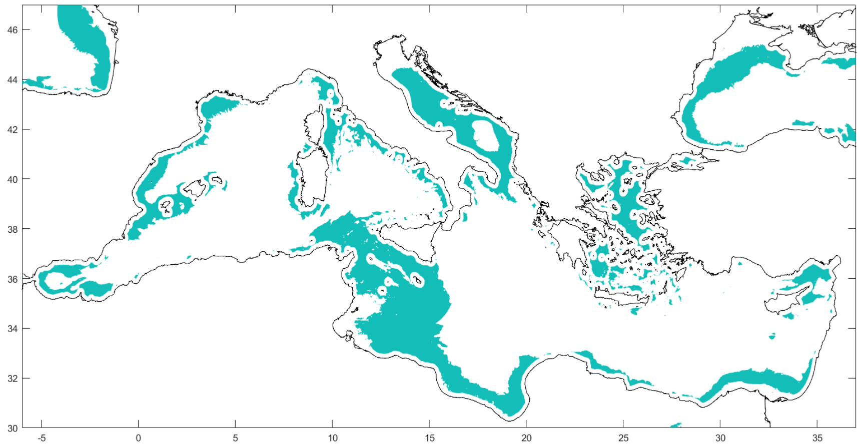

Figure 4.16: Floating wind turbine area considering also wind speed limit.

For the same technological reasons mentioned above, the second limit has been set at 4 kW/m. This limit was deliberately chosen low, even lower than the power density of already small devices, such as CETO 3 or Oyster, due to the low average potential of the Mediterranean Sea. Unfortunately this limit affect a lot the possible areas, for this reason it is necessary to develop devices able to exploit even the little energy enclosed in this wave.

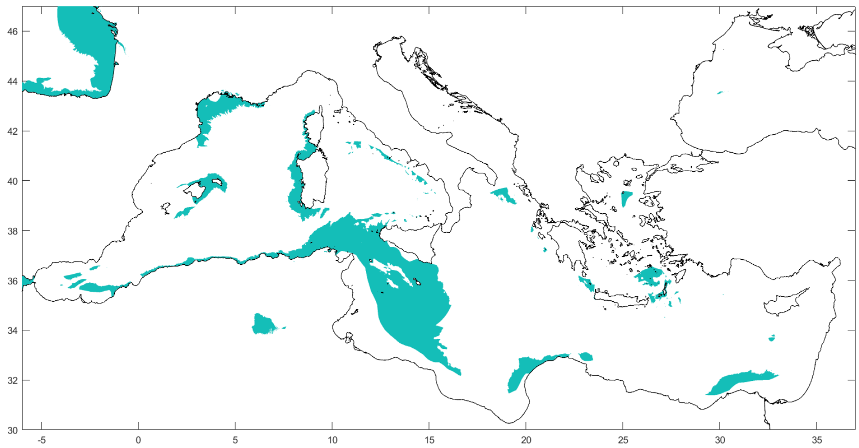

Figure 4.17: Wave energy area considering also density limit.

It should be noted that, regardless of future technological improvements and cost reductions,each of these limits are easily changed within the methodology. In such a way that the user can impose its limits according to its own dictates.

4.4 Methodology Results

Considering all the constrains together, in this paragraph the results obtained through this methodology will be shown. For the spacing of the grid was chosen the limit step equal to 0.0100 while the data used are related to the year 2010.

As a starting point it is worth looking at the potential of these two resources, without any constraints.

In the figure 4.18 it is possible to note that the first areas with high wind potential are the French coast, the west of Sardinia and the strait between Sicily and Tunisia. This is because the Mediterranean is a closed sea from every direction, having the Alps, the Balkans and the Pyrenees blocking the wind passing through Europe, while the African one is stopped by the Atlas chain. The only real passage is given by the France, which does not own mountains in the centre and therefore creates an hallway for the strong Atlantic wind. Similar to what happens in France, the Balkans block and channel the Asian wind and direct it between Turkey and Greece, thus generating the second zone with high density potential.

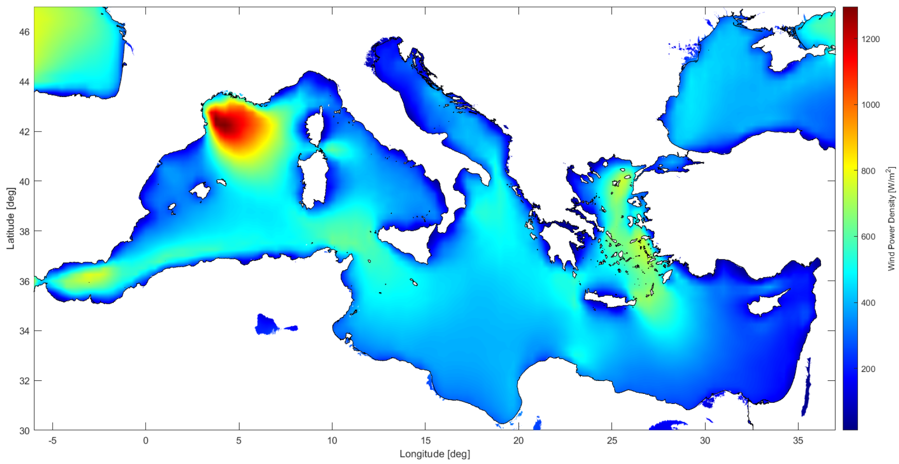

Figure 4.18: Wind Density Potential in Mediterranean Sea [W/m^2].

In Figure 4.19 we can see that the zone with higher density potential of wave energy are similar to offshore wind areas, but not equal. In fact, although wind and waves are directly related, the potential of the latter is lower. In fact being a closed sea is less energetic than that of the North or the oceans.However,the areas with the highest potential remain the same.

