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RESEARCH ARTICLE

REVISED An effective solution to boost generation from waves: Benefits of a hybrid energy storage system integration to wave energy converter in grid-connected systems

[version 2; peer review: 1 approved, 2 approved with reservations]

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v2 **First published:** 23 Mar 2022, **2**:40
https://doi.org/10.12688/openreseurope.14062.1
Latest published: 04 Sep 2023, **2**:40
https://doi.org/10.12688/openreseurope.14062.2

Abstract

Background: Wave energy represents one of the most promising renewable energies due to its great theoretical potential. Nevertheless, the electrical compliance of grid-connected systems is a great issue nowadays, due to the highly stochastic nature of wave energy.
Methods: In this paper, a Hybrid Energy Storage System (HESS) consisting of a Li-ion battery and a flywheel is coupled to a Wave Energy Converter (WEC) that operates in grid connected mode. The study is performed using real yearly wave power profiles relating to three different sites located along the European coasts. The Simultaneous Perturbation Stochastic Approximation (SPSA) principle is implemented as real-time power management strategy for HESS in wave energy conversion systems.
Results: Obtained results demonstrate how the proposed HESS and the implementation of the SPSA power management coupled to a WEC allow a reduction of more than 80% of power oscillations at the Point of Common Coupling (PCC), while proving the robustness of the developed management strategy over the investigated sites. Moreover, the average energy penalty due to the HESS integration results slightly higher than 5% and battery solicitation is reduced by more than 64% with respect to the flywheel solicitation, contributing to extend its lifetime.
Conclusions: HESS integration in renewable generation systems maximizes the WEC production while smoothing the power at the PCC. Specifically, flywheel-battery HESS together with the implemented power management strategy could provide a great

Open Peer Review

Approval Status ? ✓ ?

	1	2	3
version 2 (revision) 04 Sep 2023	? view		? view
version 1 23 Mar 2022	? view	✓ view	

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Any reports and responses or comments on the

flexibility in the view of increasing power production from waves, strongly mitigating the variability of this source while enhancing grid safety and stability.

Keywords
Wave Energy, WEC, Hybrid Energy Storage (HESS), Power Smoothing, PCC, grid-connected mode

article can be found at the end of the article.



This article is included in the Horizon 2020 gateway.



This article is included in the Energy Storage collection.

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Author roles: Barelli L: Conceptualization, Methodology, Supervision, Validation; **Bidini G**: Writing – Review & Editing; **Ciupageanu DA**: Data Curation, Formal Analysis, Methodology, Software, Writing – Original Draft Preparation; **Ottaviano A**: Data Curation, Formal Analysis; **Pelosi D**: Formal Analysis, Investigation, Software; **Gallorini F**: Supervision, Writing – Review & Editing; **Alessandri G**: Data Curation, Formal Analysis; **Atcheson Cruz M**: Data Curation, Writing – Review & Editing

Competing interests: No competing interests were disclosed.

Grant information: This research was financially supported by the European Union's Horizon 2020 research and innovation programme under the grant agreement No 764066 (Innovative Method for Affordable Generation IN ocean Energy [IMAGINE]).
The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

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How to cite this article: Barelli L, Bidini G, Ciupageanu DA *et al.* **An effective solution to boost generation from waves: Benefits of a hybrid energy storage system integration to wave energy converter in grid-connected systems [version 2; peer review: 1 approved, 2 approved with reservations]** Open Research Europe 2023, **2**:40 https://doi.org/10.12688/openreseurope.14062.2

First published: 23 Mar 2022, **2**:40 https://doi.org/10.12688/openreseurope.14062.1

REVISED **Amendments from Version 1**

The present paper aims to analyze the benefits of a flywheel-battery based hybrid energy storage system (HESS) integration to a wave energy converter for power smoothing. It is demonstrated that the HESS integration managed by a proper power management strategy based on simultaneous perturbation stochastic approximation (SPSA) algorithm allows a reduction of more than 80% of power oscillations at the PCC, with an average energy penalty slightly higher than 5%. This new version of the manuscript has been updated according to reviewers' comments. In particular, further aspects relating to hybrid energy storage sizing and implemented electrical topology have been detailed. Moreover, a deeper analysis on different types of energy storage systems also including costs is added in the Introduction. Finally, for a better understanding, a detailed layout of the electrical architecture and some significant references have been included to clarify crucial aspects relating to HESS modelling and sizing.

Any further responses from the reviewers can be found at the end of the article

1. Introduction

The growing world electricity demand and the threat of climate change due to greenhouse gases and pollution is currently pushing the research for new frontiers of energy production. In this context, renewable energy sources (RES) are widely exploited since they do not produce pollutant emissions and are largely available. Nevertheless, RES such as solar and wind energy show a stochastic nature that lead to an intermittent and fluctuating power production due to the variation of meteorological conditions. Therefore, RES are considered non-programmable power sources that can negatively affect grid stability and safety, system reliability, power quality and load management, as indicated in 1,2. Considering the future increase in the installed capacity, the grid-connected RES will create a negative impact on the grid when fault or disturbance occurs. Consequently, the grid will have to manage higher rates of variable energy production while maintaining adequate voltage levels at the Point of Common Coupling (PCC). As the voltage is a local parameter, mitigating solutions should be designed and employed locally, enhancing not only the power quality indexes, but also providing support in fault conditions.

