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Application of a revised integration of methods for wave energy converter and farm location pair mapping

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ABSTRACT

Wave energy is a promising actor for the renewable energy-mix that needs to be increasingly prominent worldwide. However, wave energy often remains too neglected in energy-mix studies. To avoid pre-selecting locations with potential underestimation of Wave Energy Converter performances, indexes and methods have been developed to pair wave energy converter(s) and locations, but (a) resource potential maps have not been compared to Wave Energy Converter performance maps; (b) often farm potentials are obtained based on individual Wave Energy Converter selection; and (c) there is a lack of assessment in the complementarity and relevancy of these indexes. This work aims to address these gaps by (i) investigating wave and converter pairing indexes to select the most relevant, complementary, and representative ones; (ii) merging and improving main pieces of these methods into a novel framework based on the selected indexes and related parameters; and (iii) mapping the most appropriate wave farm for each location according to this framework and compare with resource potential maps. This study is the first to integrate electricity demand and production from wave energy combined with other renewables for an energy-independent archipelago. Results lead to conclude that the annual energy production, energy demand-response index, and multi-criteria approach are the most compliant indexes for the framework developed in this research. Additionally, the wave resource was proven necessary but insufficient to select potential locations because the selected indexes provided a more restrictive converter-location pair potential map following this wave farm framework. The individual-converter-selection using these selected indexes showed farm energy production about twice below the one of selecting the farms directly, which reaches up to 136 GWh/year. The improved framework developed in this research also demonstrated the efficiency of a revised generator-limitation optimisation that increases the capacity factor by up to an improved average of 50% with limited reductions in annual energy production. The high technology readiness level converters highlighted the possibility for the Canary archipelago to become electrically independent (some islands could lose their thermal power stations). This sustainable solution would require an alternation of one and two Wave Dragon farms, and a mix of Wave Dragon, Undigen, Weptos, and Wavepiston farms alongshore.

1. Introduction

There is a global energy demand growth due, for instance, to an increasing numerical consumption [1], the electrification of different sectors [2], and the residential sectors are the third largest energy consumer and carbon dioxide emitter globally [3]. Therefore, recent research highlighted the important role and the potential of this sector in the energy transition and the net zero emissions pathway [4]. In fact, there is evidence of decarbonisation processes in buildings within the commercial sector [5]. To guarantee a secure and decarbonised energy system is one of the European Union (EU) energy sector's main challenges [6]. Hence, countries increasingly support and promote renewable energy resources in their energy-mix [7] and energy efficiency plans [8]. Notably, Rusu stated that marine renewable energy is necessary to achieve such an ambitious target [9]. The EU 2050 objectives proposed that the offshore wind industry must increase their 12GW of

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List of abbreviations including units and nomenclature

Short name	Units (N/A for Non-Applicable, – for non-dimensional)	Full Name
3D	N/A	3-dimension, based on wave height, period, and direction
AEP (AEP_{WLP})	MWh/year	Annual Energy Production (for a given WEC-Location Pair)
AEP_{local}	MWh/year	Mean of the Annual Energy Production over the entire area and all WECs
AEP_{max}	MWh/year	Maximum Annual Energy production a given WEC would harvest working all-year-long at its maximum capacity
CMEMS	N/A	Copernicus Marine Environment Monitoring Service
CF (CF_{WLP})	– (or %)	Capacity Factor (for a given WEC-Location Pair)
COV_{HS}	–	Significant wave Height Coefficient Of Variation
D	m	Horizontal (inter-)distance between WECs
d_{grid}	° (could be in m)	The distance between the reference point and the sea-cell
DMP	N/A	Decision-Making Process
$E0$	kWh	Monthly wave Energy production
ED (ED_{Grid})	MWh/year	Energy Demand (at the Grid station)
EDRI ($EDRI_{WLP}$)	Dependent on the Weight Function (WF): if WF is in ° or m, or € then EDRI is in °/year, m/year, or €/year, respectively.	Energy Demand-Response Index (for a given WEC-Location Pair)
ERDI	1/°/year (or 1/m/year), it is perceived as in %	Energy Response-Demand Index
Ee	kWh/m	Exploitable storage of wave energy per unit area
Ee_{local}	kWh/m	Mean of the Exploitable storage of wave energy per unit area over the entire area under consideration
ES(1–3)	N/A	Energy Scenarios (1-Island, 2-Community, 3-Power grid-station)
ETOPO	N/A	Earth TOPOgraphy/bathymetry
EU	N/A	European Union
EVA	N/A	Extreme Event Analysis
H_{EVA}	m	EVA's return wave Height over a 30-year period
H_{max}	m	Maximum significant wave Height
Hs	m	Significant wave height
Hs_{100}	m	100-year wave return Height
$Hs_{100local}$	m	Mean 100-year wave return Height over the entire considered area
J_p	kW	Maximum storm wave power
KPI	N/A	Key Performance Indicator
LCoE	€/kWh	Levelised Cost of Energy
LWW	h or days	Weather Window average Length
MCA	–	Multi-Criteria Approach
MVI_{E0}	–	Monthly Variation Index of the Energy production
N	–	Number of WECs of a given farm
n_H	–	Number of significant wave height bins in a given month
n_T	–	Number of wave peak period bins in a given month
NPV	€	Net-Present Value
NWW	–	Number of Weather Windows
O&M	N/A	Operation and Maintenance
P_{max}	kW	WEC maximum Power
P_{mean}	kW/m	Mean wave power
P_{rated}	kW	WEC (and generator's) rated Power
P_{year}	kW(/year)	Annual mean wave power flux
q	–	q-factor that measures the array interactions
r_p	–	Mean wave peak direction validity range
SG (WEC-SG)	N/A	(Wave Energy Converter) Selection-Guideline
SIWED	–	Selection Index for Wave Energy Deployments
SI_{waveR}	%	Suitability index of the wave resource
SP	N/A	Systematic Pairing
T_e	h	Theoretical exploitable time (when the wave power is above or equal to 2 kW/m)
θp	∘	Wave peak direction
Tp	s	Wave peak period
TRL	–	Technology Readiness Level
WaPEDI	–	Wave Period Exploitation Development Index
WD	N/A	Wave Dragon
WEDI	–	Wave energy development index
WEC	N/A	Wave Energy Converter
WF	In unit of distance (° or m) or in €, and it allows other possibilities	Weight Function
WFLSP	N/A	WEC-FARM/Location pair Selection Process
WLP	N/A	WEC/Location Pair
WR-KPI	N/A	Wave Resource Key Performance Indicator
WWP	h or days	Weather Windows Waiting Period between them

power installed in 2021 by 25 times, while the other marine renewables must increase their 13 MW of power installed by 3000 times [9]. Specifically, wave energy providing up to 2 TWh energy worldwide [10] shows great potential to achieve such a target. Yet, wave energy remains omitted from many of these studies, and therefore, the general motivation for this article is to help in promoting the integration of wave energy into future energy-mix plans.

Wave Energy Converters (WECs) harvest and transform the energy from ocean waves into electricity for consumption [11]. WECs are characterised by a great variety in terms of sizes [12], working principles [13], and farm configurations [14], amongst others [15]. This variety prevents from having one best technology everywhere. Consequently, WECs and locations must be paired according to their different characteristics. This leads to two opposing cases: the selection of proper location(s) for a given WEC, versus the selection of most appropriate WEC(s) for a given location [16]. Both cases are divided into two aspects that are eventually merged: (I) WECs' performance and (II) location including wave-resource characteristics.

The main parameter to assess renewable technologies is cost [17], especially the Levelized Cost of Energy (LCoE) and Net-Present Value (NPV). On the one hand, LCoE has been assessed by [18] for offshore wind globally and [19] for the European case, while [20] considered LCoE for tidal technologies. On the other hand, NPV was introduced for various renewable types to help the decarbonisation of the building sector in [21], and [22] applied it to WECs. Yet, costs are difficult to access as either confidential or sensitive information. Furthermore, estimating costs for various WEC configurations and locations is very challenging [23]. Alternatively, the Annual Energy Production (AEP) is a fundamental parameter of LCoE and NPV, and is much more accessible. The other main WEC Key Performance Indicator (KPI) is the Capacity Factor (CF). CF is the ratio of the effective AEP to the energy produced if this WEC would function at its maximum capacity yearlong [24]. CF is sometimes used instead of AEP to compare WECs [25]. Indeed, AEP may generate unfairness between WECs with different sizes as it lacks CF's normalisation by the WEC power capacity. A bigger WEC might produce more energy but could also result in higher costs [26]. Additionally, WECs can have their generator optimised to improve CF with little AEP loss [15]. However, currently, CF-optimisation lacks in WEC-location pairing leading to probable unfairness when comparing the resulting pairs, and since CF may be considered in lieu of costs, this may involve improper WEC-selection.

Aristodemo and Algieri-Ferraro developed a complex study considering 13 WECs on the Calabrian Coast [27]. However, most WECs have stopped their activities, and more recent WECs under development are missing, such as WEPTOS [28], Wavepiston [29] or Wedge W1 [30]. Additionally, although Aristodemo and Algieri-Ferraro do not consider WEC generator-optimisation, configuration-optimisation in terms of appropriate WEC size is included using the Froude scaling-law applied to all WECs [27]. This size-only Froude-based optimisation has similarly been done by Bozzi et al. for the Mediterranean offshore [31]. Yet, recently, Choupin et al. discouraged Froude-scaling all WECs without verifying the method's applicability as it may lead to unfair comparisons [15]. Nevertheless, WEC-size optimisation is necessary, but as this may not be feasible for all WECs, for each WEC, a few sizes/configurations/different power rates should be considered instead. Still, generator-optimisations must be applied in any circumstance [15]. Eventually, once the WECs were selected based on their individual performance, Aristodemo and Algieri-Ferraro investigated the farm performances of these WECs. This was not the first time it has been done in this order [32] as generally, so far, WEC farms are assessed once the WECs have been selected. Yet, there is a gap regarding the consistency between selecting a WEC and extracting its farm performances afterwards and selecting a wave farm directly. With what has been mentioned above, this gap also extends to the lack of WEC generator and size optimisation effects on such individual versus farm WEC selections.

Wave resource assessment should include wave climate [33], resource availability [34] and sustainability [35], along with area accessibility [36]. Recently, the authors have previously developed an integrated model to assess installable locations and, using indexes and metrics [37], the wave resource potential for marine/wave renewables [38]. They reduced the 40 available Wave-Resource Key Performance Indicators (WR-KPIs) to the 9 most relevant, complementary, and representative ones. When merged, they provide a map of sweetspots for wave energy, later reduced from environmental and other techno-economic restrictions. However, alone, this study does not provide where which WEC performs best, as it lacks metrics assessing WECs' characteristics and their pairing with locations. Comparing maps of wave resource potential (e.g. sweetspots) with maps of best WEC selection performance remains a consequential gap for wave energy integration into the energy-mix.

Furthermore, WEC-location performance with wave resource potential assessments have been merged in an attempt to compensate for the lack of WEC cost information [39]. This led to the development of the Selection Index for Wave Energy Deployments (SIWED) [40] over Europe, and the Multi-Criteria Approach (MCA) [33] using the Persian Gulf study case. MCA has also been applied over China's coast [41] and in Mexico by different authors [42]. However, to the authors' knowledge, the WEC-selection power of these indexes has not been investigated, yet. Choupin et al. established a comparison between AEP and CF introducing also a new KPI called Energy Demand-Response Index (EDRI) [16]. EDRI crosses information related to WEC performance, costs when available, and localised energy demand-related information not considered before [16]. There is still a gap that consists of the comparisons between the WEC-selection power of EDRI, MCA, and SIWED. Finally, despite splitting the dataset of 30 power matrices between large and small power capacities, Choupin et al. did not perform generator-optimisations [16]. Therefore, this KPI comparison also needs to be addressed considering WECs' optimised CF and AEP values.

Lavidas et al. [39] and Choupin et al. [16] have demonstrated that to properly assess suitable WECs' installation, WEC-location pair maps should be provided. However, although this concept starts to spread [43], it remains lacking from previous and current works as these two studies are the only ones considering such cartography, to the authors' knowledge. Generally, when large surfaces are considered for WEC installation, such areas are reduced to a few key points often preselected using the resource or other key selection factors independent from the WEC performances, as mentioned above ([25] is an example over the entire world, [44] a recent example of mixed farms over a Portuguese area, and even for the thorough cost-including recent study of [45] over the Ligurian Italian coast). Overall, the individual-WEC and WEC-farm KPIs' selection-power must be compared including generator-optimisations and various WEC sizes, and suitable WEC-location cartography needs to be confronted with sweetspots mapping.

By addressing these gaps, the objective of this work is to assess jointly the wave resource potential mapping with enhanced and fairer WEC-location pairing to help increase the level of penetration of wave technologies into the energy-mix. The Canary archipelago is comprised of 7 islands, each having its own wave climate assessed independently, such as La Palma [46], El Hierro [47], Tenerife [48], Lanzarote [49]. The Canary Islands lead to large wave condition variations that go from lake-type areas to highly energetic locations [50], which makes this archipelago a pertinent study case. The previous work done by the authors determined for this archipelago the areas free of technical and environmental restrictions, and mapped the wave resource potential of these installable locations [38]. This Spanish archipelago has a limited land-area orographically complex, making difficult installations of inland renewable technologies, both with solar-PV technology [51] and wind energy [52]. Its high dependency on energy importation and non-renewable energy, and its island structure lead also to question the strategy for renewable energy provision (e.g. global versus local energy-feeding), whereas this is largely unconsidered in the literature. Finally, with a total coastal perimeter of about 4434.70 km^2 (assuming a maximum WEC installation depth of 200 m), wave renewables are taken into account in energy and environmental policies developed to address the clean energy transition and climate change reduction [53], even regarding the creation of specific regulations to ensure their penetration [54]. Where previous works from the authors compared WR-KPIs [38], developed EDRI [16] and an enhanced generator-optimisation [15], this work merges their outcomes and compares EDRI, MCA, and SIWED with reference to AEP and CF in order to verify the relevancy/complementarity of these indexes and answer the present study's objective. Eventually, this research provides an answer to whether such an archipelago, or at least some of its islands, can be energetically independent, to the point of even having some non-renewable thermal power stations removed. In Section 2, these KPIs are evaluated drawing a strategic guideline for wave farm selection to map WECs and WEC farms that best adapt to any given area. The databases used in this study are described in Section 3. In Section 4, the selection of the most complementary and relevant KPIs is provided along with assessing the effect of an improved generator-optimisation to increase CF values. It is worth noting that size-optimisation is involved through the consideration of a large and small size of the WECs considered, hence in this study CF-optimisation only refers to the generator-optimisation and does not involve Froude law or other size-optimisation methods. Eventually individual WEC-selection farm performances are compared with the performances of direct WEC farm selections. Along this investigation, the wave resource and installability energy-scenarios are confronted, and the quantification of the maximum energy coverage provided to the energy-mix of the islands is calculated and discussed before concluding in Section 5.

2. Methods

Fig. 1 provides the framework's main steps. The WEC-Farm/Location pair Selection Process (WFLSP) is based on the Decision Making Process (DMP, [16]) that pairs individual-WECs and locations for farm installation. DMP (red-colors) has been improved using other researches' pieces of method ([15]-blue and [38]-green) for wave farm analysis (Section 2.3) and more KPIs' (described in Section 2.2) considerations. Further, new tasks were introduced (white). Level 0 consists of input data. Only high Technology Readiness Level (TRL) WECs were selected and the Canary Islands wave resource integrated model (synthesised in Section 2.1) was directly obtained from [38]. Following DMP's Systematic Pairing (SP), the restricted areas were removed (within the wave resource integrated model), and the WEC Selection-Guideline (SG) was applied to select WECs. Notably, SG takes into account the converters' technical specifications, such as their operation bathymetry or ease of disposition towards the predominant wave direction. If WECs show technical characteristics unsuitable for the location, this will serve as a filter for choosing the ideal WEC. The SP has been tuned by including an improved optimisation of the generator to increase CF values, hereafter the CF-optimisation from [15] (Section 2.2.1). Then, following the general DMP discussion, the single-WEC KPIs (Section 2.2) were analysed to select the most relevant one(s) for the last two steps of the WFLSP. DMP's improvements regarding wave farm

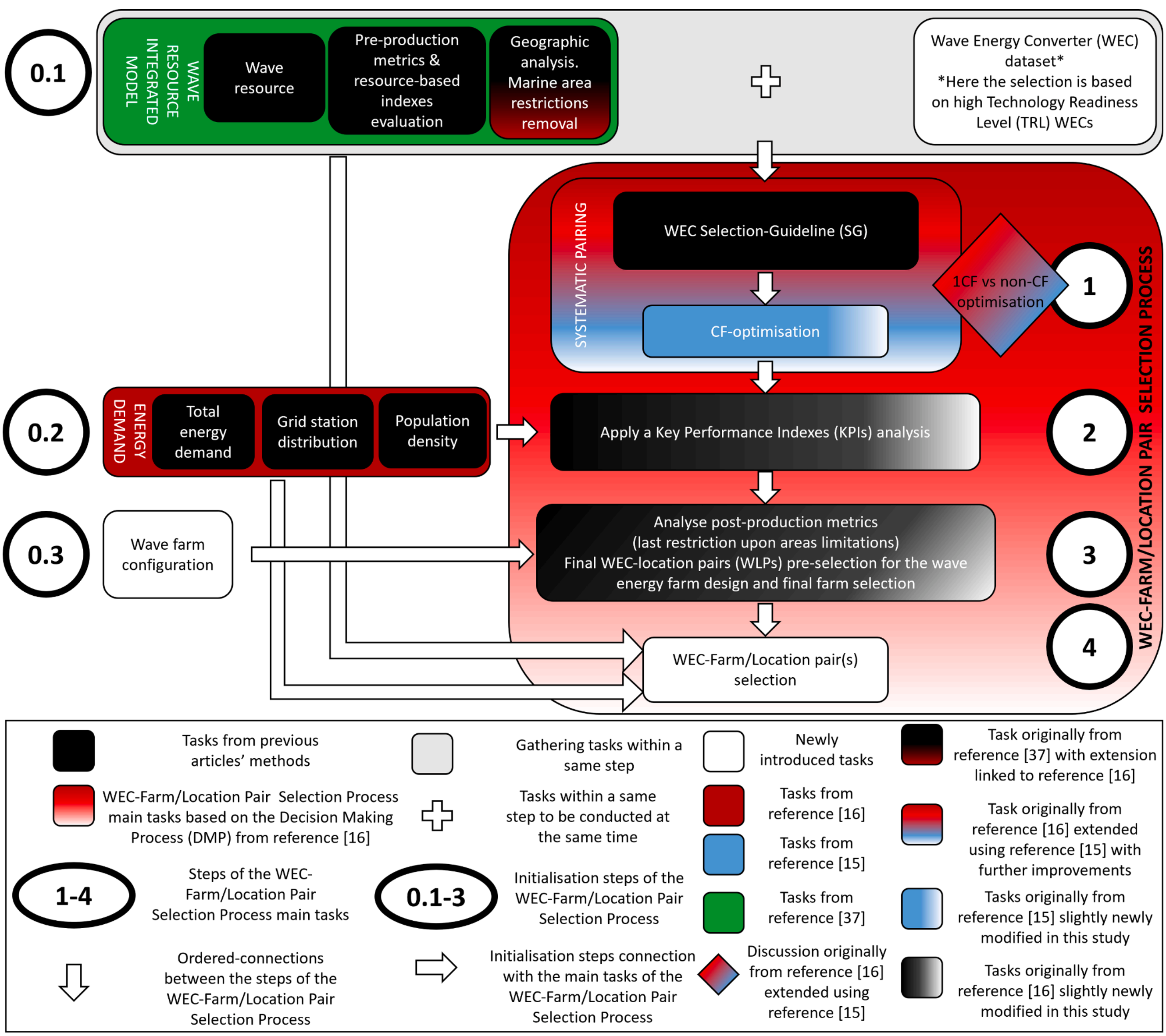

Fig. 1. Framework flow chart for assessing wave farms' energy production to select pairs of wave farms and locations. New tasks are introduced in white cells. Tasks already existing from the other references but improved in this work have the initial source's color (left-wards), which evolves eventually to white (in the direction of the new change written in the task-box's text). The diamond-shape box only consists of the analysis or discussion conducted in Section 4.

analysis are explained in Section 2.3.

2.1. Wave resource integrated model

The aforementioned integrated model to assess coastal locations and wave resource potentials for marine renewable installations [38] merges two developed methods that included (A) a wave resource analysis and (B) marine area installation feasibility:

(A) The wave resource integrated model concluded that 9 WR-KPIs (based on 40 WR-KPIs over 63 different approaches) were the most relevant, complementary, and representative of currently developed pre-production indices. Namely, the Suitability Index for wave power (*SIp*) represents inter and intra-annual variations; both the Wave Period Exploitation Development Index (WaPEDI) and mean wave peak direction validity range (r_p) compensate for the lack of wave peak period and direction analyses; the Wave Energy Development Index (WEDI) is the ratio of annual mean wave power (P_{year}) to the maximum storm wave power (J_p); the 100-year wave return height (Hs_{100}) assesses the resource harshness based on Extreme Event Analyses (EVA); the availability for power absorption; and 3-days weather window average WR-KPIs were selected with regards to Operation and Maintenance (O&M) in terms of [34] weather window length (LWW), number of days (NWW), and waiting period duration (WWP). These parameters were classified (thereby dimensionless) to adjust their weights in the integrated model.

(B) Based on the coast bathymetric feasibility alongside environmental (protected natural areas and Natura 2000 Network) and socioeconomic restrictions (military, airport, telecommunication, aeronautical easements, submarine cables and maritime transport navigation channels), available areas for WEC (farm) installation result in two geographical scenarios. The most restrictive Scenario 1 involves all environmental, technical, and economic restrictions, while Scenario 2, more flexible, discusses their relevancy for marine/wave farms.

Finally, both methods are combined to provide the definitive map of marine/wave renewable potential of possible installation.

