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Integrating a Wave Farm into an Isolated Power System with Energy Storage Systems: Analysis of Frequency Stability and Renewable Energy Penetration

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Integrating a Wave Farm into an Isolated Power System with Energy Storage Systems: Analysis of Frequency Stability and Renewable Energy Penetration

J. Nájera, M. Blanco, G. Navarro, E. Rausell, V. Urda, M. Lafoz, J.I. Sarasúa, G. Martínez-Lucas, J.I. Pérez-Díaz

Abstract—**Integrating non-dispatchable renewable energy sources (RES), such as wind, solar or wave farms (WF), into isolated power systems poses significant challenges due to their variability and limited predictability. This issue is particularly critical for islands like El Hierro (Canary Islands, Spain), where there is no interconnection with larger grids. Although wave energy offers substantial potential, assessing the maximum feasible RES penetration while maintaining system stability remains complex.**

This study analyses frequency deviations in an islanded power system integrating a wave farm supported by an energy storage system (ESS). Frequency restoration is managed using droop control, where ESS power output responds proportionally to frequency deviations. The impact of varying wave energy penetration levels and droop control parameters on the system is analysed.

The simulation environment is built in MATLAB Simulink, incorporating a dynamic model of the electrical system, which includes wind power, a pumped-storage hydroelectric plant, and diesel generators. WF model is developed based on local wave resource data, simulating power output and variability. The Spanish Grid Code is used to assess regulatory compliance.

Results identify optimal droop control parameters for each wave farm size, ensuring frequency deviations remain within acceptable limits. Additionally, the minimum required ESS capacity is estimated for stable operation under different scenarios. These insights support this methodology for effective dimensioning of wave farms and storage systems in isolated grids, enabling higher RES integration while preserving system reliability.

Keywords— **wave energy, electric grid integration, energy storage systems**

I. INTRODUCTION

GENERALLY speaking, the integration of non-dispatchable renewable energy sources (RES) into electric power systems presents inherent drawbacks, such as a lack of controllability and the variability of the renewable resources. This variability negatively impacts the reliability of the power system at manly medium-term timescales (on the order of minutes or tens of seconds). It reduces the power quality of the system, particularly the frequency, in both interconnected and isolated systems [1], [2]. In particular, wave energy integration exhibits an additional variability at short timescale (on the order of seconds). Hence, even though wave energy could be suitable for integration on islands due to its location and resource availability [3], [4], the variable nature of the resource could severely affect the stability of the power system [5].

This work focuses on El Hierro Island (Canary Islands, Spain). The El Hierro electric power system is an isolated grid with a high penetration of RES. Generation is provided by a wind farm, a pumped hydroelectric plant as a massive energy storage system, and conventional generation via a diesel power plant.

In previous analyses [6], on the one hand, the behaviour of this power system was studied, including the installation and operation of energy storage systems such as flywheels. Building on those studies, the present work

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investigates the impact of integrating a wave energy farm (WF) into the El Hierro power system, taking into account the Spanish grid code requirements regarding frequency regulation mechanisms in isolated systems [7]. On the other hand, the present analysis continues a previous works focused in the analysis of the impact in electric frequency deviation of the integration of WF [8], [9], but expanded the analysis in the evaluation of the requirements of an energy storage system (ESS) and the impact in the wear&tear of conventional generation power plants (the degradation - wear&tear - of the mechanical components of the pumped-hydro plant, caused by additional stress when providing frequency regulation).

This increased frequency regulation demand is driven by the integration of wave energy generation. Two scenarios will be considered: one with an extra energy storage system (ESS) and one without. This study will allow for the quantification of technical limitations regarding wave energy penetration in isolated systems like El Hierro and will support conclusions related to the integration of non-dispatchable RE in relation to the size of the power system. Although the ESS studied is considered in an agnostic approach, hybrid energy storage system based on batteries and supercapacitors are considered suitable due to the capacity of the batteries to face the frequency deviations and wear&tear of hydro-pump system, and the fast response of supercapacitors which reduce the cycling ageing of batteries.

Section II describes the electrical system and its generation units (RE and conventional generation plants), while Section III describes the study case and the methodology, and section IV present simulation results of the impact of the integration of a WF in an islanded electric grid, with and without the inclusion of an energy storage system. Finally, Section V presents the main conclusions.

II. Mathematical Model Description

The analysis presented in this work is based on the mathematical model described in [6], [10] and in the previous analysis presented in [8]. The case study focuses on an insular electric power system with 6 MW of installed capacity, which is supplied for most of the year by renewable energy sources (RE). The system corresponds to that of El Hierro (Canary Islands, Spain), including the hydro-wind power plant of Gorona del Viento. The mathematical model also includes the conventional power plant that has traditionally supplied electricity to the island and is responsible for meeting the demand at specific times of the day. The main goal of the inclusion of an additional ESS is to improving both the stability and reliability of the power system and reducing mechanical wear on the pumped-hydro and diesel power plants (HID and DIE), considering the frequency deviation that introduce in the electrical system a wave energy farm (WF) considered in this study includes a backup system based on battery energy storage.

In summary, the mathematical model represents the electric power system of El Hierro, enhanced with two virtual components: a wave energy farm (WF) and an additional energy storage system (ESS) as shown in Fig. 1.

