Increasing the energy production of a MRE farm considering thermal and techno-economic aspects

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ABSTRACT –Electrical power generated from sustainable energies, such as marine renewable energy (MRE), is a key to the future. However, the cost of production still remains higher than for conventional energy sources. This paper describes a preliminary techno-economic study about the energy production management of a modelled point absorber-based wave energy converters (WEC) farm that could be installed in the vicinity of the SEM-REV site, i.e. the French multi-technology open sea testing site. The approach presented in this paper relies on a wave to wire model of the farm coupled with an electro-thermal analysis of the SEM-REV export cable, and a simple WEC economic cost model. The proposed methodology, developed under Matlab-Simulink®, can be extended to other WEC types and more sophisticated models and control strategies. That makes it an interesting tool to determine the optimum number of WECs which can be added in an existing farm, as it depends highly on the sea climate of the future site, and in particular on its temporal characteristics. It is demonstrated in this paper that it could be feasible, from a techno-economic perspective, to increase the rated power of an existing WEC farm without requiring expensive grid reinforcements. This could be achieved by better exploiting the electro-thermal flexibility of its existing electric infrastructure.

Keywords – Submarine cable, energy production management, marine renewable energy, wave energy converter, thermal inertia.

1. INTRODUCTION

Electrical power generated from sustainable energies, such as marine renewable energy (MRE), is a key to the future for a greener energy mix. However, the cost of installation and production still remains higher than for conventional energy sources [1, 2, 3, 4]. Because of that, planning the cost-effective integration of MRE, and in particular of wave energy, in the energy mix remains a challenge as its levelized cost of energy (LCOE) is one of the highest among all sources of electrical energy [5, 6, 7]. Many studies have addressed the design optimization studies for the electrical infrastructure of MRE farms. More precisely, they mainly focused on cable length and rated current [8, 9, 10, 11, 12], and about WECs spatial layout [13, 14], and most of the electrothermal studies deal with windfarm export cable [15, 16]. One of the next steps consists in addressing the future challenges regarding the optimal use of the existing electric infrastructures, such as the already deployed test sites (e.g. SEM-REV, bimep, WaveHub) [17, 18].

This paper presents a techno-economic study about the energy production management of a modelled point absorber-based WEC farm that could be installed in the vicinity of the SEM-REV site (see Fig. 1), i.e. the French multi-technology open sea testing site [19]. It also discusses the potential for increasing the number of WECs in a wave farm without grid reinforcement. Indeed, previous studies showed that a submarine power cable can carry, on a temporary basis, significantly more current than its rated value that is determined using highly conservative constant current conditions [20, 21]. Hence, it was proposed to consider thermal limits rather than current limits when monitoring the cable and operating a wave farm. Indeed, thanks to the high thermal inertia of the buried cable and of its direct environment (soil) which acts as a damper, the current limits may be quite irrelevant considering the highly fluctuating power output of a wave farm and the slow variations of cable temperature, as depicted in Fig. 2.
The approach presented in this paper relies on a wave to wire (W2W) model of the wave farm coupled with an electro-thermal analysis of the SEM-REV export cable, and a simple WEC economic cost model. This paper describes three case studies based on a direct-drive, point absorber-based WEC farm with negligible energy storage, thus presenting a highly variable power output (see Fig. 2). The point absorbers are controlled passively with a predetermined damping factor which depends on the sea-state to maximize the production of electrical energy. Our approach is two-fold. First, as electric currents greater than the rated value can be safely tolerated in the system on a temporary basis, wave electricity production during highly energetic sea-states could be increased with limited to no curtailment, thus leading to an increased wave farm capacity factor. Second, a simple farm power production strategy has been applied by (de)activating the WECs with respect to marine weather conditions (i.e. sea-state parameters) in order to maximize the overall energy production while not exceeding the thermal constraints. It is worth mentioning that other solutions could be used to control the energy production more accurately, and in particular the possibility to adjust controls such as the damping factor, which is planned for future work. The proposed methodology, developed under Matlab-Simulink®, can be extended to other WEC types [22, 23, 24] and more sophisticated models and control strategies. That makes it an interesting tool to determine the optimum number of WECs which can be added in an existing farm, as it depends highly on the sea climate of the future site, and in particular on its temporal characteristics of sea states. It is demonstrated in this paper that it could be technically feasible to increase the rated power of an existing WEC farm without requiring expensive grid reinforcements. This could be achieved by better exploiting the electro-thermal flexibility of its existing electric infrastructure. However, it is worth mentioning that the profitability of wave energy farms highly depends on the feed-in-tariff (FIT), and financial return is only guaranteed on condition that FIT and subsidies are sufficiently high, especially for the smaller farms, for which the required FIT may be unrealistic.