2.2. Key-performance indicators

First, the fundamental AEP and CF are described, followed by the CF-optimisation and more developed KPIs also including local features.

2.2.1. Annual energy production and capacity factor

Generally, the "power matrix" provides the power the WEC harvests for given sea-states (of wave height, period, and direction) [55]. The sum of the product of the power matrix and the number of hours of waves occurring during that year for each sea-state gives the AEP (MWh) of that WEC at the considered location [56]. It should be noted that the WEC directional dependency is directly included via considering the 3D power matrices when necessary for higher accuracy than using DMP's wave-direction dependent curves [16].

For a given location and year, CF (%) is AEP divided by AEP_{max} (MWh). AEP_{max} is the product of the year's number of hours (approximately 8760 h) and the maximum power the WEC produced (P_{max}, kW) [57]. It must be noted that CF is equivalent to the "full load hours" index used, for example, by [58]. Due to their high similarity and since CF is much more used to compare renewables [25], only CF is considered here.

2.2.2. Generator optimisation to improve the capacity factor

The objective of this section is to improve CF. One way to do this is to reduce P_{rated} (in the denominator of CF's equation) without affecting AEP. Indeed, the most energetic part of the power matrix is associated with waves that rarely happen. Therefore, reducing P_{rated} and thereby increasing the plateau of same P_{rated} values in the power matrix barely affects the AEP, whilst increasing CF largely. Generator optimisations start with the WEC's P_{max} experienced for the local wave climate. Then, the maximum WEC power, P_{rated} (kW, $P_{max} \geq P_{rated}$), is reduced such that all sea-states with a higher WEC power than P_{rated} are set to P_{rated}. This generates an increasingly large P_{rated}-plateau in the power matrix. The method from [15] consisted of reducing for each iteration P_{rated} by 1 % of the previous iteration and the optimisation loop would stop once AEP starts to "feel" the effect of P_{rated}, i.e. when AEP of the iteration is 0.1 % below that of the previous iteration. This technique was tested and found weak for the current WEC/location dataset. Therefore, it has been improved so that the optimisation is adjusted for all resource-WEC couples. Namely, P_{rated} is decreased up to having an AEP≈0Wh. The optimum point is obtained by using the tangents at the beginning and the end of the AEP-curve in function of P_{rated} (visible in [15]). Indeed, the crossing point between these tangents projected on the AEP-curve always provided a point at the elbow of that curve, after which P_{max} reductions involve larger AEP reductions (Appendix A provides further details to apply this method).

2.2.3. Multi-Criteria Approach

The Multi-Criteria Approach (MCA, –) KPI developed by Kamranzad and Hadadpour [33] pairs WECs and locations combining AEP, Hs_{100} (m), the Exploitable storage of wave energy, *Ee* (MWh), O&M's percentage of time where the location is accessible as $Hs < 1.5$ m (accessibility) and harvestable as $0.5 < Hs < 4$ m (availability) [38], and Monthly Variability Index (MVI, [59]) of Energy production (MVI_{E0}, non-dimensional). MCA is provided in Eq. (1):

$$MCA = \frac{\frac{Ee}{Ee_{local}} \cdot accessibility \cdot availability \cdot \frac{AEP}{AEP_{local}} \cdot \frac{Hs_{100local}}{Hs_{100}}}{MVI_{E_0}} \tag{1}$$

Ee_{local}, AEP_{local}, and $Hs_{100local}$ are the respective mean *Ee*, AEP, and Hs_{100} obtained over the entire zone and considered period, to conduct a normalisation of the data. Further, the AEP_{local} is also taken over all WECs, thus it is a fixed value for all. *Ee* is calculated using Eq. (2):

$$E_e = P_{mean} \cdot t_e \tag{2}$$

For a given location, t_e is the number of annual hours in which any WEC could exploit the wave resource (2 kW/m power low-threshold following [60]), and P_{mean} (kW), the mean wave Power. *E0* (kWh) is the monthly Energy production [59]. *E0* consists of a 12-element vector as the monthly energy produced per WEC per sea-cell. For each *m*-month ($1 \leq m \leq 12$), considering n_T the number of binned wave peak periods (*Tp*, s) happening in the wave climate during that month and n_H a similar number but for the significant wave height (*Hs*, m) bins, $E0_m$ is obtained using Eq. (3):

$$E0_m = \sum_{i=1}^{n_T} \sum_{j=1}^{n_H} p_{ij} P_{ij} \tag{3}$$

where p_{ij} (h) is the number of hours the wave occurs during that month for that given *Hs*-*Tp* bin, and P_{ij} (kW) is the power the given WEC can harvest for that same bin. Finally, MVI_{E0} is calculated using the maximum (ma), minimum (mi), and average (av) of *E0* as in Eq. (4):

$$MVI_{E_0} = \frac{ma(E0) - mi(E0)}{av(E0)} \tag{4}$$

2.2.4. Selection index for wave energy deployments

As opposed to MCA based on AEP, the Selection Index for Wave Energy Deployments (SIWED, –) [40] focuses on a CF-perspective. Here, WECs' performances allude to their resource dependence (specifically the wave height). Eq. (5) provides SIWED's calculation:

$$\mathrm{SIWED} = \frac{e^{-COV_{HS}} \cdot \mathrm{CF}}{\frac{H_{EVA}}{H_{max}}} \tag{5}$$

where for a given location, COV_{HS} (non-dimensional) is the Significant wave Height Coefficient Of Variation, H_{EVA} (m) is the 30-year EVA's return wave Height, and H_{max} (m), the maximum significant wave height. H_{EVA} and H_{max} ratio quantifies the WEC survivability.

2.2.5. Energy Demand-Response Index

The Energy Demand-Response Index (EDRI, –) indicates locations where the energy production answers the closest terrestrial energy demand efficiently [16]. EDRI can be obtained as in Eq. (6):

$$\mathrm{EDRI_{WLP}} = \frac{\mathrm{ED}}{\mathrm{CF_{WLP}} \cdot \mathrm{AEP_{WLP}}} \mathrm{WF} \tag{6}$$

ED is the Energy Demand at the reference point (e.g. power grid stations, desalination plants, or islands' geometric centers). CF and AEP refer to a single WEC-Location Pair (WLP). The Weight Function (WF), is calculated as the Euclidian distance between the reference-point and WLP's location. WF represents the effect of costs and increased energy demand associated with (i) losses from the energy transfer, (ii) capital, and (iii) O&M (all variables are affected by this distance). For the lack of cost information, WF is the distance between the reference point of coordinates $[x_r, y_r]$ and the sea-cell of coordinates $[x_{sea\text{-}cell}, y_{sea\text{-}cell}]$ all in degrees, such that WF = 1 + d_{grid}, with d_{grid} (∘) the aforementioned distance calculated using Eq. (7).

$$d_{grid} = \sqrt{(x_r - x_{sea-cell})^2 + (y_r - y_{sea-cell})^2} \tag{7}$$

EDRI's units depend on WF's (here in degrees, ∘) so EDRI is in ∘/year. In this case, the Energy Response-Demand Index (ERDI), as ERDI = 1/EDRI (%, [16]) partially translates the energy supply provided by the WEC to the reference point. Notably, where EDRI highlights less suitable areas, ERDI underlines the most suitable ones. ERDI is therefore complementary to EDRI and should always be considered alongside EDRI.

2.3. From single wave technology to farm assessments and energy production

In this study, a farm is a wave farm, which is a group of WECs installed in a certain organisation and connected to other structures (such as a grid [61] or a desalinisation plant [62]) so that the energy the WECs produce can be used. Farms involve hydrodynamic interactions, both within the farm ("near field" effects e.g. between WECs) and outside ("far-field effects" e.g. with coast or port-structures) [63]. Such interactions, as well as cost efficiency and WEC security-spacing, depend on the farm and WEC configurations (individually [64] and jointly [65]). Currently, estimating the inter-distance necessary for each WEC-farm requires heavy hydrodynamic simulations for each individual location-resource pair. Optimisations generally employ the q-factor, the ratio between the power outputs of an array of N units and of N isolated units [27]. This being out of this study's scope, it is required that WECs are installed so that none of them affects the other (equivalent to a q-factor of 1), which is settled information known by the developers.

In the first application of DMP based on individual-WEC selection, the number of installable WECs was computed post-results for the high-potential areas (determined first using EDRI and then looking at MCA and SIWED values for the selected WECs). Based on the spatial resolution of the wave model under consideration, where the area covered by each model grid point is referred to as a sea-cell, the number of installable WECs was computed in function of WEC-distances and the sea-cells' coverage (~200 m edge so about 40 km^2). Generally, the area was large enough to install more WECs than the energy demand required at the closest reference point [16]. For a spatial resolution of a few kilometres, each sea-cell must be assumed to contain a complete farm of a few WECs (as many as possible to answer the energy demand at the closest reference point). Eventually, if over one sea-cell, the total energy demand is not answered, the final farm may contain two sea-cells or more (if any other renewable energy still does not complete this demand).

3. Dataset

First, the wave data, resource potential, and available installation areas are presented followed by the description of the WECs and their farm configuration, before introducing diverse energy demand-response strategies.

3.1. Wave data and area analysis

Wave hindcasts were downloaded from Copernicus Marine Environment Monitoring Service (CMEMS) [66]. This widely-validated reanalysis covers the Iberian Biscay Ireland region from 1993 to 2019 with an hourly temporal and 5 km spatial resolutions [67]. The bathymetry dataset uses ETOPO [68]. Following the previous study's method [38], the shoreline water depth boundary has been set to 20 m.

Fig. 2 introduces the integrated map, with both the geographical feasibility scenarios [38] of accepted areas for marine/wave renewable and the potential for installation (based on the 9 WR-KPIs selected in the integrated model). Scenario 1 (red-line) complies with all restrictions, while Scenario 2 (blue-line) disregards the aeronautical restrictions related to aircraft manoeuvrability, and environmental areas that are demonstrated to be less harmed or not harmed at all compared to other marine technologies (e.g. offshore wind). 200 m depth (black-line) highlights the maximum WEC installation depth [69] due to mooring/anchoring suitable pairing [70] and thereby limitations [71]. This shelves' potential is the base to compare, in Section 4, WEC-location pair-potential mapping and areas' pre-selection regardless of WECs' performance.

3.2. Wave energy converters and farms

This study focuses on high TRL (above 6 [72]) WECs that have undertaken offshore sea-trials. Two (small and large) configurations were selected for each WEC (see Appendix B for more details):

Wave Dragon (WD): is an overtopping device with water stuck in a pool. The overtopping wave pushes this water down eventually spinning a turbine located at its bottom [62]. The wave climate of the Canary archipelago is suitable for WD's 1 and 4 MW commercial sizes. 1 MW WD's installable bathymetry range is 20–50 m [16]. The minimum operating bathymetry for 4 MW WDs reaches 30 m, making it an offshore WEC [73]. It is organised using the staggered farm layout [74] with 130 m vertical WEC inter-distance and 2xD (D the distance between the tips of the WD's reflectors) for the horizontal inter-distance. With D = 152 m for 1 MW and D = 230 m for 4 MW [75], both respect the minimal lateral spacing of 255 m necessary to prevent collisions [74]. Finally, a second 2-row farm (aligned with the first farm) is required to be away from the first by 3 km to avoid wave energy absorption losses (Beels et al. estimated a maximum decrease in the wave energy of 15 % between closer rows [74]).

Wavepiston: This wave direction-dependent surge terminator contains energy-collectors along a fixedly anchored string [29]. Each collector is mainly composed of a plate that moves back and forth under the action of the wave, pumping water that eventually turns a turbine generating electricity [15]. 24 and 50 collectors spaced by 14 m and 7 m respectively are considered here with an installed power range of 0.1–0.4 MW [76]. The plates size 9x4 m. Although the 24-collector Wavepiston has been modelled for all considered water depths (20–200 m) the 50-collector simulations have been provided only between 25 and 75 m although it may be installable in broader ranges [77]. For its high wave energy density absorption, Wavepiston farm can

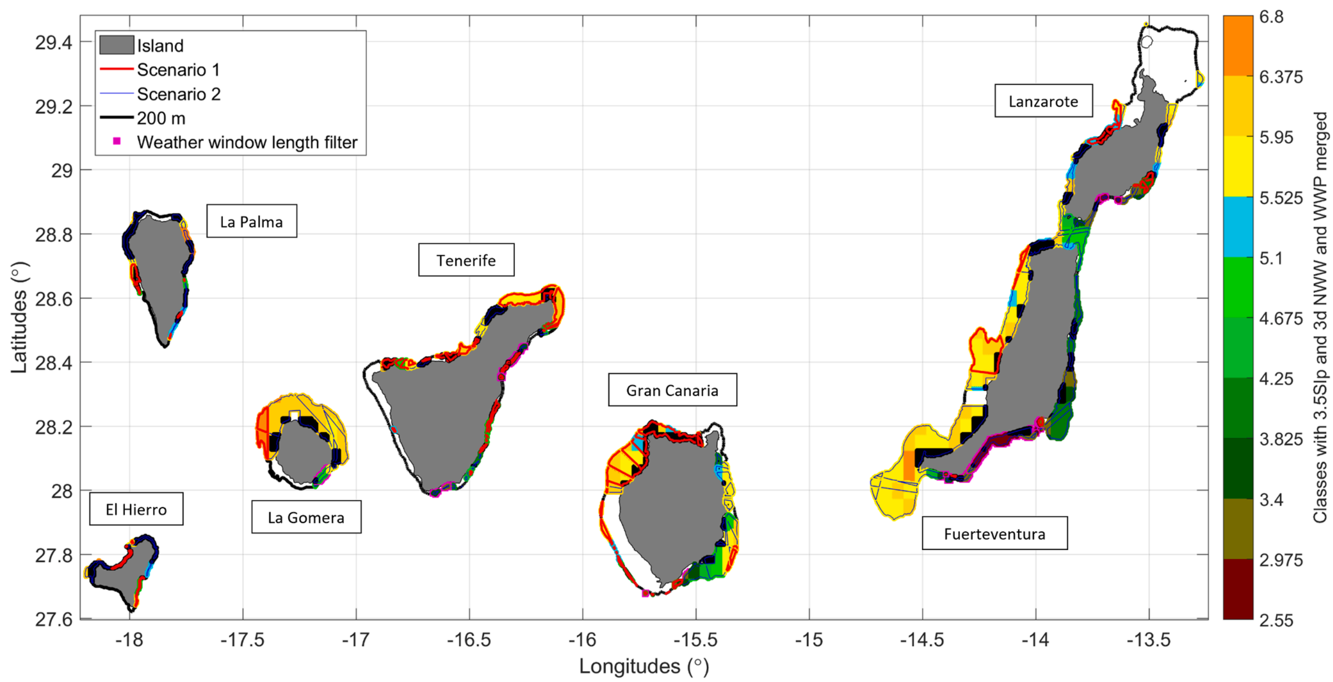

Fig. 2. The Canary archipelago wave resource potential of the available areas for marine/wave renewable installation integrated from [38] (see [38] for higher resolution and zoom of the islands). NWW and WWP stand for the 3-day (3d) operation and maintenance weather window number of days and waiting period duration, respectively, and the Suitability Index for wave power (SIp) has a 3.5 weight in the classified integrated-equation (see [38] for further information).

only possess one row (no farm – of any WEC-type – can be installed behind it) with a lateral WEC inter-distance of 60 m [62].

Weptos: is an A-shape attenuator with an average opening angle of 90° adaptable to weather conditions (smallest for stormy weather) [78]. Along both arms are installed 20 Salter's Duck-type collectors [79]. Weptos scales with the Froude law based on its collectors' rotor width [28]. The most appropriate scale for the archipelago is 50/1 (a large 12 m rotor width) with a generator range from 2 to 10 MW. The second (smaller) 8.3 m rotor width configuration was selected based on [80]. Both are installable within 30–100 m depth (expanding the 40–80 m range of previous studies [81]). Weptos adapts to the wave direction by spinning around its anchor requiring a security perimeter diameter of twice the WEC total length. The mooring total length is water-depth dependent, and so is the distance between WECs in the staggered farm configuration. Indeed, the inter-distance is proportional to the sum of the safety diameter and the location water depth (specificities can be consulted at [81]).

Undigen: point absorber Wedge W1 prototype is under development by Wedge Global company through the Undigen Project. By optimising the WEC resonance frequency over the archipelago wave climates, Wedge Global provided two omnidirectional buoys with diameters of 7.5 m [82] for 80 and 200 kW rated power. Undigen is installable from 24 m up to 100 m due to mooring costs (thereby feasibility). A reasonable WEC inter-distance (both lateral and longitudinal distances) for the archipelago is 60 m, within the minimum 5–10 times the diameter that ensures $q \approx 1$ [82]. The staggered farm configuration consists of 3 rows, and two farms distanced by 2 km are considered.

It is worth noting that despite the fact that all these WECs lay on the water surface, visual restrictions such as the tourism filter [16] have been neglected. These may be considered for a larger database containing underwater devices.

3.3. Energy demand and infrastructures

Responding to the energy demand being one of the major goals of renewables, this section presents the energy demanded at different scales (from local to global scenarios) and the energy supplied by non-wave renewables. The energy production data generated by WECs can later be compared between annexed land regions and each island's energy-mix. Then, it is possible to analyse the contribution of waves to the installed energy-mix and the reduction of locally generated conventional energy.

3.3.1. Energy demand electrical management

The first Energy Scenario (ES1) is based on the annual energy demand of each island for 2019 (avoiding the values of 2020 and 2021 years due to possible fluctuations associated with the COVID-19 pandemic) [83] (Table 1). The reference point for each island's energy demand is at its geographic center (see Fig. 5). This allows the distance used in the WF, Eq. (7), to be balanced throughout the different sea areas.

The second Energy Scenario (ES2) focuses on town centers (cities and villages). In this case, the number of inhabitants per municipality was obtained from the Canary Institute of Statistics (ISTAC) for the year 2019 [84]. Knowing this value and the energy consumption per capita in the islands during the year 2019 (4121 kWh/inhabitant) over the entire archipelago [85], the energy demand of each locality is obtained. Fig. 3 introduces the distribution of communities throughout the archipelago necessary for ES2. The colors displayed inside the circles show the energy needed per municipality, whereas edge-colors link each community to the closest marine areas that will produce wave energy supply adjacent to its demand.

Finally, the third Energy Scenario (ES3) concentrates on the power-

Table 1
Annual energy demand for 2019 in the Canary Islands [83].

Island	Energy demand (GWh/year)	Island area (km^2)
Gran Canaria	3 047.2	1 560
Tenerife	3 550.9	2 034
Lanzarote	853.7	845
Fuerteventura	686.4	1 659
La Palma	261.9	708
La Gomera	73.94	369
El Hierro	42.87	268

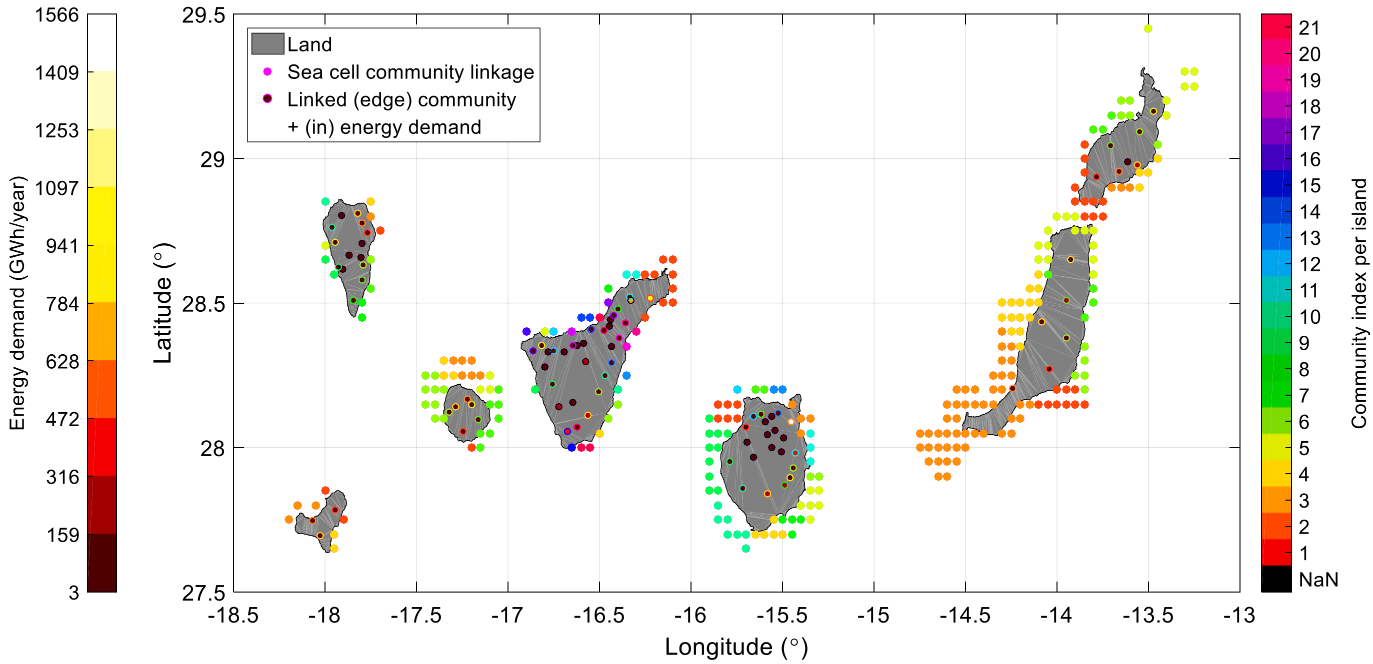

Fig. 3. Energy demand (left hand-side colorbar and inside colors of the inland circles) of the Canary Islands' community distribution linked (circle color) with marine sea-cells (5 × 5 km outland filled circles with colors referred to the right hand-side colorbar) for ES2.

grid stations. This distribution will be much more realistic in terms of WF as each wave farm will be connected to the closest station or substation [16]. For each grid station, the energy demand is estimated as the accumulation of the closest communities' energy demand. Fig. 4 shows the distribution of the electrical substations (power-grid stations) necessary for ES3. Following the same procedure as in Fig. 3, all the electrical substations (grid stations) of the archipelago are identified. Again, inside-colors provide the energy demand at each station, and edge-colors link them to the closest marine areas.