A brief description and related literature follow:

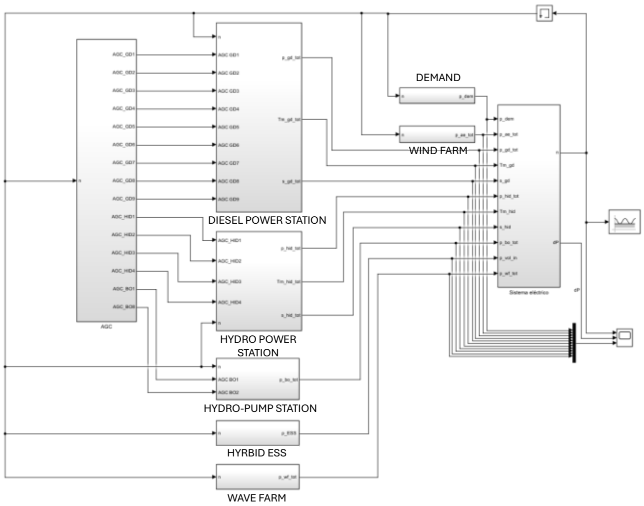

Fig. 1. Simulink dynamic model of El Hierro electric grid.

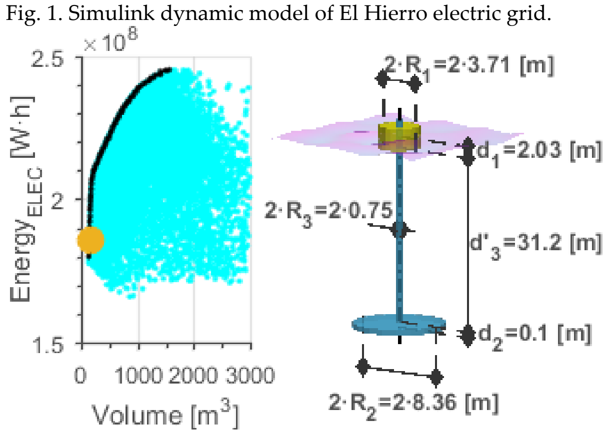

Fig. 2. WEC dimensions and PTO main characteristics have been selected by means design script based on Differential Evolution algorithms (**SOURCE: [8]**).

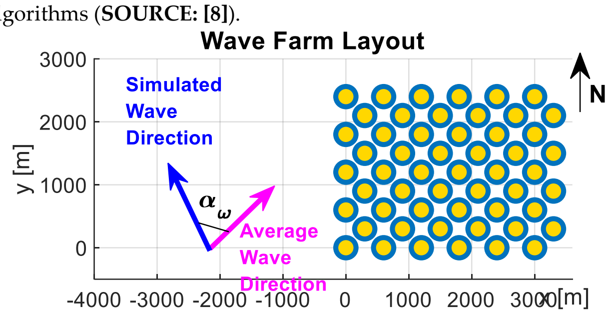

Fig. 3. Wave farm configuration takin into account the location wave energy resource and the reduction of the power oscillation [9].

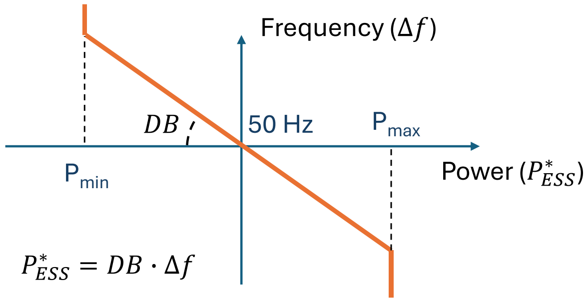

Fig. 4. Droop Based (DB) control implemented in the GSC of ESS.

- The electric power system model of El Hierro is developed as an aggregated dynamic inertial model, enabling the evaluation of frequency deviations. This approach was successfully applied to the Irish power system in [11]. To ensure that frequency remains within the limits established by grid codes, the two generation plants directly connected to the grid (Hydro power plant -HID-, and diesel power plant –DIE-) provide an inertial response.
- Automatic Generation Control – AGC – models the secondary frequency regulation, coordinating the participation of both generators (DIE and HID) [12]..
- DIE model represents the Llanos Blancos diesel power plant, composed of 9 diesel generator units (dynamic response parameterized according to the technical specifications).
- The wind farm -WdF- consists of 5 variable-speed wind turbines modelled as in [12] (considering: pitch angle to smooth power generation; rotor inertia; wind velocity time series as input).
- The HID is an ESS which includes a hydro-pump station and a hydropower plant. The energy is stored by pumping water from a lower to an upper reservoir; and electricity is generated using the stored water. The dynamic model of the hydro-pump station consists of 6 fixed-speed and 2 variable-speed pumps. The model hydropower plant consists of 4 Pelton turbines. The dynamic hydraulic models considers hydraulic (an d associated electric) machines, conduits, and a simplified electric machine [13].
- The wave farm (WF) is one of the fictitious elements integrated into the El Hierro system model was developed following the methodology in [8], [9].
  (1) The wave energy converter (WEC) consists of a two-body point absorber with a maximum peak power of 160 kW (see Fig. 2). The power take-off (PTO) is a linear generator with a nominal power of 160 kW. The WEC geometry was developed based on the optimization methodology presented in [14].
  (2) WF includes 54 WECs, grouped into 15 units arranged in 9 rows with a triangular pattern to minimize output power oscillations [5], [9] (Fig. 3).
  (3) Irregular real waves has been modelled using a JONSWAP spectrum, with a unique free-surface elevation time profile for each WEC position, and a 600 m separation between devices to minimize hydrodynamic interactions and ensure proper mooring arrangement [15], [16].
- The additional energy stored system (ESS) is the other fictitious element integrated. ESS is based on a hybrid ESS power plant based on batteries and supercapacitors. The semi-empirical lithium-ion battery model and electric double layer supercapacitor model are parameterized using lab tests conducted on commercial lithium-ion cells [17] (ANR26650M1 - A123) and commercial supercapacitors cells [18] (BCAP3000 P270 K04).