Since the 1970s, power production from sea and ocean waves has been studied, due to the major changes induced by the oil crisis of 1973[3]. Wind, as an indirect effect of the sun, blows across the surface of seas and oceans and generates waves, that can be exploited by Wave Energy Converters (WECs) to produce electricity[4]. A review of WEC technologies developed over the years is presented in 5. Although WECs are currently considered immature technologies and none of them actually predominates over the others, the theoretical potential of the wave energy resource is very high (around 29,500 TWh/year) and can totally or almost cover global yearly energy consumption[6,7]. Maximum values can be predominantly registered between the 40° and 60° lines of latitude north and south, with a larger proportion in the southern hemisphere because of the large fetch lengths and relatively high winds, especially in the higher latitudes. One of the main issues affecting the commercial utilization of wave energy is related to the difficulty in integrating power from large WECs into the electricity grid because of the intrinsically high variability of the waves[8]. In this context, different spectra have been developed to mathematically represent the wave elevation profile, using the principle of super-position of sinusoidal waves with different periods and heights. As analyzed in 4, a variety of idealized spectra have been suggested to represent a fully developed sea-state. Perhaps the Pierson-Moscowitz (PM) Spectrum[9] is the most widely used spectrum. It assumes that waves are in equilibrium with the wind when wind has been blowing across a sufficiently large expanse of water for a sufficiently long time. In this occurrence the sea state is fully developed and only wind speed affects the spectrum. Subsequently, the condition of not fully developed sea-state was performed by Hasselmann *et al.* in the Joint North Sea Wave Observation Project (JONSWAP), providing a refinement to the PM Spectrum based on the wind speed and fetch length[10]. Further details on the above mentioned and other used wave spectra are reported in 11–13.

Since the desired form of energy produced by the wave energy conversion process is electricity, the WEC systems have to encounter grid requirements and regulations. As described in 4, the main subsystems constituting a WEC are the following:

- The prime mover, the system that absorbs wave power according to different principles as: point absorber, oscillating wave surge converter, submerged pressure differential, attenuator, rotating mass, oscillating water column and overtopping. It transfers forces and motions to both reaction and power take-off subsystems, described below, through suitable connections.

- The Power Take-Off (PTO) subsystem, which converts the captured wave energy (by the prime mover) into electricity. The most common typologies are: hydraulic PTO, electro-mechanical PTO, linear generators, air turbine and low head water turbine.

- The reaction subsystem, that maintains the WEC in position relative to the seabed (e.g. mooring system) and provides a reaction point for the PTO and/or support for the hydrodynamic subsystem(s) (e.g. fixed reference or support structure).

- The control and monitoring subsystem, devoted to the WEC control and management. It mainly consists of the control software, power control system, sensors, devices for data transfer and the human interface.

As well as energy from other distributed generation sources, wave energy conversion systems produce power irregularly and intermittently and need to go through power conditioning before being fed into the electric grid as regulated in IEEE-1547-2003[14]. Three main requirements for a reliable WEC system have been suggested in 8, as it follows:

1. an efficient PTO system to convert mechanical power to electricity;

2. regularization of the unstable electricity to meet grid requirement or meet the electrical load if it is to be supplied to a standalone system;

3. the power electronics to ensure the quality of power at the user's end.

In renewable energy generation, a promising solution to mitigate and reduce the fluctuating and intermittent behavior of RES consists in integrating energy storage systems (ESSs) in renewable power plants. ESSs provide the opportunity for the generation side to meet the level of power quality as well as the reliability required by the demand side, thanks to high flexibility, scalability and efficiency[1,15]. Moreover, ESSs can also provide emergency power and peak shaving functionality towards the grid. Therefore, ESS can actually provide an additional flexibility for RES penetration in the next years.

Among the several ESS technologies developed so far, battery energy storage systems (BESS) are usually employed for smoothing renewable power generation fluctuations[16,17]. However, many of the most widely used batteries, such as Li-ion batteries, are subjected to degradation due to electrochemical side reactions in anode, electrolyte and cathode[18]. Moreover, the lifetime of many commercial BESS is strongly affected by harmful power spikes and depth of discharge (DoD), according to their specific cycle-to-failure (CTF) curves. Considering current BESS limits, researchers are investigating the use of short-term response ESSs, such as flywheel and super capacitors, aiming to absorb/provide instantaneous power spikes for wind power smoothing. Nevertheless, neither flywheels nor supercapacitors are able to provide adequate storage capacity for long term periods, not exceeding seconds or few minutes.