3.3.2. Energy supply

Table 2 shows each island's installed power for 2019. Renewables' installed power (about 609.44 MW) accounted for 18.4 % of the Canary Islands' total energy supply. Eleven thermal power plants distributed throughout the islands lead the energy production alongside imported fossil fuels [85].

Fig. 5 compiles most of the information from Section 3.3. Notably, the geometric center of each island with its associated energy consumption (colored-stars using left hand-side colorbar), and locations of the thermal power plants alongside renewable farms (see figure legend)

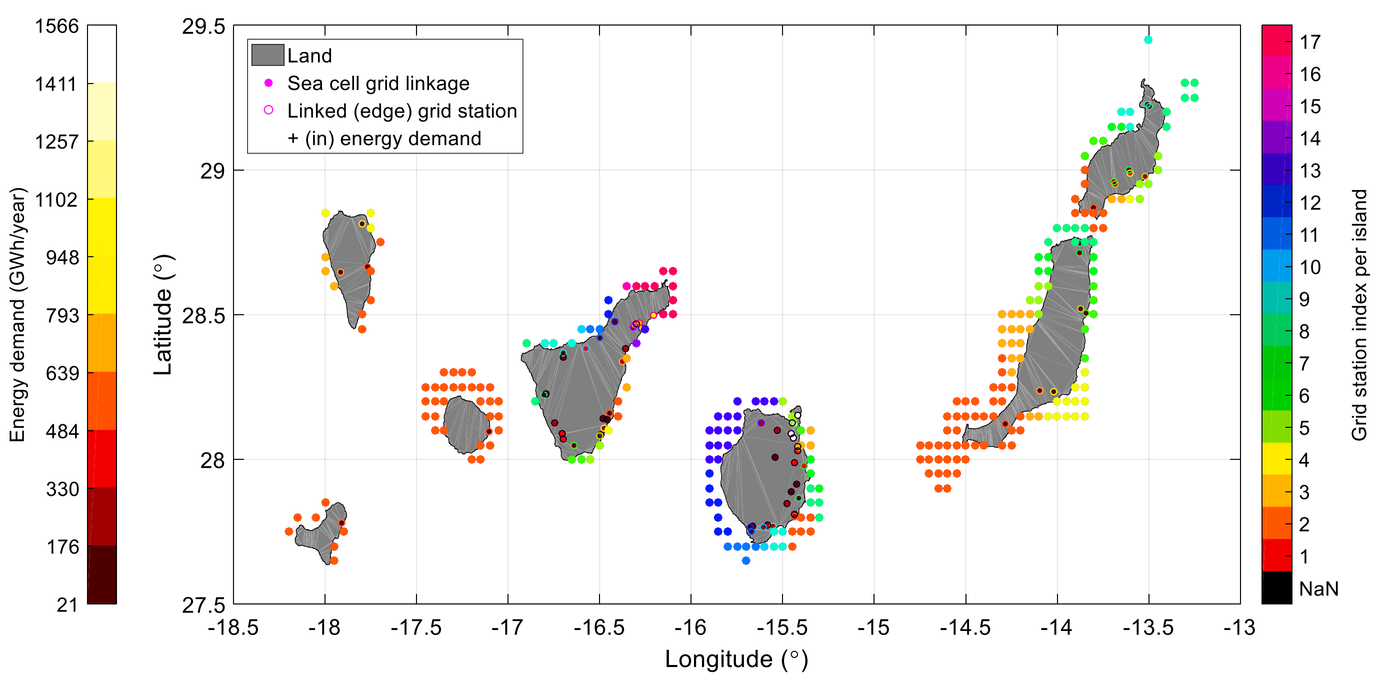

Fig. 4. Community energy demand accumulated at the closest electrical substation (grid station) distribution (left hand-side colorbar and inside colors of the inland circles) linked (outside circle color refer to the right hand-side colorbar) with marine sea-cells (5 × 5 km outland filled circles with colors referred to the right hand-side colorbar) for ES3.

Table 2
Canary Islands' electrical-generation park total installed power (MW) according to electrical power [85] in 2019 (sub-division of this power is highlighted in Fig. 11 and Fig. 12).

	Gran Canaria	Tenerife	Lanzarote	Fuerteventura	La Palma	La Gomera	El Hierro	Canarias
Petroleum products								
Thermal power stations	999.18	1 046.50	232.26	187.02	105.34	21.17	14.91	2 606.38
Refineries	–	25.90	–	–	–	–	–	25.90
Cogeneration	24.88	39.20	–	–	–	–	–	64.08
Total Petroleum products	1 024.06	1 111.60	232.6	187.02	105.34	21.17	14.91	2 696.36
Renewable sources								
Wind	159.30	195.65	22.30	28.66	6.97	0.36	0.00	413.24
Solar-Photovoltaic	37.17	107.16	7.39	11.91	4.03	0.01	0.03	167.69
Mini-hydraulic	–	1.22	–	–	0.80	–	–	2.02
Hydro-wind	–	–	–	–	–	–	22.80	22.80
Biogas (landfill)	–	1.60	2.10	–	–	–	–	3.70
Total Renewable sources	196.47	305.63	31.79	40.57	11.80	0.37	22.83	609.44
TOTAL	1 220.53	1 417.23	264.05	227.59	117.14	21.54	37.74	3 305.81

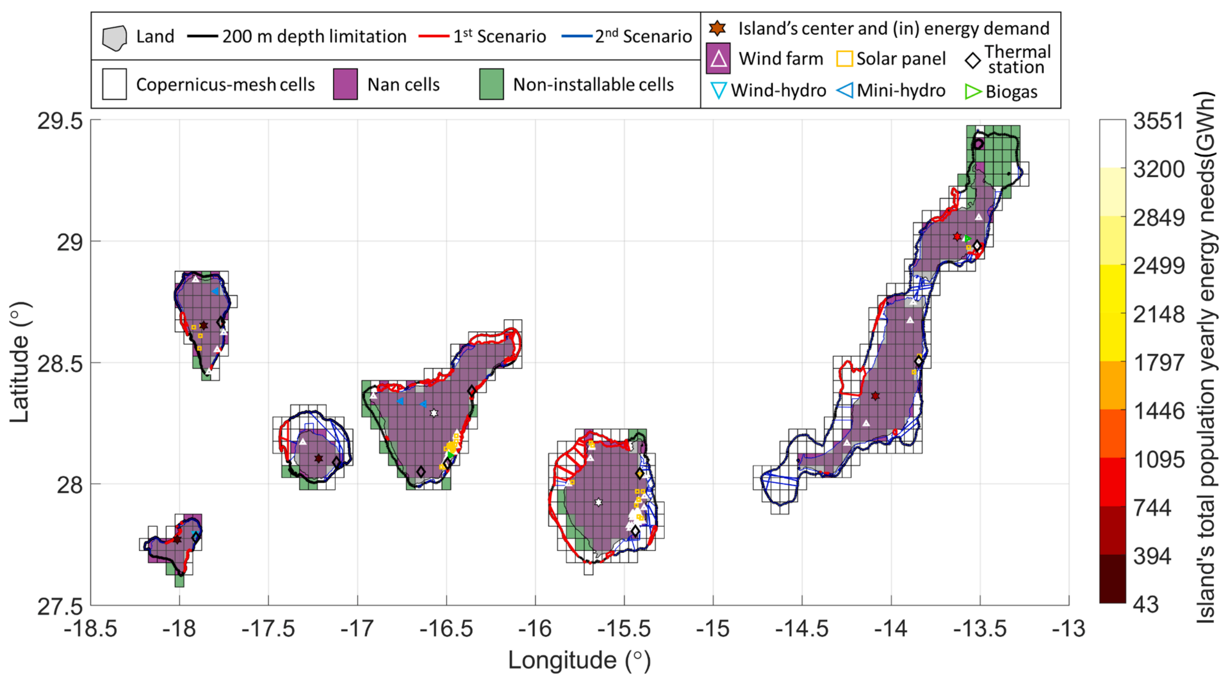

Fig. 5. The characteristics of the Canary Islands. Each island's energy demand is accumulated and shown using the right hand-side colorbar in each island's center that is also the referenced point total islands energy demand for ES1. Thermal power stations and most important renewable energy installations (see Table 2) are shown. The exact 5x5 km contour line of all sea-cells encapsulating even an inch of the shelves (200 m dark-limit) from Scenario 2 (blue lines including the red lines that belong to Scenario 1, see Fig. 2). Sea-cells overlapping none of the Scenario's contour line are considered non-installable (green), and those without wave data are the nan-cells (purple). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

are identified. It should be noted that only photovoltaic solar farms greater than 300 kW have been located, which represents 102 of the 167 MW installed. Indeed, the remaining installations are considerably small and located on the roofs of private houses, making their identification very difficult. Solar energy production was obtained using the technical characteristics of each solar plant and solar resource data (20 years) obtained from pyranometers arranged throughout the islands. A more detailed method can be found at [86]. The wind energy was estimated using an official database of the Government of the Canary Islands [87], which contains historical data of eight years of hourly wind energy production and equivalent hours. However, no data existed after 2005, which required individualised assumptions regarding the improvement of technologies (e.g. repowering or turbine-dismantling/incorporation). Finally, the rest of the renewable energy provision has been provided directly from the same reference [85]; except for the few Mini-hydraulic types, only the total annual energy was provided, so their individual value was obtained using a pondered division of the total using each rated power. Energy results are displayed (in Section 4.2) and discussed in Sections 4.2 and 4.3.

4. Development of the smart strategy of wave farm selection and related discussion

Firstly, the individual-WEC selection for the different KPIs is investigated to select the most relevant and complementary KPIs representative of the whole; then, the farm configuration's energy production/supply of these KPIs' individual-WEC selections is provided; followed by the comparison with their direct KPIs' WEC-farm selection.

4.1. Individual wave device selection and capacity factor optimisation: An investigation of key performance indicators versus resource potential

This section first aims to reduce the number of KPIs to the most relevant and complementary ones. In order to better understand the WEC-selection power/capability of these indexes, Section 4.1.1 simplifies each KPI's equation in order to highlight only the terms involving WECs. Then, Fig. 6 organises the WECs' selection-power KPI values over the archipelago in function of their most important parameters. With the understanding of the power of these KPIs in the WEC-selection, Fig. 7 provides the selected WECs for each grid point of the archipelago from each KPI. The values of KPIs for each selected WEC can be found in Fig. 8 for AEP, CF, MCA, and SIWED. Due to ES1-3, EDRI's WEC-selection values are provided separately in Fig. 9 to which is associated Fig. 10 providing the ERDI values. As the second aim of this section is to assess the effect of the generator CF-optimisation, all results are provided with and without its effect on the selection.

4.1.1. Key performance indicators equation transformation into their wave energy converter selection power/capability

First, MCA, Eq. (1), WEC-selection power/capability $MCA_{WEC\text{-}selection}$, needs the removal of all site-related parameters (i.e. the accessibility, availability, wave energy and EVA-based coefficients). Using the equation of MVI_{E0}, the first simplification of Eq. (1) leads to the final version of Eq. (8):

$$MCA_{WEC-selection} = \frac{AEP}{AEP_{local}\, MVI_{E_0}} = \frac{AEP\, av(E0)}{AEP_{local}\,(ma(E0) - mi(E0))} \tag{8}$$

In Eq. (8), AEP_{local} is the mean of AEPs for all the WECs over the entire area, diverging from the average (av), maximum (ma), and minimum (mi) of *E0*. Moreover, av(*E0*) is very close to AEP/12 (with the difference that the selected AEP is actually the total mean AEP over the entire 30-year, hence the slight divergence in the AEPs) such that $AEP_{av}(E0) \approx AEP^2$. The coefficient AEP/(ma(*E0*)-mi(*E0*)) compares the annual to the monthly performance, which is multiplied by the

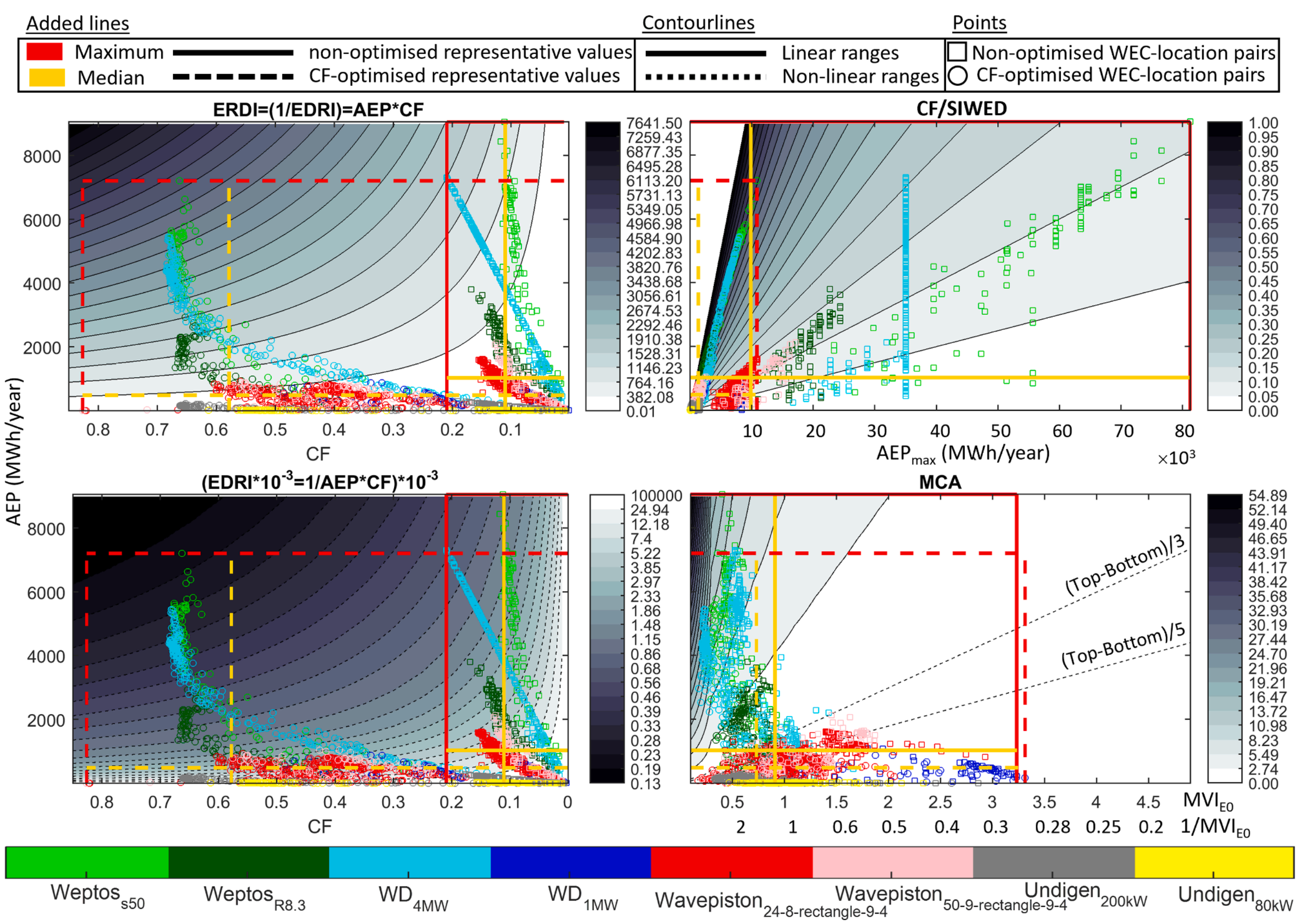

Fig. 6. Visualisation of the main parameters' values only in terms of WEC-selection capability (it could be assumed that all other parameters would equal one). The Capacity Factor (CF) has the same selection power as the Selection Index for Wave Energy Deployments (SIWED), so these selection values are provided together; where "/" is a division in other titles, "CF/SIWED" highlights that both CF and SIWED are described in the top-right panel. As the Energy Demand-Response Index ($EDRI_{WEC\text{-}selection}$) does not have a linear spread of the data (and thereby linear ranges as shown by the dashed dark lines), the Energy Response-Demand Index ($ERDI_{WEC\text{-}selection}$) has been added to help understand EDRI. While all indexes are functions of the Annual Energy Production (AEP, in MWh/year), the other main block of the Capacity Factor (CF = $CF_{WEC\text{-}selection}$, in –) is the AEP produced if the wave technology would be functioning at the maximum capacity all year long (AEP_{max}, MWh/year); and the Multi-Criteria Approach ($MCA_{WEC\text{-}selection}$) second main element is the technology Energy production Monthly Variating Index ($MVI_{E0\text{-}WEC\text{-}selection}$). To help understand MCA, two additional contour lines have been provided (hence following the written different ranges than the dark solid-lines). For each index, the representative (maximum in red, and median in gold) values for the dataset over these main blocks have been provided for both the optimised (dashed colored-lines) and non-optimised (solid colored-lines). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

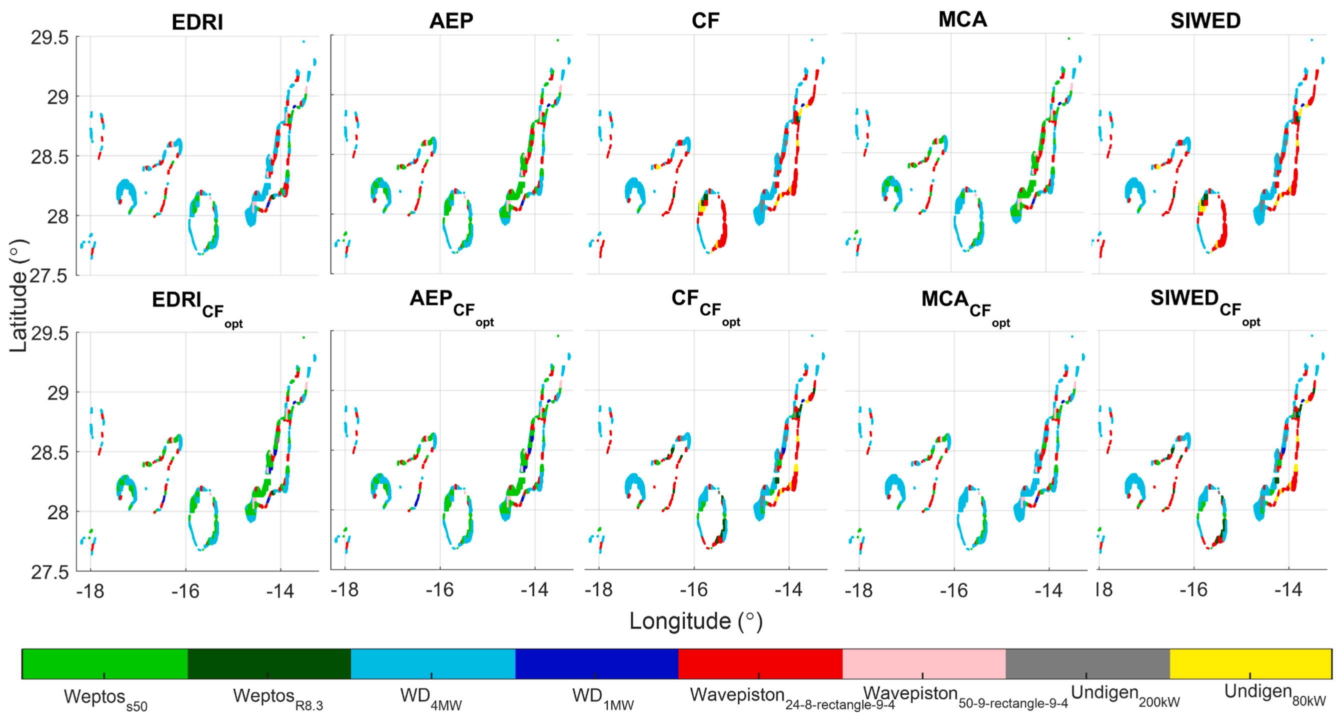

Fig. 7. WEC-selection per Key Performance Indicator. EDRI means Energy Demand-Response Index, AEP is Annual Energy Production, CF stands for Capacity Factor, MCA is Multi-Criteria Approach, SIWED refers to the Selection Index for Wave Energy Deployments, and WD is Wave Dragon. The top row is for non-optimised selected as opposed to the bottom row that shows the results for the CF-optimised (CF_{opt}) individual WEC-selection (based on Appendix A).

