SAFE WAVE
STREAMLINING THE ASSESSMENT OF ENVIRONMENTAL EFFECTS OF WAVE ENERGY

DELIVERABLE 3.2
Sound propagation modelling

This Project is co-funded by the European Climate, Infrastructure and Environment Executive Agency (CINEA)

WP 3

Deliverable 3.2 Sound Propagation Modelling

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SAFE WAVE project synopsis

The European Atlantic Ocean offers a high potential for marine renewable energy (MRE), which is targeted to be at least 32% of the EU's gross final consumption by 2030 (European Commission, 2020). The European Commission is supporting the development of the ocean energy sector through an array of activities and policies: the Green Deal, the Energy Union, the Strategic Energy Technology Plan (SET-Plan) and the Sustainable Blue Economy Strategy. As part of the Green Deal, the Commission adopted the EU Offshore Renewable Energy Strategy (European Commission, 2020) which estimates to have an installed capacity of at least 60 GW of offshore wind and at least 1 GW of ocean energy by 2030, reaching 300 GW and 40 GW of installed capacity, respectively, moving the EU towards climate neutrality by 2050.

Another important policy initiative is the REPowerEU plan (European Commission, 2022) which the European Commission launched in response to Russia's invasion of Ukraine. REPowerEU plan aims to reduce the European dependence amongst Member States on Russian energy sources, substituting fossil fuels by accelerating Europe's clean energy transition to a more resilient energy system and a true Energy Union. In this context, higher renewable energy targets and additional investment, as well as introducing mechanisms to shorten and simplify the consenting processes (i.e., 'go-to' areas or suitable areas designated by a Member State for renewable energy production) will enable the EU to fully meet the REPowerEU objectives.

The nascent status of the Marine Renewable Energy (MRE) sector and Wave Energy (WE) in particular, yields many unknowns about its potential environmental pressures and impacts, some of them still far from being completely understood. Wave Energy Converters' (WECs) operation in the marine environment is still perceived by regulators and stakeholders as a risky activity, particularly for some groups of species and habitats.

The complexity of MRE licensing processes is also indicated as one of the main barriers to the sector development. The lack of clarity of procedures (arising from the lack of specific laws for this type of projects), the varied number of authorities to be consulted and the early stage of Marine Spatial Planning (MSP) implementation are examples of the issues identified to delay projects' permitting.

Finally, there is also a need to provide more information on the sector not only to regulators, developers and other stakeholders but also to the general public. Information should be provided focusing on the ocean energy sector technical aspects, effects on the marine environment, role on local and regional socio-economic aspects and effects in a global scale as a sector producing clean energy and thus having a role in contributing to decarbonise human activities. Only with an informed society would be possible to carry out fruitful public debates on MRE implementation at the local level.

These non-technological barriers that could hinder the future development of WE in EU, are being addressed by the WESE project funded by European Maritime and Fisheries Fund (EMFF) in 2018. The present project builds on the results of the WESE project and aims to move forward through the following specific objectives:

1. Development of an **Environmental Research Demonstration Strategy** based on the collection, processing, modelling, analysis and sharing of environmental data collected in WE sites from different European countries where WECs are currently operating (Mutriku power plant and BIMEP in Spain, Aguçadoura in Portugal and SEMREV in France); the SafeWAVE project aims to enhance the understanding of the negative, positive and negligible effects of WE projects. The SafeWAVE project will continue previous work, carried out under the WESE project, to increase the knowledge on priority research areas, enlarging the analysis to other types of sites, technologies and countries. This will increase information robustness to better inform decision-makers and managers on real environmental risks, broaden the engagement with relevant stakeholders, related sectors and the public at large and reduce environmental uncertainties in consenting of WE deployments across Europe.

2. Development of a **Consenting and Planning Strategy** through providing guidance to ocean energy developers and to public authorities tasked with consenting and licensing of WE projects in France and Ireland; this strategy will build on country-specific licensing guidance and on the application of the MSP decision support tools (i.e. WEC-ERA[1] by Galparsoro et al., 2021[2] and VAPEM[3] tools) developed for Spain and Portugal in the framework of the WESE project; the results will complete guidance to ocean energy developers and public authorities for most of the EU countries in the Atlantic Arch.
3. Development of a **Public Education and Engagement Strategy** to work collaboratively with coastal communities in France, Ireland, Portugal and Spain, to co-develop and demonstrate a framework for education and public engagement (EPE) of MRE enhancing ocean literacy and improving the quality of public debates.

[1] https://aztidata.es/wec-era/;
[2] Galparsoro, I., M. Korta, I. Subirana, Á. Borja, I. Menchaca, O. Solaun, I. Muxika, G. Iglesias, J. Bald, 2021. A new framework and tool for ecological risk assessment of wave energy converters projects. Renewable and Sustainable Energy Reviews, 151: 111539
[3] https://aztidata.es/vapem/

Glossary

dB	Decibel
EMFF	European Maritime and Fisheries Fund
EU	Europe Union
f	Frequency [Hz]
H	Significant wave height
IQR	Interquartile range
LOBE	Level of Onset for Biological Effect
Q1	Quartile 25
Q2	Quartile 50 (median)
Q3	Quartile 75
Ω	Average RPM across all turbines of the Mutriku power plant
RPM	Revolutions per minute
SPL	Sound Pressure Level
SL	Source Level
TL	Transmission Losses
SSP	Sound Pressure Profile
TL	Transmission Losses
TX.Y.	Task X.Y.
WEC	Wave Energy Converter
WP	Work Package

Executive summary

This deliverable contains the methodology and results from Task 3.2 of SafeWAVE project (Acoustic Modelling), which essentially is about the modelling of underwater sound propagation with the results obtained in Task 2.3 Acoustic Monitoring. For the project, 4 WEC systems in 4 different test sites were studied. The 4 locations were: **Aguçadoura** (Portugal), **BiMEP** (Spain), **Mutriku** (Spain) and **SEM-REV** (France).

For **Aguçadoura**, the highest acoustic disturbance distance obtained was 2.5 km for the 125 Hz component for the [2, 2.5) wave height bin, and the highest SL obtained was 174 dB, surpassing both 120 dB and 160 dB impact thresholds specified by the U.S. National Marine Fisheries Service for continuous and impulsive sounds respectively (NMFS, 2024). For the acoustic propagation maps, the SPL was calculated for the commissioning phase and it was seen that for all frequencies (62.5 Hz, 125Hz and 1000 Hz) it dropped below 120 dB within the first 10 meters. No operational data was obtained, so it does not fully represent the WEC's real state.

For **BiMEP**, the PENGUIN II WEC had a maximum Source Level (SL) of 146 dB re 1 m for the 62,5 Hz component for the [4, 8) wave height bin, which also surpass the 120 dB threshold for continuous sound. Nevertheless, when studying the propagation maps, the SPL dropped below 120 dB threshold (NMFS, 2024) within the first 10 meters for any of the frequencies (62.5 Hz, 125Hz and 1000 Hz) analyzed. When considering 2 devices (the ones needed for 1200kw), the affected area was estimated as follows: 3 km for 63 Hz and 125 Hz and 6 km for 1000 Hz.

For **Mutriku**, in Task 2.3 there was a hydrophone failure, and only two hydrophones gathered data. This case is the most different one out of the four WECs, as Mutriku is an onshore power plant, and can't be categorized as a source that has "On" and "Off" states. In this case, the highest SL obtained was around 190 dB in the 62,5 Hz and 125 Hz frequencies for the [2, 2.5) wave height bin, surpassing also the 120 dB dB threshold (NMFS, 2024). However, it is suspected that the models introduced some artifacts

in the calculation of the TL, as the SPL obtained in Task 2.3 showed coherent values, and the losses were unusually high. Bearing this in mind, for low frequencies (62.5 Hz, 125 Hz) it was found that 120db threshold dropped at 50 meters from the source, while for high frequencies (1000Hz) it did at 70 meters from the source.

Finally, for **SEM-REV**, also one hydrophone failed when obtaining the acoustic data in Task 2.3. This, combined with the lack of operational data, did not allow for a good characterization of the WEC signature depending of the WEC states. For the propagation maps, all frequencies (62.5 Hz, 125Hz and 1000 Hz), the SPL dropped below 120 dB threshold (NMFS, 2024) within the first 10 meters. On the other hand, when it is considered 8 devices (to reach 1200 kW), the affected area was estimated as follows: 30 meters for 63 Hz, 6 km for 125 Hz (with an average of 2 km), and 7.4 km for 1000 Hz.

Considering the impact threshold of 120 dB at SL (NMFS, 2024), it seems that all the studied WECs systems could negatively impact the cetaceans in all the studied areas at SL. Most of them significantly reduce these values within the first 10 meters, resulting in a relatively short affected area when compared to the entire acoustic map. However, to fully understand the potential ecological impact of the SLP obtained in this study and fully implement the impact assessment methodologies recommended by experts, such as TG-NOISE methodology, additional efforts are needed. It is essential to define the affected areas, identify the species present, and establish the LOBE for these species regarding the specificities of the production project (number of devices, operational regimes, etc). As offshore energy is expected to increase in the coming years, long-term studies are needed to fully understand the environmental impacts these new energy systems are having on the marine ecosystem.

1. Introduction

This deliverable collects all the information to execute Task 3.2 of Work Package 3: Sound propagation modelling. The objective is to simulate the underwater noise levels surrounding the studied WECs, determine their spatial influence on the noise background, as well as explore the acoustic effects of arrays of such devices in the operational mode.

First, the methodology implemented, and the data used are examined in section 2. Then, results on the Transmission Losses (TL) maps for each test site are simulated (section 3.1. Combining this information with the SPL results obtained in Deliverable 2.3 (Madrid et al., 2024), the Source Levels (SLs) of the different WECs are estimated (section 3.2). Following, using the SL and TL maps, Sound Pressure Level (SPL) maps are elaborated (section 3.3). Additionally, exceeding levels are calculated (section 3.4). Lastly, the effects of WECs arrays are explored (section 3.5).

Four different wave energy devices are studied in this project: CorPower Ocean's HiWave-5 (offshore, Aguçadoura test site), Wello's PENGUIN II (offshore, BiMEP test site), Mutriku power plant (onshore, Mutriku), and GEPS-TECHNO's WAVEGEM (offshore, SEM-REV test site). More information about these devices can be found in Deliverable 2.1 (Vinagre et al., 2021).

2. Methodology

A brief introduction to the mathematical models used in this study is given below. Additionally, the datasets used in the modelling are shown for each test site. The employed methodology to obtain the SPL maps and the derived metrics is also detailed. All the following results have been obtained using routines programmed in Python.

2.1 Acoustic propagation models

The spatiotemporal propagation of an acoustic wave is commonly described by the acoustic linear wave equation[4]:

$$\nabla^2 p(\vec{r},t) - \frac{1}{c^2}\frac{\partial^2 p(\vec{r},t)}{\partial t^2} = 0 \tag{1}$$

where $p(\vec{r},t)$ is the acoustic pressure at position $\vec{r}$ and time t, and c is the sound speed in the medium.

Because solving this equation directly with arbitrary boundary conditions is computationally intensive (e.g., finite difference/elements methods), some approximations are mandatory. Three of these approximations stand out: ray theory, normal modes, and parabolic equation approximation. They are suited for different conditions concerning the frequency under study, sea depth and range dependence (Wang, y otros, 2014). Ray theory models are usually best suited for high frequencies, while normal modes and parabolic equation models are more efficient for low frequencies.

Additionally, there are other types of models much more simplistic, denoted here as analytic models. These usually ignore some (if not all) of the environmental data (bathymetry, sound speed profile, seabed properties), allowing much faster calculations. Among these, the

[4] Actually, typical acoustic propagation models are based on approximations of this equation in the frequency space (the so-called Helmholtz equation).

spreading loss model is the most well-known, in which the transmission losses (TLs) are described solely as a function of distance, as follows:

$$\mathrm{TL}(r) = a\, log(r/r_{1m}) \quad \text{[dB re 1 m]} \tag{2}$$

where r is the radial distance from the source, r_{1m} is the reference distance (1 meter), and a is a coefficient that characterizes the spreading of wavefronts typically ranging between 20 (pure spherical propagation) and 10 (cylindrical wavefront propagation).

While TL is the main output of an acoustic propagation model, to obtain levels referenced to a certain source, they must be converted to sound pressure levels (SPL) for which the acoustic source level must be known. More details about this conversion can be found in section 5.2.

Regarding the simulations, a parabolic equation acoustic propagation model was used, and a Nx2D methodology was followed, which shall be explained in detail in section 2.5.

2.2 Source level assessment

To estimate the value of the source level (SL) of any WEC backpropagation is needed. That is, once the TLs between the source and the hydrophone locations are known, these can be combined with the already known SPL results (from Madrid et al, 2023) obtaining the SL as follows:

$$\mathrm{SL}(f) = \mathrm{SPL}(x, y, z, f) - \mathrm{TL}(x, y, z, f)$$

where x, y and z are the spatial coordinates, and f is the frequency.

It should be noted that the resulting value for the SL is most likely overestimated, as the SPL at any point in the vicinity of the WEC results from the superposition of the background noise and the WEC-related noise.

2.3 Environmental data

Detailed propagation models take into account data about the bathymetry, sound speed profile, and seabed composition of the site. These environmental parameters influence the transmission of acoustic waves by different mechanisms, as explained in the following sections. In what follows, it is assumed that the data have been interpolated to a common grid (the same in which the definitive noise maps will be eventually calculated) with a cell size of 100 meters.

The coordinates system used in this study is the Universal Transversal Mercator (UTM), specified in the considered zones: for BiMEP and Mutriku (Spain) and SEM-REV (France) test sites it corresponds to the Zone 30T, while for Aguçadoura test site (Portugal) the Zone is 29S. This projected coordinate system minimizes distortions within each zone.