The main features of flywheel energy storage system (FESS), are: fast responsiveness, high efficiency, long cycling life and high power densities[19]. In comparison to other high power ESSs such as supercapacitors (SCs), FESSs are cheaper and have a higher lifespan, although low specific energies and standing losses are non-negligible aspects. Indeed, supercapacitors are often investigated in similar applications for fast dynamic power regulation (coupled to batteries in hybrid systems), as shown in 20. As current limitations, SCs have very low specific energies (up to 5–10 Wh/kg, lower than FESSs) and high daily self-discharge rates. Furthermore, SC technology has very high capital costs (a total cost project of 75,000 $/kWh with respect to 11,520 $/kWh for the FESS, as indicated in 21. This implies that FESSs and SCs are usually used for power modulation (i.e. short-term energy storage).

Consequently, hybridization among different technologies can bring significant achievements, since Hybrid Energy Storage Systems (HESS), including multiple storage devices complementary to each other, are able to cope with storage requirements for different timeframes, merging the positive features of base-technologies and extending their application ranges[22].

In the scientific literature, many research activities have been focused on the integration of ESSs in wave energy farms, coupled to different kind of WECs. Hazra and Bhattacharya[23] propose a hybrid energy storage system comprising of a battery and ultra-capacitor for power smoothing of oscillating wave energy. In 23 it is demonstrated how HESS minimizes the grid side converter rating improving grid stability, while claiming the cost-effectiveness of this solution in comparison to a battery and ultra-capacitor not-hybrid solution. In 24 a new control strategy for power smoothing was applied to a wave farm coupled to a FESS. The authors obtained grid losses reduction by 51%, improving the energy efficiency of the power network. According to 25, the integration of FESSs into a WEC plant achieves a reduction of 50% in power oscillations, covering 85% of the frequency excursions at the grid, on the basis of real power generation profiles delivered to the electric grid. Another noteworthy research employed FESS in order to enhance dynamic stability of an integrated offshore wind and marine-current farm[26]. In 27 an interesting study concerning FESS for wave power leveling was carried out. Among the several ESS technologies for power smoothing, supercapacitors were also analyzed[28,29], due to the similar features with respect to FESSs, as mentioned before. Fang *et al.*[30] presented a coordinated and stable control for a hybrid energy storage system constituting a battery and a flywheel with the purpose to inhibit power fluctuations when wave generator works in grid connected mode. Other noteworthy studies on HESS integration to renewable energy sources are detailed in 31–36.

In the present paper, a hybrid energy storage system including a Li-ion battery and a flywheel has been developed and implemented with the purpose of reducing power oscillations produced by WEC system and sent to the grid. A specific and optimized power management, based on the Simultaneous Perturbation Stochastic Approximation (SPSA) algorithm[37–40], has been implemented aiming to minimize power fluctuations sent to the grid. The study presented in 30 is focused on the assessment of voltage and frequency stability in grid connected mode, while no quantitative information is provided for what concerns power oscillations reduction at the PCC.

Therefore, the main objective of the present work is to demonstrate how HESS features can improve power quality at the PCC while minimizing the related energy penalty due to the storage integration. Dynamic simulations were carried out in MATLAB® Simulink (R2019a) environment considering three different wave power profiles. Xcos is suggested as an alternative open source software that can be used to replicate the simulation method. All the details concerning Simulink to Xcos conversion in order to replicate the implemented methodology are available here.

In Section 2, the wave energy fundamentals and the methodology regarding data selection and power profile generation are described. A statistical characterization of the generated annual power profiles for the three sites has been realized both considering their yearly features and daily ones as reported in Section 3. A description of HESS modelling and sizing is illustrated in Section 4–Section 5. Section 6 reports the simulation results achieved over several daily profiles extracted as the most representative of the wave yearly production. Furthermore,

the advantages of the SPSA power management strategy are highlighted resulting in about 80% power fluctuations reduction at the PCC with respect to the wave-generated profile, with an average energy penalty of only 5.3%.

2. Methods

In this section, the applied methodology for the considered case studies is discussed. In particular, Section 2.1 shows the fundamental equations to assess wave energy potential. In the subsequent sections the generation of the power profiles for the three studied sites, used as input for the dynamic model, is explained.

2.1 Wave energy fundamentals

Being a consequence of wind, wave nature is inherently stochastic and the conversion of this energy is extremely complex due to the hydrodynamic processes present in the diffraction and radiation of the waves as they propagate to shore[41]. The power per unit width of a wave front is given by 41 (Equation 1):

$$P = \frac{1}{64}\frac{\rho g^2}{\pi} H_s^2 T_e \quad (1)$$

Where:

P is the power per unit width (kW/m);

ρ is the density of sea water (kg/m^3);

g is the acceleration due to gravity (m/s^2);

H_s represents the significant wave height (m);

T_e is the wave energy period (s).

T_e value differs from the wave peak period T_p in accordance with the considered spectrum used for hindcasts. For instance, $T_e = 0.857\ T_p$ considering the PM spectrum[35].

