Final publishable summary report

Executive summary

The 2-year research activities carried out under the Sea2grid project lead to a series of relevant conclusions about the approach, results, and still open issues in the wave energy sector. The research activities showed the importance of keeping a multi-disciplinary perspective when dealing with wave energy conversion systems (WECs). To correctly deal with and to simulate a wave energy project by a "wave-to-wire model" it is fundamental to identify the main characteristics of all the subsystems which comprise the device and especially their mutual interactions. It is important to clearly define the purpose of any specific analysis, to consequently identify the level of detail needed in the corresponding simulation model.

It has been emphasized the importance of control both to improve the power extraction and to allow the grid connection of the WECs, while ensuring proper power quality and grid code compliance at the point of connection. It has been also highlighted the role of the Power Take-off (PTO) and the importance of an optimized design of the PTO itself, especially as regards its efficiency. The specific analyses performed confirmed that direct-driven point absorbers are an especially challenging application due to the extremely high peak to average extracted power ratio, which calls for a consistent oversizing of the PTO system. It is worth noting that when multiple WECs are deployed in a wave farm, a consistent reduction can be obtained in the peak-to-average power ratio, due to the natural spatial displacement among the WECs in the farm. A small reduction is also obtained in the average power capture.

The specific test-case of points absorbers connected to the *bimep* and AMETS infrastructures was considered. *bimep* is an infrastructure for research and testing of offshore WECs connected to a strong electric grid whereas AMETS corresponds to a real test site connected to a weak grid. In the case of single WEC / multi-MW wave farm connected to *bimep*, in all the considered cases, grid code compliance is ensured. Thus, for this case, grid integration does not present special concerns and specific energy storage provisions are not required. Since any consideration about grid integration is specifically dependent on the specific grid code and on additional requirements from local Distribution System Operator (DSO) or TSO (Transmission System Operator), an absolute generalization is not possible.

The grid integration of a multi-MW wave farm in AMETS, would provoke high voltage drops at the Point of Common Coupling) PCC. In this weak grid scenario, energy storage deployment becomes fundamental to solve power quality issues and ensure grid code compliance. Performed analyses on the short-term showed that a power rating of the storage in the range of the wave farm installation and an energy rating in the order of magnitude of few hundred KWh would be necessary. Based on such power & energy rating, suitable storage technology technologies could be lead-acid batteries, flywheels and potentially Ni-Cd batteries. This should be considered as a preliminary indication since final technology selection should be based on the analysis of multiple wave profiles it must also consider other parameters as storage life-time and efficiency. Long-term energy storage studies, for energy management, showed potential for the combination of wind and wave energy farm, with a potential improvement in further stabilizing the output power if a centralized energy storage device is jointly deployed.

Finally an additional investigation focused on the grid integration of a wave farm to cover the energy need of an isolated community, showed that in isolated networks matching power generation and consumption is a clear priority and that their correlation is fundamental to define the energy storage requirements. In this case the convenience to deploy an energy storage device and the corresponding decision on the optimal rating was based on economical parameters. It was shown that this approach may significantly differ from the one based on technical requirements only. Moreover, in this case a stochastic approach to energy storage sizing, which takes into account all the different operating conditions of the storage along the years was adopted. This is considered the most advisable approach to energy storage application and further investigation is encouraged in order to consider additional parameters to refine the storage sizing procedure.

Summary description

The Sea2grid project is developed in the field of Renewable Energy and it is targeted towards the exploitation of sea waves for the production of electricity to be injected into the power grid. To allow the grid connection of Wave Energy Converters it is necessary that the delivered power is conveniently smoothed and satisfies strict Grid Codes requirements. This is a critical point for very intermittent sources as sea waves. The lack of established storage solutions to mitigate this problem is, at present, one of the main bottlenecks restraining Wave Energy from grid integration and consequent commercial exploitability. The core of this project is in the systematic investigation of storage alternatives for both single Wave Energy Converters and Wave Farms (Arrays).

Wave Energy Overview

Compared to other renewable energy sources, marine energy has been only recently investigated and the corresponding energy industry is still relatively immature. However, it has a consistent potential, whose exploitation calls for additional research efforts and custom technology solutions. As can be seen from Figure 1, wide and tidal energy could potentially cover up to 2 times the world energy consumption as it was in 2007 [1]. The contribution from wave energy is much higher than the one expected from tidal energy. A recent study [2] showed that on a 60 m bathymetry the world wave energy potential can be quantified, on average, on 2 TW of available power. Furthermore, wave energy has also several advantages compared to other resources, as its higher constancy and predictability than wind energy and its high wave energy density.

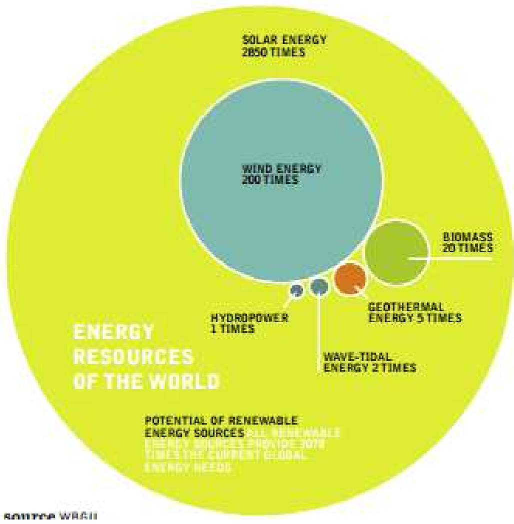


Figure 1 Potential of renewable energy sources [1]

It is worth noting that, according to the roadmap elaborated by the EU-Ocean Energy Association [3], the ocean energy sector in general is expected to experience the same trend of growth that onshore wind has experienced in the last 20 years and that offshore wind is experiencing right now (Figure 2).

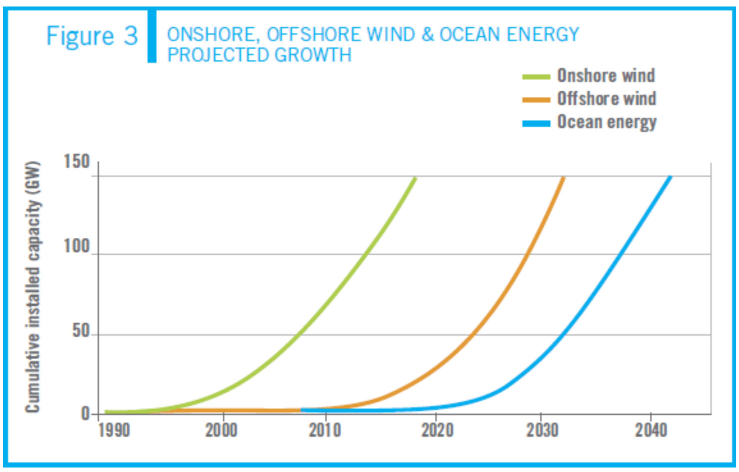


Figure 2 Ocean energy roadmap and trends in wind energy [7]

The target is to reach 3.6 GW of installed power by 2020 and then achieve 188 GW by 2050. This ambitious target can be hit provided that suitable support will be given to the sector. Obviously the most important step is to achieve a higher technological maturity, but there are also non-technical aspects that are of paramount importance. Among them: a favourable legal framework, presence of incentives and easy access to electric infrastructures.

The main problem is that with current technology only a small percentage of the huge energy potential can be exploited. From the 70s, large part of the studies was concentrated on the design of new and diverse devices for Wave Energy Conversion, with a strong focus on their hydrodynamic and mechanical optimization and on survivability requirements. In spite of these differentiated efforts, no leading technology has emerged yet and several different concepts ([4], [5], [6]) are still considered promising and extensively investigated to prove their technical and economic feasibility. Among such different concepts, one of the most promising is that of point absorbers [7], due to their low infrastructural cost, good power performance and easy scalability.

Despite the plurality of wave energy converters, all of them have in common the basic energy conversion train, which is composed of several steps. In the most general case, the first one is the conversion of the energy contained in the waves into the energy of a pressurized fluid (water, hydraulic oil, etc.). Then, through the secondary conversion stage, the energy of the intermediate fluid is turned into mechanical energy via hydraulic motor or a turbine. The last conversion stage is from mechanical energy to electricity through an electrical generator. Presently the so-called «direct drive solutions» are gaining momentum, where the presence of an intermediate fluid is avoided. They consist of two conversion stages, the first one from the waves to mechanical energy and the second one from mechanical energy into electrical energy. The direct driven solution, applied to point absorbers in heave, is the subject of the Sea2grid project and will be analysed in detail in the following sections.

The ultimate, incontrovertible test to determine the real viability of the several devices will be in their grid interconnection. This aspect will be ruled by the regulatory frame in the different countries and it will impact on the requirements for the WECs, significantly conditioning the design of the electric and electronics equipment. Up to now the issues related to grid connection have been often neglected or oversimplified, since very few devices ([5], [6]) - and often in a reduced scale- have reached the stage of grid integration. Moreover, most of them have been connected to the power grid for quite a short time. In all of these cases, customized solutions have been adopted for the grid connection, but a wider and more systematic approach to the problem is needed in order to reach the commercial exploitability of wave energy.

In its most general form a grid connected Wave Energy Converter (WEC) is composed by the following parts, schematically depicted in Figure 3.

(1) The mechanical device directly excited by the waves and that reflects the specific concept to be implemented (In Figure 1 it is represented by a point absorber- PA).
(2) The electric machine (G) that converts the mechanical motion into electricity.
(3) The power electronics equipment (machine drive + grid interface) that is needed in order to suitably control the device and allow its interconnection to the electric grid (In Figure 3 it is represented by the widespread ac/dc/ac topology).

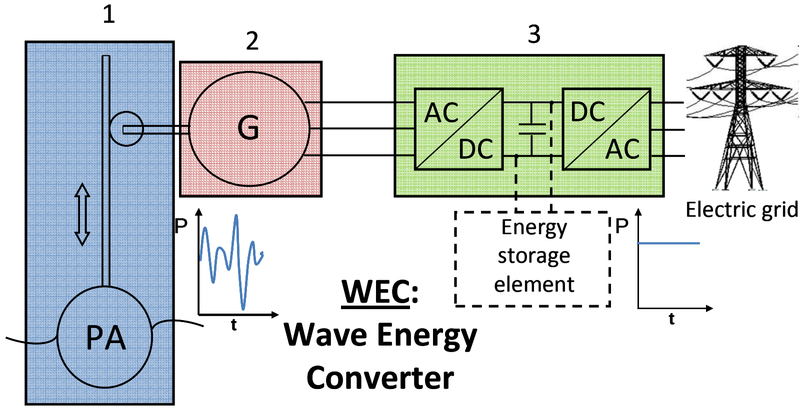


Figure 3 Schematic *sea to grid* approach to grid connection of Wave Energy Converters.