2.3.1 Sound Speed Profile

The sound speed profile (SSP) describes the dependence of sound speed with respect to water depth and influences the path of propagation of the wavefronts through the refraction phenomenon. Because sound speed in the ocean depends mainly on temperature, pressure (or equivalently, depth), and salinity, these three variables define the sound speed profile in the water column. Naturally, the SSP in a particular point is not constant in time; although the depth may vary daily (surges) and salinity may vary drastically in certain locations, it is the temperature the most relevant parameter in the temporal characterization of SSPs. In this context, SSPs usually show seasonal dependence, as shown in Figure 1. It is most relevant in deep waters, in which boundary reflections are less prevalent.

For this report, the Copernicus Physics database[5] was used to obtain temperature and salinity across depths for the considered spatiotemporal domains corresponding to the test sites. In particular, the

[5]Link: https://marine.copernicus.eu/

IBI_ANALYSISFORECAST_PHY_005_001 dataset was used, particularly the version with monthly averages of temperature, salinity, and depth. From these data, the sound speed in the water column was readily calculated using the Mackenzie model for the speed of sound in the ocean (Mackenzie, 1981).

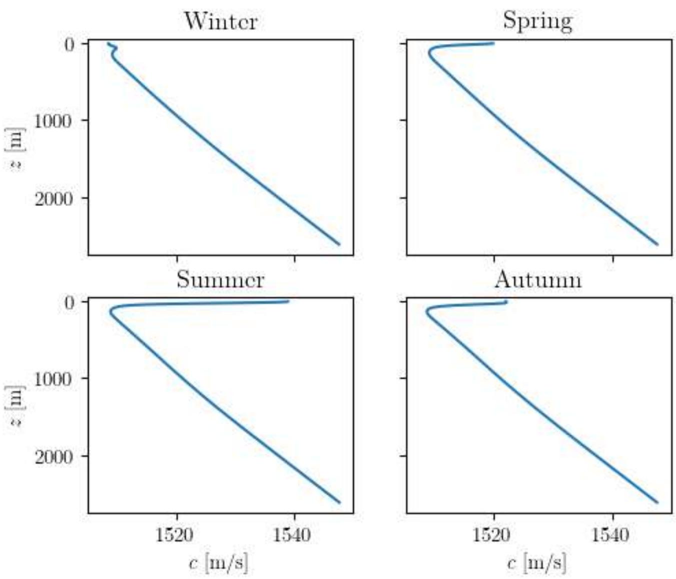

Figure 1. Example of seasonal dependence of real sound speed profiles calculated in the Western Mediterranean.

Because of numerical artefacts nearshore, and given the low level of variability for a small area, it was decided not to consider the spatial variation of the SSP.

2.3.1.1 Aguçadoura

For illustration purposes, the spatially averaged SSP (that is, averaging along latitude and longitude) for the Aguçadoura test site is shown in Figure 2.

2.3.1.2 BiMEP

In the case of the BiMEP test site, the different seasonal SSPs are shown in Figure 3.

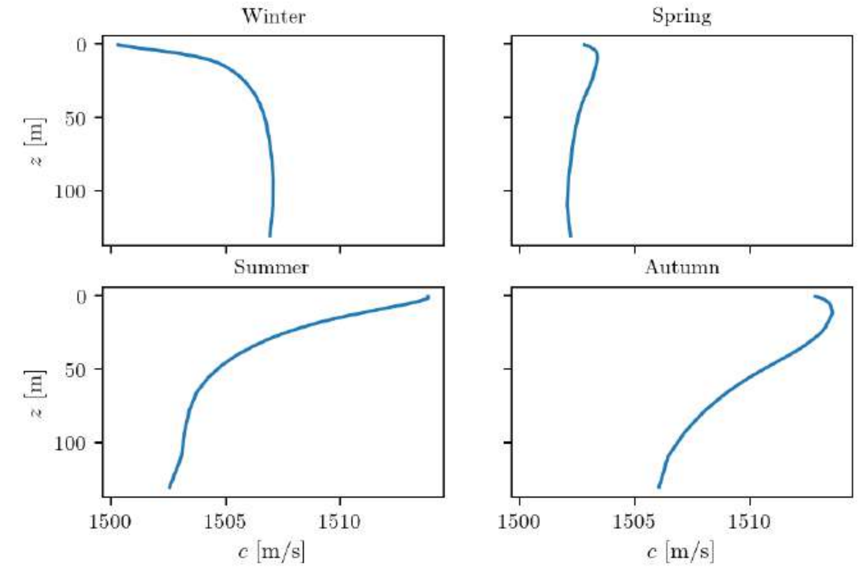

Figure 2. Spatially averaged seasonal SSP for the Aguçadoura test site.

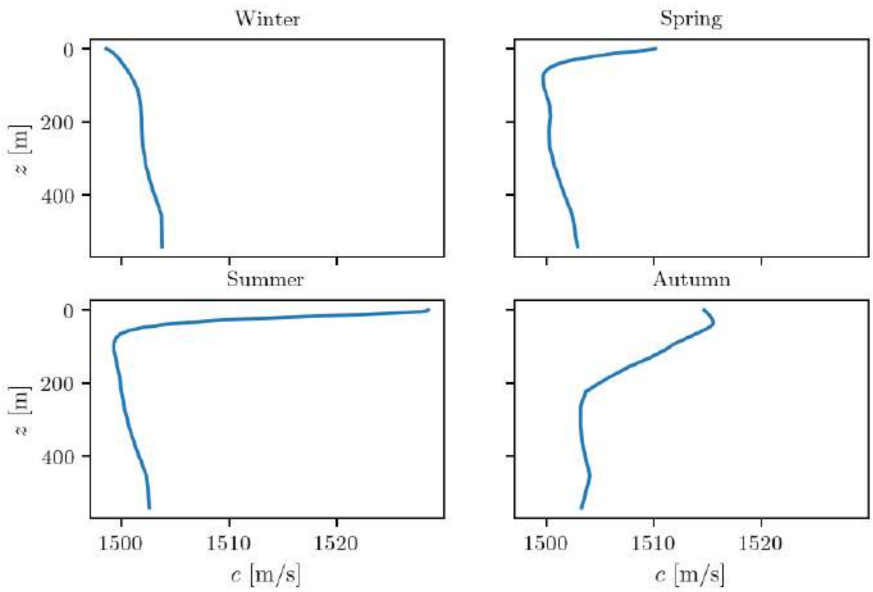

Figure 3. Spatially averaged seasonal SSP for the BiMEP test site.

2.3.1.3 Mutriku

The case for Mutriku is quite similar to that of BiMEP, as both test sites are located very close to each other. Its seasonal SSPs are shown in Figure 4.

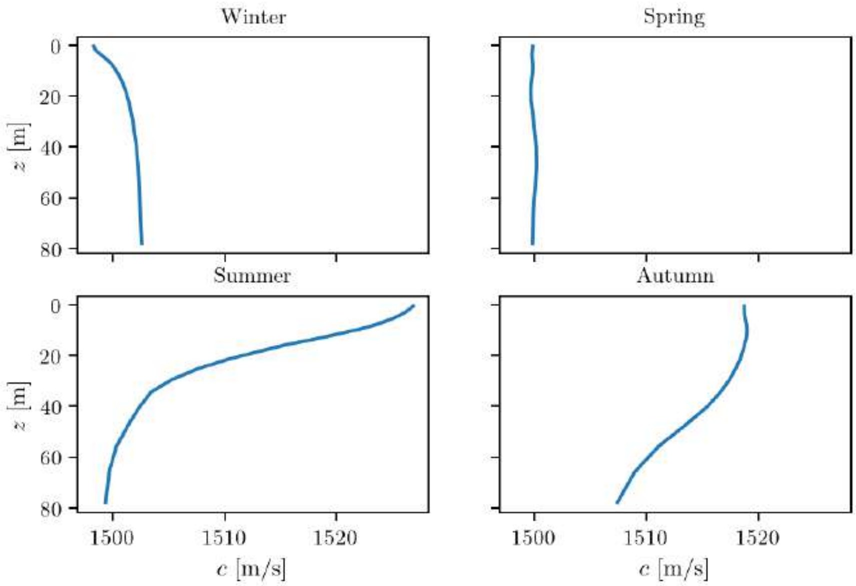

Figure 4. Figure 1. Spatially averaged seasonal SSP for the Mutriku test site.

2.3.1.4 SEM-REV

For the SEM-REV test site, the spatially averaged SSP (that is, averaging through latitude and longitude) is shown in Figure 5.

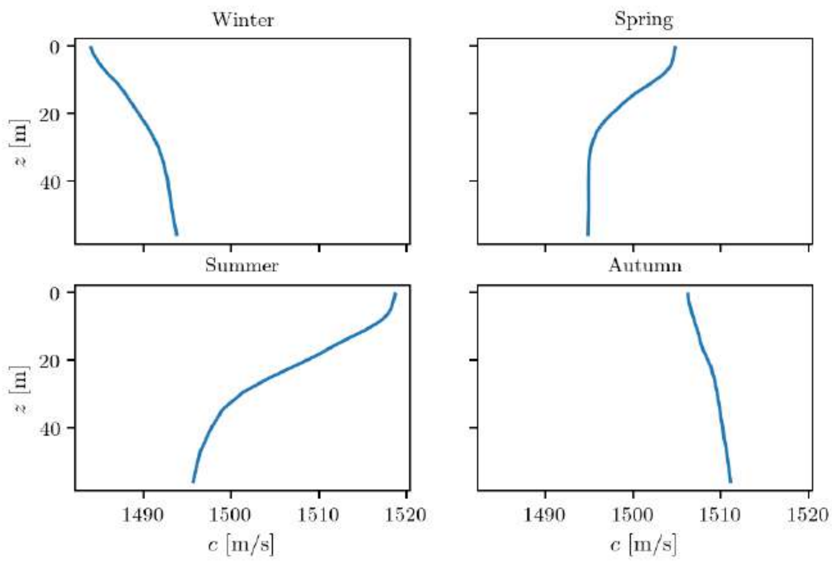

Figure 5. Spatially averaged seasonal SSP for the SEM-REV test site.

2.3.2 Bathymetry

The bathymetry, along with the sea surface, are essentially the only boundaries that acoustic waves meet in their propagation. The sea surface is usually modelled as a free pressure (vacuum), which consists of a very good approximation, considering the great difference in acoustic impedance between air and water. The seabed, spatially characterized by its bathymetric profile, is a more complex media altogether (see section 2.3.3).

The bathymetry influences how the acoustic waves are reflected, and therefore, influences the distribution of TLs along their course, as is explicitly shown in Figure 6. It is particularly important in shallow water environments.

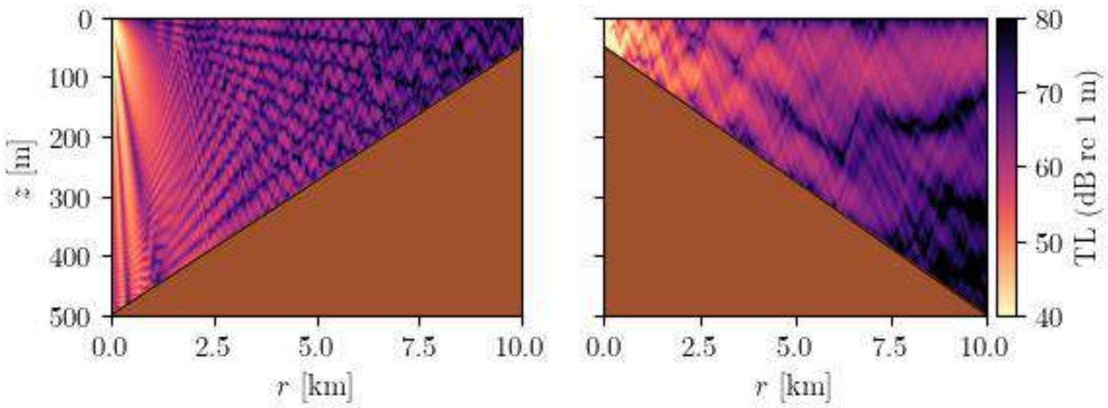

Figure 6. Effect of bathymetry on TL, simulated by a parabolic equation model for a source depth of 20 meters and frequency of 100 Hz.

In fact, the bathymetry has a clear effect in this study, as all the test sites are characterized by shallow waters. This is because shallow water channels work as a low frequency filter with the cut-off frequency approximately given by the expression

$$f_c = \frac{c_1}{4z}\sqrt{\frac{1}{1-(c_1/c_2)^2}} \tag{3}$$

This phenomenon causes the lower frequencies to propagate poorly in these environments, as will be presented in the results (section 3.1).

All bathymetries of this study were obtained from the EMODnet bathymetry service[6]. It has a spatial resolution of 0.001 decimal degrees, which is equivalent to about 80 meters of distance for the typical latitudes in this work. Even though additional bathymetry datasets were gathered from other sources, they did not satisfy the spatial requirements needed for the simulations.

2.3.2.1 Aguçadoura

The Aguçadoura test site is quite shallow. The average depth is 52.5 meters (Figure 7).

