Wave and Wind RES Platform database and algorithms description

10 ottobre 2022

Giulia Cervelli, Alberto Ghigo and Giuseppe Giorgi

CONTENTS

FIGURE

1 Introduction

Wave and Wind RES Platform is a web tool developed to support the research and the policy during wave and wind resource evaluation activity and identify the best areas for renewable energy converter device installation. *RES Platform* provides downloadable datasets and diagrams. The users can use the datasets to carry out their own analysis, while the diagrams immediately synthesize the primary wave and wind information.

The present document aims at providing an overview of the *RES platform* capabilities, including theoretical background and practical guidelines.

Section **Tool Features** synthetically describes the main features of the Wave and Wind portal for introducing users to various benefits of the tool. Indeed, nowadays, *RES Platform* is a unique portal able to analyze the wave and wind resources, evaluate the best location for the installation, and define the most suitable energy converter device.

Users can discover the methodology and datasets used to realize the tool in the Methodology and Datasets sections, respectively. In particular, Section **Methodology** describes the main parameters used to analyze the wave and wind resource, and the sea area studied, in addition to the description of wave energy converters and wind turbines considered. Bathymetry and other human activity information (for example, shipping routes and protected areas) have been considered for identifying the best area. Instead, Section **Datasets** describes the underlying open-source portals used to obtain the starting information.

Moreover, Section **Algorithms** describes the main algorithms used to obtain the wave and wind energy resource and WEC's and wind turbines productivity evaluation. In addition, the main figures commonly used to give information about the wave energy are illustrated to support the user during the *RES Platform* use.

Finally, in the Section **Tutorial,** the user is supported in discovering the features of the *RES Platform* through sample videos and step-by-step tutorial

In order to improve the service offered and meet the needs of the Blue Energy community, we believe that the contribution of users is fundamental. Therefore, we encourage users to contact us via the dedicated Section Contact to provide feedback and receive further clarification.

1.1 Purpose

The tool can map the wave and wind energy resource and study the potential Wave Energy Converters (WECs) and wind turbine productivity, starting from some key time-series available on online public databases. *Wave and Wind RES Platform* can be used as support in the energy transition and decarbonization; indeed, the exploitation of the wave and wind energy resource is desirable for its huge global potential, the reduced environmental impact of the devices, and diversification of the energy mix.

1.2 Limitations

Wave and Wind RES Platform is the first-of-a-kind platform designed to support the energy transition. Many efforts have been made to identify the information needed to perform the evaluations and the best sources to acquire the starting data and define how to use this information to produce a smart and helpful tool for assisting the planning.

Current work is directed towards increasing the analysis area up to the whole Globe. In addition, techno-economic analyses and productivity assessments of WEC arrays and offshore wind farms will be forthcoming.

In the current open access platform, the available features involve the resource analysis in a arbitrary point of the European Seas, and the productivity assessment of technologies provided by default in the platform. Future commercial versions of the platform will include the possibility to study custom-devices, the techno-economic optimization of arrays on large extension of the sea, including maritime spatial planning constraints, and productivity analysis certified as an independent third-party, as well as a common marketplace to make supply and demand meet.

1.3 Product Details

The current version of *Wave and Wind RES Platform* results from a successful partnership between two research groups of Politecnico di Torino: the MOREnergy Lab (Marine Offshore Renewable Energy Lab) and EST (Energy Security Transition) Lab. The web implementation is the result of the collaboration with the company GDP Analytics. *The RES Platform* website will continue to be developed to better support decarbonization and all stakeholder activities.

1.4 Acknowledgements

Wave and wind data:

ERA5 hourly data on single levels from 1979 to present[1] has been downloaded from the Copernicus Climate Change Service (C3S) Climate Data Store. The results contain modified Copernicus Climate Change Service information 2020. Neither the European Commission nor ECMWF is responsible for any use that may be made of the Copernicus information or data it contains.

Bathymetry:

Data used in this platform was made available by the *EMODnet Bathymetry*[2] project, funded by the European Commission Directorate General for Maritime Affairs and Fisheries.

Environmental layer, Military areas, Oil and Gas Facilities, Shipping density, Exclusive Economic Zones, Ocean Energy Facilities, Wind Farms and Ports:

Data used in this platform was made available by the *EMODnet Human Activities*[3] project, funded by the European Commission Directorate General for Maritime Affairs and Fisheries.

The data layers used for this work were:

- Environment: Nationally Designated Area and Natura 2000;
- Military Areas;
- Oil and Gas: Active Licenses, Borehole and Offshore Installations;
- Shipping density: Vessel Density;
- Other Forms of Area Management/Designation: Exclusive Economic Zones;
- Ocean Energy Facilities: Project Locations and Test Sites;
- Wind Farms;
- Main Ports.

Both portals operate on the principle of open data.

2 Tool Features

Policymakers, researchers, planners, and investors can benefit from *Wave and Wind RES Platform* to evaluate the wave and wind characteristics in a specific site, compare the wave and wind resources concerning different locations, and then identify the best sites and areas for installation. Moreover, the platform supports the preliminary decision of the best device technology.

2.1 Wave RES Platform

Wave RES Platform mode aims to be as versatile and intuitive as possible, supporting the user's choice. The interactive map, with which the user displays the sea areas, is characterized by a colour scale that can provide information about the trend of the seabed. In this way, it is possible to choose the site of interest according to the depth, which is fundamental in choosing the WEC and the eventual construction costs. In addition, once the site is chosen, it is possible to view representative graphs of the wave characteristics and download the hourly time series of each parameter. As far as the productivity evaluation, the user can choose between different WECs, considering the characteristics of the sea site or area that optimize WECs' operation.

The operating diagram is shown in Figure 2.

---

[1] ECMWF ERA5: https://confluence.ecmwf.int/display/CKB/Use+Case+1%3A+ERA5-and+hourly+data+from+1950+to+present

[2] EMODnet Bathymetry: https://www.emodnet-bathymetry.eu/

3 EMODnet Human Activities: https://www.emodnet-humanactivities.eu/

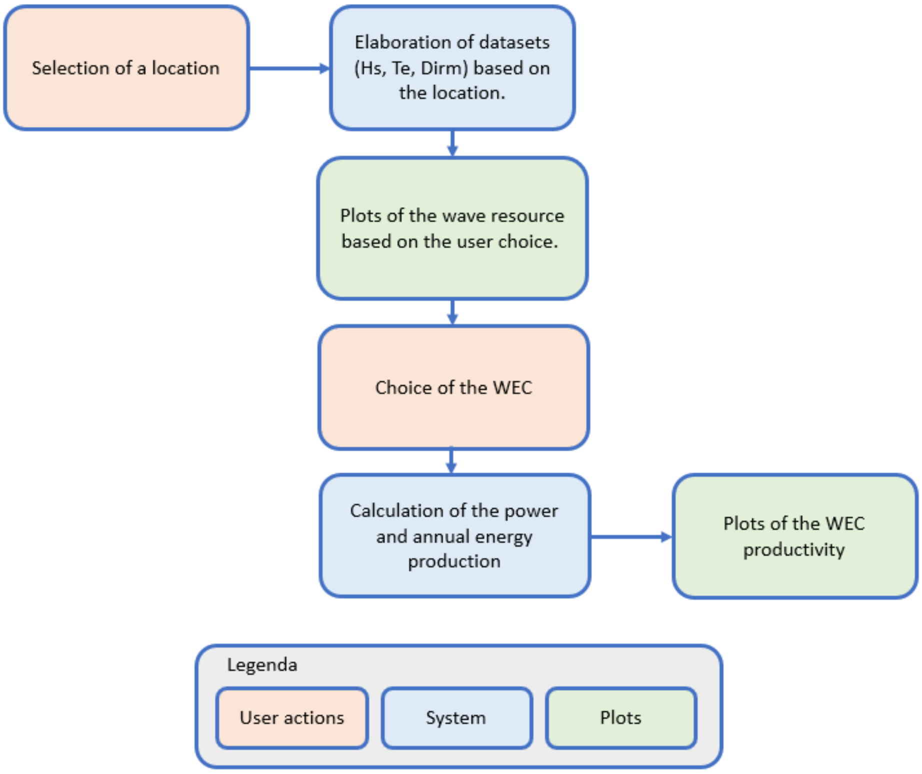


Figure 1 – Operative diagram concerning Wave RES Platform

Wave RES Platform mode allows the open user to perform the following operations:

- View the supporting layers for site selection:
    - The bathymetry of the marine areas for which the analysis of interest can be performed;
    - The average significant wave height;
    - Nationally Designated Areas;
    - Natura 2000;
    - Military areas;
    - Oil & Gas Facilities (Active licenses, boreholes and offshore installations);
    - Shipping density;
    - Exclusive Economic Zones.
    - Ocean Energy Facilities (Project locations and test sites);
    - Wind farms;
    - Ports.
- Choose the site or area of interest the water depth and respective latitude and longitude are displayed.
- Visualization of the graphs is helpful in understanding the wave climate characteristics on a specific site. To this end, the graphs that can be represented for the wave synthetic parameters and the instantaneous mean power are the probability distribution, the inter-annual and intra-annual variability, in addition to the rose of the instantaneous mean power, the occurrences scatter, and the energy scatter. These graphs can be set at different time scales (annual average, monthly averages, inter-annual variability, hourly profiles).
- Calculation of the productivity for the WECs already provided by default in the technology database.

2.2 Wind RES Platform

Offshore Wind RES Platform mode is similar to that previously described for the *Wave RES Platform*. Starting from the bathymetry interactive map, the user can view the different layers of human activity and select the site of interest based on the depth of the sea, a key parameter in the definition of an offshore wind project with regard to the definition of the type of foundation.

Once the site has been chosen, it is possible to view representative graphs of the wind resource characteristics and download the hourly time series of each parameter. Once the type of turbine has been selected among those proposed, it is possible to calculate the overall wind turbine productivity.

The operative diagram is shown in Figure 2.

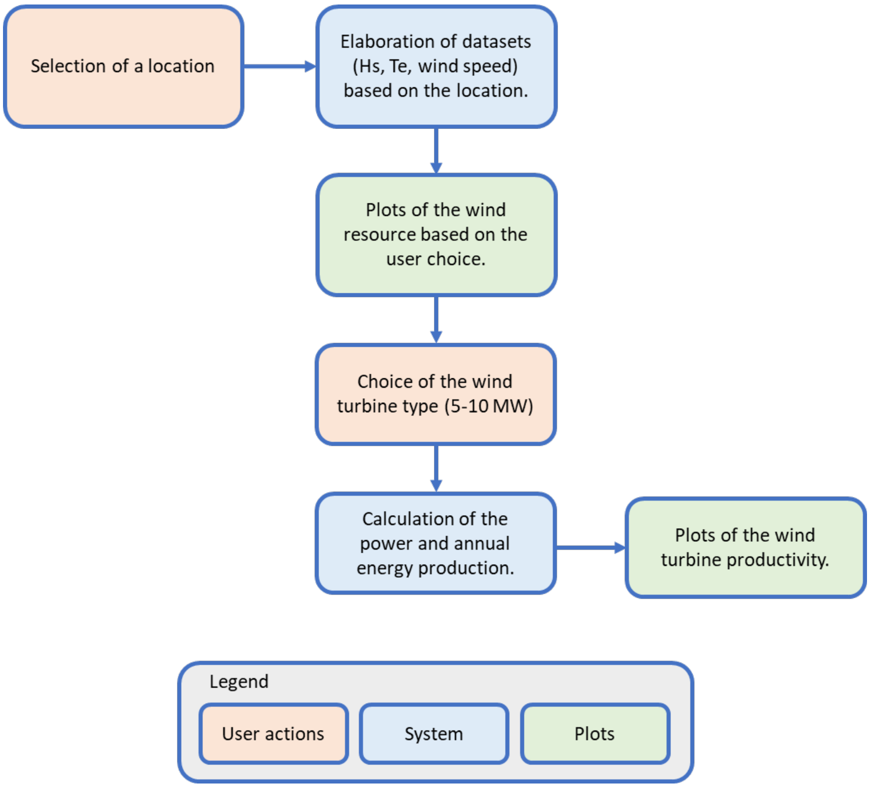


Figure 2 – Operative diagram concerning Wind RES Platform

Offshore Wind RES Platform mode allows the basic user to perform the following operations:

- View the supporting layers for site selection:
    - The bathymetry of the marine areas for which the analysis of interest can be performed;
    - The average significant wave height;
    - Nationally Designated Areas;
    - Natura 2000;
    - Military areas;
    - Oil & Gas Facilities (Active licenses, boreholes and offshore installations);
    - Shipping density;
    - Exclusive Economic Zones.
    - Ocean Energy Facilities (Project locations and test sites);
    - Wind farms;
    - Ports.
- Choose the site or area of interest the water depth and respective latitude and longitude are displayed.

- Visualize graphics of the wind climate for the chosen site. To do this, the most frequent triplets of three representative synthetic parameters (Hs, Te, Wind Speed) were identified. The system allows users to view through graphs the probability distribution, the inter-annual and intra-annual variability in addition to the rose of the wind power density and the wind speed. These graphs can be set at different time scales (annual average, monthly averages, inter-annual variability, hourly profiles).
- Perform a productivity estimate based on the wind turbine chosen by the user, among the default technology portfolio. Once the turbine has been chosen, it is possible to graphically view the most required triplets (Hs, Te, Wind Speed), the average power, and the energy produced overall and relative to the single triplet.

3 Methodology

This section describes the main parameters used to describe the wave characteristics and the study area. In particular, section 3.1 illustrates the main parameters used to evaluate the wave energy, and section 3.2 depicts the imposed limitation of maximum admissible depth and distance from the coast.

Currently, wave, wind, and bathymetry information cover the follwing sea areas:

- Mediterranean Sea
- Black Sea
- Azov Sea
- North Atlantic Ocean
- Irish Sea
- North Sea
- Southern Baltic Sea
- Norwegian Sea

3.1 Wave Energy Parameters

The significant wave height (H_s), energy wave period (T_e), and mean wave direction (Dir_m) are the synthetic parameters that describe the wave characteristics. They can be obtained considering the multidirectional wave spectrum E(f, θ) that shows how the wave energy is distributed over the frequencies (f) and the directions (θ).