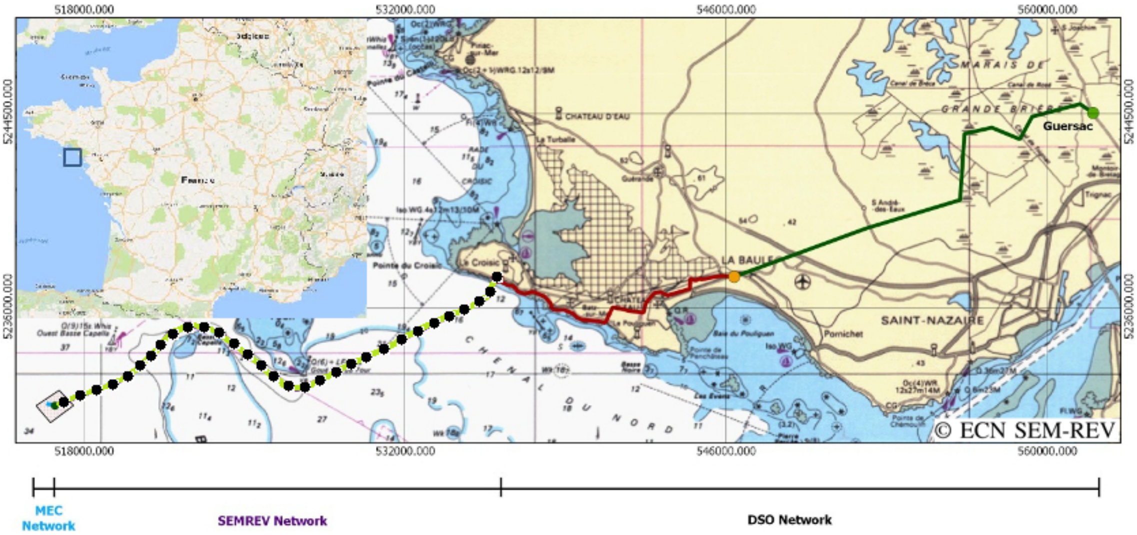

Figure 1. The SEM-REV open sea test site is located in western France, near Le Croisic. The physical installation of the 24 km export cable studied in this paper follows the dotted path. It connects the SEM-REV offshore hub to an onshore substation and finally to the local network belonging to French DSO Enedis (red and dark green paths). Figure modified, courtesy of École Centrale de Nantes [19].

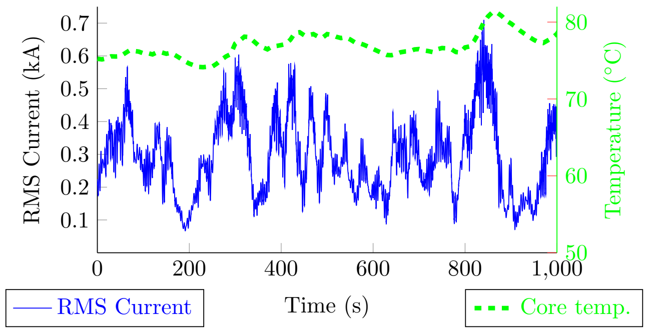

Figure 2. Example of a RMS current profile generated by a WEC farm composed of 20 WECs considering a $Hs = 6$ m and $Tp = 9$ s sea-state. One can see the high current fluctuations while the temperature of the core of a phase remains almost constant.