  The ESS governor control scheme (GSC) defines the power reference set point that the ESS should inject into or absorb from the grid based the system frequency. A Droop Based GSC has been implemented, where the ESS power setpoint is proportional to the frequency deviation. The proportionality constant DB is defined as: $P^*_{ESS} = DB \cdot \Delta f$ [6], [10] (Fig. 4).

For more detailed information of the El Hierro mathematical model, please consult [6], [8], [10].

III. Methodology: Study Case Definition

This study case focuses on the electrical grid of El Hierro, one of the Canary Islands (Spain) [19], whose system model has been described in Section II.

The analysis aims to evaluate the impact of integrating RES into this isolated grid. On one hand, such a source may offer positive effects due to the temporal decoupling of energy inputs, which can reduce both the need for energy storage and the required capacity of power transmission infrastructure [3], [20], [21].

However, on the other hand, wave energy introduces additional short-term variability due to the inherently oscillatory nature of ocean waves. This fluctuation affects the power balance of the system and, consequently, poses challenges for frequency regulation (and restoration) and stability mechanisms.

It is worth mentioning that the model used in this study is built based on certain assumptions, such as: the scheduling of the generation mix does not change with the inclusion of the wave power plant; and although the ESS response models allow for delay modelling, perfect frequency measurement and zero communication delay have been assumed, while delays in power electronics systems have been neglected. These assumptions should be taken into account for future work and when considering the applicability of the results to real-world scenarios.

A. *Electric grid simulation cases (generation mixes)*

To analyse the electrical system of El Hierro and evaluate the impact of variable RES (in particular wave energy) on grid frequency stability, a set of 25 simulation scenarios was developed. These scenarios result from the combination of: (1) 5 synthetic wind speed profiles, generated using historical wind data and a stochastic modelling approach [13]; (2) 5 representative generation mixes, selected based on operational data from the local electricity system operator, *Red Eléctrica de España* (REE) [22]. These mixes define which generation technologies and units (along with their corresponding capacities) are active in each scenario.

The 5 generation mixes, arranged in order of increasing wind energy penetration, are summarised in Table I. The Hydraulic Short Circuit scenario (CCH) represents the simultaneous operation of pumps and turbines, in which

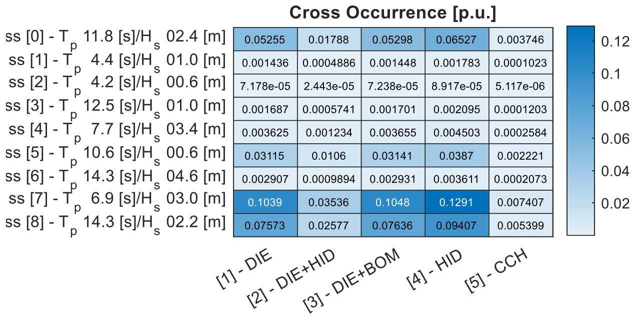

Fig. 5. Yearly cross-occurrence of sea states and generation mixes.

the power consumed by the pumps exceeds the power injected into the grid by the Pelton turbines.

B. *Wave farm simulation cases (sea states)*

Additionally, 11 representative sea states were selected to evaluate the integration of WF into the electrical grid. From the hourly wave data for the year 2022, recorded along the coast of El Hierro and provided by the Spanish national agency *Puertos del Estado* [23] (8,760 hourly data points), 11 cases were selected using the MAXDIFF algorithm, as described in [24]. This method considers key wave parameters—significant wave height, wave period, and direction—to identify the most representative scenarios. The goal of the selection process is twofold: (1) to preserve the annual wave energy distribution; and (2) to ensure the inclusion of extreme cases from the scatter diagram. This approach guarantees a balanced representation of both typical and edge-case conditions. The selected wave scenarios are summarized in Table II.

C. *Methodology*

Additionally, this study aims to assess the potential benefits of integrating an auxiliary energy storage system (ESS) to mitigate the negative effects associated with the variability of wave energy (WF). Such a system would contribute to frequency restoration mechanisms.

In this context, the analysis focuses on evaluating the impact on the power grid, particularly in terms of frequency deviations and the wear&tear derived from the operational stress on conventional power plants involved in primary and secondary frequency regulation [25].

- Frequency Deviation Variable [t_{OVER_fLIM}/h]: This metric represents the ratio of time, within a one-hour period, during which the grid frequency exceeds the predefined upper or lower limits. In the case of insular systems within the Spanish power grid, these frequency deviation limits are set at ±250 mHz [7]. This variable is also weighted annually based on the data presented in Fig. 5.
- Wear&Tear Variable of Conventional Plants Due to Frequency Regulation [$dz = dz_{DIE} + dz_{HIB}$]: This parameter refers to the accumulated displacement rate of the actuators in the diesel generation plant (dz_{DIE}) and the hydraulic generation plant (dz_{HIB}). It reflects the mechanical wear&tear associated with power modulation in conventional plants as part of frequency regulation services. This variable is also annually weighted based on the data presented in Fig. 5.

Furthermore, in assessing the impact of the auxiliary energy storage system, the relationship between its involvement in frequency restoration mechanisms and the required nominal energy and power will also be evaluated, with the following definitions:

- Nominal Energy [E_{ESS_rt}]: The peak-to-peak value of the energy evolution within ESS over the simulation.
- Nominal Power [P_{ESS_rt}]: The maximum absolute value of the power handled by ESS.

IV. RESULTS

Ten-minute simulations were performed for each of the considered scenarios.

