Underwater noise impact assessment of a wave energy converter in the northern Atlantic (Spain)

E.Madrid, I.Felis, J.A.García, L.Clementino, P.Ruiz, P.Vinagre, J.Bald

Abstract— **The SafeWAVE project monitored and modeled the impacts of wave energy converters (WECs) on the marine environment, using four different WECs deployed in test sites in Spain, France, and Portugal.**

The aim of the present work is to showcase progress beyond the current state of the art by focusing on underwater noise from one of the WECs. Two monitoring campaigns were conducted: one before/during installation and one during operation/ decommissioning using hydrophones. Acquired data was analyzed for Sound Pressure Levels (SPL) at different frequencies and sea states. The study also modeled underwater transmission losses to assess potential acoustic disturbances caused by the WEC and hypothetical arrays of WECs.

Initial results show differences in SPL distributions before and after mooring deployment and during WEC operation compared to background noise levels at the hydrophone location.

*Keywords—***Acoustic disturbance, monitoring, sound pressure level (SPL), underwater noise, wave energy converter (WEC).**

I. INTRODUCTION

As most nations around the world commit to decarbonize their economies, the electrification of various sectors is gaining momentum and is expected to continue growing in the coming years. However, meeting the energy demands of this transition requires substantial resources. Renewable energy sources are being actively promoted as alternatives to fossil fuel technologies.

While marine renewable energy (MRE) is not as mature as wind, hydraulic, or photovoltaic energies, it holds great promise as a mostly untapped resource. MRE can effectively complement the production curves of wind and solar power, offering non-fossil energy to coastal populations and those residing in land-constrained areas such as islands. Given that a significant portion of the population is located near the coast, the development of MRE is particularly important for many countries.

One significant advantage of MRE is its ability to produce energy without CO2 emissions. However, it is crucial to acknowledge and address the potential impacts on the marine environment that may arise from the deployment of wave energy converters (WECs). Theoretical studies have already identified several possible impacts, such as encounters with moorings and cables, collisions with marine organisms, and underwater pollution. Nevertheless, uncertainties remain regarding the actual impacts of operational WECs on their surrounding ecosystems.

To further advance the development of the wave energy sector, various research projects are dedicated to investigating the non-technological barriers associated with MRE. Initiatives like WESE project, SafeWAVE project, and others are focused on understanding and addressing the challenges that hinder the widespread adoption of wave energy technology. These efforts aim to ensure the sustainable and responsible growth of the wave energy sector, balancing energy production with the protection of marine ecosystems.

Overall, as nations strive to achieve their decarbonization goals, the development of MRE presents an exciting opportunity to harness the power of ocean waves and contribute to a cleaner and more sustainable energy future.

In the following sections it is shown, firstly, a description of one of the devices analysed in SafeWave project (Penguin II) as well as its operational profile. After that, we discuss about the methodology of measurements, processing and modelling of the underwater noise radiated by this device, focusing on find the signal radiated from the background noise (special focus on Source Level and Sound Pressure Levels around the source). Lastly, achieved results are shown and first conservative tests for modelling an arrangements of WECs are exhibited.

Funding from the SAFEWAVE Project.

E.M. is at Centro Tecnológico Naval y del Mar, Spain.

Digital Object Identifier: https://doi.org/10.36688/ewtec-2023-675

II. UNDERTEST WEC DESCRIPTION

In SafeWAVE project, the above descripted environmental pressures and impacts have been undertaken for four different types of Wave Energy Converters (WEC): onshore Mutriku Wave Power Plant (Mutriku, Spain), and offshore CorPower Ocean (CPO) HiWave (CPO test site, Portugal), Wello Penguin II (BiMEP test site, Spain) and GEPS Techno WAVEGEM (SEM-REV test site, France). Here, it is presented the results of Wello Penguin II.

A. *WEC description and deployment*

The Wello Penguin II consists of a vessel shaped attenuator device with 43.3 m length, 10.6 m depth, 6.8 m draught, 21.8 m beam and 2.2 t of weight (Figure 1).

Fig. 1. Wello Penguin II WEC.

The installation of the Penguin II mooring cables is scheduled to take place in May 2021, followed by the deployment of the device itself in June 2021 at the Biscay Marine Energy Platform (BiMEP), located in the Basque Country along the Northern Coast of Spain. BiMEP, an open-sea facility, serves as a dedicated site for conducting research, technical testing, and commercial demonstration of pre-commercial prototype utility-scale floating WECs. It offers manufacturers of such devices readily available facilities to validate their designs and assess the technical and economic feasibility of their products.

The Penguin II uses a 6-legged mooring system (Figure 2). Each leg develops a catenary ending with two chain clump anchors. Each mooring leg (319 m as straight) can be divided into four main sections: i) Anchor – From the seafloor; ii) Lower catenary – From the anchor to the buoy; iii) Buoy – Junction between the upper and lower catenary; iv) Upper catenary – From the buoy to Penguin.

The Penguin II umbilical design is a Lazy-S with a mid-water arch, which consists of buoy and two cable bend stiffeners in length of 2.1 m each.