One of the main concerns about wave energy is related to the fact that the power that can be extracted from the sea is highly fluctuating, both on a short term scale (minutes) and on a seasonal time-frame. This is in sharp contrast with the grid connection regulations, requiring the injection of an almost constant and well regulated power even from renewable energy generators. The only way to balance the high variations in the power input and the required smooth power output is to include into the system suitable energy storage elements (dashed part in Figure 1). Their task is to store energy when the power coming from the sea exceeds the grid power demand and to deliver power to the grid when the generation coming from the Wave Energy Converter is not sufficient to satisfy the loads demand.
The vital importance of energy storage is recognized in any project related to active grids, integrating distributed and renewable energy sources. Thus, several studies have been carried out regarding storage element options [7], [3], but very few of them have been specifically focused on Wave Energy. Thus, the specific literature is very poor and fragmented. Since, however, wave energy is an extremely peculiar and demanding application from this standpoint, the lack of an extensive knowledge on energy storage requirements and available options is a real bottleneck preventing this technology to reach the market.
It must be also underlined that previous literature mainly focused on the Oscillating Wave Column (OWC) devices [8]-[11], with few different applications [12]. But in OWC specific case the ratio between peak and average power extracted from the sea, which is the fundamental index for energy storage sizing, is not one of the highest among the different concepts. This means that other concepts (non OWC based) can be even more demanding in terms of requirements for grid connection. Consequently the few storage solutions proposed so far are unsatisfactory.
Furthermore, some of the studies that were previously carried out considering different energy storage options are too closely related to state of advancement of involved technologies (e.g. Supercapacitors and Superconductive Magnetic Energy Storage systems) and need to be updated according to the improvements in a fast growing sector as the power electronics components one.

SEA2GRID Project

The goal of this project is to analyse and propose solutions for the problem of grid connection and energy storage needs of a specific concept of WEC -that of point absorbers- which is one of the most demanding from this standpoint (high peak to average extracted power ratio [13], [14]) The point absorber technology is quite widespread and has gained the interest of many scientists and several national and international projects [14]-[16] in the last decades. Thus an important insight on the feasibility of this technology will be gained from this project and relevant indications can be borrowed also by other concepts. The proposed project is divided into nine workpackages (WPs), with related milestones and deliverables, as summarized in the following:

- WP1: Selection and modelling of the WEC
- WP2: Implementation of complete WEC to grid model
- WP3: Real data collection and grid codes review
- WP4: Analysis of the grid power fluctuation due to single WEC connection
- WP5: Investigation on energy storage requirements and alternatives
- WP6: Implementation and control of an array of WECs
- WP8: Impact of the array on a weak grid and related compensation techniques
- WP9: Final report on the project

It is worth pointing out that the project is intrinsically multi(and inter)-disciplinary, since it requires competences in the field of hydrodynamics, mechanics, electrical machines and drives but especially a good expertise in the fields of power electronics and power systems operation and control. The value of the project is furthermore increased since it promotes collaboration between University and Industrial environment. The ***main results*** expected from the Sea2Grid project are:

- Evaluation of feasibility of Wave Energy Systems including a single device of the most critical type for power quality degradation at the grid connection point. Requirements and solutions in terms of energy storage are a primary outcome from the project.
- Evaluation of feasibility of corresponding Wave Energy Systems of small-to-medium size in term of power quality degradation at the grid connection point. Peculiarities, requirements and solutions in terms of energy storage are expected.
- Quantification of the impact of a weak grid on the Wave Energy System (WES) connection to the power system.
- Individuation of the most suitable compensation techniques in order to ease the plant-grid integration and to cope with the disturbances potentially injected into the power system.

The project requires the application of several different methodologies, according to the specific tasks to be accomplished. The most important are:

- Bibliographical research (WP1, WP3, WP5 and WP6).
- Theoretical analysis (WP1, WP4, WP6 and WP7.
- Simulation based analysis (WP2, WP4, WP5, WP6, WP7, and WP8).
- Collection/analysis and use of real data coming from Bimep site or Tecnalia database (WP3).

The main reasons making Sea2Grid project strategic in favouring a real, global turning point, are

- It is developed in the field of Renewable Energy and specifically in the Wave Energy sector that is highly promising but still far from technological maturity. An immediate, systematic and well-structured research effort is required in order to push forward Wave Energy contribution towards the EU's Renewable Energy target by 2020.
- The issue of the grid connection of WECs and specifically the topic of energy storage (requirements and solutions) is the bottleneck that can prevent Wave Energy from feasible commercial exploitation.
- Very scarce investigations have dealt with this delicate issue so far and therefore further systematic research urges.
- The project is intrinsically international due to the contribution of three different countries (Spain, Italy and Norway). Its impact is even wider, since across Europe and beyond there are several projects based on the point absorber technology and the lesson learned from this concept can be beneficial also for grid connection of other less demanding devices.
- The project has a strong multi and inter-disciplinary nature and it takes advantage of a partnership between Industry and Academia.

Description of the main S&T results/foregrounds

Wave-to-wire modelling of Wave Energy Converters

Development of new wave power technologies and devices cannot depend entirely on investigations with physical prototypes due to the cost and complexity of testing in the real sea. Theoretical modelling and simulation therefore plays a vital role in order to favour more resource efficient and successful development. The Sea2grid project is especially focused on complete, wave-to-wire, modelling of wave energy systems based on point absorbers. The "wave to wire" model of a wave energy converter is aimed at representing in a unified way all the steps of the power conversion train from the resource (waves) to the electric grid (wire).

A schematic representation of the wave-to-wire system considered in the Sea2grid project is shown in Figure 4. It is composed of a prime mover, in this case a point absorber (buoy). Then there is the Power Take-Off (PTO). The PTO includes both the electrical machine for the electro-mechanic conversion and the power electronics used as an electric drive and for the grid connection. Finally, the wave-to-wire model comprises the electric grid/infrastructure to which the Wave Energy Converter (WEC) is connected. The system may include also an energy storage device to smooth out the power coming from the sea before injecting it into the electric grid.

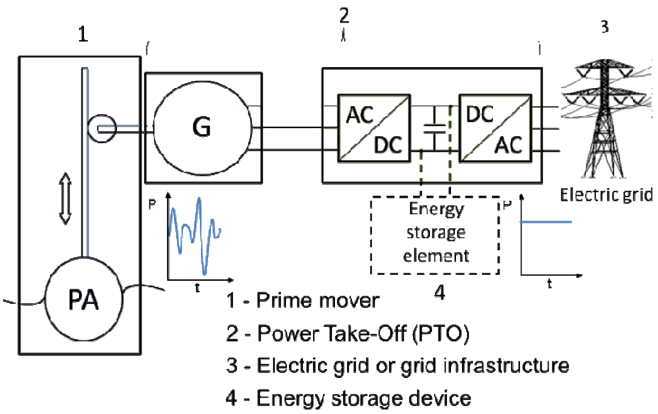


Figure 4 Scheme of principle of the wave-to-wire model of the considered point absorber

Wave Energy Converter to grid modelling

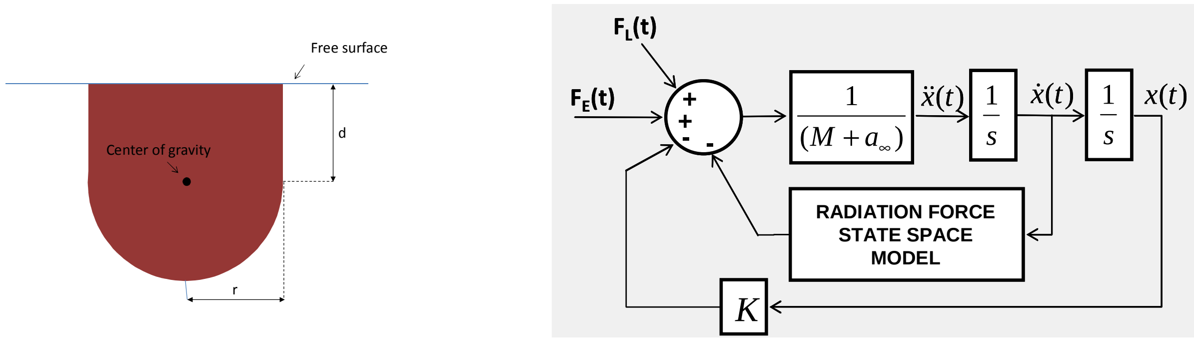
In order to develop a corresponding simulation model of the wave-to-wire WEC system, three main components must be implemented:

- Hydrodynamic model of the WEC
- Electrical machine and related control
- Grid power converter and related control

The ***hydrodynamic WEC model*** is used to represent the considered point absorber, which is composed of a cylindrical part with a hemispherical bottom, as reported in Figure 5 (a). It is assumed to have a radius, *r*=5 m which is equal to the height of the cylinder, *d*=5 m. The mass of the considered buoy is *M* = 670140 Kg and the other hydrodynamic parameters, added mass, *A*, and (added) damping, *B*, were derived by using the software ANSYS-AQWA as a function of the frequency. In order to develop time domain simulations of the system, the hydrodynamic model of the point absorber was represented by using the Cummins equation [8]:

$$(M + a_{\infty})\ddot{x}(t) + \int_{-\infty}^{t} K_{rad}(t-\tau)\dot{x}(\tau)d\tau + \rho\, g\, S\, x(t) + F_L(s,\dot{s},t) = F_E(t) \quad (1)$$

In the above formula, *M* is the point absorber mass and a_{∞} the corresponding added mass at infinite frequency; *x* represents the point absorber position and the dot sign indicates time derivation operation. $K_{rad}(t)$ is the radiation impulse response function, representing a memory effect due to the radiation force originated by the past motion of the body. Furthermore, *g* is the gravity constant, ρ the water density and *S* the surface defined by the intersection between the free surface and the buoy. F_L, represents the external forces applied to the system due, for example, to the PTO or to the moorings, while F_E is the waves excitation force. In the following analysis the force contribution due to the moorings and other is neglected thus F_L is reduced to the PTO force. Formula (1) can be converted into the block-diagram of Figure 5 (b), which is especially suitable for software implementation (e.g. by using Matlab/Simulink).



(a) (b)

Figure 5 (a) Considered point absorber. (b) Block diagram of the hydrodynamic model of the point absorber

Specific analyses to calculate the radiation response function of the point absorber and to derive irregular excitation force profiles to be used as system input were performed during the first WP of the Sea2grid.

In the case of the Sea2grid project, the model of the electrical machine with related control (**Control, AFE & PMS rotating machine model**) developed during WP1 includes the model of a traditional rotating Permanent Magnet Synchronous Machine and of the electric drives required to control the torque of the machine. The rated power of the machine is of 125 kW, with rated speed 430 rpm. At this stage, all the electrical parameters of the machine are derived from an ABB datasheet. The torque control of the machine is realized in the *dq0* frame and it takes into account the reciprocating nature of the point absorber velocity.