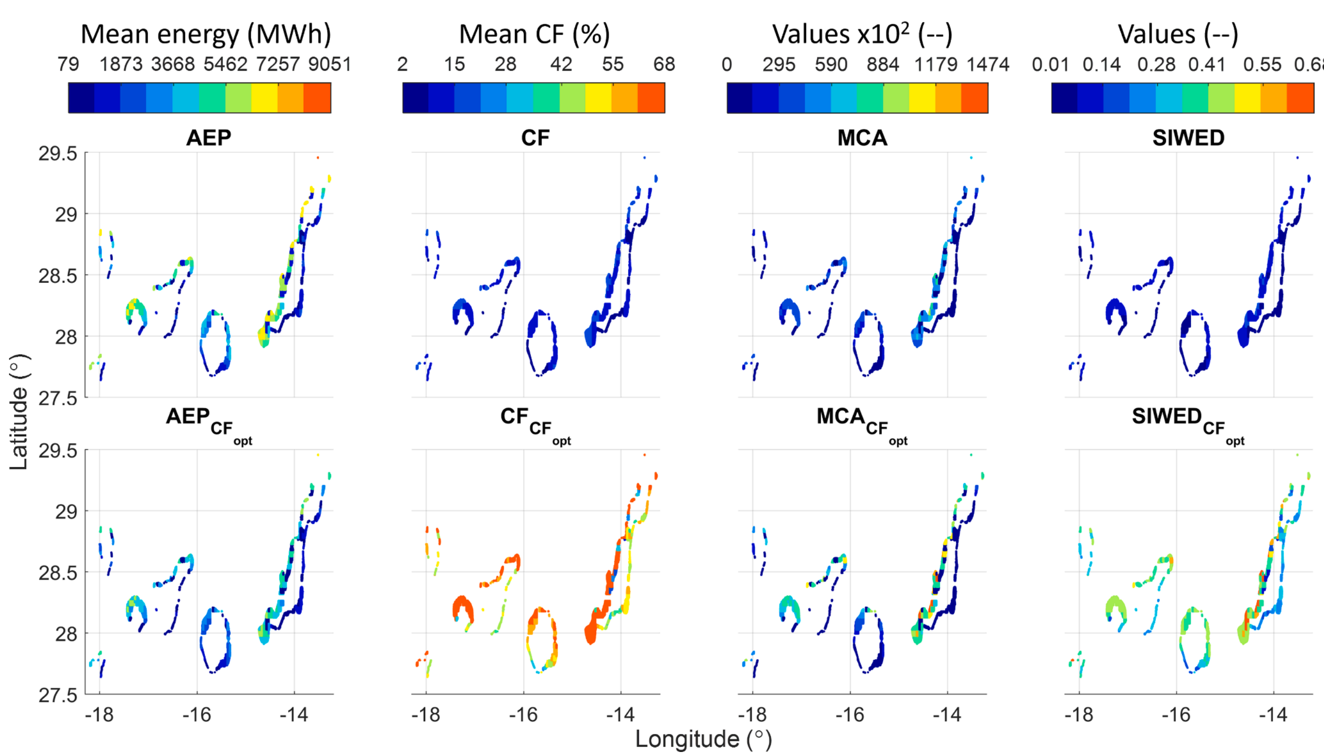

Fig. 8. Key Performance Indicators value for the wave technologies selected in Fig. 7 (with the same non-optimised top-row, CF-optimised bottom-row): the Annual Energy Production (AEP), Capacity Factor (CF), the Multi-Criteria Approach (MCA), and the Selection Index for Wave Energy Deployments (SIWED). Each index is provided a single colorbar per index, so that red color in one sub-figure shows the highest potential over both sub-figure within the same column. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

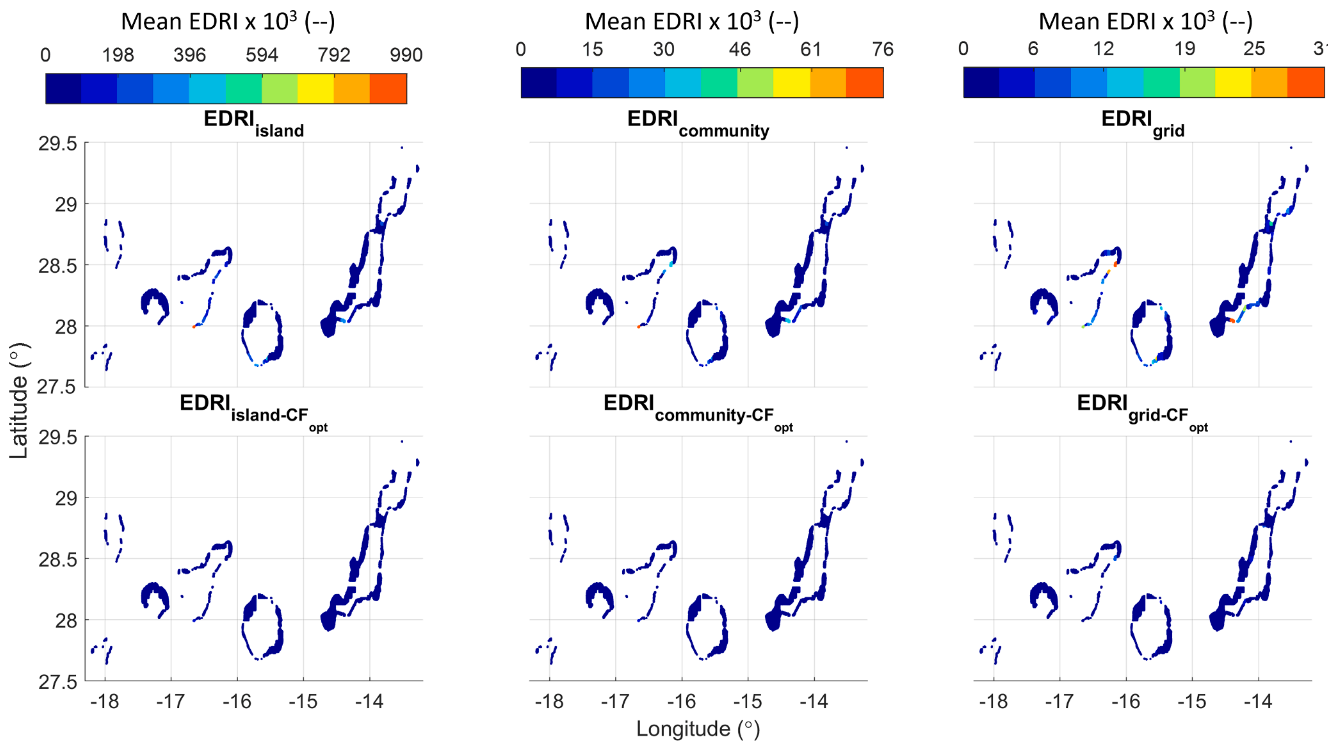

Fig. 9. Same as Fig. 8 but for the Energy Demand-Response Index (EDRI) values for the individual WECs selected in Fig. 7.

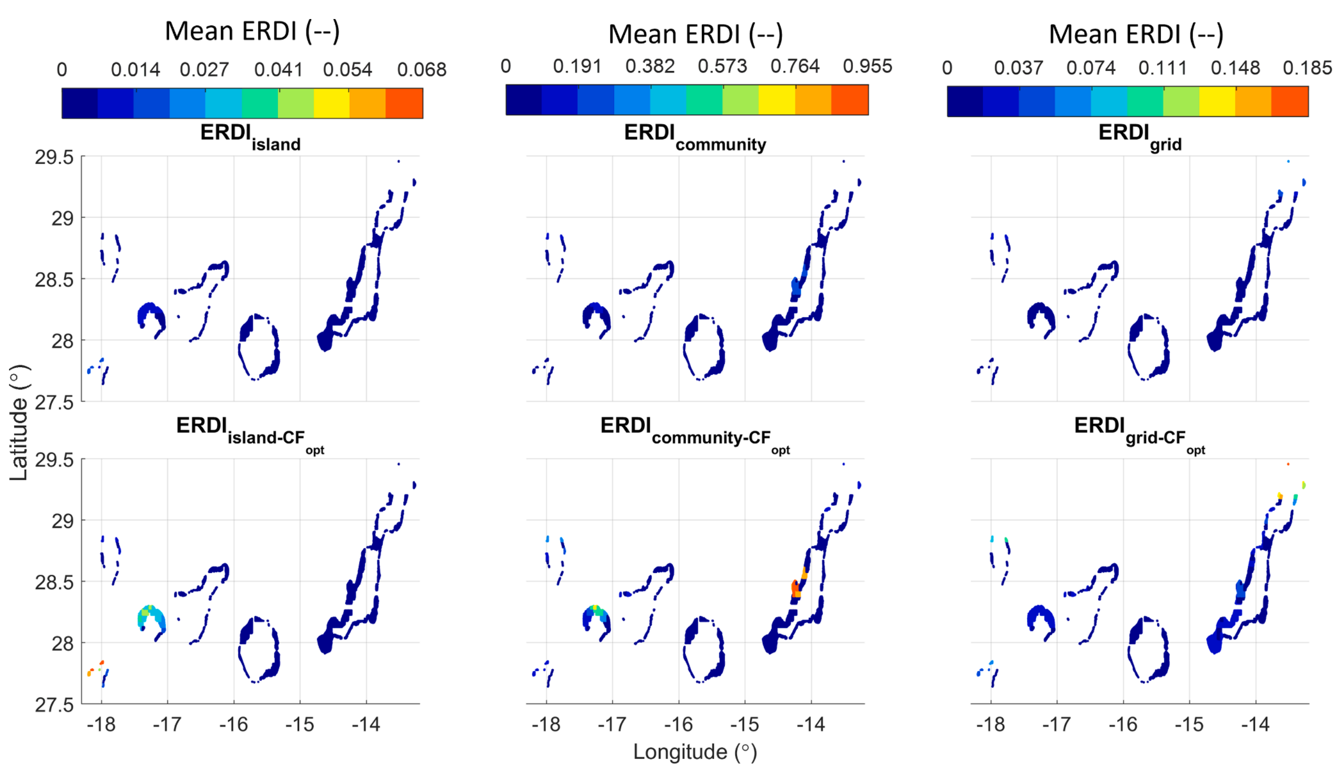

Fig. 10. Same as Fig. 8 but for the Energy Response-Demand Index (ERDI) values for the individual WECs selected in Fig. 7.

performance against the other WECs over the area. Consequently, MCA translates in $MCA_{WEC\text{-}selection}$, Eq. (9), as the multiplication of the WEC potential against all other WECs and over the entire area (left-term, energy production stability) and its individual performance (right-term).

$$MCA_{WEC-selection} \approx \frac{AEP^2}{AEP_{local}\,(ma(E0) - mi(E0))} = \frac{AEP}{AEP_{local}} * \frac{AEP}{ma(E0) - mi(E0)} \tag{9}$$

Second and similarly to $MCA_{WEC\text{-}selection}$, SIWED WEC-selection power/capability is referred to hereafter as $SIWED_{WEC\text{-}selection}$. The simplifications of SIWED's Eq. (5), i.e. removal of wave height covariance and EVA-related factors to obtain Eq. (10), shows that $SIWED_{WEC\text{-}selection}$ demonstrates that SIWED selects literally the same WECs as CF that is unchanged between its WEC-selection-based ($CF_{WEC\text{-}selection}$) and original form. Consequently, SIWED is an estimation of the design performance of each WEC independently from the others.

$$SIWED_{WEC-selection} = CF_{WEC-selection} = CF = \frac{AEP}{AEP_{max}} \tag{10}$$

Finally, EDRI's Eq. (6), when being removed the site-related parameters (i.e. ED and WF) to obtain $EDRI_{WEC\text{-}selection}$ in Eq. (11), 1becomes a mid-term between CF and AEP (as a CF dominated by AEP index). Consequently, EDRI is an estimation of how well the WEC performs in terms of energy production and how well-designed each WEC is independently from the others.

$$EDRI_{WEC-selection} = \frac{1}{CF^*AEP} = \frac{AEP_{max}}{AEP^2} \tag{11}$$

Overall, AEP and CF, compared to the MCA, SIWED, and EDRI, are much less developed such that, individually, their WEC-selection power is weak. Indeed, they answer only one question, how much AEP, in the first case, and how well-rated in the second case. It is much less about the global WEC performance. All KPIs only assess a WEC for a WEC, except for MCA that involves a division by the total mean (over all WEC-location pairs considered), and thereby increases the discrepancy between the WECs regarding AEP-potential: a device that absorbs a greater amount of energy will always be the best choice, while the other converters will become worse the further away they are from that amount of absorbed energy. Indeed, a bigger AEP value has more chance to be less consistent as it allows a bigger difference between minimum and maximum *E0* and vice-versa. Specifically, with a small AEP, the term "$ma(E0) - mi(E0)$" is more likely to be small. Hence, WECs have more chances to increase their MCA in the CF-optimisation approach as their AEP is generally diminished thereby diminishing the E0 gradient. For its part, the EDRI parameterisation involves CF, which not only prioritizes the amount of energy produced, but also its quality. EDRI favours devices that generate energy in an optimised way in terms of design. Here, a large energy production must be associated with a good CF value for the EDRI to provide a small result (which is the ideal situation). WECs with CF adequate for the resource despite a lesser energy contribution may dominate those with higher AEP. Overall, SIWED's WEC-selection is precisely the same as for CF. MCA mostly orchestrates WECs with larger AEP, while EDRI gives a chance to all devices, generating a fairer WEC-comparison than MCA.

4.1.2. Analysis of the wave energy converter selection power/capability for Canary archipelago and considered wave energy converters

Fig. 6 illustrates the effects of these parameterisations for various WECs and wave climates using the considered WEC dataset and archipelago's grid points' nuanced wave climates.

Both generator CF-optimised (circles) and non-optimised (squares) KPI values are provided for all WECs over the entire archipelago in Fig. 6. In both scenarios, Fig. 6 demonstrates the high dependency of all KPIs on AEP. MCA's energy production stability over time smooths the selection if it gets bigger. Generally, three cases distinguish themselves: WEC-location pairs with high AEP and low MVI_{E0} (e.g. WD and Weptos), both low MVI_{E0} and AEP (mix of WECs), and low-AEP WECs show high MVI_{E0} (mostly $WD1_{MW}$). Yet, generally, the results have higher than 0.75 MVI_{E0}, which means that at least half of the data is permanently considered by MCA as if it produces below 1GWh/year no matter their AEP (see WD and Weptos inside the contour line starting from 0.19 MWh/year in Fig. 6-MCA). Overall, the converters that produce the highest AEP values first lead the selection, reaching their final classification in the ranking based on the consistency of energy production over time. All this promotes an underestimation of the devices that do not produce large amounts of energy. Finally, regarding its high dependency on MVI_{E0}, the thinking of $MCA_{WEC\text{-}selection}$ extended to the globe would decrease WEC-installation potentials towards the poles for their increased monthly wave climate variability [88].

Regarding EDRI the aforementioned balance between AEP and CF is explicit in the non-optimised part of Fig. 6-EDRI as some lower AEP WECs dominate higher AEP WECs due to a better CF and thereby a more appropriate fit for the wave climate. Fig. 6-CF/SIWED highlights a diagonal pattern of their value spread that may remind of the LCoE pattern underlined in [61]. Highlighting the maxima and medians in Fig. 6-CF/SIWED clearly shows the CF WEC-selection power improvement in the CF-optimised scenario. For instance, Weptos CF/SIWED WEC-selection power is improved by 50 % on average. This shows an improvement of the method from [15] which only reached a maximum of 40 % CF increase. The limitation of the WEC rating is visible in the vertical line of WD_{4MW} under the non CF-optimised case that becomes a diagonal in Fig. 6-EDRI.

4.1.3. Wave energy converter selection and performance

The findings of Sections 4.1.1 and 4.1.2 were highlighted by Fig. 6 such as the distancing of high versus low AEP WECs by MCA; the improvement of CF/SIWED values from CF-optimisation; and the fairness of WEC assessments from EDRI. To have a better understanding of the implications of these findings, Fig. 7 provides the final WEC-selection of each KPI, and the associated values for each WEC follow in Fig. 8 to Fig. 10. In such a way, Figs. 8-10 display the best index values since they have been selected for the best WEC at each location; for each index and location any other WEC would provide a lesser result.

The WEC-selection shown in Fig. 7 displays the resemblance between MCA and AEP and the exactitude between SIWED and CF. Only EDRI presents a selection of WECs that intersperses results of the other KPIs as a hybridisation between MCA and SIWED generating a fairer map in terms of WEC diversity. The advantage of higher-CF WECs despite less AEP, from EDRI's WEC selection, is visible southeast of Tenerife with the Wavepiston versus 1 MW WD cases. Furthermore, the fact that MCA advantages high AEP-WECs is emphasised in Fig. 7 by the consistency between CF-optimised and non-optimised MCA results due to little AEP-loss between both cases. CF-optimisation (Fig. 7 bottom line) shows a profit in terms of technology diversity in most KPIs. Overall, optimisation favours the homogenisation of KPIs for a fairer comparison between the WECs. AEP and MCA distance themselves, whereas EDRI gives a fairer comparison between WECs and its optimised WEC-selection gets a little closer to the AEP values. By contrast, EDRI and MCA are very close to AEP values, but, in places of high sweetspot-potentials, EDRI and MCA show very different WEC-selection, therefore the reasons for selecting one against the other are crucial.

In terms of values, Fig. 8 shows that SIWED, despite having the same WEC-selection capability as CF, provides an entirely different potential-reading of the WECs than CF. Indeed, as opposed to CF (Fig. 6 shows a stronger AEP-effect on CF than AEP_{max}), SIWED involves additional wave-height-distribution-dependent parameters, such that the map does not show a WEC-potential (only provided by AEP and CF) but a WEC-location-potential (similarly to MCA). In fact, the least wave-resource-dependent KPI is CF in its CF-optimised form.

The discontinuity (and sudden low values) of MCA and SIWED in Fig. 8 is highly due to EVA's wave height parameters [16]. It is also increased by WECs' installation-depth limitations (Appendix C), which explains for instance the low MCA and AEP values of Tenerife. Nevertheless, the maps generally concur with Fig. 2 (sweetspots for WEC-installations). Even CF in its CF-optimised form fairly aligns with Fig. 2, which also means that where the resource has a lower potential, CF-optimisation is less efficient. Allegedly, more WECs in the database would increase the correlation between the maps and diminish the discontinuities [16].

Analogously, ERDI provides results that quite respect Fig. 2; the divergence comes from involving land characteristics totally independent from the wave-potential as opposed to other KPIs. Then, the hotspots that align with high-potential sweetspots are even more narrowed down than in Fig. 2. Indeed, ERDI literally tells specifically where to install the farm as opposed to the other KPIs that allow more debate on location selection from their larger high-potential areas. Similarly, EDRI indicates where not to install a farm, and there is a fair alignment between EDRI and the discouraged locations for WEC-installation from Fig. 2. Scenarios are similar in the potential ranges and highlighted areas, but diverge in their final favouring (or rejecting) locations for they have different energy-demand configurations (Fig. 3 to Fig. 5).

Despite this consequent alignment between the results and the sweetspot-map, one does not replace the other; all KPIs integrate the indirect effect of the resource-potential through WECs' AEP. KPIs results, no matter the index selected, should be considered alongside but not merged with the sweetspot-map because it also assesses factors that are not directly affecting the WECs (including the fact that some resource parameters may be redundant as in MCA see [38]). Overall, EDRI/ERDI provides the most direct answer to where to put a farm, whereas other KPIs are more nuanced. Yet, MCA provides an alternative interpretation and selection to ERDI. EDRI/ERDI includes CF of SIWED, and MCA the energy production consistency along with H_{EVA} similar to SIWED. Finally, high MCA locations narrow down those of SIWED. Consequently, as both EDRI/ERDI and MCA are based on AEP and are complementary, they may be jointly considered for WEC-selection. Yet, their joint consideration requires more investigations in terms of WEC-farm-selection capability (which remains the same as individual-WEC-selection for CF and SIWED; see Section 4.3). Finally, the CF-optimisation scenario shows a tremendous increase of CF compared with little AEP decrease and an overall increase in the KPI's values, therefore, there is no question regarding the permanent need for considering only the CF-optimisation case.

4.2. Wave farm potential based on single wave device selection

Fig. 11 and Fig. 12 show AEP for the individual-WEC-selection (Fig. 8) from MCA (Fig. 11) and EDRI (Fig. 12) in the CF-optimised scenario. The farms are considered under the assumptions of only one farm (two-arrays) of WD and that Wavepiston farms do not shadow any other WECs. Here, each location-WEC pair AEP has been multiplied by the number of WECs that can be installed in 5x5 km (Fig. 5 blank-cells). The installable areas of the boundary scenarios (Fig. 2 and Fig. 5) are assumed to be extendable to the 200 m limitation to complete each 5x5 km sea-cell and thereby WEC-farm. Except for the WECs' performance, MCA only considers sea-location information, and so the other renewable energy farms' AEPs have been included in the map for comparison. The thermal power stations have also been integrated as reference points. This way, they can be tracked down in the EDRI-Fig. 12 that also provides all ES1-3's energy demand reference points at once. Therefore, in Fig. 12 the other renewables should complement the wave farms in responding to the energy demand.

Firstly, MCA provides a map much more continuous than EDRI because of the more prominent selection of WDs. Indeed, Weptos, largely selected by EDRI in places of WD for MCA, in a farm configuration reduces its AEP compared to other WECs, especially to WD. In Fig. 11, the smaller islands show a wave farm energy potential greater (La Palma) or equal (El Hierro and La Gomera) to the other exploited renewable resources (Table 2). In the case of El Hierro, the Wavepiston farm produces twice the energy compared to the hydroelectric plant, below what the 4 MW WD offers on the west coast of the island. Although La Gomera's wind farm provides the equivalent energy of

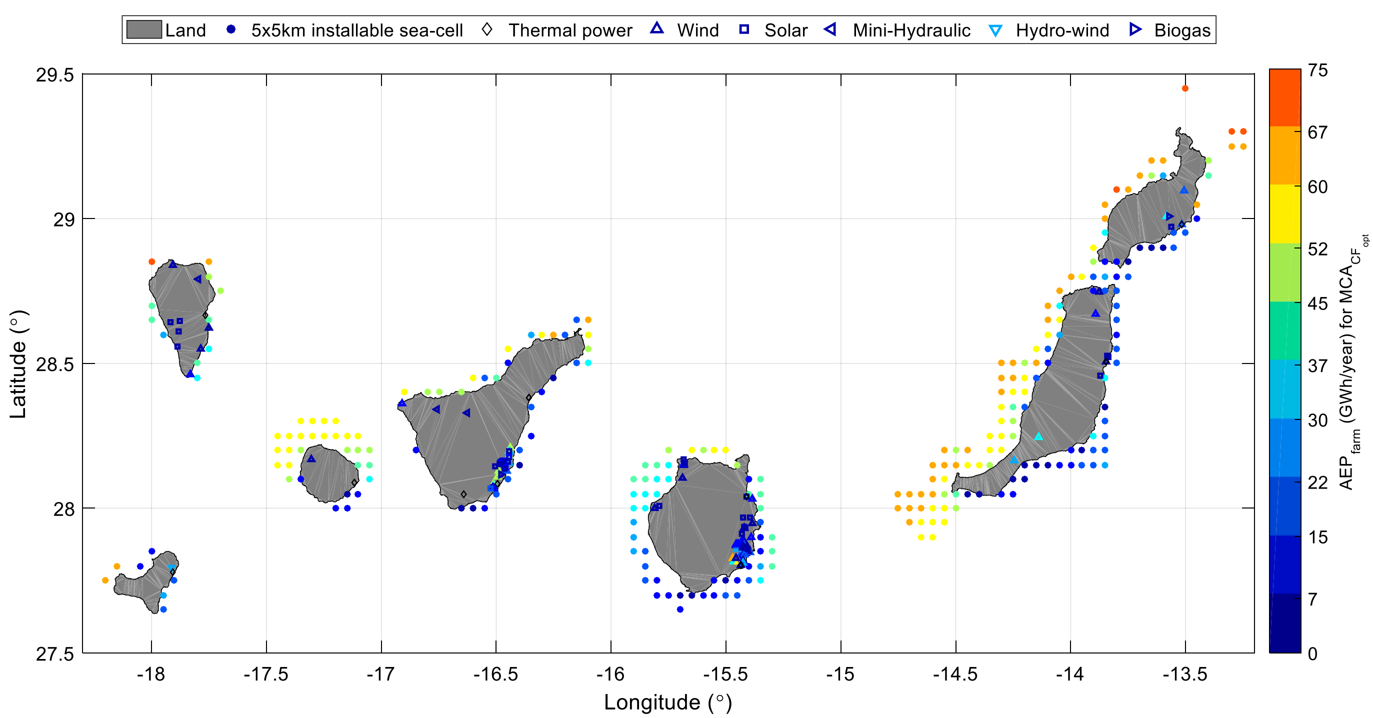

Fig. 11. Annual Energy Production (AEP in GWh/year) for the 5x5 km farms (based on Appendix B) of the Multi-Criteria Approach (MCA) individual wave energy converter selection (see Fig. 7). The location of the thermal power stations, and the renewable energy estimated AEP is provided (with reference for the AEP to the right hand-side colorbar).