2.2 Generation of the power profiles

Wave energy data were obtained from thirty-year wave hindcast data validated through experimental measurements[42]. The hindcast was performed using the National Oceanic and Atmospheric Administration WAVEWATCH III model data (see here for more details), and was driven by winds from the NCEP Climate Forecast System Reanalysis (CFSR), a coupled reanalysis of the atmospheric, oceanic, sea-ice and land data (access to the CFSR data requires registration via the website).

Three different sites located in the European region are considered (Figure 1), with an annual mean wave power that ranges between 30 and 50kW/m. The selection of these sites was made in the framework of the IMAGINE project in order to match the available wave power at the WEC inputs with the power of the PTO system developed during the project.

The measured wave occurrences related to the three sites were elaborated in the form of yearly scatter matrices by aggregating the samples with same wave height H_s and period T_p. The number of sea states resulting for each location is:

- Site 1, located in France: 143 sea states;
- Site 2, located in England: 144 sea states;
- Site 3, located in Norway: 132 sea states.

Figure 2 represents the considered Oscillating Wave Surge Converter, OWSC, WEC type with two PTOs having a rated power of 250 kW each, for the calculation of the generated electrical power.

For each cell of the scatter matrix (with a specific spectrum, wave period T_p and wave height H_s) a numerical simulation was performed by using the WEC-Sim (Wave Energy Converter SIMulator) software[43], an open-source WEC simulation tool developed in MATLAB/Simulink environment.

With the purpose to build a dataset to study the dynamic response of the HESS in reducing power oscillations at the PCC, a proper sample time step of 0.1 s was chosen. This provides the main features needed to characterize the power take off (PTO) according to the specific input conditions. Specifically,

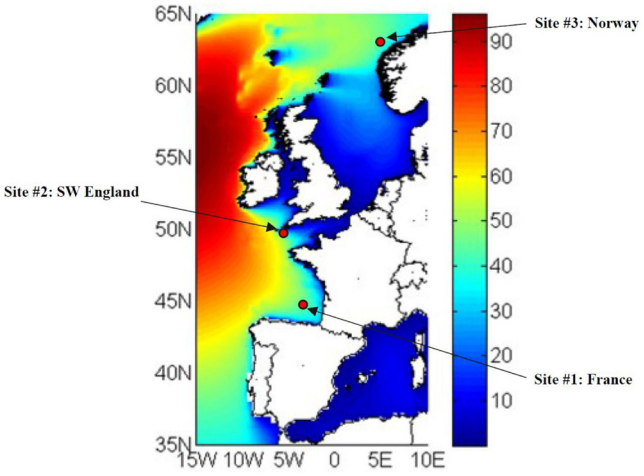


Figure 1. Selected locations for simulating the wave power in input to the hybrid energy storage system.

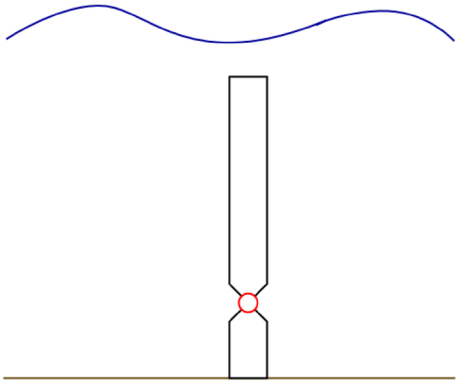


Figure 2. The Oscillating Wave Surge Converter (OWSC) wave energy converter type, bottom mounted, submerged.

the following parameters related to the PTO input axis were evaluated from the simulation tool:

- Acceleration;
- Speed;
- Stroke;
- Load.

On the basis of these data, it is possible to determine the instantaneous power in output from the PTO system, through the following equation (Equation 2):

$$P = \eta v D \tag{2}$$

Where:

η represents PTO system (from input axis to DC bus) efficiency;

v is the instantaneous speed value at the PTO expressed in m/s;

D is the instantaneous force at the PTO input axis, expressed in N.

In this work it has been assumed a PTO efficiency equal to 80%, in line with data obtained by the same system in similar applications[44].

Three random vectors of the instantaneous electric power were generated in MATLAB® for each site, in order to evaluate any quantitative difference due to the randomization process. Each vector represents the instantaneous power profile generated in a year, with a time step of 0.1 s. Such vectors were constructed by randomly concatenating each 30 minutes power data sequence obtained through simulation, globally repeating each sequence for a number of times equal to the related occurrences number.

2.3 Random vectors comparison

Based on the wave characteristics depicted in Section 2.2, three random yearly power vectors are generated for each site, having a 0.1 s time step. Figure 3 depicts as example a part (1 hour) of one of the generated electric power profiles. It must be emphasized how the power trend is very oscillating and fluctuating.