The **grid power converter with related control** represents the inverter which is used to connect the system to the local electrical grid. It includes a control loop. As a first step, in WP1 it is assumed that the power is injected into the power system with a unity power factor.

It is worth noting that both the electrical machine converter and the grid converter are fully controlled, thus a back-to-back configuration is obtained in order to guarantee the highest degree of controllability of the system.

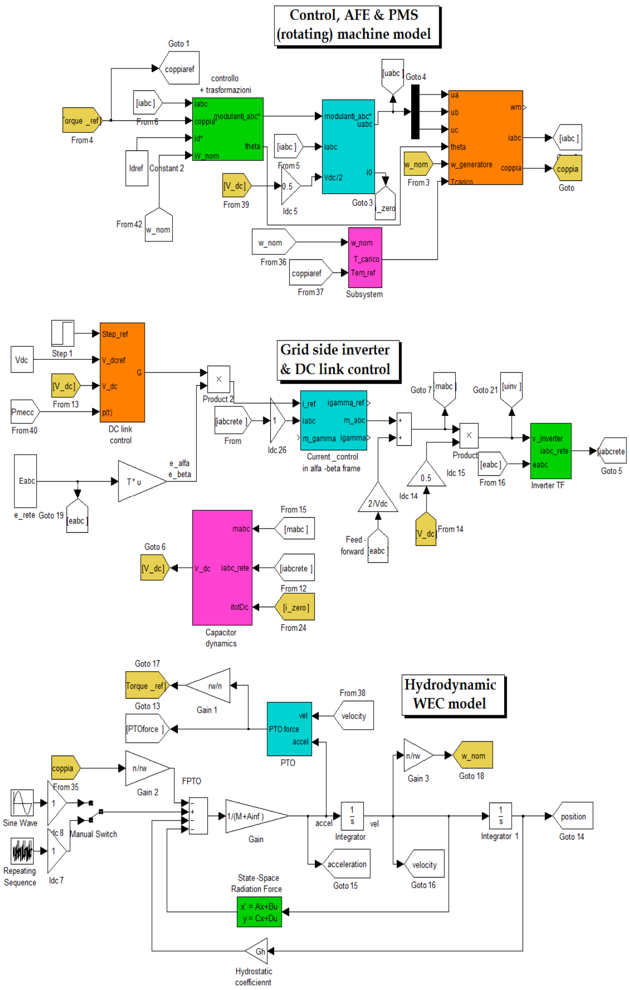


Figure 6 Wave-to-wire Simulink model developed in WP1 [9]

Control of the Wave Energy Converter

Control issues related to the considered system present a twofold nature. On one hand they pertain to the control of the WEC, which is related to the goal of maximizing the power extraction from the waves. On the other hand they refer to the control that must be performed on the grid side in order to mitigate, if needed, the impact of the point absorber connection to the PCC, in terms of voltage drop, reactive consumption etc. When the WEC is assumed to be equipped with a fully controlled bi-directional converter, both the WECs control and the grid side control can be performed independently.

Excitation force representation

In order to represent in the time domain the excitation force to be used as an input of the hydrodynamic model of the WEC it is necessary to know the excitation force coefficients for the selected point absorber.

The excitation force coefficients can be derived by the Haskind equation [10] from the hydrodynamic damping coefficients. The time domain force profile can then be well represented by the superposition of a large number, of sinusoidal components, if the incident wave energy spectrum is known, according to [11].

In the following, the wave energy spectrum defined according to the Bretschneider model [12], is adopted for each selected couple of values: significant wave height (H_s) and peak frequency (f_0).

Relationship with the Sea2grid WPs and deliverables

The first workpackage, WP1, from the Sea2grid project was focused on the implementation of a complete simulation model of the "Wave Energy Converter (WEC) to grid" system, which was realized in Matlab/Simulink software (Figure 6). The goal of the model was allowing real-time simulations of the point absorber, with special focus on the effect of control strategies and PTO design on the power capture. Further details can be found in [9].

Array (of WECs) to grid model

In order to test the effect of the grid interconnection of both a single point absorber and an array of point absorber it is necessary to select a realistic electrical infrastructure, to develop realistic simulation models. The *bimep (Biscay Marine Energy Platform, [17])* is selected as main reference test case in the Sea2grid project.

bimep is an offshore facility for testing and demonstrating small scale WECs, which is being developed South East of the Bay of Biscay, 20 kilometres from Bilbao and which is expected to be fully operative by the end of 2013.

bimep accounts for 4 offshore benches, rated 5MW each and composed of subsea cables of different lengths, between 3 and 6 km [18]. All the electric parameters used to model of the electric infrastructure reflect the present state of development of the *bimep* project.

Short description of the model:

The "array to grid" model of the considered wave farm has been realized using the DIgSILENT Power Factory software [19] and it is composed of several parts. The three most important ones are:

- Schematic of the electric infrastructure;
- Main block model, setting system interconnections;
- Hydrodynamic model of the point absorber.

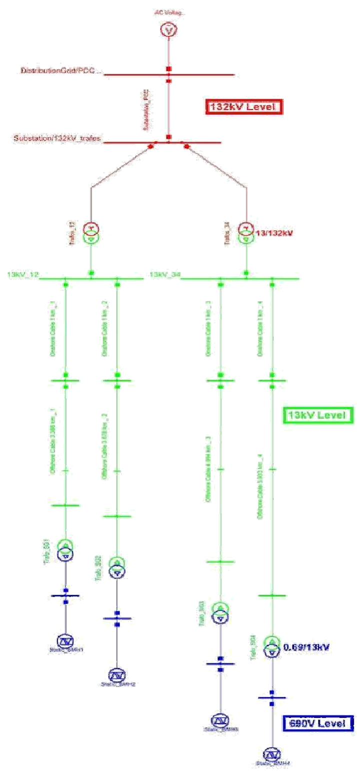


Figure 7 Array-to-grid DIgSILENT model Schematic of the electric infrastructure [9]

The ***schematic of the electric infrastructure*** (Figure 7) is a single-phase equivalent of the electric infrastructure associated to the wave farm. It has been modelled to resemble the *bimep* infrastructure. It includes all the components that are relevant from the electric standpoint, with corresponding characteristics and parameters, i.e. transformers, cables, equivalent of the main electric grid (Point of Common Coupling, PCC), WECs, etc.

The ***main block model*** is used to correctly represent the interactions and interconnections among the different subsystems used to model the electric infrastructure.

The ***hydrodynamic model*** of the point absorber (Hydrodyn ElmHyd) is used to include the Cummins equation (1) into the “array to grid model”, so that the dynamics of the considered point absorbers can be taken into account and a fully integrated closed loop model is obtained. In this case the radiation force is represented by an appropriate transfer function. Furthermore, the hydrodynamic model assumes that the electrical machine perfectly tracks the PTO force reference.

Relevant parameters for the test case of the grid integration of WECs

Once a suitable array to grid model is developed, in order to perform realistic simulations a few additional aspects have been taken into account. One of them is the consideration of the real wave resource at the *bimep* test site, so that the excitation force profile can be created by considering realistic test cases. The second aspect, in the case of grid connection of arrays of point absorbers, is the farm lay-out and the possible interactions among groups of WECs.

Wave energy resource at bimep

In order to quantify the available wave resource at *bimep*, the corresponding scatter diagram (Figure 8) was considered, which was made available by TECNALIA during the course of the project. The scatter diagram quantifies the occurrence of different sea states, based on accurate meteorological models of the location that had been validated using the data measured in the period 2007-2009 by a measuring buoy deployed at the *bimep* site. Consequently, as a reference sea state, the most occurring at bimep has been considered (5.5%), which has: H_s = 1.5 m and T_0=9 s

		altura significante en metros																			
		0,5	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8	8,5	9	>9.25	
Periodo de pico en segundos	3	0,01%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,02%
	4	0,36%	0,17%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,52%
	5	1,19%	0,74%	0,21%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	2,15%
	6	0,76%	1,52%	0,78%	0,22%	0,02%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	3,29%
	7	0,39%	1,06%	0,33%	0,33%	0,10%	0,01%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	2,23%
	8	1,93%	5,50%	2,63%	0,83%	0,44%	0,15%	0,11%	0,01%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	11,62%
	9	1,52%	3,86%	5,50%	1,90%	0,54%	0,21%	0,13%	0,11%	0,01%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	13,78%
	10	1,29%	3,70%	5,21%	3,70%	0,95%	0,33%	0,17%	0,19%	0,06%	0,01%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	15,62%
	11	1,48%	2,93%	3,67%	3,91%	3,59%	1,42%	0,45%	0,35%	0,21%	0,06%	0,02%	0,01%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	18,09%
	12	0,90%	1,32%	2,78%	2,56%	3,24%	2,83%	1,60%	0,43%	0,27%	0,13%	0,05%	0,05%	0,02%	0,00%	0,01%	0,01%	0,00%	0,00%	0,00%	16,18%
	14	0,41%	0,56%	1,29%	1,31%	1,62%	1,68%	1,52%	1,00%	0,51%	0,24%	0,10%	0,10%	0,05%	0,03%	0,01%	0,00%	0,00%	0,00%	0,00%	10,40%
	16	0,29%	0,37%	0,88%	0,51%	0,37%	0,56%	0,57%	0,53%	0,46%	0,40%	0,25%	0,34%	0,15%	0,10%	0,09%	0,04%	0,04%	0,02%	0,01%	5,95%
	18	0,01%	0,03%	0,02%	0,00%	0,00%	0,01%	0,02%	0,01%	0,00%	0,01%	0,00%	0,03%	0,01%	0,01%	0,00%	0,00%	0,00%	0,00%	0,00%	0,15%
	20	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
	> 20	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
		10,54%	21,75%	23,29%	15,28%	10,87%	7,19%	4,57%	2,63%	1,52%	0,85%	0,41%	0,52%	0,22%	0,13%	0,10%	0,05%	0,04%	0,02%	0,01%	1

Figure 8 Scatter diagram of the bimep site

Different lay-out configurations of the wave farm

In order to consider realistic scenarios, the impact of different wave farm lay-outs and smoothing effects has been taken into consideration as a part of the Sea2Grid. This was aimed at quantifying the consequences of possible interactions on the power capture from the array and on the operation of the local power system.

The interference among groups of WECs mostly depends on the distance among them: if they are deployed close to each other, some masking effects of the front rear on the back rear can be detected. This has been quantified in a recent study on the mutual interaction of WECs array [14], which also reports the findings of previous experimental tests. It is also shown, however, that such mutual interaction strongly depends on the wave direction and considered wave energy converters.