Each complete scenario consists of 5 different generation mixes, simulated under 5 distinct wind profiles (see Subsection III.A) and 9 different sea states (see Subsection III.B). In the presentation of results, the average outcomes across the 5 wind profiles are shown. The joint probability distribution of these 5 (generation mixes) × 9 (sea states) is derived from historical hourly generation data and sea state occurrence matrices at the selected location, as illustrated in Fig. 5.

The following simulation cases were evaluated:

- BASE CASE: A single scenario composed of 5 (generation mixes) × 9 (sea states), each with 5 different

TABLE I. INITIAL POWER DISTRIBUTION IN EACH REPRESENTATIVE GENERATION MIX FOR THE POWER SYSTEM

Generation mix		Demand	Pumps	VSWT	Pelton Turbines	Diesel units
1	DIE	-3.40	(-)	0.15	(-)	3.25
2	DIE +HID	-4.50	(-)	0.78	0.82	2.90
3	DIE +BOM	-4.95	-4.00	4.05	(-)	4.90
4	HID	-6.67	(-)	4.40	2.27	(-)
5	CCH	-5.25	-6.00	8.23	3.02	(-)

DIE = diesel, DIE+HIH = diesel plus hydraulic, DIE+BOM = diesel plus pumping, HID = hydraulic, CCH = hydraulic short circuit

Values are in MW. A negative value is the power consumption from the grid, and a positive value is the power generation to the grid.

SOURCE: [8]

TABLE II. INITIAL POWER DISTRIBUTION IN EACH REPRESENTATIVE GENERATION MIX FOR THE POWER SYSTEM

Case Number	Hs [m]	Tp [s]	Dir [rad]	Occ. [%]
1	4.20	0.60	1.1155	0.1712
2	14.30	4.60	-0.2967	0.0047
3	12.50	1.00	-2.7417	0.0002
4	6.90	3.00	-1.3978	0.0055
5	14.30	2.20	1.7961	0.0118
6	7.70	3.40	1.7961	0.1015
7	4.40	1.00	-2.1483	0.0095
8	10.60	0.60	0.2603	0.3386
9	16.70	3.00	-0.2967	0.0102
10	6.70	1.40	3.0528	0.1000
11	11.80	2.40	-0.3506	0.2468

HS = SIGNIFICANT WAVE HEIGHT (METTERS), TP = PEAK WAVE PERIOD [S], DIR = MAIN WAVE DIRECTION [RAD], OCC = ANNUAL OCCURRENCE

SOURCE: [8]

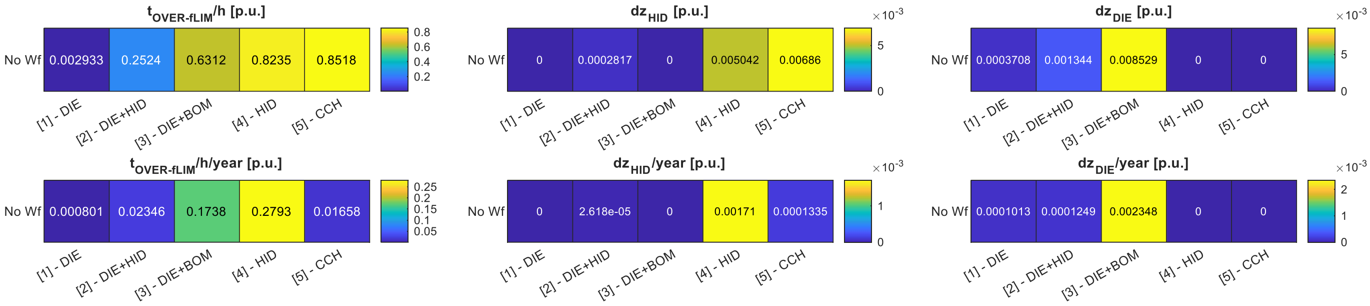

Fig. 6. Frequency deviation variable and Wear&Tear variable for the base case.

wind profiles, without any additional components (i.e., no wave energy plant or auxiliary storage system).

- WAVE FARM IMPACT ANALYSIS [$P_{WF\text{-}rt}$]: A total of 13 scenarios were analysed, representing different levels of wave energy penetration into the system. The wave energy integration levels (in per-unit) were: [2, 3.8, 5.7, 7.4, 9.1, 10.7, 12.3, 13.8, 15.3, 16.7, 23.1, 28.6, 33.3] % based on a system base power of 6 MW.
- AUXILIARY STORAGE SYSTEM IMPACT ANALYSIS [db]: A total of 15 cases were simulated to evaluate frequency regulation capabilities, considering the following values for the primary frequency regulation constant db = [120, 160, 172, 192, 214, 240, 320, 480, 640, 960, 1920, 3200, 4800, 9600] ΔkW/ΔHz, representing power variation in response to frequency deviation from the nominal 50 Hz.

A total of 47250 cases has been analysed (5 mixes, 5 synthetic wind energy profiles, 9 sea states, 13 WF configurations and a base case without WF, and 14 ESS cases and a base case without ESS).

A. *Base case – Study case without wave farm integration and without additional energy storage system*

The results obtained for the base case reveal significant frequency deviations in the electrical grid (see Fig. 6). These deviations are particularly pronounced in MIXES 4 and 5. As the MIX number increases, so does the wind speed (the variable energy source), while the synchronized conventional power decreases. This results in a system with lower inertia, and consequently, for the same power imbalance, the frequency deviation becomes more severe.

The wear&tear variable for conventional generation systems was disaggregated into its diesel and hydro components, showing increased mechanical wear&tear when frequency deviations are more pronounced (particularly in MIXES 3, 4, and 5).

Additionally, the results were weighted according to the annual occurrence probability of each MIX. It was observed that although MIX 5 is the most demanding scenario (showing the highest frequency deviations and wear&tear), it also has the lowest probability of occurrence throughout the year.