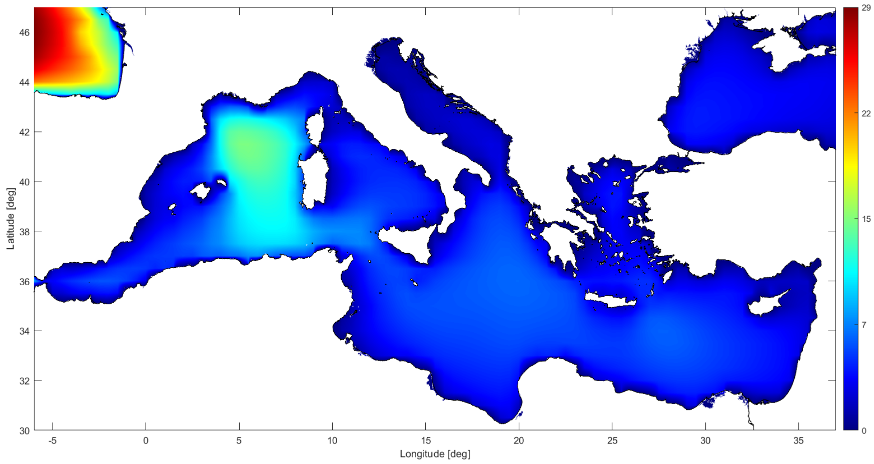

Figure 4.19: Wave Power Potential in Mediterranean Sea [kW/m].

In the following figures it is possible to observe the results regarding the power density of the resources obtained through the methodology .

Figure 4.20 shows how, regarding the offshore fixed wind turbine, the suitable areas are few and small. As already noted in the previous paragraph, the factor that most limits this technology is the bathymetry of the Mediterranean Sea. Basically, the only areas that could be used would be the Northern Adriatic and a portion of the sea between the coasts of Libya and Tunisia. The first zone, does not have a high potential, just above 200 W/m^2, while in the second is higher, being around 400 W/m^2. Coming out of the Mediterranean, however, we observe how the Black Sea has, in its northern zone, a high wind power density.

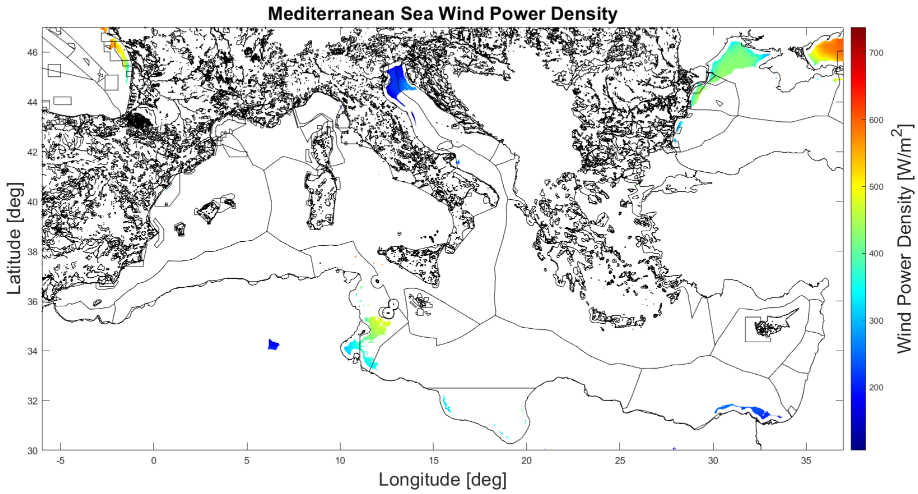

Figure 4.20: Resulting Fixed Wind Power Density Potential in Mediterranean Sea[W/m^2].

In figure 4.21, the one with floating offshore results, it is clear that the situation is different. Although a huge part of the Mediterranean is eliminated due to bathymetry, several potential areas remain. All the Coastline between France(Golf on Lion) and Spain is now present, with the first having the area with the highest wind power density, about 1100 [W/m^2]. Unfortunately, it is strongly limited by a protected natural area.

A very interesting area is between Sicily and Africa, which before was practically non-existent and now is not limited a lot.This area is also one of those with the highest potential, about 600 W/m^2 .

The other area with high average density power, between Greece and Turkey is not too much limited, only by the distance from the coast. Regardless of many coasts, such as Italy, Libya and Egypt, although with low potential, can still be considered.

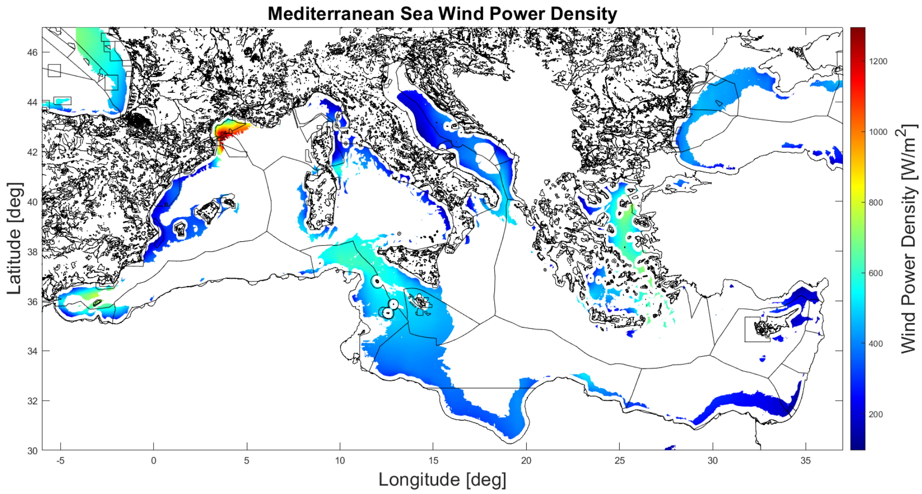

Figure 4.21: Resulting Floating Wind Power Density Potential in Mediterranean Sea [W/m^2].

In this last figure 4.22, it is possible to observe how the most suitable areas for the exploitation of this resource are always the same, the one that starts from the Gulf of Lyon and continues to Sicily through the west coast of Sardinia. Without the limit of the distance from the coast this area would have a potential,it is still high because the area with highest density is located right between France and Sardinia.

Unfortunately, due to the very low power density of the waves, in this case the whole Adriatic Sea and almost all Sea at East of Italy are no longer exploitable.