For axisymmetric bodies as the here considered point absorbers, interaction effects are reduced, because they are less sensitive to wave direction and destructive and constructive interference tend to balance each other when it comes to the overall (yearly) power capture. However, they can be also exploited to smooth out the power profile, as potentially required by grid codes.

To the extent of electrical analyses the most relevant case is the one where all the WECs connected to the electrical infrastructure are excited by the same excitation force in every instant. From the grid impact standpoint, this represents a worst case scenario, to be accurately analysed. However, in order

to quantify how the spatial displacement of the WECs group can affect the performance of the array, different excitation forces acting on the WECs have been considered. The studies have been carried out under the simplifying assumption that the forces acting on the different groups of WECs can be derived from each other by a simple time-shift. On the other hand, it is considered that all the WECs in the same group are reached by the same excitation force. To compute the appropriate time shift among WECs groups, reference is made to the peak period T_o = 9 s of the considered sea state.
As a first case, no masking effect among the groups of WECs is considered. As an additional case, it has been considered that two of the WECs groups partially mask the other two. As reported in [14] such masking effect can be accounted for by a reduction in the significant wave height between 2% and 14% in the affected area. In the presented analysis a reduction of 10% of the excitation forces reaching WECs group 1 and WECs group 3 has been considered.

Relationship with the Sea2grid WPs and deliverables

The second workpackage from the Sea2grid project was focused on the implementation of a complete simulation model of an "Array of Wave Energy Converters (WECs) to grid" configuration, which was realized using the DIgSILENT Power Factory software. The main goal of the model was allowing real-time simulations of a multi-MW wave farm, with special focus on its impact on the local power system depending on control strategies and wave farm lay-out.

The Spanish Grid Codes

In order to evaluate the impact of the grid integration of a wave farm it is required to refer to a specific test case (and location), so that compliance to the local grid code can be verified. The main reference test case for the *Sea2grid* project is the *bimep* and thus the Spanish Grid code is the relevant one, possibly complemented by the recommendations from the local Distribution System Operator (DSO).
On this respect, a summary of the Spanish regulatory frame can be found in [15], [16] and it takes into account:

- Government regulation: (Government law 1985, OM1985; Law 54/97; Law 07/2007; Royal Decree 1955/2000, Royal Decree 436/2004; Royal Decree 661/2007; Royal Decree 6/2009).
- Regional rules by autonomous regional government
- European Standard (i.e. EN 50160)
- Operating procedures issued by the Transmission System Operator (TSO) and Distribution System Operator (DSO).
- Market rules

From the technical standpoint the current reference point in Spain is the Operating Procedure **P.O. 12.3 "Requisitos de respuesta frente a huecos de tensión de las instalaciones eólicas"** [20]. It sets the requirements to be fulfilled by wind farms to ensure the continuity of supply during voltage dips, in addition to the Royal Decree 436/2004.
At present a new Operating Procedure is under preparation. It is P.O. 12.2 "**Instalaciones conectadas a la red de transporte: requisitos mínimos de diseño, equipamiento, funcionamiento y seguridad y puesta en servicio**" [21] that is applicable to renewable plants (not based on synchronous generators) of more than 10 MW rated power. The P.O.12.2 is more demanding that the current P.O.12.3 and besides establishing the requirements of the system in the presence of any kind of disturbances, it also regulates the performance requirements in steady state.
It is also worth noting that in addition to local grid codes also TSO and DSO recommendations must be taken into account when considering renewable installations. As an example, Iberdrola, the DSO of the Basque Country, which is responsible for the grid at *bimep* PCC, recommends to admit a maximum voltage variation at the PCC equal to ±7%.

Approach to grid interconnection studies

When it comes to the analysis of the impact of a wave energy farm on the local power system, several different analyses can be undertaken. Some of them are classified as steady-state analyses, meaning that they analyse the operation of the installation where the WECs work at constant load. The typical studies in this case are: the evaluation of active and reactive power circulating along the installation as well as the voltage levels at different points. The calculation of losses along the infrastructure is also closely related to the active power analysis. The evaluation of the loading factor of the various components can be also evaluated, which gives an indication on which components work close to their limit. The complementary type of analyses is dynamic analyses. They are extremely useful for those applications working in highly variable load conditions. Thus it is extremely meaningful to evaluate the instantaneous values of active and reactive power and corresponding voltages. Then a crucial point is the behaviour of the system under fault condition. Moreover, basic energy storage considerations can be derived from dynamic analyses as well.

Grid connection of point absorbers to a strong grid

The goal of the following analysis is, at first, to evaluate the power extraction from the considered point absorber when different control strategies are applied. Both passive loading and reactive control will be considered, assuming that the PTO includes a fully controlled power electronics interface. The average and peak power will be quantified and consequently, the peak to average power ratio will be derived, which is an important parameter for the rating of PTO systems in wave energy applications. The reference sea state for the bimep location (Hs = 1.414 m and T0=9 s) will be used for this test.
It is worth noting that the considered reactive control is not the so called complex-conjugate control [22], implying a condition of perfect resonance where control parameters are used to perfectly cancel the contribution of the mass and spring stiffness of the point absorber. This because, although theoretically allowing the maximum power extraction from a point absorber, complex-conjugate control results into very high solicitations for both the mechanical and electrical equipment and thus it is not viable in real applications. However, a reactive component in the point absorber control can be still added, which is much smaller than the one required by the complex-conjugate control. This is aimed at improving the average power extraction while reducing the solicitations on the system, as shown in [22],[23].
As a basic step, steady state analyses have been performed, which assume that the single point absorber connected to the bimep is working under its nominal conditions. Such analysis is performed in two different cases: assuming that the point absorber is equipped with a PTO rated power of 250 kW and 500 kW, respectively. When steady state analysis is performed, the same results are obtained irrespective of the WEC control strategy (passive loading or reactive control) that is applied.

Steady state analysis

Under rated conditions active (positive if generated, negative if consumed) and reactive (inductive is positive, capacitive if negative) power exchange and loading level at different points of the infrastructure can be evaluated. It is assumed that the point absorber is connected to berth 1 (shadowed in the tables), i.e. the closest to the shoreline.
The performances at the PCC are especially meaningful in order to evaluate the impact of the single point absorber interconnection to the electric grid.
For the sake of comparison, also the case of point absorber equipped with an asynchronous machine (rated power 500 kW) directly connected to the grid has been considered. It is worth noting that in this case there is no power electronics interface and no control flexibility can be obtained.

Dynamic analyses

To exemplify the expected power performance of the selected WEC when different control strategies are applied, a case of reactive control is here reported, which assumes a back-to-back configuration for the power converter. Other test-cases can be found in DL.3.1 [24].

Conclusions about the grid connection of a single point absorber to a strong electric grid

From the analysis of the grid connection of a single point absorber to a strong grid it should be noted at first that the connection of a single WEC, having a very small rated power, in the order of few hundred kW, (and even smaller average power production) compared to the rated power of the bimep can lead to an undesired operating condition for the infrastructure. This is because it is necessary to magnetize the infrastructure itself and the resulting very low-load operations cause a high reactive consumption at the PCC. Such condition is basically unsustainable so, when a single WEC is connected to the infrastructure, the magnetization of cables and transformers of the unloaded berths should be avoided.
Another option, when possible, is to use the residual power capability of the WEC to perform a partial reactive compensation within the infrastructure, injecting power into the grid with a power factor lower than one.
The potentially critical operating conditions related to the magnetization of the bimep, depends on the infrastructure itself and should be evaluated case by case, taking into account the power rating of the connected device.
That being stated it can be observed that in all considered cases ***grid codes requirements are satisfied***, since the grid connection of a single point absorber with a rated power of few hundreds kW produces very small voltage and frequency variations at the PCC, also under fault conditions. This is due to the favourable conditions of the selected grid connection point, as reported also in [25].

Grid connection of an array of point absorbers to a strong grid

The goal of the following analysis is, at first, to evaluate the power performance of an array of 40 grid connected point absorbers when different control strategies are applied. Both passive loading control and reactive control will be considered, with reference to the bimep reference sea state (Hs = 1.414 m and T0=9 s). As in the case of a single point absorber, average and peak extracted power will be quantified and consequently, the peak to average power ratio will be derived.
As a basic step, steady state analyses have been performed, which assume that all the point absorbers connected to the bimep are working under their nominal conditions. Such analysis is performed assuming that each point absorber is equipped with a PTO rated power of 500 kW. If not differently specified it is assumed that back-to-back power electronics converters are considered as power electronics interfaces and that they inject power into the grid with a unity power factor.

Steady state analysis

Under rated conditions active (positive if generated) and reactive (inductive is positive, capacitive if negative) power exchange and loading level at different points of the infrastructure can be evaluated. It is assumed that a group of 10 WECs is connected to each of the bimep berths, so that the rated power of bimep is reached. The performances at the point of interconnection with the local power system (PCC) are especially meaningful in order to evaluate the impact of the array of 40 point absorbers on the electric grid.
For the sake of comparison it is worth performing the same steady-state analysis under rated (full load) conditions under the assumption that each point absorber is equipped with a 500 kW asynchronous machine that is directly connected to the local grid.

Dynamic analyses

Dynamic simulations have been performed, with the aim of evaluating the effect of the extreme variability of the wave energy source and of the impact of the different WEC control strategies and lay-outs of the array both on the power capture from the sea and on the grid connection of the wave farm.
As already mentioned, regarding the grid side control, it is assumed that the PTOs of all the point absorbers inject power into the grid with a unity power factor at their point of connection.
Such time domain analyses focus on the performance at the PCC and they allow the determination of the local voltage drop, frequency variations, instantaneous, average and maximum power exchange. The ratio between peak and average power is also calculated.

Conclusions about the grid connection of an array of point absorbers to a strong electric grid

The main results obtained from the analyses on the interconnection of arrays of point absorbers to the bimep infrastructure clearly show that the direct connection of WECs equipped with asynchronous machines should be avoided, due to the high reactive power consumption, which worsens the efficiency of the power transfer. If asynchronous machines are to be used, reactive power should be supplied close to the WECs.

It is worth noting that the WECs are assumed to start their operation at time t=0 s and a certain time is required to the hydrodynamic systems to overcome the initial mechanical transient. Such transients affect differently the WECs depending on the specific profile of the excitation force.

In all the considered cases ***grid codes requirements are widely satisfied***, since the grid connection of the considered 20 MW WECs array produces extremely small voltage and frequency variations at the PCC, also under fault conditions.

It is worth underlining that when the effect of both spatial displacement and masking effects among the groups of WECs are neglected, is for sure the most critical case regarding the impact on the local power system. Thus, this should be in general considered as a worst case scenario for further dynamic analyses.