The differences among the three vectors are analyzed for each site, considering as a principal comparison criterion the distribution of the instantaneous power ramp R^t_{wave}, expressed by Equation (3) as the difference between the power values P^t_{wave} and P^{t-1}_{wave} at two consecutive time steps, with a 1 s window. This quantity is considered as an objective of further research, since it is strictly related to the smoothing of the power output generated by the wave energy converter.

$$R^t_{wave} = P^t_{wave} - P^{t-1}_{wave} \tag{3}$$

In reference to the first site, it is remarked that the instantaneous power ramp is always under 3.8 kW/s, regardless of the random vector considered. This threshold reduces to 3.4 kW/s for the second site, while the maximum value of the instantaneous power ramp for the third site grows up to 4.2 kW/s.

Table 1 presents a comparison in reference to the power ramp 90% Cumulative Density Function (CDF) threshold value, averaged for the three vectors and for each site. It is emphasized that the maximum deviation from the average (if comparing, for each site, a single random vector to the average value) doesn't exceed 0.5%. Thus, no significant difference arises among

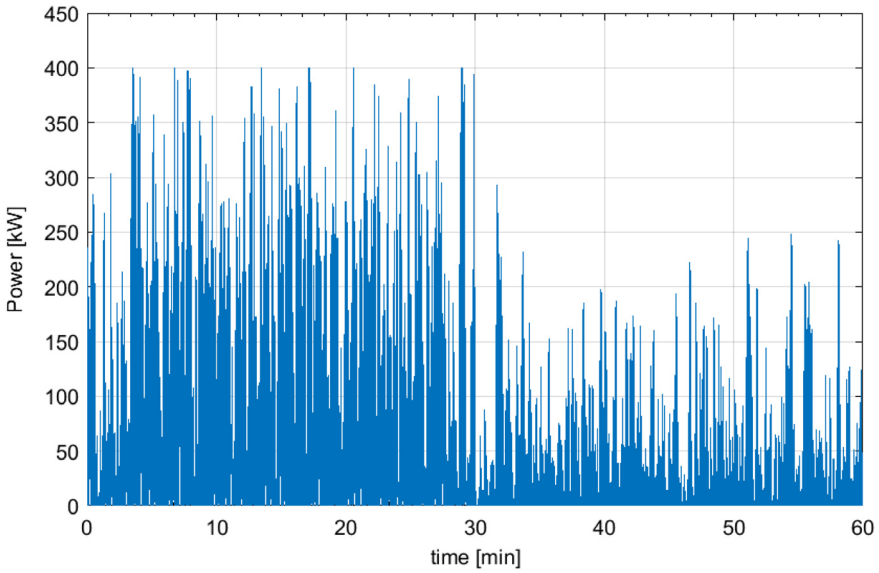


Figure 3. Wave generated power profile for 1 hour.

the three random vectors. So, further analyses are made based on the first vector generated for each site.

3. Statistical characterization of wave energy generation

In this Section, the statistical procedure is implemented aiming at extracting the yearly and daily features of the power profiles for each site. The daily profiles, chosen by means of statistical criteria defined in Section 3.2, demonstrate the wide coverage of the power variations in each of the studied cases.

3.1 Yearly features

In the following section, a brief comparison among the power generation sites is presented in terms of the variability features for few characteristic quantities. The assessments are carried out on the random yearly power vectors selected (one for each site) at the previous stage, highlighting the diversity of the generation spectrum at each site and pointing out their suitability for a comprehensive analysis on wave energy integration in interconnected systems. Therefore, it is emphasized that the representative quantities are considered based on their relevance in properly describing the operating conditions on yearly basis. Specifically, the selected quantities to describe the behavior of the wave generation at each site are:

- generated energy;
- daily mean power;
- the power generation daily bandwidth, calculated as the difference between the daily maximum and minimum recorded values;
- the ratio between the daily bandwidth and the mean power, being a measure of how wide the spread of the power trend around the mean is;
- the instantaneous power ramp, determined as the difference between two consecutive values, introducing the highest perturbations to the grid (in terms of fluctuating power profile at the interconnection point), being at the same time the most stressful condition for the energy storage devices.

Figure 4 depicts a comparison among the three sites for all the quantities introduced above, a detailed discussion in reference to each one being provided below.

Table 1. 90% CDF threshold values comparison.

Site	Average power ramp [kW/s]	Percentage power ramp deviation (relatively to the average) [%]
1	3.235	0.36
2	2.675	0.41
3	3.451	0.26

