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Economical layout optimization of wave energy parks clustered in electrical subsystems☆

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ABSTRACT

To obtain a maximum power output and minimized capital and operational costs, the layout of wave energy parks needs to be optimally designed. An economical model for large-scale wave energy systems is built and merged into an evolutionary optimization routine for arrays of point-absorbing energy converters. The model includes all the parameters that affect the total system revenue such as electrical cable lengths, distance from grid connection point, number of substations and hydrodynamic interaction among the devices, with the goal to find the optimal layout which minimizes the levelized cost of electricity. Converters inside the park are grouped in clusters via a *k*-means clustering algorithm, which allows to minimize the intra-array cable length under the input of real wave climates. The results show that the hydrodynamical interaction has a large impact on the optimal design of wave energy parks, and that the length of the intra-array cable does not play a significant role in the economical layout optimization routine for the studied wave energy park system.

1. Introduction

The optimization of wave energy converter (WEC) arrays is one of the key factor for a successful commercialization of wave energy devices. In order to increase the competitiveness of the technologies, the layout of WEC units within wave parks needs to be meticulously evaluated with the purpose of minimizing the related costs, as well as maximizing the power output of the converters. Layout optimization has been carried out in many studies using different strategies, e.g. genetic algorithms [3,15,39], parabolic intersection [2,3], covariance matrix adaptation evolution strategies, glowworm swarm optimization, metamodel based optimization [8,11,38]. See [19] for a recent review on wave energy park optimizations.

The optimization proposed in this paper is performed using the genetic algorithm introduced by Giassi and Göteman [14] for the optimization of a single point-absorbing WEC, and subsequently extended for multiple WECs in Giassi and Göteman [15] and Giassi et al. [16]. These studies focused on finding the best distribution of WEC units in a park, primarily considering power take-off characteristics and the geometrical layout of the array: a systematic search of the layout with the highest power production was implemented. However, the profitability of a wave energy park depends also on economical aspects which cannot be neglected.

Several studies have evaluated costs of wave energy devices and parks. Rinaldi et al. [36] investigated how the downtime of renewable energy technologies affects the total profit. O'Connor et al. [31] and Guanche et al. [22] estimated operation and maintenance costs in relation to the placing of wave energy parks. Teillant et al. [41] assessed the WEC installation costs based on production, location and maintenance strategies. Rinaldi et al. [37] developed a computational tool for maintenance operations which computes key performance indicators such as annual electricity generation and total gross revenue. Macadré et al. [27] proposed a financial model which studies a combined wind and wave power plant with respect to availability and maintenance. Curto et al. [6] proposed a combined technical and economical model to identify optimal systems of combined renewable energy sources. Martins [28], as well as Ericsson and Gregorson [9], presented a risk assessments of wave energy systems based on costs established from databases and other sources. Similar methods have also been applied in [10,32,33,35] to identify optimal farms in offshore wind energy.

In order to assess the economical profitability of a wave energy project, the levelized cost of energy (LCOE) is commonly used as an objective function [30]. An LCOE optimization based on the point-absorber dimensions was carried out by Piscopo et al. [34]: the EU Strategic Energy Technology Plan forecasts that the LCOE of wave energy

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will decrease to 0.15 EUR/kWh by 2030 and 0.10 EUR/kWh by 2035.

For these reasons, our economical model presented in Giassi et al. [13] includes the LCOE, a function of capital (CapEx) and operational (OpEx) expenditure in relation to the park power output. The model takes into account device dimensions, number of WEC units, marine area and layout, distance between WECs and shadowing effects. The water depth, distance to shore and electrical configurations, offshore work and cabling are also considered.

However, the study in [13] examined a single specific unidirectional wave climate input and one substation for each park. In the present work, the tool has been extended to perform economical optimization over an annual wave climate and several offshore electrical connection hubs. Moreover, a new clustering algorithm allows to assign a certain group of WECs to a substation, so that the total length of the electrical cables is minimized. The final park of wave energy converters will therefore be divided into a defined number of clusters.

The paper is organized as follows: the mathematical model and its implementation is outlined in Section 2. Section 3 includes the description of the data used, the simulations performed and their specifics. In Section 4, results of the simulations are presented, and further discussed in Section 5. Conclusions are drawn in Section 6.

2. Method

The model used in this paper consists of three different and connected sub-models: an optimization model, an economical model and a hydrodynamic model. The optimization model uses the hydrodynamic model to compute hydrodynamic coefficients, the motions and the power output of the WECs in the parks; this output is subsequently fed into the economical model for the calculation of the LCOE. The LCOE value is used as objective function in the optimization model. The three blocks are described in detailed in the upcoming subsections.

2.1. Model

The WEC technology studied in this paper is the point-absorber device developed by Uppsala University (Sweden) and shown in Fig. 1. It consists of a floating buoy and a direct-driven linear generator on the seabed, interconnected by a connection line [24]. The parameters that characterize the geometry of the buoy are its radius R and mass m_b, while the generator is characterized by the translator mass m_t and its damping value Γ. The total mass of the two mechanical parts is indicated as $m = m_b + m_t$. In the model, the i^{th} WEC is therefore defined by the parameters $(R^i, m_b^i, m_t^i, \Gamma^i)$.

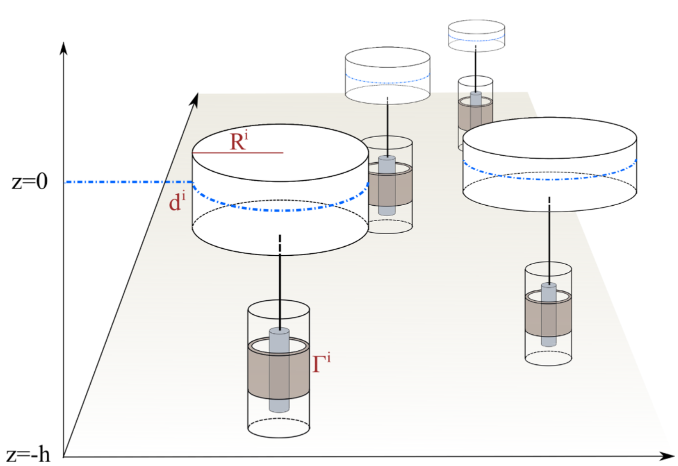


Fig. 1. Park of wave energy converters considered in the study. Highlighted are the parameters of the devices (draft d^i, radius R^i and PTO constant Γ^i), as well as the mean water level and the reference system, where $z = -h$ is the water depth. (Adapted from [21]).

Considering a large scale park installation of such devices, we define n_b the number of WECs in the park and (x^i, y^i) their coordinates, where $i = 1, \cdots, n_b$ is the index of the WECs in the park. An arbitrary number n_{ss} of electrical offshore substation will serve as a connection point to transmit the power to shore; each substation has the coordinate (x_{ss}^j, y_{ss}^j), and will be connected to a cluster of $n_{b,c}$ devices. In this case $j = 1, \cdots, n_b/n_{b,c}$ is the index of the substations in the park. Hence, the parks are defined by the parameters $(n_b, x^i, y^i, n_{b,c}, x_{ss}^j, y_{ss}^j)$.

2.1.1. Hydrodynamic model

The hydrodynamical interaction between the WECs in the park is based on the linear potential flow theory, i.e. on the assumptions that the fluid is irrotational, non-viscous and incompressible, and that the waves have low amplitude and steepness. Using the multiple scattering method, described in detail in [17], the fluid velocity potential is computed and the hydrodynamical forces calculated as surface integrals of the potentials over the wetted surfaces of the floats. Restricting to heave motion and assuming a stiff connection line between the surface buoy and translator, the equation of motion for the i^{th} WEC takes the form

$$m\ddot{z}^i(t) = F_{\text{exc}}^i(t) + F_{\text{rad}}^i(t) + F_{\text{PTO}}^i(t) + F_{\text{stat}}^i(t), \tag{1}$$

The hydrodynamical forces are given by the excitation force $F_{\text{exc}}^i(t)$, and the radiation force $F_{\text{rad}}^i(t)$. The hydrostatic restoring force $F_{\text{stat}}^i(t) = \rho g \pi R^{i2}(d^i - z^i(t))$ is proportional to the vertical displacement of the buoy, and the power take-off force is $F_{\text{PTO}}^i(t) = \Gamma^i \dot{z}^i(t)$, where Γ^i is the damping constant of the generator. The equations of motion are solved in the frequency domain and the vertical position $z^i(t)$ of the translator transformed into the time domain, after which the instantaneous power of each WEC in the park is given as $P^i(t) = \Gamma^i[\dot{z}^i(t)]^2$. The power output of the park is the sum of all buoys' instant absorbed power,

$$P^{\text{park}}(t) = \sum_{i=1}^{n_b} P^i(t) \tag{2}$$

and the same is valid for the time-averaged value,

$$\bar{P}^{\text{park}} = \sum_{i=1}^{n_b} \bar{P}^i. \tag{3}$$

For further details, see [17,18].

Running this model for many sea states gives the aggregated results in terms of a power matrix, i.e. a bivariate vector that contains, for each combination of wave height and energy period, the average power generated by the array.

2.1.2. Economical model

The economical model presented here computes the CapEx, the OpEx, the net present value (NPV) and the LCOE. It was firstly introduced in [13] but is reproduced here for clarity. The inputs required are the following: the buoys' and park's description parameters, the output power of the device or park, the rated power of the WECs, the lifetime of the project, the distance between deployment area and shore, the discount rate and the feed-in tariff. The parameters will be discussed further in the next paragraphs, while a summary block diagram of the economic model is shown in Fig. 2.