It is important to note, however, that spatial displacement among the groups of WECs affects the average power absorption in a limited way (reduction of less than 10% for both passive loading and reactive control when masking effect is considered). It is though very important to underline that WECs spatial displacement can reduce the peak to average power ratio of around 60%, thus actually strongly mitigating the impact of the grid connection on the power system due to resource variability.

Relationship with the Sea2grid WPs and deliverables

The third workpackage from the Sea2grid project aimed at quantifying the grid impact of both a single point absorber and an array of point absorbers considering different WEC controls and farm lay-outs. The grid connection point was assumed to be the bimep (Biscay Marine Energy Platform) one. Corresponding results, summarized here, were presented in DL.3.1 and 3.2 and further discussed in ML.1

State of the art of energy storage for wave energy applications

A brief state of the art of Energy storage technologies and their application in wave energy has been carried out. Between others the following has been reviewed:

- Pumped hydroelectric storage (PHS)
- Compressed air energy storage (CAES)
- Flywheel Energy Storage (FES)
- Supercapacitors
- Superconductive Magnetic Energy Storage (SMES)
- Battery energy storage
- Hydrogen Energy Storage (HES)

Trends of energy storage application for point absorber devices

It is worth to briefly consider some current trends in the market of point absorbers, with a specific focus on their impact on energy storage.

While in the first years of development, hydraulic solutions were mostly considered in order to smooth out the electric power to be delivered to the power system, at present all the main manufacturers rely on direct-driven "All-Electric" solutions. This is the choice of OPT Technologies [26], which is probably the buoy producer that is closest to the market (http://www.oceanpowertechnologies.com/about.html). Also Fred Olsen [28], [29] (http://www.fredolsen-renewables.com/) and Resen Waves (http://www.resenwaves.com/default.asp?Action=Menu&Item=82) exclude hydraulic systems. Also for

the SEAREV point absorber the All-Electric solution is preferred, when considering potential industrial applications [30]. The decision of avoiding hydraulic or pneumatic stages is aimed at improving the overall reliability and increasing the efficiency of the system. The direct-driven solution, however, poses major challenges in terms of energy storage, since the output power does not experience the smoothing effect of the hydraulic stage. The preference for all-electric solution also favours the investigation of electric or electro-chemical storage alternatives for wave energy applications.
It is worth noting that a possible approach is that of applying hybrid storage solutions, including more than one storage technology. This is, for example, the case of Fred Olsen [28], coupling supercapacitors and batteries for their Bolt2/Lifesaver WEC. Other hybrid options (potentially including also non-electric storage mechanisms) deserve further investigation.

Energy storage for the grid connection of a multi-MW wave farm to a strong grid

The goal of this section is to focus on power quality issues arising from the grid integration of a 20 MW wave farm on a strong electric grid, to specifically analyse the beneficial effect of a short term energy storage device to ease the grid connection. Based on the results obtained during WP3 of the Sea2grid, it is considered that the interconnection of a single point absorber of rated power of few hundred kW to the bimep has a completely negligible effect on the PCC from the power quality standpoint. Thus the following analyses focus on a multi-MW wave farm of point absorbers connected to the bimep and they assume that the corresponding energy storage system acts at farm level (centralized onshore storage system).

Energy storage model

In the following analysis it is considered that the wave farm can be equipped with a generic onshore energy storage device connected at the PCC. It acts at farm level and it is assumed to have the capability of smoothing the power profile and reducing the variability of the power injected into the electric system without affecting the power capture from the waves. It is modelled as a low-pass filter acting on the instantaneous active power profile extracted from the farm, in a similar way to what was done in [31] for wind energy applications. Three different cases are analysed, ideally corresponding to different storage capability. The considered options lead to a power smoothing on a time scale of 5 s, 25 s and 50 s, respectively [32]. Maximum storage power and energy capacity have been taken into account, where indicated, while no preferred state of charge for the storage system is considered in the following analysis.

Considered test cases

In order to analyse the power performance of the array of point absorbers in various sea conditions, three different sea states have been considered: a low-energy sea state, characterized by significant wave height H_s = 1.3 m and peak period T_{pk} = 13.8 s, a medium-energy sea state, having H_s = 2.4 m and T_{pk} = 11 s and an high-energy sea state having H_s = 5.7 m and T_p = 16.5 s.
Three different 900 s time series have been generated from selected Hs and Tp to represent the required incident wave profiles. The following aspects are here considered in un-faulted conditions, both without and with energy storage systems of different ratings:

- Peak to average power ratio;
- Voltage level fluctuations;
- Flicker level;
- Voltage variation during farm shut down.

Conclusions on the grid integration of a multi-MW wave farm to a strong grid, including storage requirements and limits

The analyses dealing with short term energy storage and its effect when integrated into a 20 MW wave farm connected to *bimep* confirmed the results obtained during WP3. *bimep* is a strong electrical grid and the interconnection of a 20 MW wave farm does not provoke power quality issues that can undermine grid code compliance.

This said, it has been noted that even the smallest storage devices (corresponding to a filtering time constant of 5s) consistently reduces the voltage oscillation and the flicker level. Since however both of these levels were already very small the introduction of a storage devices is not advised [33].

However, for the sake of completion, a preliminary evaluation, which only takes into account power and energy requirements, is performed to define the storage technologies that would be suitable to face power quality issues, if arising. In the considered cases it has been shown that a storage power rating higher than 25% of the installed power capacity is required, with discharge times between 0.002 s and 0.02 s.

For such power and energy ratings lead acid batteries and nickel-cadmium batteries are good candidates and flywheels can also be considered for such application, once proved that they all have a suitable life-cycle.

The effect of non-ideal efficiency and initial state of charge of the storage devices are proved to be relevant, and consequently general conclusions can be drawn only after analysing a large number of cases, both in term of initial state of charge of the storage and in terms of incident wave profile.

Finally it can be said that a profitable coupling between the WEC/WECs farm and the energy storage system largely depends on a smart selection of the reference set point for the instantaneous power to be injected into the local power system. This, in turns, depends on the requirements of Transmission or Distribution System Operators. As seen, having a constant power delivery from wave energy converters would be impossible with present storage technologies and ratings, but different choices can be made. As a consequence, it is also fundamental to optimize the storage control strategy in order to comply with local grid codes, improve the performances of the storage device itself and, eventually, to act profitably on the energy market. This is recognized as a strategic research area, which can affect the profitability of wave energy farms. This of course partly relies on the availability of accurate wave forecasting that can help planning the production hours or even days ahead.

Relationship with the Sea2grid WPs and deliverables

The fourth workpackage from the Sea2grid project aimed at quantify the energy storage requirements and alternatives for the grid connection of both a single WEC and a wave farm to a strong electric grid, after an introductory review of energy storage technologies for wave energy application. The grid connection point is assumed to be the bimep (Biscay Marine Energy Platform) one.

Corresponding results, summarized here, were presented in DL.4 and further discussed in ML.2

Energy storage for the grid connection of a single point absorber to a weak grid

Electric infrastructure

In order to test the effects of the grid connection of a single point absorber to a weak grid the properties of the electric infrastructure must be re-defined. Specifically, in the present case it has been decided to keep the lay-out and main characteristics as in the *bimep* test case, and to only reduce the short circuit power (Scc) at the PCC in order to achieve conditions corresponding to a weak electrical grid.

With the aim of classifying an electric network as weak its short circuit ratio (SCR) should be lower than 5 [34]. Such condition is achieved by modifying the grid impedance, and consequently the short circuit power, in the *bimep* model.

In the present analysis two different conditions are considered.

- CASE A: it has been considered bimep to be the only user to be connected at the considered point of common coupling. Thus, making reference to the rated power of the farm (20 MW), a grid impedance corresponding to about 300Ω has been selected, to achieve a Scc< 100 MVA and thus a SCR<5.

- CASE B: it has been considered a more realistic solution. In this case bimep is not the only user connected to the PCC, but another load, absorbing a constant current of 500 A, is connected at the PCC as well. Due to the current absorbed by the additional load (and thus to the total load connected to the considered PCC) a much smaller grid impedance (Zcc = 44 Ω) is now sufficient to achieve the “weak grid condition” [35].

Steady state analysis

As a first test a steady state analysis under the specified conditions has been run, which corresponds to the limit case where the WEC injects a constant power P=500 W.

Dynamic analysis

The analysis of the interconnection of a single point absorber to a weak grid has been performed considering the same sea states as in the case of wave farm connection to *bimep*, i.e. a low-energy sea state, characterized by significant wave height H_s = 1.5 m and peak period T_{pk} = 9 s, a medium-energy sea state, having H_s = 2.4 m and T_{pk} = 11 s and an high-energy sea state having H_s = 5.7 m and T_p = 16.5 s. Correspondingly, the same excitation force profiles have been used for this analysis.
The goal of the study is to analyse the effect of the grid connection of a single WEC to a weak electric grid in terms of:

- Average extracted power and peak to average power ratio;
- Reactive power exchange at the PCC;
- Voltage level variations;
- Flicker level;

The analyses are carried out under un-faulted conditions both without and with energy storage systems of different ratings. Based on the considerations presented from the steady state analyses, dynamic simulations have been carried out by de-energizing the unused berths in bimep. Finally, also the transient consequent to WEC sudden shutdown is evaluated.

Conclusions on the grid interconnection of a single point absorber to a weak grid

The analyses on the grid interconnection of a single point absorber confirmed some of the observations made in previous analyses and added new considerations specifically related to the “weak grid scenario”.
At first it can be recalled, as explained also in DL.4 [36], that the connection of a single point absorber to an electric infrastructure designed for operating at a much higher power rating can bring the system to work in an onerous condition, especially for the reactive power consumption and corresponding losses. To avoid this it is recommended to de-energize the unused berths whenever possible.
Then it has been shown how the presence of a weak grid scenario does not only depend on the nominal voltage level at the connection point and on the installed power of the point absorber (or wave farm). It is also fundamental to know if the point absorber/farm is the only load connected at the PCC. In fact, if other loads are connected at the same point, the WEC generally works in worse operating conditions (i.e. lower voltage) and thus more stringent limitations must be respected to comply with local grid codes. It should be noticed, however, that this depends mostly on external events that cannot be directly controlled. Thus, on this respect, the indications of the DSO (Distributed System Operator) or TSO (Transmission System Operator) are fundamental to guarantee the stable operation of the local system even at the maximum installed power.
In general, the analyses performed on the single grid-connected point absorber confirmed the findings of DL.3 and DL.4 and especially the facts that:

- WEC control is crucial to increase the wave power extraction and potentially to limit the peak power (and peak to average power ratio), especially in high energetic sea states.
- It is also fundamental to tune control parameters according to the incoming sea state, in order to maximize the power performance.