However, the average value in the available waters is around 6-7 kW/m.

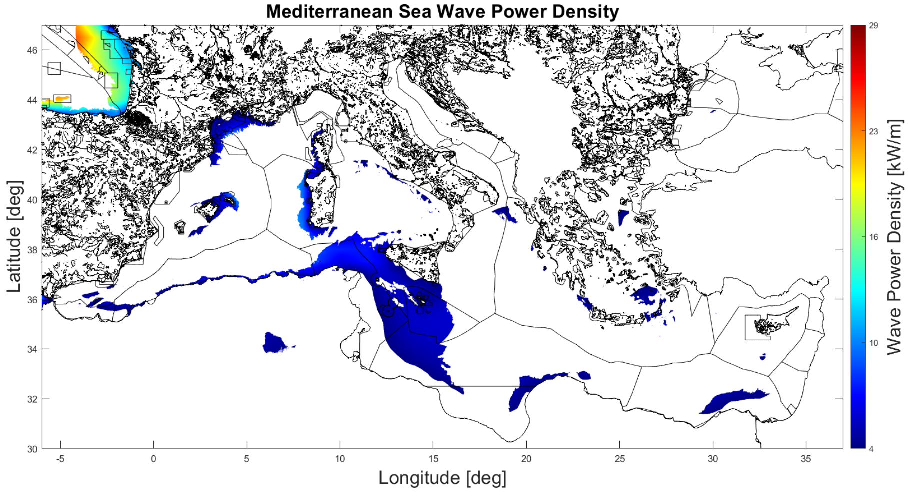

Figure 4.22: Resulting Wave Power Density in Mediterranean Sea [kW/m].

As for the technical potential of each resource, the following figures will show the results, that have been obtained considering the area of the matrix cells equal to 1,234 km^2.

The image 4.23 illustrates again as the remaining areas for this technology do not possess high technical potential. In the Adriatic sea it is around 17 GWh/year/km^2, while between Sicily and Tunisia the value is slightly higher, it oscillates between 25 GWh/year/km^2.

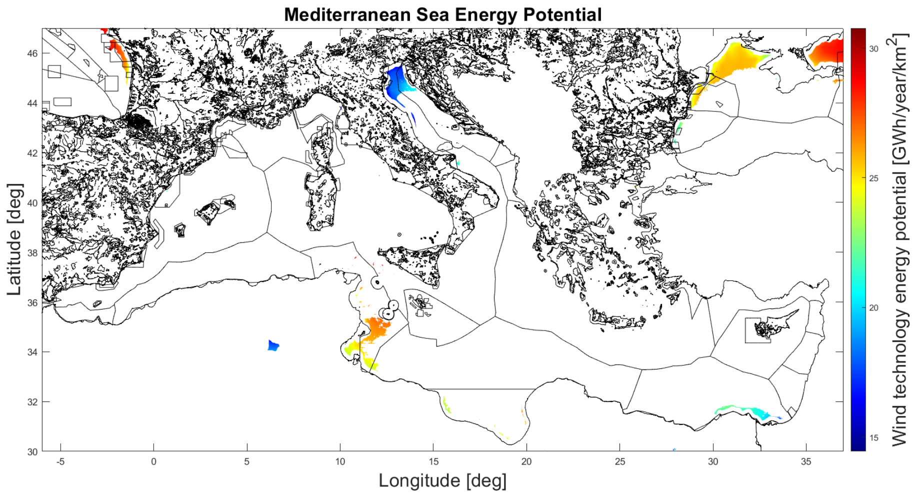

Figure 4.23: Resulting Fixed Wind technical potential in Mediterranean Sea [GWh/year/km^2].

On the other hand, the figure 4.24 demonstrates how the areas suitable for floating wind turbine installation have greater potential. The whole area between Sicily and Tunisia fluctuates between 24 GWh/year/km^2 and 28 GWh/year/km^2,moreover, the area between Greece and Turkey has a similar potential. Instead, in the Adriatic Sea the technical potential is around 20 GWh/year/km^2.

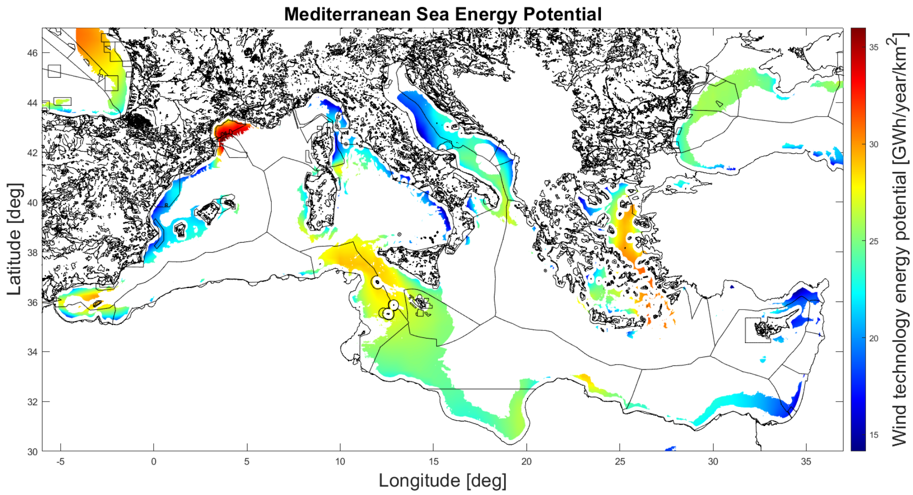

Figure 4.24: Resulting Floating Wind technical potential in Mediterranean Sea [GWh/year/km^2].

And finally, the technical potential of the wave energy resource in image 4.25.Its average is around 13-14 GWh/year/km^2, a value which, although lower than in previous cases, is nevertheless remarkable.