Generally, the most used wave spectrum is the one-dimensional frequency spectrum (Equation 1) and not the two-dimensional frequency-direction spectrum, since it contains information needed to compute a lot of wave parameters, except for the mean direction.

$$E(f) = \int_0^{2\pi} E(f, \theta) d\theta \quad [1]$$

In a statistical sense, the wave spectrum can completely describe waves, and the synthetic parameters can be evaluated, expressing them in terms of the moments of that spectrum. Equation 2 defines the moment m_n that is called the ‘nth-order moment’ of the spectrum.

$$m_n = \int_0^{\infty} f^n E(f) df \quad [2]$$

Equations 3, 4, and 5, respectively, report the relation used to compute the significant wave height, the energy period, and the mean wave direction from the wave spectrum.

$$H_s = 4\sqrt{m_0} \quad [3]$$

$$T_e = \frac{m_{-1}}{m_0} \quad [4]$$

$$Dir_m = arctan\frac{\int_0^{2\pi}\int_{f_{min}}^{f_{max}} sin\theta\, E(f,\theta)\, d\theta\, df}{\int_0^{2\pi}\int_{f_{min}}^{f_{max}} cos\theta\, E(f,\theta)\, d\theta\, df} \quad [5]$$

Finally, the significant wave height and the energy period are fundamental to define the average power (Equation 6) and the averagely available annual energy (Equation 7), and, together with the mean wave direction, they are fundamental in designing WECs.

$$\overline{P_{wave}} = \frac{\sum_i^N 0.49 {H_s}^2 T_e}{N} \quad with\ N = number\ of\ hours \quad [6]$$

$$E = \overline{P_{wave}} N = \sum_i^N 0.49 {H_s}^2 T_e \quad [7]$$

3.2 WECs

The RES Platform includes power matrices of existing technologies openly available in the literature. In addition, the MOREnergy Lab team has carried out ad hoc analysis to provide the power matrix of two notional wave energy converters, i.e. a having point absorber and an oscillating surge wave energy converter. The former uses a constrained optimal control, while the latter a reactive control with displacement constraints. Moreover, the productivity evaluation in each sea state has been made according to a stochastic approach for irregular waves.

Among the different devices, the following types of WECs were considered: Onshore Oscillating Water Column, Notional Heaving Buoy, Oscillating Surge Wave Energy Converter and Attenuator-type. Although the future goal is to expand the technology portfolio, the included devices already represent a broad spectrum of the types of WECs present in the international landscape. In particular the Notional Heaving Buoy is an omnidirectional device, i.e. able to produce energy from wave motion regardless of the direction of incoming waves; the other devices, however, are directional WECs and therefore their efficiency is sensitive to the direction of the wavefront. Another significant difference between the different WECs present in the platform is the depth ranges for which their installation is preferable: Oscillating Surge Wave Energy Converter and Onshore Oscillating Water Column are both designed for shallow areas and therefore usually for areas close to the coastline. In contrast, the others are designed for greater depths.

In Table 1 – WECs' general characteristics are listed the main characteristics of the WECs evaluated. In particular, the range of the best bathymetry depth and the directionality information are reported. More details can be found in the appropriate sections of each device.

Table 1 – WECs' general characteristics

Device	***Minimum depth [m]***	***Maximum depth [m]***	***Omnidirectional***
Onshore Oscillating Water Column	0	-20	No
Notional Heaving Buoy	0	-100	Yes
Oscillating Surge Wave Energy Converter	-10	-15	No
Attenuator-type	-50	-70	No

3.2.1 Attenuator-type

Attenuator-type is a device that behaves similarly to floating point absorbers but is constituted by several floating bodies connected to one another. This chain of floating bodies orients itself to the same direction as the incoming wave, and the waves on the system generate a flexing motion.

This motion drives hydraulic pumps, ultimately generating electricity.

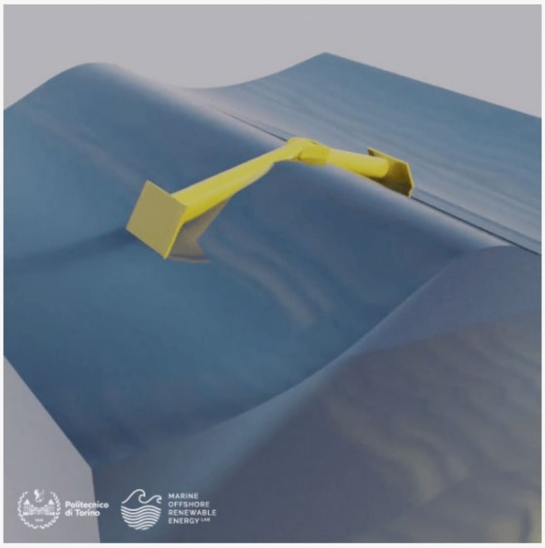


Figure 3 –Simplified representation of an Attenuator-type WEC

3.2.2 Oscillating Surge Wave Energy Converter

Oscillating Surge Wave Energy Converter is typically characterized by a structure fixed on the seabed, and an oscillating part connected to the structure. Energy is collected from the relative motion of the oscillating part concerning the fixed structure.

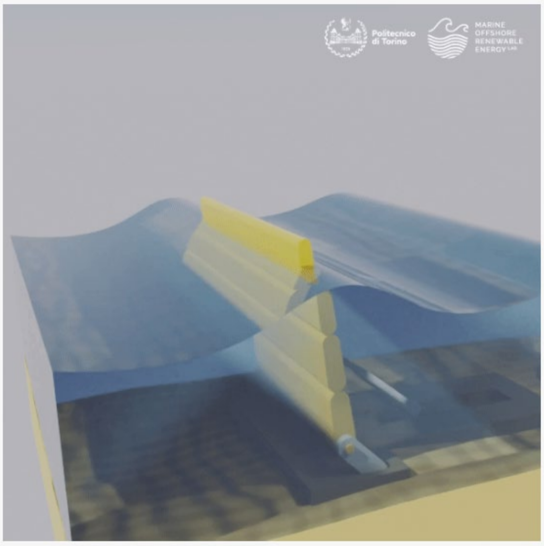


Figure 4 –Simplified representation of a Oscillating Surge Wave Energy Converter

3.2.3 Onshore Oscillating Water Column

Onshore Oscillating Water Column can be located onshore or in deeper water offshore and is characterized by an air chamber. The rising level of the water compresses the air in the chamber due to the waves: the swelling of the water forces the air through an air turbine to create electricity.

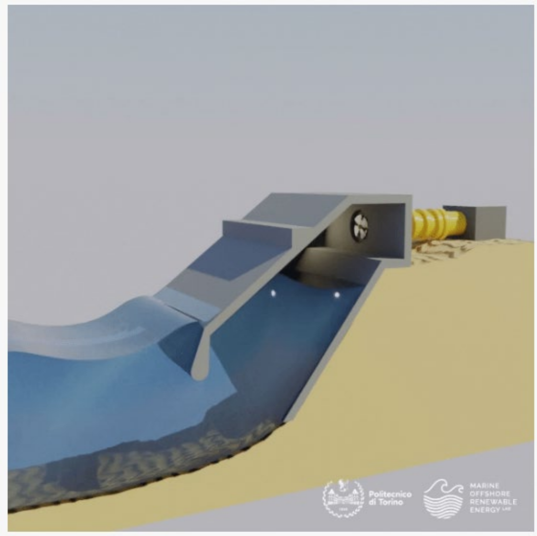


Figure 5 – Simplified representation of an Onshore Oscillating Waver Column

3.2.4 Notional Heaving Buoy

Notional Heaving Buoy is a type of device that floats on the free surface of the ocean. They can be placed both nearshore or offshore and are held in position by a mooring system connected to the seabed. The wave energy is absorbed by radiating a wave with destructive interference to the incoming waves. The device is self-referenced, with a floater moving with respect to the seabed. A PTO system uses the relative movement of the buoy to extract energy. The production of electrical energy can be achieved via linear generators or via generators driven by mechanical linear-to-rotary converters or hydraulic pumps.

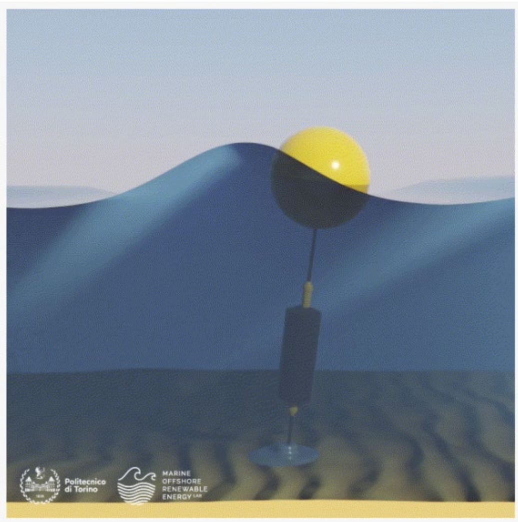


Figure 6 – Simplified representation of Notional Heaving Buoy

3.3 Wind Energy Parameters

For the calculation of the extracted power and productivity, the Betz theory is used. The hypotheses underlying this theory concern:

- The control volume consists of a flow tube (Figure 7);
- The flow at the inlet and outlet of the rotor has a purely axial motion;
- The turbine is represented by an actuator disk which creates a pressure discontinuity along the flow tube;
- A uniformly distributed thrust acts on the disc;

- The air density is constant along the entire flow tube;
- The static pressure upstream and downstream of the disc is equal to the static pressure of the undisturbed environment ($p_1 = p_4$).

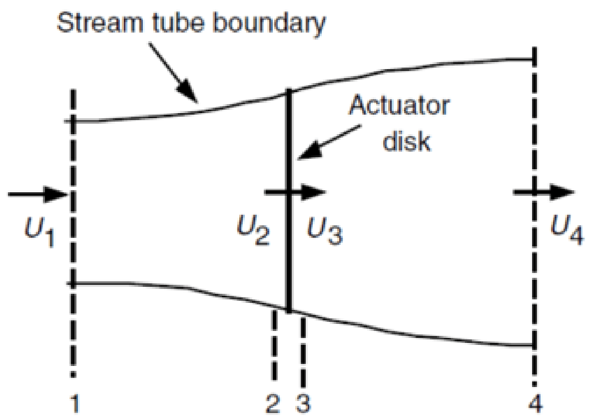


Figure 7 – Control volume

The power extracted from a wind turbine is a function of the power coefficient C_p and the available wind power:

$$P_{wind} = \frac{1}{2}\rho\, C_p\, A\, V^3 \quad [8]$$

Where A represents the rotor area, V the wind speed and ρ the air density.

Similarly, the wind power density is equal to:

$$W = \frac{P}{A} = \frac{1}{2}\rho\, V^3 \quad [9]$$

The electrical power generated can be determined as: assumed constant and equal to 1.225 kg / m^3.

$$P_{wind\ output} = \eta_m\, \eta_e \frac{1}{2}\rho\, C_p\, A\, V^3 \quad [10]$$

Where is it:

- η_m is the overall mechanical efficiency of the transmission shaft between the turbine and the rotor of the electric generator and the gearbox;
- η_e is the efficiency of the electric generator.

3.4 Wind Turbine

A further parameter chosen by the user concerns the wind turbine: currently, two offshore turbines have been implemented, the NREL 5 MW and the DTU 10 MW. These are academic, i.e. non-commercial, wind turbines developed by the National Renewable Energy Laboratory and Danmarks Tekniske Universitet, respectively. The choice to use these turbines is mainly linked to the availability of technical data, such as power curves. In addition, since they are widely used in research, they allow for useful comparisons with other scientific works and publications. Their characteristics are shown in Table 2.

Table 2 – Wind turbine's general characteristics

Device	**Power rating**	***Class***	***Rotor diameter [m]***	***Hub height [m]***	***Cut-in speed [m/s]***	***Cut-off speed [m/s]***
NREL 5 MW	5 MW	1	126	90	3	25
DTU 10 MW	10MW	1	178.3	119	4	25

For the calculation of productivity it is essential to know the values of the power coefficient for each wind speed between the cut-in speed, which allows the rotation of the blades, and the cut-off speed, above which the turbine stops for safety reasons. These parameters, which are visible in Figure 8 have been reported in an excel sheet for each turbine.

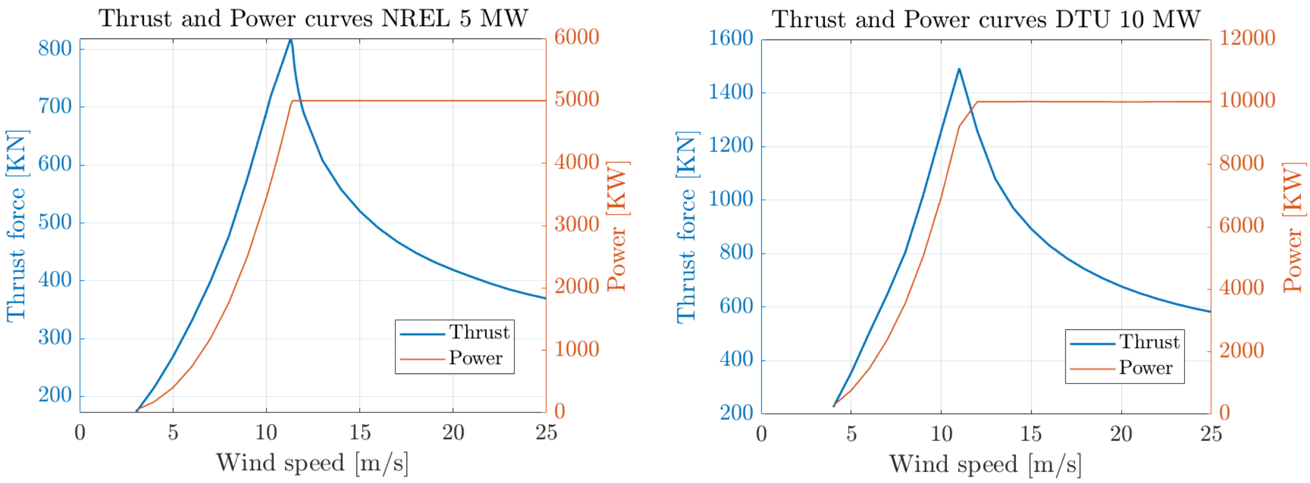


Figure 8 – Thrust and Power curves

3.5 Bathymetry

The bathymetry has a crucial role in the planning stage since, with the same resources, not every location can be suitable. For economic reasons, the device installations must be realized in areas not too far from the coast, and, according to operational reasons, these areas must be characterized by suitable depth since each device has a specific range of optimal depth.

For this reason, all areas with depths of more than 1000 m and a distance of more than 50 km from the coast were excluded because, beyond these areas, the installation is deemed not feasible.

Figure 9 – Sea area of shows the marine areas analyzed, taking into account the European sea and the restrictions imposed on depth and distance from the coast.

Figure 9 – Sea area of analysis

4 Datasets

Wave and wind, Bathymetry and Human Activity data have been acquired by two of the most used open-source portal. This information is complex and expensive to obtain through offshore survey campaigns or specific studies, and the scientific community often obtain them from a third party. The wave data must be obtained by a numerical model to simulate the real sea and environmental conditions. Instead, the bathymetry can be obtained only with instrumental observations.