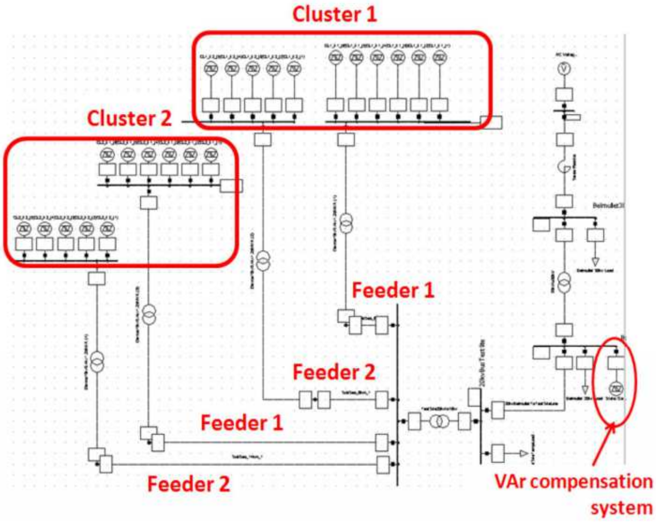
It has also been verified that voltage oscillation produced by the WEC connection are generally very limited. However, grid limit can be approached due to the concurrent action of other loads.
Similarly, flicker level produced by the point absorber is completely negligible, but external load action could deteriorate also this indicator in case of shared PCC.
As a consequence of this it can be seen that the grid integration of a single point absorber of few hundred kW of rated power is not a concern *per se*, however it can become critical in extremely demanding grid scenarios (similar to case B).
Although not necessary for grid compliance in the considered scenarios, the impact of short-term energy storage on the power quality at the PCC has been quantified. Considerations about the importance of setting a proper reference for the storage device are still valid.
Performed analyses showed that power fluctuation and voltage fluctuation can be reduced of 22 % in the case of a 5s energy storage and of 65% in the case of 50 s energy storage. In terms of storage ratings, this requires a power rating equivalent to about 100% of the buoy rating and energy rating in the range 0.6-4.3 kWh. As already mentioned, however, such estimation are strongly dependent on the power profile to be followed. It is worth noticing that in the presented case it is assumed that at instant t=0 the whole wave energy is to be stored in the storage device, thus potentially representing a critical case for the storage itself. Thus, different reference choices could reduce the power rating of the storage device.
Based on these preliminary evaluations, it is shown that supercapacitors, flywheels and possibly Ni-MH batteries are the most appropriate storage technologies for short term energy storage in single WEC applications.
Finally, it is worth highlighting that here presented analyses considered the energy storage device to be deployed onshore (centralized short term storage). This is probably not the most natural solution for small rating applications, however in principle it can bring an advantage in the fact that an electric storage using an inverter for grid connection could potentially perform local reactive power compensation. This requires the power electronics interface to be suitably sized and can be extremely useful in case of high reactive power consumptions from the point absorber/farm and stringent limits on the power factor at the PCC.

Energy storage for the grid connection of an array of point absorbers to a weak grid

The goal of the following analyses is to focus on the power quality issues arising from the grid integration of a 20 MW wave farm on a weak electric grid and to analyse the beneficial effect of a short term energy storage device to ease the grid connection. The following analyses focus on the realistic weak-grid test-case offered by the Irish AMETS infrastructure located at Belmullet. Usefulness of a centralized energy storage system acting at farm level is proved.

AMETS electric infrastructure

The considered test case is that of the Atlantic Marine Energy Test Site (*AMETS,* Figure 9) of the Republic of Ireland and corresponding data are available thanks to the collaboration with the Hydraulic and Maritime Research Centre of The University College Cork [18].
The AMETS test site is located off the north-west coast of Ireland. It is still under development and it is envisaged that this site will be used by developers for the final stages of device testing prior to commercial deployment. The conceptual wave farm consists of two clusters each including up to 11 generators. Two clusters are connected to the shore by two ac subsea cables each, one being 6.5 km long, the other being 16 km long. Each cluster consists of two radial feeders to which wave energy converters are connected. Each



feeder cable is connected to an offshore 0.4 kV/10 kV transformer.
AMETS is also equipped with an on-shore VAr compensation system, which is designed to maintain the power factor at the PCC between 0.92 and 0.95 lagging as specified by the network code [37] of the distribution system operator (DSO), ESB. Due to the weak grid condition, the Irish DSO also imposes lower flicker limits than the IEC 61000-4-15, requiring Pst< 0.35. It is also worth recalling that according to the European Standard EN 50160 [38], it is required that for connection at medium voltage level, rapid voltage variations are smaller than 4%. Common practice [39], [40] is to limit rapid voltage variation to 3%.

Figure 9 AMETS grid model

Considered test cases

The following analysis is structured so that it is perfectly comparable with the corresponding analysis on the grid integration of a 20 MW wave farm to a strong electric grid (*bimep* case). Thus, the same sea states and excitations profiles, (corresponding to a low-energy sea state, characterized by significant wave height H_s = 1.3 m and peak period T_{pk} = 13.8 s, a medium-energy sea state, having H_s = 2.4 m and T_{pk} = 11 s and a high-energy sea state having H_s = 5.7 m and T_p = 16.5 s) have been used.
The following aspects are here considered in unfaulted conditions, both without and with energy storage systems of different ratings:

- Peak to average power ratio;
- Voltage level fluctuations;
- Flicker level;
- Voltage variation during farm shut down.

Relationship with the Sea2grid WPs and deliverables

The fifth workpackage from the Sea2grid project dealt with the effect the inter-connection of both a single point absorber and a multi-MW wave farm to a weak grid. It focused on power quality issues and short term energy storage requirements. It refers to the real test case offered by the Atlantic Marine Energy Test Site (AMETS). AMETS is located in the north-west coast of Ireland and is actually a weak grid. The study is performed in collaboration with HRMC-University College Cork and is dual to the bimep case presented for strong grids. Corresponding results, summarized here, were presented in DL.5.1 and 5.2 and further discussed in ML.3 and ML.4

Conclusions on the grid integration of a multi-MW wave farm to a weak grid, including storage requirements and limits

The analyses dealing with short term energy storage and its effect when integrated into a 20 MW wave farm connected to *AMETS* showed that coping with such a weak electric networks poses relevant challenges, especially in high energy sea states. Due to the extreme variability of the primary resource severe voltage drops are experienced, which lead to violate the limits set by the Standard EN 50160.
This requires the introduction of suitable energy storage provisions. It has been shown that the smallest storage device (corresponding to a filtering time constant of 5s) can be not sufficient to reduce the voltage oscillations (rapid changes) below the allowed limit. Thus, a larger energy storage device should be included (corresponding to a filtering time constant of 25s or 50s).
It is also worth noting that, even if the installed power of the wave farm is the same as in the *bimep* test case reported in DL.4, in this case the actual power that can be collected at the PCC is significantly lower. This is because, due to the lower voltage level at the PCC, higher currents circulate in the electric infrastructure and consequently higher losses are experienced.
The preliminary sizing of the energy storage device showed that an ESS power rating of about 10 MW is required for all the three considered cases (corresponding to filtering time constants of 5s, 25s, and 50s). On the other hand, the energy rating increases with the time constant and varies in the range 20 - 140 kWh. As expected, such values basically confirm the results of corresponding analyses performed in

WP4 in the case of strong grid. In this case, however, a reduced sizing of the EES is not advisable due to the need of complying with international standards.
Once more it should be underlined how the sizing of the storage system storage system largely depends on wise selection of the reference set point for the instantaneous power to be injected into the local power system.
In case of non-ideal devices having limited power and energy ratings, non-unity efficiency and finite initial state of charge, the quality of reference following appears to be dependent on the initial energy states and improves with the increase of the energy rating.
Based on power and energy rating only, lead acid batteries, flywheels and potentially nickel-cadmium batteries can be considered for such application.
Before performing final technology selection, it is however mandatory to consider other factors as life-cycle of each technology.

Energy storage for energy management

In the following part two case studies including the application of energy storage acting on a long term time scale (hours) are presented. Both of them represent scenarios that are considered especially relevant for the development of the wave energy sector:

- The first one deals with an integrated solution, coupling a wave energy array of point absorbers with a wind turbine, to create a hybrid ocean energy farm to be deployed offshore.
- The second one deals with the application of wave energy arrays and, if convenient, of energy storage systems, in the isolated power system of a small island.

Analysis of the impact of (long-term) energy storage on a combined wind and wave energy farm

The combined installation of wind and wave energy converters is being proposed more and more often [41], [42] as a solution to exploit the potential complementarity between these two natural resources and to share the costs of their offshore infrastructures. Up to now, however, very few contributions [43], [44] have actually dealt with the complementarities of the wind/wave resource and with the expected performances of corresponding combined energy farms. Other studies [45] have been mainly focused on the required sizing of the wave array in order to reach a balance between wind and wave power extraction.
In the following analysis the attention is focused on the effects of macro-meteorological fluctuations, i.e. large-scale weather patterns acting on a time scale of several hours, on the power output of a wind/wave energy farm. Starting from real meteorological data, the expected power performance of a 1.5 MW wind turbine (WT) is compared to that of a system composed of the same WT combined with an array including an increasing number of WECs for an additional maximum power of 1.5 MW. Following, the introduction of an energy storage element in the farm is also considered and the benefits in the mitigation of the output power variability are discussed, with reference to different ratings and efficiencies of the storage device itself.

Considered test case

The system under investigation is schematically represented in Figure 10. It is a combined offshore wind/wave energy farm composed of a 1.5 MW wind turbine and of an array of WECs deployed at the same location. In the second part of the paper the wind/wave farm is assumed to be also equipped with an onshore energy storage system.

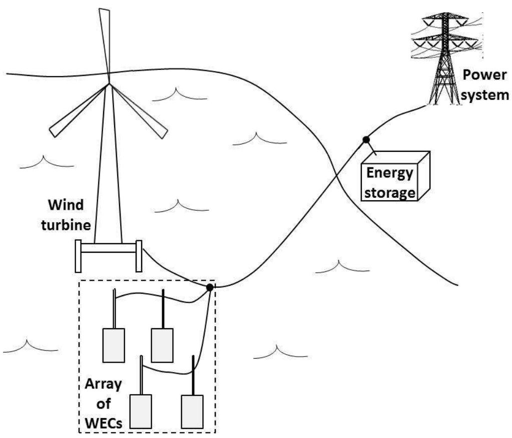


Figure 10. Schematic, not to scale, representation of the combined wind/wave energy farm equipped with a storage device.