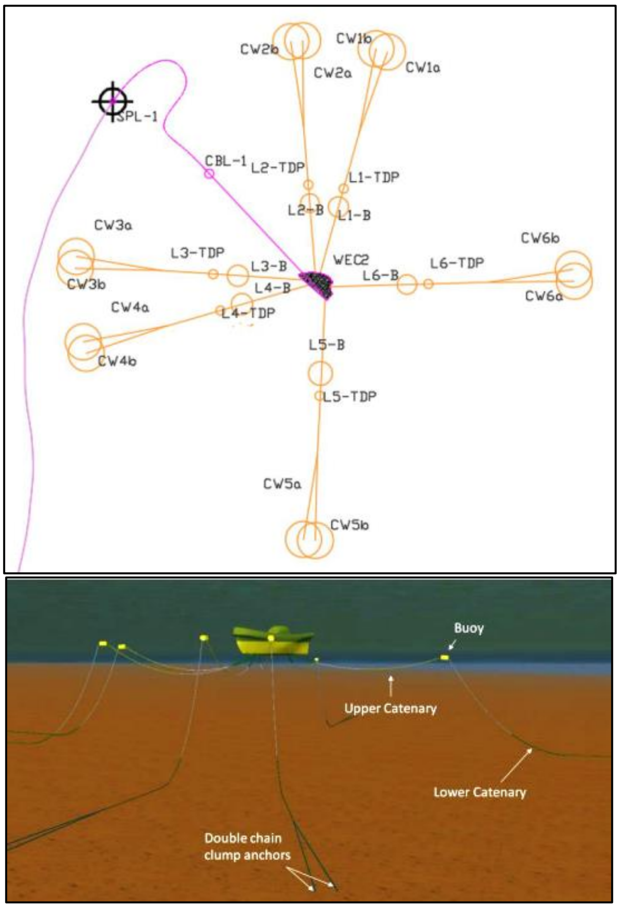

Fig. 2. Schematic view of Penguin II mooring components (top) and positioning of the mooring system (bottom).

B. *WEC operation*

Two monitoring periods were carried out, collecting data in different operating modes and at key dates, such as before and during the installation of the WEC and its subsequent decommissioning.

1) *Pre-operational and installation phase*

Pre-operational and installation phase took place between 16/06/2021 and 10/08/2021, where a hydrophone registered 10 minutes each hour. During this period, two key events occurred, those being the installation of the moorings (vessels) around the 1^{st} of July, and the deployment of the Wello Penguin II WEC around 28^{th} of July.

During the WEC installation, the 20MW total power is distributed over four offshore connection points of 5 MW each (see Figure 3).

2) *Operational phase*

Operational phase took place about four months after the pre-operational and installation phase, between 11/01/2021 and 25/01/2022. In this campaign three hydrophones were deployed in the area to monitor the noise.

During the campaign, different activities were identified, such as "On" (WEC operating), "Vessels" (nearby passage of vessels), and "Decommision" (dismantling of the WEC)

III. METHODOLOGY

According to the Marine Strategy Framework Directive (MSFD), "noise" is defined as an "anthropogenic sound that has the potential to cause negative impacts on the marine environment, including component biota but not necessarily the whole environment" [1].

Operational noise of WECs is of concern to several regulators and stakeholders by the potential impact on marine life. Noise monitoring is a key procedure to characterize the noise emitted by a source and to verify its acoustic propagation.

Information about the sources of noise expected from wave energy devices can be gathered from works done in air for their individual components. The main expected sources of noise are bearings, gearbox, pumps, and ropes. However, depending on their location in the device the noise would not propagate underwater or if it happens their frequency and sound pressure level might not be the same [2].

This section presents the monitoring, processing and modelling plan for "underwater noise" generated by the Penguin II under study.

A. *Underwater noise monitoring*

The underwater noise monitoring plan provides the guidelines for the acoustic monitoring of the WEC under study, particularly for underwater noise measurements. This will address one of the knowledge gaps identified in the MaRVEN report [3] and the OES-Environmental 2020 state of the science report [4] related with the need to characterize sound levels of different MRE technologies.

The parameters to monitor can be divided into three groups: i) acoustic parameters, ii) auxiliary parameters, and ii) complementary parameters.

1) *Acoustic parameters*

Taking into account the different behaviour of the MRE under study, it is possible to measure both background noise and underwater radiated noise.

The background noise (sometimes referred as 'ambient noise') may be distinguished from radiated noise (sound radiated by a specific source under study), and self-noise (the noise generated by the recording equipment and its deployment/platform).

In the context of this study, background noise would exclude radiated noise from the specific device under study. Thus, the background noise would be measured when the source was silent (or absent). In any case, the background noise will not include self-noise of the recording system nor platform noise from the deployment, operation, and recovery of the instrumentation.

In the case that background noise of any of the equipment under study have been already measured, it may be susceptible to be used as background. For this, it will be verified if the site, duration, and quality of the measurements are correct for such consideration.

Radiated noise is the sound emitted by the specific source. This is distinct from background noise, which is the noise received from many indistinguishable sources. Thus, the noise of interest is the noise radiated during operation.

Underwater measurements have been carried out using thre hydrophones model SoundTrap ST300 HF (manufactured by Ocean InstrumentsNZ) sound recorder (Table I).

TABLE I
CHARACTERISTICS OF THE SOUNDTRAP ST300 HF HYDROPHONES

Feature	Value
Sample rate	576, 288, 192, 96, 72 & 48 kHz
Bit depth	16-Bit SAR
Self-noise	Less than 37 dB re 1 μPa above 2 kHz
Sensitivity	-204 dB re 1μPa
Bandwidth	20 Hz to 150 KHz ± 3dB
Dynamic Range	96 dB
Autonomy	Up to 13 days continuous operation
Memory	256 GB
Calibration	Factory OCR calibration certificate
Ancillary Sensors	Temperature – 0.1 °C precision, 1 °C uncalibrated accuracy in water

The hydrophones have been deployed on a mooring line constituted by a mooring of 50-70 kg, followed by a line on which the hydrophone is placed. The whole line stands upright thanks to a subsurface buoy.

These static measuring stations have been sited around 100 m from the device, far enough to ensure far-field conditions but close enough to detect noise from the Penguin II WEC. The planned sampling stations are shown in Figure 4.