4.1 ECMWF

The wave and wind synthetic parameters can be derived from different sources. The most detailed is undoubtedly the measurement in situ; nevertheless, in situ wave measurements are carried out at only a few locations in the oceans. Therefore, experts often get information from other sources as satellite measurements and computer simulations. The scientific community often uses wave and wind parameters acquired by the opensource portal of European Centre for Medium Range Weather Forecast (ECMWF)[4], which enables final users to acquire data deriving from reanalysis models. The most recent ECMWF reanalysis dataset is ERA5, which provides data for several macro-area as wave, wind and solar. The parameters are available on a large timescale, from 1979 to the present, and, generally, with a time resolution of 1h. However, they are characterized by a low spatial resolution, around 50 km. This database supplies the following useful parameters:

- H_s [m]: significant wave height
- T_e [s]: energy wave period
- Dir_m [degree]: mean wave direction of the incoming waves
- U [m/s]: component of the horizontal wind speed toward East at 100 m a.s.l.
- V [m/s]: component of the horizontal wind speed toward North at 100 m a.s.l.

Finally, the wave and wind parameters have been acquired by the ECMWF portal, with a hourly temporal resolution, from 2010 up to 2019.

4.2 EMODnet

4.2.1 EMODnet Bathymetry

The European Marine Observation and Data Network (EMODnet) Bathymetry[5] is a portal that provides bathymetry information. In particular, it was initiated by the European Commission. The latest version of EMODnet's digital terrain model (DTM), updated to 2020, was obtained using the best bathymetry datasets available from a growing number of data providers.

The bathymetric data provides depth information with a spatial resolution of 0.001° x 0.001° (115m x 115m). This resolution allows identifying the altimetric trend of the seabed with great detail, especially in areas where this trend is particularly variable.

4.2.2 EMODnet Human Activity Data

To allow the user to identify the most energetic maritime areas, but also taking into account the environmental constraints, maritime routes, etc., the following layers have been implemented:

- Environment: it is possible to visualize both Nationally Designated Area and Natura 2000 sites;
- Military Areas;
- Oil and Gas Facilities, classified in Active Licenses, Borehole and Offshore Installations;
- Shipping Density;
- Exclusive Economic Zones;
- Ocean Energy Facilities, divided into Project Locations and Test sites;

---

[4] ERA5: https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5

[5] EMODnet: https://www.emodnet-bathymetry.eu/

- Wind Farms;
- Main Ports.

The data was downloaded from the Emodnet Human Activities portal.

5 Algorithms

Several algorithms are implemented to evaluate the resource characteristics in an assigned site and analyze the productivity of devices. In particular, section 5.1 is focused on the wave energy resource, section 5.2 is focused on the WECs' productivity section, 5.3 is focused on wind energy resource and finally section 5.4 on wind turbine productivity.

5.1 Wave Energy Resource

The evaluation of wave energy resources is based on several algorithms which use the synthetic wave parameters. Each algorithm provides a figure which summarizes the main results.

Once the site of interest has been selected, the analysis regarding the wave resource is carried out considering 10 years of wave data.

The graphical interface allows the visualization of the following graphs:

- Probability distribution of power, wave height and energy period
- Monthly variability of power, wave height and energy period
- Yearly variability of power, wave height and energy period
- Monthly variability of wave energy resource
- Annual variability of wave energy resource
- Power rose
- Matrix of occurrences
- Matrix of occurrences and probability distribution of wave height and energy period
- Power matrix

In addition, it is possible to select the year(s) of interest and the month(s) for which the analysis is to be performed. As for the matrices, there is also the possibility of selecting the single direction or directions for which the information is desired.

5.1.1 Distribution Plot

Figure 10, Figure 11, and Figure 12 are distribution plots, showing the probability distribution of the corresponding parameter. The probability distribution allows showing synthetically which are the values with greater frequency of happening and therefore more probable. To give a further indication, the average value of the chosen parameter is also provided.

In particular, the main parameters analyzed are the power of the wave (Figure 10 – Power distribution plot), the significant wave height (Figure 11) and the energy period (Figure 12).

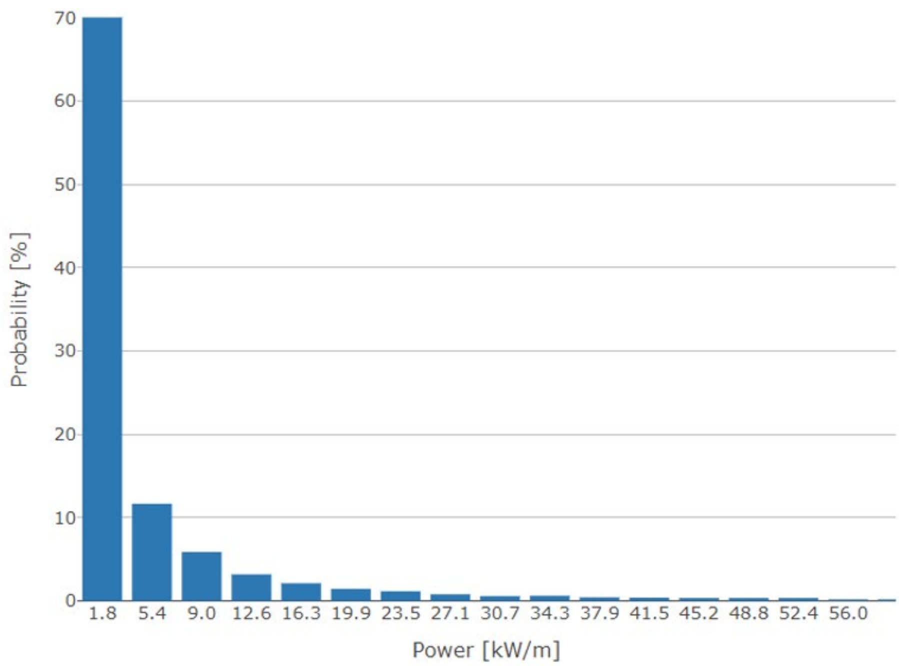


Figure 10 – Power distribution plot

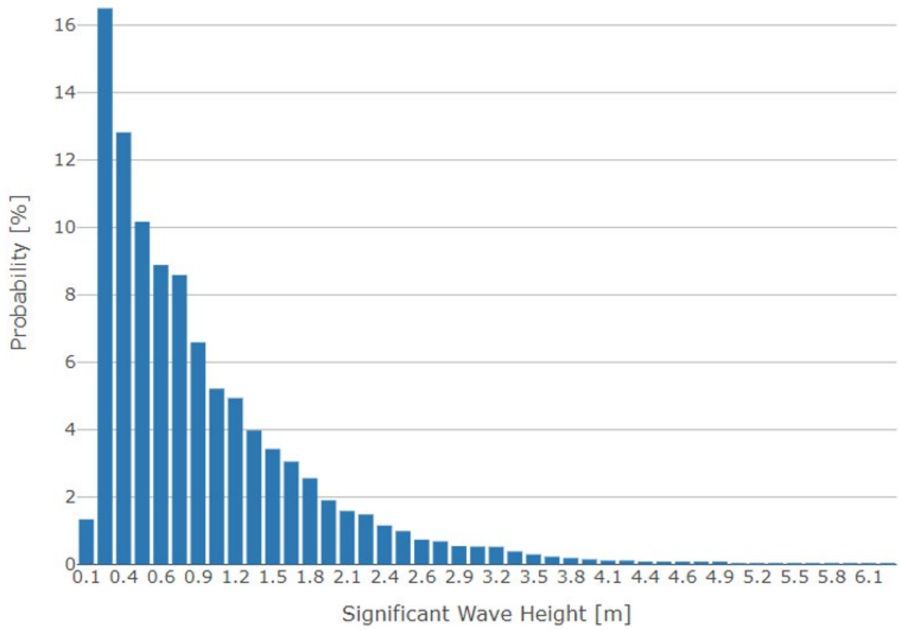


Figure 11 – Significant wave height distribution plot

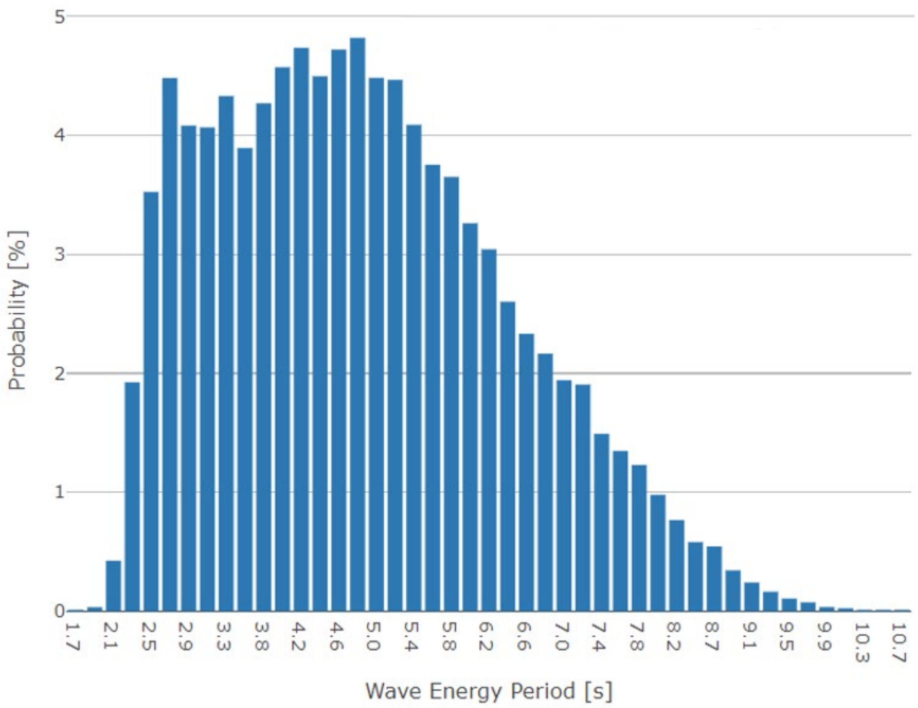


Figure 12 – Wave energy period distribution plot

The correlated algorithms are reposted in the Appendix "Mathematical background".

5.1.2 Monthly Resource Data

In order to evaluate the monthly variability of power, wave height and energy period, the user can view the graph of Figure 13, Figure 14 and Figure 15 respectively, in which both the 5th and 95th percentile, as well as the average value, are reported. Moreover, the maximum value can be identified as the value corresponding to the height of the bar of the respective month. In order to visually show the distribution of the values, a point cloud representing a representative sample of the values corresponding to the respective month is also shown.

Figure 13, Figure 14 and Figure 15 represent the monthly variability of the wave power, the wave height and the energy period considering the period from 2010 up to 2019.

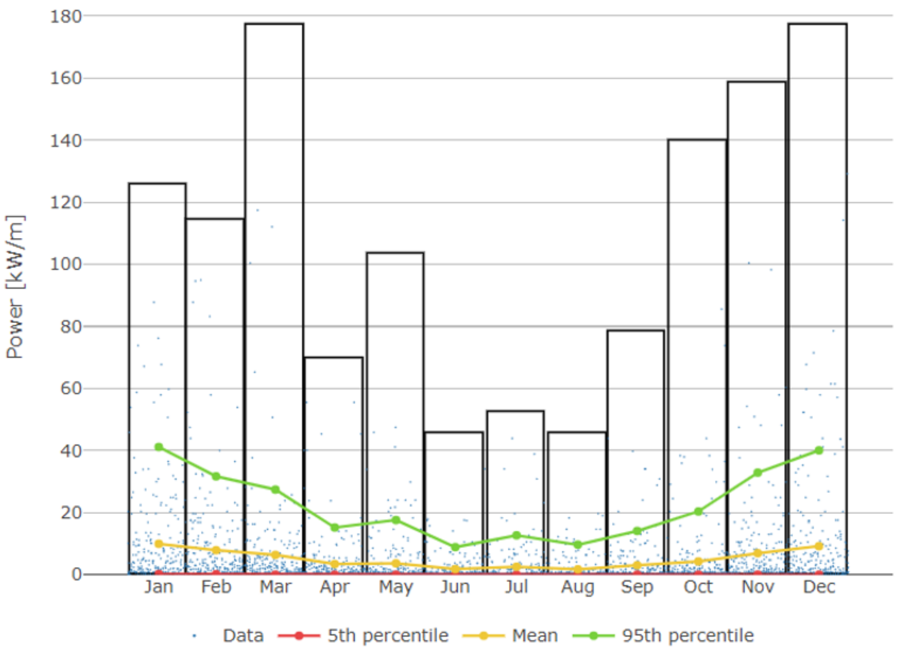


Figure 13 – Power monthly variability

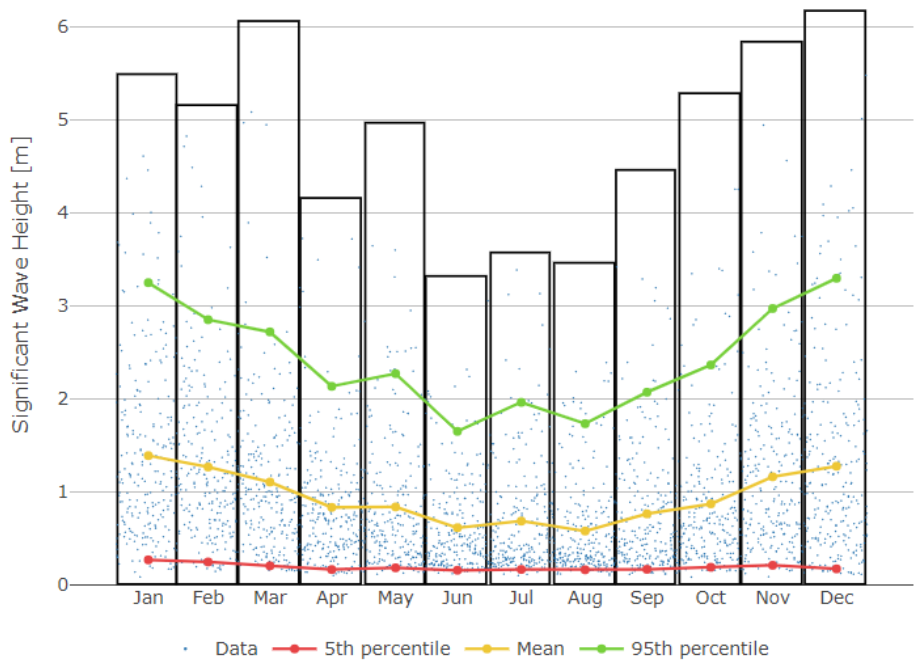


Figure 14 – Significant wave height monthly variability

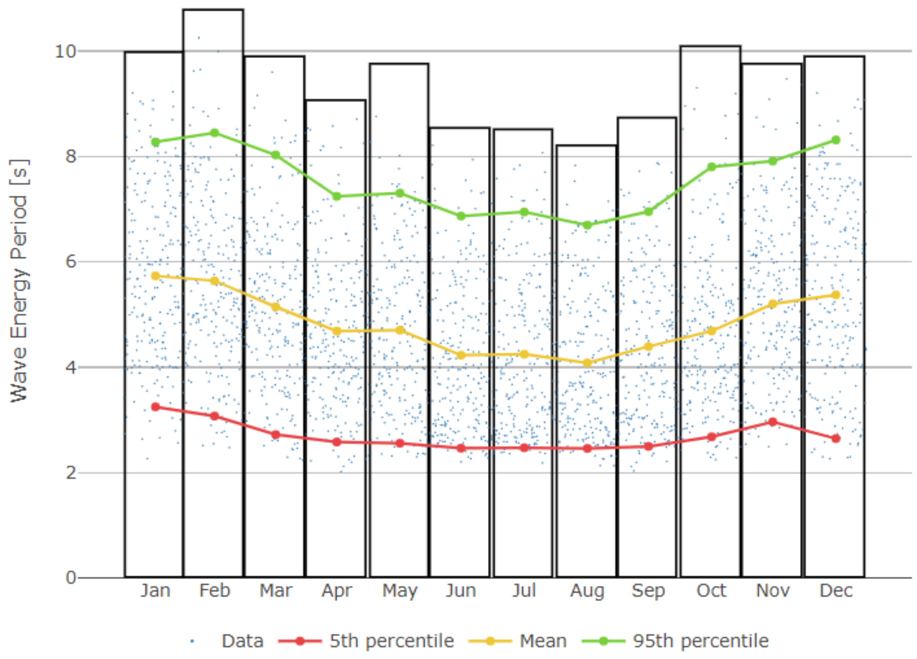


Figure 15 – Wave energy period monthly variability

The correlated algorithms are reposted in the Appendix "Mathematical background".