B. *Impact of wave farm (WF) integration.*

Detailed results of the wave farm (WF) integration analysis are provided in the appendix (Fig. 10, Fig. 11, and, Fig. 12). Fig. 7 presents a summary of the impact of WF integration on the El Hierro power grid.

As expected, the introduction of wave energy leads to an increase in both frequency deviation and wear&tear of the conventional generation systems involved in frequency restoration mechanisms. Specifically, for a wave energy penetration level of approximately 33%, the time during which frequency falls outside the allowable limits

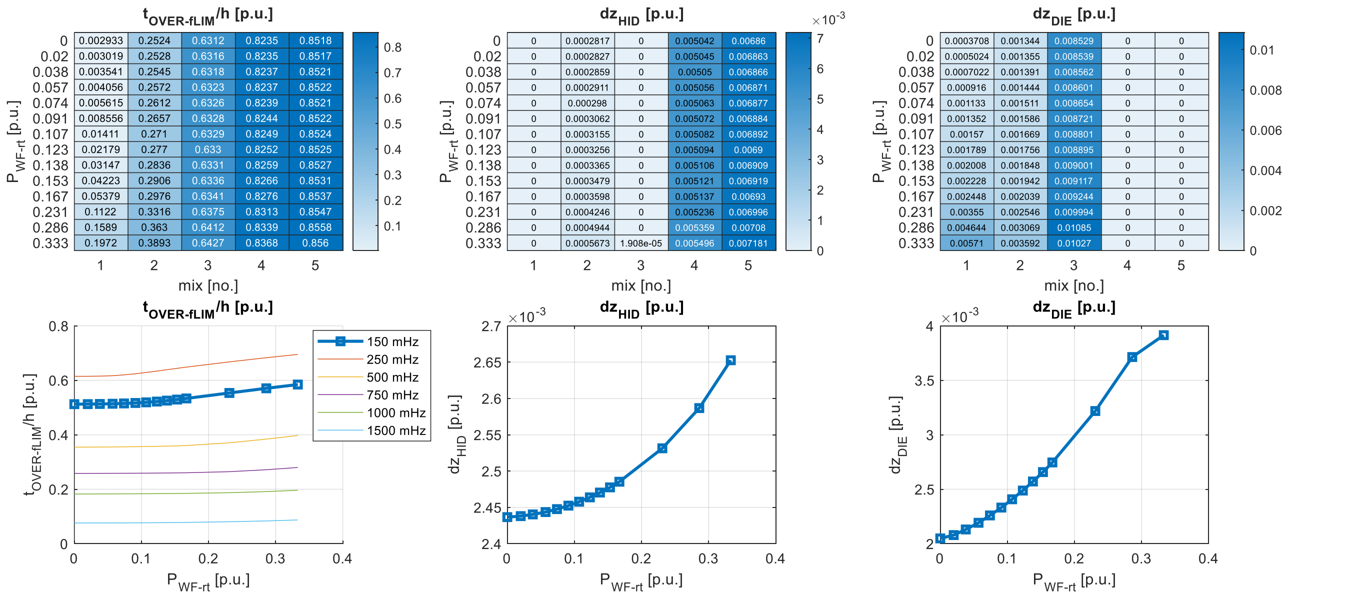

Fig. 7. Frequency deviation variable and Wear&Tear variable (Hydraulic power plant and Diesel power plant) variable (1 hour based) for different wave energy penetration ($P_{WF\text{-}rated}$). The upper figures represent the variables with respect to MIX and wave energy penetration, and the lower figures represent these variables weighted by MIX with respect to wave energy penetration.