Capital costs In general terms, the capital costs or expenditure [EUR] of a wave energy project include the costs of the devices ($\text{CapEx}_{\text{WECs}}$), of the electrical systems (CapEx_{ES}), of installation ($\text{CapEx}_{\text{Inst}}$) and decommissioning ($\text{CapEx}_{\text{Dec}}$):

$$\text{CapEx} = \text{CapEx}_{\text{WECs}} + \text{CapEx}_{\text{ES}} + \text{CapEx}_{\text{Inst}} + \text{CapEx}_{\text{Dec}}. \tag{4}$$

In our model, which is based on a specific technology, these costs include the following:

- *CapEx of the devices*: includes the costs of the buoy, the linear

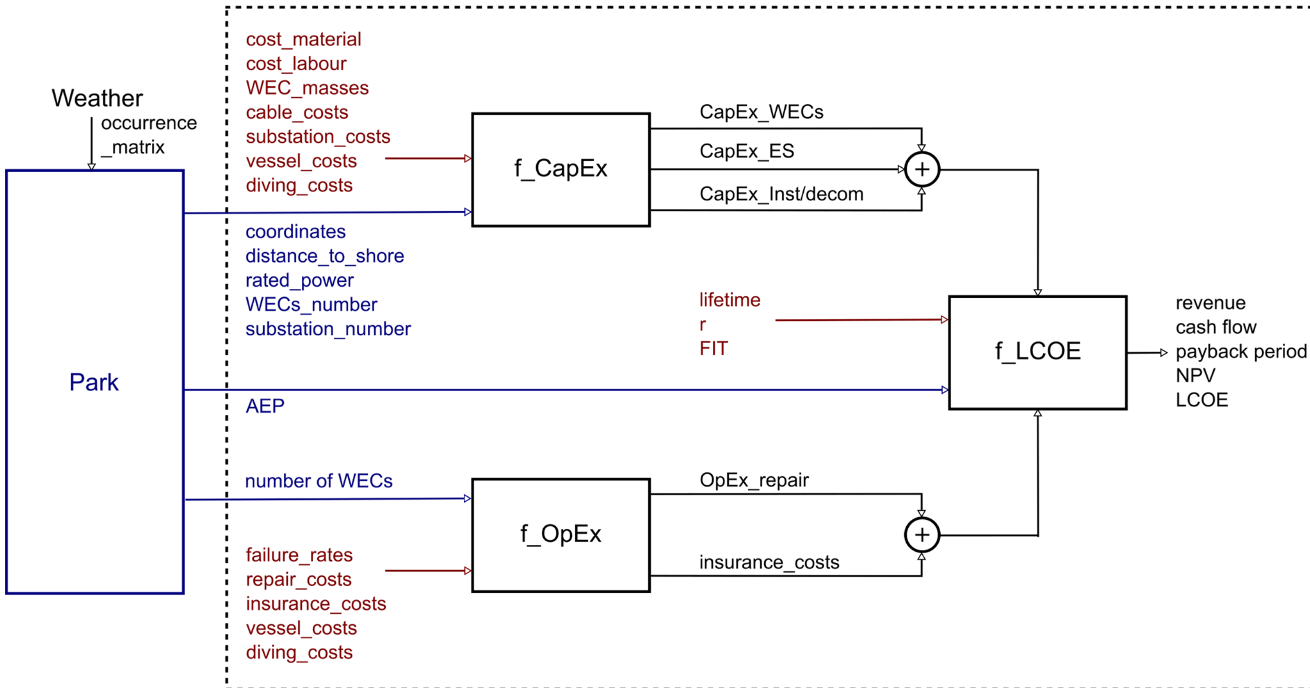


Fig. 2. Schematic block diagram of the economic model. The inputs from the park model are highlighted in blue, in red the user defined inputs and in black the economical model outputs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

generator (casing, foundation, stator and translator), labour and extra material:

$$\mathrm{CapEx}_{\mathrm{WECs}} = C_{\mathrm{buoy}} + C_{\mathrm{casing}} + C_{\mathrm{foundation}} + C_{\mathrm{stator}} + C_{\mathrm{translator}} + C_{\mathrm{labour}} + C_{\mathrm{extra\text{-}material}}. \tag{5}$$

- *CapEx of the electrical systems*: includes the length and costs of the electrical connections and the costs of the marine substations. The electrical connections include the intra-array cables (i.e. from the WECs to a marine substation) plus the sea cables and the communication cable (which connect the substations to the grid connection point onshore):

$$\mathrm{CapEx}_{\mathrm{ES}} = \mathrm{CapEx}_{\mathrm{cables}} + \mathrm{CapEx}_{\mathrm{ss}}. \tag{6}$$

The CapEx of the cables are expressed as:

$$\mathrm{CapEx}_{\mathrm{cables}} = C_{es,wc} \cdot l_{wc} + [C_{es,cc} + C_{es,sc}] \cdot l_{sc} \tag{7}$$

where $C_{es,\ wc}$ is the cost of the WECs cable (or intra-array cable) [EUR/m], $C_{es,cc}$ and $C_{es,sc}$ are the costs of the communication and sea cable, respectively ; l_{wc} is the total length [m] of the intra-array cables, while l_{sc} is the total length of the cables connecting the substations to shore. The number of substations n_{ss} is specified beforehand, while their costs ($C_{es,ss}$ [EUR/kW]) depend on the rated power of the installed and connected WECs (RPW):

$$\mathrm{CapEx}_{\mathrm{ss}} = \sum_{j=1}^{n_{\mathrm{ss}}} (C_{es,ss} \cdot n_{b,c}^{j} \cdot \mathrm{RPW}) \tag{8}$$

where $n_{b,c}^{j}$ is the number of WECs in the j^{th} cluster.

- *CapEx of installation and decommissioning*: includes the costs of hiring vessels and divers per day, and depends on the number of devices to be deployed and the time required for the whole offshore operation to be finalized:

$$\begin{aligned}\mathrm{CapEx}_{\mathrm{Inst}} &= \mathrm{CapEx}_{\mathrm{Inst\text{-}WECs}} + \mathrm{CapEx}_{\mathrm{Inst\text{-}ES}} \\ &= \frac{n_b}{I_{\mathrm{WEC}}} \cdot C_{inst,\mathrm{WEC}} + \frac{n_b}{I_{dive}} \cdot C_{inst,dive} \\ &\quad + \frac{n_{ss}}{I_{ss}} \cdot C_{inst,ss} + \frac{l_{cables}}{I_{cables}} \cdot C_{inst,cables}\end{aligned} \tag{9}$$

where $C_{inst,\mathrm{WEC}}$, $C_{inst,ss}$, $C_{inst,cables}$ [EUR/day] represents the daily costs to hire a vessel to perform installation of WECs, substations and cables, respectively. $C_{inst,\ dive}$ is the daily cost of hiring divers. I represent the number of WECs/substation/cables that can be deployed per day or how many installations can be finalized by divers in one day. l_{cables} [m] is the total length of all cables in the park. Decommissioning costs are assumed to be equal to the installations costs:

$$\mathrm{CapEx}_{\mathrm{Dec}} = \mathrm{CapEx}_{\mathrm{Inst}}. \tag{10}$$

In the capital costs calculations, no influence of the serial production on the devices price has been taken into account, and losses in the energy conversion or transmission have been neglected.

Operational costs The operational costs [EUR/y] are the costs associated with the daily operation of a project. In this model, these costs include yearly repair costs due to failures of the devices ($\mathrm{OpEx}_{\mathrm{r\text{-}Buoy,y}}$ for the buoy, $\mathrm{OpEx}_{\mathrm{r\text{-}Gen,y}}$ for the generator) and insurance costs ($C_{\mathrm{insurance,y}}$):

$$\mathrm{OpEx}_y = \mathrm{OpEx}_{\mathrm{r\text{-}Buoy,y}} + \mathrm{OpEx}_{\mathrm{r\text{-}Gen,y}} + C_{\mathrm{insurance,y}} \tag{11}$$

where:

$$\mathrm{OpEx}_{\mathrm{r\text{-}Buoy,y}} = \mathrm{fr}_b \cdot n_b \cdot \left(C_{rep,buoy} + 2 \cdot \frac{C_{inst,dive}}{I_{dive}} \right) \tag{12}$$

and

$$\mathrm{OpEx}_{\mathrm{r\text{-}Gen,y}} = \mathrm{fr}_g \cdot n_b \cdot \left(C_{rep,gen} + 2 \cdot \frac{C_{inst,\mathrm{WEC}}}{I_{\mathrm{WEC}}} + 2 \cdot \frac{C_{inst,dive}}{I_{dive}} \right). \tag{13}$$

fr_b and fr_g [1/year] are the failure rates of buoy and generator, respectively, while $C_{rep,buoy}$ and $C_{rep,gen}$ [EUR] are the average cost of repair of one WEC's buoy/line or one generator. Only failure of the generator requires vessels; failure of buoy or line requires only divers. Constant failure rates for the buoy and generator parts have been assumed, as well as constant OpEx costs over the wave power park lifetime. These are valid approximations when considering the main operational time of WECs, but are not valid at the beginning nor at the end of the lifetime of the devices [7,40]. Moreover, given the fact that we do not focus on failure rates or losses, instantaneous repair has been assumed, i.e. the devices are fully available over the whole year (no downtime considered). Different failure rates and how they affect the downtime and park availability were considered in [20], but are not the focus of the current paper.

Levelized cost of energy After computing capital and operational expenditure, the yearly revenue, the cash flow, the payback period, the NPV and the LCOE are calculated. The annual revenue [EUR] equals the annual park production times the feed-in tariff (FIT), and is constant over the lifetime for a certain number of WECs and a fixed layout. The yearly cash flow (CF_y) is the amount of money left after subtracting the operational expenditure from the annual revenue. The payback period is defined and calculated as the time (in years) needed for the cumulated cash flow to become positive.