5.1.3 Yearly Resource Data

In order to evaluate the yearly variability of power, wave height and energy period, the user can view the graph of Figure 16, Figure 17 and Figure 18 respectively, in which both the 5th and 95th percentiles are shown, as well as the average value. Moreover, the maximum value can be identified as the value corresponding to the height of the bar of the respective year. To visually show the distribution of values, a point cloud is also shown representing a representative sample of the values corresponding to the respective year.

Figure 16, Figure 17 and Figure 18 represent the annual variability of the wave power, the wave height and the energy period considering the period from 2010 up to 2019.

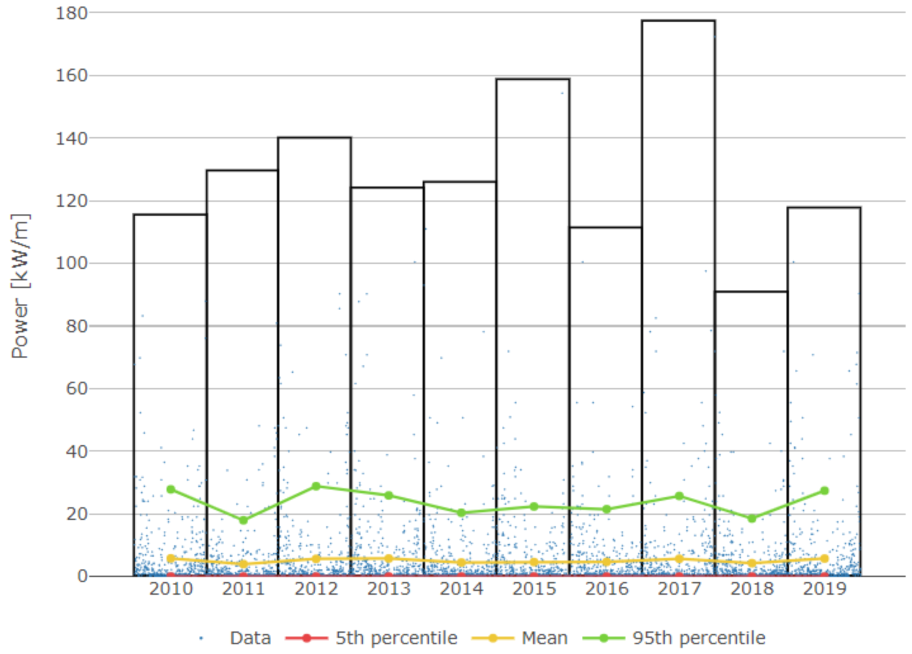


Figure 16 – Power yearly variability

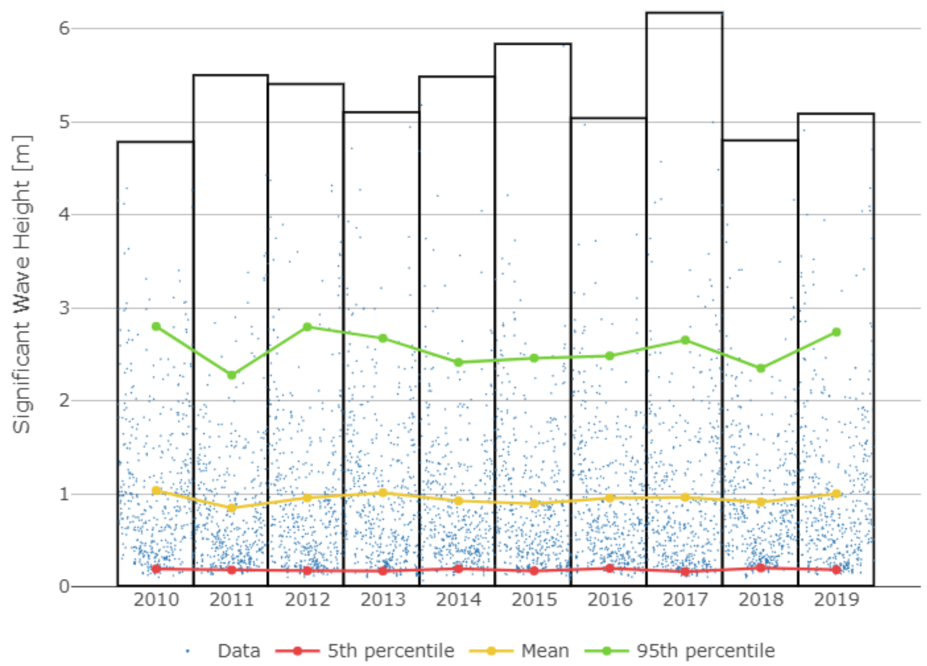


Figure 17 – Significant wave height yearly variability

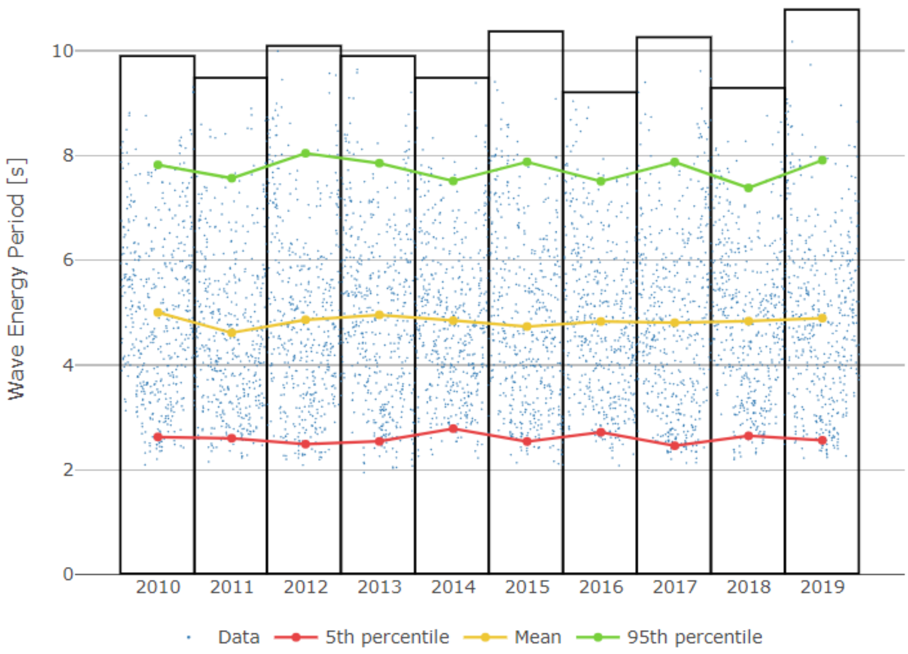


Figure 18 – Wave energy period yearly variability

The correlated algorithms are reposted in the Appendix "Mathematical background".

5.1.4 Monthly Wave Energy

In order to evaluate the monthly variability of the wave energy resource, the user is provided with the Figure 19.This has been obtained by considering the minimum, average and maximum value of the resource in the reference time period.

Therefore, the minimum value corresponds to the energy of the respective month of a given year with the lowest value, the maximum value was calculated in the same way, while the average value corresponds to the average of the reference month with respect to the years of analysis (equal to 10 years).

Figure 19 allows users to identify the more energetic months and those more variable.

For the sake of clarity, the energy shown in the figure refers to the monthly temporal period.

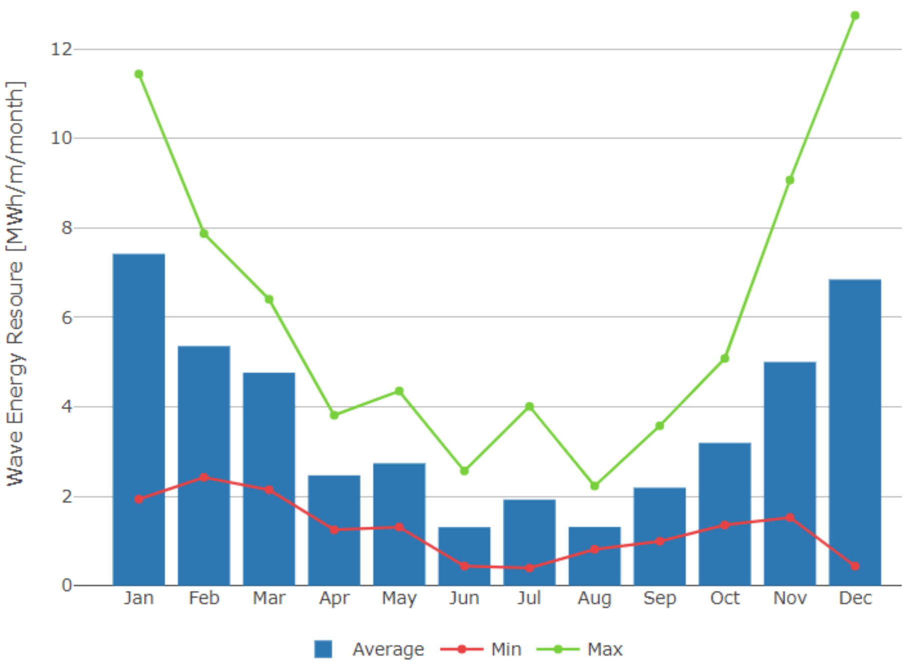


Figure 19 – Monthly wave energy resource

The correlated algorithms are reposted in the Appendix "Mathematical background".

5.1.5 Yearly Wave Energy

To assess the annual variability of the wave energy resource, the user is provided with the Figure 20. It allows the user to identify the most energetic years, as well as the variability recorded in the past.

For clarity, the energy shown in the figure refers to the annual time period.

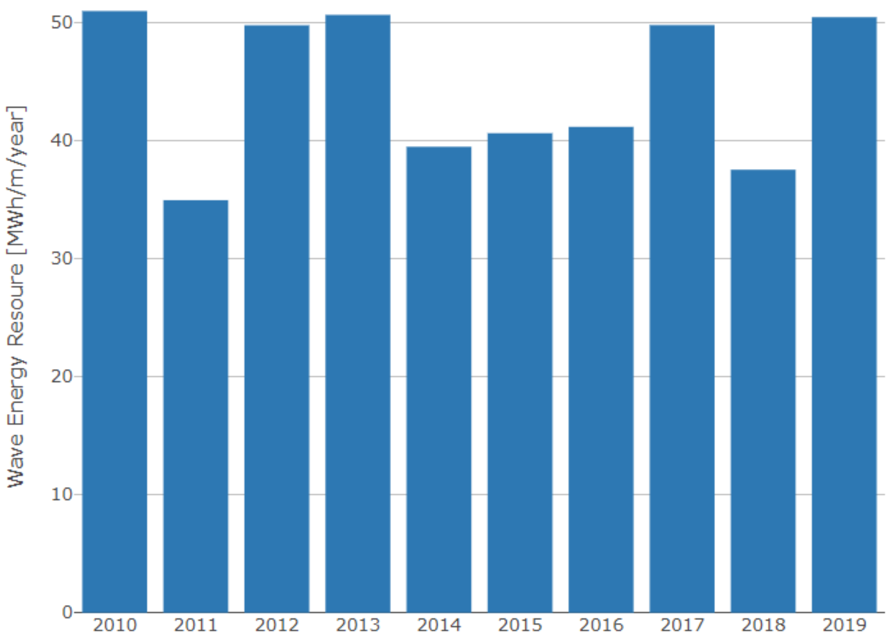


Figure 20 – Yearly wave energy resource

The correlated algorithms are reposted in the Appendix "Mathematical background".

5.1.6 Wave Power Rose

Since some devices are sensitive to the direction (directional devices), the user can also display the power rose (Figure 21). The directional devices are those devices that cannot align themselves correctly with the incoming waves for construction or operational reasons, and/or whose conversion efficiency is sensitive to the relative direction between the device and the wave. This feature is significant for sites with high variability concerning the direction of origin of the waves. The power rose, similar to the better-known wind rose, allows identifying the direction in which the maximum wave power is concentrated.

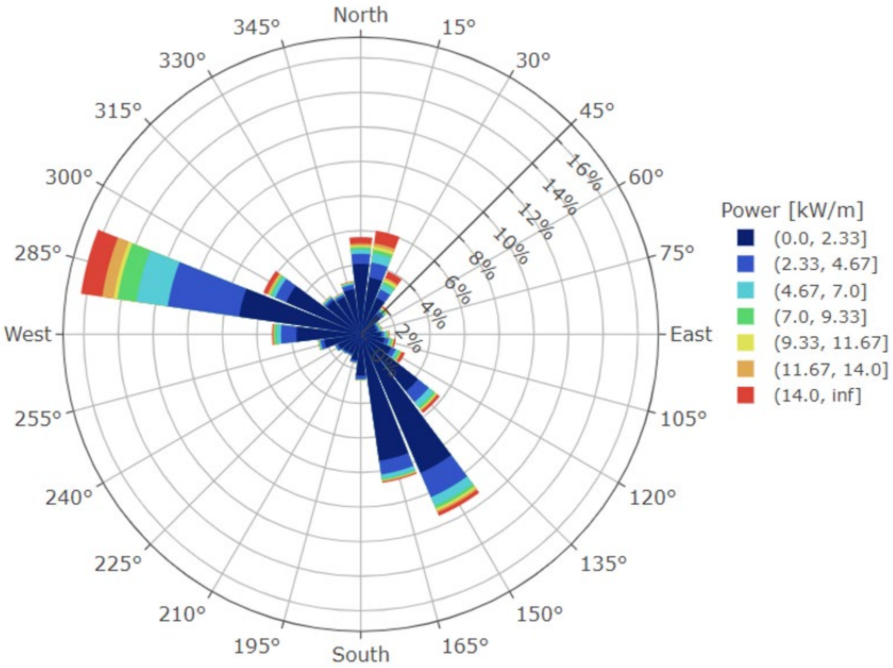


Figure 21 – Power rose

The correlated algorithms are reposted in the Appendix "Mathematical background".