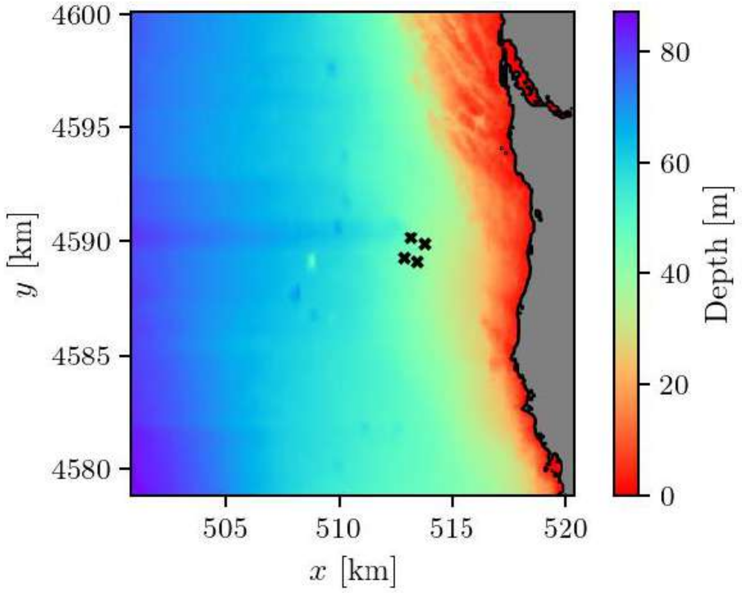

Figure 7. Bathymetry of the area surrounding the Aguçadoura test site. The position of the four[7] WECs is marked with a cross.

2.3.2.2 BiMEP

The bathymetry in the BiMEP test site is shown in Figure 8. The bathymetry quickly declines in the northern part (visible in the top right corner) and has an average depth of 73 meters.

[6]Link: https://portal.emodnet-bathymetry.eu/#.

[7] Only one WEC is installed, and the remaining ones are foreseen.

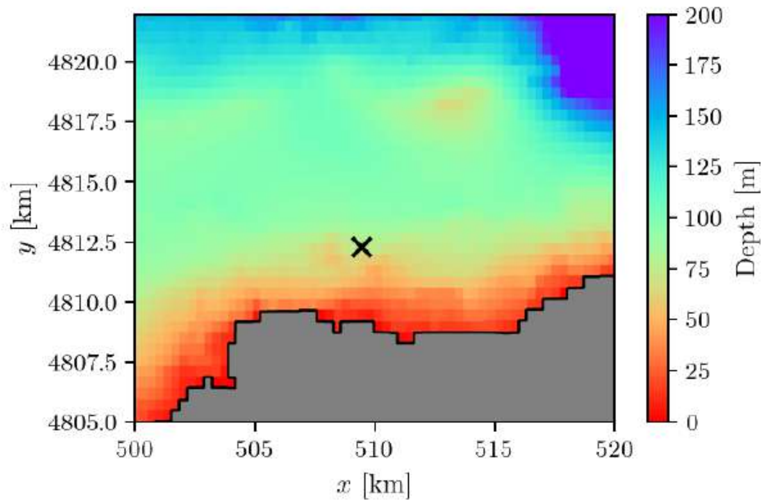

Figure 8. Bathymetry of the area surrounding the BiMEP test site. The position of the WEC is marked with a cross.

2.3.2.3 Mutriku

The bathymetry in the Mutriku test site is shown in Figure 9. This area is characterized by shallow waters, being a coastal area, with maximum depths of about 80 meters, and an average depth of 43 meters.

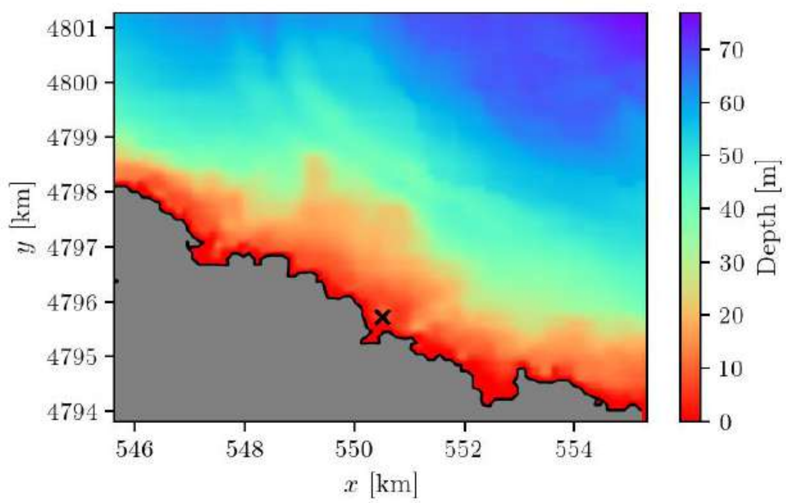

Figure 9. Bathymetry of the area surrounding the Mutriku test site. The position of the WEC is marked with a cross.

2.3.2.4 SEM-REV

Lastly, the bathymetry in the SEM-REV test site is shown in Figure 10. This zone is too characterized by very shallow waters, with maximum depths of approximately 50 meters, and an average depth of 32 meters.

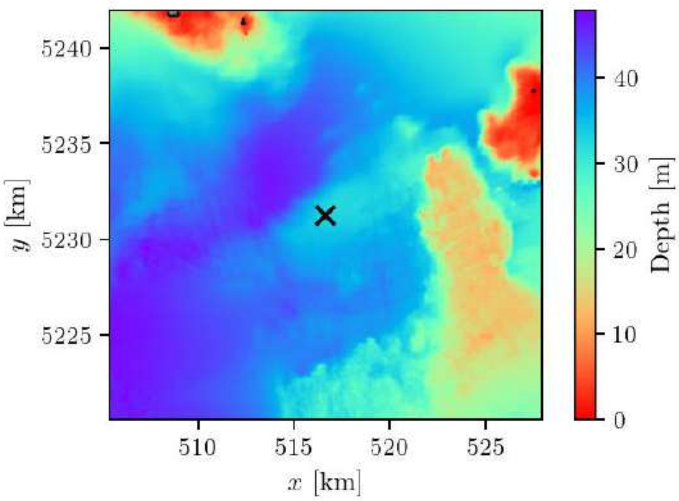

Figure 10. Bathymetry of the SEM-REV test site. The position of the WEC is marked with a cross.

2.3.3 Seabed geo-acoustic properties

Seabed geo-acoustic properties refer in this study to density, sound speed, and acoustic sound attenuation of transversal and longitudinal waves, denoted as ρ, c_T, c_L, a_T, and a_L, respectively.

These five parameters characterize the transmission, reflection, and absorption of acoustic waves in the water-substrate boundary, therefore being essential to obtaining correct acoustic energy levels in the water channel. Therefore, they are particularly essential in shallow water environments, in which reflections play a big role in acoustic transmission. In Figure 11, a clear example of the effect of seabed geo-acoustic properties on TL can be seen.

In the following sections, these properties are specified for each test site. They have been extracted from different data sources that shall be specified for each case.

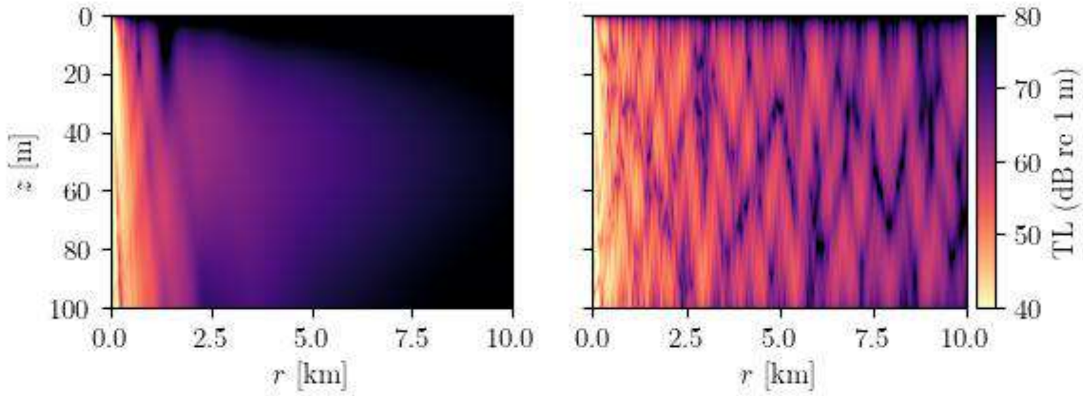

Figure 11. Effect of seabed geo-acoustic properties on the transmission losses in the acoustic duct for a source in 20 m and 100 Hz of frequency. Left: $\rho = 1.5$ g/cm^3, $c_L = 1515$ m/s, $a_L = 0.15$ dB λ^{-1}. Right: $\rho =$ 2 g/cm^3, $c_L = 1800$ m/s, $a_L = 0.9$ dB λ^{-1}.

2.3.3.1 Aguçadoura

The seabed in the Aguçadoura test site consists mostly of muddy sand and sand (Figure 12).

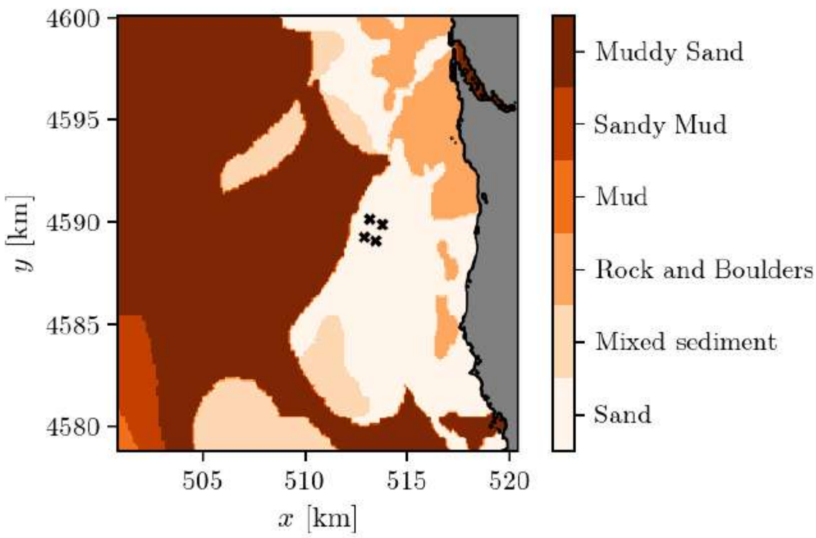

Figure 12. Seabed types (Folk7 scale) in the Aguçadoura test site. The four WECs are marked with crosses.

2.3.3.2 BiMEP

In the BiMEP test site, the seabed is comprised mostly of rocks and sand (Figure 13).

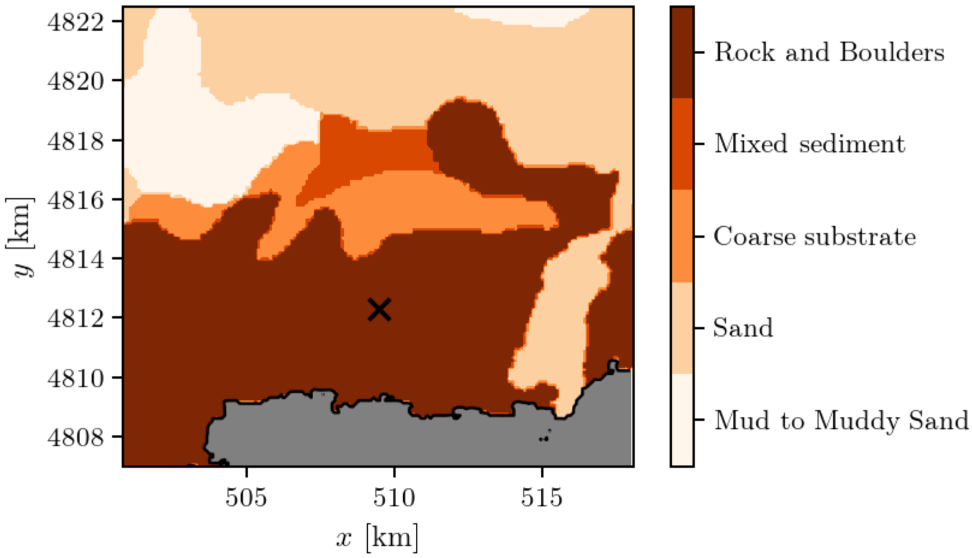

Figure 13. Seabed types in the Aguçadoura test site. The WEC is marked with a cross.

2.3.3.3 Mutriku

Similarly to the BiMEP, the Mutriku test site shows a seabed mostly comprised of rock and boulders, as well as sand (Figure 14).

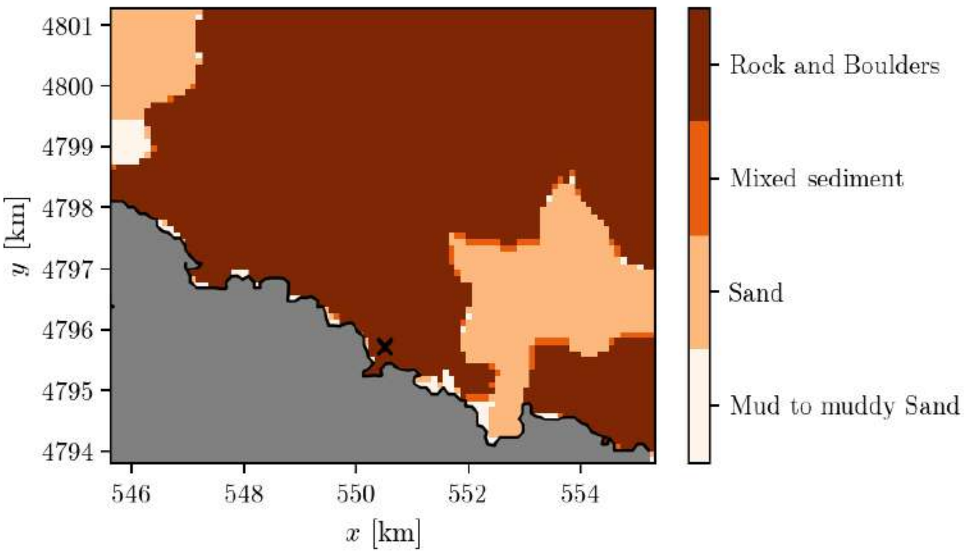

Figure 14. Seabed type (Folk5 scale) in the Mutriku test site. The WEC is marked as a cross.