The net present value is a parameter used to verify the profitability of a project, or in this case, of a wave power plant. It is calculated as:

$$\mathrm{NPV} = \sum_{y=0}^{L} \frac{\mathrm{CF}_y}{(1+r)^y} = -\mathrm{CapEx} + \sum_{y=1}^{L} \frac{\mathrm{AEP}_y \cdot \mathrm{FIT} - \mathrm{OpEx}_y}{(1+r)^y} \tag{14}$$

where CF_y is the cash flow at year y [EUR/y], L are the total years of the lifetime of the project, r is the discount rate, CapEx is the capital expenditure [EUR], $OpEx_y$ the operational expenditure [EUR/y], AEP_y is the annual energy production of the wave power park [MWh/y], and FIT is the feed-in tariff [EUR/MWh] (which is often subsidized to encourage renewable energy projects). The NPV must be positive to ensure that the investment is profitable.

Finally, the goal of the economical model is to compute the LCOE [EUR/MWh], as the wave energy park costs in present value divided by electricity generation in present value according to Eq. 15 [4]:

$$\mathrm{LCOE} = \frac{\mathrm{CapEx} + \sum_{y=1}^{L} \frac{\mathrm{OpEx}_y}{(1+r)^y}}{\sum_{y=1}^{L} \frac{\mathrm{AEP}_y}{(1+r)^y}}. \tag{15}$$

This value represents the average minimum price at which the electricity produced should be sold in order to break-even over the lifetime of the project. For this reason, it is the most commonly used parameter to compare different methods of electricity generation.

Both the discount rate and the feed-in tariff are considered constant along the project lifetime; moreover, no inflation is assumed.

2.1.3. Optimization model

On top of the two models presented in subsections 2.1.1- 2.1.2, an optimization routine based on a genetic algorithm has been implemented. The goal of the optimization is to find the best array layout (i.e. set of coordinates of the WECs (x^i, y^i)) which minimizes the value of the LCOE. The routine has been implemented in house in MATLAB [29], and formerly presented and applied to different problems in [13–16]. In the present work it has been extended to operate over a yearly wave climate, with a new economical cost function and with a new clustering algorithm.

The genetic algorithm optimization is connected and inspired by Charles Darwin's theory of evolution based on natural selection, and its fundamental steps recall its nomenclature. A first random *population* containing k chromosomes (or individuals) is created and subsequently forced to "evolve" through the *reproduction* process, which consists of *natural selection, pairing, mating* or *crossover* and *mutation*. Each chromosome represents a wave power park, and contains a number $i = 1, \cdots, n_b$ of genes, i.e one couple of coordinates for each WEC in the park. The first population is evaluated through the calculation of the cost of electricity with the economical cost function. Afterwards, based on the LCOE value (or fitness), the chromosomes are ranked in descending order and the individual with the lowest LCOE is taken as best solution of that GA iteration:

$$f_{\mathrm{cost}} = \min_q(\mathrm{LCOE}^q) \tag{16}$$

where $LCOE^q$ is the levelized cost of electricity computed for each park and q is the park index in the population. If convergence has not been reached, the population goes through *reproduction*, creating a new generation that has inherited some genetic traits from the parents, and some new genetic material from *mutation*. The new population is then re-evaluated and the process iterates until convergence. For more details about the genetic algorithm the reader is invited to refer to [13–16].

To verify the reliability of the genetic algorithm optimization routine, several verifications have been carried out by means of parameter sweep. This has been done for an optimization of a single WEC [15] and for an array of 9 WECs [12]. For the large systems considered here, a direct computation of the full solution space is not possible, which is the main motivation for using a metaheuristic optimization model. Instead, convergence around global maxima is justified by well-defined convergence criteria.

3. Simulations

3.1. Case study: The Wave Hub test site

The model described above has been used to simulate a case study scenario in a real offshore test site. It means that the real wave climate of a site was used as input, together with the geographical location of the marine area.

The chosen site is the Wave Hub test site, which is located around 16 km offshore from Hayle on the north coast of Cornwall, United Kingdom. The normalized hourly occurrence matrix has been produced from data presented in [43] and is shown in Fig. 3a, which represents the number of hours of the year with a specific sea state. From each couple of significant wave height H_s and peak period T_p, 60 minutes time series have been produced assuming a Bretschneider spectrum distribution.

At each sea state time series, the corresponding time-averaged power output of the park can be aggregated in a power matrix. By multiplying the power matrix and the occurrence matrix and summing up for all the different sea states (cells), we get the yearly mean annual energy production (AEP_y) in [KWh/y]:

$$\mathrm{AEP} = \sum_{w=1}^{W} (\overline{P}_w^{\,\mathrm{park}} \cdot H_w), \tag{17}$$

where $\overline{P}_w^{\,\mathrm{park}}$ is the yearly array mean power production and H_w the number of hours of the w-th sea states (from the occurrence matrix).

For each sea state, a corresponding value of the optimal gamma has been previously calculated (Fig. 3b) and used to calculate the motion and the power output of the WECs. In other words, a passive damping control is applied to adjust the generator damping to an optimal value in each sea state.

3.2. Parks of different sizes in a line layout

The first simulations performed using the economical model have the goal to evaluate the cost of parks of different sizes, deployed in a line at a specific location. The wave direction will be either along the line or perpendicular to it, as these represent the worst/best scenarios with respect to minimizing shadowing effect and maximizing power output. These two cases are important, as they can be viewed as upper and lower bounds for a realistic LCOE value.

We considered up to 100 identical devices with buoy radius $R = 3$ m and buoy plus translator mass $m = 13$ ton. The rated power of the WECs were assumed to be 20, 50, 75 and 100 kW. The number of buoys in each cluster $n_{b,c}$ is equal to 25, i.e. maximum 25 WECs are connected to each substation. Each device is connected directly to a substation. The location of the substation depends on the size of the park, and it is

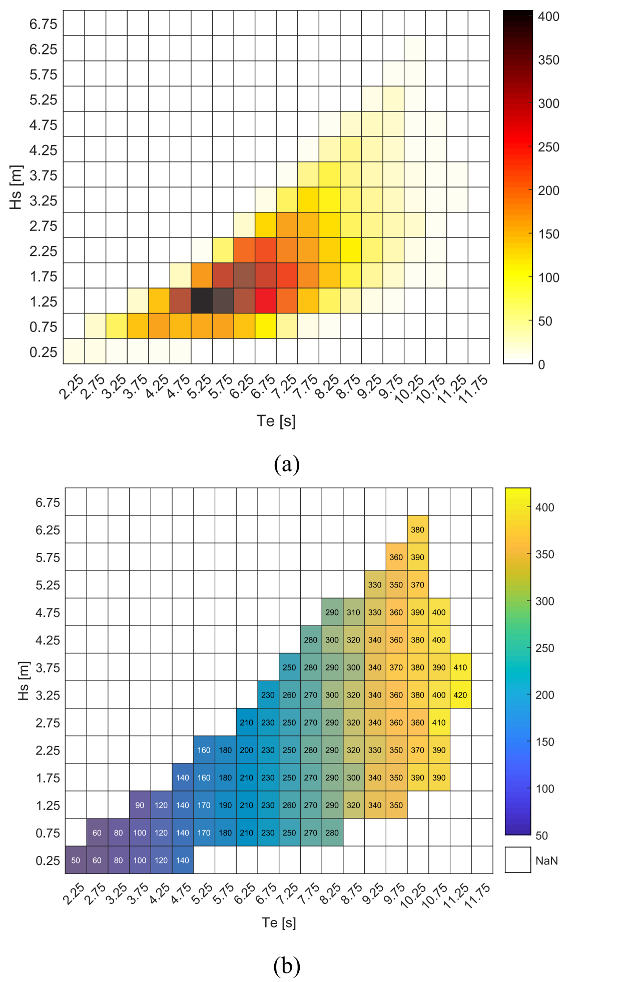


Fig. 3. Sea states distribution in [hours] for the Wave Hub test site (a); optimal PTO coefficient matrix [kNs/m] (b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

chosen to be in front of the row of WECs, minimizing the total intra-array cable length (shown in Fig. 4). The wave power plant has a lifetime of 20 years.

The input wave climate is the one measured at Wave Hub and presented in Section 3.1, which has two different incoming directions (also shown in Fig. 4):

- *x*-waves: waves propagate parallel to the row of WECs, i.e. along the x-axis;
- *y*-waves: waves propagate perpendicular to the row of WECs, i.e. along the y-axis;

These alignments between incoming waves and the wave energy power plant represent the worst and the best possible alignment achievable, i.e. with complete shadowing among the devices or with no shadowing among the WECs, respectively.

Finally, to reduce the computational time, a cut-off distance of 200 m for the radiation and diffraction hydrodynamical interaction has been set [18]. It allows to reduce the CPU computational time by lowering the number of WECs that are hydrodynamically coupled, which are those within the interaction distance cut-off.

