On the errors in annual energy yield estimation due to monodirectional wave spectra assumption

Cervelli G., Giorgi G., and Mattiazzo G.

Abstract—**The wave energy sector has made significant progress, and its potential is tangible. However, in order to make wave energy production a key tool in the energy transition, it is crucial to minimize the uncertainty associated with the energy production assessment. Trustworthy evaluations are reachable only through detailed analyses based on reliable, accurate and representative wave data. The use of synthetic parameters exclusively derived from a frequency spectrum leads to the neglect of directional information and the combination of wind waves and swells is treated incorrectly. This study investigates errors associated with relying solely on the frequency spectrum and points out the relevance of directionality. The island of Pantelleria serves as a case study, and the results show that PeWEC (Pendulum Wave Energy Converter) performance is overestimated when the monodirectionality of the waves is assumed. Neglecting the directional information contained in the frequency-direction spectra results in an overestimation of energy production of 40%.**

Index Terms—**Wave energy, Wave frequency-directional spectrum, PeWEC, Dynamic response, Sea states**

I. INTRODUCTION

THE energy transition is a crucial factor in achieving the Sustainable Development Goals outlined in the United Nations Agenda 2030 [1]. Wave energy has the potential to significantly improve energy security and reduce environmental impact due to its predictability, persistence and high energy content [2], [3]. However, compared to other renewable sources, such as wind, the exploitation of wave energy is still in its early stages [4]. Several Wave Energy Converters (WECs) are designed, each using different principles to produce energy from the sea [5]. Attenuators, point absorbers, and terminators [6] are the three types of WECs, classified according to their size and direction of operation: attenuators are aligned with the dominant wave direction, while point absorbers are smaller in size than the wavelength of the waves. As for the terminators, they produce energy when oriented perpendicular to the direction of wave propagation. According to this classification, attenuators and terminators, unlike point absorbers, are sensitive with respect to the wave direction [7], whereby, the energy produced decreases as the difference between the direction of operation and the direction of incoming waves increases. Despite their different operational characteristics, the frequency spectrum is commonly used to quantify the amount of energy produced by the WEC. In general, waves can be fully described as a superposition of harmonics, whose energy is distributed over various frequencies and directions [8]. Frequently the computational time and the complexity of the problem is reduced analysing only the distribution of energy on the frequencies. Although this approximation may be legitimate for some applications, the error in the productivity estimate is rarely quantified. In fact, only the significant height (H_s) and the energy period (T_e) can be calculated from the frequency spectrum, while the mean wave direction (Dir_m) and directional spreading (s) are ignored. An overestimation of energy, calculated using the synthetic parameters H_s and T_e and keeping out Dir_m, is estimated to be between 31% and 47% [9]. Furthermore, neglecting the directional spreading (s), the variability of the direction of the components of the waves would also be omitted: [10] shows that the directionality of the components of the waves influences the dynamic response of the PeWEC (Pendulum Wave Energy Converter) [11] up to 5% for the pitch motion, also inducing roll and yaw rotations that would otherwise be overlooked. A similar study [12] shows that the closer the sea state is to the monodirectional case, the more directional devices operate under optimal design conditions.

To account for the directional information of the wave spectrum, in the study of the dynamic response of the WECs, the frequency-direction spectrum must be used. This approach considers the distribution of energy along different frequencies and directions and is particularly useful for studying WEC response to sea states with multiple peaks, where locally generated wind waves overlap with swell generated by winds far from the study area [13]. The present study highlights the limitations of the monodirectional approach and compares the PeWEC energy production origin by the frequency spectrum and by the frequency-directional spectrum. The objective of this investigation is to quantify the influence of direction in evaluating PeWEC performance. Using the frequency-directional spectrum, not only direction and directional spreading are included, but the multi-peak energy distribution for the combination of wind and swell waves is analyzed. The paper investigates the sea states of the island of Pan-

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telleria, utilizing frequency-direction spectra of ERA5 reanalysis dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) [14]. The results of the study are based on a specific device whose performance has been evaluated with reference to the sea states occurring on a specific site of interest. Despite the specificity of the analysis, the results suggest the importance of using the frequency-direction spectrum in quantifying the energy produced; similar implications are expected when considering other WEC concepts.