2.3.3.4 SEM-REV

Lastly, the seabed in the SEM-REV test site is quite varied, with most of the area consisting of rock and boulders and coarse substrate (Figure 15).

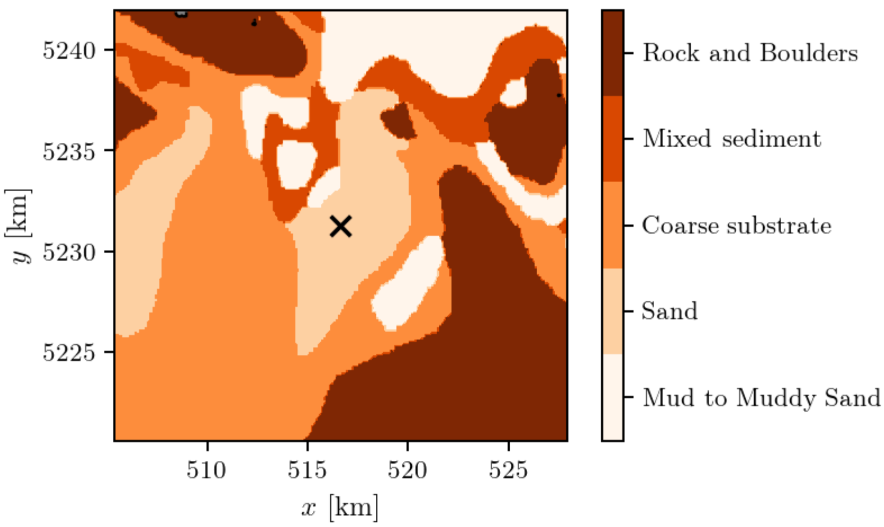

Figure 15. Seabed type (Folk5 scale) in the SEM-REV test site. The WEC is marked as a cross.

2.4 Simulations parameters

In this section, we specify the values of some parameters more related to the mathematical aspects of simulations per se. Without any specific order, these are:

- The transect resolution (e.g., distances at which the environmental data are sampled along the transect) is set to 50 meters. However, this value will be set to higher values for the longest transects because of numerical limitations. In the other hand, for very short transects, this distance will be iteratively halved until at least 20 samples can be taken. The transect coordinates are calculated considering the curvature of the Earth, that is, transects are geodesics.
- The distance between receptors (points at which the model samples results) is 20 meters in radial distance whereas for depth receivers it is 0.5 m (these must not be confused with the points at which the model

performs the calculations – these are automatically calculated by itself depending on the frequency).

- Regarding the sound speed profile, it will be sampled between 2 and 5 meters (depending on the maximum depth along the transect).
- Acoustic absorption has been considered in the model (although it is mostly irrelevant for the selected frequencies).

In any case, at the end of the simulations (for each device) all these results are accordingly interpolated to a uniform grid of 100 m distance between adjacent cells, for the depths in the following list: 5, 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 meters.

2.4.1 Source position

All sources are considered a point (acoustic monopole). While this is unrealistic, for other than short propagation ranges (e.g., where far-field conditions are met), it is a fairly good approximation. The coordinates of the equivalent point sources for each test site are specified in the following subsections.

2.4.1.1 Aguçadoura

The Aguçadoura case is particular, in the sense that four identical WECs were expected to be installed in the area, instead of a single WEC. The coordinates of these four devices are specified in Table 1.

Since the new C5 generation is still under development, only the C4 was installed during the duration of the project.

In Table 2, the installation depth along with the latitude and longitude of the source are found.

2.4.1.2 BiMEP

The coordinates and the depth of the equivalent point source of the PENGUIN II WEC in BiMEP are specified in Table 3. In this case, a source depth of 3 meters was chosen, which is half the draught of the PENGUIN II.

Table 1. Planned location of the HiWave equipment (WGS 84; Degrees, Decimal Minutes) (Source: CPO).

Description	Latitude	Longitude
WEC Equipment		
C4	41° 27.523'N	8° 50.533'W
C5.1	41° 27.429'N	8° 50.431'W
C5.2	41° 27.353'N	8° 50.468'W
C5.3	41° 27.277'N	8° 50.505'W
Collection Hub Equipment		
Anchor – A1	41° 27.770'N	8° 50.541'W
Anchor – A2	41° 27.446'N	8° 50.209'W
Anchor – A3	41° 27.411'N	8° 50.579'W
Hub	41° 27.509'N	8° 50.408'W
Electrical equipment		
Export cable anchor	41° 27.509'N	8° 50.372'W
C4 cable anchor	41° 27.513'N	8° 50.444'W
C5 cable anchor	41° 27.482'N	8° 50.416'W
Export cable quadrant	41° 27.510'N	8° 50.313'W
Signalling/Boundaries		
HiWave 1	41° 27.770'N	8° 50.541'W
HiWave 2	41° 27.630'N	8° 50.111'W
HiWave 3	41° 27.310'N	8° 50.770'W
HiWave 4	41° 27.200'N	8° 50.350'W

Table 2. Coordinates and depth of the equivalent source point for the C4 WEC.

WEC	Latitude ['N]	Longitude ['W]	Depth [m]
C4	41° 27.523'	8° 50.533'	45

Table 3. Coordinates and depth of the equivalent source point for the PENGUIN II WEC.

WEC	Latitude ['N]	Longitude ['W]	Depth [m]
PENGUIN II	43°27'49,2012''	2°52'59,4012''	3

2.4.1.3 Mutriku

As for Mutriku, since there is no significant expected coupling between the moving parts (turbines) and the concrete wall that is partially submerged in water, the source was placed as close to the sea surface as possible, as shown in Table 4.

Table 4. Coordinates and depth of the equivalent source point for the Mutriku Power Plant.

WEC	Latitude [° N]	Longitude [° W]	Depth [m]
Mutriku Power Plant	43°18'45,5328''	2°22'37,6464''	0.1

2.4.1.4 SEM-REV

The coordinates and depth of the WAVEGEM equivalent point source are shown in Table 5. A depth of 1.5 meters was chosen as this value is equal to half the draught of the device.

Table 5. Coordinates and depth of the equivalent source point for the WAVEGEM WEC.

WEC	Latitude [° N]	Longitude [° W]	Depth [m]
WAVEGEM	47°14'5,9388''	2°46'49,1988''	1.5

2.5 Methodology

For the calculation of TLs fields, a Nx2D approach was used. The chosen acoustic model was the Monterey-Miami Parabolic Equation (MMPE) model, which can take into account range dependency on SSP, bathymetry, and seabed geo-acoustic properties. This allows us to maximize the amount of information we can input into the model. It is also expected to behave correctly in the mostly shallow water environments in which the WECs are located, as well as in the lower part of the frequency spectra. As a possible downside, is the increasing computation costs for higher frequencies, which, fortunately, are not key in this study, in which a focus on the MSFD Descriptor 11 (D11 – Energy and Noise) frequencies has been favoured (63, 125 Hz).

The main steps of the methodology followed are:

1. Homogenize the environmental datasets (bathymetry, SSP, geo-acoustic properties) into a common spatial grid. Interpolation from the original data (usually georeferenced) to this common grid, after transforming the coordinates to the transversal Mercator projection

(UTM) if necessary[8], which is a projected coordinate system. As yearly data of SSP is available, all seasons are taken into account in the analysis.

2. Draw transects (geodesics) from the source up to the end of the grid, spanning the whole polar plane, and sample the environmental parameters along them. In this study, a transect is a 2D plane that slices the water media and is defined by the radial distance r and the depth z. Run the model for each frequency and transect (for the whole water column) and store in memory the resulting TL values as well as their corresponding spatial coordinates and depths. An angular resolution of 3 degrees was used.
3. Interpolate the unstructured TL data into the grid for each frequency and depth of interest; that way, the TLs field is obtained for each case. Section 3.1 shows some results of this step.
4. After obtaining the SL values using the results from Deliverable 2.3 and the TLs models for all frequencies and wave heights considered, the definitive SPL field caused by the device (denoted simply as SPL), is easily calculated as $SPL = SL - TL$. As data from several hydrophones is available, and therefore several values for SL can be extracted, the average SL (and its standard deviation) are used as the definitive result (and its corresponding uncertainty). These will be the results from which posterior analysis will be carried out to extract useful metrics, as shown in section 3.3.

[8] There are interpolation routines in curvilinear coordinates, which can be readily applied to latitude-longitude data.

3. Results

In this section, the results of the simulations are detailed and summarized. The TLs fields are calculated for the following combination of parameters:

- Frequencies: 62.5 and 125 Hz.
- Depths: 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100 meters.
- Spatial range: up to 15 km.

3.1 Transmission Losses

Following the described methodology, first, the results of the TLs for each test site are calculated and shown in this section.

3.1.1 Aguçadoura

For the sake of Figure 16, the TL maps at 5 m depth for all seasons of the year are shown. Due to the low-frequency shallow waters filter, it can be appreciated how the higher frequency components propagate better especially close to the shore (shallower waters).

3.1.2 BiMEP

Results for the BiMEP test site are shown in Figure 17. The difference between frequencies (125 Hz component propagates much better) is again due to the low-frequency filter effect of shallow waters. This effect can be seen with more clarity nearshore.

It is noticeable a very slight difference between seasons, less than 2 dB re 1 µPa in average.

3.1.3 Mutriku

In the case of Mutriku, the results shown in Figure 18, indicate a very inefficient propagation of the underwater sound, which is reasonable, as in this case the source is onshore, therefore existing extremely shallow waters in the area. As explained before, the frequency component with the best propagation efficiency is 1kHz due to the shallow waters filter.

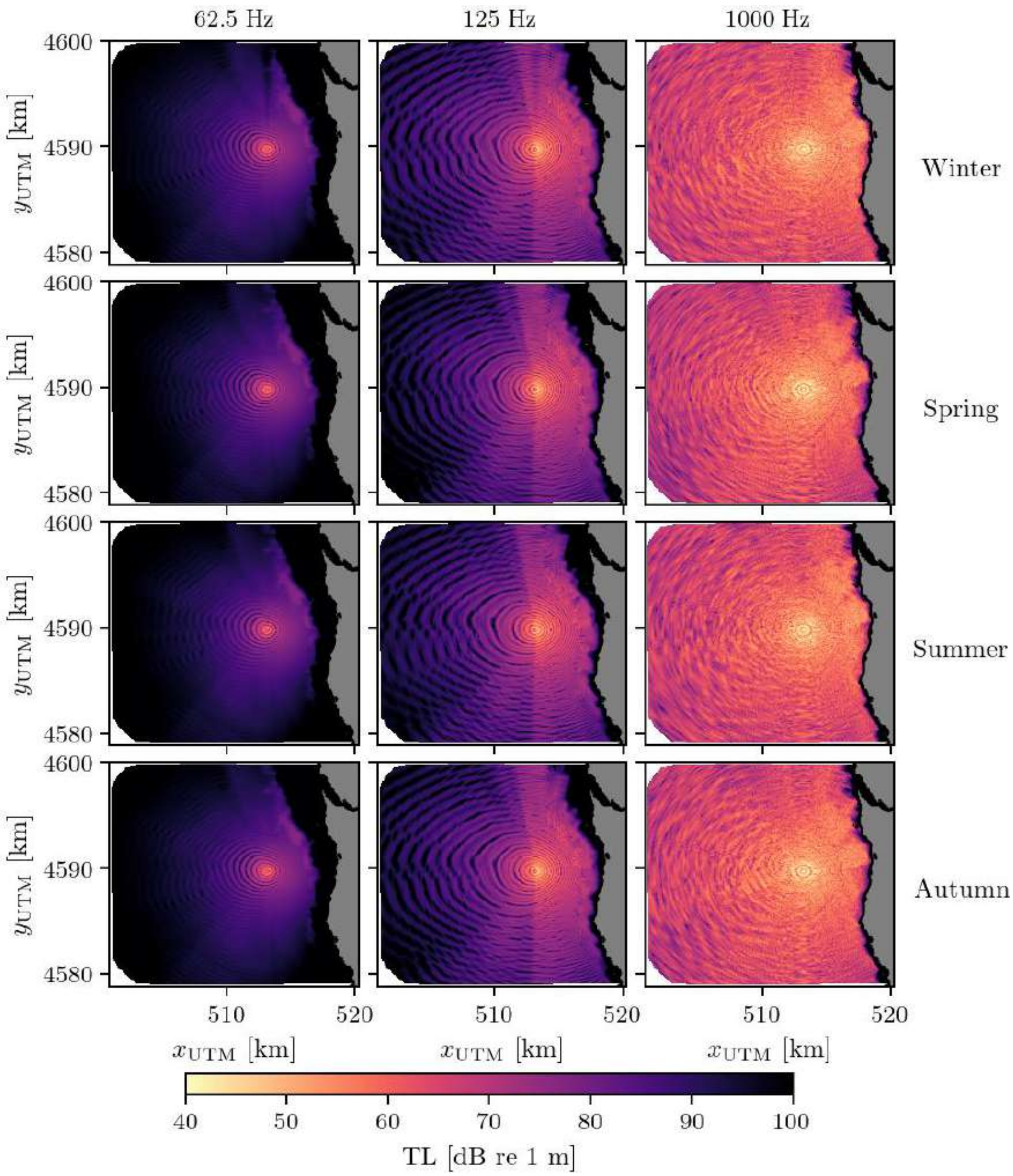

Figure 16. TL sound maps at 5 m depth for all seasons for the Aguçadoura test site.