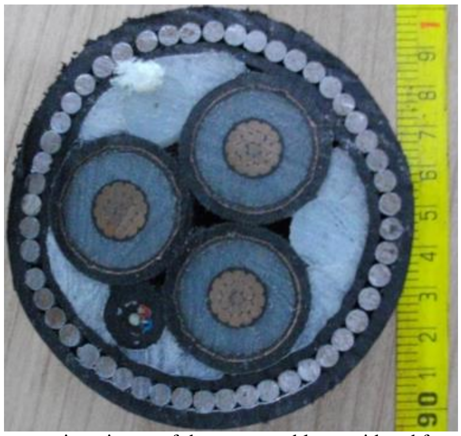

Figure 3. Cross section picture of the export cable considered for our case studies. The cable is currently installed in the SEM-REV test site located off Le Croisic (see Fig. 1), France and is managed by École Centrale de Nantes [19].

2. MODELLING

2.1. Electrothermal model of the export cable

The 3-phase, 20 kV, 8 MVA export cable used in this study is physically installed in the SEM-REV test site (see Fig. 1). A 2-dimensional discrete model of this cable and of its direct environment have been implemented under Matlab® using the well known thermal-electrical analogy that is used in IEC standards [25, 26] and in many large scale application [27, 28, 29, 30]. Such modelling approach allows to model the thermal behaviour with linear or nonlinear electrical circuit elements, and shows shorter computation time than finite element method with a good accuracy compared to our previous work [20]. The cable is buried at a 1.5 m depth in sediment and soil, where thermal properties are deemed to be homogeneous and constant, and where thermal resistivity $\rho_{th} = 0.7$ m·K·W^{-1} and heat capacity $C_{th} = 2$ MJ·m^{-3}·K^{-1}. Regarding the export cable, that is depicted in Fig. 3, it is composed of 3×95 mm^2 copper cores that were designed to carry a constant electric current of 290 A. The temperature dependence of the specific heat $C_p(T)$ in J/(kg.K), of the thermal conductivity $\kappa(T)$ in W/(m.K), and of the electrical resistivity $\rho_e(T)$ in Ω.m were considered. Also, based on a previous work [31], it was considered necessary that their non-linear relationships to temperature be used. One can find the materials data we used in [26, 32, 33, 34]. It is important to emphasize that the Matlab-Simulink® model used here was validated against the model based on the finite element method, itself validated against experimental results [35]. The cable and its environment were discretized in numerous elements as depicted in Fig. 4. The multiphysical modeling has been implemented starting from the general heat equation :

$$\rho_m C_p(T)\frac{\partial T}{\partial t} = \nabla.(\kappa(T)\nabla T) + Q_J\,, \tag{1}$$

where ρ_m is the mass density of each material taken from [26]. The total Joule losses inside the cable is computed from the electric model and defined by $Q_J = \int_V \rho_e J^2 \, dV$, where J is the electric current density in A/m^2. The armor losses and the screen losses (in semiconductor and copper) were computed with respect to the IEC standard 60287-1-1 [25]. We also used non-linear laws of cooling on the external boundaries to model the heat transfer in the sea water that is defined as :

$$Q_c = h(\Delta T) \cdot S \cdot (T_w - T_s)\,, \tag{2}$$

where T_s (in K) is the soil temperature of the element adjacent to the sea water, S is its area (in m^2), T_w is the sea water temperature in K, and $h(\Delta T)$ is an effective non-linear convection coefficient expressed in W/(K·m^2), and where $\Delta T = T_w - T_s$.