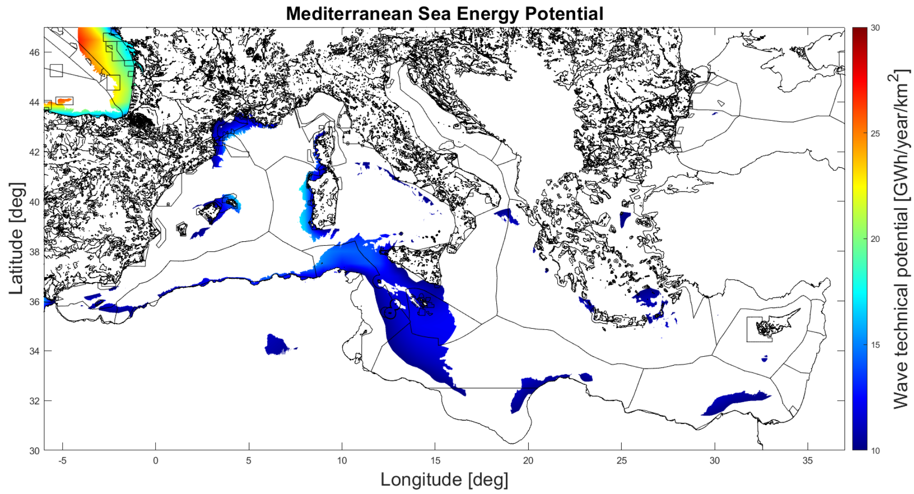

Figure 4.25: Resulting Wave Energy technical potential in Mediterranean Sea [GWh/year/km^2].

The following table shows the total potential energy contained in each of these technologies, in this summation, however, the areas of the Black Sea and the Atlantic Ocean have not been considered. It is a clear the difference between bottom fixed wind turbine and wave energy converter compared to floating wind turbines. The first has the lowest potential, about 2.410 TWh/year, the second slightly higher, around 4.670 TWh/year. Offshore floating wind is even an order of magnitude higher, with a value of around 18.500 TWh/year. This is mainly due to the available area superiority of the latter compared to the other two, and subsequently to the greater reliability of the wind compared to the waves.

Technical Potential	Bottom Wind	Floating Wind	Wave Power
Total [TWh/year]	2.410	18.500	4.670

Instead, the follow table shows the resulting technology capacity. For the same reasons mentioned above, here too there is the same difference. The values of offshore fixed wind and WEC are similar, respectively 224 GW and 533 GW, while for the latest technology the capacity has a value around 3.290 GW.

Capacity Potential	Bottom Wind	Floating Wind	Wave Power
Total [GW]	224	3.290	533

Summing up the results we can say that the renewable source that today is most suitable for the Mediterranean Sea is floating offshore wind. Fixed offshore turbines are too limited by bathymetry, which however regardless is the most binding factor for this resource.

Unfortunately, the shallow seabed eliminates the possibility of installing turbines attached to the ground. It could be possible to consider all areas within 20 kilometers from the coast, this would obviously increase productivity, but would lead to complicate other factors, such as the need for a greater number of permits and problems with visual and acoustic pollution of the coast.

Regardless of the type of wind turbine, it would be possible to install only the medium-sized ones, because of the moderate wind speed.

The areas instead predicted to the installation of wave energy converter are many, however, all with a not very high technical potential so these analyses will require more care to decide which devices are best suited to the different locations.

Chapter 5

Metocean time series of specific location

In this chapter in explained in detail the second methodology created, that relating to punctual analysis.

Its goal is to perform a detailed local analysis of wind and wave resources. In order to provide information on the average values and fluctuations these sources have over the years.

It was also performed using the MATLAB® programming platform. By inserting in script the coordinates of a desired point, the methodology will combine an analysis of the resources of the place, providing as output graphs containing information on wind and waves.

5.1 Data Manipulation

As with the previous methodology, the first aspect to observe are the data.

Here too, they are downloaded from ERA5, but all the information from 2010-2020 were used together .However they were not interpolated because, having to do a temporal analysis, it would not make sense to do so.

In this case the user has to insert the coordinates of the desired location and the methodology takes them and selects in the ERA5 files the points closest to them.

Taking for example the coordinates 12 longitude and 37.5 latitude, the script, to indicate that the analysis in progress is done on a point that is precisely the one chosen by the user, returns the answer:

```
Closest coordinates for Wind value are Lot=12 and Lan=37.5
Closest coordinates for Wave value are Lot=12 and Lan=37.5
```

Figure 5.1: Output message for coordinate selection.

If instead the chosen coordinates are for example 12.2 longitude and 37.3 latitude, therefore a point that is not present precisely in the vectors of latitude and longitude, the obtained message would be:

```
Closest coordinates for Wind value are Lot=12.25 and Lan=37.25
Closest coordinates for Wave value are Lot=12 and Lan=37.5
```

Figure 5.2: Output message for coordinate selection.

And the script will automatically study the coordinates indicated by the message.This obviously creates a misalignment between the locations where the valuations of the two resources are made, which the user must keep in mind.

If instead by mistake are inserted coordinates that do not represent a point located in the sea, the script shows as message:

```
The chosen site does not correspond to a location in the  Mediterranean Sea
>>
```

Figure 5.3: Output message for error coordinate selection.

Once the coordinates are obtained,the script continues initializing the different matrices in which will be inserted the various data related to the properties of the chosen location.

These properties are the same that have been used in the previous methodology. Therefore, regarding the wind, speed and direction, calculated through its components U100 and V100 using formulas 4.1 and 4.2, and then the wind power density and offshore wind technical potential are calculated respectively with the formula 4.3,4.5.

An extra feature that is evaluated for the wind and is visible as output in this methodology is the $wind_rose$, for which the MATLAB® function wind_rose[64] is used, which syntax is:

$$wind\_rose(wind\_direction, wind\_speed) \tag{5.1}$$

It is based on the *polarhistogram* function and by inserting the respective vectors of the wind direction and speed it automatically plots a graph containing the wind rose of the location.

Instead, as for waves always their period, their significant height and their direction are considered. With the first two components, using the formula 4.7, wave power density is calculated,while their technical potential with equation 4.9.