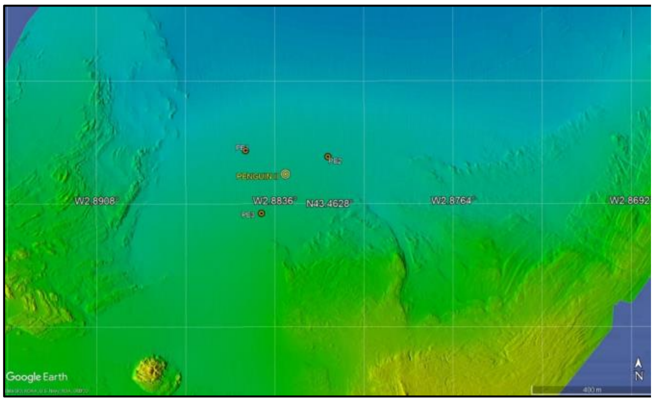

Fig. 4. Static sampling stations around Penguin II device in BiMEP test site.

Since the devices are positioned in shallow waters a bottom mounted system has been used. The hydrophones have been installed for more than two months (from mid-November 2021 to end of January 2022) during which they will record for 10 minutes every hour, with a sampling rate of 96 kHz.

2) *Auxiliary parameters*

Auxiliary parameters are relevant to complement the measured noise levels during analysis. The following parameters will be monitored:

i) Clock synchronization and time: to ensure that all sensors and the control clock are synchronized, time have been specified in UTC, and the drift over determined by comparing the system time with GPS clock time.

ii) Conductivity, temperature, and depth (CTD): probes from Sea&Sun Marine Tech and Sea-Bird have been used to collect data in different points into the test site.

iii) Sound velocity in the water column: it have been calculated accurately using the gathered CTD data.

iv) Sea-state, wind speed and rain: they have been monitored to plan field work and correlate it with underwater noise levels. Data have been obtained from WindGuru and requested from national meteorological entities with 10-minute resolution.

v) GPS location: GPS have been used to collect the precise coordinates of each deployment site, following the WGS 84 coordinates system.

vi) Operational regime: information about the operational regime of the device and its components have been provided by the responsible company at each test site. Additional relevant information such as bearings and pumps have been also provided.

3) Complementary parameters

Complementary parameters correspond to the information that is needed, not only to design the monitoring plan, but also to model underwater noise, those being: i) Bathymetry; ii) Seafloor properties (Bottom type); iii) Sound Speed profile; iv) Shipping.

These data have been obtained mostly from open-source data platforms such as EMODnet and Copernicus and from the technical staff of the test sites.

B. *Underwater noise processing*

To characterize the noise radiated by the WEC, three operational regimes of the device have been selected: Off, On, Uninstalled.

In this work, both spectrograms and spectral analysis will be used to show the most relevant characteristics of the source. This information will be calculated using the PAMGuide (Merchant et al., 2015). Standards for signal processing will be followed [5].

Once all necessary data was gathered, the proposed processing methodology in this project consists of two steps:

1) Obtain the Sound Pressure Level (SPL)

After clear recorded data, the SPL metric is obtained for all underwater noise recordings obtained in 1/3[th] octaves from 15.62 Hz to 20 kHz, but special emphasis will be placed on the central frequencies 62.5 and 125 Hz (following the recommendation of the MSFD).

Mathematically, the SPL is defined as:

$$SPL = 20 \log_{10} \left(\frac{p_{rms}}{p_{ref}}\right) \quad (1)$$

where p_{rms} is the root mean square of the pressure in some chosen interval of time and p_{ref} is a reference pressure (in water, $p_{ref} = 1\ \mu Pa$). The resulting SPL will slightly depend on such interval, that will be equal to 1 second in this study.

2) Obtain the Source Level (SL)

Once the sound files are processed and the SPL is obtained, the following methodology is applied to obtain the contribution of noise from the WEC:

i) All monitored data (SPL, WEC operational regime, sea state) are interpolated to the same timestamps.

ii) The state of operation of the WEC are classified by using a binary class (Off, On). Moreover, the time periods by sea state are classified (following Beaufort Sea state scale) allowing an evaluation of the dependence of SPL on the state of the sea when the WEC is operating.

iii) The percentile SPL distribution is calculated for all these cases. That is, for the baseline or background, and for the "On regime" (and possibly others, such as decommission activities, vessels activity, etc.). Depending on the case, it should be noted that baseline may stand for the existing noise when the device is not operating, or when it is not yet installed.

iv) The difference between cases is explored and serves as an assessment of the contribution of the radiated noise by the WECs to the background noise.

v) Once SPL data is processed, an underwater acoustics propagation model is used to compute the losses over the area.

vi) Source Level (SL) is the sound pressure level at 1 m from the source. With SPL and TL at the points where the hydrophones are placed, backpropagation is carried out, so that $SL = SPL + TL$. It should be noted that three SL will be obtained, as there are three hydrophones, so a mean of these values will be the representative SL.

C. *Underwater noise modelling*

The objective of underwater noise modelling is to simulate the underwater noise levels surrounding the studied WEC, determine their spatial influence on the noise background, as well as explore the acoustic effect of placing many of such device in arrays.

For the calculation of transmission losses (TL) fields, a Nx2D approach was used. The chosen acoustic model was the Monterey-Miami Parabolic Equation (MMPE) model, which is a parabolic equation model able to take into account range dependency on sound speed profile, bathymetry, and seabed geo-acoustic properties. This allows us to maximize the amount of information we can input the model. This model is also expected to behave correctly in the mostly shallow water environments in which the WECs are located, as well as in the low frequencies.

As explained before, underwater noise modelling is necessary to obtain SL, and therefore, it is key to obtain SPL and extract metrics to assess the impact that the WEC may have from an acoustic point of view.

The main steps of the followed methodology are:

1) Obtain the TL

From the source up to the end of the grid, radial transect have been identified, with an angular resolution of 3 degrees, and sampled the environmental parameters along them. Then, the model is run for the main frequencies under study (62.5 and 125 Hz) and transect properties (depths: 5, 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 meters; spatial range: up to 15 km).