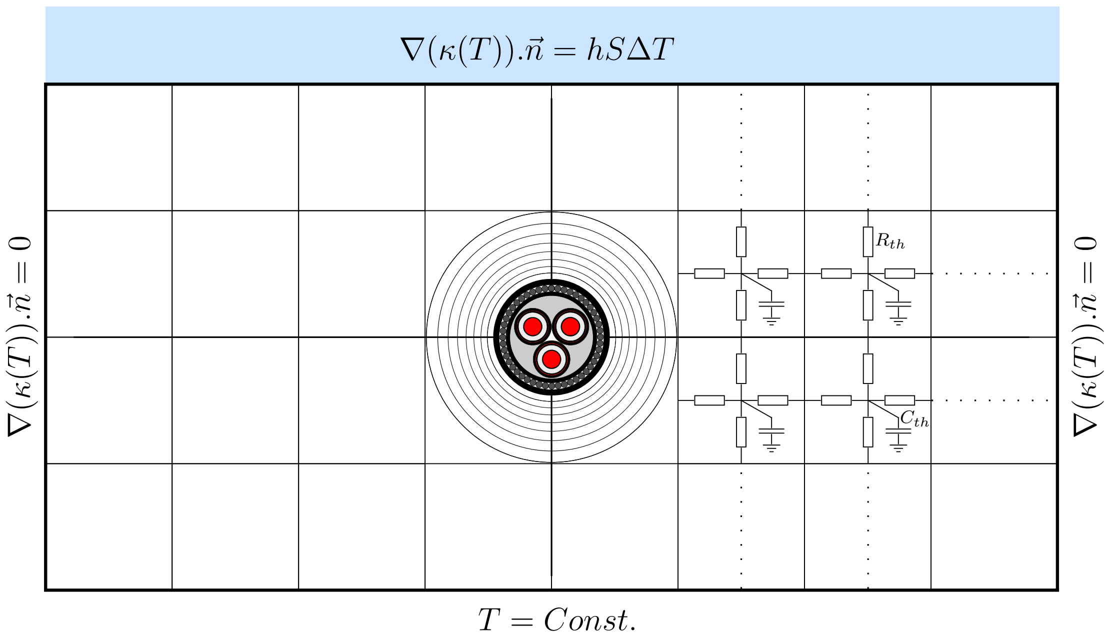

Figure 4. Discretization of cable and of its direct environment as implemented under Matlab® where we used elements of different sizes (not to scale). The sea surface is not discretized in electro-thermal elements and we only considered a boundary condition for the heat transfer as described in eq. (2). One can see the thermal equivalent electric circuits composed of non-linear resistors R_{th} and capacitors C_{th} that are used to discretized the geometry.

Term $h(\Delta T)$ is based on materials data and formulae given in [36, 37], and is defined by the following equation :

$$h(\Delta T) = \frac{\kappa}{L_c} \times 0.15 \times [Ra(\Delta T)]^{1/3} , \quad (3)$$

where $Ra(\Delta T)$, i.e. the Rayleigh number, depends on the difference between the considered boundary temperature and the sea water temperature. It is defined as:

$$Ra(\Delta T) = \frac{g \times \beta \times \Delta T \times L_c^3}{\upsilon \times \alpha} , \quad (4)$$

where g is the acceleration due to gravity in m/s^2, β is the thermal expansion coefficient of the fluid in K^{-1}, L_c is the characteristic length in m, υ is the kinematic viscosity in m^2/s and α is the thermal diffusivity in m^2/s. According to Berx and Hughes [38], the soil and the sea water temperatures can be estimated to be equal to 12 ˚C, which is typical of northwestern European coastal conditions. Simulations were realized assuming that the export cable is buried at a constant 1.5 m depth under the sea bed. One can find more details about boundary conditions for the thermal problem in Fig. 4. We have also computed the cable current carrying capacity $I_{cc} \approx 330$ A which corresponds to the maximum constant RMS value of the current that can be transmitted in the cable without exceeding the maximum allowed temperature of the cable cores, i.e. $T_{max} = 90$ ˚C for a XLPE-insulated cable, as it is the case here. The difference between the rated value of 290 A and the calculated current carrying value, i.e $I_{cc} \approx 330$ A, may be explained by the fact that we do not consider potential hot spots, which could be the case at landfall or at each junction box. Also, a security margin, unknown to the authors of this paper, may have been taken into account in the initial design studies, thus decreasing the value of the rated current. Without more information on these specific points, we deliberately chose to use the highest value, i.e. $I_{cc} \approx 330$ A, as a reference in this paper. This constitutes a worst-case scenario leading to a minimal margin for current increase. However, it is important to note that the goal of this paper is to assess the potential for current increase on a submerged, continuous section of an export cable, independently of the influence of other cable elements and parts for which specific actions, such as replacement, may be undertaken.