The following section presents a description of the methodology used in this study, which includes the spectrum approach and PeWEC dynamic response analysis. In Section 3, a case study is detailed, describing the occurred sea states in Pantelleria in 2022 and highlighting that swells hold 35% of the total annual wave energy. Finally, the results of the study are presented, revealing an overestimation of the energy production by 40% in the monodirectional assumption. These analyses emphasize the importance of utilizing a frequency-direction spectrum approach for a more accurate assessment of the performance of WECs under realistic sea states.

II. Methodology

To evaluate the performance of the PeWEC, the study considers both the frequency-direction and frequency spectra of the sea states that occurred on Pantelleria in 2022. To quantify the error in calculating the PeWEC productivity, the forces acting on the hull have been determined using monodirectional and multidirectional hypotheses. Starting from the identification of the main direction of the incoming waves, the optimal operating direction of the device is assigned; in fact, it is assumed that the mooring system does not allow the device to self-align with the direction of the main wave. The frequency-direction spectra have been obtained from the European Center for Medium-Range Weather Forecasts (ECMWF), whereas the frequency spectra have been obtained by integrating the frequency-direction spectra over the directions [15]. To evaluate the energy distribution corresponding to wind waves and swells, the partitioned parameters significant wave height and mean direction were also obtained from the ERA5 dataset. The zero-order momentum of the spectrum [16] is used as a proxy to evaluate the wave energy, starting from the significant wave height parameter. The mean direction of the waves, on the other hand, has been used in combination with the zero-order momentum to reproduce the partitioned wave roses. The sea surface elevation has been then evaluated as a superposition of Fourier components with different amplitudes, phases, angular frequencies and directions [17].

The dynamic response of the PeWEC system has been analyzed using the time series of sea states. The time series of the forces acting on the device have been obtained by combining the coefficients of the wave components with the coefficients of the excitation forces, which depend on the hydrodynamics of the PeWEC.

Finally, the performance of the PeWEC has been obtained by representing the linear time-invariant state space of the system. In particular, the hydrodynamic modelling of the WEC has been achieved using the Cummins equation in the time domain and the Lagrange equation has been used to derive the mechanical interaction between the float and the pendulum. These analyses help provide a comprehensive understanding of the dynamic behaviour of the PeWEC in different sea states, which is essential for the accurate evaluation of its performance. Using frequency-direction spectra, the study ensures a more accurate assessment of PeWEC productivity, while the use of time-series data provides a more realistic representation of the forces acting on the system.

A. Wave dataset

The WAM wave propagation model [18], which is used by the European Center for Medium-Range Weather Forecasts (ECMWF), provides wave parameters such as significant wave height, wave energy period, and mean wave direction. These parameters can be obtained as a combination of wind and swell waves or through spectrum partitioning [19], which provides a more detailed understanding of the characteristics of the sea state. Additionally, the frequency-directional wave spectra are provided with 24 directions and 30 frequencies, offering valuable information on the distribution of wave energy across different frequencies and directions.

While the accuracy of ERA5 dataset is lower than that obtained from in-situ instrumentation or downscaling models, the information provided can still be helpful for a preliminary assessment of the sea conditions [20]. It's important to note that the spatial resolution of the model is 0.5° x 0.5° (about 50km x 50km), which may not be sufficient for some applications that require higher resolution data. Nonetheless, the open access to the ECMWF wave model data provides a valuable resource for wave energy resource assessment [21] and the evaluation of WEC performance [22], allowing stakeholders to gain a better understanding of the potential of wave energy in different regions and inform the development of more effective strategies for its exploitation.