5.1.7 Wave Occurrences Matrix

The occurrences matrix (Figure 22 and Figure 23) allows the user to identify the most frequent sea states, i.e., the most occurring wave height-energy period pairs. To provide the user with additional information, it also has the option of displaying the probability distribution of the significant wave height and energy period, as shown in Figure 23Figure 23.

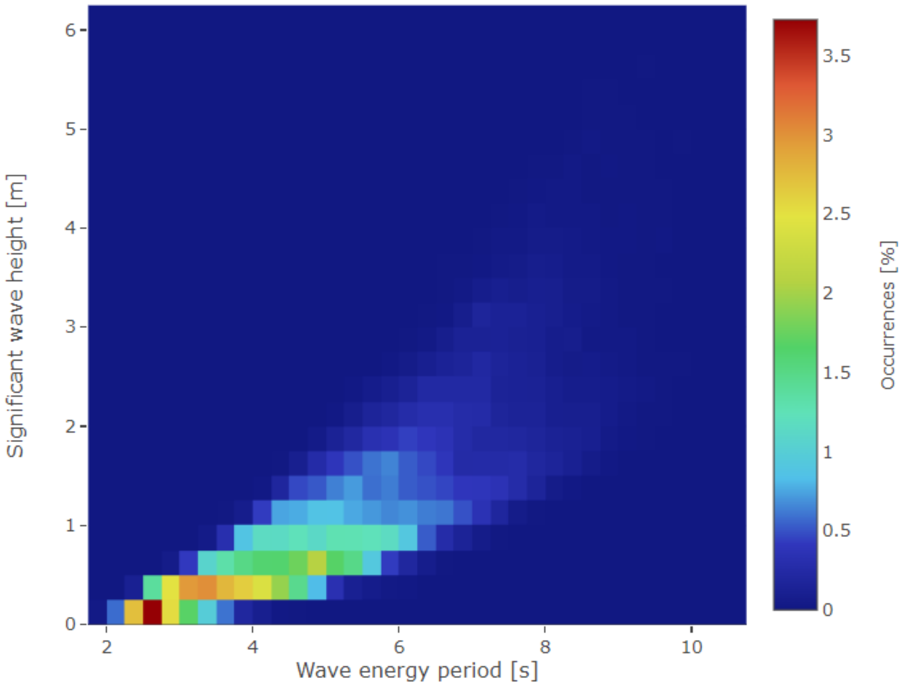


Figure 22 – Occurrences scatter

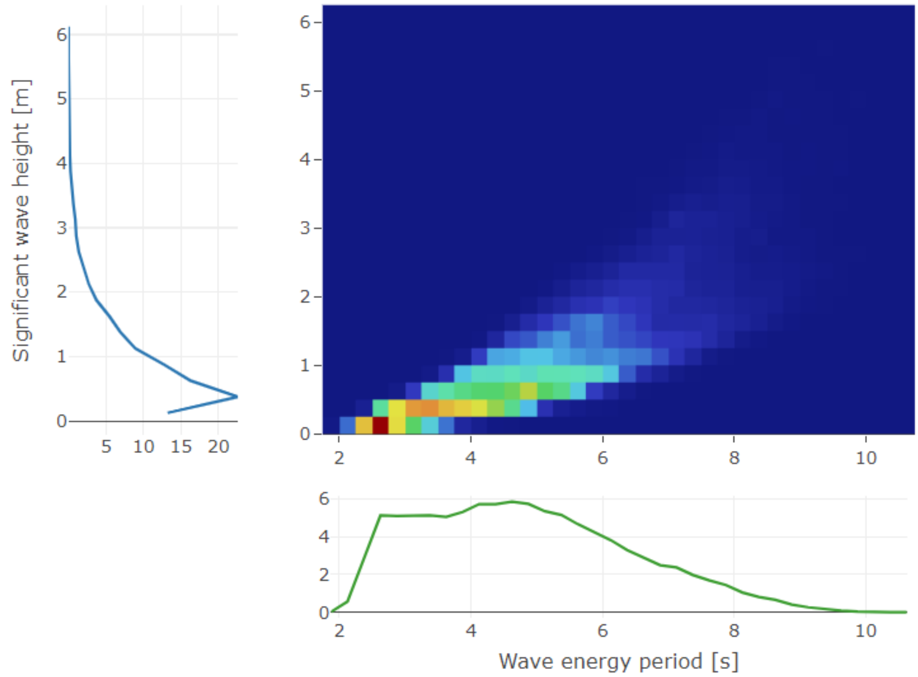


Figure 23 – Occurrences scatter and probability distribution of significant wave height and energy period

The correlated algorithms are reposted in the Appendix "Mathematical background".

5.1.8 Wave Power Matrix

A further useful representation concerning the analysis of the wave resource, is that provided by the power matrix (Figure 24). This graph represents the power potentially extractable per meter of wave, in fact, it refers both to the average power of each sea state and to the matrix of occurrences, thus considering the probability that a certain pair of significant height-energy period, occurs.

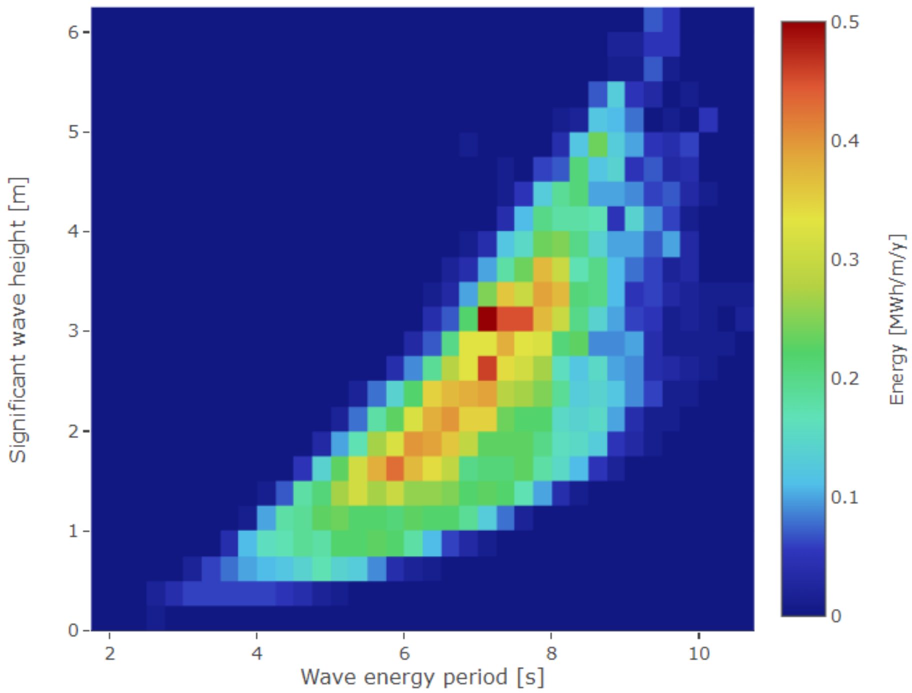


Figure 24 – Power matrix

The correlated algorithms are reposted in the Appendix "Mathematical background".

5.2 WEC's Productivity

After selecting the site and analysing the resource, the user can carry out the analysis of the productivity estimation. In particular, the section regarding the device selection is displayed.

The different technologies implemented in the portal are displayed in a table, which is enriched by a series of helpful information:

- Directionality of the device
- Number of parameters describing the different possible configurations
- Minimum and maximum optimal installation depth
- Additional information regarding the description of the device and references in literature.

In addition, there are ticks at the side of the list, indicating the suitability or not, for each device, concerning the average depth of the chosen site and the optimal depth of the device itself.

Once the device has been chosen, it is possible to save the project and view the productivity results. These graphs are:

- Hourly variability of energy production
- Monthly variability of energy production
- Annual variability of energy production
- Matrix of producible energy
- Device matrix

5.2.1 WEC Hourly Productivity

Figure 25 represents the hourly variability of the energy produced by the chosen device, concerning the wave conditions of the site identified by the user.

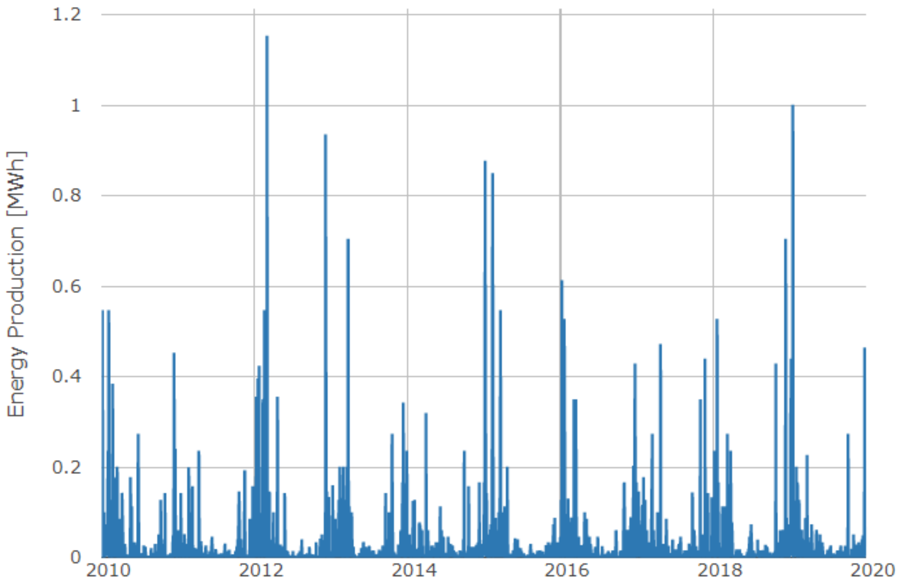


Figure 25 – WEC hourly productivity

5.2.2 WEC Monthly Productivity

Figure 26 Figure 26 – WEC monthly productivityrepresents the monthly variability of the energy produced by the chosen device, concerning the wave conditions of the site identified by the user. In particular, the minimum, average and maximum values for each reference month are highlighted.

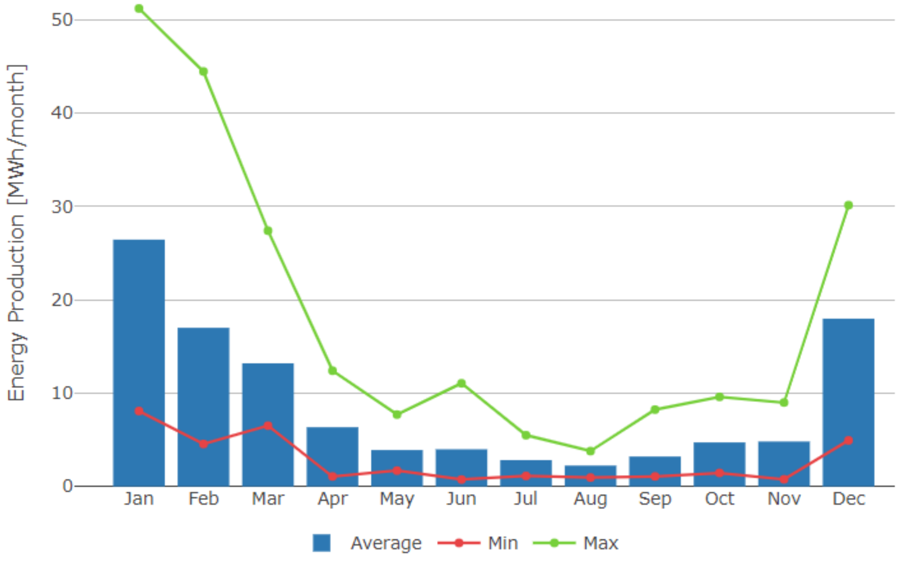


Figure 26 – WEC monthly productivity

5.2.3 WEC Yearly Productivity

Figure 27 represents the annual variability of the energy produced by the chosen device, with reference to the wave conditions of the site identified by the user.

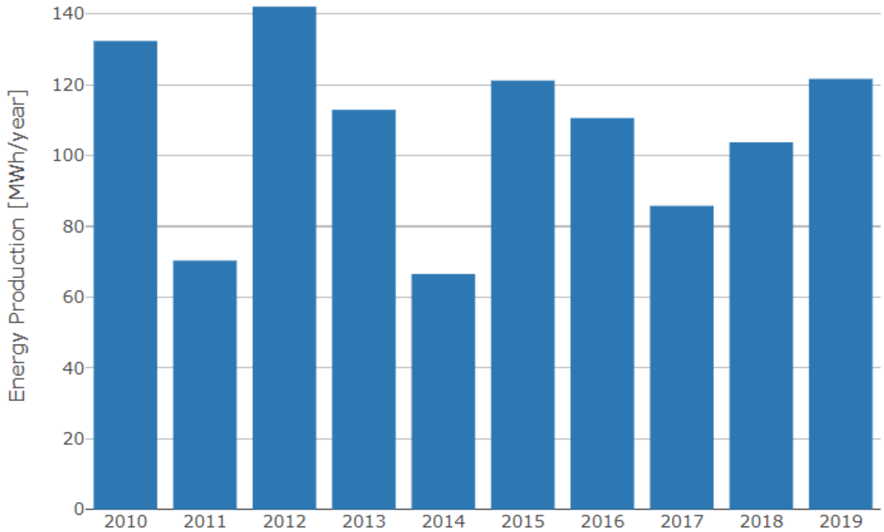


Figure 27 – WEC yearly productivity

5.2.4 WEC Power Rose

The power rose shows the power produced concerning the specific direction (Figure 28). Devices can be differentiated into i) *directionally sensitive*, that is, those that cannot correctly align with incoming waves for construction or operational reasons, and/or whose conversion efficiency depends on the wave direction; and ii) *non-sensitive*, which are not affected by wave direction (e.g., axisymmetric devices). This differentiation may be significant for sites with high variability in wave source direction. Similar to the better-known wind rose, the wind rose makes it possible to identify the direction in which maximum wave power is concentrated. There are three cases depending on the type of device and the power matrix provided:

- Non-sensitive device, whereby the device produces in the same way, regardless of the direction of the waves. The power matrix of such devices is not a function of wave direction and is applied to every wave direction.

- Sensitive device, for which the sensitivity of the energy conversion efficiency to the direction of the wave is provided. In this case, a different power matrix is provided for each angle of incidence concerning the direction of operation of the device. The power rose will show power production in all directions, aligning the device about the direction with maximum wave power.