2.2. *Current profile generated by a WEC farm*

In order to model the wave farm, we used a wave-to-wire model implemented under Matlab-Simulink®, as described in [39]. The farm was composed of up to 36 identical 1 MVA heaving buoys controlled passively, as modelled in [40]. Note that a single peak period $T_p = 12$ s is considered, and the value of the damping factor B_{pto} is constant and equal to an average value of the optimal damping factor that is representative for the whole sea-state sequence, i.e. $B_{pto} = 680 \times 10^3$ Nms. Due to the random nature of wave power, the power generated by a WEC farm, especially when it is based on direct-drive point absorbers with little to no storage, can be extremely fluctuating. This is reflected in the current that flows in the export cable as shown in [20, 22] and as illustrated in Fig. 2. Considering sea states, the sequence that has been used relied on plausible durations and transitions between each sea-states based on the Reedsport wave energy site [41]. According to this sea-states sequence, current generated by the WEC farm is computed using a Matlab-Simulink® W2W model that represents a farm composed of up to 36 heaving buoys with a power of 1 MVA each.

3. CASE STUDY

3.1. *Introduction*

All the case studies presented in this paper used the same initial conditions and the same sea-state sequence shown in Fig. 5. Regarding the initial conditions, we used a predefined sea-state with wave height $H_s = 1$ m and wave period $T_p = 12$ s. It was assumed that at initial time t=0 s, the system was in a dynamic steady-state where the cable temperature fluctuates around a constant value which is assumed to be the initial temperature for the simulations considered here. Based on this assumption, the corresponding constant current generated by the farm was evaluated, in order to define the initial temperature for each element of the electrothermal model. Techno-economic model of the WEC farm relies on SANDIA report, where their refer-

Table 1. Description of the sea-state sequence+.

Region	Wave height H_s (m)	Duration (h)
0	1	1
1	1 to 3	12[a]
2	3	24
3	3 to 6	12[b]
4	6	24
5	6 to 3	12[b]
6	3	12
7	3 to 1	12[a]
8	1	12

+ The sea-states sequence is based on a single peak period $T_p = 12$ s, for all wave heights H_s.
[a] Increase or decrease by step of $\Delta H_s = 0.2$ m distributed uniformly over the region duration.
[b] Increase or decrease by step of $\Delta H_s = 0.25$ m distributed uniformly over the region duration.

ence model 3 deals with point absorbers [1]. Costs have been considered reflecting a large WEC farm to emulate large scale production, as if WEC technologies were ready and available on the market. The feed-in tariff (FIT) has been assumed to be between 173 and 300 €/MWh, which is representative of FITs that are used in different countries [2, 42].

3.2. *Case studies description*

The objective is to determine the number of additional WECs that could be installed in the farm without exceeding temperature constraints and regarding the economic performance of each WEC. To do so, three different scenarios are considered:

- Case 1 : The number of WEC is kept constant with $N_{WEC} = N^i_{WEC}$. Term N^i_{WEC} corresponds to the maximum number of WECs that can be connected to the wave farm without exceeding the constant current carrying capacity of the cable I_{cc}, i.e.

$$max\,(I_{farm}(t))\,|_{N_{WEC}} \leq I_{cc} \tag{5}$$

- Case 2 : N_{WEC} is kept constant with $N_{WEC} = N^+_{WEC}$. Term N^+_{WEC} corresponds to the maximum number of WECs that can be connected to the wave farm without exceeding temperature constraints, i.e.