1) wave elevation: In the wave energy field, the frequency density spectrum $S(\omega)$ is often used to show how the energy of sea surface elevation is distributed over the angular frequency ω. However, to fully describe the complex motion of three-dimensional waves, the frequency-direction wave spectrum $S(\omega, \theta)$ must be used, which provides a complete statistical description of the waves. The monodirectional and multidirectional wave spectra are related by a simple relationship expressed as:

$$S(\omega, \theta) = S(\omega) D(\theta; \omega) \tag{1}$$

where $D(\omega, \theta)$ is the directional spectrum, a frequency-dependent function that is normalized to

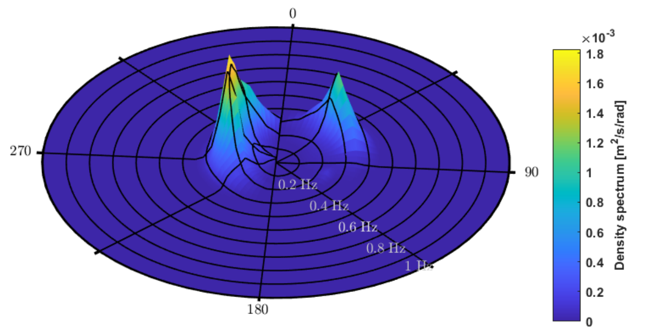

Fig. 1. Example of a frequency-directional spectrum of a multi-peak sea state, occurrenced at Pantelleria, where wind wave and swell have a similar frequency range.

ensure its direction integral is unitary. To obtain the frequency spectrum from the frequency-directional spectrum, it is necessary to integrate along the directions:

$$S(\omega) = \int_0^{2\pi} S(\omega,\theta) d\theta \quad (2)$$

The frequency-directional spectrum makes it possible to evaluate how the energy is spread over the different frequencies and directions. Furthermore, when wind waves and swell overlap simultaneously in the same area, only the frequency-directional spectrum fully describes sea conditions. Indeed, if the energy of wind waves and swell is distributed on the same frequencies, it is erroneously assumed that the energy is also distributed over the same directions. Figure 1 represents a multi-peak sea state occurrenced at Pantelleria, i.e. characterized by the superimposition of a wind wave and a swell and having the same frequency range and different directions.

Moreover, the parameter m_0 can be used to evaluate the total variance of the sea state, using it to identify the total energy of the waves:

$$m_0 = \int_0^{2\pi} \int_0^{\omega_\infty} S(\omega,\theta) d\omega d\theta \quad (3)$$

Through the irregular wave theory, the movement of the sea surface is analyzed as a sum of various sine wave components with different amplitude, angular frequency, direction and random phases, thus characterised by a fixed shape and periodic features. Through the superposition of the wave components, it is possible to study the irregularity of the real state of the sea by means of a finite number of components since waves characterised by high frequency tend to have a negligible impact on the analysis [23]. The elevation of the free surface is described using the double summation method [24].

$$\eta(t) = \sum_{j=1}^{N} \sum_{l=1}^{M} a_{jl} cos(\omega_{jl} t + \varphi_{jl}) \quad (4)$$

The amplitude of each component is represented by a_{jl}, the angular frequency of the wave is ω_{jl} and the phase is φ_{jl}. The indices j^{th} and l^{th} represent the frequency and direction of the wave, respectively. Using the Deterministic Amplitude Scheme (DAS) [25], random phases and deterministic amplitudes derived from the spectrum: according to this method, the phase is randomly distributed between 0 and 2π with uniform probability. As far as the angular frequency is concerned, a range between 0.216 rad/s and 3.43 rad/s has been considered, while all directions of the incoming waves have been considered.

B. PeWEC

The analyzed device is the PeWEC [11], [26] , a self-referenced inertial based floating system, composed of a curved hull containing a pendulum and the Power Take-Off (PTO). The energy is converted thanks to the relative pitching motion, between the hull and the internal pendulum, induced by the action of the waves on the device. In particular, the pendulum moves due to the inertial motion of the floater and the potential variation of energy given by the oscillating mass: the Power Take-Off connected to the hinge of the pendulum converts the kinetic energy relating to this movement into electrical energy. Given the mode of operation, the PeWEC can be classified as a sensitive device with respect to the direction of origin of the waves. A control law is implemented in the PTO to optimize the pendulum dynamics at different sea states, maximizing its energy output. Thus, the PTO generates a reaction torque, which is regulated by the driver's control system. The inertial properties, necessary for the correct distribution of the masses, are obtained through the use of internal sandboxes. The PeWEC hull is designed as a sealed steel structure with a curved keel, two sidewalls and a flat top. The device is kept in the same installation site by means of a mooring system which does not allow its orientation with respect to the direction of the incident wave.