3.3. GA Layout optimization

Park layout optimizations by mean of the genetic algorithm have

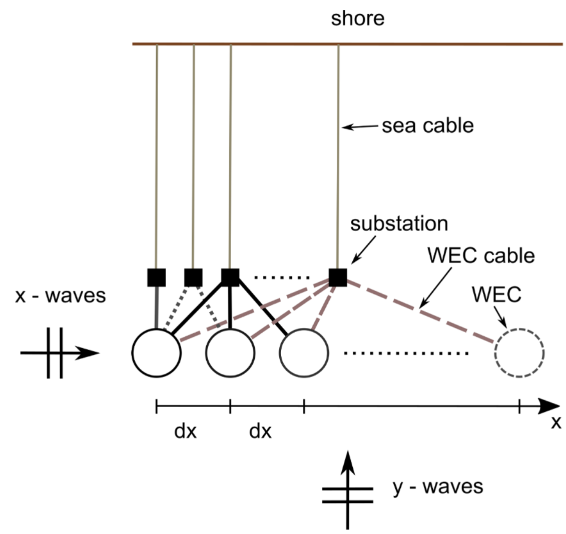


Fig. 4. Sketch of the WECs and substation locations for the simulations of 1 to 100 WECs in a line layout. The WECs are deployed along the axis $y = 0$, while the substation at $y = 20$, i.e. 20 m apart. For each size of park (i.e. park with different number of WECs), the substation is located in different places (shown with different stroke styles), in order to minimize the cable distance. For example, when there is only one WEC the substation is situated right in front of it, while when there are two WECs it is situated at equal distance from both of them, and so on. *y*-waves and *x*-waves represent the wave field propagating perpendicularly and parallel to the row of WECs, respectively. Figure adapted from [13].

been performed in the following cases:

- 10 WECs, grouped in 2 clusters, in an area of 100 x 100 m^2;
- 20 WECs grouped in 4 clusters, in an area of 160 x 160 m^2;
- 50 WECs grouped in 10 clusters, in an area of 280 x 280 m^2.

The WECs are allowed to locate on the nodes of a grid that has cells 20 x 20 m wide. The area has been chosen in order to allow about the same area per WEC in the park, while the number of clusters is chosen to have a constant amount of WECs per substation. A new clustering method has been implemented in the code that performs the placement of the electrical substations within the park and clusters the WECs. More details will be presented in the next subsection 3.3.1.

Differently from the parks with the line layout previously described, two distances cut-off of 40 m and 100 m have been set for both the radiation and diffraction problem and the power output has been calculated over the 280 yearly sea states of Wave Hub offshore test site.

To evaluate each chromosome, the economical and hydrodynamical models are used; the cost function of the optimization is the minimization of the levelized cost of energy. The GA settings for each simulations have been chosen based on previous results and validation in [15] as well as considerations of computational costs, and are reported in Table 1. The computations were performed on resources provided by SNIC through Uppsala Multidisciplinary Center for Advanced Computational Science (UPPMAX).

3.3.1. Clustering algorithm

The capital costs of the electrical system depend, among other variables, on the length of the power cables. Therefore, within a wave power park, it is extremely important to decide the number of electrical substations and their location within the park such as the total intra-array cable length is minimized. Moreover, the devices need to be divided into smaller clusters, which is not a straightforward decision, especially for big parks.

Consider a park with $i = 1, \cdots, n_b$ WECs and a certain number $j = 1, \cdots, n_{ss}$ of electrical offshore substations; each substation will be

Table 1
Parameters of the GA simulations.

	10 WECs		20 WECs		50 WECs	
Interaction distance	40 m	100 m	40 m	100 m	40 m	100 m
Iterations	510	899	1000	1000	250	60
Population	20		20		20	
Mutation rate	30%		30%		30%	
Elitism rate	2		2		2	
Area	100 x 100 m^2		160 x 160 m^2		280 x 280 m^2	

connected to a certain number $n_{b,c}^{j}$ of WECs. Hence, the costs of the intra-array cables will specifically depend on which one among the n_b devices of the whole park will be assigned (i.e. connected) to the substation j^{th} (i.e. belong to the cluster j). Therefore, the clustering of the WECs of the park should be performed by minimizing the sum of total distances from the WECs to the substation.

***k*-means clustering** A very efficient method to partition big sets of data is the so called *k*-means clustering, or Lloyd's algorithm [25]. For this reason, it can be used in the evolutionary layout optimization routine as clustering method to evaluate the best position of the substations in each layout.

This method defines k cluster centroids and then assigns each data point to one of the clusters using an iterative procedure. The number of clusters k is decided a priori and is equivalent to the number of substations n_{ss} in the wave power park.

The algorithm, implemented through the Matlab function `kmeans`, proceeds as follows:

1. Define the initial number k of clusters and the initial coordinates of the cluster centers (called centroids); to initialize the centers, the *k*-means + + algorithm is used [1], which selects the centroids according to a certain probability among the data points that are being clustered. More specifically, the first center point is sampled uniformly at random from the data set, while the subsequent cluster centers are chosen from the remaining data points, one by one, with probability proportional to their squared distance from the point's closest existing cluster center [29].
2. Compute all distances between all the WECs and each centroid (substation).
3. In order to minimize the sum of point-to-centroid distances, summed over all k clusters, the *k*-means algorithm proceeds iteratively as follows:
   i. Batch update – assign each WEC to the cluster with the nearest centroid,
   ii. Online update – sometimes the batch update doesn't converge to a local minimum. Therefore, a second iterative phase is performed where points are individually reassigned if doing so will reduce the total sum of squares point-to-centroid distances (variance).
4. Calculate new centroid position as the arithmetic mean position of the cluster points.
5. Repeat step 2 to 4 until convergence has been reached (maximum number of iterations reached or unchanged cluster assignment).

An example of the *k*-means clustering results of a random park of 50 WECs is shown in Fig. 5, for different numbers of clusters.

The problem of finding the global minimum can only be solved in general by an exhaustive choice of starting points, but using several replicates with random starting points typically results in a solution that is a global minimum. For this reason, 50 different replicates for the initial centroids of each data set (WECs park) have been executed, meaning that the software repeats the clustering routine using 50 different set of seeds for the initial cluster centroid positions. Moreover, the algorithm was set to compute each seed replicate in parallel on several processors.

With this method, the number of elements $n_{b,c}$ assigned to each cluster is not constant. Nevertheless, the intra-array cable length variance is minimized and, even though the different substations will have different power, the total rated power of the park will be constant. Thus, the average cost of all the substations will be the same as if the substations were of equal power rating, and so the total costs of the substations will be unaltered.

3.4. Costs calculation

In this section we outline the costs calculation for the specific WEC system studied, i.e. the point absorber of Fig. 1. If not differently stated, values expressed hereafter refer to the work of Ericsson and Gregorson [9] and concern a single device. The cost values presented refer to a specific device size and deployment location, and are summarized in Table 2. The parameters of the offshore site (distance to shore and water depth) are the ones reported in Section 3.1, while the parameters of the WECs (sizes, lifetime) are the ones reported in Section 3.2.

The CapEx of the WEC consist mainly of the price of the floater, the linear generator (foundation, casing, translator and stator) and construction costs. The cost of the buoy and the casing are calculated based on their masses and the cost of the steel (2.1 EUR/kg). The translator price is calculated according to the magnets and steel masses. The generator foundation cost is calculated analogously, with a cost of concrete of 125 EUR/m^3 (40 tons, 17 m^3). The cost of the stator is based on the cost of the copper windings (3 x 900 m x 3 EUR/m). Construction costs split into assembly (25 000 EUR, 1 month of work for 5 persons) and extra material (estimated 10 000 EUR).

The capital costs for the electrical system include the costs of the power cables and of the marine substation hub. The cost of the marine substation is very difficult to compute, so a simplified average cost of 168 EUR/kW has been assumed based on the review in [5]. The intra-array power cable is assumed to be a 1 kV (TECWATER EMV FC S1BC4N8-F, 1kV), with a cost of 46 EUR/m. The sea cable (PROTOLON(ST) NTSCGEWOEU, 10kV) transmits the power from a substation at the deployment site to shore at 10 kV with a cost of 72.5 EUR/m, over 16 000 m distance. The communication cable has a cost of 2 EUR/m.

Installation costs include vessel and diving operations. The considered vessel can deploy 4 WECs or one substation per day at the cost of 10 000 EUR/day, and divers can finalize installations of 5 WECs per day to a cost of 8 000 EUR/day. Regarding the installation of the power cables, it has been estimated that the operating vessel can install 10 km cable per day to a cost of 5 000 EUR/day.

Operation and maintenance costs consist mainly of the costs of repair in case of failure of the devices. It can be assumed that failure rates of wave energy converters vary over their lifetime according to the bathtub curve: the failure rate is high after installation due to defects in manufacturing or assembly, it reduces to a more or less constant value during the operational time of the device, and increases again when the device is reaching the end of its lifetime due to material degradation and fatigue [7,40]. Here, when computing the LCOE, the failure rates are included in the OpEx, which is based on the operational lifetime of the device; thus a constant failure rate can be assumed. Due to the immature stage of technology for wave energy, there is not enough data to compute or measure failure rates for wave energy converters. One recommended method of obtaining failure rates is to use established failure rates for components, and adjust them according to environmental and uncertainty factors [44]. This methodology was applied in [9] to compute the failure rate of subsystems and full WECs of the same kind as considered in this paper. The failure rate of the generator parts were computed to 0.757/year, and the failure rates for the buoy and mooring lines were computed to 0.139/year. These are the values for the failure rates that will be used in this paper. 2 000 EUR and 5 000 EUR are the estimated repair costs per failure of the buoy and generator respectively. Repair costs per year include removal of the WECs and redeployment. It has been considered that only failures of the generator