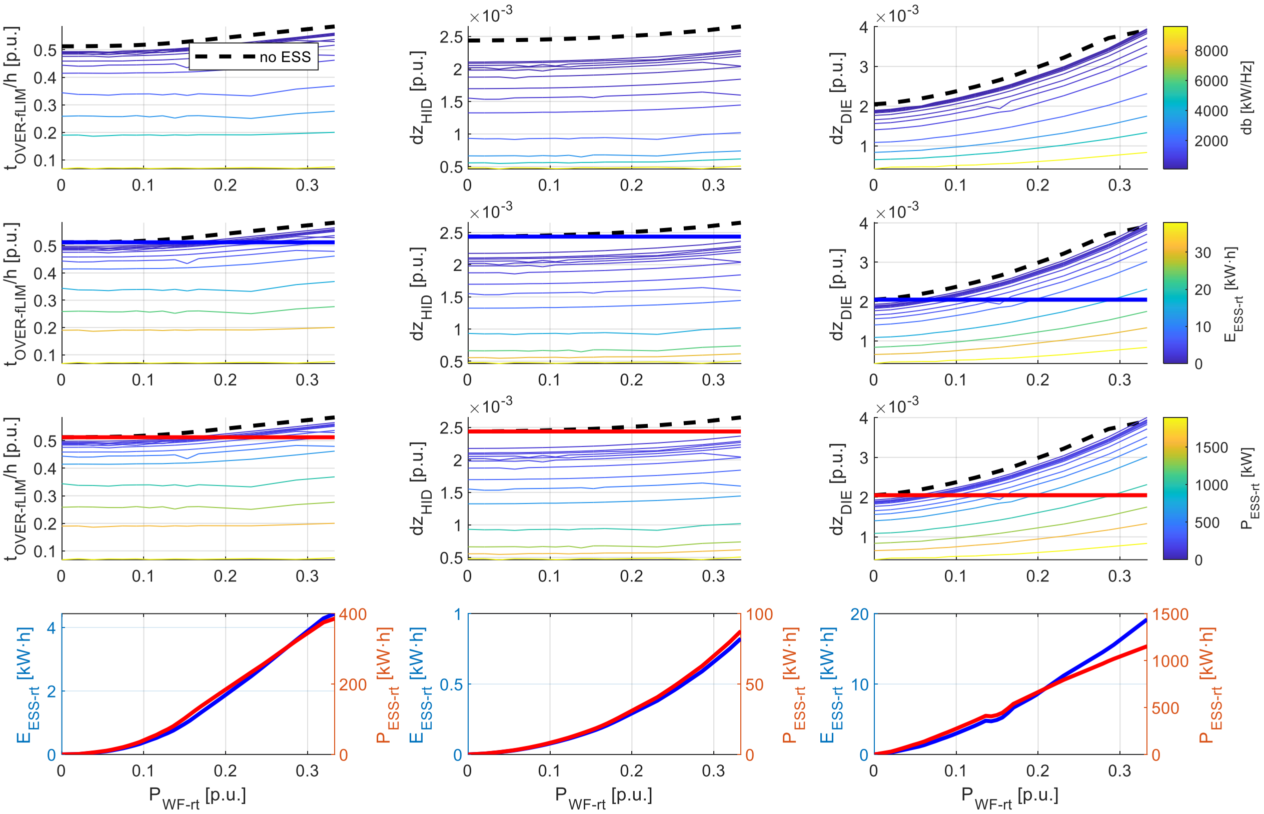

Fig. 8. Frequency deviation variable and Wear&Tear variable (Hydraulic power plant and Diesel power plant) variable (1 hour based) for different wave energy penetration ($P_{WF\text{-}rated}$) and for different values of the constant of power variation at frequency deviation (db) and rated power and energy of ESS ($E_{ESS\text{-}rt}$ and $P_{ESS\text{-}rt}$). The dashed black line represents the values for the base case (without ESS), and the red and magenta plots represents the ESS requirements (rated energy and power) for mitigate completely the influence of the WF (the Frequency deviation variable and Wear&Tear variable values equal to the base case without WF).

increases by around 14%. Additionally, wear&tear on the diesel generation plant increases by approximately 9%, while that on the hydro plant increases significantly, by nearly 90%.

The substantial rise in wear&tear of the hydro system is particularly noteworthy. This is primarily due to the dual role of the hydro plant, which also functions as a pumped-storage system. It takes over frequency regulation duties, especially in scenarios (MIXES) where wind generation is present, leading to increased mechanical the wear&tear derived from the operational stress.

C. *Impact of additional energy storage system (ESS) integration.*

The negative impacts of WF integration (presented in the previous subsection IV.B) can be mitigated, and even reversed, with the integration of an Energy Storage System (ESS).

One option is to focus the ESS on and integrate it with renewable energy generation systems to address the root cause of the problem—power oscillations. This approach was studied in [5] and has the main limitation that the ESS acts to mitigate power oscillations in the associated generation system. While it can reduce or even eliminate the negative impacts, it does not improve the overall performance of a particular electrical system.

The approach chosen in this study is to integrate the ESS in a way that participates in frequency restoration mechanisms. Detailed results of the ESS integration analysis are shown in Fig. 13 in the appendices.

Fig. 8 illustrates the frequency deviation variable and wear&tear variables (for both the hydraulic and diesel power plants, based on one-hour intervals) for different wave energy penetration levels (PWF-rated) and various

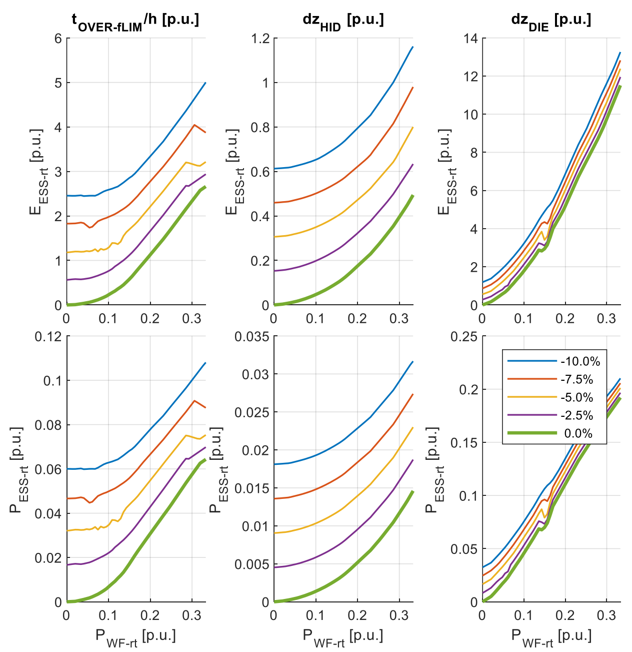

Fig. 9. ESS requirements ($E_{ESS\text{-}rt}$ and $P_{ESS\text{-}rt}$) to mitigate or even reduce the Frequency deviation variable and Wear&Tear variable to certain percentage.

values of the primary frequency regulation constant (db), along with the rated power and energy of the ESS (EESS-rt and PESS-rt). The dashed black line represents the values for the base case (without ESS), while the red and magenta plots represent the ESS requirements (rated energy and power) needed to completely mitigate the influence of WF (i.e., the frequency deviation and wear&tear variables reach the same values as in the base case without WF).

This graph allows us to determine the necessary values for the storage system that can fully mitigate the impact of the wave farm on the El Hierro power grid. In fact, as mentioned in subsection IV.B, the greatest impact was on the wear&tear of the hydro plant. Mitigating this effect requires the highest storage capacity.