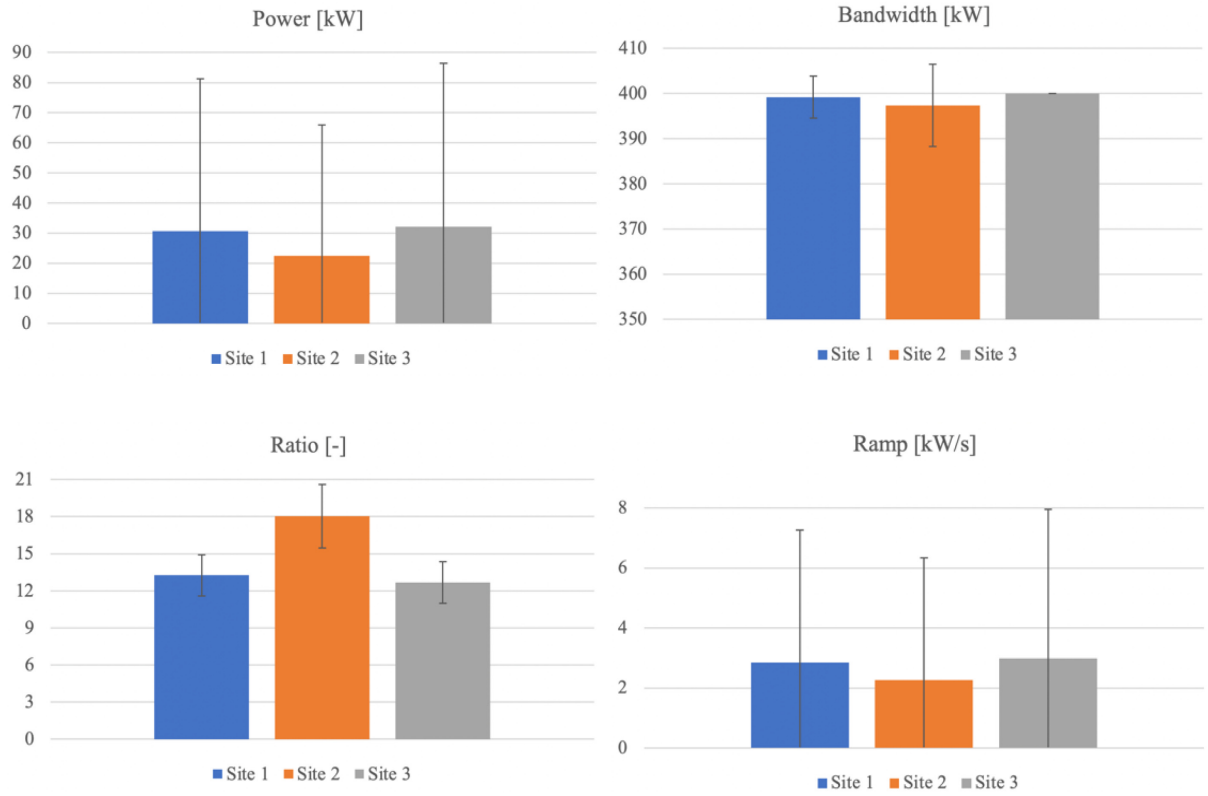


Figure 4. Statistics comparison.

a. Site 1 – France. The generated energy over one year in the first site reaches 256.85 MWh, resulting the second among the three sites. According to Figure 4 (blue columns), it is noted that both power and ramp distribution results are very widespread, and that the deviation from the mean exceeds more than 65%. For what concerns the bandwidth, the deviation is reduced, representing around 1% of the mean, highlighting that in most of the days, the difference between maximum and minimum power is approximately the same and equal to the maximum possible. As a consequence of quite different distributions of the quantities involved, the deviation corresponding to the ratio between the bandwidth and mean power gets up to 12.6% relatively to the mean.

b. Site 2 – England. The yearly generated energy adds up to 188.97 MWh for the second site, being the smallest amount among the three. Both power and ramp distribution spread are very wide also for this site as evident in Figure 4 (orange columns), outranking the first one. Specifically, the deviation nearly doubles the mean for both quantities. The bandwidth deviation reaches around 2.3% of the mean, being doubled if compared to the first site. The deviation corresponding to the ratio between the bandwidth and mean power reaches 14.2% relatively to the mean, being the highest among the three sites. Therefore, it can be concluded that the second site shows the highest variability and the lowest production (with up to 30% smaller than the others).

c. Site 3 – Norway. The annual energy generation at the site located in Norway reaches 269.12 MWh, the highest value among the three sites. It is noted that both power and ramp distribution is very widespread, according to Figure 4 (grey columns), close to the values evaluated for the first site, the deviation exceeding the mean by up to 69% (65% for site 1). The bandwidth shows a particular behavior in this site, being remarkable that every day the power generation varies between 0 and the maximum possible power (400 kW). So, the bandwidth is constant and maximal. The deviation corresponding to the ratio between the bandwidth and mean power gets up to 13.3% relatively to the mean.

3.2 Daily features

Subsequent to the characterization of the yearly profiles randomly generated with a time step of 0.1 s, it is intended to select some representative days in order to run numerical simulations for sizing a hybrid energy storage system for each considered installation site. The target of integrating this system coupled to the wave energy plant is to smooth the power profile exported to the grid. In order to obtain simulation profiles compatible with the response time of the energy storage devices, control time step and ease the computational burden, the yearly profiles are averaged over 1 s time frame. Consequently, simulation profiles (with 1 s time step for 24 hours) are extracted from the yearly profile and employed in simulation. The representative days are selected based on the statistics previously defined, as it follows:

- Day 1: maximum bandwidth;
- Day 2: maximum mean power;
- Day 3: maximum bandwidth to mean power ratio;
- Day 4: minimum bandwidth to mean power ratio;
- Day 5: maximum mean ramp.