For this methodology, the technical potential is however calculated with a small different consideration. Unlike the spatial one, where grid_area changes every time depending on the spacing grid itself, in this case, being a point study, it is kept constant with the value of 1 km 2.

For each of these components is made the hourly,monthly and annual average, and are also calculated the respective 95 and 5 percentiles, in order to obtain a final analysis more detailed.

A peculiarity of this methodology is the analysis of extreme cases. It allows us to understand how often and with what intensity extraordinary weather events occur, and therefore has a great importance from the engineering ,safety and monetary point of view , because it allows us to understand if and how risky it is to install a certain plant in a certain location.

The MATLAB function $my\_EC\_omni\_3D\_v3$, with the following syntax, was used for this purpose:

$$[Hs, T, W, GOF, Dist_value] = myEC(Hs, T, W, loc, nn, Tr, M, J) \tag{5.2}$$

Its structure is complex. The first three input data are the vectors containing the data of significant height, period associated with wave motion and wind speed. Location_Hs is a parameter used to fit the data with a distribution of Weibull to three parameters, while nn indicates the hourly type of sample. M and J are respectively the number of points in the boundary for Hs i the number of evaluations for twenty different, are the parameters that give the size MxJ to the outgoing data. The last input, Tr, is the return period.

As output instead the relevant data that are returned are in Hs an array of containing the values of significant contour height, in T and W respectively the associated period and the wind associated with Hs.

Processing of all data relating to resources is done within two loops. The first has the task to, at each iteration,take the data from a different year, in order from 2010 to 2020 and also to select the only the data at the indicated coordinates.

The second, internal to the first, is the one in which the local averages and percentile calculations are concretely made.

To do this, since the data relating to the properties of the resources do not show monthly indications, the MATLAB® unique function is used, utilized with the following syntax:

$$[month,\ ,hours] = unique([year(time), month(time)],' rows'); \tag{5.3}$$

Where the time vector is also taken from the ERA5 files, and corresponds to the hourly scan of the year Using this function in this way, it remains two vectors. The first month,is very simple, it contains the months in year and it is needed only to indicate to the internal loop how many iterations to do, precisely twelve.

The second is particular, it is as long as the hours that make up a year, from 1 to 8760 or 8784, but each of them is associated with the number of the respective month. In this way it is possible to associate every given hourly time of wind or waves to the corresponding month.

At this point it remains only to concatenate in the vectors previously created the hourly values, the monthly averages and the annual ones, so as to plot them together as a result, component by component.

5.2 Methodology Results

In this last paragraph it will be illustrated an example of real results from the methodology just described.

The chosen location is situated near the west coast of Sicily, with precision to 12° longitude and 37.5° latitude.In this way the methodology will be able to carry out the analysis exactly in the indicated place.

This point was not chosen randomly, as it should be in the Mediterranean areas with medium-high power density.

As a first aspect, thanks to the figure 5.4 and 5.5 it is possible to observe that the wind on average affects with an angle of 210°-220°,in fact, both wind rose and the direction graph indicate this average values.

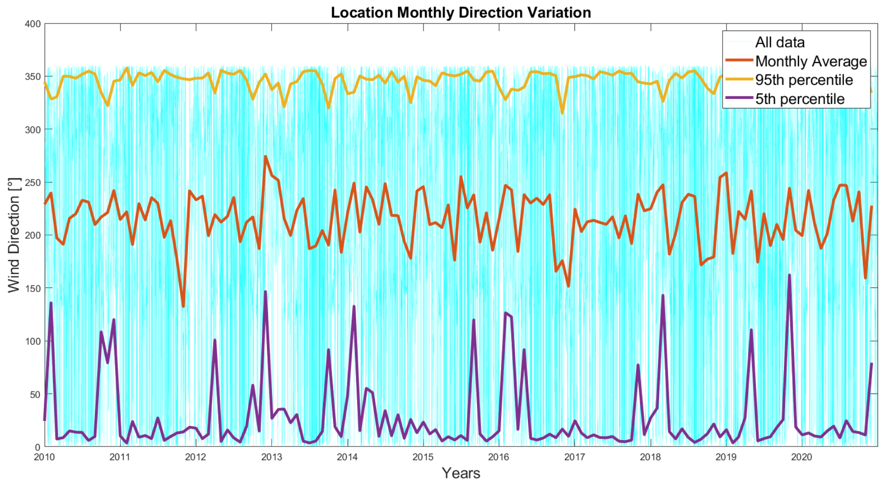

Figure 5.4: Mean Wind Direction [°].

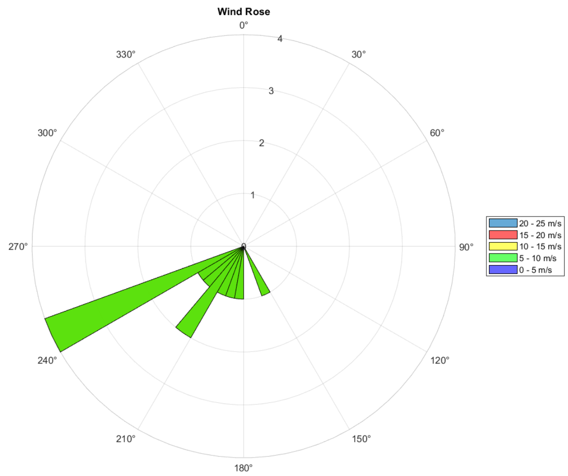

Figure 5.5: Wind Rose [°].

For what concern the speed of the wind, and therefore of its wind power density, it is possible to observe that the results are those expected. In fact, the wind affects with a decent speed of about 8-9 m/s, which then leads the location to have a good power density of about 500 W/m^2.