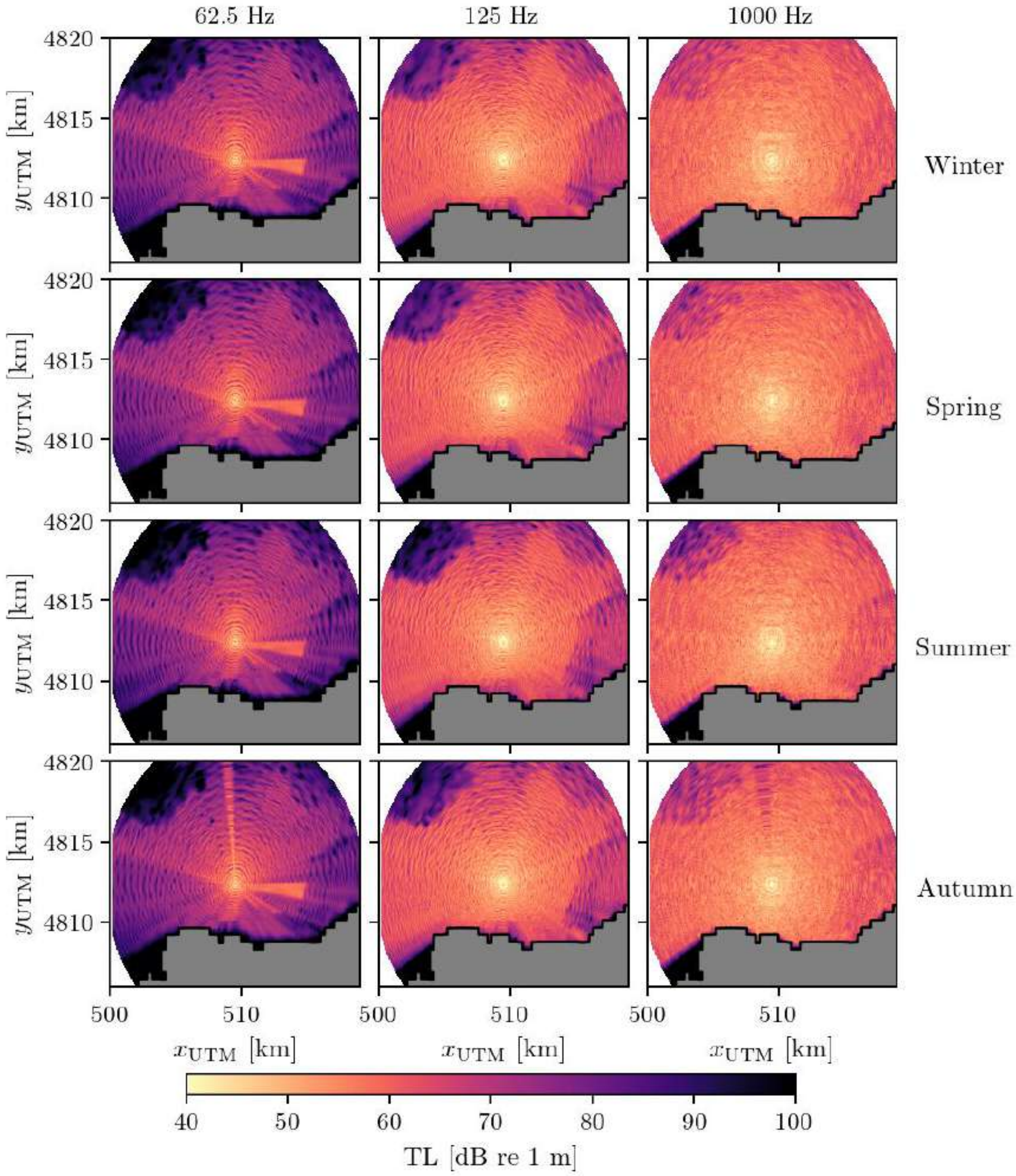

Figure 17. TL sound maps at 5 m depth for all seasons for the BiMEP test site.

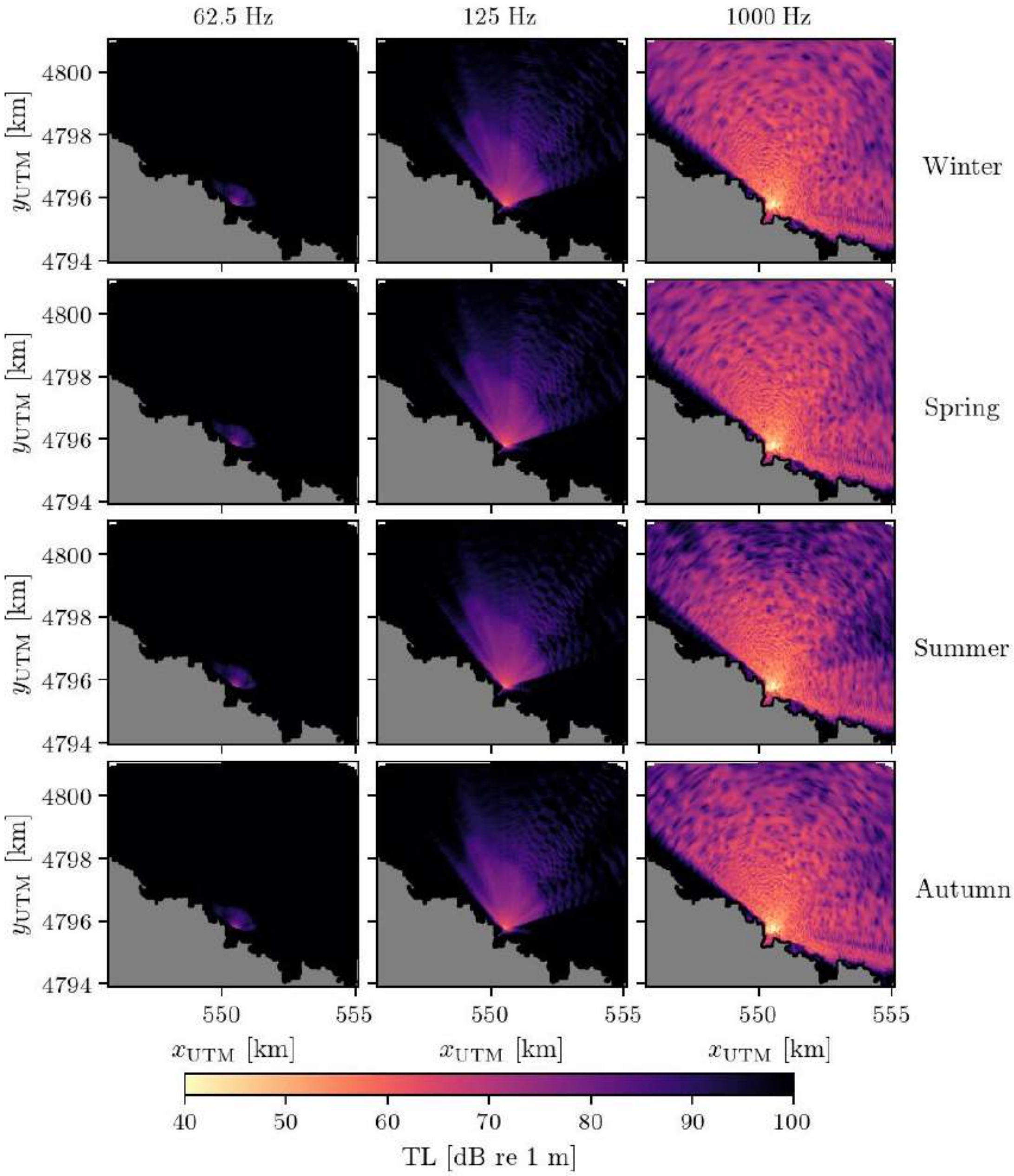

Figure 18. TL sound maps at 5 m depth for all seasons for the SEM-REV test site.

3.1.4 SEM-REV

Lastly, the results for the SEM-REV test site are shown in Figure 19. A very slight difference between seasons is noticeable for both 62.5 and 125 Hz frequencies. On the other hand, there are several differences between frequencies, where 62.5 Hz shows an inefficient propagation compared to 125 Hz due to the low-frequency filter effect originated by shallow waters. Also, the 1 kHz component shows a very efficient propagation due to the same effect.

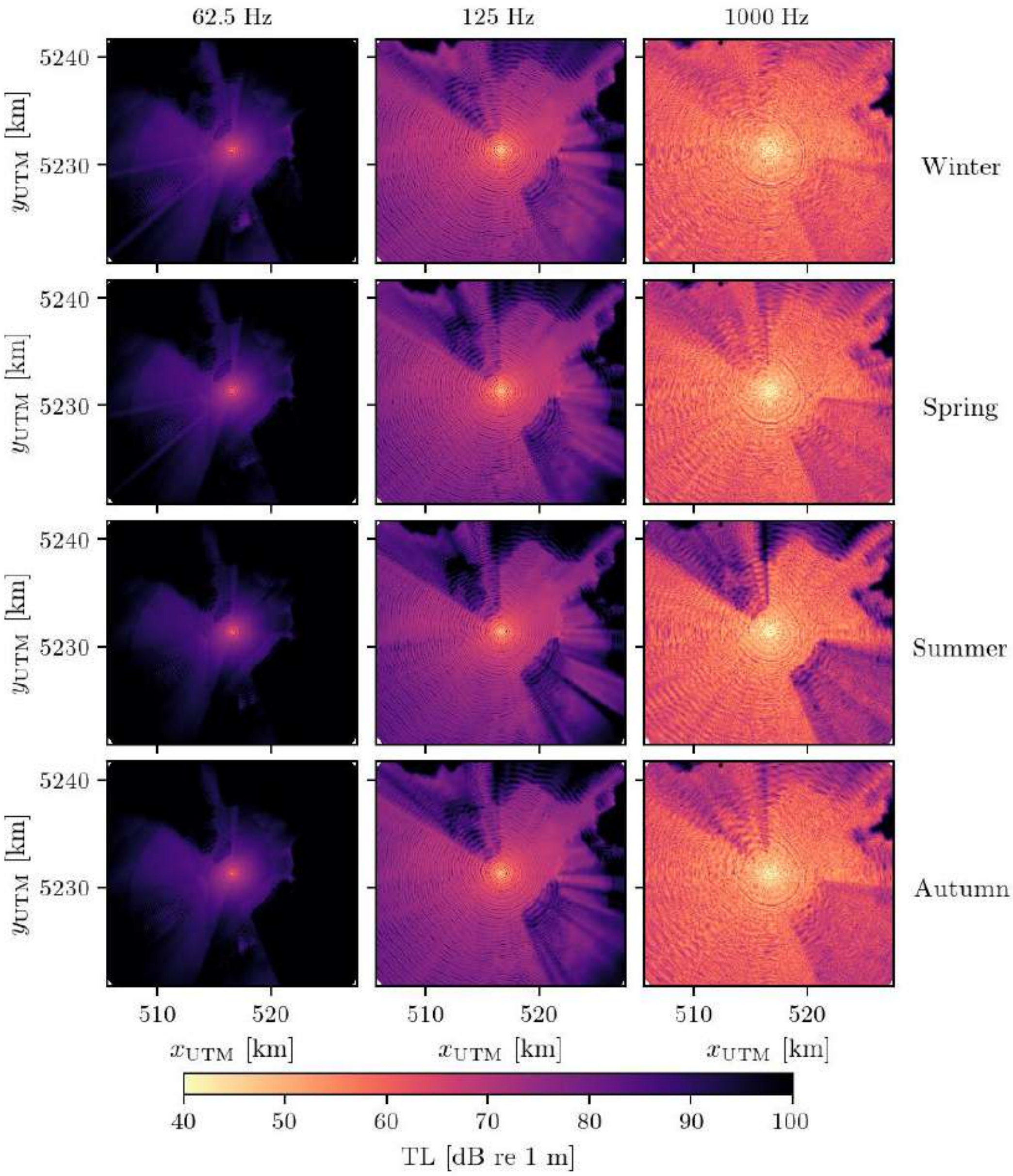

Figure 19. TL sound maps at 5 m depth for all seasons for the SEM-REV test site.

3.2 Source Levels

To find the SLs, the SPL results obtained for each considered frequency and significant wave height bin are taken from Deliverable 2.3 (Madrid et al., 2024). As these data are also classified with respect to the operation status of the device, it is possible to define the variables $\mathrm{SPL_{off}}$ and $\mathrm{SPL_{on}}$, as the characteristic SPL values when the WEC is off and on, respectively.

$\mathrm{SPL_{off}}$ will also be referred to as background noise levels in the rest of this document. On the other hand, $\mathrm{SPL_{on}}$ refers to SPL when the devices under study are working.

3.2.1 Aguçadoura

For the Aguçadoura case, the SLs are obtained per hydrophone, frequency component, and wave height bin. In Table 6, the resulting SL values can be found for the C4 WEC.

3.2.2 BiMEP

In BiMEP, three SLs can be identified, one for each hydrophone that acquired acoustic data (details about the sampling stations can be found in Deliverable 2.3). In Table 7, the resulting SL values can be found for the PENGUIN II WEC.

3.2.3 Mutriku

In Mutriku, only two SLs can be identified, one for each hydrophone that acquired sufficient acoustic data (details about the sampling stations can be found in Deliverable 2.3).

In Table 8, the SL of the Mutriku power plant is obtained.

As the acoustic model showed high TLs values even close to the source (probably due to the bathymetry, which in some transects shows strange behaviours), the SLs obtained are higher than expected (maximum of 187 dB).