1) Dynamic response: A fully linear model is implemented in the time domain and it is based on linear potential flux. The NEMOH software [27] has been used to analyze the hydrodynamic characteristics of the PeWEC, which implements the boundary element method: the radiation and diffraction problems in the frequency domain have therefore been solved and the excitation forces coefficient (f_w), the addition mass (A) and radiation damping (B) calculated. The dynamic response of the device has been analyzed using the dynamic equation in the time domain:

$$M\ddot{X}(t) = T_{ext}(t) + T_h(t) + T_r(t) + T_x(t) \quad (5)$$

where the inertia of the floater with respect the rotation axis is M, $T_{ext}(t)$ is the excitation torque, $T_h(t)$ is the hydrostatic restoring torque, $T_r(t)$ is the radiation torque, and $T_x(t)$ is the reaction torque generated by the dynamic coupling between the pendulum and the floater. The radiation torque $T_r(t)$ has been identified by the Cummins equation:

$$\mathcal{T}_r(t) = -m_\infty \ddot{X}(t) - \int_0^t h(t-\tau)\dot{X}(t) d\tau \quad (6)$$

where m_∞ represents added mass at infinite frequency and $h(t)$ is the causal radiation impulse response. The linear time-domain equation of motion then becomes:

$$(M + m_{\infty})\,\ddot{X}(t) + \int_0^t h(t-\tau)\dot{X}(t) + (K_h + K_p)X(t) = T_{ext}(t) \quad (7)$$

K_h is the hydrostatic stiffness, K_p the restoring force of the pendulum and $X(t)$ is the state vector. The excitation forces $T_{ext}(t)$ is composed of $T_{PTO}(t)$, that is PTO action, and wave force $F_w(t)$, consisting in diffraction and Froude-Krylov forces, felt by the device due to the incoming waves. The values of the wave force coefficients have been combined with the amplitudes, frequencies and phases of the wave components to evaluate the temporal evolution of the wave force acting on the PeWEC:

$$F_w(t) = \sum_{j=1}^{N} \sum_{l=1}^{M} |f_{w_{jl}}| a_{jl} cos(\omega_{jl} t + \varphi_{jl} + \angle f_{w_{jl}}) \quad (8)$$

where $f_{w_{jl}}$ are the complex coefficients of the wave. In the monodirectional study, the direction of each component has been assumed parallel to the orientation of the PeWEC. Conversely, in the multidirectional case, each component has been characterised by the respective direction. In order to compare comparable results, the orientation of the PeWEC was fixed with respect to the main wave direction.

III. Case study

In the present study, the error induced by the monodirectional assumptions is evaluated by comparing the PeWEC performance in regard to multidirectional assumptions. The island of Pantelleria is the case study and it is located in the Mediterranean Sea, between Sicily and Tunisia, and it is of interest in exploring the wave energy potential having favourable conditions for its high wave energy potential [28]. In fact, the island is located in the Strait of Sicily, and it is exposed to strong Mistral winds, which generate energetic waves.

A. Sea States characterization

An accurate analysis of the characteristics of the sea states acting on Pantelleria has been conducted to identify the main characteristics of the waves. A three-hourly time series have been analysed to evaluate the sea states occurrences in 2022. In particular, the wind waves and swell information are obtained by ERA5 dataset, computed partitioning the spectra. The directional distribution of the zero-order moment m_0 (Figure 2) has been used to compare the amount of energy of the wind waves and swell, occurring in Pantelleria, with reference to the direction of incoming waves. In Figure 2, both the wind and swell waves with more amount energy and more occurring have an incoming direction from the North-West sector, secondarily in the South-East sector. This is due to the geographical position of the island, where the waves and winds arriving from the North-East and South-West sectors do not find obstacles due to the presence of lands or islands. As regards the main sector (North-West), more than 50% of the waves have a