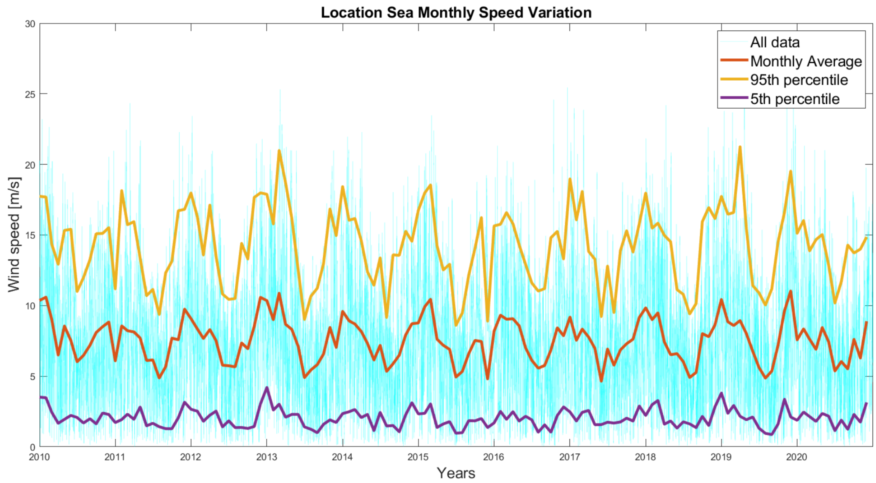

Figure 5.6: Mean Wind Speed [m/s].

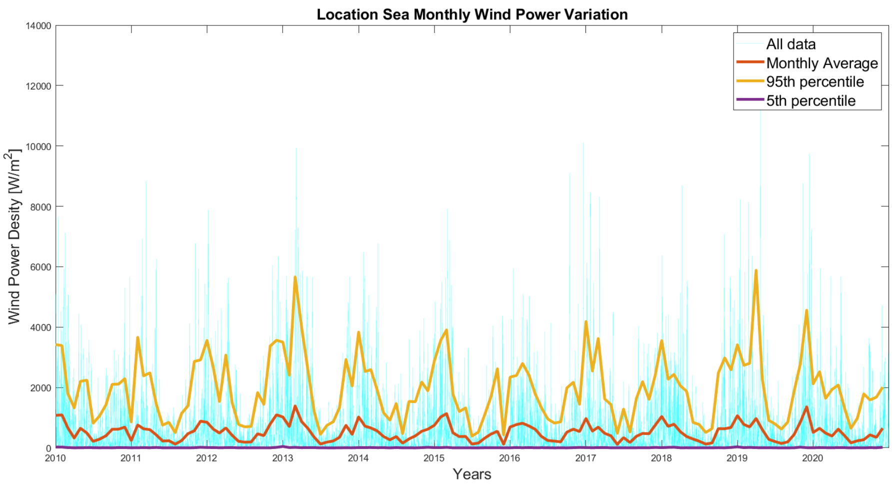

Figure 5.7: Mean wind Power Density [W/m^2].

On the other hand, the technical potential of the offshore wind resource is moderate, with values around 30 [GWh/year/km^2].

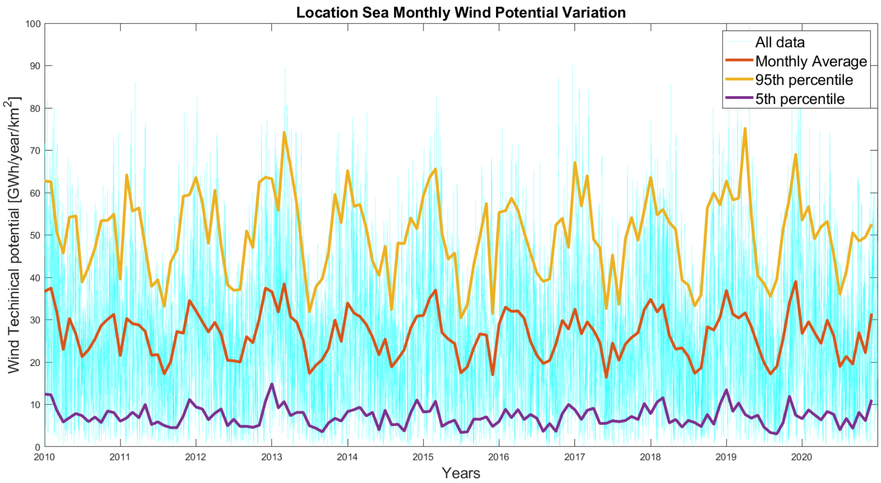

Figure 5.8: Wind technical potential [GWh/year/km^2].

Observing instead the characteristics of the waves in the locality, through the figures below, it is possible to see that the period oscillates periodically between pikes slightly higher than 6 s and bottom around 3.5 s.

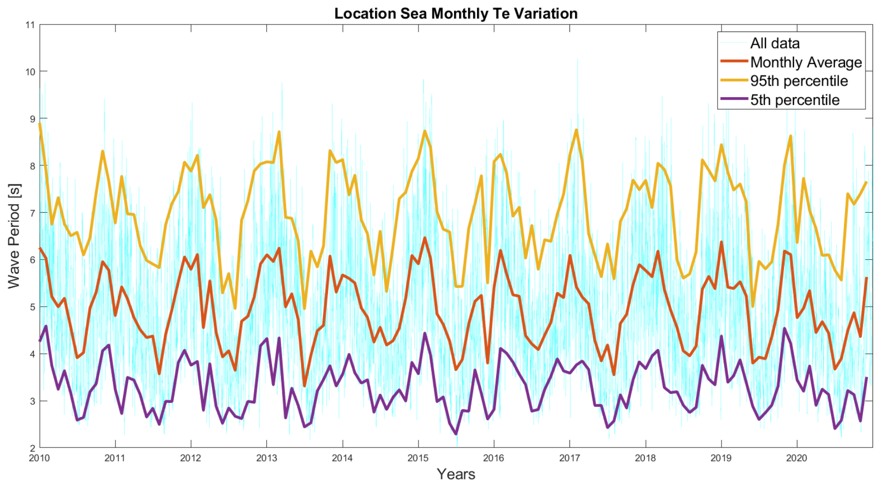

Figure 5.9: Mean Wave Period [s].

The same pattern is present in the significant wave high (figure 5.10), which oscillates between 0.5-2 m approximately,confirms once again that the waves in this sea are not very high, considering that it is one of the areas with the highest power density.