Fig. 9 shows the ESS requirements to mitigate or even reduce the frequency deviation and wear&tear values of the conventional plants by a certain percentage of base case values. It can be observed that ESS power requirements are small when compared to the size of the wave farm, reaching 20% of the wave farm size at the maximum simulated wave energy penetration level (33%).

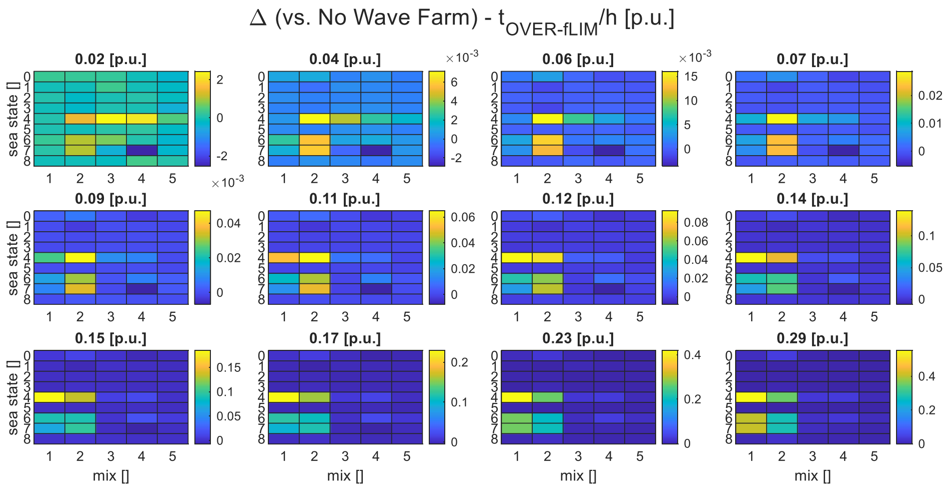

Fig. 10. Frequency deviation variable (1 hour based) for different wave energy penetrations ($P_{WF\text{-}rated}$) with respect to the base case

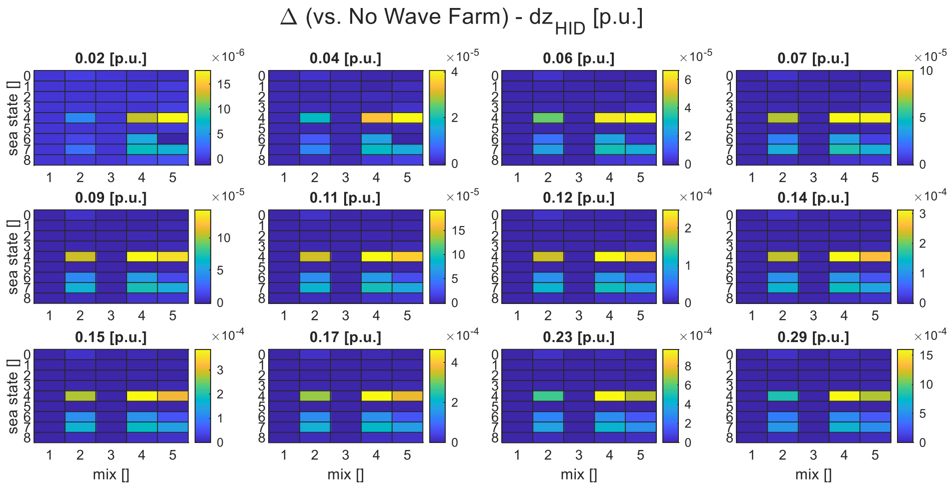

Fig. 11. Wear&Tear variable in Hydraulic plant (1 hour based) for different wave energy penetrations ($P_{WF\text{-}rated}$) with respect to the base case.

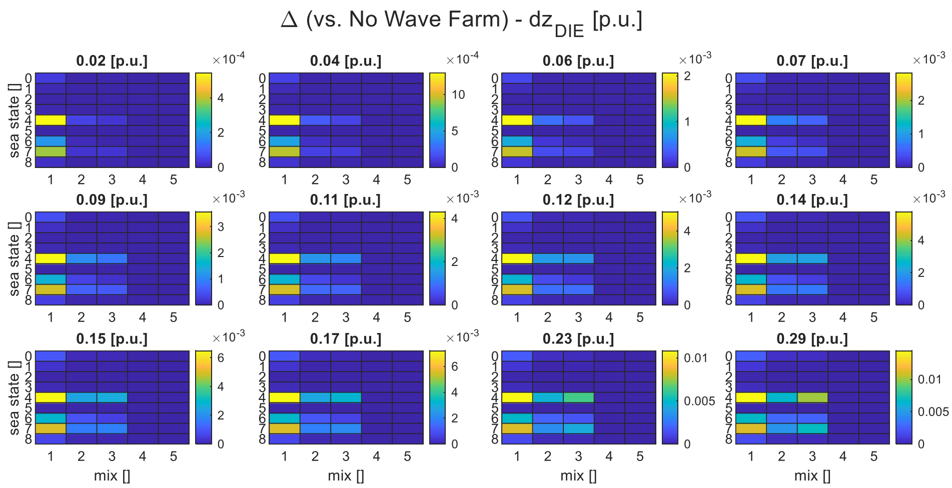

Fig. 12. Wear&Tear in variable Diesel plant (1 hour based) for different wave energy penetrations ($P_{WF\text{-}rated}$) with respect to the base case.

V. Conclusions

The impact of wave farm (WF) on an island electrical grid (El Hierro, Spain) has been analysed, along with the mitigation of this impact through the implementation of Energy Storage Systems (ESS). This case is of particular interest due to the high electricity prices in island systems and the proximity of the wave energy resource, making island grids especially attractive for renewable energy integration. However, issues related to electrical frequency deviations are more pronounced in these systems.