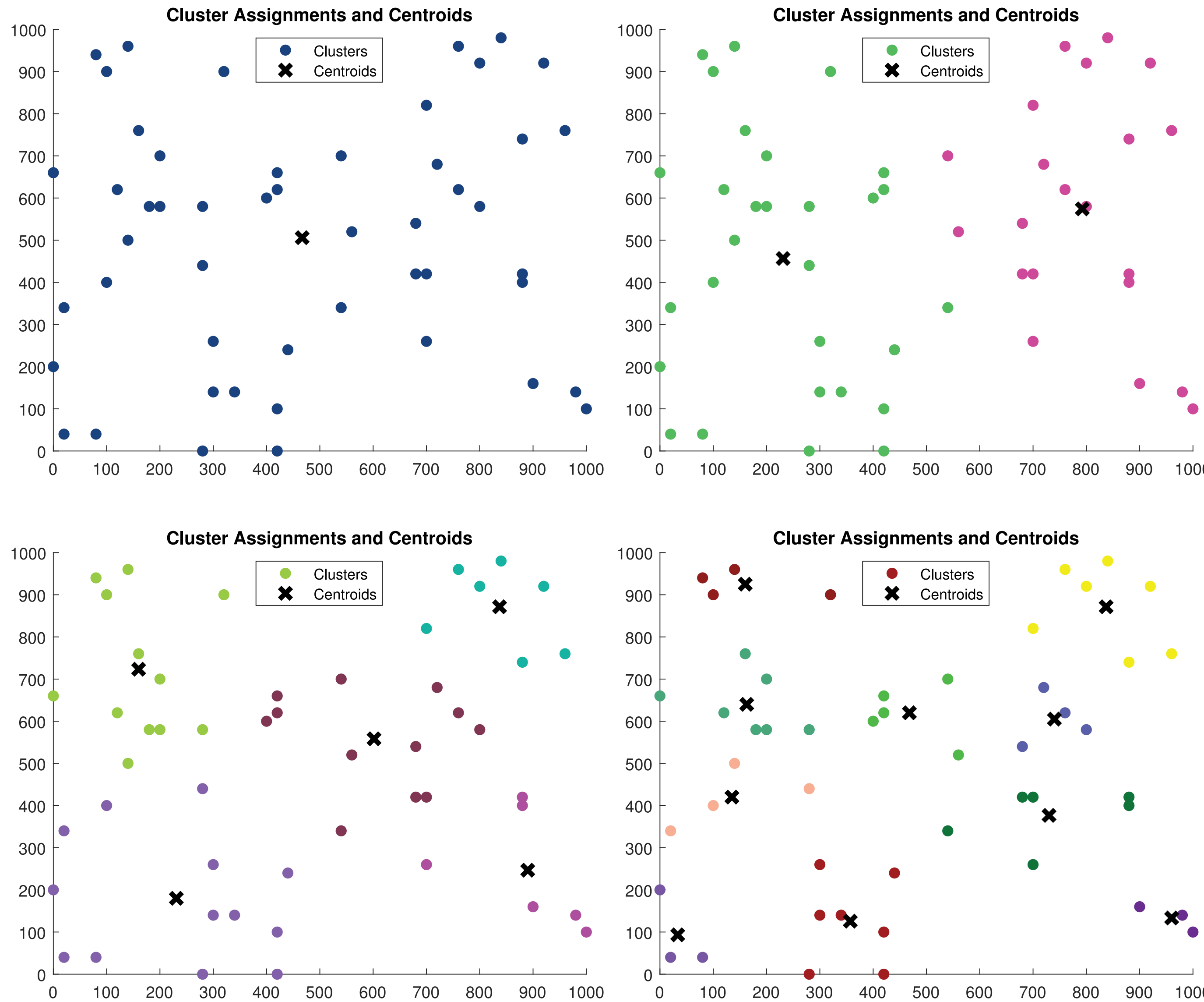


Fig. 5. Example of the *k*-means clustering algorithm for a random park with 50 WECs. Best solution for 1 cluster (up-left); best solution for 2 clusters (up-right); best solution for 5 clusters (bottom-left); best solution for 10 clusters (bottom-right). (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article).

require vessel operations, while failures of buoy/line/electrical system outside the WECs require only divers. 5 000 EUR per year to cover for site lease and insurance are included in the costs.

Regarding the LCOE calculations, a constant discount rate of 8% has been assumed [4,23,42], and a FIT of 250 EUR/MWh is chosen [26].

The input parameters, as well as of the CapEx and OpEx costs of a single device are summarized in Tables 2, 3, 4.

4. Results

4.1. Parks of different sizes in a line layout

Results of the first case study (WECs deployed in a line at a specific location) are shown in Fig. 6. The LCOE and NPV for parks up to 100 WECs have been calculated for different rated power of the converters, i.e. the model has been run for each combination of rated power and number of WECs. The sharp increases/decreases in the plots correspond to additional number of electrical substations that are installed in the park with increasing number of WECs. The lowest LCOE is obtained for parks of WECs rated 100 kW and with waves coming along the y-axis and the worst results are obtained for 20 kW of power rating in waves coming along the x-axis.

By looking at the power rating, we can observe that the lowest cost of energy (or the highest net present value) is achieved with converters of 100 kW, in all the wave directions, followed by 75 kW, 50 kW and 20 kW. It means that converters of 100 kW are optimally rated for the wave climate at Wave Hub. With lower power rating the annual energy production is greatly reduced, with an increase of the cost of energy. Results might differ in milder wave climates, for example.

If we consider the different wave directions studied, the results show that shadowed WECs have the highest LCOE and lowest NPV (*x*-waves, yellow lines), while the line of WECs facing the incoming waves (*y*-waves, magenta lines) has significantly improved results, with a difference among them of up to 38% for 100 WECs rated 100 kW. In parks of 25 devices and more, the LCOE value keeps decreasing slightly for parks without shadowing, and increases in parks with negative

Table 2
Summary of the input parameters of the economical model.

CapEx	Symbol	Description	Cost	
WEC	$C_{w,\ steel}$	steel	2.1	EUR/kg
	$C_{w,\ concrete}$	concrete	125	EUR/m^3
	$C_{w,\ copper}$	copper	3	EUR/m
Electrical system	$C_{es,\ wc}$	intra-array cable	46	EUR/m
	$C_{es,sc}$	transmission cable to shore	72.5	EUR/m
	$C_{es,cc}$	communication cable	2	EUR/m
	$C_{es,ss}$	substation	168	EUR/kW
Installation	$C_{inst,\mathrm{WEC}}$	cost of WEC deployment vessel/day	10 000	EUR/day
	$C_{inst,ss}$	cost of substation deployment vessel/day	10 000	EUR/day
	$C_{inst,cables}$	cost of cable deployment vessel/day	5 000	EUR/day
	$C_{inst,\ dive}$	cost of divers/day	8 000	EUR/day
	I_{WEC}	number of WECs that can be installed/day	4	1/day
	I_{ss}	number of substations that can be installed/day	1	1/day
	I_{cables}	length of cables that can be installed/day	10 000	m/day
	I_{dive}	installations that can be finalized by divers/day	5	1/day
OpEx	**Symbol**	**Description**	**Value**	
Repair	fr_b	failure rate buoy	0.139	1/year
	fr_g	failure rate generator	0.757	1/year
	$C_{rep,buoy}$	repair of one WEC buoy/line	2 000	EUR
	$C_{rep,gen}$	repair of one WEC generator	5 000	EUR
LCOE	**Symbol**	**Description**	**Value**	
	r	discount rate	8	%
	FIT	FIT	250	EUR/MWh
	L	lifetime	20	year

Table 3
Summary of the capital costs/WEC.

CapEx	Symbol	Description	Cost	
WEC	$\mathrm{CapEx}_{\mathrm{WEC}}$			
	$C_{\mathrm{foundation}}$	gravity foundation	2 125	EUR
	C_{buoy}	buoy	8 400	EUR
	$C_{\mathrm{translator}}$	translator	21 120	EUR
	C_{stator}	stator	8 100	EUR
	C_{casing}	casing	5300	EUR
	C_{labour}	labour	25 000	EUR
	$C_{\mathrm{extra\text{-}material}}$	extra material	10 000	EUR
Electrical system	$\mathrm{CapEx}_{\mathrm{ES}}$			
	$\mathrm{CapEx}_{\mathrm{cables}}$	cables		
	$\mathrm{CapEx}_{\mathrm{ss}}$	substation		
Installation	$\mathrm{CapEx}_{\mathrm{Inst}}$			
	$\mathrm{CapEx}_{\mathrm{Inst\text{-}WECs}}$	WEC	4 100	EUR
	$\mathrm{CapEx}_{\mathrm{Inst\text{-}ss}}$	substation	10 000	EUR
	$\mathrm{CapEx}_{\mathrm{Inst\text{-}cables}}$	cables	500	EUR/km
Decommissioning	$\mathrm{CapEx}_{\mathrm{Dec}}$			
	$\mathrm{CapEx}_{\mathrm{Dec\text{-}WECs}}$	WEC	4 100	EUR
	$\mathrm{CapEx}_{\mathrm{Dec\text{-}ss}}$	substation	10 000	EUR
	$\mathrm{CapEx}_{\mathrm{Dec\text{-}cables}}$	cables	500	EUR/km

Table 4
Summary of the yearly operational costs/WEC. The insurance cost refers to the whole site.

OpEx	Symbol	Cost	
OpEx/year	OpEx_y		
Repair of buoy	$\mathrm{OpEx}_{\mathrm{r\text{-}Buoy,y}}$	723	EUR/y
Repair of generator	$\mathrm{OpEx}_{\mathrm{r\text{-}Gen,y}}$	10 000	EUR/y
Site lease and insurance	$C_{\mathrm{insurance,y}}$	5 000	EUR/y

interactions or increased costs of the electrical systems. However, the highest reduction of the cost of energy is achieved with number of WECs greater than 10 (LCOE reduction around 80% from 1 to 10 WECs). The importance of the inclusion of the hydrodynamic interaction is visible comparing these results with the blue line, where hydrodynamic coupling has been neglected. Positive interaction improves the results (LCOE reduction between 3–4%), while shadowing makes the LCOE value around 50% higher. Here we have simulated the best and the worst possible alignment, and we then expect a realistic park to have a LCOE value in between.