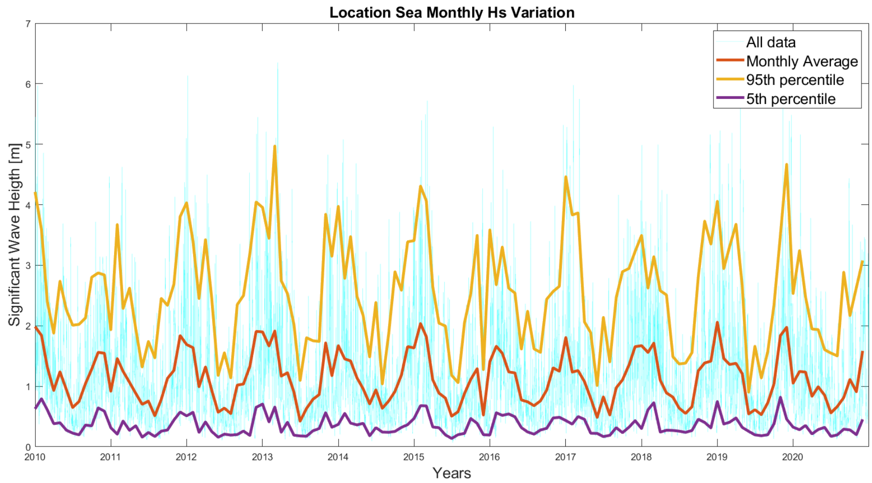

Figure 5.10: Mead Significant Wave Height [m].

As last feature it is possible to observe their direction,rightly is similar to that of the wind, being around 220°.

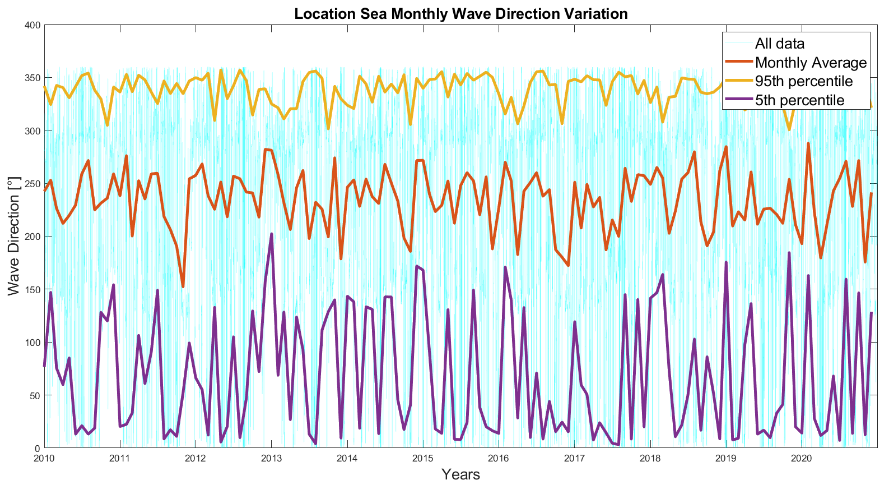

Figure 5.11: Mead Wave Direction [°].

Significant wave height and wave period together form a power density of approximately 5 kW/m, which of course has the same fluctuations as the two components.

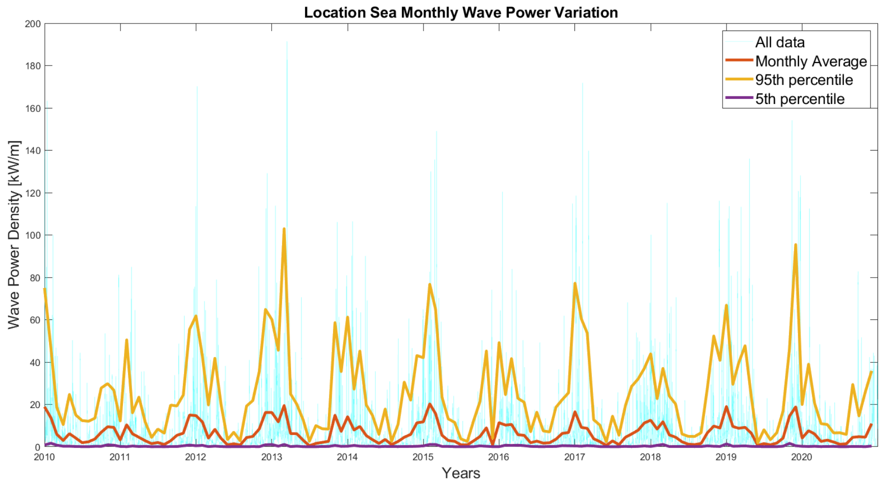

Figure 5.12: Mean Wave Power [kW/m].

Finally, it is possible to obtain the potential energy of the site,with a value around 10 [GWh/year/km^2].

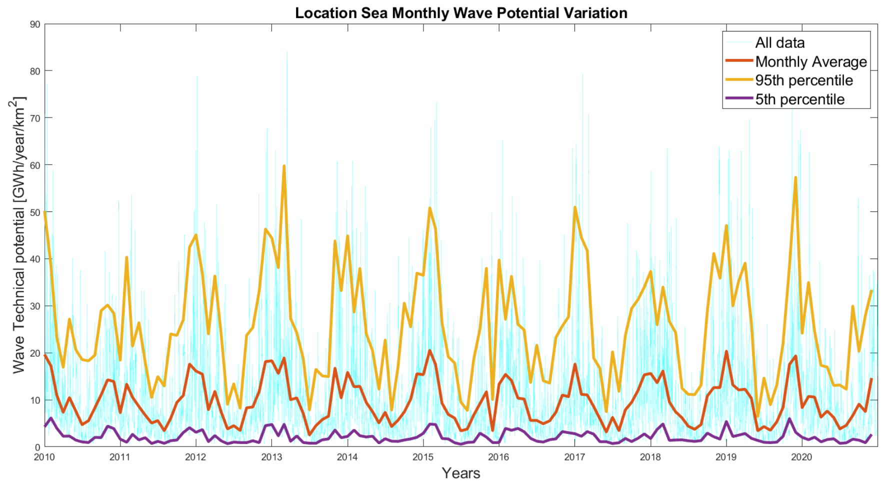

Figure 5.13: Wave technical potential [GWh/year/km^2].