In this study, the electrical grid was modelled using a single-node model in which frequency regulation mechanisms were implemented. However, the changes in the scheduling of different scenarios, resulting from the integration of the WF (which could reduce the participation of conventional sources), and the ESS (which could reduce the regulatory burden on conventional sources), were not modelled. In this regard, a future work will address the scheduling of energy mix planning scenarios that incorporate wave energy as part of the generation portfolio. Additional efforts will focus on studying different strategies for mitigating frequency deviations, comparing power smoothing techniques with direct control actions over frequency deviation, and assessing alternative control schemes to manage this variable effectively. Further developments will also include more detailed modelling of energy storage systems, accounting for their degradation and aging processes. Lastly, techno-economic analyses will be carried out to evaluate both single and hybrid storage solutions, considering the long-term impact of system aging on performance and cost-effectiveness.

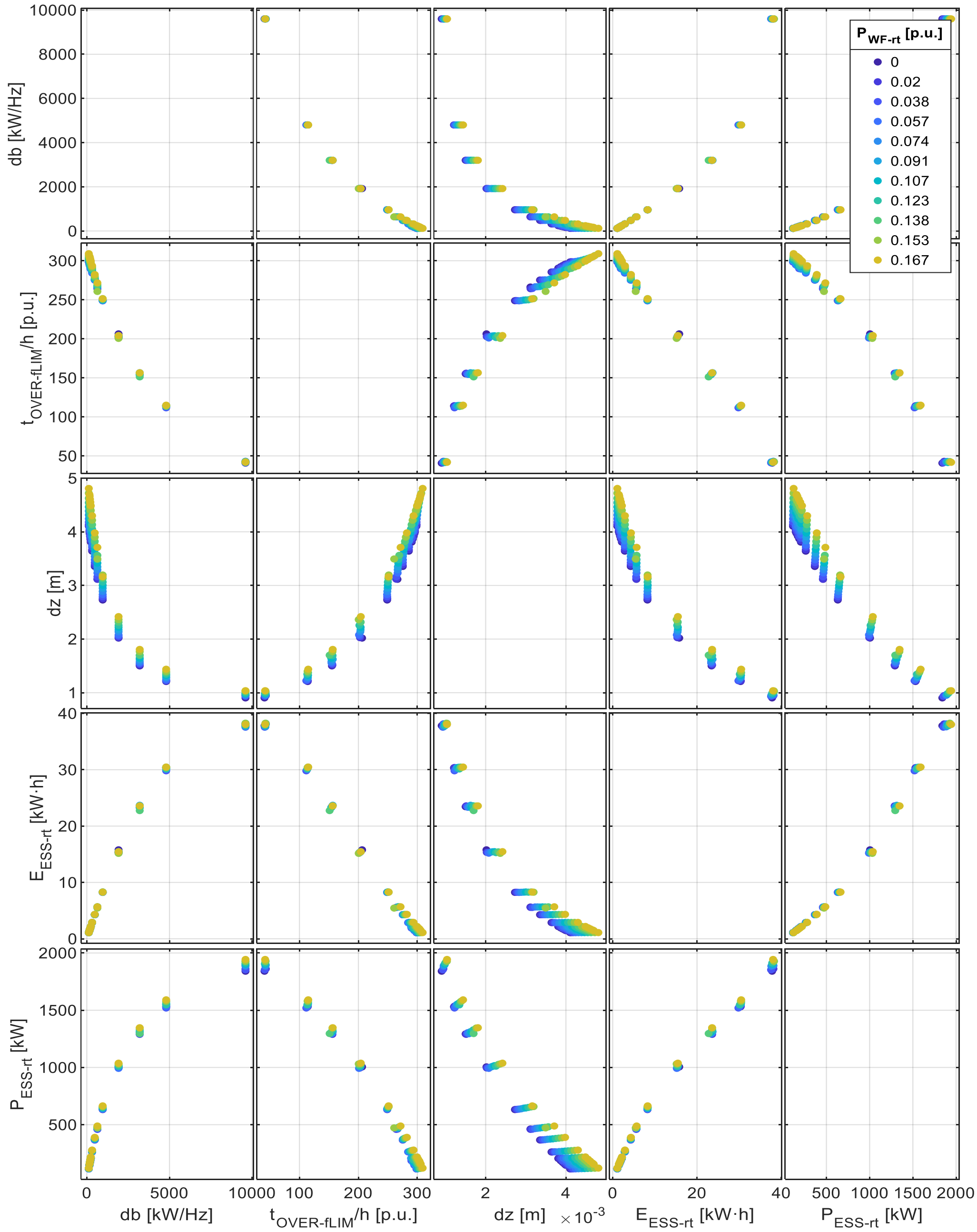

Fig. 13. Scatter plot matrix of the variables of constant of power variation at frequency deviation of the ESS (db); frequency deviation ($t_{OVER\text{-}flim}$), Wear&Tear, (dz); and rated power and energy of ESS ($E_{ESS\text{-}rt}$ and $P_{ESS\text{-}rt}$).

The simulations demonstrate the fully mitigation of the WF impact by means of an ESS across a wide range of wave energy penetration levels (up to 33%). The ESS required to completely mitigate the WF's impact on the El Hierro power grid needs to have a power capacity approximately equal to 20% of the WF rated power.

APPENDIX

As discussed in subsections IV.B and IV.C, the detailed results of the wave farm (WF) integration analysis are shown in Fig. 10, Fig. 11,, and Fig. 12,, while the detailed results of the ESS integration are presented in Fig. 13.

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