The result is a list of 2D slides with TL defined by the radial distance r and the water-depth z. This list of 2D slied of TL have been interpolated into a rectangular grid for each frequency and depth of interest. Then a rectangular georeferenced set of 3D values of TL for each frequency is obtained.

2) Obtain the SPL

After obtaining the SL values, using the results from underwater monitoring and processing phases, and the TL modelled for all frequencies and wave heights, the definitive SPL field caused by the device are 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 definitive result (and its corresponding uncertainty).

3) Obtain the Acoustic Disturbance distance

The acoustic disturbance distance is defined as the area in which the SPL surpasses the background noise levels. It is a useful metric to condense the multidimensional information from the SPL sound maps that were shown in the previous sections. Therefore, using this metric the information from the SPL fields is transformed into a scalar value, which is more convenient to report.

4) Scalling

The objective of scalling is to understand how noise will distribute across the area when working with multiple devices to assess the acoustic impact. The main steps of the followed methodology are:

i) Fit MMPE model to a geometric loss model: To avoid computation problems, MMPE model is fitted to a geometric loss model, which will follow the next equation:

$$TL = a \log_{10}(r) \qquad (2)$$

ii) Set the sources position and obtain losses: Once MMPE model is fitted to a geometric loss model, the number of sources and its positions are selected. After that, TL is obtained for every source.

iii) Obtain SL: For every source, SL is computed the same way it was for the single source case. That is SL = SPL + TL.

iv) Obtain SPL: For every source, SPL is obtained with its respective SL and SPL the same way it was done in the single source case. That is SPL = SL – TL.

v) Add the SPL maps: The SPL maps of every source are transformed into pressure maps (Pa units). After that, we assume a coherent and 100% constructive addition of the acoustic waves in order to assess the most critical case in terms of impact. That assumption means that in every point of the spatial mesh, the result will be the addition of the pressions of every pressure map on that point.

IV. RESULTS

Following the chronological order, the pre-operational and installation phase of the BiMEP campaign is analysed and its results are shown.

A. *Pre-operational and installation phase*

In Figure 4 the main results are plotted, in various ways, as a comprehensive synthesis of the acquired information.

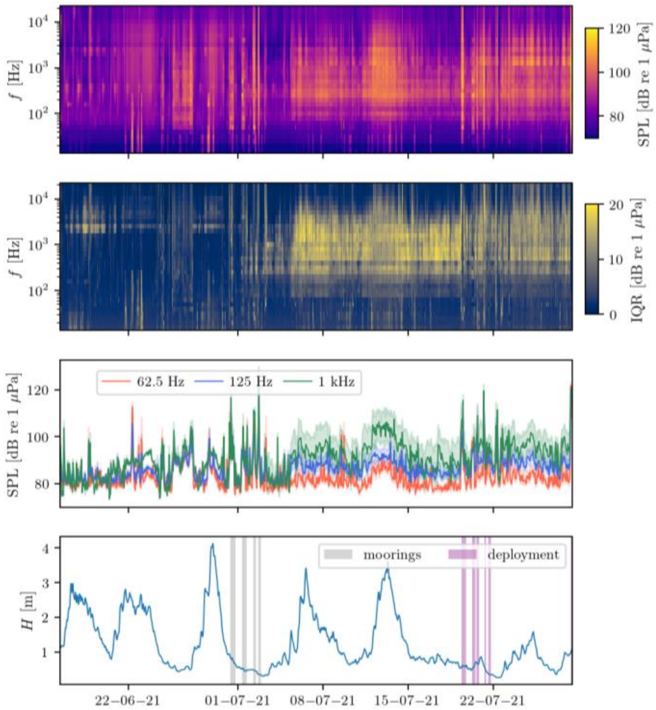

Fig. 4. From top to bottom: spectrogram from hourly SPL median values; the corresponding IQR (Q3-Q1); hourly SPL median time series (IQR in filled bands); significant wave height and relevant periods of activity.

It is particularly noticeable the change brought about by the installation of the mooring lines around the 3rd of July 2021. The noise from vessels during the installation (moorings) and the deployment of the device can also be clearly detected. Although barely visible in the bottom graph, the device was deployed in the end of the monitoring period (around the 28th of July).

To characterize the noise in different regimes, time periods are classified according to two activities or states: "Installation activities" (comprise both "moorings" and "deployment" periods from Figure 4, as they were the main periods in which vessels operated in the area performing field work) and "Background" (further classified into "pre-moorings" and "post-moorings" periods, i.e. before and after full deployment of mooring lines, in order to distinguish the contribution of mooring lines to ambient noise).

In Figure 5 this classification is binned in sea states (i.e., significant wave height: 0,0.75,1.5,2.5,4,5 m) to later find the dependence of SPL with this variable. The total counts of "Installation", "Post-moorings", and "Pre-moorings" are 368 (36.40 %), 643 (58.06 %), 56 (5.54 %), respectively.

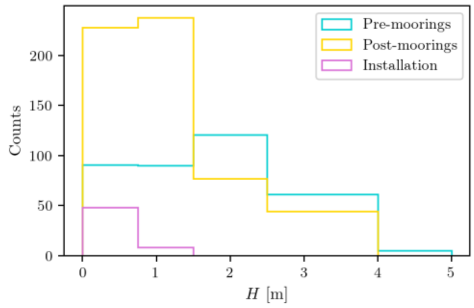

Fig. 5. Histograms of significant wave height values for the different regimes.

With this classification in mind, in the Figure 6 the full percentile distributions are shown. Note that the blank graphs are due to absence of data in the given regime.