Table 6. SL [dB re 1 m] of the HiWave C4 WEC in the Aguçadoura test site.

	H **[m]**	[0, 0.75)			[0.75,1.5)			[1.5, 2)			[2, 2.5)		
Sampling Station	**f [Hz]**	62.5	125	1k	62.5	125	1k	62.5	125	1k	62.5	125	1k
H1		-	-	-	166	155	151	162.4	146.3	147.7	174	158.6	159
H2		-	-	-	142.6	145	156	142	137	152.4	156	151	167
H3		-	-	-	117	131	120	121	128	124.6	131	140.4	139

Table 7. SL [dB re 1 m] of the PENGUIN II WEC in the BiMEP test site.

	H **[m]**	[0, 0.75)			[0.75,1.5)			[1.5, 2)			[2, 2.5)			[4,8)		
Sampling Station	**f [Hz]**	62.5	125	1k	62.5	125	1k	62.5	125	1k	62.5	125	1k	62.5	125	1k
PE1		-	-	-	-	-	-	139.1	134.4	134.3	142.3	136.4	136.7	146.2	139.2	139.9
PE2		-	-	-	-	-	-	136.2	133.2	130.6	138.8	134.4	132.9	143.1	136	136
PE3		-	-	-	-	-	-	131.4	138.6	134.1	134.4	140.8	136.9	140.5	144.8	140.1

Table 8. SL [dB re 1 m] of the Mutriku power plant in the Mutriku test site.

	H **[m]**	[0, 0.75)			[0.75,1.5)			[1.5, 2)			[2, 2.5)			[4,8)		
Sampling Station	**f [Hz]**	62.5	125	1k	62.5	125	1k	62.5	125	1k	62.5	125	1k	62.5	125	1k
PE1		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PE2		167.6	161.4	145.8	168.7	162.3	145.1	178.1	167.6	145.5	181.6	169.8	145.2	-	-	-
PE3		173.9	167	148.2	176.8	169.5	148.2	186.1	177.5	149.5	189.6	189.6	150.3	-	-	-

3.2.4 SEM-REV

In SEM-REV, as in Mutriku, only two SLs can be identified, one for each hydrophone that acquired sufficient acoustic data (details about the sampling stations can be found in Deliverable 2.3). In Table 9, the SL of the WAVEGEM WEC can be seen.

3.3 Sound Pressure Level

In this section, the SPL maps for each test site are shown.

3.3.1 Aguçadoura

Once the TL and SL are computed for the Aguçadoura case, the resulting SPL fields are obtained (Figure 20) for each significant wave height bin (only shown here those cases with data coming from Deliverable 2.3).

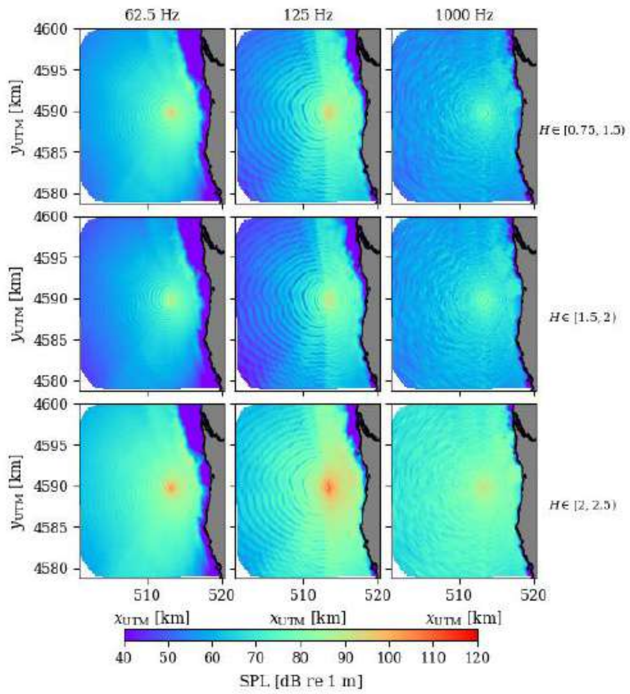

Figure 20. SPL sound maps at 5 m depth (averaged through seasons and Source Levels) for the Aguçadoura test site.

Table 9. SL [dB re 1 m] of the WAVEGEM WEC in the SEM-REV test site.

	***H* [m]**	[0, 0.75)			[0.75,1.5)			[1.5, 2)			[2, 2.5)			[4,8)		
Sampling Station	**f [Hz]**	62.5	125	1k	62.5	125	1k	62.5	125	1k	62.5	125	1k	62.5	125	1k
PE1		-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PE2		141.4	141.2	120.1	140.5	142.4	120.5	142.5	144	123.1	-	-	-	-	-	-
PE3		147.7	136.9	137.3	148.7	138.2	138.7	150.7	140.4	140.8	-	-	-	-	-	-

3.3.2 BiMEP

After combining the SL and the TL for the BiMEP case, the resulting SPL fields are obtained (Figure 21) for each significant wave height bin (only shown here those cases with data – the [0, 0.75) and [0.75, 1.5) bins were empty). As expected, except very close to the source, the levels are quite low, being mor than 120 dB on the source.

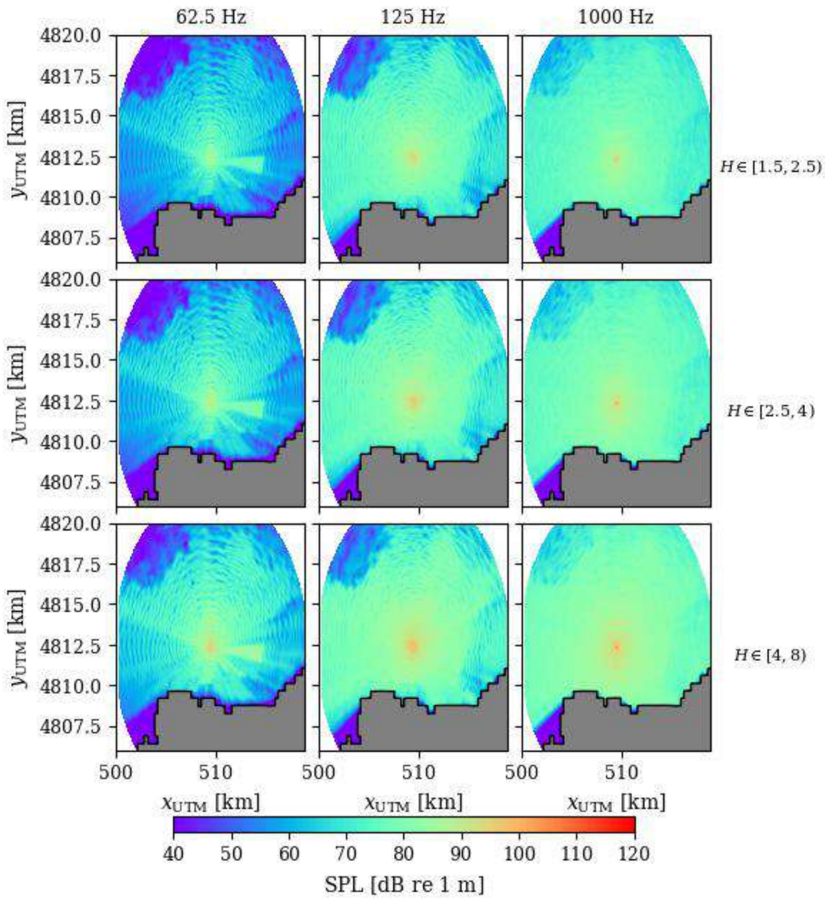

Figure 21. SPL sound maps at 5 m depth (averaged through seasons and Source Levels) for the BiMEP test site.

3.3.3 Mutriku

After combining the SL and the TL for the Mutriku case, the resulting SPL fields are obtained (Figure 22) for each significant wave height bin (only shown here those cases with data – the [4, 8) bin was empty). As expected, the levels are quite low (even close to the source). As there was virtually no 'OFF' state data to process the background noise, the distinction was between SPL obtained during the day and at night (given that Mutriku is a very busy location in terms of human coastal activity and most anthropogenic coastal activity is carried out in daylight).

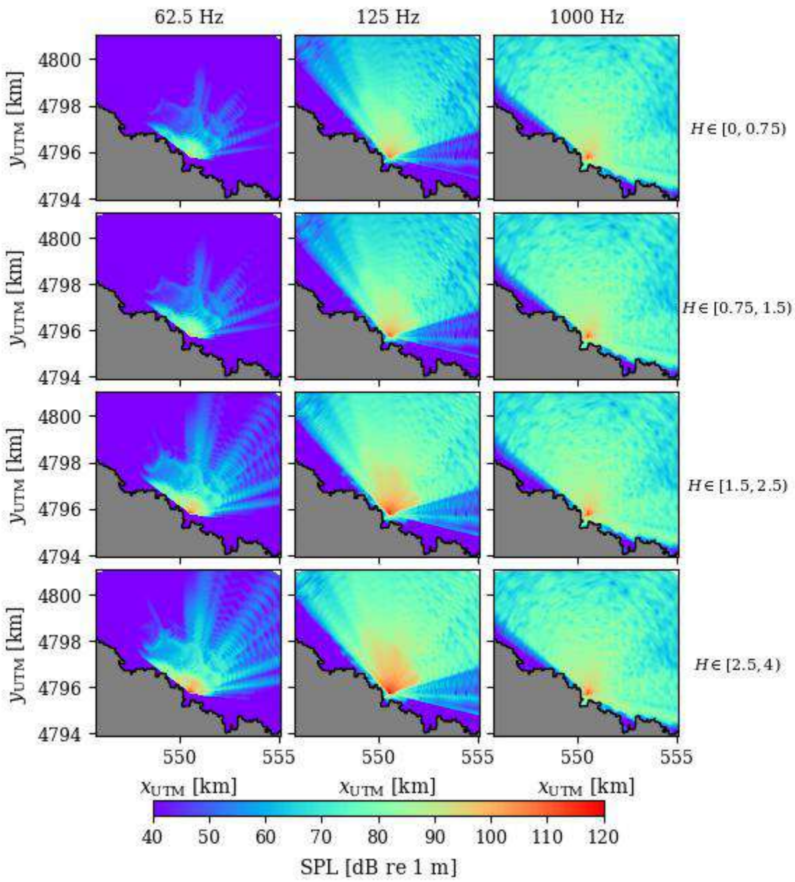

Figure 22. SPL sound maps at 5 m depth (averaged through seasons and Source Levels) for the Mutriku test site.

3.3.4 SEM-REV

After combining the SL and the TL for the SEM-REV case, the resulting SPL fields are obtained (Figure 23) for each significant wave height bin (only shown here those cases with data – the [2.5, 4) and [4, 8) bins were empty). As expected, except very close to the source, the levels are quite low.

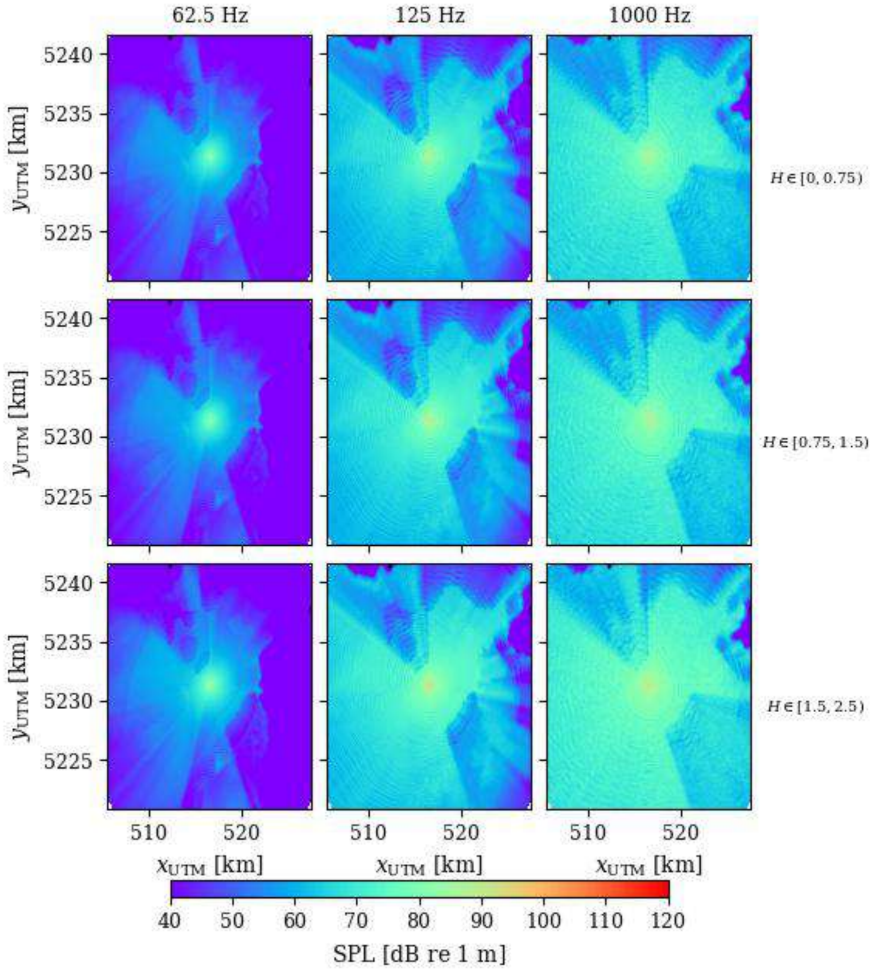

Figure 23. SPL sound maps at 5 m depth (averaged through seasons and Source Levels) for the SEM-REV test site. In blue contours are encircled the area in which $\mathrm{SPL}_{\mathrm{on}} > 85dB$.