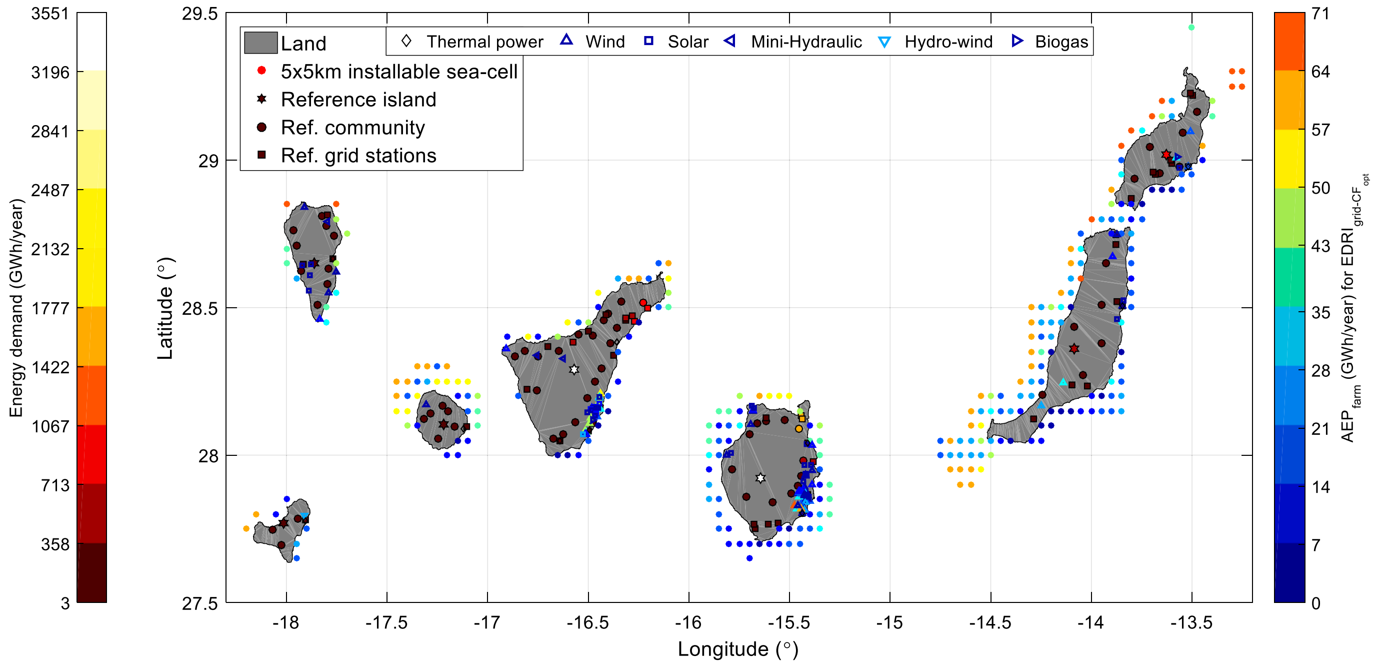

Fig. 12. Annual Energy Production (AEP in GWh/year) for the farms (based on Appendix B) of the Energy Demand-Response Index (EDRI) individual wave energy converter selection (see Fig. 7). Reference (Ref.) points of all EDRI-Scenarios (ES) are provided with their energy demand colored following the left hand-side colorbar. The locations of the thermal stations are also provided alongside the renewable energy devices whose estimated AEP is colored with reference to the right hand-side colorbar.

Weptos in the southeast of the island, in the islands' north, WD offers great energy-producing potential. Energy provisions of Lanzarote and Fuerteventura do not exceed 40 GWh/year, which is similar to the east-coastline of the islands as opposed to an almost minimum of 20 GWh/year AEP-increase on the western side. Gran Canaria does show a wind farm with a higher production than surrounding wave farms and another with similar values. Likewise, Tenerife has a greater wave potential than Gran Canaria, but more wind farms in higher ranges.

With EDRI the analysis is no longer about comparing renewables but about their joined contribution towards answering the energy demand. Individual-WEC-selections of La Palma and El Hierro are the same for MCA and EDRI. In both cases, the thermal power grid stations could be removed from the islands and be replaced by wave-energy production (solely based on AEP-potential, regardless of temporal variations). Notably, La Palma's four high-potential sea-cells are closed either to a grid station or a wind farm (that should have the infrastructures to connect the waves' energy to the grid), and the rest of the energy would come from the already installed renewables. Only one farm is enough to cover El Hierro's energy demand. Despite La Gomera's wave-energy production potential, just the two 37–45 GWh/year sea-cells (also sweetspot locations in Fig. 2) next to the grid station could cover its energy demand. It could potentially replace the nearby thermal power station. EDRI provides maximum community and grid energy-feeding potentials (also located in mild-range sweetspots) for Fuerteventura and Lanzarote, respectively. For both ES2-3, the energy harvested from the waves has the potential to answer each island's entire energy demand. Finally, even if waves cannot supply the global energy demand, they answer the needs of the opposite fronts of the islands opposed to the high-concentration of other renewables.

4.3. Direct wave farm versus farms based on single wave energy converter selection in order to answer energy needs

Most studies select a farm based on the individual-WEC performance, however, the WEC-selection capability of the KPIs for WEC-farms as a whole is yet to be investigated. This is the objective of this section, such that Section 4.3.1 shows the effect of the farm on the KPIs' equations and Fig. 13, the spread of the results. Section 4.3.1 and Fig. 13 are the equivalent of Section 4.1.1 and Fig. 6, except that they consider the whole wave farm instead of a single WEC. Following the above reasoning, this section only investigates MCA and EDRI for the CF-optimisation approach.

4.3.1. Farm key performance indicators equation transformation into their wave energy converter selection power/capability

In this study, the farm version of AEP, AEP_{farm} (MWh), is multiplied by the number of WECs (supposing the WECs are far enough from each other to not affect each other's energy production) as in Eq. (12), although in the future this may be improved considering farm interactions.

$$AEP_{farm} = \mathrm{AEP}^{*} nb_{WECsinfarm} \tag{12}$$

In the farm case, the left hand-side AEP-based term of the initial MCA's Eq. (1) changes, whereas the right hand-side (MVI-based) remains approximatively the same (almost a multiplication on the top and bottom of the terms by the number of WECs). Indeed, Eq. (12) leads to $\mathrm{MCA}_{\mathrm{farm,WEC\text{-}selection}}$ in the form of Eq. (13):

$$MCA_{farm,WEC-selection} = \frac{AEP_{farm}}{AEP_{local-farm} MVI_{E_0}} \tag{13}$$

Eventually, since $nb_{WECs\ in\ farm}$ changes between WECs, $\mathrm{AEP}_{\mathrm{local\text{-}farm}}$ cannot be simplified with $\mathrm{AEP}_{\mathrm{farm}}$. Consequently, $\mathrm{MCA}_{\mathrm{farm,WEC\text{-}selection}}$ translates into a farm comparison (left-term) and an individual performance (right-term) as shown in Eq. (14):

$$MCA_{farm,WEC-selection} \approx \frac{AEP_{farm}}{AEP_{local-farm}} * \frac{AEP}{\mathrm{ma}(E0) - \mathrm{mi}(E0)} \tag{14}$$

Similarly to MCA, in the farm analysis, $\mathrm{EDRI}_{\mathrm{farm,WEC\text{-}selection}}$, Eq. (15), eventually contains a part independent from the farm (that is the individual-WEC EDRI) and a part dependent on the farm that is the number of WECs within the farm:

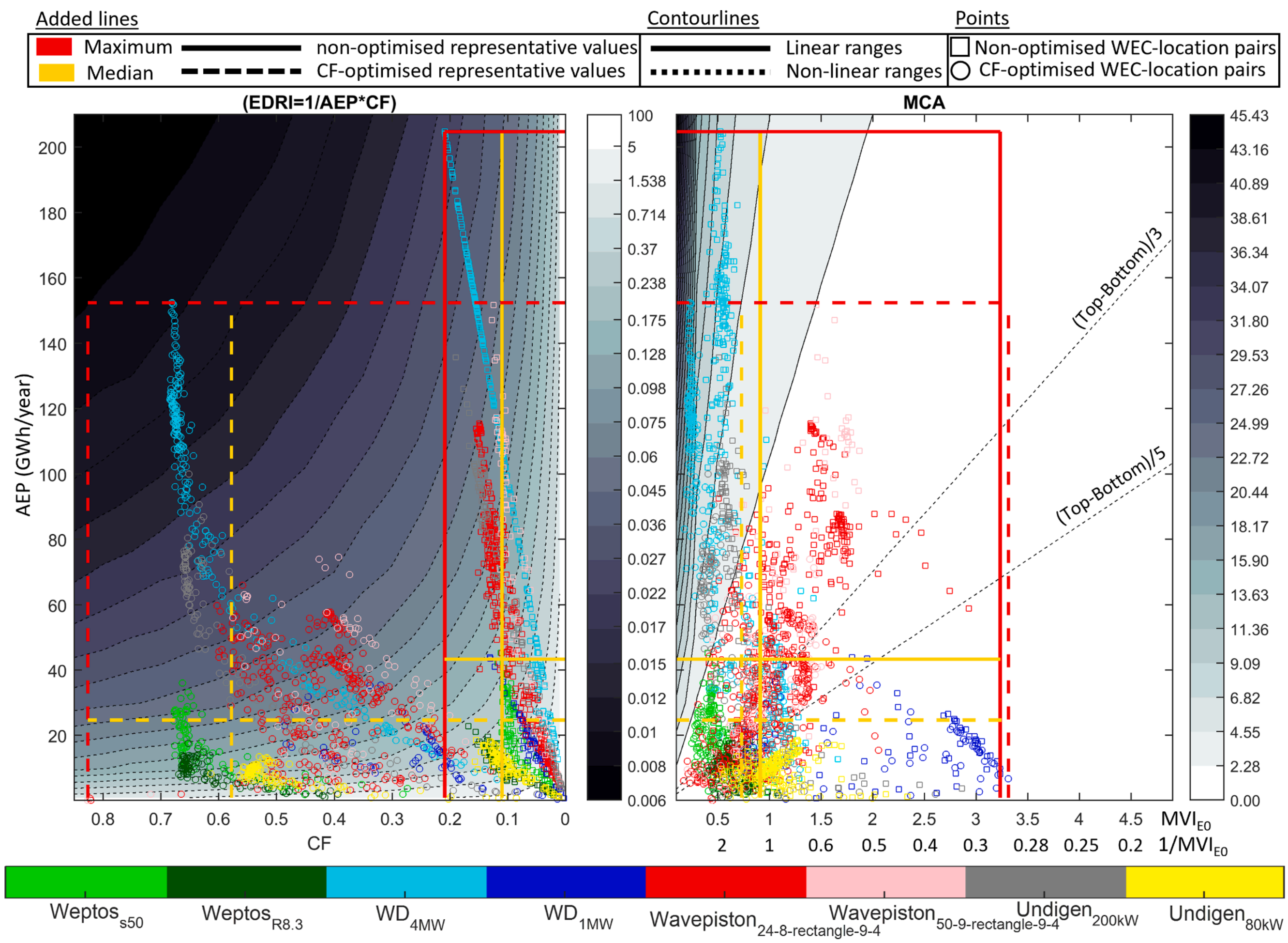

Fig. 13. Same as for Fig. 6 but, here, in the case of the WEC-farm selection, hence with each WEC's AEP multiplied by its number of WECs placed in a 5x5 km sea-cell. As only the Multi-Criteria Approach (MCA) and the Energy Demand-Response Index (EDRI and thereby the Energy Response-Demand Index) are affected by this change, and to avoid redundancies with Fig. 6 only these two indexes are shown here. It is assumed here a 2-farm Wave Dragon (WD) configuration (see Figure D.1 for the 1-farm case).

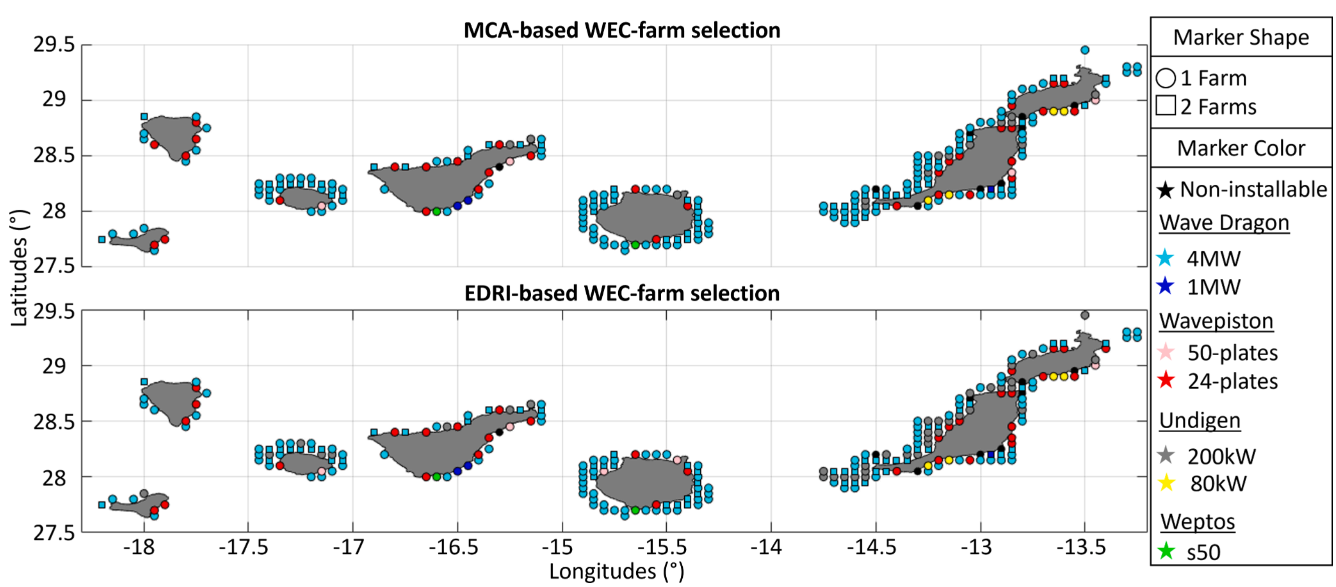

Fig. 14. WEC-farm selection for both the Multi-Criteria Approach (MCA) and Energy Demand-Response Index (EDRI) for the CF-optimisation scenario. The background islands are the large-grey areas (omitted in the legend). Black circles are Non-installable sea-cells.

$$EDRI_{farm,WEC-selection} = \frac{1}{CF^{*}AEP_{farm}} = \frac{AEP_{max}}{AEP^{2}{*}nb_{WECsinfarm}} = \frac{EDRI_{WEC-selection}}{nb_{WECsinfarm}} \tag{15}$$

4.3.2. Analysis of the wave energy converter farm selection power/capability for the Canary archipelago and considered wave energy converters

With the new equations for MCA, SIWED, and EDRI, Fig. 6 needs to be reconsidered. Fig. 13 is the recompilation of Fig. 6 in light of these new changes.

Due to the limited number of WECs a 5x5 km Weptos farm can contain (see Section 3.2 and Appendix B), Fig. 13 demonstrates the new disadvantage of Weptos compared to the other WEC-farms. Notably, Undigen and Wavepiston highly increased their potential compared to WD that remains consistent with Fig. 7.

4.3.3. Wave energy converter farm selection and performance

This new WEC-farm-potential-distribution diverging from the individual-WEC-selection is visible in Fig. 14 that shows the optimised WEC-farm selection for both MCA and EDRI. This selection aims to respect the limiting installable space (see Scenarios 1–2 from Fig. 5, additionally, where a cell would have limited space next to a nan-cell with more space, a 2-farm WD would be considered if best) and farm-installation conditions of WD and Wavepiston in function of the wave direction (see Sections 3.2, 2.3 and Appendix D).

Fig. 14 mainly consists of an alternation between 1-farm and 2-farm WD. Specifically, in some locations, the 1-farm higher MCA-potential is often below 200 kW Undigen (see Figure D.1) from EDRI's perspective (see Figure D.3). This represents the main divergences between the WEC-farm-selection for both KPIs. Nevertheless, both KPIs are fairly consistent in their WEC-selection. This new alignment diverges from the individual-WEC-selection that provided much more differences between both KPIs' WEC-selections (Fig. 7). This finally suggests the need for mixing WECs, especially for alongshore farm installations, even in locations not limited by the available space.

Following Section 4.2 and specifically Figs. 11 and 12, Fig. 15 provides the AEP (right hand-side colorbar) of Fig. 14's WEC-farm selection. Where MCA and EDRI WEC-farm-selection diverge, both solutions (EDRI-left and MCA-right) are provided on the side of the concerned location connected by a light-grey link. Since the objective is to feed this AEP to the energy demand, all ES1-3 (left hand-side colorbar) have been deducted from the amount of energy supplied by already installed (non-wave) renewable technologies. It was assumed that if the total closest energy supply exceeds the local demand, the remaining energy was redirected to the next energy demand point.

Fig. 15 shows a lower energy demand than Fig. 12. Furthermore, the zero-energy demand reference points (dark-points) are close to low-AEP wave energy farms. Regardless of the other renewable technologies (as opposed to Fig. 12), the minimum AEP is increased to 3 GWh/year. Moreover, by selecting the most appropriate farms, the maximum AEP is almost doubled compared to the WEC-farms of the individual-WEC-selection. This strongly affects the color-range of the islands, such that where Gran Canaria had yellow–red colors in Fig. 12, now it looks unfavourable. Where Fig. 12 shows better offshore potentials, due to space limitations, here, extreme offshore farms have generally low AEP (yet, comparable to the maximum range of Fig. 12), such that the inside cells, enabling larger farms, have higher AEP. In fact, the entire analysis of Fig. 12 is consistent, except that fewer WEC-farms are needed here. Despite that EDRI/MCA-mismatching points demonstrate that EDRI always selects higher AEP than MCA. Altogether, the results are much more favourable for wave installation of direct wave farm selection than

Table 3
Extreme values of the energy demand minus the closest installed renewable energy technologies.