$$max\,(T_{core}(t))\,|_{N_{WEC}} \leq T_{max} \tag{6}$$

- Case 3 : The number of WECs $N_{WEC} = N^v_{WEC}$ is allowed to vary by (de)activating WECs between different sea-states. However, the temperature constraints must still be satisfied, i.e.

$$max\,(T_{core}(t))\,|_{N_{WEC}(t)} \leq T_{max} \tag{7}$$

Case 1 is considered to be the initial and existing WEC farm, where only maximum current constraints were considered. Case 2, where N_{WEC} remains constant, considered temperature constraints instead of current constraints. Finally, Case 3 represents a further enhancement compared to Case 2, where variations of N_{WEC} are allowed during the simulation.

Considering the economic aspects, we assumed that the initial farm, that is composed of 11 WECs, was already installed. Following this assumption, its costs are not taken into account and the techno-economic study only considers the additional energy output, and associated revenues of extra WEC(s).

4. RESULTS

As presented in Fig. 6 the simulation results show that the temperature calculated in Case 1 is far below 90 °C, which leaves room to increase the power of the farm. Case 2 shows improvement with 2 extra WECs that can be permanently connected to the farm without exceeding T_{max}. Considering Case 3, where the number of WECs is between 13 and 15, the core temperature is close to $T_{max} = 90$ °C, and the cable is almost used to its full potential. Regarding the energy production only, Case 3 is between 12.7% and 33.5% more than this of Case 1 and is up to 12.8% more than this of Case 2. If we consider the entire duration of the simulation, Case 3 generates significantly more energy than this of Case 1 (+27.0%). Considering economic constraints, one can determine that optimal number of 2 additionnal WECs maximizes the benefits per WEC, as depicted in Fig.7. Under these conditions, exploiting the electro-thermal flexibility of an existing farm may allow to increase its rated capacity of 18.2%, without grid reinforcements. However, the feed-in tariff has a big impact on the economical profitability, and subsidies and/or as increasing the FIT may be needed in some countries to encourage the development of WEC farms.

5. RESULTS

5.1. *Case 1*

As we can see in Fig 6, the temperature of the cable cores is far below the limit of 90 °C that is suggested in IEC standards and is used by many power cables manufacturers. Such results confirm, as shown in a previous study [20, 31], that eq. (5) was not suitable for sizing power cables in the case of a WEC farm generating highly fluctuating currents. A number of 11 WECs has been found ($N^i_{WEC} = 11$). This number corresponds to the number defined based on the most conservative approach taking into account maximum current constraints only. It will be used as the baseline to compare the results for the two other case studies.

5.2. *Case 2*

The result of Case 2 is presented in Fig. 6. In this case, 2 more WECs could be installed in the farm permanently, i.e. (N^+_{WEC}=$N^i_{WEC} + 2$). This represents an increase of 18.2%, both in terms of WEC number and in terms of harnessed energy compared to Case 1 (see Table 2).

5.3. *Case 3*

The result of Case 3, where N^v_{WEC} was varying between 13 to 15, is presented in Fig. 6. Note that we neglect Region 0, which represents the first step for the computation of the temperature, where initial conditions and short duration of the period lead to an irrelevant number of WECs. One can see that the temperature calculated in Case 3 is closer to $T_{max} = 90$ °C over the total duration of the simulation, which means that the cable utilization is approaching its maximum. However, considering that the calculated temperature remains below 90 °C over the entire sea-state sequence, there is still room for improvement in terms of energy production with finer tuning and more comprehensive control of the WECs. Excluding Region 0, the expected energy production of Case 3 is between 12.7% and 33.5% more than this of Case 1 and is up to 12.8% more than this of Case 2 (see Table 3). If we consider the entire duration of the simulation, Case 3 generates 27.0% more energy than this of Case 1, which is significant (see Table 2). The results of the techno-economic study are presented in Fig. 7. The first observation concerns the optimal number of extra WECs, which does not depend on the FIT in our case study. Indeed, one can see that 2 extra WECs