The answer to the shape of the waves can be found in the wind pattern. In fact, it also has its peaks of intensity at the beginning of each year, we can say in general in the coldest weather, and therefore autumn and winter. This is repeated on wind power density but also obviously on wave density, making these resources, although good, not continuous and subject to seasonality.

A final observation can be made on the graph about extreme cases. It shows how almost all the points in 10 years fall within the delimitation area. This means that this particular location is an area not subject to high intensity situation, or that differ greatly from the average.

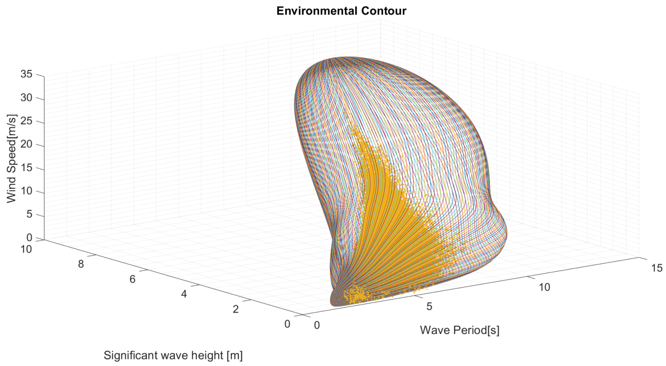

Figure 5.14: Location extreme case.

It should be noted, however, that usually this evaluation is carried out using 50 years of data, therefore to carry out a more detailed study several decades should be added.

Chapter 6

Conclusion

First of all, in this study have been illustrated the reasons why in the future it will be necessary to increase the exploitation of renewable resources.

Indeed, over the next few years, the use of more RES will be essential, as pollution caused by the use of fossil fuels has become unsustainable. The United Nations itself and the European Union have concluded agreement to encourage and, in some cases, to oblige member of countries reduce the greenhouse gases emissions.

To increase the flexibility and reliability of these sources, however, it will be necessary to use also those that are currently under-exploited, especially offshore ones. To date, those that have better prospect are two: offshore wind and ocean energy. In particular, the first refers to two different technologies, bottom fixed and floating wind turbines, while for the second the most promising technology is the one of wave energy converter.

For now bottom fixed wind turbine is the only one that is actually able to produce energy, the others are still in the state of research, although at different level, depending on the prototypes and resources.

To study and to exploit these resources, the most famous research institutes and databases have been illustrated, most of which are free of charge and are funded by bodies such as universities(DTU) or the European Union. Majority are specialized in wind description and evaluation, for example Global Wind Atlas and New European Wind Atlas, while few others also have wave or current data, like ORECCA or EMODnet.

Given the importance that they have within an assessment, the heart of this study was to produce a methodology capable of carrying out an analysis of the energy potential of wind and waves within the Mediterranean Sea.

It consists of two parts, both made with MATLAB as interface and language, in order to use its specialized map and graphics functions.

The first aims to illustrate, through geographical maps, which areas are most suitable for the installation of a given offshore technology, in order to allow the user to understand if the area under study can be exploited or not for an installation, and in the case how much would be its producibility. Two factors underlie this first part. The first is the interpolation of the meteorological data, in fact, they are downloaded from the ERA5 database, but have a low precision, therefore it was decided to increase it by using the MATLAB *interp2* function. The second factor is the imposition of limits on resources, both physical and technological. These limits are of different kinds, and they change depending on the type of source and technology. Those that have been considered in the methodology are the following: bathymetry, distance from the coast, protected natural areas, exclusive economic zones and technological.

The second part of the methodology, on the other hand, is a metocean time series evaluation of a specific location. By entering the coordinates of a specific location, the user obtains resource trends and average values over a period of time from 2010 to 2020.

The purpose of this step is to analyze in the detail every component of every resource, in such a way as to understand how a given location is subject to fluctuations, and therefore whether there is the possibility of ineffective energy production, or even whether possibility of damaging the installation by observing extreme cases.

The results of the analysis show that the Mediterranean Sea is not suitable for the installation of bottom fixed wind turbine, while instead it has a large potential regarding those floats.In fact, the areas suitable for the first technology are not only a few, even their power density is not very high, from 200 W/m^2(Adriatic Sea) to 400 W/m^2 (south Sicily), while those for floating wind are a lot, with average values of 600 W/m^2 (south Sicily), and peaks of 1100 W/m^2(France coast).

It is possible to observe the gap between these two technologies also by evaluating their capacity potential, which in fact is 224 GW and 3.290 GW, respectively for bottom fixed and floating turbines.

This huge difference in power and energy potential is mainly given by the seabed, which, in this sea, reaches high depths quickly away from the coast, making it difficult to find suitable areas for the installation of fixed turbines, whereas the minimum distance from the coast (selected in this study of 20 km) has to be respected.

For what concern wave energy, the available area is greater than that of bottom fixed turbines, even if it is still far from the floating ones. It lies almost entirely between Sicily and Africa, although there is a small portion on the West coast of Sardinia and in France. In general, the power density is around 6-7 kW/m, while the theoretical capacity measured 553 is GW.

This is a particular aspect of the Mediterranean, being a closed sea with a moderate wind, its waves are small, and therefore the energy stored in its waves is very different from that present in open seas in contact with the oceans.

These results highlight how, in future, in order to fully exploit the potential of the Mediterranean Sea, as regards the wind resource, it will be necessary to think about installing floating wind turbines, monitoring how the prototypes installed so far are behaving and continuing with the research to develop new foundations.

On the other hands, the situation for wave energy is more complex, as new devices are needed for the exploitation of these waves.

Nevertheless, the Mediterranean remains a sea with a very high energetic potential, with the ability to help nations that bathe in the goals of reducing CO2 emissions and energy diversification.

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