EDRI-Scenarios (ES)	Maximum energy demand (GWh/year)	Minimum energy demand and second minimum (GWh/year)
ES1: Islands	2942.4166	1st minimum: 19.6181 2nd minimum: 73.3937
ES2: Communities	1565.6709	1st minimum: 0 2nd minimum: 0.35371
ES3: Grid stations	1565.6709	1st minimum: 0 2nd minimum: 21.1119

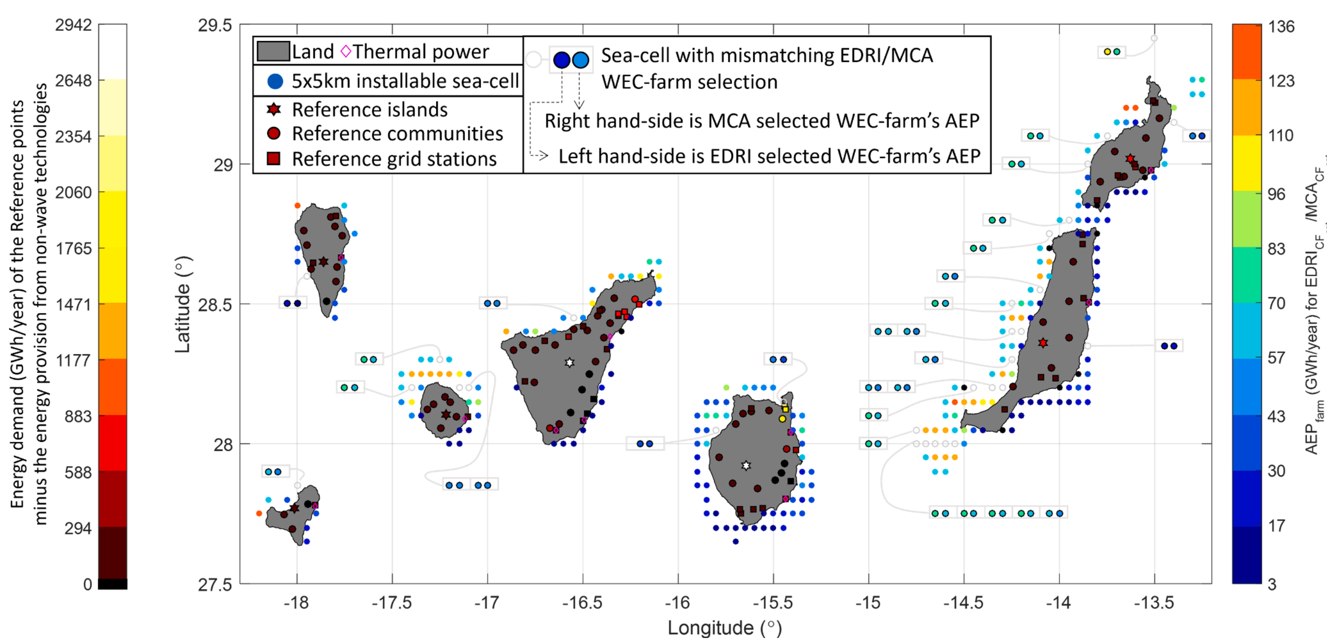

Fig. 15. Annual Energy Production (AEP) value (right colorbar) of the selected wave energy converter farms from Fig. 14 similarly to Fig. 12 (Fig. 12's maximum AEP stops at the light blue AEP here). Where the Multi-Criteria Approach (MCA) and the Energy Demand-Response Index (EDRI) have common values, sea-cells have been provided directly, otherwise left empty in grey circles for which both MCA and EDRI selected WEC-farm's AEP values are provided in eccentric rectangles. Left hand-side colorbar corresponds to all EDRI-scenarios' reference points' energy demand (removed from the closest installed renewable sources). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

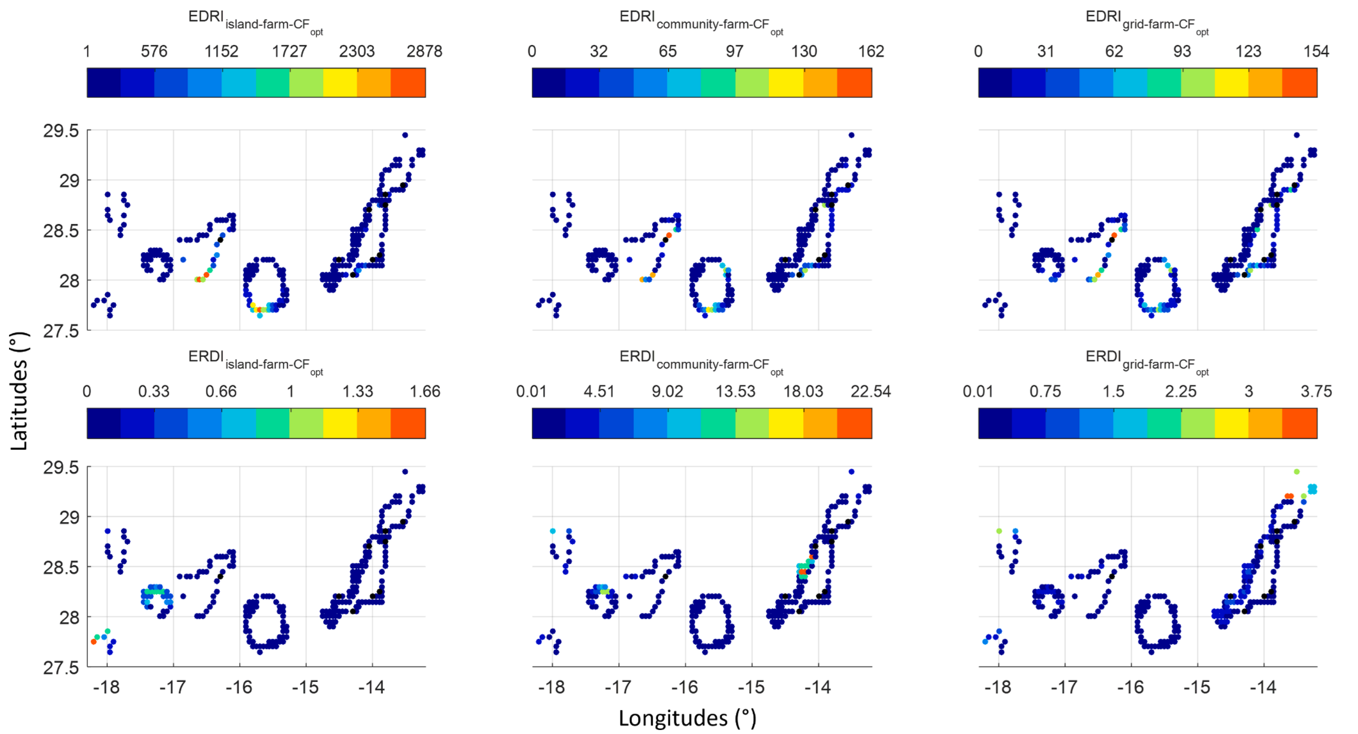

Fig. 16. Energy Demand-Response and Response-Demand Indexes, EDRI and ERDI, respectively, values for the different EDRI-scenarios in function of the WEC-farm adjusted selection using EDRI. It is worth noting that this map focuses on the Multi-Criteria Approach (MCA) WEC-farm selection.

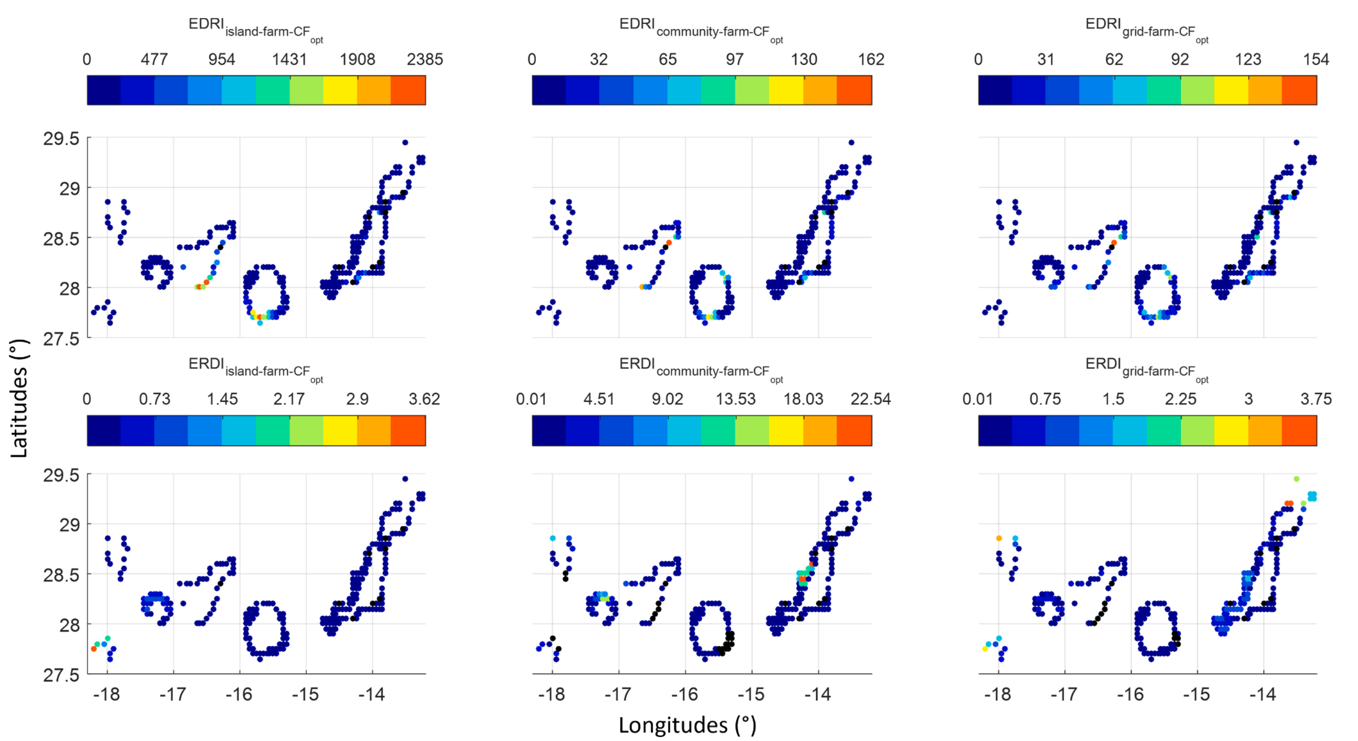

Fig. 17. Same as Fig. 16 but for the adjusted WEC-farm selection with a focus on the Energy Demand-Response Index (EDRI) selected WECs and for the case where the energy supply from already installed energy technology (other than wave) has been removed from the energy demand of the closest reference point (transferred to the next closest reference point and so on if the reference point is fully satisfied by the energy supply of these technologies). For the Energy Response-Demand Index (ERDI), due to the 0 kWh energy demand leading to 0 EDRI and infinity ERDI, the latter has been replaced by a NaN of the other finite obtained ERDI and the reader is referred to Fig. 16 to see the cells' actual potential regardless of the other energy supply.

the wave farm of the individual-WEC-selection.

It is worth noting that the individual best WEC-location pairs from AEP-selection provide 9 GWh/year and 7 GWh/year (islands northwest), while one orange point is above 110 GWh/year, and so, Table 3 leads to the conclusion that a few WECs (only one for ES2) can easily respond to the energy demand. Therefore, Fig. 16 and Fig. 17

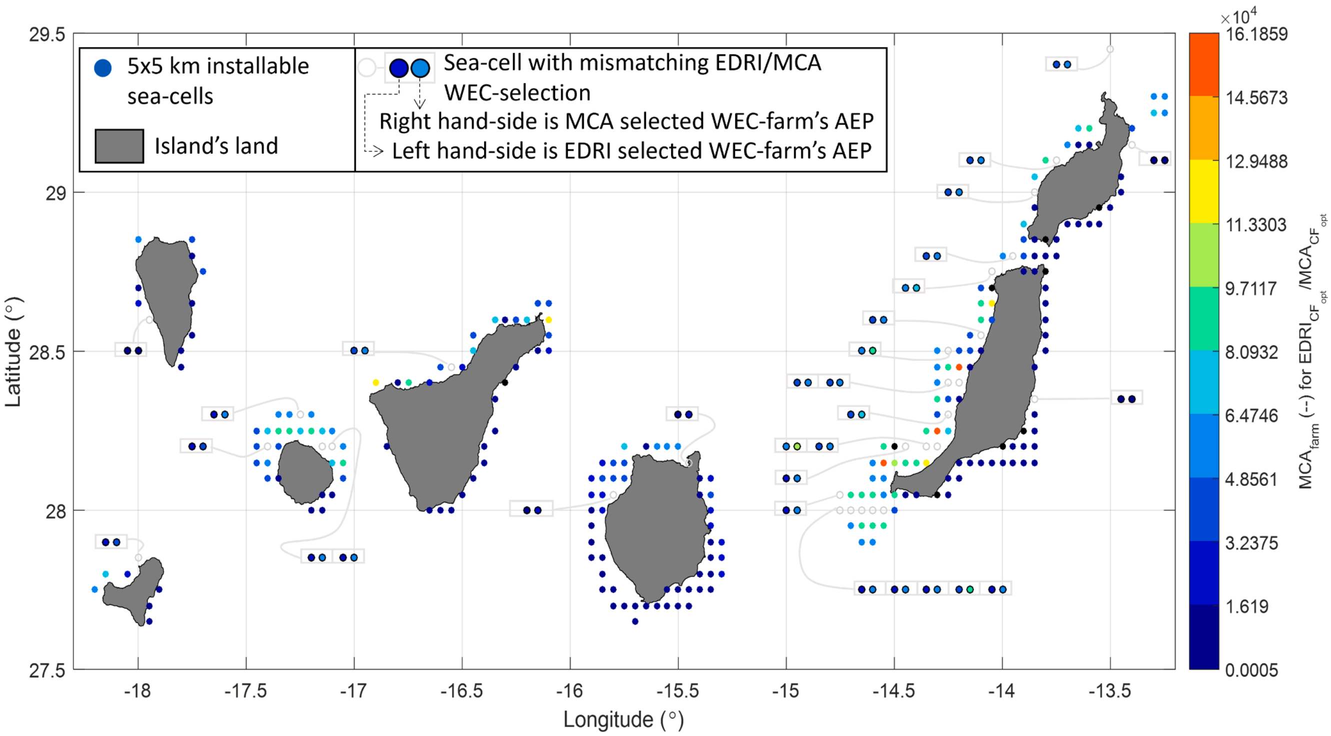

Fig. 18. Same as Fig. 15 but providing the Multi-Criteria Approach values (MCA, non-dimensional) for both the Energy Demand-Response Index (EDRI) and MCA adjusted WEC-farm-selection (left and right hand-side of the grey square, respectively, if they have a different WEC-farm selection).

show an analysis of EDRI/ERDI results and Fig. 18 the MCA results. Some locations show high potential no matter the index. This is especially visible for El Hierro that has one of the highest ERDI, yet primarily for ES1. ES1-3 provides different readings of the farm potentials, remaining still in line with individual-WEC selections (Fig. 10). None of EDRI's scenarios favours Gran Canaria and Tenerife because of their much higher energy-demand, diverging from the MCA results that highlight some potential in the north of both islands. MCA and AEP stress a more promising potential for Tenerife than Gran Canaria, although wave farms in Gran Canaria can be deemed more necessary due to much higher energy demand. Even by installing all wave farms, there is little chance to cover Gran Canaria's energy demand while approximately 50 % of Tenerife's energy demand may be covered with the northern farms only. The total electricty demand on the island of Gran Canaria reaches 3047.2 GWh/year (83.9 % from conventional energy sources and 16.1 % from renewable sources) [83] The sector with the highest demand is the residential sector, which represents more than 34.8 % of the island's total electricity demand [83]. In this context, the avoidable CO_2 emissions in the residential sector through increased penetration of renewables could reach 690,405 tCO_2/year (0,776 kg CO_2/KWh final energy use from conventional resources consumed) [89]. Fuerteventura's ERDI is the highest from ES2′s point of view (in the absence of a nearby grid station) in the western part of the island characterised by a mix of Undigen and WD WECs. There, a single point has one of the highest MCA surrounded by reasonable MCA and AEP. Altogether the south of the islands are dissuading WEC-farm installations for all MCA, EDRI, and AEP. The previous analysis demonstrated the complete independence of four of the seven Canary Islands. Especially, the best energy scenario feeding is the community scenario (ES2) northwest of Fuerteventura. Finally, most of the archipelago can be practically energetically independent with the help of wave energy and could greatly help the reduction of the archipelago's carbon footprint.

Above, AEP was found weak in terms of location-selection, but instead, EDRI/ERDI and MCA provided more insight on the WEC-location (thereby WEC-farm/location) potential. Finally, once the wave farms are selected, the location potential changes a lot from the wave-resource potential (Fig. 2); although high wave farm-location pair potentials are in the high wave-resource potential (making it a necessary condition), high wave-resource potential is not a sufficient condition for location selection as some of the worst wave-farm potentials are located in these regions (e.g. Fuerteventura western Wavepiston farms). Consequently, there are no real patterns between AEP/EDRI/ERDI/MCA/wave-resource-potential maps such that they all are complementary and needed to make a final choice. Typically, the spots AEP/ERDI/MCA/wave-resource-potential highlighted jointly are the most promising sweetspots for wave energy farm installation, and generally, bad EDRI (totally concurring with the weather window length filter of Fig. 2) stresses the worst potential areas. Finally, when MCA is high, AEP and SIWED (Figure E.1) are high, otherwise, they may add other high-potential points but these points are never common between them. Hence, with MCA/ERDI being so restrictive with the high-optimised-CF wide-coverage (Figure E.2), AEP/EDRI/ERDI/MCA/wave-resource-potential are enough to select WEC-farm-location pairs.

5. Conclusions

In a world that must move towards a higher renewable energy source diversification with islands needing to become energetically independent, this research aims to improve the selection process of WECs (Wave Energy Converters). For this purpose, the WFLSP (WEC-Farm/Location pair Selection Process) is introduced as a revised integration of improved pieces of published methodologies. Using this WFLSP, multiple KPIs (Key Performance Indicators) previously developed for WEC-location pairing have been investigated to reduce them to the most relevant, complementary, and representative ones. Following earlier studies' standards, they were used to select WECs individually, and from these selections, each farm's AEP (Annual Energy Production) was analysed. WFLSP also included an optimisation method that consists of reducing WEC generator limitations to improve the KPI called CF (Capacity Factor: how well rated the WEC is for the wave resource) with little AEP reduction. Finally, farms based on single WEC selection were compared with results from a direct WEC-farm selection. Along the way, this work also aimed to assess jointly the wave resource potential mapping with enhanced WEC-location pairing. To have results better representative of the global complex wave climate system, the Canary archipelago was selected for this research; and to ensure the currentness and relevancy of this study, only high technology readiness level WECs were considered.

1. Generator improved CF-optimisation revealed to benefit all KPIs' selections compared to their non-optimised values. Specifically, KPI values of optimised and non-optimised direct individual-WEC-selection were compared showing up to an average increase of 50 % in the CF, above previous studies. KPIs were therefore applied to select the WEC-farm directly under that optimisation.
2. Individual-WEC-selections highlighted the relevancies, complementariness, and representativeness of MCA (Multi-Criteria Approach) and EDRI (Energy Demand-Response Index) varying for WEC-farm-selection as opposed to CF and SIWED (Selection Index for Wave Energy Deployments, wave-height-based, versus MCA considering more general wave-resource features). EDRI-selection's fruitful interpretation needed ERDI (Energy Response-Demand Index) alongside AEP-maps. To further analyse the energy provision potential, these three KPIs' maps were considered under three complementary electrical-management approaches referred to as the communal, grid-station, and island energy-feeding scenarios.
3. Direct WEC-farm selection provided farms performing better than those from the individual WEC-selection. Notably, WEC-farm-selections diverged significantly from individual-WEC-selections that diminish the WEC-farm-location potential comparatively. Individual-WEC-selections change a lot between KPIs, while over WEC-farms, common grounds could be found in many locations.
4. Results show the need for using different WECs, each associated with at least two different sizes, to supply the energy demand. Specifically, in the Canary archipelago, due to the limited installable areas, farm wake-effect, and complex wave climate coverage, an alternation between 1-farm and 2-farm Wave Dragon leads the selection. However, a combination of all WECs seems most needed alongshore.
5. Using the aforementioned WEC-farm selection, the Canary archipelago demonstrates a high potential for WEC/WEC-farm installation in the northwesternmost regions, while the south has little potential. Yet, in the south, lots of renewables already answer the energy demand, such that with the waves, most islands can become energetically independent with a sustainable and uniform energy-coverage through renewables. Only Gran Canaria and Tenerife will still need the thermal stations to satisfy this energy demand.
6. The wave-resource potential map appeared to be a necessary but not sufficient condition for individual WEC and wave farm selections. The wave-resource potential map shall always be considered not just individually but alongside the WEC-KPI maps, namely, those of EDRI, ERDI, MCA, and AEP.

To conclude, WEC databases should consider each WEC under different sizes; then each WEC should first undergo generator CF-optimisation and then be selected for each considered location following the WFLSP using EDRI and MCA direct WEC-farm-selections, while investigating selected-WECs' farms' EDRI/ERDI/AEP/MCA and wave-resource potential maps. It is worth noting that renewable energies are subject to temporal variations disregarded in annual analyses such as here. Furthermore, WEC-farm coverages were large enough to avoid WEC-wake interactions. Consequently, future studies may investigate the optimisation of the farm design to better fit the limited installable areas and temporal variations to ensure the consistency of the renewable energy-mix supply.'

CRediT authorship contribution statement

B. Del Río-Gamero: Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing, Conceptualization. **Ophelie Choupin:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Noemi Melián-Martel:** Data curation, Formal analysis, Investigation, Resources. **Julieta Schallenberg-Rodriguez:** Data curation, Formal analysis, Funding acquisition, Resources, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Capacity Factor and generator optimisation

Fig. A1 displays the steps to conduct the CF-optimisation, i.e. finding the right rated power generating a plateau on the power matrix at the verge of affecting deeply AEP, and Fig. A2 provides the equivalent but in the 3D-space (wave height, period, and direction) as opposed to the 2D-space (regardless of the wave direction) of Fig. A1. By taking the tangents on the extreme right and left of the curve, see e) pink and green lines, respectively, CF-optimised point (i.e. at the maximum bending of the AEP-curve where AEP starts experiencing larger decreases from diminishing the rated power) would be the closest point of the curve to the crossing-point between the two tangents (black stars).