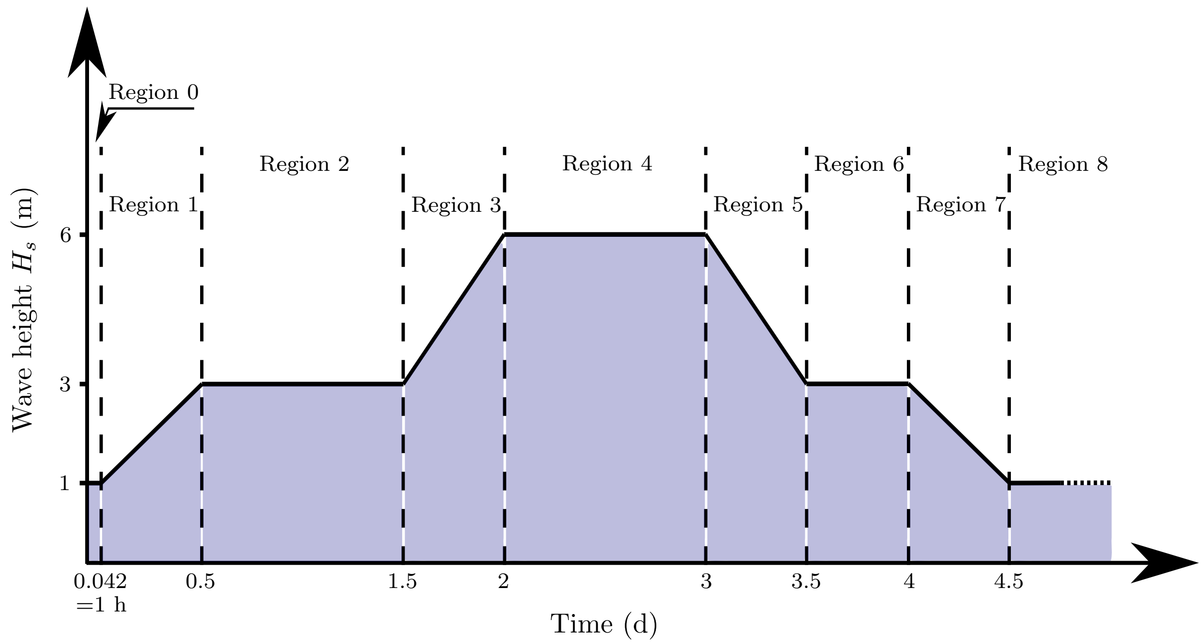

Figure 5. Sequence of sea-states that has been used for all simulation cases (see Table 1). Note that it is a completely fictitious sequence but based on plausible durations and transitions between each sea-states based on Fig. E2 and E3 of [41].

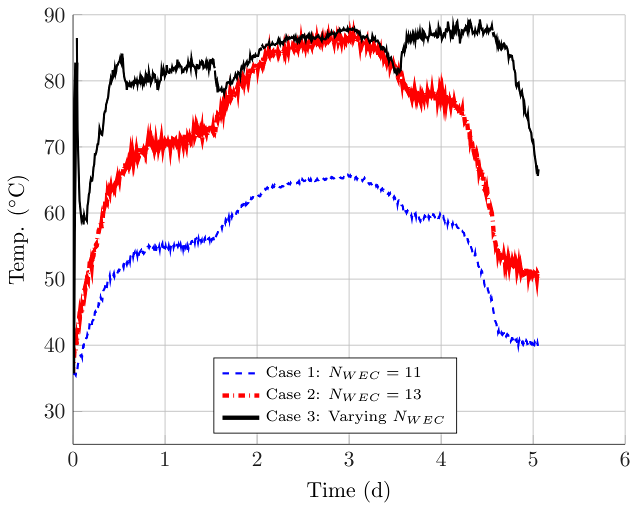

Figure 6. Cores temperature calculated for Case 1 to Case 3, with respectively 11, 13 and 13 to 15 WECs. Compared to Case 1 and 2, Case 3 shows cores temperature that remain closer to T_{max} = 90 °C over time.