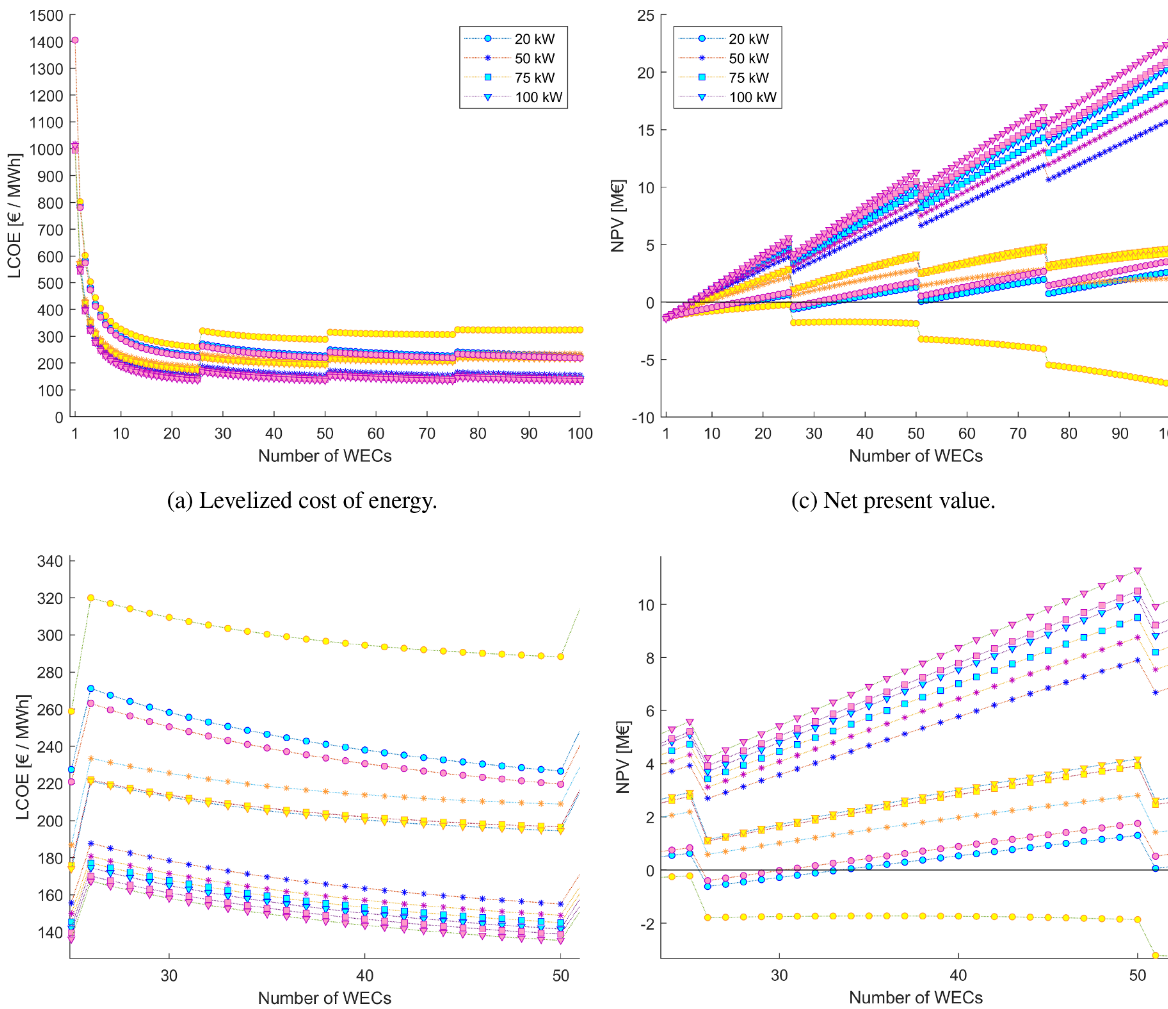
According to the results of this simulations, a rated power of 100 kW has been chosen for the simulations of the genetic algorithm optimization.

4.2. GA Layout optimization

The optimal layouts obtained from the genetic algorithm optimization are shown in Fig. 7, together with the partition of the parks in clusters. Results of 10 and 20 WECs reached convergence, while results of the parks of 50 WECs may not have converged yet. In fact, these simulations are so computationally heavy that an unreasonable amount of time would be needed to reach convergence. Therefore, we present here the results that we could achieve for 50 WECs, without claiming that these represents optimal solutions. Results on the left column are obtained for an interaction distance of 40 m, which speed up the simulations quite significantly; on the right column the interaction distance has been set to 100 m, which is more reasonable, but implies a much slower computation.

The final best layouts differ for the two different settings: when the interaction distance is 40 m the optimal layouts consist in general in rows of WECs facing the incoming wave field which are distant enough to avoid hydrodynamic coupling (Figs. 7a, 7c). In Fig. 7a it can be seen that the substation is co-located with a WEC; in reality, the substation would be placed a few meters away, which would not significantly change the results or alter the conclusions. Figs. 8a, 8c show the devices' average yearly power output and it can be seen how the WECs do not experience shadowing, having an higher power output in comparison to Figs. 8b, 8d, where wider hydrodynamic interaction is computed. In this latter case, the optimal layouts consist of two consecutive rows (park of 10 WECs, Fig. 8b), and two consecutive rows and a more distant rows for the park of 20 WECs (Fig. 8d). However, it can be noted that in Fig. 7a, full hydrodynamic coupling among all the devices is computed, which is not the case in Fig. 7c. Although the parks with 50 WECs may not have reached convergence, it can be seen that the WECs are clustered to minimize the cable length and costs, and show some tendencies to alignment in rows perpendicular to the wave direction.

Fig. 9 displays the variation of the intra-array cable length, the AEP, the LCOE and the NPV versus the iterations in the optimization process. It can be seen that the energy production and the NPV increase with the iterations, while the LCOE decreases, as expected. However, the intra-array cable length varies with a non monotonic trend. This can be explained by looking at Fig. 10, which represents a scatter diagram of the lifetime costs vs. the lifetime output of all the solutions evaluated during the GA: it shows that the variation (among different layouts) of the park costs is much lower than the variation of the park power



(a) Levelized cost of energy.

(c) Net present value.

(b) Zoom of levelized cost of energy.

(d) Zoom of net present value.

Fig. 6. Results in terms of LCOE and NPV for different sized parks in a fixed line layout (1 to 100 WECs). In blue results without hydrodynamic interaction; in magenta results with hydrodynamic interaction and waves propagating perpendicular to the line (*y*-waves); in yellow results with hydrodynamic interaction and waves propagating along the line (*x*-waves). The four different markers represent results of simulations with different rated power of the WEC (circle: 20 kW, star: 50 kW, square: 75 kW, triangle: 100 kW). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

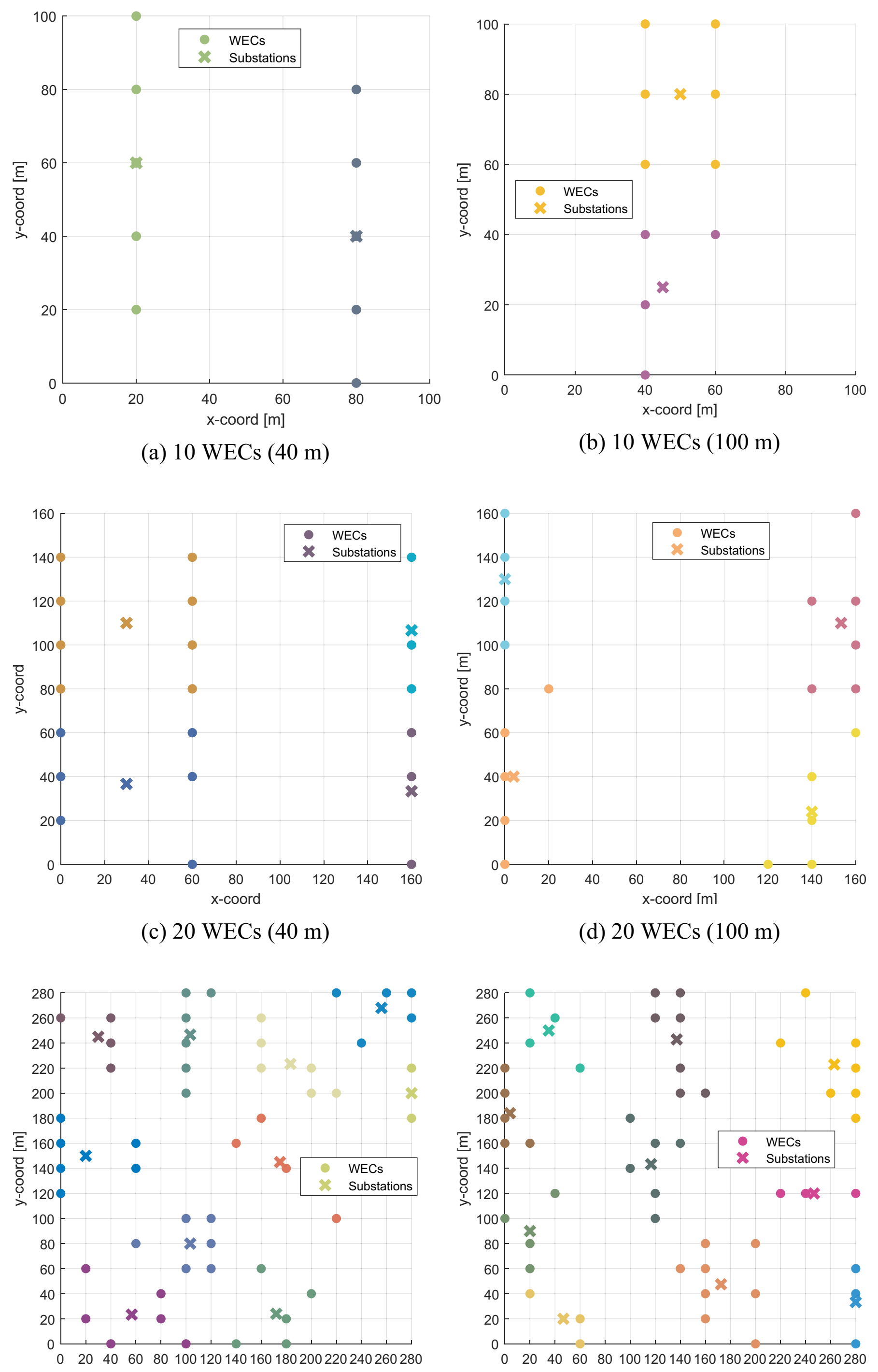
output. It means that different geometrical layouts of the same park do not have such a big cost variation in terms of CapEx and OpEx (which are related to the intra-array cable length), while the power production due to diffracted and radiated waves, together with shadowing effects, play a bigger role. Therefore, the optimal solution is the one with the higher energy production, and not necessarily the one with the lowest cables length. The same conclusion holds for all the parks studied.