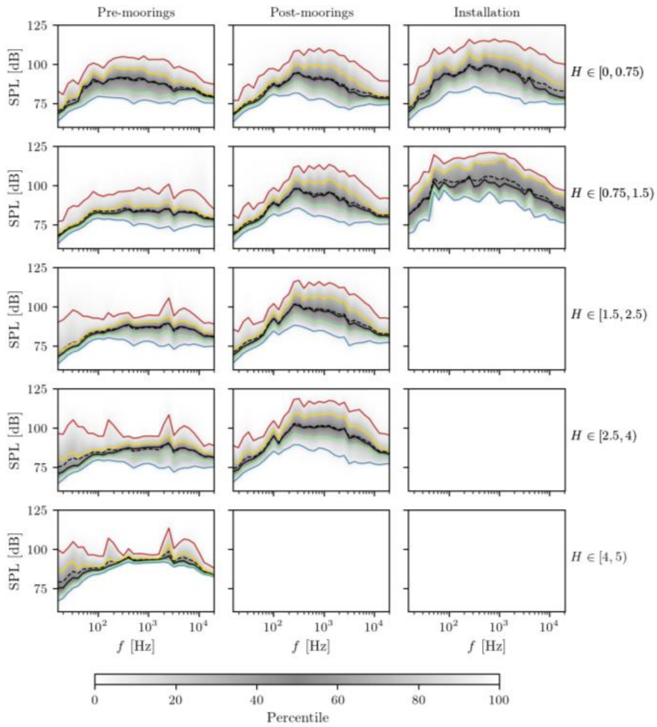

Fig. 5. Percentile distribution of the SPL for each regime and sea state. Percentile 5, 25, 50, 75, and 95 in blue, green, black, yellow and red lines, respectively. The median is shown as a dashed line.

The differences between all regimes are quite noticeable. Overall, noise levels are higher during installation activities (even though data is only limited to wave heights less than 1.5 meters). Post-moorings noise is also consistently higher than that of the pre-moorings period, especially in the mid frequencies and for stronger sea states.

B. Operational phase

In Figure 6, the whole content of the SPL distributions in both main frequency (63, 125 and 1000 Hz) and time is shown as spectrograms, which allows for a quick assessment of the most relevant acoustic signatures, as well as the global hourly median SPL values for the three key frequencies, and the significant wave height whose shadowed areas represent different activities: "On" (meaning WEC operating), "Vessels" (meaning nearby passage of vessels), and "Decommission" (meaning the activities related to the dismantling of the WEC).

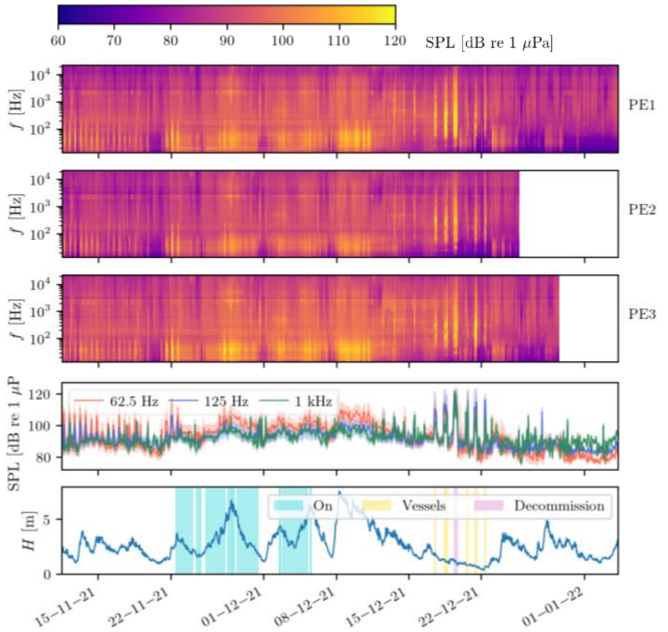

Fig. 6. From top to bottom: spectrogram from hourly SPL median values; the corresponding IQR (Q3-Q1); hourly SPL median time series (IQR in filled bands); significant wave height and relevant periods of activity.

The three spectrograms show great similarity, well correlated with wave height (and vessel passings), and with levels between 80 and 105 dB re 1 μPa, depending on the frequency.

For the previous significant wave height values (0, 0.75, 1.5, 2.5, 4, 8 m), a detailed classification of the SPL distribution for all hydrophones is plotted in Figure 7.

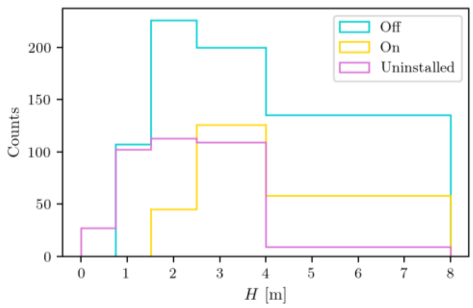

Fig. 6. Histograms of wave significant height for Off, On and Uninstalled regimes.

The total counts were 220 (17.4 %), 669 (53 %), and 373 (29.6 %), for the Off, On and Uninstalled regimes, respectively. It can be noted that lower wave heights (<1.5 m) are absent in the Off and On regime, respectively. But the highest wave heights were very infrequent during the Uninstalled period.

In the Figure 8, the median with Q1 and Q3 statistics curves corresponding to all wave height bin for all sampling sites are presented.