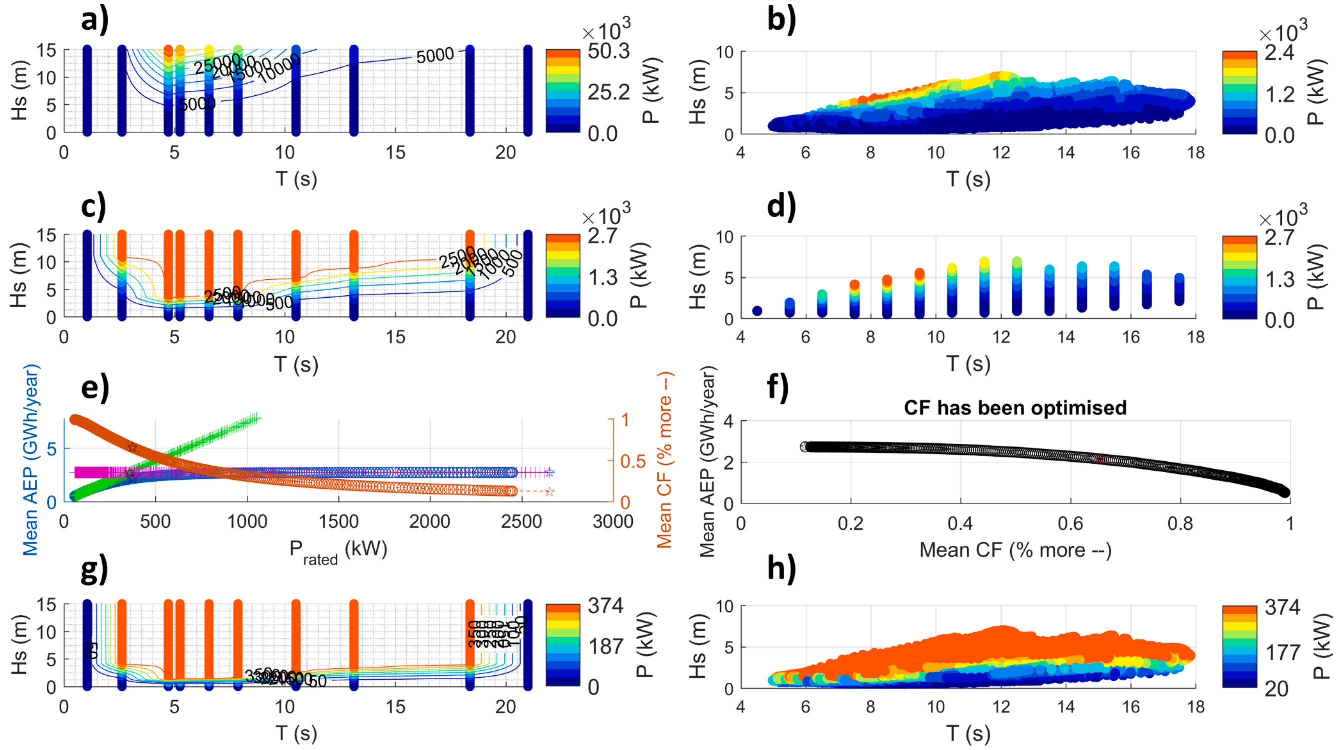

Fig. A1. Example of Capacity Factor (CF) optimisation (each line is explained from left to right). The first line provides the initial power matrix and distribution of the time series of absorbed power (P, kW) by Weptos (~8.3 m rotor-size). The second line provides the power matrix with the plateau from the maximum scatter-diagram-based calculated power and associated power harvested for each scatter diagram sea-cell. The third line provides the CF-optimisation with e) showing in blue and red circles the evolution as the rated power (P_{rated}) is diminished of the Annual Energy Production (AEP,GWh/year) and Capacity Factor (CF, non-dimensioned), using the left and right y-axis, respectively. Their crossed evolution is given by f). The pink crossed-axis of e) is the tangent to the AEP-curve in the high P_{rated} and the green to the low P_{rated}. Their crossing point is highlighted with a black star. The closest point to this star on the AEP-curve is the black star on that curve, and its projection is provided in the black star on the CF-curve as well as in a red star on the right hand-side panel. The last line provides the CF-optimised power matrix and the associated distribution of the time series of absorbed power.

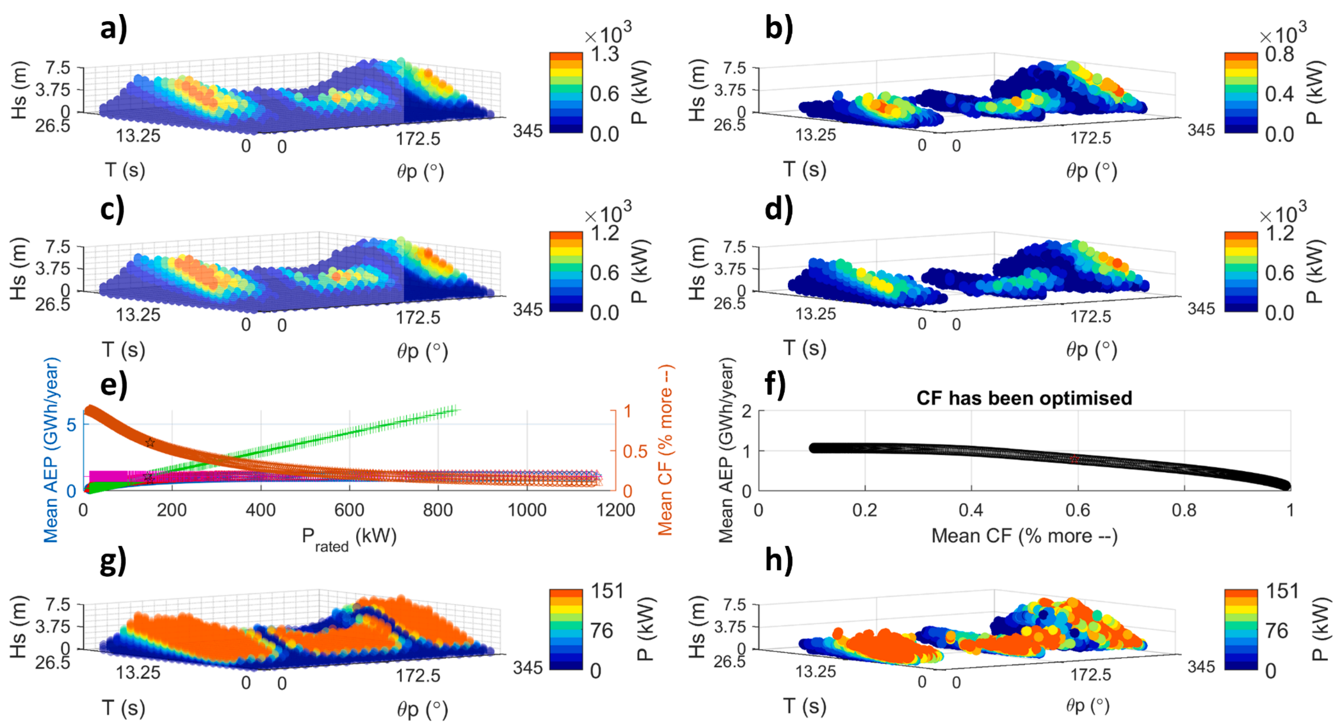

Fig. A2. Same as Fig. A1 but for Wavepiston with 24 plaques of size 9 m by 4 m as the 3D example. Here, all the axes have been adjusted to the power matrix's original size, and to enhance its visibility, all nan or zero cells in the power matrices (left column) have been removed.

Appendix B. Wave farms layout

Figure B1 illustrates the farm configuration of the WECs to help understand Section 4.2's discussion.

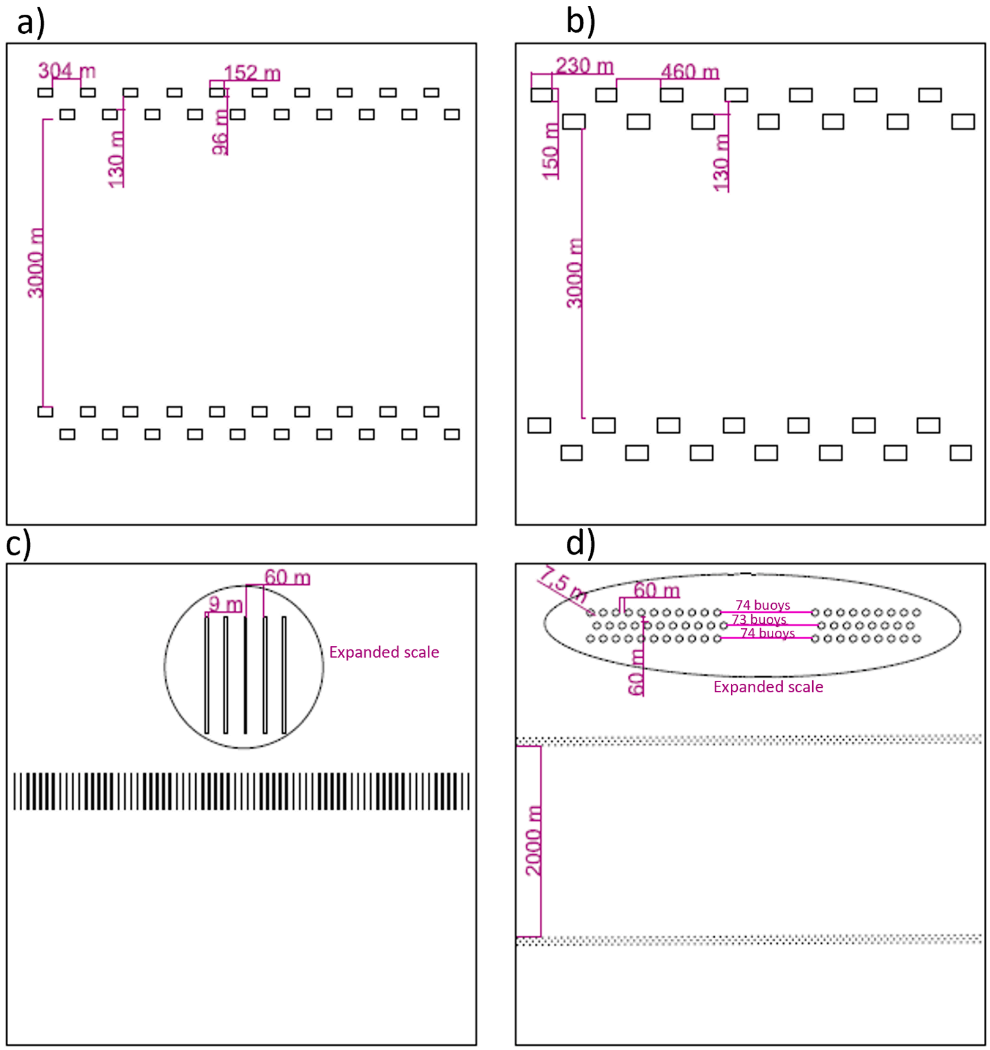

Fig. B1. Farm configuration with implementing as much WECs as possible in the 5x5 km sea-cell. Panel a) is Wave Dragon 1 MW farm; b) is Wave Dragon 4 MW farm; c) is Wavepiston farm; and d) Wedge Global farm. Due to the smallness of the WECs, panels c) and d) each contain a bubble-zoom to highlight the precise dimensions between the wave energy converters.

Appendix C. Eight wave energy converters' Annual energy production and Capacity Factor

To help understand the selection, AEP (Fig. C1) and CF-optimised AEP (Fig. C2) are provided for each WEC under the same colorbar and only in their individual installation range. The corresponding CF (Fig. C3) and CF-optimised CF (Fig. C4) follow.

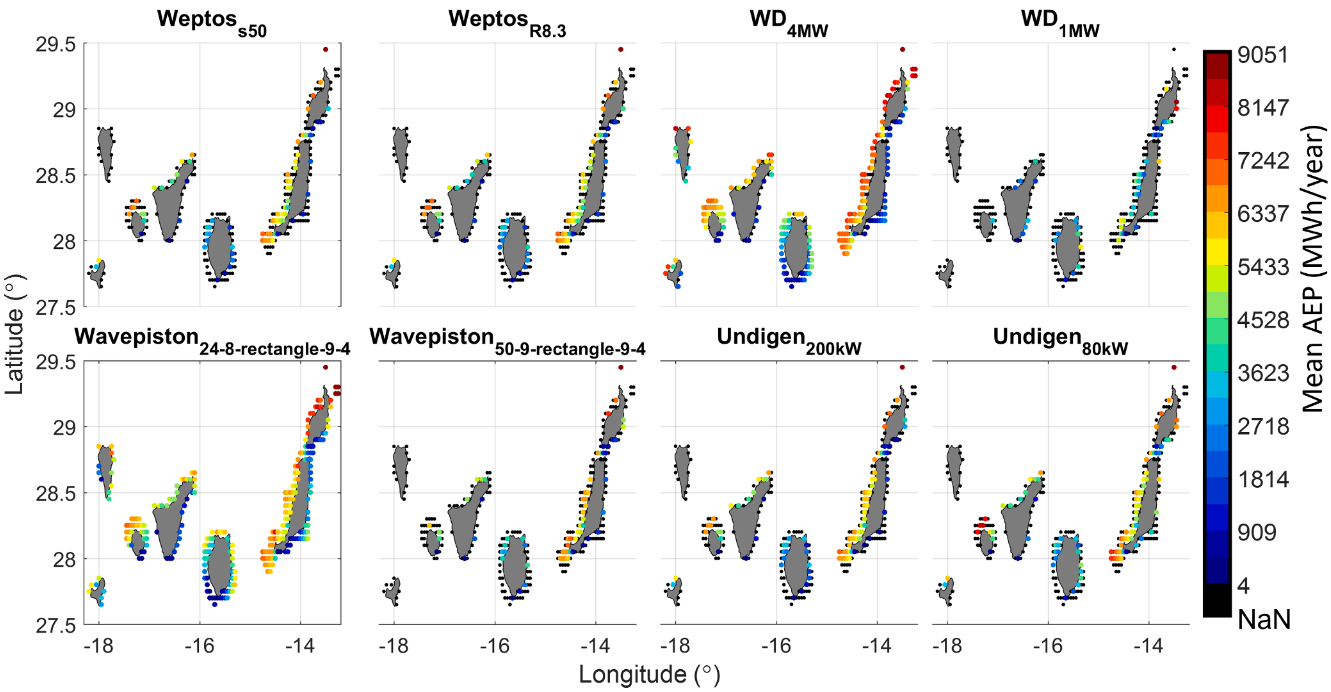

Fig. C1. Mean annual energy production (Mean AEP in MWh/year) over the 27 years considered here. Each sub-figure provides the values for each wave energy converter considered here and within their ranges of installation. Sea-cells, where they are not installable, have been colored in black alongside providing all sub-figures under the same colorbar to enable the precise location-comparison between them. WD stands for Wave Dragon.

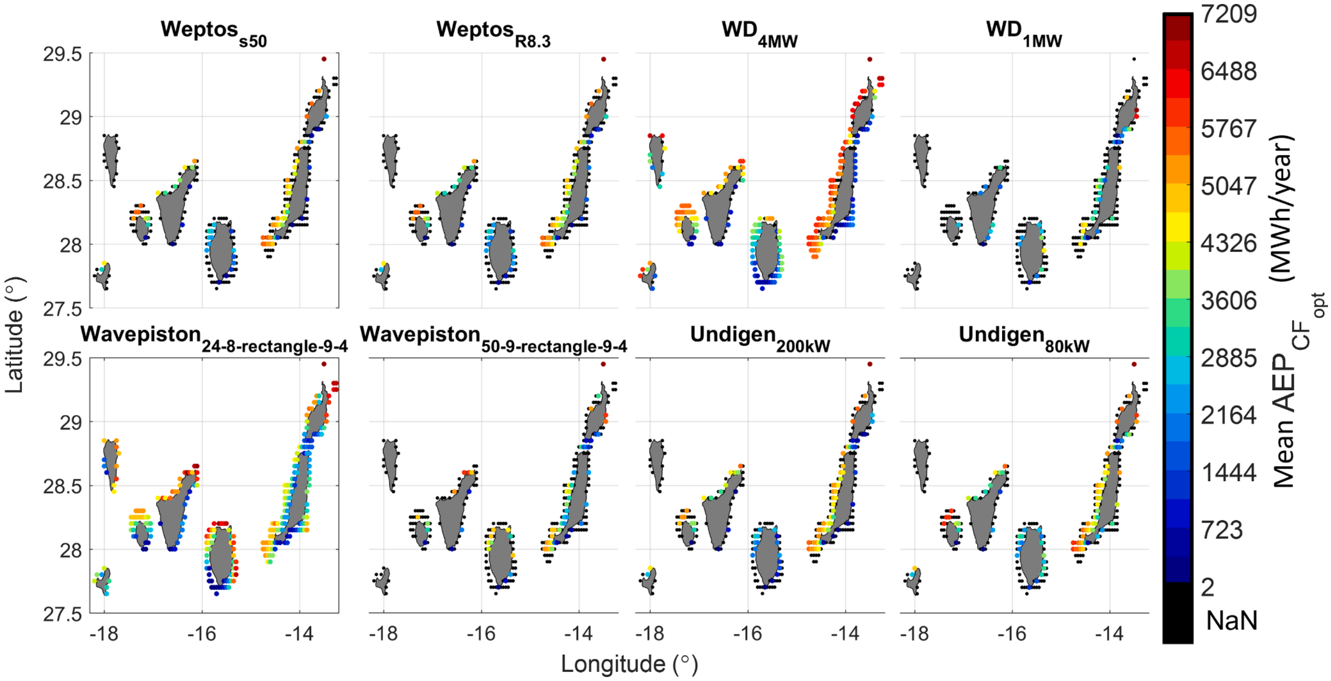

Fig. C2. Same as Fig. C1 but for the Mean Annual Energy Production (Mean AEP in MWh/year) obtained after the optimisation of the Capacity Factor (CF) broadly described in Appendix A.

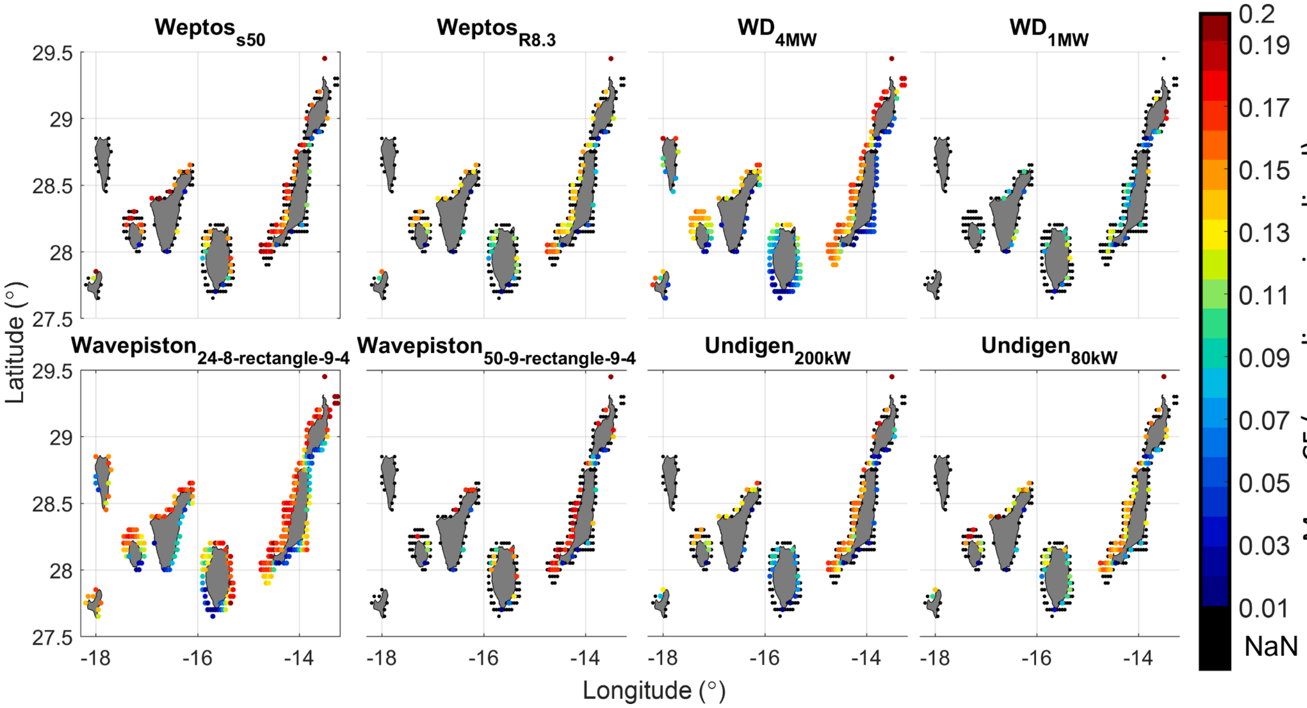

Fig. C3. Same as Fig. C1 but for the Mean Capacity Factor (Mean CF in –).

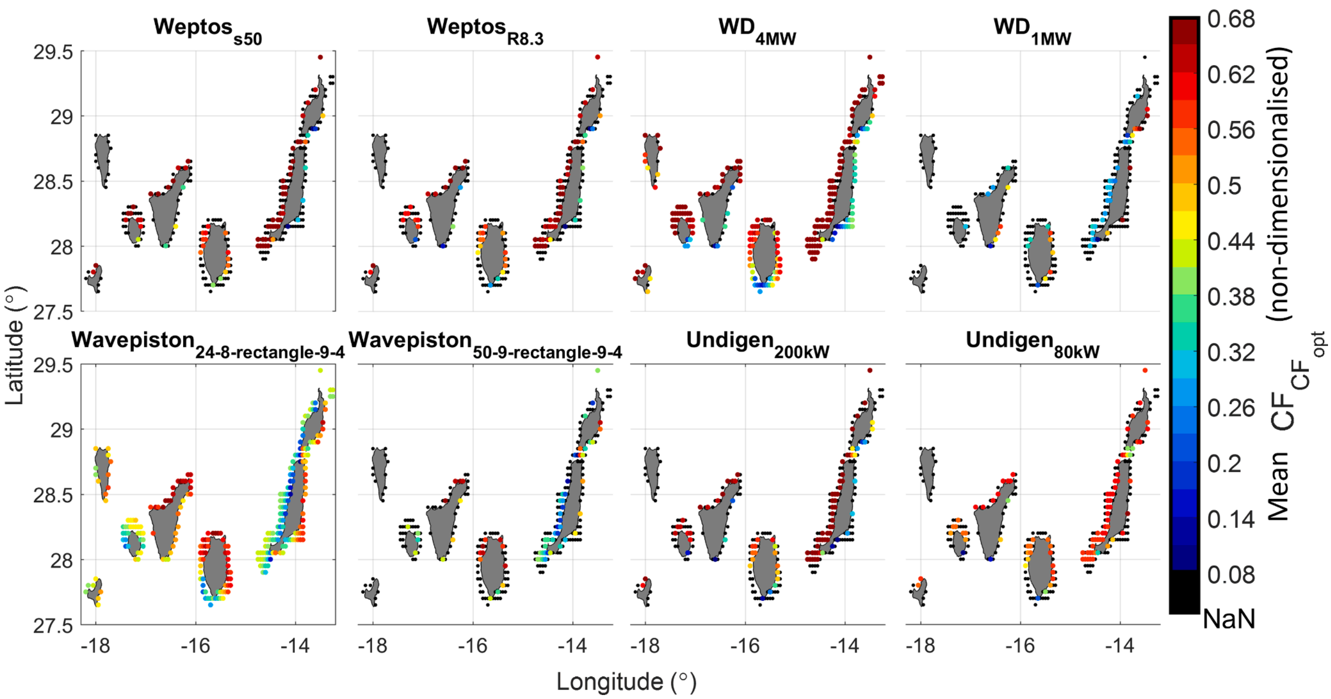

Fig. C4. Same as Fig. C1 but for the Mean Capacity Factor (Mean CF in –) obtained after the optimisation of the Capacity Factor (CF) broadly described in Appendix A.