- Sensitive device, for which the sensitivity of the energy conversion efficiency to the direction of the wave is NOT provided. In this case, the power matrix is given only with respect to the main direction of operation of the device, and it is assumed that it does not produce at all in all other directions. The power rose will show power production only in the direction with maximum wave power.

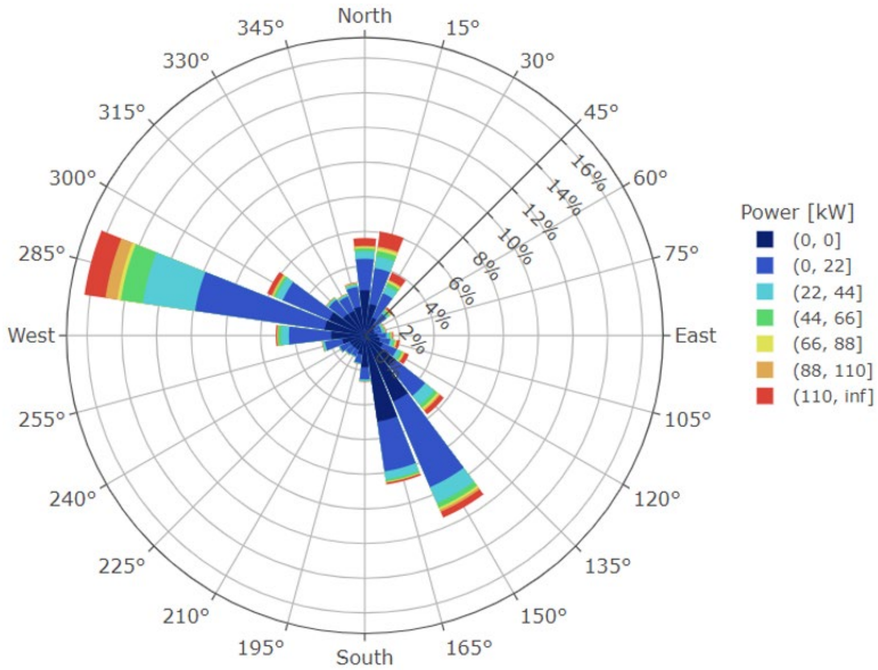


Figure 28 – WEC power rose

5.2.5 WEC Energy Production

Figure 29 represents the average annual energy concerning each sea state, i.e., at each significant wave height - energy period pair.

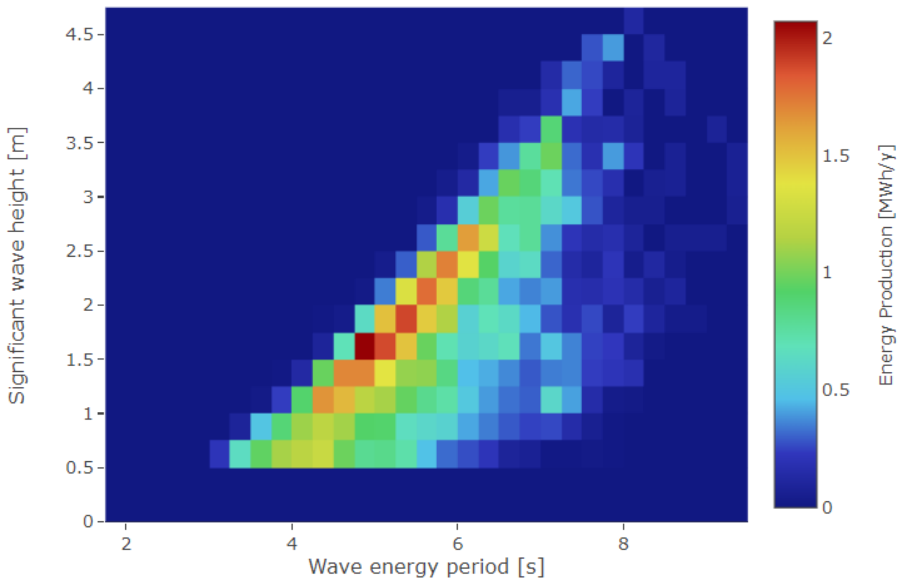


Figure 29 – WEC energy production

5.2.6 WEC Power Device

The user can view the matrix representing the chosen device as additional information. Figure 30 represents the device's electrical power about each sea state

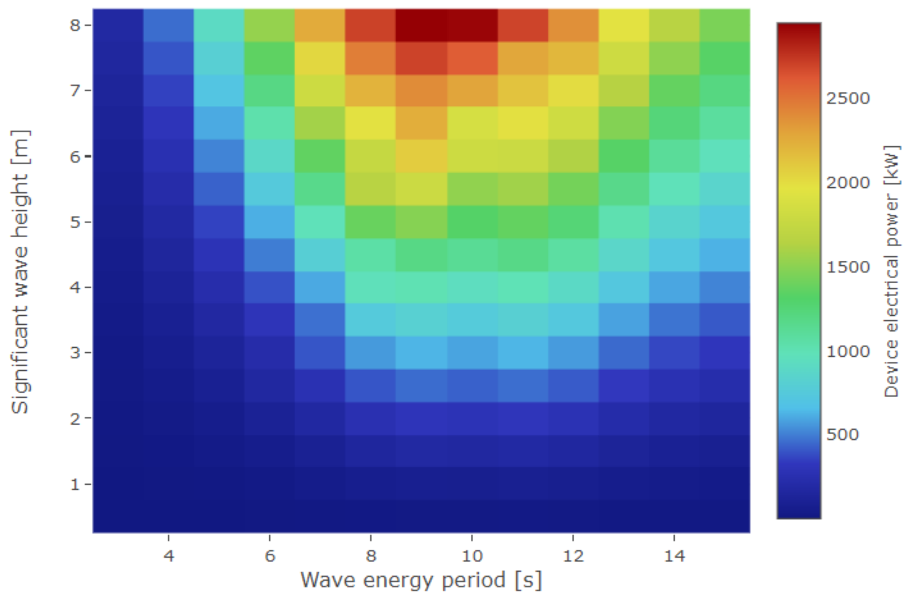


Figure 30 – WEC power device

Figure 31, on the other hand, provides the same information contained in Figure 30 but it is interpolated on the sea states occurring at the chosen site.

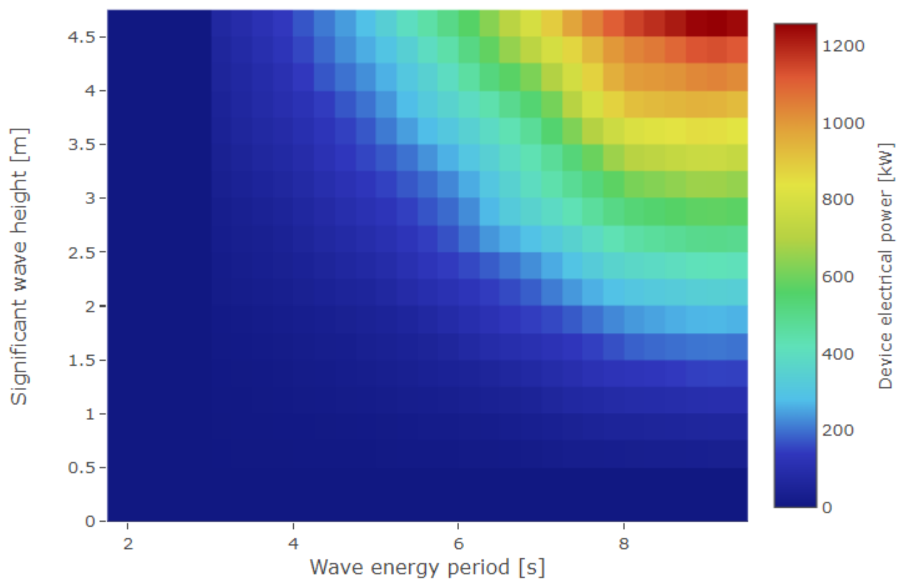


Figure 31 – Interpolated WEC power device

5.3 Wind Energy Resource

The wind resource evaluation is based on several algorithms that use wind parameters (Wind Speed) and wave parameters (Hs, Te). Each algorithm provides a figure which summarizes the main results.

Once the site of interest has been selected, the analysis regarding the wind resource is carried out considering 10 years of wind data.

The graphical interface allows the visualization of the following graphs:

- Probability distribution of wind power density and wind speed
- Monthly variability of wind power density and wind speed
- Yearly variability of wind power density and wind speed
- Wind power density rose and wind speed rose

In addition, it is possible to select the year(s) of interest and the month(s) for which the analysis is to be performed.

5.3.1 Distribution Plot

Figure 32 and Figure 33 are distribution plots showing the probability distribution of the corresponding parameter. The probability distribution show synthetically which values occur more frequently and are therefore more probable. To further indicate, the average value of the chosen parameter is also provided.

In particular, the main parameters analysed are wind power density (Figure 32) and wind speed (Figure 33).

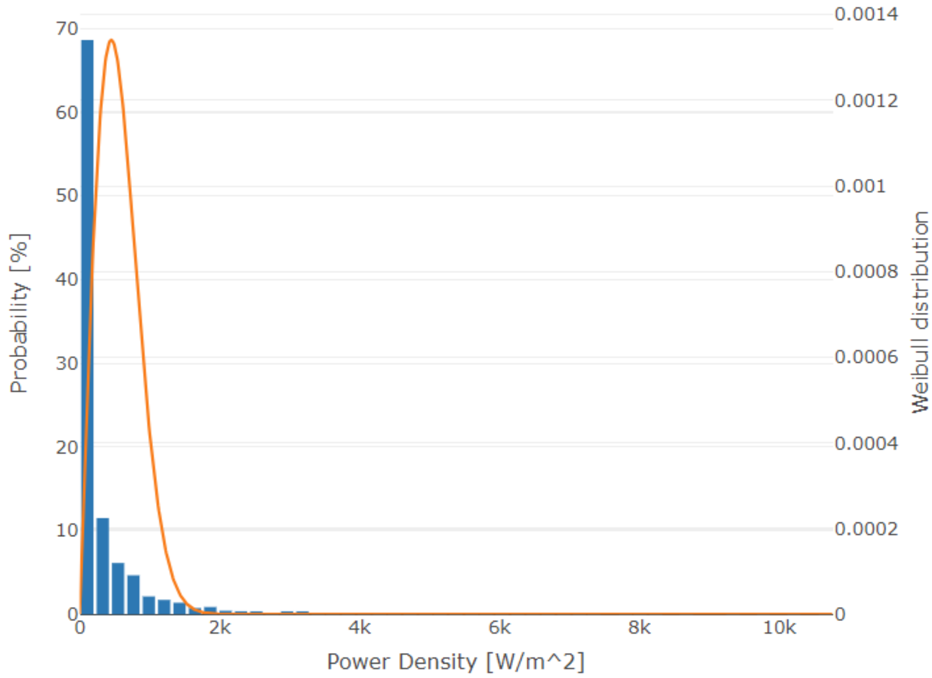


Figure 32 – Wind power density distribution plot

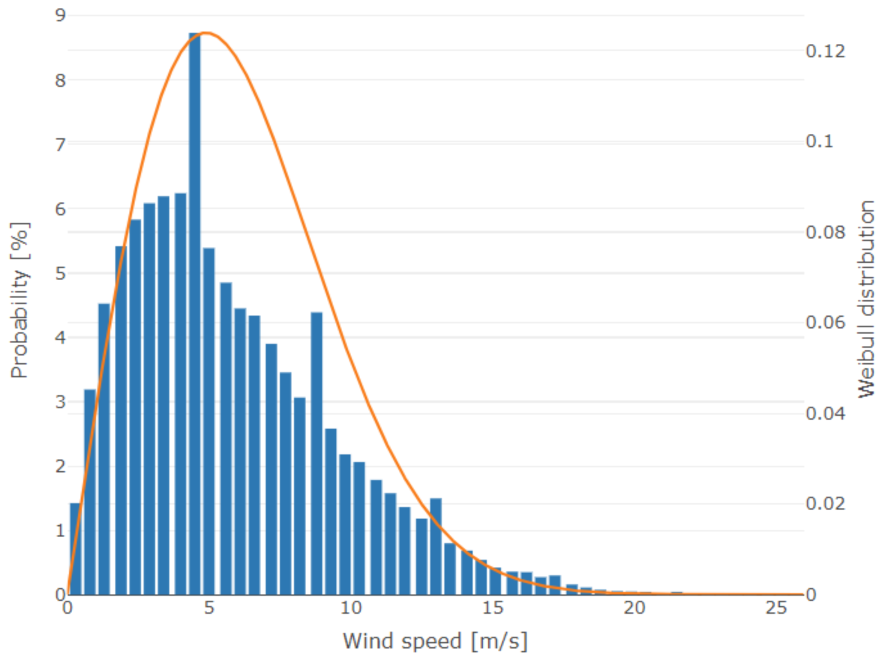


Figure 33 – Wind speed distribution plot

The related algorithms are reposted in the Appendix "Mathematical background".

5.3.2 Monthly Resource Data

In order to evaluate the monthly variability of power, wind speed and wind power density, the user can view the graph of Figure 34 and Figure 35 respectively, in which both the 5th and 95th percentile, as well as the average value, are reported. Moreover, the maximum value can be identified as the value corresponding to the height of the bar of the respective month. In order to visually show the distribution of the values, a point cloud is also shown, which is a representative sample of the values for the respective month.

Figure 34 and Figure 35 represent the monthly variability of the wind power density and the wind speed considering the period from 2010 up to 2019.