3.4 Acoustic disturbance metrics

To assess the impact of the WECs at the four test sites, two metrics were obtained, namely:

a) Acoustic Disturbance Area for Cetaceans. This is defined as the area where the sound pressure level (SPL) exceeds the threshold that is considered to disturb cetaceans. The established limits are 120 dB re 1 μPa for continuous noise and 160 dB re 1 μPa for impulsive noise, according to NMFS (2024).

b) Acoustic Disturbance Distance. Given the acoustic disturbance area, the acoustic disturbance distance is obtained as the radius of the circle with the equivalent area.

3.4.1 Aguçadoura

With the SPL maps obtained and the levels when the device is not operating, acoustic disturbance area (and distance are calculated for each wave height bin and frequency) (Table 10 and Table 11).

Table 10. Acoustic disturbance areas (km^2) for the Hi-Wave C4 WEC, in Aguçadoura.

	H [m]	[0.75, 1.5)			[1.5, 2)			[2, 2.5)		
Season	**f [Hz]**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**
Winter		8.9	7	1.2	1.8	0.7	0	15.4	19.3	6.4
Spring		7.8	5.9	1	1.6	0.6	0	13.4	15.9	5
Summer		7.8	6.3	1.2	1.6	0.6	0	13.3	17.2	6
Autumn		8.3	6.4	1.2	1.7	0.6	0	14.4	17.3	5.5

Table 11. Acoustic disturbance distance (km) for the Hi-Wave C4 WEC, in Aguçadoura.

	H [m]	[0.75, 1.5)			[1.5, 2)			[2, 2.5)		
Season	**f [Hz]**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**
Winter		1.7	1.5	0.6	0.76	0.47	0	2.2	2.5	1.4
Spring		1.57	1.37	0.56	0.71	0.44	0	2.06	2.25	1.26
Summer		1.57	1.41	0.62	0.71	0.44	0	2.05	2.34	1.4
Autumn		1.62	1.42	0.6	0.73	0.44	0	2.1	2.34	1.32

3.4.2 BiMEP

Using the SPL sound maps, combined with the $\mathrm{SPL_{off}}$ information from Deliverable 2.3, we obtain the acoustic disturbance area in BiMEP, leading to the following results for each wave height bin and frequency (Table 12 and Table 13).

Table 12. Acoustic disturbance areas (km²) for the PENGUIN II WEC, in BiMEP.

	H [m]	[1.5, 2.5)			[2.5, 4)			[4, 8)		
Season	**f [Hz]**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**
Winter		0.1	0.6	0.3	0.1	0.7	0.6	0	0.4	0.5
Spring		0.1	0.6	0.3	0.1	0.7	0.6	0	0.4	0.5
Summer		0.1	0.5	0.3	0.1	0.6	0.6	0	0.4	0.5
Autumn		0.1	0.6	0.3	0.1	0.7	0.6	0	0.4	0.4

Table 13. Acoustic disturbance distances (km) for the PENGUIN II WEC, in BiMEP.

	H [m]	[1.5, 2.5)			[2.5, 4)			[4, 8)		
Season	**f [Hz]**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**
Winter		0.17	0.44	0.31	0.18	0.47	0.44	0	0.35	0.40
Spring		0.17	0.44	0.31	0.18	0.47	0.44	0	0.35	0.40
Summer		0.17	0.44	0.31	0.18	0.47	0.44	0	0.35	0.40
Autumn		0.17	0.44	0.31	0.18	0.47	0.44	0	0.35	0.35

3.4.3 Mutriku

The acoustic disturbance areas for the Mutriku power plant WEC cannot be computed due to, as explained in section 3.3.3, lack of "OFF" state data. However, 85 dB was chosen as a typical baseline noise level based on the curves obtained by Piggot [1] to provide an approximation of the range of acoustic disturbance (Table 14 and Table 15).

Table 14. Acoustic disturbance areas (km²) for the Mutriku power plant in Mutriku.

	H [m]	[0, 0.75)			[0.75,1.5)			[1.5, 2.5)			[2.5, 4)		
Season	**f [Hz]**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**
Winter		0.1	0.5	1	0.2	0.9	0.9	0.7	5.0	1.3	1.0	6.5	1.6
Spring		0.1	0.5	1	0.2	0.9	0.9	0.7	5.0	1.3	1.0	6.5	1.5
Summer		0.1	0.5	1	0.2	1.0	0.9	0.8	5.0	1.3	1.1	6.5	1.5
Autumn		0.1	0.5	1	0.2	0.9	0.9	0.8	5.0	1.2	1.1	6.5	1.5

Table 15. Acoustic disturbance distances (km) for the Mutriku power plant in Mutriku.

	H [m]	[0, 0.75)			[0.75,1.5)			[1.5, 2.5)			[2.5, 4)		
Season	**f [Hz]**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**
Winter		0.18	0.40	0.56	0.25	0.53	0.53	0.47	1.26	0.64	0.56	1.44	0.71
Spring		0.18	0.40	0.56	0.25	0.53	0.53	0.47	1.26	0.64	0.56	1.44	0.71
Summer		0.18	0.40	0.56	0.25	0.56	0.53	0.50	1.26	0.64	0.56	1.44	0.69
Autumn		0.18	0.40	0.56	0.25	0.53	0.53	0.50	1.26	0.62	0.56	1.44	0.69

3.4.4 SEM-REV

The exact acoustic disturbance areas for the WAVEGEM WEC cannot be computed due to, as explained in section 3.3.4, lack of "OFF" state data. However, the same process as for the Mutriku test site was followed to obtain an approximation of the disturbance area (Table 16 and 0).

Table 16. Acoustic disturbance areas (km^2) for the WAVEGEM WEC, in SEM-REV.

	H [m]	[0, 0.75)			[0.75,1.5)			[1.5, 2.5)		
Season	**f [Hz]**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**
Winter		0.2	0.6	4.4	0.2	0.9	6.7	0.4	1.6	13
Spring		0.2	0.5	3.6	0.2	0.7	5.4	0.3	1.2	10.2
Summer		0.1	0.4	3.1	0.2	0.6	4.7	0.3	0.9	8.9
Autumn		0.2	0.5	3.7	0.2	0.7	5.5	0.3	1.1	10.4

Table 17. Acoustic disturbance distances (km) for the WAVEGEM WEC, in SEM-REV.

	H [m]	[0, 0.75)			[0.75,1.5)			[1.5, 2.5)		
Season	**f [Hz]**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**
Winter		0.25	0.44	1.18	0.25	0.53	1.46	0.35	0.71	2.03
Spring		0.25	0.40	1.07	0.25	0.47	1.31	0.31	0.62	1.80
Summer		0.2	0.35	1	0.25	0.44	1.22	0.31	0.53	1.68
Autumn		0.25	0.40	1.08	0.25	0.47	1.32	0.31	0.59	1.82

3.5 WEC arrays

Sound maps for WEC arrays were also calculated for some of the test sites, namely BiMEP and SEM-REV. To do so, the previously followed methodology was expanded by considering more than one noise source. This can be done by simulating the TL from each device of the considered array, and then adding the individual contributions (in pressure units) in a coherent and 100% additive way[9]. It should be noted that a coherent and 100% additive way means that all the acoustic waves emitted by the whole array would add themselves, which in real terms is impossible. However, this simulation is useful for understanding the most critical and unfavourable scenarios.

No fixed number of devices was set for these simulations, but a target output of 1200 kW was set, and the number of devices required for each test site was determined to obtain that target output.

For these simulations, only two test sites were taken into account. Mutriku test site was excluded as it is not a mobile device, but an onshore power plant. Also, the HiWave-5 device was excluded due to delays in receiving data because of a delay in the start of the operational phase. Also, only the winter season was used to alleviate the computational cost as no significant differences were found between seasons.

3.5.1 SEM-REV

WAVEGEM's power capacity is about 150 kW, so, a simulation of 8 WECs was carried out to obtain a maximum power capacity of 1200 kW (Figure 24).

For this case, some unexpected channels of propagation can be appreciated. Those are probably related with the location of the sources, owing to the fact that some bathymetry transects show behaviours of

[9] Coherent here refers to the wave analysis meaning, which assumes that two or more waves have a constant phase relationship.

dubious veracity. However, the simulation is useful to understand the general noise propagation over the whole area.

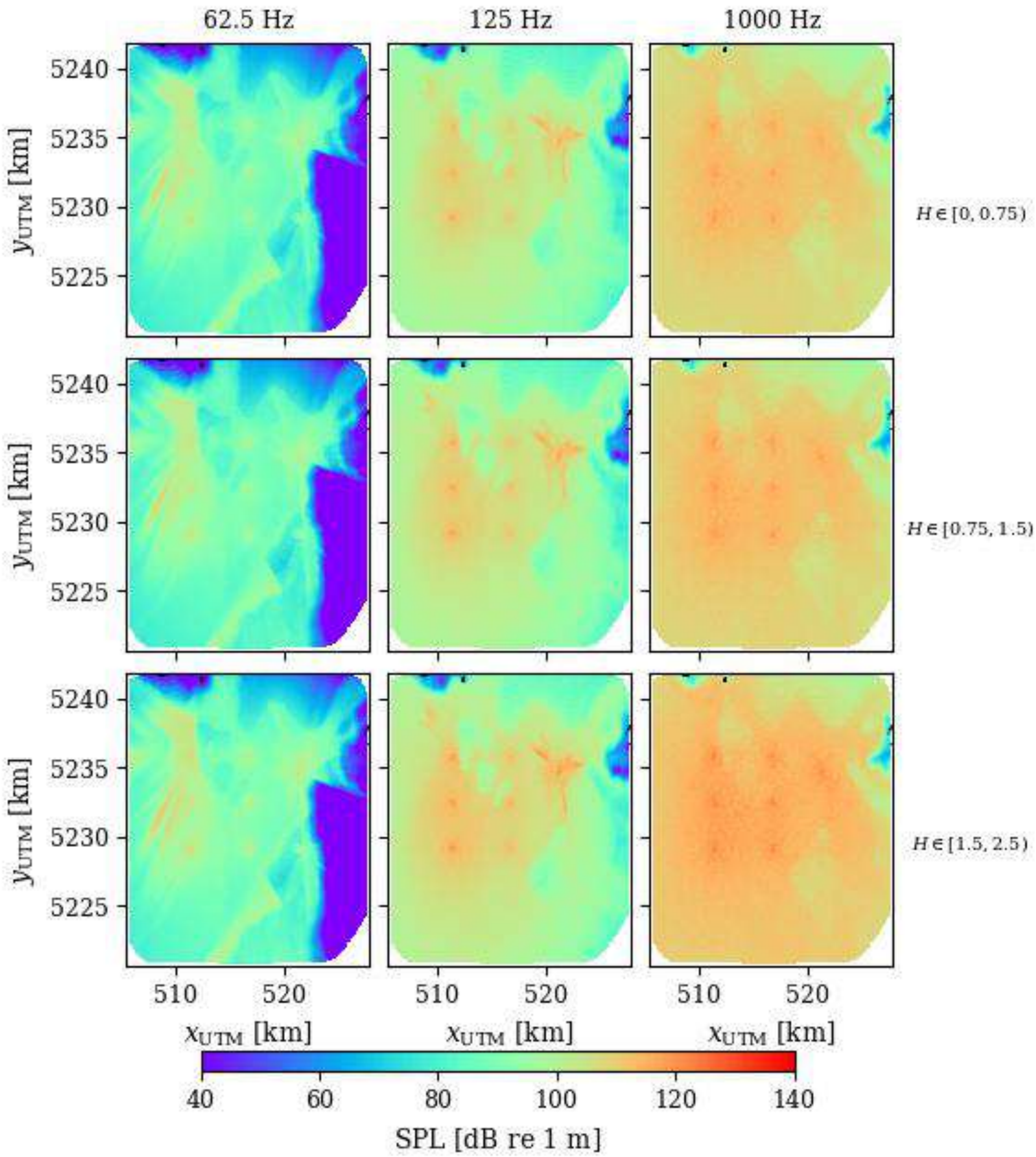

Figure 24. SPL sound maps for the eight devices case at 5 m depth (averaged through Source Levels) for the SEM-REV test site.

In order to compare the impact of 8 WECs against the 1 WEC case, the acoustic disturbance distance has been obtained for this case and the difference between the two cases has been calculated to obtain the acoustic disturbance distance increase (Table 18).

Table 18. Acoustic disturbance distance (km) comparison between the 8 WAVEGEM WECs and the single source cases, in SEM-REV.

	H [m]	[0, 0.75)			[0.75,1.5)			[1.5, 2.5)		
Case	**f [Hz]**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**
Single source		0.2	0.4	1.2	0.2	0.5	1.5	0.3	0.7	2
Array		8	11.4	12	8	11.5	12	8.8	11.6	12
Increase		7.8	11	10.8	8	11	10.5	8.5	10.9	10

As can be seen in Table 18, on average there is a perceived increase of about 10 km radius for all cases. The biggest increases perceived come at 1kHz, as the low-frequency shallow waters filter effects would no longer affect the acoustic waves.

3.5.2 BiMEP

PENGUIN II power capacity is about 600 kW, so, a simulation of 2 WECs was carried out to obtain a maximum power capacity of 1200 Kw (Figure 25).

As for the SEM-REV example, to assess the impact generated by two sources and to compare with the single source case, the acoustic disturbance distance is obtained and the increase between the two cases is computed.

In Table 19, an average increase of 6 km can be found for all cases. However, the biggest increase is given again at the 1kHz frequency with a value of 8.3 km.

Table 19. Acoustic disturbance distance (km) comparison between the 2 PENGUIN II WECs and the single source cases, in BiMEP.