Fig. 11 shows the qualitative results comparison of the LCOE and NPV. It can be seen that an higher interaction distance imply a lower power output of the park (as shown before in Fig. 8) and therefore an higher value of the cost of energy. In other words, if the hydrodynamical interaction between devices is neglected, a too optimistic prediction of the LCOE is obtained.

5. Discussion

In addition to the model inputs described in Section 3.4, other constraints that influence the economical optimization presented in this work are the number of WECs within the park, the number of clusters, the size of the deployment area and the distance to the grid connection point onshore. These parameters influence directly or indirectly the costs and therefore the final LCOE value. They can be regarded as optimization constraints and in this paper they have been chosen to fixed values (or in relation to the Wave Hub test site). Given a real commercial deployment site, the area and the connection point distance will be known quantities, and most likely the number of devices as well. As said, in this work the number of substations (or number of clusters) within the wave power park has been decided a priori to have the same ratio WECs/substations. The influence of changing the number of substations within a certain park is not investigated here. Different number of clusters could lead to a different optimal layouts.

The lifetime costs of the park are not highly affected by the geometrical layout, i.e. the influence of the intra-array cable length price variation on the total CapEx is minimal in such small park and for such a distance to the shore. This can be seen in the evolution of the power output and of the cable length in Fig. 9, where the trend of the optimal cable length is not monotonically increasing, while the optimal power output always increases with progressive iterations. It means that the optimal solution in terms of LCOE is not always the one with the shortest intra-array distance. For the current model, where the costs only depend on the cable length within the park, we see that optimizing the power output has a larger impact than the costs, in other words we could obtain the same results (in terms of park layout) had we only optimized upon the power output. However, this might be not true for



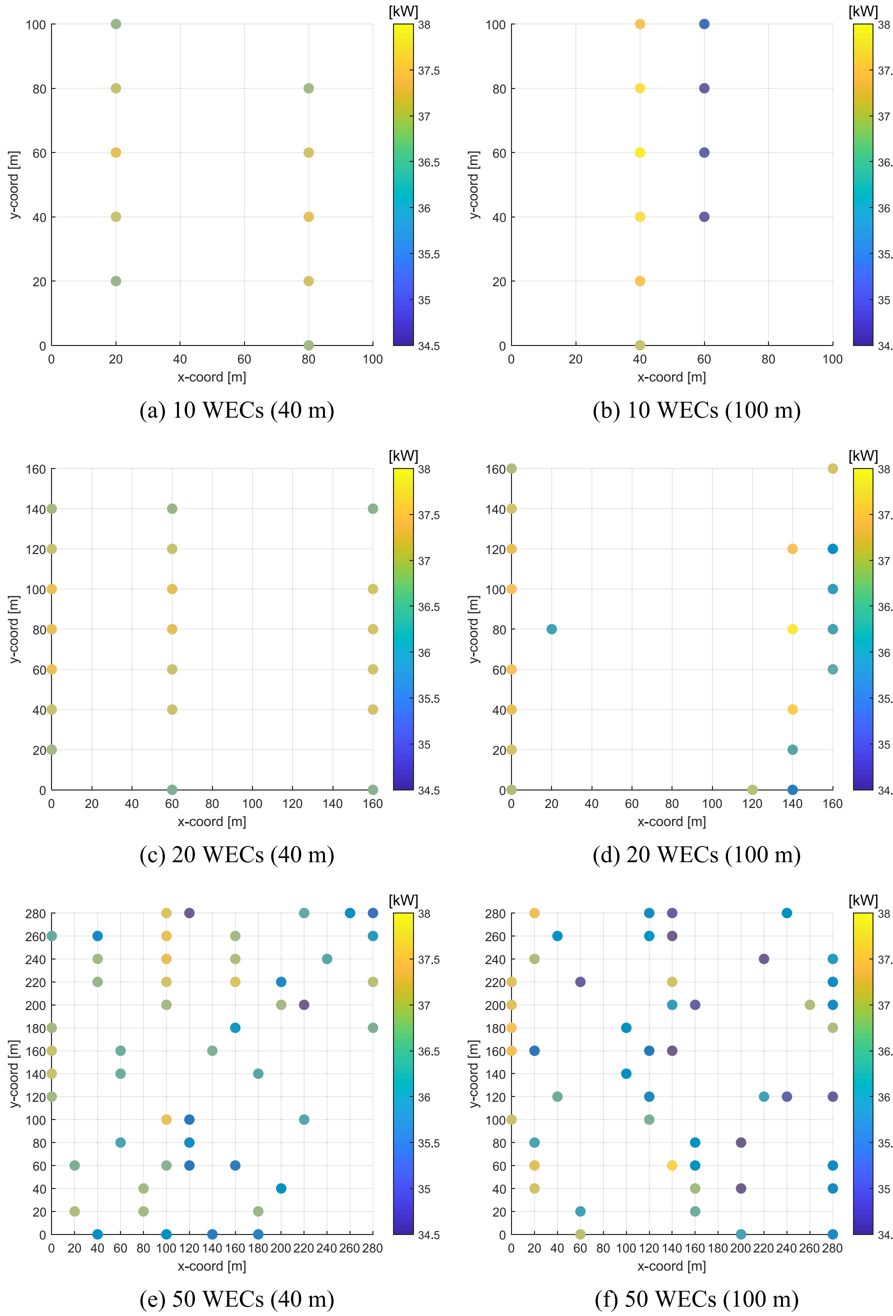
(a) 10 WECs (40 m)
(b) 10 WECs (100 m)
(c) 20 WECs (40 m)
(d) 20 WECs (100 m)
(e) 50 WECs (40 m)
(f) 50 WECs (100 m)

Fig. 7. Results of the GA layout optimization for parks of 10, 20 and 50 WECs, with interaction distance of 40 m (left column) and 100 m (right column). WECs are grouped in cluster by the *k*-means algorithm, shown with different colors. Waves propagates from West. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

other systems, or if other economical factors would be included in the model. For example, different input values in terms of cable costs per unit length or a different number of substations would imply that the capital costs would vary over a larger interval. Nevertheless, the presented economical optimization model can be useful for developers to obtain predictions of the commercial viability of wave energy plants.

The optimization algorithm used in this paper has been validated for small parks up to 9 WECs in [12,14,15], and the resulting optimal layouts for 10 and 20 WECs are in agreement with other optimal layouts obtained by other research groups [19], which increases the reliability of the achieved layouts. However, less confidence should be attributed to the resulting layouts for 50 WECs, as the system is so large that convergence is not guaranteed.

For big parks, a direct application of the tool is still highly computationally demanding, and some trial results have shown that the algorithm did not converge in a reasonable amount of time. The



(a) 10 WECs (40 m) (b) 10 WECs (100 m)

(c) 20 WECs (40 m) (d) 20 WECs (100 m)

(e) 50 WECs (40 m) (f) 50 WECs (100 m)

Fig. 8. Results of the GA layout optimization showing the average yearly power output [kW] of the devices within the parks, with interaction distance of 40 m (left column) and 100 m (right column). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

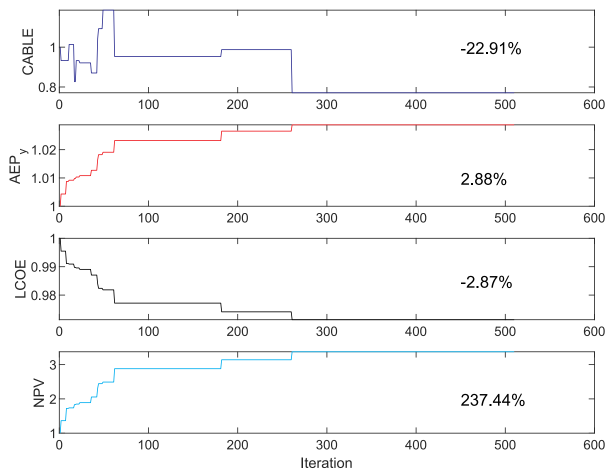
simulations can be speed up by reducing the interaction distance, at the expense of the exactness of the power calculation. This aspect is crucial in defining the optimal solution; as shown by the present study, the optimization results are sensitive to the accuracy of the computation of the power production.

The LCOE values presented throughout the results section are strongly dependent on the input parameters, which, given the lack of data in the wave energy sector, were partially based on assumptions. Once correct data will be available, the simulations will predict more accurate results in terms of absolute values. Nevertheless, at this stage of wave energy industry development, an optimization can be made in order to reduce the costs of the power park, since the relative comparison among different configurations is still valid.