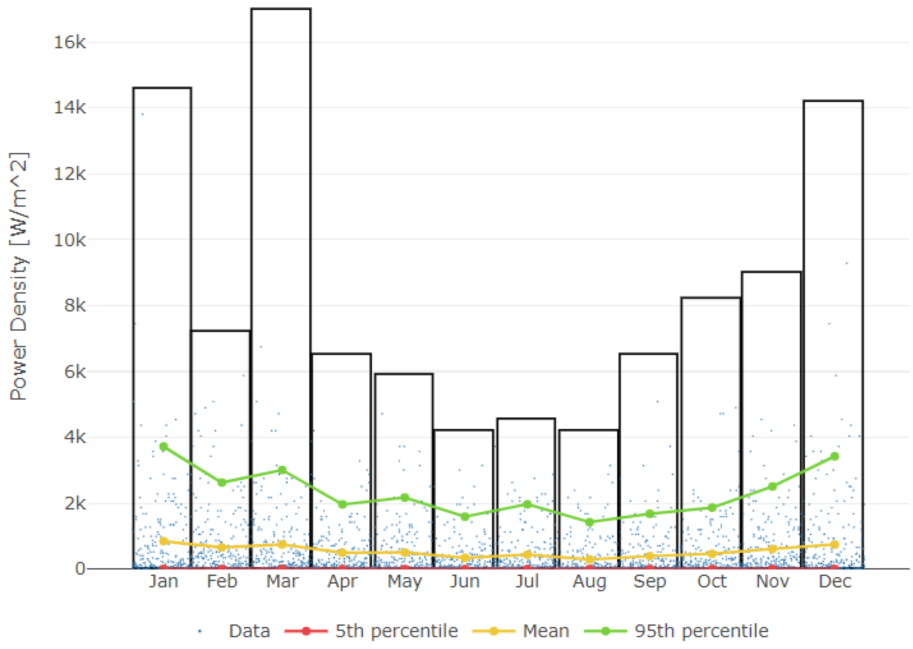


Figure 34 – Wind power density monthly variability

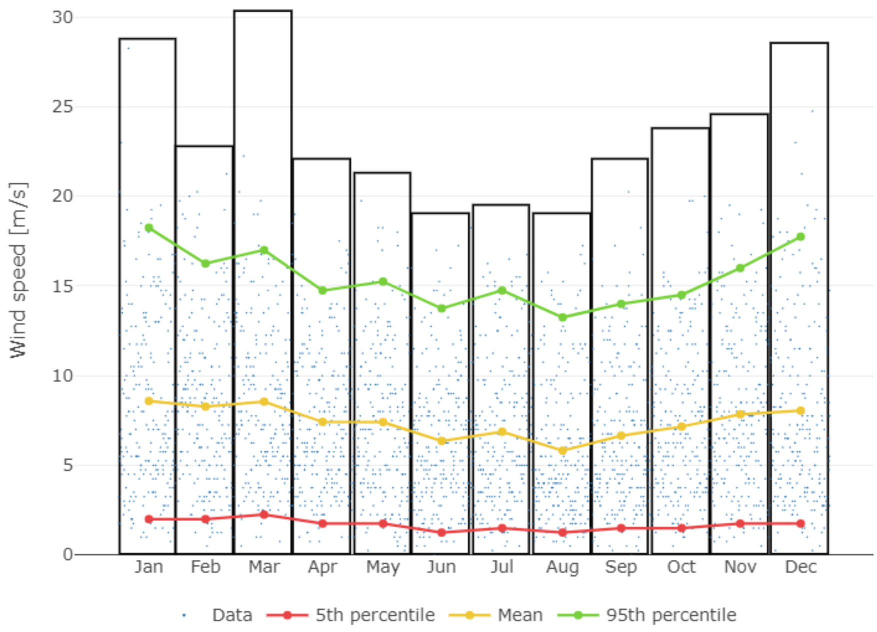


Figure 35 – Wind speed monthly variability

The correlated algorithms are reposted in the Appendix "Mathematical background".

5.3.3 Yearly Resource Data

In order to evaluate the yearly variability of wind power density and wind speed, the user can view the graph of Figure 36 and Figure 37, respectively, in which both the 5th and 95th percentiles are shown, as well as the average value. The maximum value, moreover, can be identified as the value corresponding to the height of the bar of the respective year. To visually show the distribution of values, a point cloud is also shown representing a representative sample of the values corresponding to the respective year.

Figure 36 and Figure 37 represent the annual variability of the wind power density and wind speed considering the period from 2010 up to 2019.

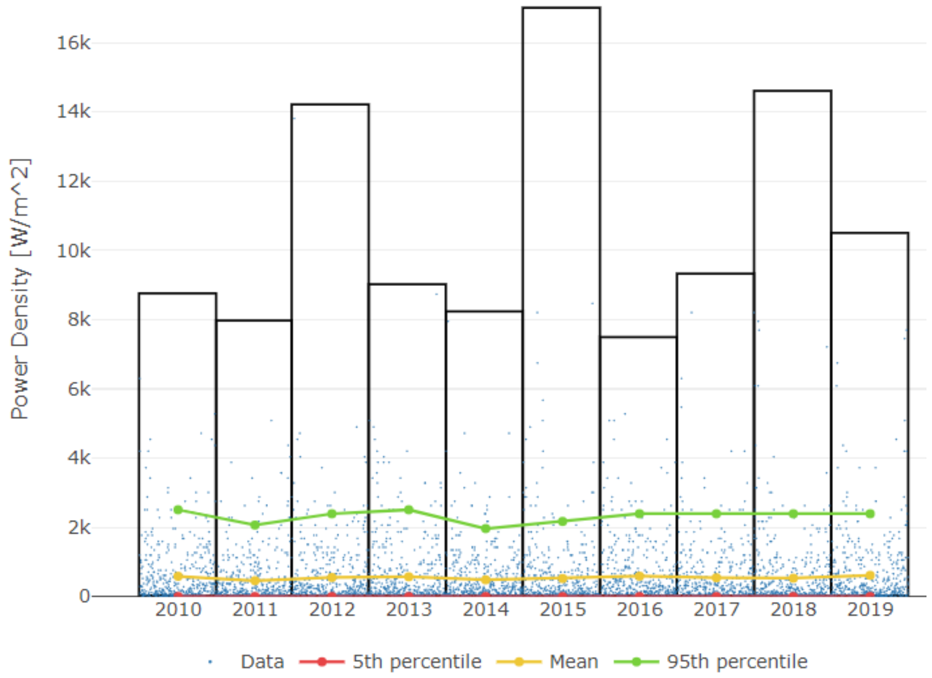


Figure 36 – Wind power density yearly variability

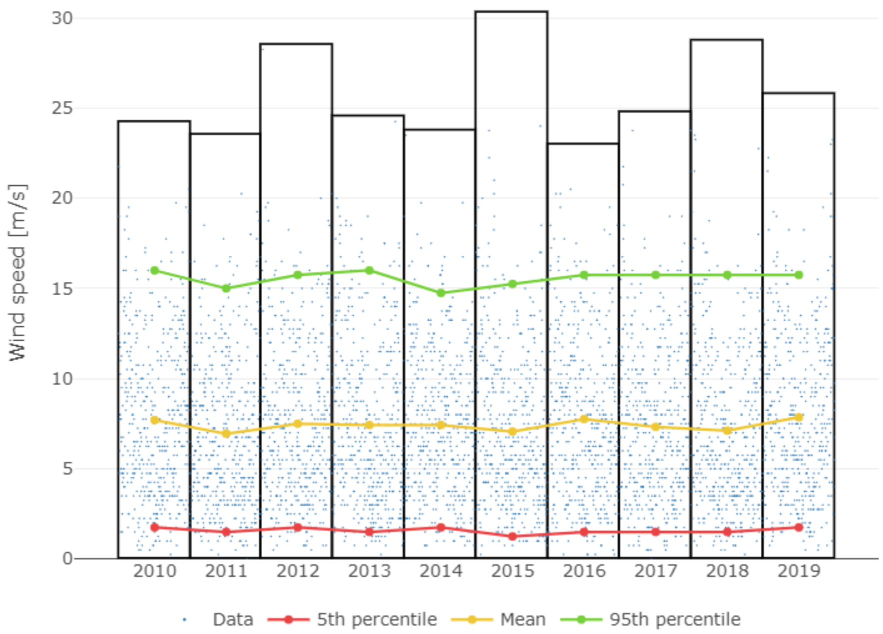


Figure 37 – Wind speed yearly variability

The correlated algorithms are reposted in the Appendix "Mathematical background".

5.3.4 Wind Power Density Rose and Wind Speed Rose

Since the wind direction is highly variable in many offshore sites, the wind rose has been reported for both wind speed (Figure 38).

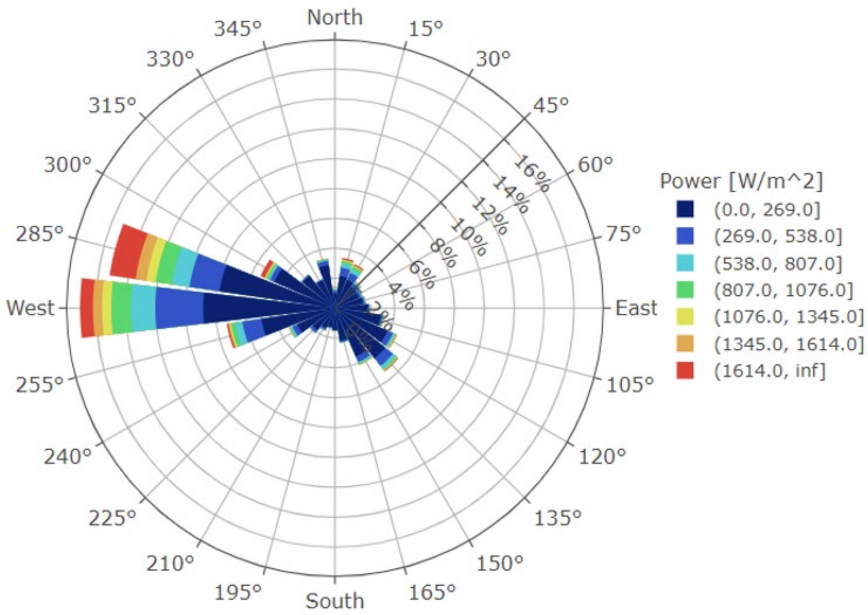


Figure 38 – Wind speed rose

The correlated algorithms are reposted in the Appendix "Mathematical background".

5.4 Wind Turbine Productivity

After selecting the site and analyzing the resource, the user has the option to estimate productivity. The user can select a turbine from those available with which to carry out subsequent analyzes.

The technical information reported for each turbine include:

- Name
- Power rating
- Class
- Rotor diameter
- Hub height
- Cut-in speed
- Cut-off speed
- Power curve

Once the device has been chosen, it is possible to save the project and view the graphs and results regarding productivity. These graphs are:

- Occurrences Matrix
- Power Matrix
- Energy Matrix

5.4.1 Wind Occurrence Matrix

Figure 39 represents the most probable combinations of wave height Hs, period Te and wind speed for the considered site. The frequency of these triplets is shown in the coloured bar on the side, passing from the least probable (in blue colour) to the most probable ones (in red colour). This information can be downloaded from the website: this allows you to identify the most necessary combinations for a site and is particularly important for running simulations.

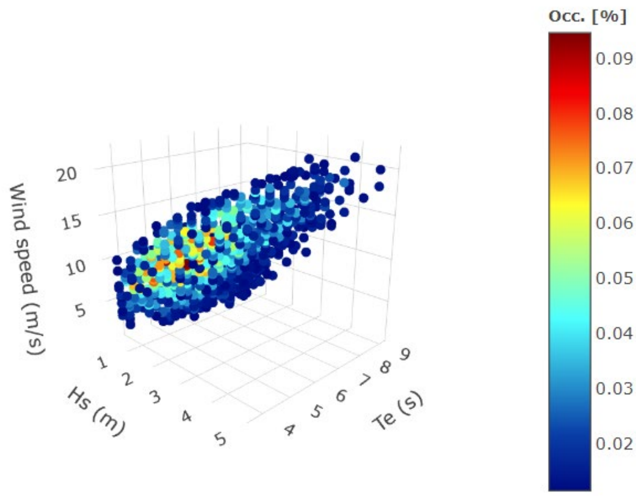


Figure 39 – Occurrences

The correlated algorithms are reposted in the Appendix "Mathematical background".

5.4.2 Wind Power Matrix

Figure 40 represents the wind turbine mean power as a function of the wave height Hs, the period Te and the wind speed. As a result, the most productive triplets are easily identified. Furthermore, the platform allows the calculation of the average power of the turbine at the chosen location, considering all the triplets.

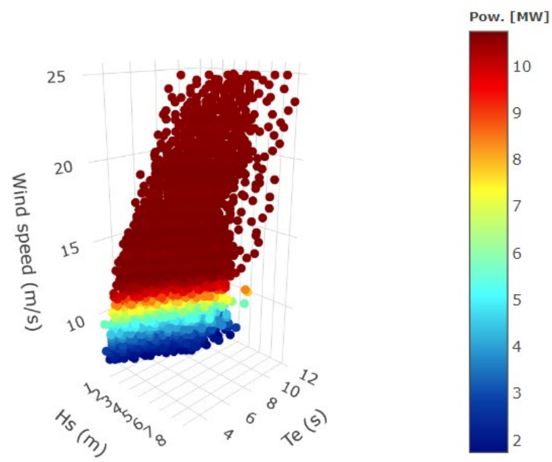


Figure 40 – Wind turbine mean power

The correlated algorithms are reposted in the Appendix "Mathematical background".

5.4.3 Wind Energy Matrix

Figure 41 represents the energy produced by the wind turbine as a function of the wave height Hs, the period Te and the wind speed V. As a result, the most energetic triplets are easily identified. Furthermore, the platform allows the calculation of the average power of the turbine in the chosen site, considering all the triplets.

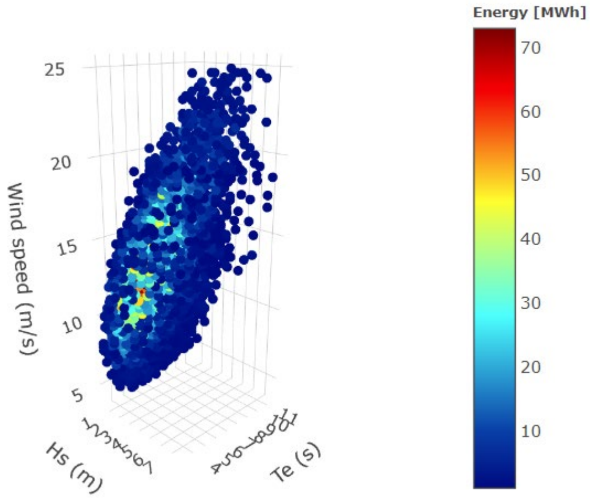


Figure 41 – Wind turbine energy produced

The correlated algorithms are reposted in the Appendix "Mathematical background".

6 Tutorial

A video tutorial is available at http://www.morenergylab.polito.it/more-est-platform/ and at https://youtu.be/elmPl_cbatY .