Table 2. Summary results of case studies

Case	N_{WEC}	Energy (MWh)	Gain [a]
1	11	1113	0% [b]
2	13	1315	+18.2%
3	13 to 25[c]	1414	+27%

[a] Considering the sequence of sea-states given in Fig. 5 and neglecting the Region 0 that is irrelevant in Case 3.
[b] Considered as the reference case.
[c] See Table III for more details.

seems to be optimal when considering economic aspects as it maximizes the benefits per WEC. Then, exploiting the thermal electro-flexibility of the existing farm may allow to increase its rated capacity of 18.2% without any modification of the export cable. One can remark that the break-even point is 225 €/MWh. Ideed the revenue is positive, and maximal, when 2 WECs are added to the farm for FIT greater than or equal to 225€/MWh. However, it is worth mentioning that our case studies considers high energy sea-states, and one can expect to observe higher required FIT when considering real sea states over several months, which will be addressed in future work.

Table 3. Detailed results and energy production gain for Case 3.

Region	N^v_{WEC}	Gain 1[a]	Gain 2[b]
0[c]	25	+224.2%	+189.2%
1	15	+33.5%	+12.8%
2	14	+25.9%	+6.7%
3	13	+24.3%	+0%
4	13	+28.7%	+0%
5	13	+24.3%	+0%
6	14	+25.8%	+6.6%
7	14	+26%	+6.6%
8	14	+12.7%	+4.8 %

[a] Compared to Case 1.
[b] Compared to Case 2.
[c] First step of the simulation. Due to the initial temperatures and the short duration of Region 0, the number of WECs is irrelevant.

6. CONCLUSION

The study described in this paper shows first steps toward the optimal use of existing MRE farm electrical infrastructures using the thermal response of an export cable installed in a wave farm, and considering a sea-state sequence with different wave heights. It has been shown that one can take advantage 1)of the thermal inertia of the cable that is directly buried in the soil and 2)of the wave farm fluctuating electrical current, to increase the number of WECs and increase the energy production of up

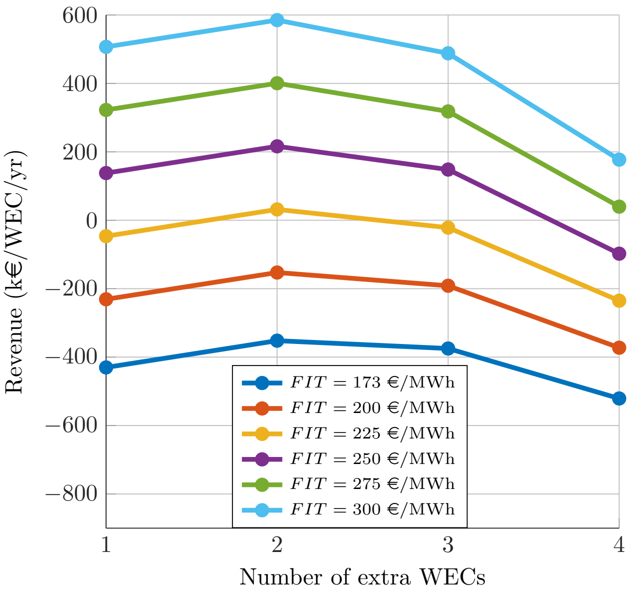

Figure 7. An optimal number of 2 additionnal WECs maximizes the benefits per WEC, which brings the number of WEC to 13. One can also remark that the economical profitability is not guaranteed for the lowest FITs.

to 27%. However, economic considerations lead to an optimal number of WEC that reduces the increase of energy production to 18.2%, which maximizes the benefits per WEC. It must be noted that, based on current data and estimation regarding WEC costs, adding WECs to an existing farm may be profitable only if high feed-in tariffs are applied. The objective of the next steps is to carry out a more comprehensive study using several months of sea-state data measured on the SEM-REV test site.

7. ACKNOWLEDGEMENT

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