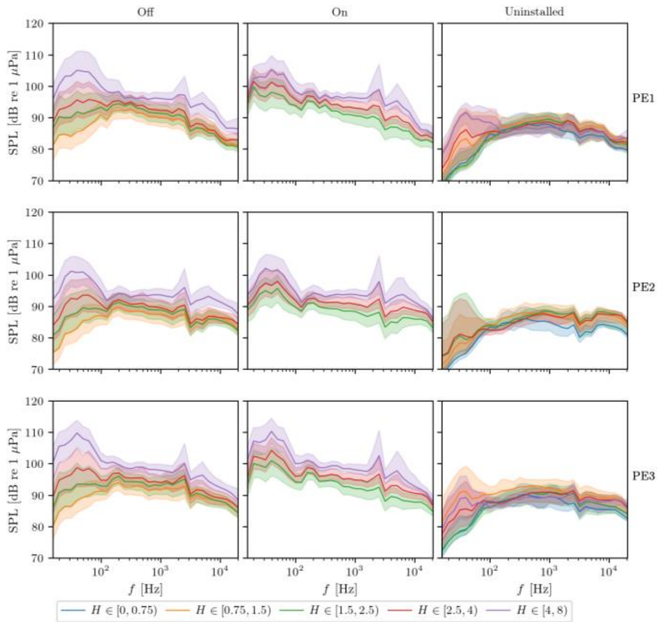

Fig. 8. Median, and Q1-Q3 (bands around) for all sampling sites, regimes, and wave heights for the Operational phase monitoring campaign in BiMEP.

SPL values are generally (for all sampling sites) higher during the On regime, specially in the lowest frequencies, although the difference is slight with the Off regime (it's more pronounced with respect the Uninstalled). There seem to be a contribution from the mooring links at around 2.5 and 5 kHz for all cases, specially for higher wave heights (>1.5 m). This can be checked in Figure 9, in which the actual differences are computed and shown for all sampling sites, regimes, and wave height bins.

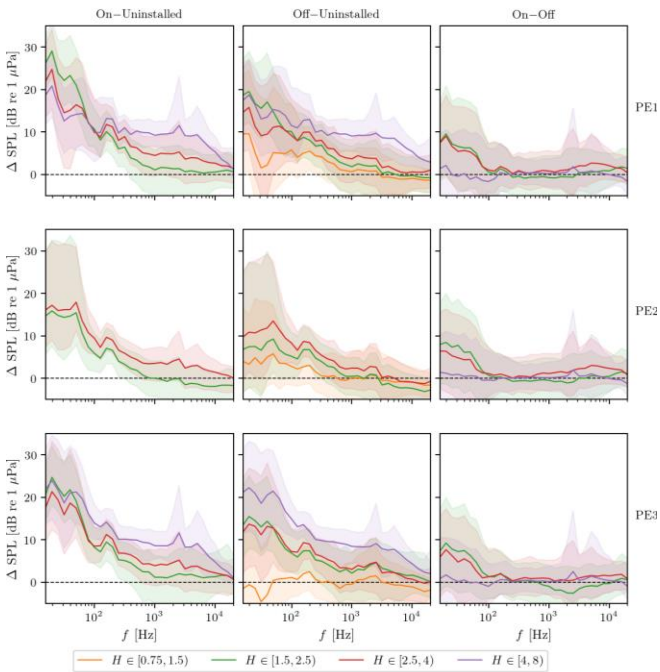

Fig. 9. Median (Q1-Q3 in solid bands around) SPL differences between regimes, for all wave heights, as function of frequency.

As expected, differences of up to 28 dB re 1 µPa can be found when comparing On-Uninstalled regimes (for PE1). If we take into account the deviations, the significant differences are indeed found for the On-Uninstalled and Off-Uninstalled regimes. In average, the more energetic sea states (and the lower the frequency), the bigger the difference in SPL.

Finally, the percentile SPL distribution corresponding for the period of decommission is shown in Figure 10, which show the highest overall levels during the whole campaign, with median values surpassing 120 dB re 1 µPa for the band centred in 300 Hz.

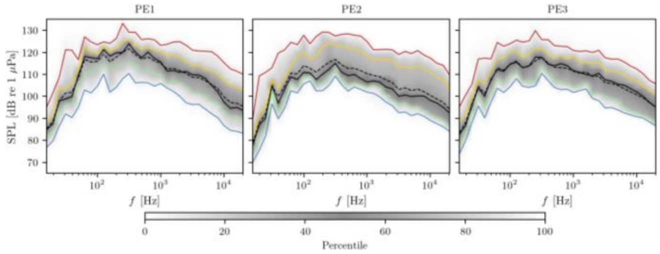

Fig. 10. Percentile distribution of the SPL for each sea state and sampling sites, for the "Decommission" period. Percentile 5, 25, 50, 75, and 95 in blue, green, black, yellow, and red lines, respectively. The mean is shown as a black dashed line.

Summarizing, for the main frequencies under study (63 y 125 Hz), the following Source Levels of Penguin II have been identified, one from each hydrophone:

TABLE II
SL [DB RE 1 M] OF THE PENGUIN II WEC

H [m]	[0,1.5)		[1.5, 2.5)		[2.5, 4)		[4,8)	
f [Hz]	62.5	125	62.5	125	62.5	125	62.5	125
PE1	-	-	139.1	134.4	142.3	136.4	146.2	139.2
PE2	-	-	136.2	133.2	138.8	134.4	143.1	136
PE3	-	-	131.4	138.6	134.4	140.8	140.5	144.8

After combining the SL and the TL for the PENGUIN II device, the resulting SPL fields are obtained (see Figure 11) 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, exceeding the background levels (marked with black contours) just in the vicinity of the WEC.