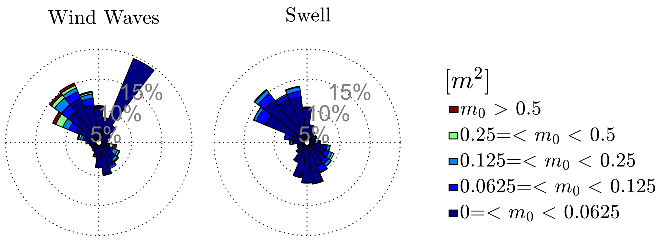

Fig. 2. Directional distribution of the zero-order moments of the wind and swell waves obtained from the partition of the spectra, considering a three-hourly time series of the year 2022 at Pantelleria

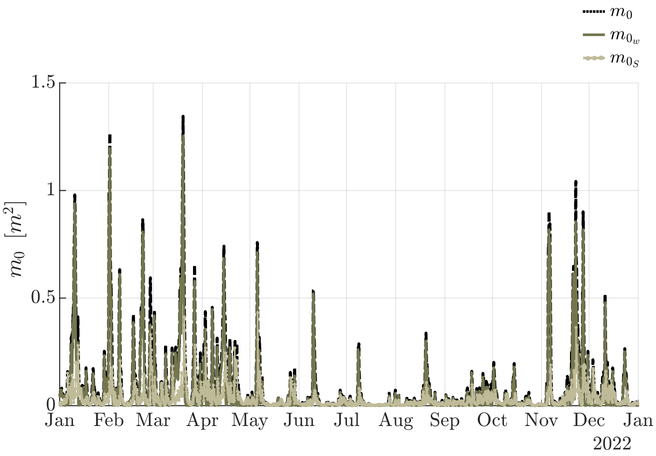

Fig. 3. Time series comparison of zero-order moments of the combination of wind and swell waves m_0, wind waves m_{0_w} and swell waves m_{0_s} in the year 2022 at Pantelleria

zero-order moment greater than 0.0625 m^2, reaching the maximum value of 1.25 m^2. Swells, on the other hand, have significantly less energy: less than 50% of swells from the North-West sector have a zero-order moment between 0.0625 m^2 and 0.43 m^2. Furthermore, the greatest percentage of wind waves that occur on the island have a direction of origin at 15°, where the strong Grecale winds, blowing from the North-East, do not have enough fetch to generate waves with a high energy content; moreover, this wind does not generate swell since the island of Sicily restricts their propagation until Pantelleria. Since the analysis carried out is based on the PeWEC, anchored with a system of chains that limits the rotation in yaw, the direction with the greatest energy has been determined to hypothesize its optimal orientation: this orientation corresponds to 330° and makes reference to wind waves only.

The use of conventional synthetic parameters, obtained without partitioning the spectrum, can, from the beginning, induce errors in the calculation of the productivity of wave energy converters. To investigate the impact of the assumption of monodirectionality versus multidirectionality, and therefore also of partitioning, the time series of the zero-order momentum of the combination of wind and swell waves, and their partitioning (Figure 3), has been analysed.

Considering the 2022 three-hourly time series of zero-order moments, it is possible to deduce that the energy of swells is always lower than that of wind waves, expressed through the parameters m_{0_s} and m_{0_w}, respectively. Furthermore, the time series of sea

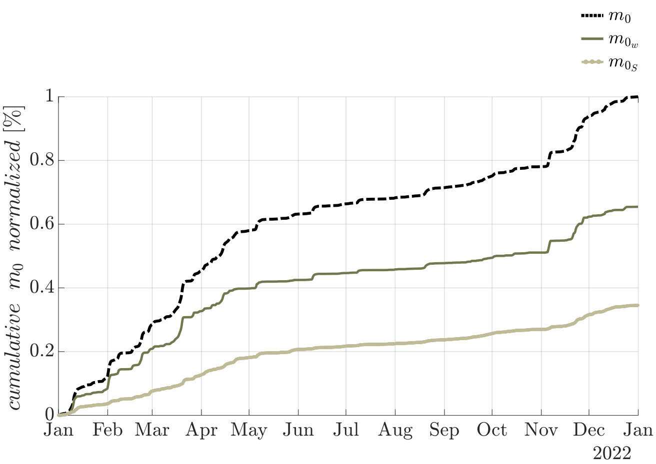

Fig. 4. Comparison of the cumulative zero-order moments of the combination of wind and swell waves m_0, wind waves m_{0w} and swell waves m_{0_s} in the year 2022 at Pantelleria