Figure 5–Figure 7 present the probability distribution for the selected representative days in all the three sites. It is evidenced that they cover the domain of power variation with different densities, making therefore the simulation results significant in the sizing process. Numerical characteristic values corresponding to each site are listed in Table 2, Table 3 and Table 4.

The power profiles selected for simulation for each site are represented in Figure 8, together with a detail on the same time window. The provided representation allows us to highlight

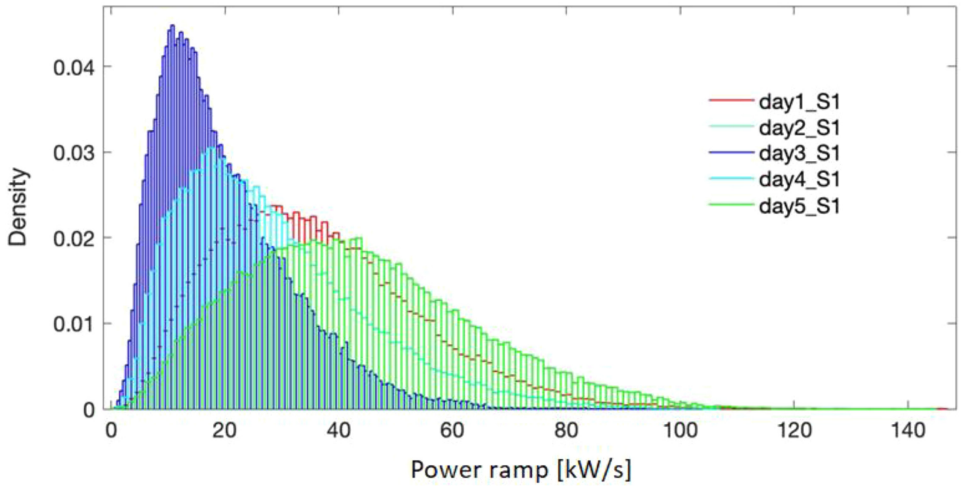


Figure 5. Probability density for the selected days - site 1.