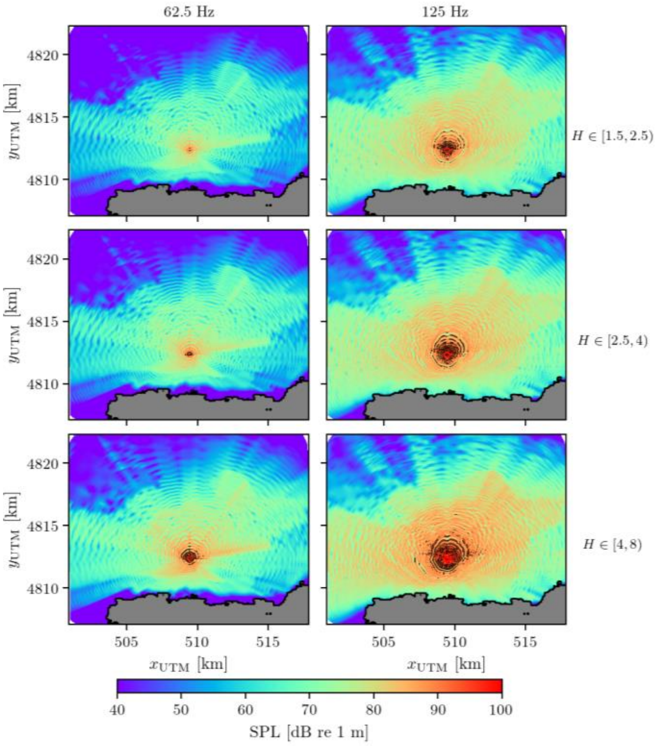

Fig. 11. SPL sound maps at 5 m depth (averaged through seasons and Source Levels) for the BiMEP test site. In black contours are encircled the area in which SPL>SPL_{off}.

C. *Acoustic disturbance distance from the WEC*

Using the SPL sound maps, combined with the SPL_{off} information from *Section IV.B* (see figure 8), it is obtained the distance of acoustic disturbance of Penguin II WEC, which leads to the following results for each wave height bin and frequency.

TABLE III
ACOUSTIC DISTURBANCE DISTANCE (KM) FOR THE PENGUIN II WEC

H [m]	[0,1.5)		[1.5, 2.5)		[2.5, 4)		[4,8)	
f [Hz]	62.5	125	62.5	125	62.5	125	62.5	125
Winter	-	-	0,18	0,44	0,18	0,47	0,00	0,36
Springer	-	-	0,18	0,44	0,18	0,47	0,00	0,36
Summer	-	-	0,18	0,40	0,18	0,44	0,00	0,36
Autumn	-	-	0,18	0,44	0,18	0,47	0,00	0,36

As expected, acoustic disturbance distance is larger for the 125 Hz frequency than for the 62.5 Hz frequency. This is due to the shallow nature of the test site water, which acts as a low frequency cut-off filter, resulting in more efficient propagation at 125 Hz. It should also be noted that there are almost no differences between seasons even though the work was carried out in shallow waters.

D. *Preliminary scaling for arrangements of WECs*

In order to pave the way to assess the impact that a farm of WECs would produce from the acoustic point of view, conservative several simulations has been conducted using the methodology described in *section C.4.*

1) Four close sources:

As can be seen in Figure 12, SPL ranges from 90 to 150 dB. It is worth noting that SPL is higher the closer to the source, but it decreases very fast when distance from the sources increase.

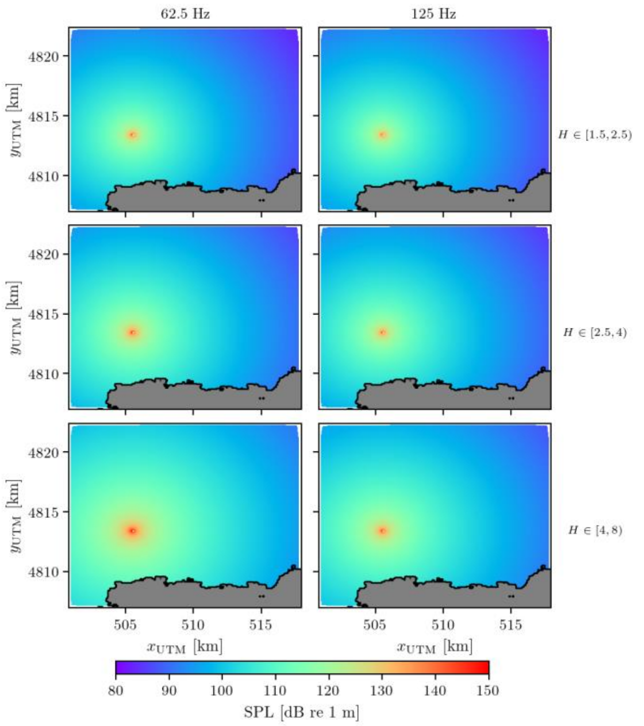

Fig. 12. SPL sound maps at 5 m depth (averaged through seasons and Source Levels) for the BiMEP test site for the two close sources test.

The calculation of the acoustic disturbance distance can be calculated in the same way as for the single source case (see *Section IV.C*). That is, using the SPL map and the SPL_{off} information and defining the contour where SPL > SPL_{off}.

TABLE IV
ACOUSTIC DISTURBANCE DISTANCE (KM) FOR FOUR PENGUIN II WECS

H [m]	[0,1.5)		[1.5, 2.5)		[2.5, 4)		[4,8)	
f [Hz]	62.5	125	62.5	125	62.5	125	62.5	125
Winter	-	-	7,98	8,00	7,61	8,10	6,83	7,75
Springer	-	-	7,98	8,00	7,61	8,10	6,83	7,75
Summer	-	-	7,98	8,00	7,61	8,10	6,83	7,75
Autumn			7,98	8,00	7,61	8,10	6,83	7,75

A coherent and 100% constructive addition is the most critical case in terms of acoustic impact, as the noise emitted by the four acoustic sources would be added. In this case the largest disturbance distance obtained (8 km) is expected to be larger than expected in a real deployment of these devices due to the conservation of this approach.

2) Four separated sources:

As shown in Figure 13, for the case of five separated sources the SPL values range between 100 and 145 dB. The same pattern of values decreasing fast when distance to the source increases appears. This is due to the fitted model, which essentially only depends on distance to the source.