Input meteorological data

In order to evaluate the potential of a combined wind/wave energy farm, wind and wave data measured at the same time and at the same location are required. A time resolution t=1 hour is considered sufficient to evaluate the effect of macro-meteorological fluctuations [43], [46]. The one-year data measured in 2010 by the buoys owned and maintained by National Data Buoy Centre [47] at three different locations of both the Atlantic and the Pacific Ocean are considered: site 1 corresponds to the buoy deployed in the North Atlantic offshore the Dominican Republic (Station 41049, 27°30'0" N 63°0'0" W); site 2 corresponds to the buoy deployed South Southwest of Hilo, in the Hawaii Islands (Station 51002,17°5'39" N 157°48'27" W) and site 3 corresponds to the buoy deployed at Half Moon Bay in California(Station 46012, 37°21'45" N 122°52'52" W).

The first step of the analysis implies evaluating the available raw power associated to the wind and wave resource at the selected sites. In the case of wind the available resource is calculated from the wind speed as power per unit area, *Praw_wind*, according to:

$$P_{raw\_wind} = \frac{1}{2}\rho_{wi} v^3 \quad (8)$$

where ρ_{wi} is the air density, assumed to be 1.225 kg/m3.

In the case of wave energy, the power per unit of crest width, *Praw_wave*, for irregular sea waves and under the assumption of deep water, is evaluated by [10]

$$P_{raw\_wave} = \frac{\rho_{wa} g^2 H_s^2 T_e}{64\,\pi} \quad (9)$$

where ρ_{wa} is the water density, assumed to be 1025 kg/m3, and *g* is the gravity acceleration.

Complete model of the system has been developed including following subsystems:

- Model of the wind turbine
- Model of the wave energy converter
- Model of the energy storage system

Evaluation of complementarity of wind and wave raw resources

In order to evaluate the potential complementarity between the wind and wave resource, their contemporary availability at the same location has be evaluated. This can be done by calculating the cross-correlation of the raw power signals, at time τ = 0 s, and the *STD*, that indicates the (normalized) standard deviation of the corresponding quantity. The value of the cross-correlation has been calculated for the three selected locations, both on a yearly basis and for each quarter of the year, to better highlight the seasonal variability of the resources.

Evaluation of complementarity of wind and wave energy converters power production

As a following step, the expected power performance of the WT and WEC-array has been evaluated. At first the extracted powers from the WT and single WEC have been evaluated separately. Then a combined farm composed of one WT combined with a single point absorber and with an array of two, three, and four point absorbers has been considered. No smoothing effect due to the interactions of the point absorbers in the array is here taken into account, both because of the small size of the WEC array and because the constructive and destructive interference occurring at different wave frequencies tend to compensate each other when added on a yearly wave spectrum [48], [49]. A maximum power limitation of 1500 kW has been assumed both for the WT and the overall WEC array.

The power performance of the farm along the entire year has been evaluated in terms of average and maximum power production, and their corresponding ratio. The standard deviation has been selected as an indicator of the output power variability in the considered configurations and it has been calculated adapting (9). The application of a power saturation, whose level is here kept constant for the WEC array irrespective of the number of point absorbers, can help reducing the peak-to-average power ratio and improving their efficiency [50].

To better evaluate if point absorbers can well complement a WT, it is also relevant to analyse the potential impact of their control on the overall power extraction. At first a single WEC having fixed response characteristics, meaning that its control is kept constant along the year, was considered. Different options for the tuning of the WEC have been analysed. This is obtained by changing the central frequency f_c of the PTF in the range [0.05-0.15] Hz, assuming its response to be optimized for different reference sea states.

In the case of fixed control a maximum WEC yearly efficiency of 23% compared to the available raw power can be obtained at site 3 for f_c=0.09 Hz. However it is shown how such efficiency is more than halved if control is not properly set. It is also worth noting that an hourly tuning of the WEC control based on the present sea state increases the overall WEC efficiency up to 25 %, corresponding to an average yearly extracted power of 170 kW from the considered WEC.

Effect of the energy storage

In the second part of this analysis a preliminary evaluation of the energy storage effect in mitigating the output power variability is performed. It is here assumed that the desired power output, of the farm corresponds to the one resulting from the application of a moving-average filter acting on the power profile produced by the farm when no energy storage is included, similarly to the approaches followed in [46], [51], [52].

The last part of the analysis verifies how an energy storage device of specified power capacity, energy capacity and efficiency actually performs when the desired power reference, is the one corresponding to *T*=12 hours. Several different storage power capacities in the range 500-3000 kW have been considered. This takes into account that for wind energy applications, storage power rating between 25 % and 100 % of the plant rated power are suitable for services requiring a response time of several hours (as production levelling) [27]. The corresponding energy capacity range has been selected in this case to ensure a time response of 24 hours for the smallest power capacity.

It can be clearly seen that for the considered application and energy storage capacities, power ratings higher than 1 MW would bring no additional advantages. It can be also noted how the reduced efficiency worsens the tracking of the desired profile up to 5% for the highest energy capacities. In this case the variability of the power output from the wind/wave farm is *STD* = 0.684, meaning that the storage system further reduces by 7% the output variability compared to the case of the wind/wave farm only.

The same storage system, coupled with the WT, only reduces the output power variation from *STD* = 0.9607 to 0.8514, which shows the usefulness of the combined installation to smooth the output power production. It is also worth noting that in the case of WT only, such 11 % of variability reduction is in very good agreement with the results of [46], foreseeing that a 10 % reduction in the yearly fluctuation can be achieved with 2-3 MWh storage capacity per MW of wind power. If an efficiency of 80 % is considered for the energy storage, the variability reduction in the case of WT only decreases by 6.85 %. It has been verified, however, that such variation of the output power can be reduced up to 4 more times with the same non-ideal storage system if a 4 WECs array is deployed in the farm. This result is due to both the complementarity of the wind and wave resource and to a well-tuned control strategy of the WECs, but it is achieved at the expense of an increased installed power capacity in the combined farm.

Relationship with the Sea2grid WPs and deliverables

The fourth and fifth workpackages from the Sea2grid project were focused on energy storage applications to wave energy. As a subtask, they investigated also the effect of energy storage acting on a long-term time scale in order to ease the grid connection of a multi-MW wave farm. Analysis similar to those presented here, but limited to the wave energy case (without wind) were presented in DL.4 and further discussed in ML.2.

Conclusions on wind and wave energy farm potential and corresponding storage application

The goal of this analysis was to provide a preliminary evaluation of the reduction in the variability of the power output from a combined wind/wave farm compared to the standard case of a wind turbine only. The output power performance resulting from the connection of energy storage systems of different ratings is also analysed.

Based on real wind and wave measurements, the analysis considers the impact of macro-meteorological fluctuations affecting the power generation of a combined farm on a time scale of several hours. At first it has been shown how wind and wave resources can show a very good complementarity, which is however highly site-dependent. Thus, specific preliminary studies are required to identify suitable sites for the deployment of a combined wind-wave energy farm. In the considered test case, coupling a 1.5 MW wind turbine to a 4 WEC array of comparable peak power, a reduction of more than 20 % of the output power variability (and the elimination of hours at zero output power) is obtained compared to the case of the WT only. Following, the importance of point absorber control to improve the WEC array performance is shown and an adaptive tuning of central frequency, f_c, based on the actual sea conditions is encouraged.

The study of the effect of storage on the combined farm shows that a storage system with energy capacity of 3MWh could further reduce the power output variability by 7 % (for ideal efficiency), when following a power reference smoothed out along 12 hours. It is however important to underline that this is a preliminary analysis and that the selection of a specific storage technology for this application is out of the scope of this study. More accurate evaluations will be carried out for this purpose by introducing detailed models of the storage system. It is also expected that improved performance could be obtained if a smart control strategy, including adapting the reference to the resource availability, is applied to the same energy storage system.

Wave farm integration and energy storage deployment in an isolated community

Small and remote islands represent an ideal framework for wave energy exploitation, due both to resource availability and to the high cost of electricity that mostly relies on diesel generation. Energy storage can be the enabling technology to match the intermittent power generation from waves to the energy needs of the local community. In the following study real data from La Palma, in the Canary Islands, are used as a basis for the considered test case. As a first step the study quantifies the expected power production from WEC arrays, based on data from the *Lifesaver* point absorber developed by Fred Olsen. Then, a stochastic optimization approach is applied to evaluate the convenience of energy storage introduction for reducing the final cost of energy and to define the corresponding optimal rating of the storage device.

Considered test case

The present analysis focuses on the real test case offered by La Palma, the most north-westerly of the Canary Islands, located offshore the coast of Morocco (Figure 11). Local electricity demand oscillated between 9 and 43 MW in 2012 and it was mostly covered by diesel generation, with a small contribution from wind energy.

Figure 11 The La Palma Island, in the Canary Island Archipelago

Canary Islands have a significant wave energy availability, the average power per width unit being around 25-30 kW/m, but with the advantage of availability intervals spread all along the year [53]. This analysis considers the potential for a combined wave/diesel system to meet the local energy demand. The isolated system under investigation is composed of a diesel plant, which supplies most of the electricity and is in charge of the voltage and frequency control in the local weak grid. In the considered test case it is assumed that a wave farm composed of several WEC arrays contributes to the local power generation. The local electricity consumption can be generically represented by a set of electric loads and an additional dump load is required to balance energy production and consumption whenever an excess of generation occurs.

Input Meteorological Data

In order to estimate the expected power production from the wave farm, wave data at the considered location are required in form of time series. Such data were provided by "Puerto del Estado" [54] for the La Palma site (exact location 18.00 W, 29.00 N), corresponding to the WANA point n. 1008016. Among available data the relevant quantities for the following analysis are: significant wave height H_s, average period of zero up-crossing, and wave direction φ, which were provided with a time resolution of 3 hours. Data of the year 2012 were considered for the present study, to derive the expected wave power production, as explained in detail in the following. To match the per-hour resolution of the analysis, the meteorological data were up-sampled by spline interpolation.

Input Electric Data

Electric data about real electricity generation in La Palma are made available online with an hourly time resolution by "Red Eléctrica de España" [55]. Data for the year 2012 have been used for the present investigation. To estimate the electricity consumption it has been assumed that electricity generation exactly matches electricity consumptions (thus excluding electric self-production). Such hypothesis has been corroborated with comparison to real data about electricity consumption of the same island [56], which however, where not available for the entire year 2012. Models both for the diesel power generation and the wave power generation have been developed.

Regarding the diesel generator, in this analysis it is considered that the rated capacity of the diesel generation plant equals the yearly peak load and that the diesel generator is always switched on and operates according to the minimum load constraint. Such operation strategy of the diesel generator requires a dump load to dissipate the power excess, whenever power production exceeds power consumption.