Appendix D. Selection of wave farm based on the Multi-Criteria approach and the energy Demand-Response index with guidance for the farm selection

Figs. D2 and D3 show the WEC-farm selection only for installable sea-cells (Fig. 5's non-fully-nan/grey/green squares) of MCA and EDRI, respectively. Black dots highlight an absence of AEP production. The limitations over WD and Wavepiston have not been considered. Due to WD's constraint, both the 2-farm-based (top-line) and 1-farm-based (bottom-line) are provided. Indeed, WD requires alternations between 1- and 2-farm sea-cells (to respect the 3 km distance between farms). The difference in WEC selection between 1/2-farm WD affects results meaningfully in the EDRI case; hence, Fig. 13 has been reproduced in Fig. D1, but using a 1-farm WD instead of a 2-farm. Following, Fig. D4 shows the wave roses of the wave peak direction distributions, θp-distributions, for more sea-cells (all falling even a little in Scenario 1, see Fig. 5). These roses allowed guiding the WEC-farm adjusted-selection (Fig. 14). Three selection levels (so that for a given point, level 1 is the best WEC-farm, levels 2 and 3 the next bests) were required since two Wavepiston-designed are considered. Indeed, if both first levels select Wavepiston in a place where it cannot be placed, because it would make it impossible to install WECs behind, then the third level provides the alternative WEC (if any). Due to limiting conditions at level 2 or 3, lesser and lesser WECs may be installed in the location, which explains the increasing number of black points in these levels.

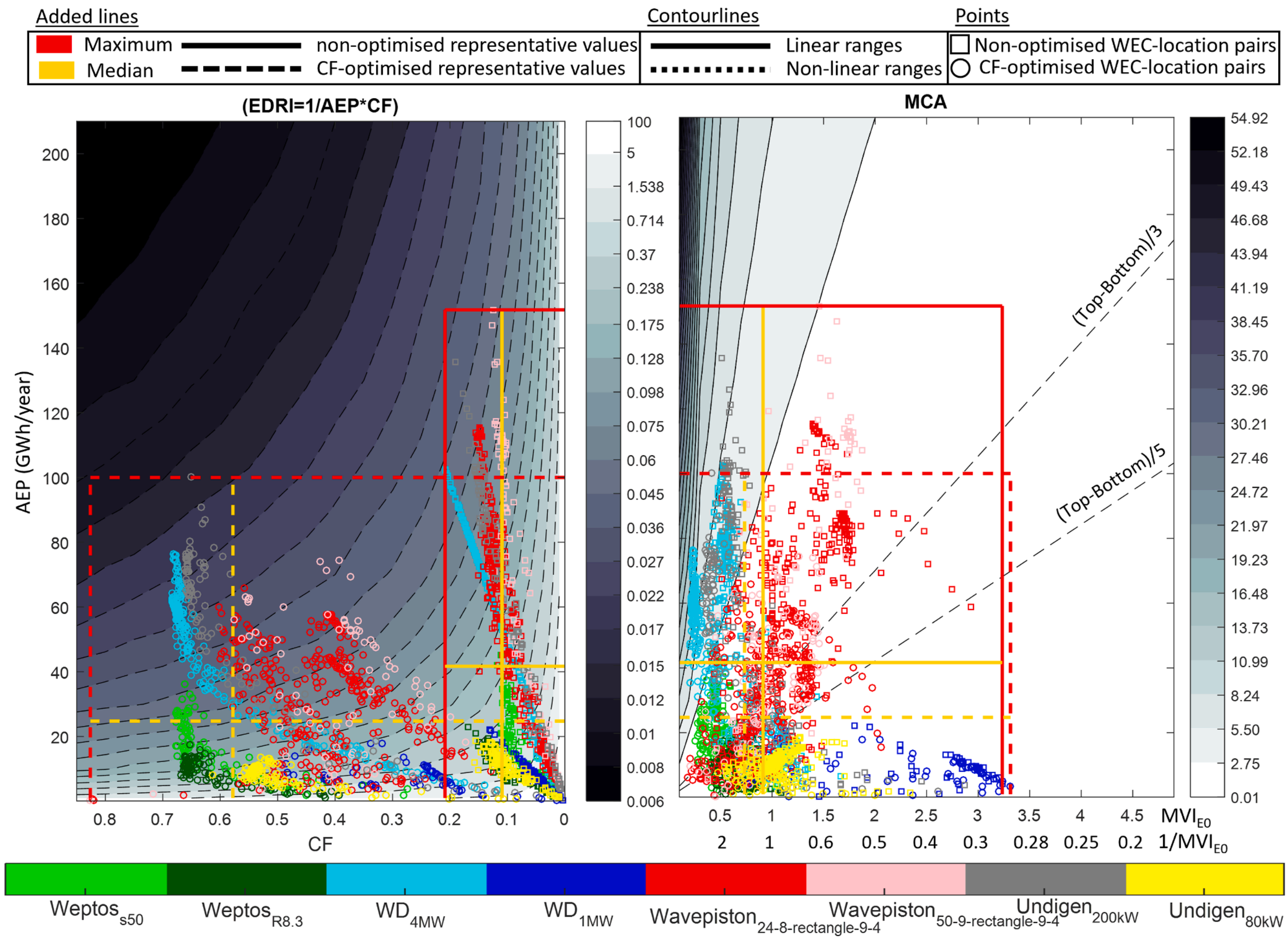

Fig. D1. Same as Fig. 13 but with 1-farm Wave Dragon (WD).

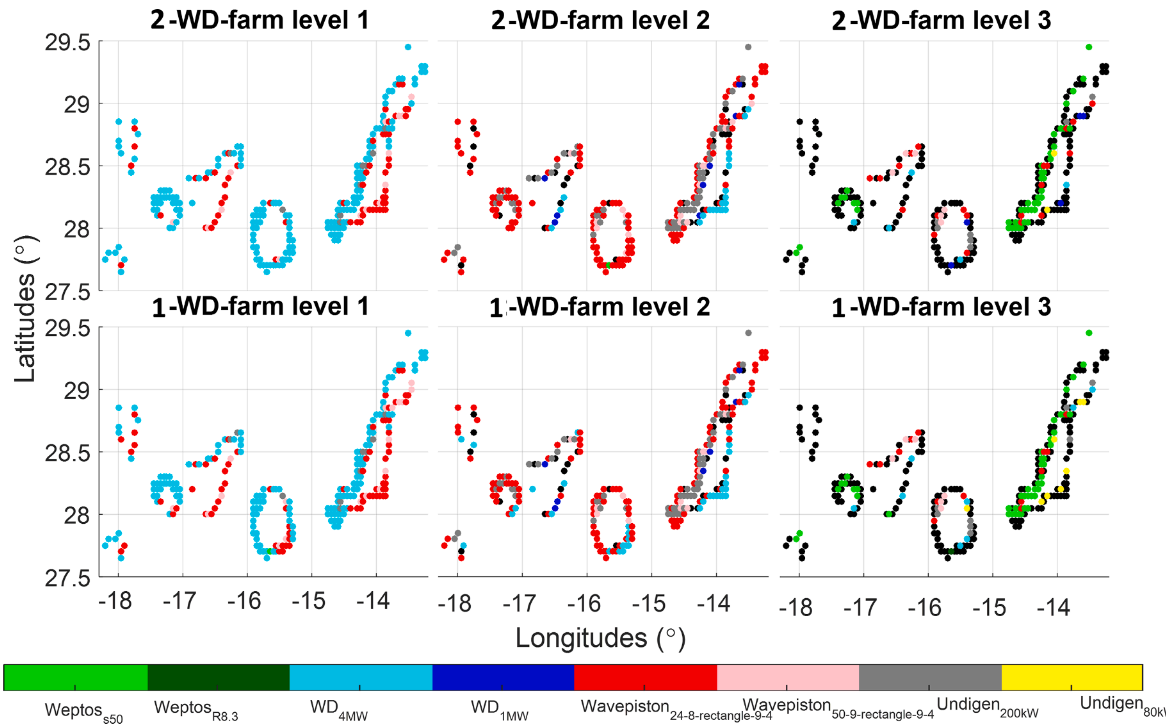

Fig. D2. Multi-Criteria Approach (MCA) selection of wave energy converter 5x5 km farms. WD stands for Wave Dragon such that the top line provides the WEC-farm selection for the scenario where WD is considered with two farms of two arrays (see) and the bottom line one farm of two arrays.

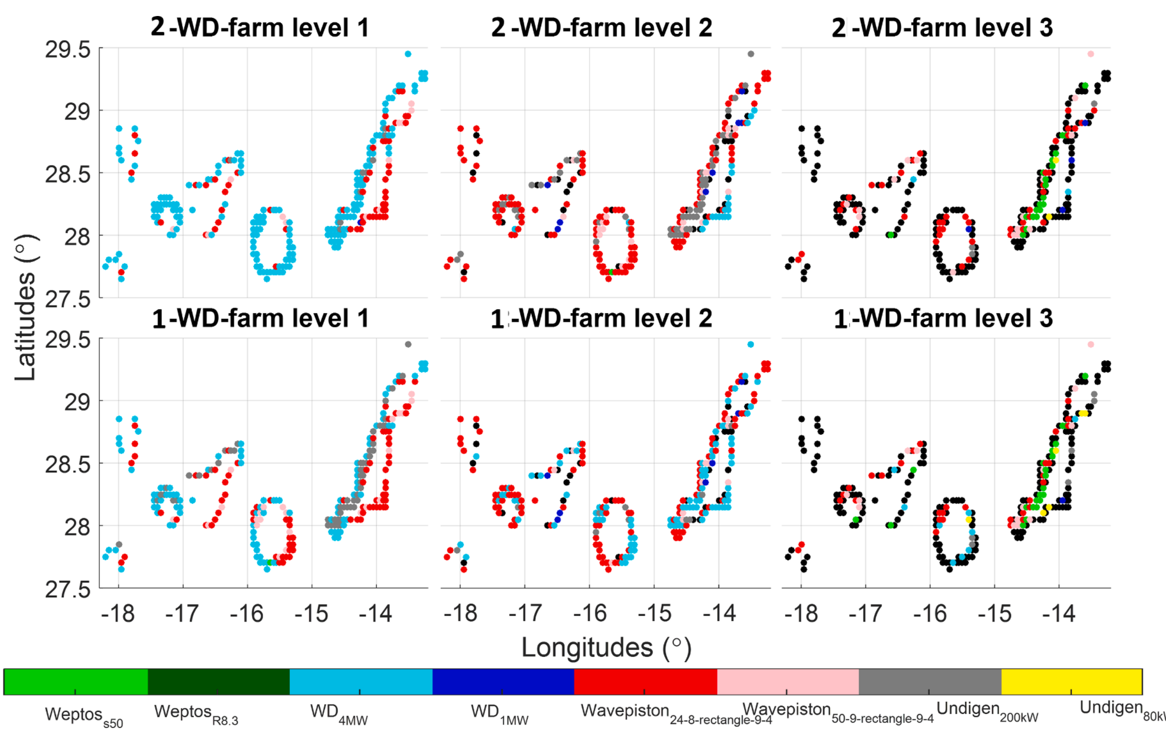

Fig. D3. Same as Fig. D2 but for the Energy Demand-Response Index (EDRI) selection of wave energy converter 5 × 5 km farms.

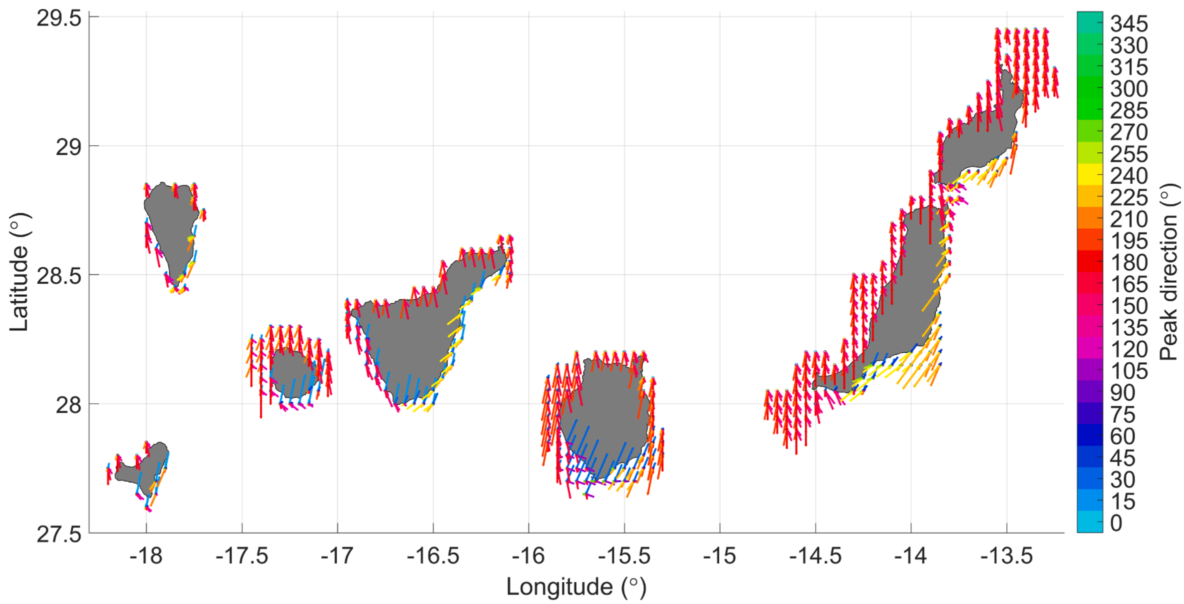

Fig. D4. Wave roses as the sum of the peak wave direction that happened during the 27 years on an hourly-basis. The larger the vector the more waves. Each arrow points clockwards (following the oceanography convention) towards the direction the wave is going (see associated colorbar to help appreciate each's arrow pointing-direction). It may be observed that the North is at 0° and the colorbar aims to help visualisation the direction of each vector and thereby which direction(s) is(are) prominent(s) for each point that has even a shred of surface in contact with Scenario 1 (blue contourline of Fig. 5).

Appendix E. . Capacity factor and selection Index for wave energy Deployments for the farm-based selection

Complementary figures of missing KPIs for the WEC-farm-selection of Fig. 14.

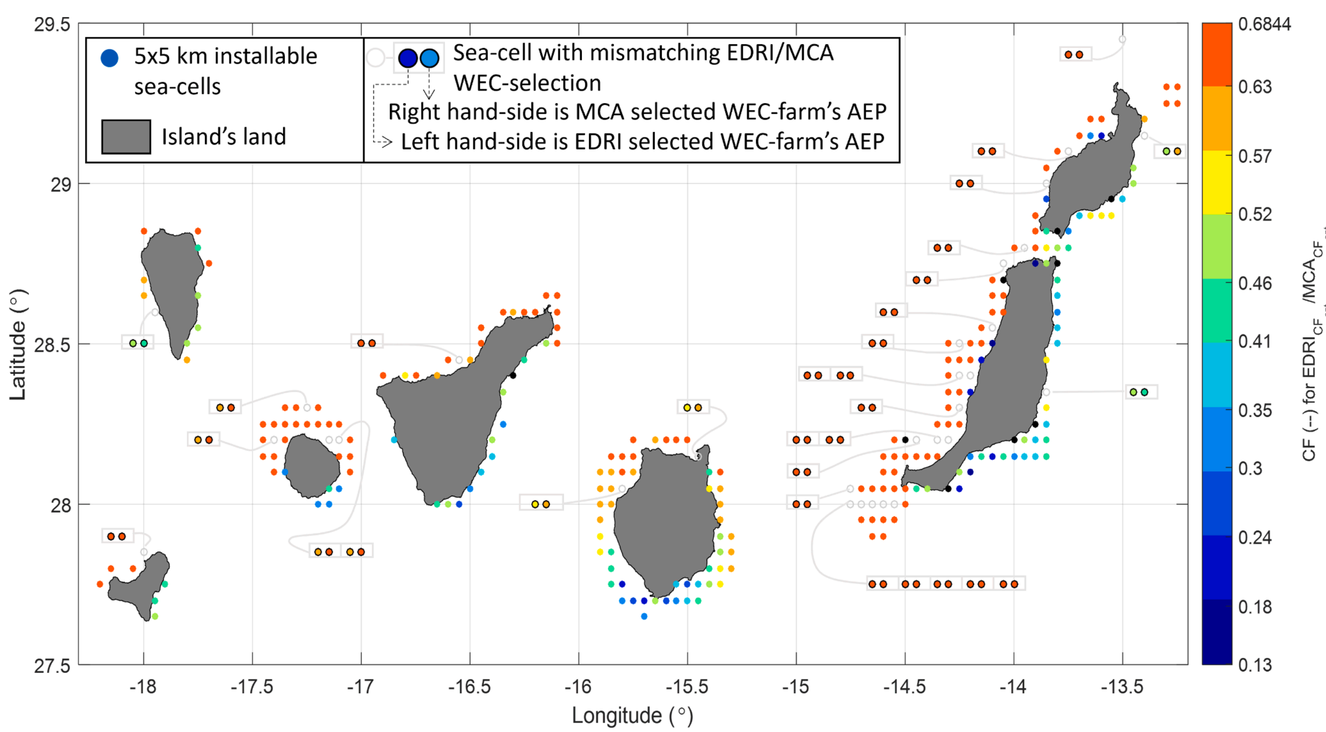

Fig. E1. Capacity Factor (CF) value of the selected wave energy converter farms from Fig. 14. Where the Multi-Criteria Approach (MCA) and the Energy Demand-Response Index (EDRI) have common values, sea-cells have been provided directly, otherwise left empty in grey circles for which both MCA and EDRI selected WEC-farm's AEP value are provided in eccentric squares.

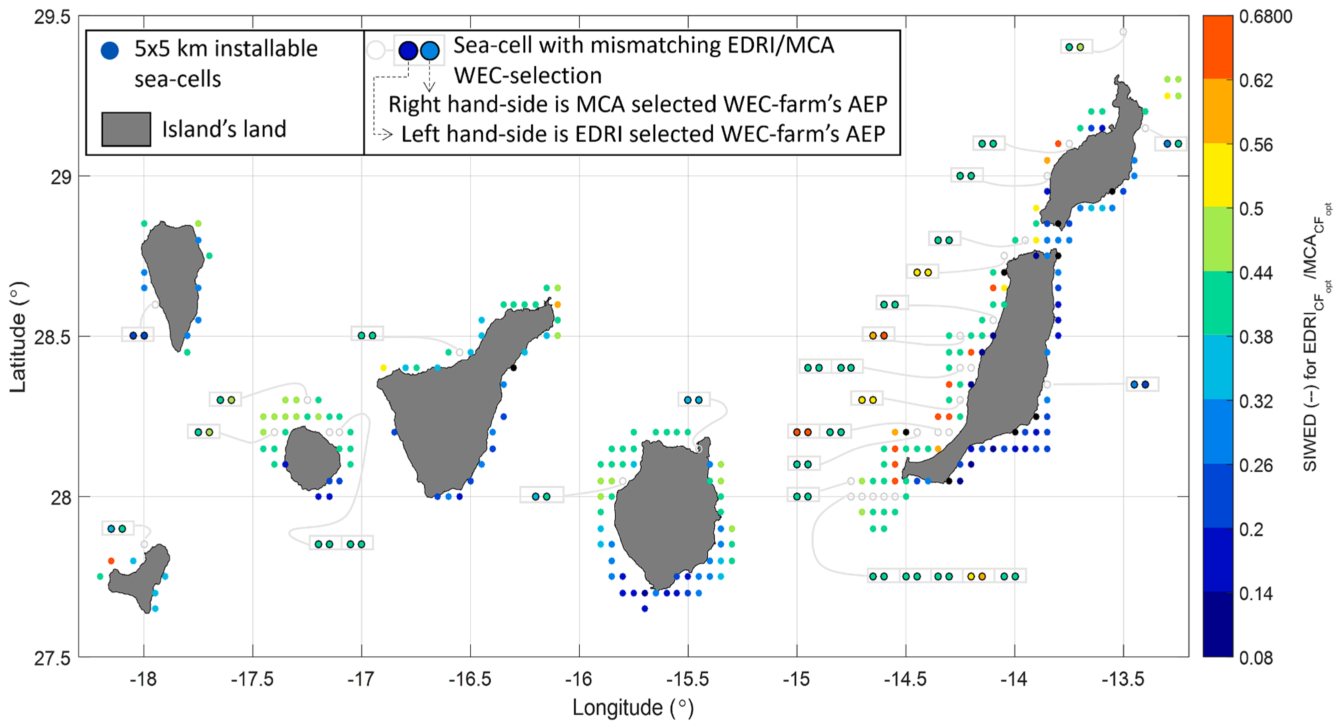

Fig. E2. Selection Index for Wave Energy Deployments (SIWED) value of the selected wave energy converter farms from Fig. 14. Where the Multi-Criteria Approach (MCA) and the Energy Demand-Response Index (EDRI) have common values, sea-cells have been provided directly, otherwise left empty in grey circles for which both MCA and EDRI selected WEC-farm's AEP value are provided in eccentric squares.

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