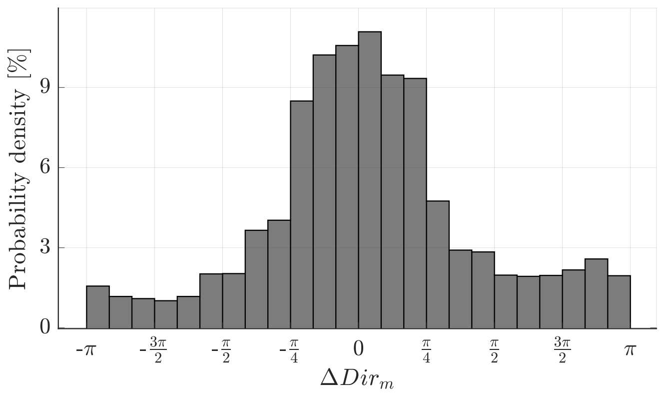

Fig. 5. Probability density of the angular difference between the mean directions of wind and swell waves in the year 2022 at Pantelleria

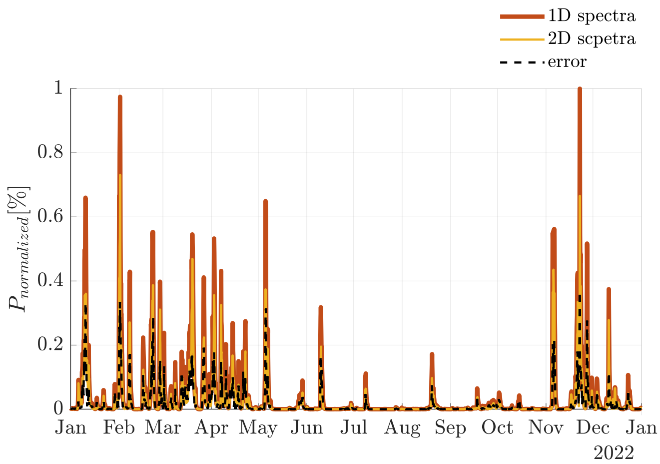

Fig. 6. Time series comparison of normalized PeWEC power in monodirectional (1D spectra) and multidirectional (2D spectra) cases and error induced by monodirectional versus multidirectional hypothesis, in the year 2022 at Pantelleria

states of Pantelleria is characterized by multi-peak spectra, and for this reason, the use of the frequency spectrum is not suitable. Moreover, the greatest amount of energy is between the months of November and April, with the exception of some sporadic medium energy sea states caused by singular storm events.

In order to quantitatively evaluate the percentage of energy that overall, in the year 2022, is attributable to wind and swell waves, the cumulative energy has been normalized with respect to the total of zero-order moment (m_0) obtained from the combination of the two sea states. Figure 4 shows that about 65% of wave energy is attributable to wind waves, while the remaining 35% is due to swell waves.

To fully describe the sea conditions, the difference between the mean wind directions and the mean swell directions have been calculated and analyzed:

$$\Delta Dir_{m_i} = Dir_{m_{w_i}} - Dir_{m_{s_i}} \tag{9}$$

where $Dir_{m_{w_i}}$ corresponds to the i^{th} mean direction of the wind wave, while $Dir_{m_{w_i}}$ corresponds to the i^{th} mean direction of the swell wave. The probabilistic distribution of the angular difference between the mean wind directions and the swell wave directions is shown in Figure 5. Over 63% of the waves have an angular difference between -$\pi/4$ and $\pi/4$, while the remaining sea states have great differences. In some cases, the wind and swell waves have nearly opposite directions.

In evaluating the response of the PeWEC, considering the direction of wave energy is determinant. The results indicate that the energy of the frequency-direction spectrum does not necessarily refer to the same direction. This implies that the device is subject to forces arising from the superposition of sea states with different directions. In particular, if the mean direction of the wind waves is parallel to the orientation of the PeWEC, the mean direction of the swell could be different and thus contribute less to the energy production.