As far as the power production from the waves is concerned, this production is evaluated based on the performance of the point absorber WEC *Lifesaver*, developed by Fred Olsen [57] and the corresponding modelling has been developed by them. *Lifesaver* is a toroid shape WEC equipped with five individual all-electric Power Take-Off (PTO) units. The PTOs are tightly moored to the sea floor by a winch and drum system, which directly ties surface movements to the generator through a custom designed transmission system. The generator is controlled by a full-scale converter, which allows for direct torque control at various speeds. An advanced control algorithm that is optimized for maximized power extraction is implemented, but results in high fluctuations and low power quality on the output. The array consists of 5-10 devices so that a full wavelength is covered. A complete wave farm will consist of multiple arrays to meet the demand for the given location. In this study, the farm is scaled to optimize the balance between production and consumption. The detailed simulation model developed by Fred Olsen to simulate the performance and output power from the WEC has been implemented.

Wave energy capability to match electric demand

In order to quantify the contribution of wave energy to the electricity balance of the La Palma Island, few metrics must be defined. At first the wave power penetration, i.e. the level of penetration of the power generated by the wave farm over the maximum power consumption, is defined. Once defined the considered power load from real data, the wave power penetration depends on the number of arrays used for wave power production and is then constant for the considered wave farm.

To analyse, however the time evolution of generation and consumption, and thus the wave energy contribution on a daily basis, it is worth introducing two additional metrics. The daily energy penetration is the ratio between the daily amount of energy produced by the wave farm over the corresponding local energy consumption.

The cross-correlation, between the generated power from the farm and the corresponding local power consumption depends on the time evolution of one power profile compared to the other. Cross-correlation varies between -1 and 1, and it is desirable for it to be as high as possible, to have a good matching between the power produced by the wave farm and the contemporary power consumption.

Daily energy penetration and the power cross correlation have been calculated from the available data. The average value of daily power cross-correlation in 2012 for the La Palma location was -0.023, which is indeed very low.

Methodology for energy storage sizing (ESS)

Applying a stochastic optimization to the ESS sizing for a wave/diesel application is similar to the approach presented in [58] for the wind case and it is here recalled for the sake of completeness. After a data pre-processing, storage sizing procedure has been carried out.

The stochastic approach to energy storage sizing is based on the minimization of the cost of energy. It provides the optimal values for the energy rating and power rating of the ESS based on the daily generation and consumption power profiles of the scenarios, weighted with their occurrence probability.

This requires at first, to set a financing model for the ESS, which takes into account the fixed energy costs and fixed power cost associated to the acquisition of the storage device itself.

Amortization of the initial investment can be turn into additional daily costs and. The optimization process is subject to a series of constraints.

- Power balance.
- Diesel operation limit.
- Dumping load constraint.

Additional constraints directly derive from the mode of operation of the ESS:

- ESS power rating

- ESS system operation
- ESS energy rating

Relationship with the Sea2grid WPs and deliverables

The fifth workpackage from the Sea2grid project were focused on energy storage applications to wave energy in weak grids. Isolated communities are a typical example of very weak grid. As a subtask of WP5, it was investigated also the effect of energy storage acting on a long-term time scale in order to match energy production and consumption. Presented analyses are contained in DL.5.2 and further discussed in ML.4.

Conclusions on wave farm integration and energy storage deployment in an isolated community

The analyses dealing with the application of <u>long term energy storage</u> to a multi-MW wave farm connected to an isolated (very weak) power system showed that despite the very low correlation between the wave energy and the electricity consumption in the specific test-case:

- Energy storage becomes more and more convenient with the increase of the wave power penetration level in the local power balance.
- The less flexible the operation strategy of the main diesel generators is, the more convenient the ESS deployment becomes.
- For the considered reference case, the introduction of the optimally sized ESS could lead to a 0.32% reduction on the cost of served energy. Such percentage can increase up to 1.1% if generation costs (from both diesel and wave) increase by 70%, while storage costs are kept constant.

Unlikely in previous analyses contained in this document, in this case the energy storage sizing has been performed on a stochastic basis. It is worth noting, however, that specific results are dependent on the physical and economic parameters used for the analysis. Moreover, the probability of occurrence of each scenario has been calculated based on data from a single year, while an extended database would be desirable to increase the reliability of the analysis. Finally, the validity of the results is based on the ambitious assumption that wave energy cost equals the cost of offshore wind and on minimum, although reasonable, costs for energy storage.

Based on those hypotheses, a preliminary evaluation of the suitable energy storage alternatives for the considered application has been performed, based both on cost and on achievable power and energy limits of each technology. Feasible ESS could be based on Lead-Acid batteries, PS batteries or CAES systems, with the optimal rating of the ESS for the considered test case varying approximately in the range 5-15 MW and 25-65 MWh. Such ESS technology selection is however to be considered as purely indicative, since the ESS efficiency has been kept constant irrespective of the specific technology and the actual life-cycle of each of them has been here neglected. Also in this case, refined analyses based on the procedure presented above and taking into account, among others, all the above mentioned aspects could be performed for the final selection of the appropriate ESS technology and rating.

<u>Main conclusions: ML.5 Milestone n. 5</u>

ML.5 Milestone n.5: Synthesis of the main conclusions

The 2-year research activities carried out under the Sea2grid project lead to a series of relevant conclusions about the approach, results, and still open issues in the wave energy sector.

At first, the research activities showed the paramount importance of keeping a <u>multi-disciplinary perspective</u> when dealing with wave energy conversion systems (WECs). To reach a deep understanding of the operation and performance of a WEC an insight into different field of investigation is required: from hydrodynamics, for studying the interaction between the waves and the prime mover, to

mechanics for the construction and survivability of the prime mover; from electrical machines and power electronics which are the basis for the PTO study to the field of power systems, to deal with the grid connection of a WEC device. To correctly deal with a wave energy project, and correspondingly to simulate it by a “wave-to-wire model” it is fundamental to identify the main characteristics of all these subsystems and especially their mutual interactions. It has been also underlined that it is important to clearly define the purpose of any specific analysis, to consequently identify the level of detail needed in the corresponding simulation model. This is relevant since phenomena occurring in different time scale are involved in the wave energy conversion (from the millisecond to the minute or hour time-scale) and it would be impossible or unpractical to treat them with equal precision in the same model.
During the sea2grid project it has been specifically underlined, through several test-cases and examples, the importance of control both to improve the power extraction from sea waves and to allow the grid connection of the WECs, while ensuring proper power quality and grid code compliance at the point of connection. It has been also highlighted the role of the PTO as enabling technology of the control action and the mutual relationship between selected control strategy and PTO topology and operation. Finally, the importance of an optimized design of the PTO itself has been stressed, especially as regards its efficiency, since this parameter can severely affect the overall power performance of the WEC.
The specific analyses performed during the Sea2grid confirmed that direct-driven point absorbers are an especially challenging application due to the extremely high peak to average extracted power ratio (possibly higher than 20), which calls for a consistent oversizing of the PTO system. It is worth noting that when multiple WECs are deployed in a wave farm, a consistent reduction (more than 40%) can be obtained in the peak-to-average power ratio due to the natural special displacement among the WECs in the farm. This results in a natural power smoothing, but possibly also in a small reduction (some % points) in the average power capture, due to possible masking effects of point absorber in the front rear on those on the back rear.
The specific test-case of points absorbers of rated power of few hundred kW connected to the *bimep* infrastructure was considered. *Bimep* is an infrastructure for research and testing of offshore wave energy converter, which is located in the Basque Country. Its point of connection to the main power system constitutes a strong electric grid, whit a Short Circuit Ratio of 227.5. It has been shown that the connection of a single point absorber to such strong grid has a negligible effect on the voltage drop and frequency level at the PCC. It is however worth noticing that when a single point absorber is connected to an infrastructure having a rated power of several MW (20 MW in the case of *bimep)* it is recommended to de-energize the unused berths, to avoid the circulation or reactive power that represents a consistent fraction of the active power delivered at the PCC by the single WEC. It has been shown that also in the case of a 20-MW wave farm of point absorber, the voltage and frequency drops at the PCC are very small and the low-voltage ride-through behaviour of the farm is fully satisfactory, at least in the most widespread case of WECs equipped with a fully controlled power electronics interface (e.g. back-to-back solution). The case of WECs equipped with an asynchronous machine directly connected to the main grid (with no power electronics) is potentially more critical, anyway this solution is strongly discouraged since the desired controllability of the WEC is totally lost.
It is worth noting, however, that in all the considered case of grid connection to the bimep strong grid, grid code compliance is ensured, thus showing that grid integration of single WEC/wave farm to a strong grid does not present special concerns and specific energy storage provisions are not required. It should be mentioned however, that any considerations about grid integration is specifically dependent on the specific grid code and, potentially, on additional requirements from local D.S.O or T.S.O., thus an absolute generalization is not possible.
On the other hand, it has been shown that the grid integration into a weak grid is much more critical, especially in the case of a multi-MW wave farm. Considering in this case the real test case offered by Atlantic Marine Energy Test Site (AMETS) having an SCR = 3.15, it has been shown that the grid integration of a 20-MW wave farm, would provoke high voltage drops at the PCC both in steady state

conditions and under transient conditions, thus violating the limits imposed by the local grid codes. In this weak grid scenario, energy storage deployment becomes fundamental to solve power quality issues and ensure grid code compliance. Performed analyses on the required short-term energy storage required to solve such issues showed that a power rating of the storage in the range of the wave farm installation and an energy rating in the order of magnitude of few hundred KWh would be required. Based on such power & energy rating, suitable storage technology technologies could be lead-acid batteries, flywheels and potentially Ni-Cd batteries.

It is worth noting, however, that this should be considered as a preliminary indication, since final technology selection should be based on the analysis of multiple wave profiles it must also consider other parameters as storage life-time and efficiency. Thus, further investigation is encouraged to evaluate in detail these aspects before final decision. Moreover, the analyses showed the importance of a smart selection of the energy storage control strategy depending on the reference set and potentially affected by the availability of good weather forecast. This is another interesting field of investigation for the future.

Finally, studies focused on the application of long-term energy storage for energy management, showed potential for the combination of wind and wave energy farm, with a potential improvement in further stabilizing the output power if a centralized energy storage device is jointly deployed.

Finally an additional investigation focused on the grid integration of a wave farm to cover the energy need of an isolated community (real test case of the La Palma island), showed that in isolated networks matching power generation and consumption is a clear priority and that their correlation is fundamental to define the energy storage requirements. In this case the convenience to deploy an energy storage device and the corresponding decision on the optimal rating was based on economical parameters, in order to minimize the final cost of energy. It was shown that this approach may significantly differ from the one based on technical requirements only. Moreover, in this case a stochastic approach to energy storage sizing, which takes into account all the different operating conditions of the storage along the years was adopted. This is considered the most advisable approach to energy storage application and further investigation is encouraged in order to consider additional parameters (extended data-base for input data, efficiency of different storage technologies, storage life-time etc.) to refine the storage sizing procedure.

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