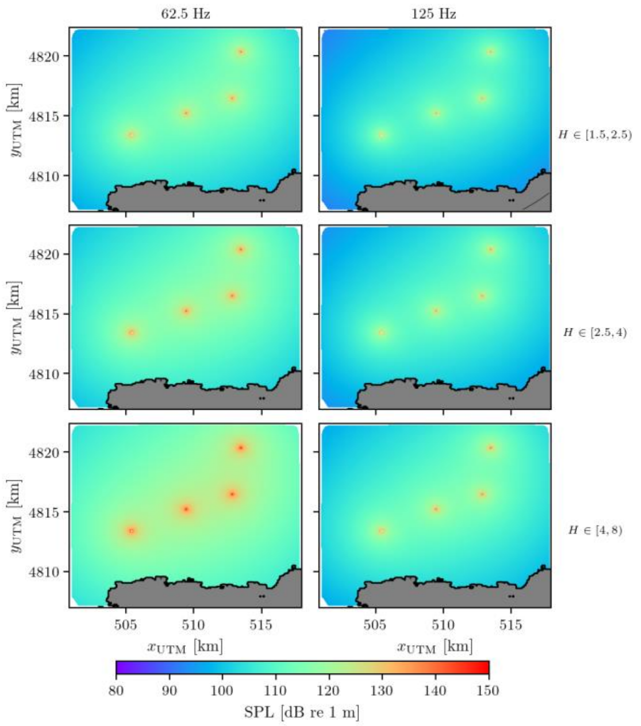

Fig. 13. SPL sound maps at 5 m depth (averaged through seasons and Source Levels) for the BiMEP test site for the four separated sources test.

As described for the four close sources case, acoustic disturbance distance is obtained following the same methodology:

TABLE V
ACOUSTIC DISTURBANCE DISTANCE (KM) FOR FOUR PENGUIN II WECS

H [m]	[0,1.5)		[1.5, 2.5)		[2.5, 4)		[4,8)	
f [Hz]	62.5	125	62.5	125	62.5	125	62.5	125
Winter	-	-	8,98	8,95	8,83	8,97	8,52	8,86
Springer	-	-	8,98	8,95	8,83	8,97	8,52	8,86
Summer	-	-	8,98	8,95	8,83	8,97	8,52	8,86
Autumn			8,98	8,95	8,83	8,97	8,52	8,86

Values in this case are slightly bigger than the ones with the four separated sources case as expected despite of the bigger distances between sources. In any case, all the obtained values can be understood as an upper limit from the expected real values of these arrangements of WECs.

V. Conclusion

The SafeWAVE project has carried out acoustic monitoring and modelling to assess the impact of four WECs in the Atlantic. This paper describes the methodology used and applies it to the BiMEP test site in the Bay of Biscay.

Regarding monitoring, for the **pre-operational and installation phase**, we see an increase in the SPL after deployment of moorings (+15 dB re 1 μPa for high wave heights), and even a greater increase during the installation phase (differences up to 20 dB re 1 μPa). If we consider the interquartile range as a measure of uncertainty, for the post-mooring – pre-mooring case the main relevant frequencies (> 0 dB) are found within the 100-300 Hz (upper bound rising up to 1 kHz for the strongest sea state). On the other hand, during the installation activities the difference was more broadband (all spectrum except frequencies above 5 kHz).

For the **operational phase** (and decommission), there seem to be some contribution of the WEC operation to the background noise. In this regard, all sampling sites and regimes show a similar behaviour, with the lower frequencies showing the greater differences in SPL. Separating in cases:

i) On-Uninstalled: all wave height bins show significant (e.g., lower bound above 0 dB) differences (up to 28 dB re 1 μPa that approximately lineally decrease with frequency) in SPL up to 300 Hz (for $H \in [1.5,2.5)$, which is the minimum case) or up to 20 kHz (for $H \in [4,8)$, which is the maximum case).

ii) Off-Uninstalled: similarly to what happens with the case before, generally all SPL in wave height bins show a resemblance in their behaviour with the frequency. The differences are less significant than with respect to the On-Uninstalled case, but still significant for the stronger sea states. Stronger sea states lead to higher differences, with the bin $H \in [4,8)$ causing all frequencies to show a significant increase in SPL (~20 dB re 1 μPa for low frequencies).

iii) On-Off: in this case the differences are much smaller, and in fact, there is no frequency for which the difference can be deemed as significant by our criterium.

iv) The decommission period was acoustically characterized by the highest values of SPL found in the campaign, with values over 120 dB re 1 μPa (centred around 300 Hz).

Regarding the modelling of the acoustic source, as stated before, the 62.5 Hz frequency showed an inefficient propagation compared to the 125 Hz frequency (see Figure 11) due to the shallowness of the test site water. It is also worth noting the dependence of SPL with wave heights, which is particularly noticeable in the vicinity of the WEC.

After scaling tests, acoustic disturbance distances for multi-source case show an increase compared to the single source case. However, it is important to note that these tests represent the most critical case in terms of acoustic impact, as they were carried out with a fitted geometric loss model and assessed the most critical case due to the 100% constructive and coherent addition.

References

[1] MSFD, "establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive) (Text with EEA relevance)," 2008.

[2] J. Walsh, I. Bashir, J. K. Garrett, P. R. Thies, P. Blondel, and L. Johanning, "Monitoring the condition of Marine Renewable Energy Devices through underwater Acoustic Emissions: Case study of a Wave Energy Converter in Falmouth Bay, UK," *Renew Energy*, vol. 102, pp. 205–213, Mar. 2017, doi: 10.1016/j.renene.2016.10.049.

[3] F. Thomsen, "MaRVEN - Environmental Impacts of Noise, Vibrations and Electromagnetic Emissions from Marine Renewable Energy," 2015.

[4] A. Copping and L. Hemery, "OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES)," Richland, WA (United States), Sep. 2020. doi: 10.2172/1632878.

[5] J. Pajala, "BIAS-Baltic Sea Information on the Acoustic Soundscape," 2015.