IV. Results

An analysis of the error induced by the hypothesis of monodirectionality, with respect to that of multidirectionality, for the calculation of the wave components and, therefore, of the dynamic response of the device has been carried out. In particular, the time series of the excitation forces F_w of equation (8) have been calculated both with reference to frequency spectra (1D) and to frequency-directional spectra (2D). Figure 6 shows the time series of the normalized produced energy by the PeWEC for the monodirectional (1D) and multidirectional (2D) cases.

Figure 7 represents the comparison between the normalized cumulative energy referred to the monodirectional (1D) and multidirectional (2D) cases, i.e. the normalized energy that is cumulatively produced by the PeWEC over time, and the error between the two cases.

From the analysis conducted, the energy produced by PeWEC under the assumption of monodirectionality in the year 2022 overestimates the energy extracted from multidirectional conditions by 41%. It is interesting to note how the trend of the zero-order moment of the combination of wind and swell waves m_0 in Figure 4 follows a similar trend of the power

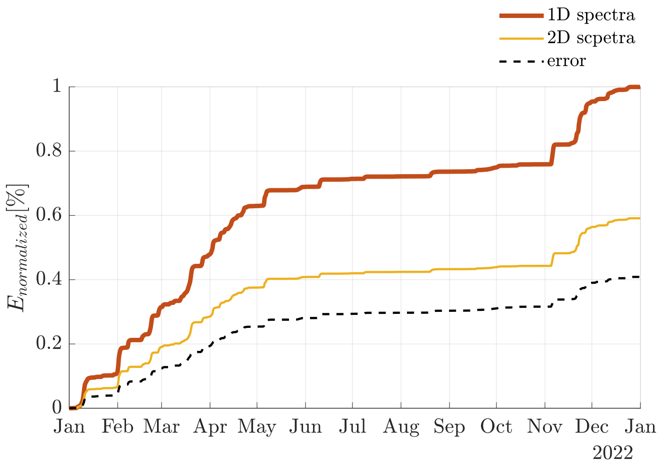

Fig. 7. Normalized cumulative energy converted by PeWEC in the monodirectional (1D spectra) and multidirectional (2D spectra) cases and error induced by monodirectional versus multidirectional hypothesis, in the year 2022 at Pantelleria

generated by the PeWEC in the monodirectional case. This similarity comes from the fact that the waves generate the excitation forces that move the device. Indeed, in the months between May and November, when the wave energy is lower, the energy conversion of the PeWEC is minimum.

V. Conclusion

This article presents an analysis of the error induced by the assumption of monodirectionality, versus multidirectionality, in the calculation of the wave components and dynamic response of the PeWEC. Generally, to simplify the problem, the frequency spectrum is used to analyze sea states. This approximation assumes that the wave directions are constantly aligned with the operating direction of the device and directional spreading is neglected. Especially in the case of direction sensitive devices, the common approach can lead to an optimistic quantification of the energy produced. When WECs are assumed to be hit by wave components having the same direction, the energy distribution in the directions is overlooked. Also, as in the case of Pantelleria, the combination of wind waves and swells would be treated incorrectly. To analyze the sea states at the study site, the frequency-direction spectra of the ERA5 reanalysis data, provided by the European Center for Medium-Range Weather Forecasts (ECMWF), have been used. The results show that the conventional frequency spectrum approach overestimates the energy production by 41% compared to the multidirectional case, mainly because it neglects the directional information on the wave spectrum: less energy is produced by the interaction between the device and incoming waves characterized by different directions. Swells, which account for about 35% of wave energy in Pantelleria in 2022, have an absolute angular difference of less than $\pi/4$ for around 64% of the time. The remaining sea states consist of swells having a mean direction very different from that of wind waves. Assuming that the energy of the waves comes from a single direction can lead to an undue simplification, such that the estimation of the energy produced becomes unbearably different from the one based on the multidirectional analysis. Therefore, this study highlights the importance of preliminarily quantifying the impact of the monodirectional assumption, to evaluate its coherence with the performances deriving from multidirectional approach. Further analysis of the energy distribution on the frequency-direction spectrum could provide additional insight into the characteristics of the waves, which, if simplified, lead to an overestimation of the energy production.

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