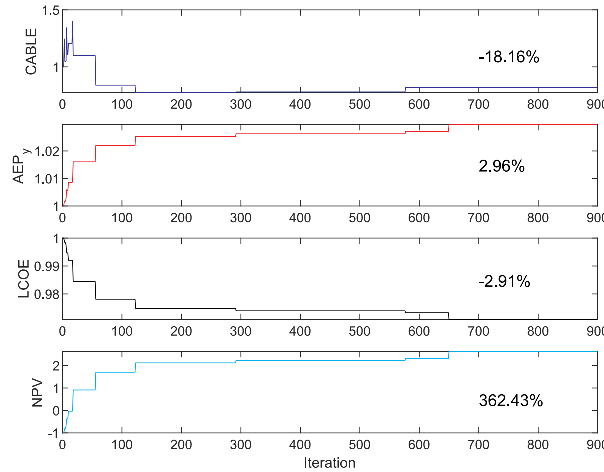
In this work as in others, the minimization of the levelized cost of electricity is still a, so called, single-objective optimization, which is one way to solve the array design process. A different approach would imply a multi-objective optimization in which several conflicting objective functions are optimized simultaneously. The solution of a single-objective optimization is defined, while the multi-objective approach would results in a set of Pareto optimal solutions that are equally good, which then need to be evaluated with different methods or by means of a human decision maker.

6. Conclusions

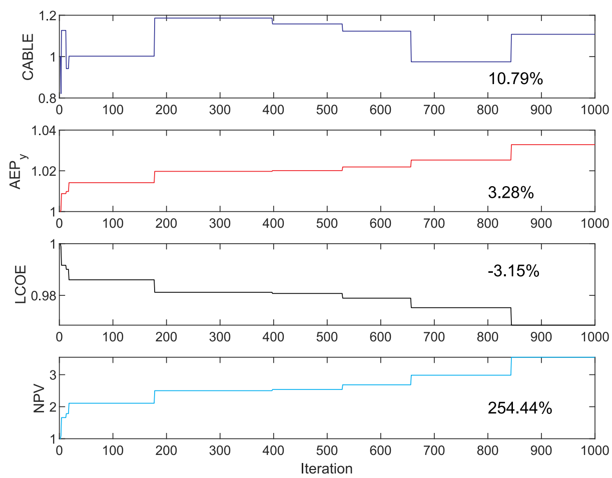
A new model for the economical optimization of wave power systems has been presented. It is based on a genetic algorithm optimization routine coupled with an economical model used as evaluation function. The optimal solutions found are based on the minimization of the LCOE. A *k*-means method has been used to perform clustering of the



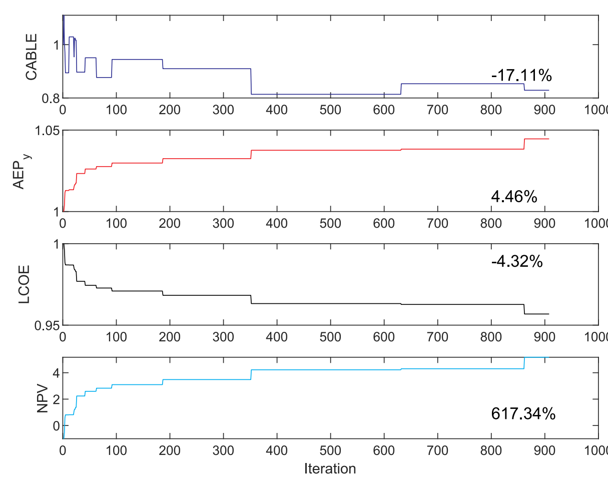
(a) 10 WECs (40 m)



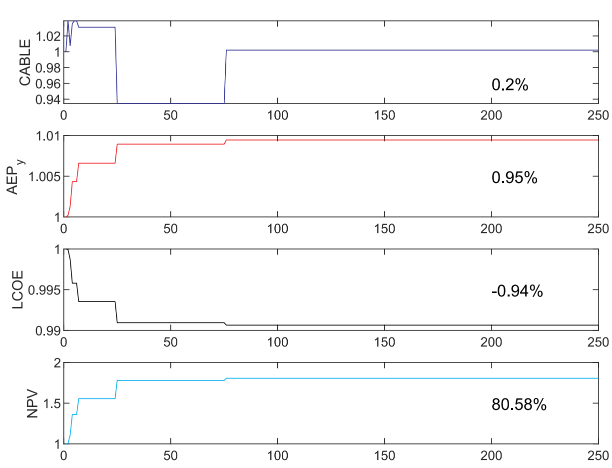
(b) 10 WECs (100 m)



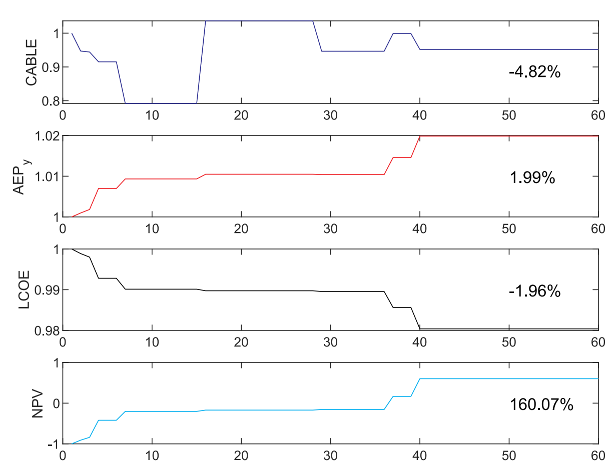
(c) 20 WECs (40 m)



(d) 20 WECs (100 m)



(e) 50 WECs (40 m)



(f) 50 WECs (100 m)

Fig. 9. Normalized variation of intra-array cable length, AEP$_y$, LCOE and NPV vs iterations, with interaction distance of 40 m (left column) and 100 m (right column). The best solution of each iteration is plotted. Text values in the graphs represents percentage variation between initial and final values.

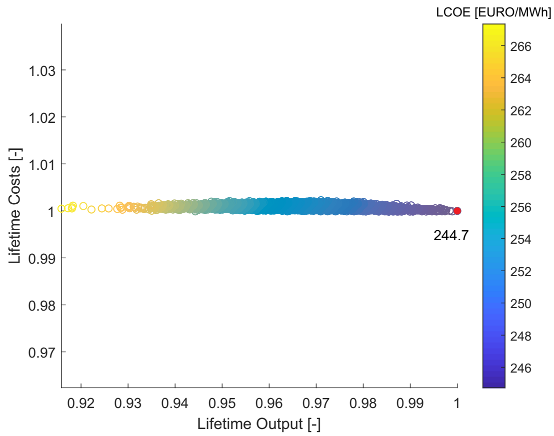


Fig. 10. LCOE of all the configurations evaluated for the park of 10 WECs (100 m). Axis are normalized. In red the final optimal solution. Similar plots are obtained for the other park optimizations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

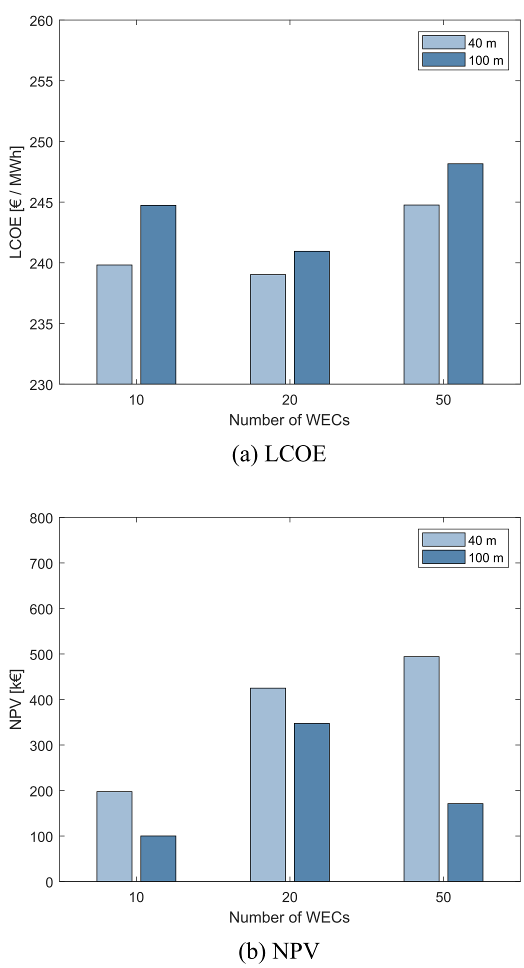


Fig. 11. LCOE and NPV results of the GA optimization.

devices for substation connection, in order to minimize the intra-array cable length and resulted efficient enough for implementation in such complex optimization problem.

The findings of the present work highlight how sensitive the results of the combined hydrodynamical and economical modelling and optimization of wave power parks are to the different parameters.

Since our work shows that hydrodynamical interaction has a large impact on the optimal design of wave energy parks, any assumption or use of simplified models for the hydrodynamics in the park should be motivated by careful analysis or experimental validation. Our results show that the hydrodynamical interaction in large parks is largely dictated by destructive interactions, and shadowing effects lead to lower power production and lower net present values. It was found that the intra-array cable length does not play a significant role in the economical optimization routine for the studied wave energy park system and that other aspects of the electrical system could highly influence the LCOE value (such as changing the ratio of the number of electrical substation per WECs).

For parks with 20 WECs or fewer, optimization considering several design parameters and hydrodynamical interactions can be carried out with convergence to optimal park designs (typically clusters arranging perpendicular to the wave direction with minimized cables length). However for larger parks with 50 units, additional assumptions or alternative methods are required to reach full convergence.

Author Contributions:

M.Gi. built the model, carried out the simulations and prepared the manuscript, with help, discussions and contributions from M.Gö. and V.C. All authors have proofread the final paper.

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.

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