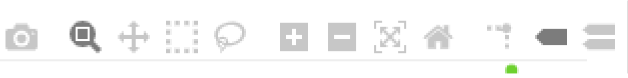
The following are the steps the user should take to carry out his or her analysis:

1. Access the page via (All pages can be accessed from)
2. Click on the Map window to access various services
   a. Measurement: you can calculate the distances between two or more points:
      i. Click on the measurement icon : at each corner, there is the distance from the previous point (top) and the total distance from the starting point (bottom). More than one polygon can be drawn.
      ii. Corner points of the line/polygon can be dragged to update the measurement, as well as deleted (shift + right click)
      iii. Press ESC to stop measuring
      iv. Click on to stop measuring
   b. Layers: bathymetric trend, average significant wave height, and various human activities can be visualized
      i. Bathymetry is always present (shown if distance < 50km OR depth <1000m). Here is where metocean analysis can be performed.
      ii. Click on to see additional layers
      iii. Click on a point on the map to receive information from any of the active layers.
   c. Select a point to start the simulation
      i. Select a point on the map:
         1. Either by clicking on an area where there is the bathymetry layer or by typing the coordinates in the bottom right and clicking on the search button
         2. Then click on Start Simulation
         3. The platform sends the user to a new page to “Create a new case” of analysis

Alternatively, the user can start from a case already simulated

        a. Here all saved cases are Stored, in 

        b. And there is the option to create a new case: 

    ii. Navigate through the different tabs, examine the charts with the provided graphical functions , download either the chart or the underlying table

d. By clicking Next, it will be possible to choose the technology: in the open access version, only the default portfolio of technologies is available, so no new technology can be added. Different information about the technology are provided:
    i. Sensitivity to Direction:
        1. If “No”, it means that the device performs in the same way, regardless of the incoming wave direction.
        2. If “Yes”, it means that the performance of the device is different according to the relative alignment between the device and the wave direction. Different power matrices are provided for different wave directions. The platform optimally aligns the device with respect to the main wave direction at the specific site.
    ii. Depth:
        1. The min and max depths are provided as a rough reference and do not affect the calculation
    iii. Click Next to assign a label and include the case in an existing of a new project

e. The platform automatically runs the analysis () and directly takes the user to the Results window 

    i. Results are shown for the Resource 

(metocean data) and the device productivity 

3. Simulated results can be accessed at the Cases tab 
    a. Here it is possible to create new cases (and follow the entire workflow above), or Open, Delete, or Duplicate and view past cases, or Modify  the label of a past case
    b. It is possible to re-run a case with a different technology. A suggested workflow is the following:
        i. (Optional): Select and duplicate an existing Case, then Modify its name
        ii. Select and Open the Case
        iii. Select Analysis  from the menu
        iv. Select a different technology and click Run 

, then Run the simulation

7 Terms and Conditions

Please refer to the Terms and Conditions document, available on the platform.

8 Credits

ECMWF ERA5

Hersbach, H. et al., (2018) was downloaded from the Copernicus Climate Change Service (C3S) Climate Data Store.

The results contain modified Copernicus Climate Change Service information 2020. Neither the European Commission nor ECMWF is responsible for any use that may be made of the Copernicus information or data it contains.

EMODnet Bathymetry

The bathymetric metadata and Digital Terrain Model data products have been derived from the EMODnet Bathymetry portal - http://www.emodnet-bathymetry.eu.

EMODnet Bathymetry Consortium (2020): EMODnet Digital Bathymetry (DTM).

https://doi.org/10.12770/bb6a87dd-e579-4036-abe1-e649cea9881a

This concerns the current EMODnet DTM version of December 2020, which has a resolution of 1/16 * 1/16 arc minutes.

EMODnet Human Activities

Data used in this platform was made available by the EMODnet Human Activities project, www.emodnet-humanactivities.eu, funded by the European Commission Directorate General for Maritime Affairs and Fisheries.

9 Contact

morenergylab@polito.it

Appendix

Mathematical background

1. Distribution Plot

The variable of interest is called X and can be the wave power $P_{wave}[kW/m]$, the significant wave height $H_S[m]$, the wave energy period $T_e[s]$, the wind power density $P_{wind}[W/m^2]$ or the wind speed $V[m/s]$.

$$X = [x_{1,}x_2, \dots, x_{N-1}, x_N]$$

The mathematical steps are:

a. Calculate the total number of values of the variable X

$$N_x$$

b. Calculate the maximum and minimum value of the variable X

$$x_{min} = \min(X)$$

$$x_{max} = \max(X)$$

c. Define the number of categories of normalized distribution plot

$$N_c$$

d. Calculate the width of the categories

$$\Delta_x = \frac{x_{max} - x_{min}}{N_x}$$

e. Calculate the extreme values of each i-th category

$$C_{ex} = [x_{min}, x_{min} + \Delta_x, \dots, x_{min} + (N_c - 1)\,\Delta_x, x_{min} + N_c\Delta_x]$$

f. Calculates the number of values corresponding to each i-th category

$$N_{C\,i}$$

g. Calculate the frequency for each i-th category

$$F_i = \frac{N_{C_i}}{N_x}$$

h. Calculate the probability for each i-th category

$$P_i = F_i 100\%$$

2. Monthly Resource Data

The variable of interest is called X and can be the wave power $P_{wave}[kW/m]$, the significant wave height $H_S[m]$, the wave energy period $T_e[s]$, the wind power density $P_{wind}[W/m^2]$ or the wind speed $V[m/s]$. Each of these variables refers to a specific time t (it is therefore unequivocally identifiable by a specific hour h, a specific day d, a specific month m and a specific year y):

$$X = [x_{1,}x_2, \dots, x_{N-1}, x_N]$$

The mathematical steps are:

a. Group the values of the variable X into 12 new variables (one for each corresponding month of occurrence m)

$$X = \{X_1, \dots, X_m, \dots, X_{12}\}$$

b. Calculate the mean values of the 12 new variables

$$x_{mean_m} = \mathrm{mean}(X_m)$$

c. Calculate the 5th percentile and 95th percentile for the 12 new variables

   i. Calculate the total number of values of the variable X_m

$$N_{x_m}$$

   ii. Sort the N_{x_m} values in ascending order

$$X_m = sort(X_m)$$

d. Calculate the 5th percentile and 95th percentile positions

$$K_{5th} = N_{x_m} 0.05$$

$$K_{95th} = N_{x_m} 0.95$$

NOTE:

If K is not an integer, round up

$$K_{5th} = round(K_{5th\,old}) \rightarrow x_{m_{5th}} = X_m(K_{5th})$$

$$K_{95th} = round(K_{95th\,old}) \rightarrow x_{m_{95th}} = X_m(K_{95th})$$

If K is an integer you have to average between the values of K-th and the K-th +1

$$x_{m_{5th}} = \frac{X_m(K_{5th}) + X_m(K_{5th} + 1)}{2}$$

$$x_{m_{95th}} = \frac{X_m(K_{95th}) + X_m(K_{95th} + 1)}{2}$$

3. Yearly Resource Data

The variable of interest is called X and can be the wave power $P_{wave}[kW/m]$, the significant wave height $H_S[m]$, the wave energy period $T_e[s]$, the wind power density $P_{wind}[W/m^2]$ or the wind speed $V[m/s]$. Each of these variables refers to a specific time t (it is therefore unequivocally identifiable by a specific hour h, a specific day d, a specific month m and a specific year y):

$$X = [x_{1,}x_2, \dots, x_{N-1}, x_N]$$

The mathematical steps are:

a. Group the values of parameter X into 10 new variables (one for each corresponding year of occurrence y)

$$X = \{X_1, \dots, X_y, \dots, X_{10}\}$$

b. Calculate the mean values of the 10 new variables

$$x_{mean_y} = \text{mean}(X_y)$$

c. Calculate the 5th percentile and 95th percentile for the 10 new variables

i. Calculate the total number of values of the variable X_y

$$N_{x_y}$$

ii. Sort the N_{x_y} values in ascending order

$$X_y = sort(X_y)$$

d. Calculate the 5th percentile and 95th percentile positions

$$K_{5th} = N_{x_y} 0.05$$

$$K_{95th} = N_{x_y} 0.95$$

NOTE:

If K is not an integer, round up

$$K_{5th} = round(K_{5th\,old}) \rightarrow x_{y_{5th}} = X_y(K_{5th})$$

$$K_{95th} = round(K_{95th\,old}) \rightarrow x_{y_{95th}} = X_y(K_{95th})$$

If K is an integer you have to average between the values of K-th and the K-th +1

$$x_{y_{5th}} = \frac{X_y(K_{5th}) + X_y(K_{5th} + 1)}{2}$$

$$x_{y_{95th}} = \frac{X_y(K_{95th}) + X_y(K_{95th} + 1)}{2}$$

4. Monthly Wave energy

The variable of interest is the average hourly power per wave meter $P[kW/m]$.

$$P = [P_{1,}P_2, \dots, P_{N-1}, P_N]$$

The mathematical steps are:

a. Group the P parameter values into 12x10 new variables (one per month m of each year y corresponding to the event)

$$P = \{P_{1,2010}, \dots, P_{m,y}, \dots, P_{12,2019}\}$$

b. Calculate the monthly wave energy for each year $E_{m,y}$ $[MWh/m]$ as the sum of their respective hourly average powers per wave meter

$$E_{m,y}$$

c. Transform from [kWh/m] to [MWh/m] by dividing by 1000

$$E_{m,y}[MWh/m] = E_{m,y}[kWh/m]/1000$$

d. Calculate the mean, minimum and maximum energy of each month

$$E_{m_{mean}} = \text{mean}\ (E_{m,y})$$

$$E_{m_{min}} = \text{min}\ (E_{m,y})$$

$$E_{m_{max}} = \text{max}\ (E_{m,y})$$

5. Yearly Wave Energy

The variable of interest is the average hourly power per wave meter P_{wave}[kW/m].

$$P = [P_{1,}P_2, \dots ,P_{N-1}, P_N]$$

The mathematical steps are:

a. Group the P parameter values into 10 new variables (one per year y corresponding to the event)

$$P = \{P_{2010}, \dots, P_y, \dots, P_{2019}\}$$

b. Calculate the yearly wave energy E_y [KWh/m] as the sum of their respective hourly average powers per wave meter

$$E_{m,y}$$

c. Transform from [kWh/m] to [MWh/m] by dividing by 1000

$$E_y[MWh/m] = E_y[kWh/m]/1000$$

6. Wave And Wind Power Rose

The variables of interest are called X and Y and can be the wave power $P_{wave}[kW/m]$ and the mean wave direction $Dir_{m_{wave}}[degree]$, or can be the wind power density $P_{wind}[W/m^2]$, the wind speed $V[m/s]$ and the mean wind direction $Dir_{m_{wind}}[degree]$, respectively.

$$X = [x_{1,}x_2, \dots ,x_{N-1}, x_N]$$

$$Y = [y_{1,}y_2, \dots ,y_{N-1}, y_N]$$

The mathematical steps are:

a. Calculate the total number of values of the variable Y

$$N_Y$$

b. Define the number of categories of the variable Y

$$N_c$$

c. Calculate the width of the categories

$$\Delta_Y = \frac{360°}{N_c}$$

d. Calculate the extreme values of each i-th category

$$C_{ex} = \left[0, \Delta_Y, \dots, (N_c - 1)\ \Delta_Y\ \right]$$

e. Calculate the number of values of the variable Y for each i-th category

$$N_{C_i}$$

f. Calculate the number of frequencies for each i-th category

$$F_{Y_i} = \frac{N_{C_i}}{N_Y}$$

g. Calculate the probability for each i-th category

$$P_{Y_i} = F_{Y_i} 100\%$$

h. Calculate the probability of the variable X for each i-th category of the variable Y

$$P_{X_i}$$

7. Wave Occurrences Matrix

The variables of interest are called X and Y and are the significant wave height $H_S[m]$ and the wave energy period $T_e[s]$.

$$X = [x_{1,} x_2, \dots, x_{N-1}, x_N]$$

$$Y = [y_{1,} y_2, \dots, y_{N-1}, y_N]$$

The mathematical steps are:

a. Associate each X with the reference Y, so each (X, Y) pair identifies a sea state

b. Calculate the total number of values of the variable X

$$N_x$$

c. Calculate the maximum and minimum value of the variable X and Y

$$x_{min} = \min(X)$$

$$x_{max} = \max(X)$$

$$y_{min} = \min(Y)$$

$$y_{max} = \max(Y)$$

d. Calculate the number of categories according to a width (usually Δ_x=0.25 m and Δ_y=0.25 s)

$$N_{x_c} = \frac{x_{max} - x_{min}}{\Delta_x}$$

$$N_{y_c} = \frac{y_{max} - y_{min}}{\Delta_y}$$

e. Calculate the extreme values of each i-th category

$$C_{X_{ex}} = \left[x_{min}, x_{min} + \Delta_x, \dots, x_{min} + \left(N_{x_c} - 1\right) \Delta_x, x_{min} + N_{x_c} \Delta_x\right]$$

$$C_{Y_{ex}} = \left[y_{min}, y_{min} + \Delta_y, \dots, y_{min} + \left(N_{y_c} - 1\right) \Delta_y, y_{min} + N_{y_c} \Delta_y\right]$$

f. Calculate the number of values for each category pair $(C_{X_{ex}}, C_{Y_{ex}})$

$$N_{C_i}$$

g. Calculate the number of frequencies for each i-th category

$$F_i = \frac{N_{C_i}}{N_x}$$

h. Calculate the probability for each i-th category

$$P_i = F_i 100\%$$

8. Wave Power Matrix

The variables of interest are called X, Y and Z and are the significant wave height $H_S[m]$, the wave energy period $T_e[s]$ and the wave power $P_{wave}[kW/m]$.

$$X = [x_{1,} x_2, \dots, x_{N-1}, x_N]$$

$$Y = [y_{1,} y_2, \dots, y_{N-1}, y_N]$$

$$Z = [z_{1,} z_2, \dots, z_{N-1}, z_N]$$

The mathematical steps are:

a. Associate each X with the reference Y and Z, so each (X, Y, Z) triad identifies a sea state

b. Calculate the total number of values of the variable X

$$N_x$$

c. Calculate the maximum and minimum value of the variable X and Y

$$x_{min} = \min(X)$$

$$x_{max} = \max(X)$$

$$y_{min} = \min(Y)$$

$$y_{max} = \max(Y)$$

a. Calculate the number of categories according to a width (usually Δ_x=0.25 m and Δ_y=0.25 s)

$$N_{x_c} = \frac{x_{max} - x_{min}}{\Delta_x}$$

$$N_{y_c} = \frac{y_{max} - y_{min}}{\Delta_y}$$

b. Calculate the extreme values of each i-th category

$$C_{X_{ex}} = \left[x_{min}, x_{min} + \Delta_x, \dots, x_{min} + \left(N_{x_c} - 1\right)\Delta_x, x_{min} + N_{x_c}\Delta_x\right]$$

$$C_{Y_{ex}} = \left[y_{min}, y_{min} + \Delta_y, \dots, y_{min} + \left(N_{y_c} - 1\right)\Delta_y, y_{min} + N_{y_c}\Delta_y\right]$$

c. Sum the Z values for each corresponding category $(C_{X_{ex}}, C_{Y_{ex}})$

$$E_{X,Y}$$

d. Divide each $E_{X,Y}$ value by the number of years of analysis, i.e., 10, to get the average annual energy of each sea state

$$E_{X,Y_{mean}} = \frac{E_{X,Y}}{10}$$

d. Transform from [kWh/m] to [MWh/m] by dividing by 1000

$$E_{X,Y_{mean}}[MWh/m] = E_{X,Y_{mean}}[kWh/m]/1000$$

e. Add up the energy values for each (X, Y) pair to get the annual average energy value

$$E_{mean} = \sum_{i}^{X}\sum_{j}^{Y} E_{X,Y_{mean}}$$