	H [m]	[1.5, 2.5)			[2.5, 4)			[4, 8)		
Case	**f [Hz]**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**	**62.5**	**125**	**1k**
Single source		0.2	0.4	0.3	0.2	0.5	0.4	0	0.3	0.4
Array		4.1	5.2	7	4.8	5.8	7.9	5.9	6.5	8.7
Increase		3.9	4.8	6.7	4.6	5.3	7.5	5.9	6.2	8.3

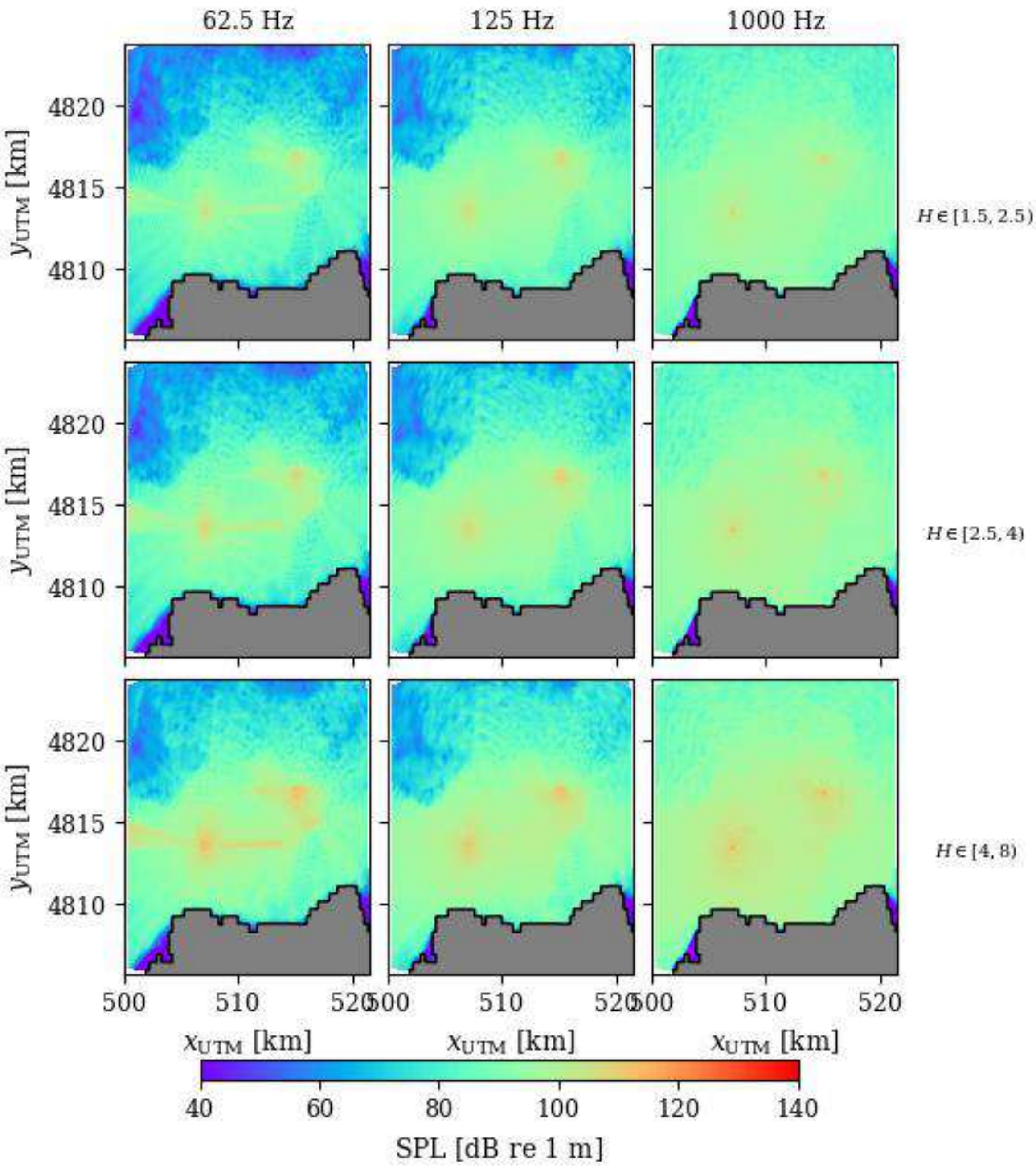

Figure 25. SPL sound maps for the two devices case at 5 m depth (averaged through Source Levels) for the BiMEP.

4. Environmental Impact

The field of studying the impact of noise on cetaceans has been, and continues to be, a heavily explored area, especially since the European Commission included underwater noise as one of its descriptors, Descriptor 11, in the Marine Strategy Framework Directive (MSFD) (Directive 2008/56/EC). Adopted in 2008, the MSFD is a key piece of European Union legislation aimed at the integrated and sustainable management of European seas and oceans. Its main goal is to ensure that all human activities affecting the seas are carried out sustainably, promoting the health and Good Environmental Status (GES) of marine ecosystems. This directive establishes a framework for cooperation among EU Member States and sets clear objectives to achieve GES in all European marine waters.

More specifically, Descriptor 11 states that "the introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment." This can cause some confusion. What does it mean for “the levels to not adversely affect the marine environment?”

Traditionally, 120 dB has been used as a regulatory criterion for disturbances to cetaceans for continuous noise, especially in relation to their feeding (Malme et al., 1986, Richardson et al., 1990). This value has been generalist and based on some studies carried out on mysticetes (baleen whales) during vessel movement to observe oil prospecting activities. Since then, the permitted noise levels in countries like the United States have increased up to 195 dB re 1 μPa^2s for received energy flux density causing Temporary Threshold Shifts (hereafter TTS) and 215 dB re 1 μPa^2s for Permanent Threshold Shifts (hereafter PTS). Energy flux density is a measure that incorporates the duration of exposure based on very limited data from a few individuals of a few species. For a sound of 1-second duration, this level for TTS (195 dB) is over 10,000,000 times more intense than 120 dB re 1 μPa (Weilgart et al., 2007). TTS is the acronym of “Temporary threshold shift”. Exposure to sounds of sufficient intensity can lead to a reduction in acoustic sensitivity, either temporarily and recoverable within minutes or hours (TTS), or permanently (PTS). The accumulation of temporary damage to the auditory system can result in permanent damage. The received sound pressure, along with the repetition and duration of the sounds, will determine the degree of cellular wear in the auditory cells (metabolic exhaustion) or anatomical damage to the cochlear stereocilia. When it is considered the impact in cetacean, TTS and PTS are considered extreme noise levels that should not be reached. That is the reason why, more conservative values have to been taking into consideration. Therefore, in the latest updates from the U.S. National Marine Fisheries Service regarding underwater noise, the criterion of 120 dB re 1 µPa for continuous noise and 160 dB re 1 µPa for impulsive noise has been maintained as the maximum level that should be reached to avoid affecting cetaceans (NMFS, 2024).

On the other hand, the European Union's expert group on underwater noise, TG-NOISE, has developed a methodology within the framework of the MSFD to establish noise threshold levels that allow for assessing effects on biodiversity. This methodology covers both continuous and impulsive noise (Borsani et al., 2023; Sigray et al., 2023) and aims to harmonize the efforts of Member States to ensure that the acoustic energy emitted into the marine environment is not harmful to marine species.

Regarding continuous noise, which is the focus of this analysis, the methodology outlines a series of key steps. The first step is to define the affected area and the species involved. The next step is to identify the Level of Onset for Biological Effect (LOBE), which represents the threshold beyond which individuals begin to experience adverse effects that may compromise their welfare and reproductive success. These effects include behavioral changes, elevated stress levels, reduced communication, and, in more severe cases, the temporary or permanent loss of habitat. Although temporary exceedance of the LOBE is not necessarily critical, prolonged exposure can have negative consequences at population level.

TG-NOISE recommends that LOBE values be established regionally or by Member States, based on available scientific studies. In the absence of data, the precautionary principle is suggested. Once the LOBE is defined, it can be used to determine whether the noise level in a habitat over a given period is tolerable or not. Unfortunately, the methodology was finalized in 2023, so Member States have not yet had sufficient time to define the specific LOBE for each species and habitat.

For this study, given the present situation and in the absence of more specific threshold values, 120 dB re 1 μPa has been used has limit dB that should not be crossed.

4.1 Aguçadoura

The C4 WEC device was monitored in the Aguçadoura test site, in Portugal. In this case, the maximum SL value obtained was 174 dB and it happened for the lowest frequency component (62.5 Hz) and for the wave height bin [2, 2.5) (the bigger recorded in the 9 days that the campaign lasted). The maximum acoustic disturbance distance obtained when assuming an omnidirectional propagation was 2.5 km for a single device in the 125 Hz component for the [2.5, 4) wave height bin.

Bearing in mind that the campaign lasted 9 days, not allowing to capture all the variability in the environment, and also that it was a commissioning campaign, which is not fully representative of the WEC operational and real functioning, no significant conclusions can be drawn for the operational phase for the operational phase. The results obtained could be related with the impacts during commissioning phase. However, for the noise propagation maps, the SPL was calculated for the commissioning phase and it was seen that for all frequencies (62.5 Hz, 125Hz and 1000 Hz) the SPL dropped below 120 dB within the first 10 meters.

4.2 BiMEP

The PENGUIN II device was studied in the BiMEP test site, in Spain. In this case, the maximum SL value obtained was 146 dB re 1 m for the 62,5 Hz component for the [4, 8) wave height bin. In contrast, all the SL values obtained for all the studied frequencies and wave height bins surpass 120 dB. Nevertheless, when studying the propagation maps, the SPL dropped below 120 dB within the first 10 meters for any of the frequencies (62.5 Hz, 125Hz and 1000 Hz) analyzed.

When studying 2 devices (the ones needed for 1200kw), the affected area was estimated as follows: 3 km for 63 Hz and 125 Hz and 6 km for 1000 Hz. As well as for SEM-REV the model accounted for constructive wave interference, representing a worst-case scenario for the impact assessment.

The highest acoustic disturbance area obtained ($SPL_{on} > SPL_{off}$) was 0.7 km^2 and 0,47 km for the 125 Hz band in the [2.5, 4) m band of wave heights for a single device at 1kHz frequency and a mean of 6 km for an array of 2 devices in a scenario of production of 1.200 kw considering all the frequencies (62,5Hz, 123Hz and 1kHz).

4.3 Mutriku

The Mutriku power plant was studied in the Mutriku test site, in Spain. For this device, the highest SL obtained was around 190 dB in the 62,5 Hz and 125 Hz frequencies for the [2, 2.5) wave height bin, highly surpassing the 120 dB. The highest acoustic disturbance area and distance were 6.5 km^2 and 1.44 km respectively for the 125 Hz band and the [2.5, 4) m wave height band. No array was simulated for this test site as the device is an onshore power plant.

For this case, for low frequencies (62.5 Hz, 125 Hz) it was found that 120 db threshold dropped at 50 meters from the source, while for high frequencies (1000Hz) it did at 70 meters from the source.

4.4 SEM-REV

The highest SL obtained was around 150 dB for the lowest component under study (62.5 Hz). The highest acoustic disturbance distance and area obtained was around 2 km and 13 km^2 respectively for the 1 kHz band in the [1.5, 2.5) m band of wave heights for a single device.

For the propagation maps, all frequencies (62.5 Hz, 125Hz and 1000 Hz) as well as with Aguçadora and BiMEP, the SPL dropped below 120 dB within the first 10 meters. On the other hand, when it is considered 8 devices (to reach 1200 kW), the affected area was estimated as follows: 30 meters for 63 Hz, 6 km for 125 Hz (with an average of 2 km), and 7.4 km for 1000 Hz. It is important to highlight that the model accounted for constructive wave interference, representing a worst-case scenario for the impact assessment.

5. Conclusions

Considering the impact threshold of 120 dB re 1 µPa (NMFS, 2024), it seems that all the WECs at source level, could impact negatively cetaceans. However, it is worth noting that in Aguçadora, BiMep and SEM-REV, the values dropped below 120 dB the first 10 meters. For Mutriku, the distance was higher, 50 meters for low frequencies and 70 at 1000 Hz.

In addition, compared to other sites, BiMEP location had a longer sampling period, being the results more representative. In case of Aguçadora for example, no operational data was recorded, being the propagation maps of the commissions not the best representation for "real working scenarios".

Furthermore, achieving a target output of 1200 kW will require the deployment of additional devices. For this project, the SEM-REV and BiMEP sites were analyzed. In these cases, the affected area extended up to 7.4 km for high frequencies at SEM-REV, while at BiMEP, the affected area was approximately 6 km. For low frequencies, the affected area ranged between 2 and 3 km for both sites. Considering the anticipated growth in offshore energy systems in the future, this information is crucial for understanding and mitigating potential impacts.

Therefore, although the obtained results may suggest potential environmental impacts, it is essential to highlight some critical assumptions and recommendations:

- Except for BiMEP, the sampling period was insufficient for some sites. Thus, further data collection is required to better understand the real impact. Extending the monitoring period would be beneficial to assess any correlation between SPL and WEC operation.
- At SL all the devices show higher values that 120dB, nevertheless, the affected area highly varies, being in most of all the cases but Mutriku less than 10 meters effects, not being a big area compared to the whole studied map.

- To better understand the ecological impact of the SLP and apply the TG-NOISE methodology, further efforts are required. This includes defining affected areas, identifying species, and establishing the LOBE based on specific project details (number of devices, operational regimes). These uncertainties remain unresolved.
- As offshore energy is expected to increase in the coming years, long-term studies are needed to fully understand the environmental impacts these new energy systems are having on the marine ecosystem.

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