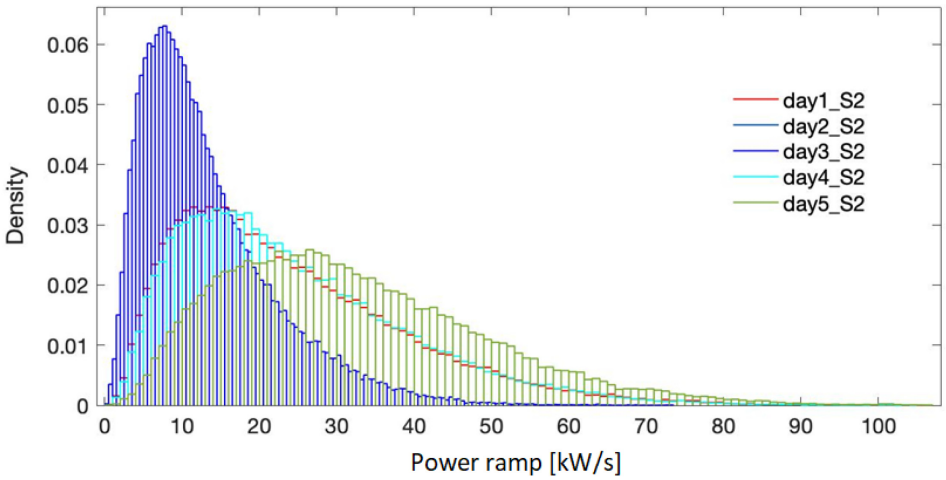


Figure 6. **Probability density for the selected days - site 2.**

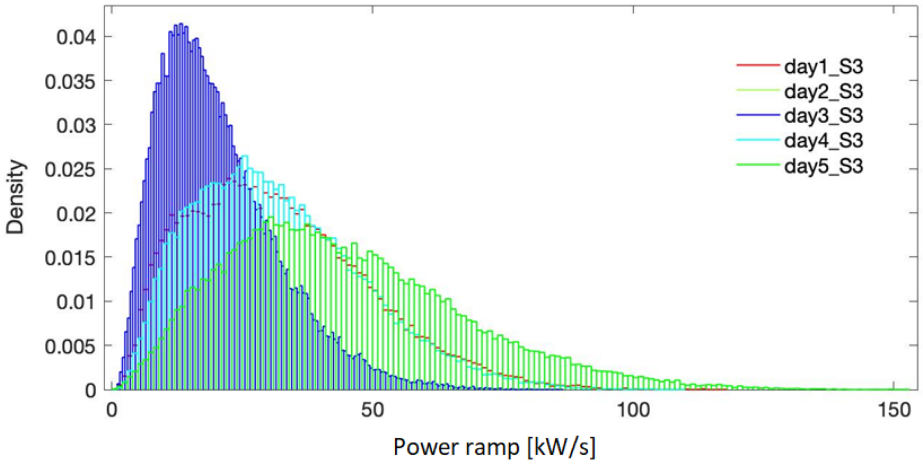


Figure 7. **Probability density for the selected days - site 3.**

Table 2. **Characteristics of the selected days – site 1.**

Day	*Daily average power [kW]*	*Energy generated [kWh]*	*Maximum & Minimum power [kW]*	*Bandwidth [kW]*	*Bandwidth/ Average power*	*Daily Average power ramp [kW/s]*
1	36.01	864.15	146.19 / 1.16	145.03	4.03	1.59
2	42.97	1 031.3	144.71 / 0.47	144.24	3.36	1.73
3	19.94	478.58	101.88 / 0.60	101.29	5.08	0.89
4	28.17	676.08	106.18 / 0.83	105.35	3.74	1.18
5	42.97	1 031.3	144.71 / 0.47	144.24	3.36	1.73

the differences in amplitude and shape among the representative days of each location and, moreover, the three sites, while allowing to consider a wide range of profiles, with high/low generation, strong/weak fluctuation.

4. Hybrid energy storage system modeling and control

In the following, the modeling of the system and the implemented power management strategy are briefly described.

Table 3. Characteristics of the selected days – site 2.

Day	Daily average power [kW]	Energy generated [kWh]	Maximum & Minimum power [kW]	Bandwidth [kW]	Bandwidth/ Average power	Daily Average power ramp [kW/s]
1	24.09	578.17	105.30 / 0.74	104.56	4.34	1.34
2	32.08	770.01	106.39 / 0.67	105.72	3.29	1.46
3	13.31	319.39	73.38 / 0.39	72.99	5.48	0.73
4	24.47	587.39	105.65 / 0.62	105.03	4.29	1.11
5	32.08	770.01	106.39 / 0.67	105.72	3.29	1.46

Table 4. Characteristics of the selected days – site 3.

Day	Daily average power [kW]	Energy generated [kWh]	Maximum & Minimum power [kW]	Bandwidth [kW]	Bandwidth/ Average power	Daily Average power ramp [kW/s]
1	31.94	766.48	117.69 / 1.02	116.66	3.65	1.46
2	44.36	1 064.7	152.90 / 0.31	152.59	3.44	2.09
3	20.49	491.81	86.82 / 0.45	85.92	4.18	0.91
4	31.91	765.82	109.54 / 0.34	109.20	3.42	1.45
5	44.36	1 064.7	152.90 / 0.31	152.59	3.44	2.09

4.1 Modeling considerations

Figure 9 depicts the model of the hybrid energy storage system (HESS) as developed in the Matlab/Simulink environment. Specifically, the Li-ion battery and flywheel are implemented on the basis of their governing equations. Further details on the HESS implementation can be found in 1,41,45. Regarding the Li-ion battery, open circuit voltage and internal resistance data were gathered by the authors, varying the state of charge in both charging and discharging phases, through a dedicated experimental campaign and implemented in the Simulink model. For what concerns the flywheel, the instantaneous delivered/absorbed power is computed taken into account the instantaneous aerodynamic and friction power losses according to the current flywheel speed value. Moreover, considering the specific application, under the assumption of connecting the components in a common DC bus, a buck/boost converter with efficiency of 0.95 was taken into account for both storage units. The power profile delivered by the wave converter enters the SPSA power management module together with the power processed by the battery and exchanged with the grid at the previous time step. This to perform the real time management of both flywheel and battery aiming to the management targets indicated in the next section 4.2. The outcomes provided by the SPSA power management module are processed by the main control section to take into account constraints due to the technical features of both battery and flywheel and current operating conditions related to their state of charge. Thus the instantaneous values of the three shares, in which the power produced by the WEC is shared by the SPSA algorithm among the battery, the flywheel and the grid, are imposed.

The implemented $LiFePO_4$ battery pack is characterized by a maximum charge current of 1C A and maximum discharge current of 3C A, with a nominal voltage of 420 V. The low-speed flywheel is a mechanical one, equipped with low-friction mechanical bearing and housing under vacuum. The rotor is cylindrical and made of steel, while its rotational speed varies from 366 to 890 rad/s. The torque vs. speed saturation curve and the efficiency curve for the driving electrical machine are based on values measured on a real machine and then properly scaled.

4.2 Power management strategy

For the on-line management optimization the SPSA algorithm is chosen, among several stochastic ones, to overcome drawbacks of conventional algorithms[37,38] since it has proven to be an effective stochastic optimization method in a wide range of practical applications[40]. The SPSA algorithm exhibits fast convergence for the global optimization problem of an unknown functional form of systems performance, i.e. the loss function, with a reduced computational burden[38]. Moreover, its implementation doesn't need of a mathematical uncertainty model.

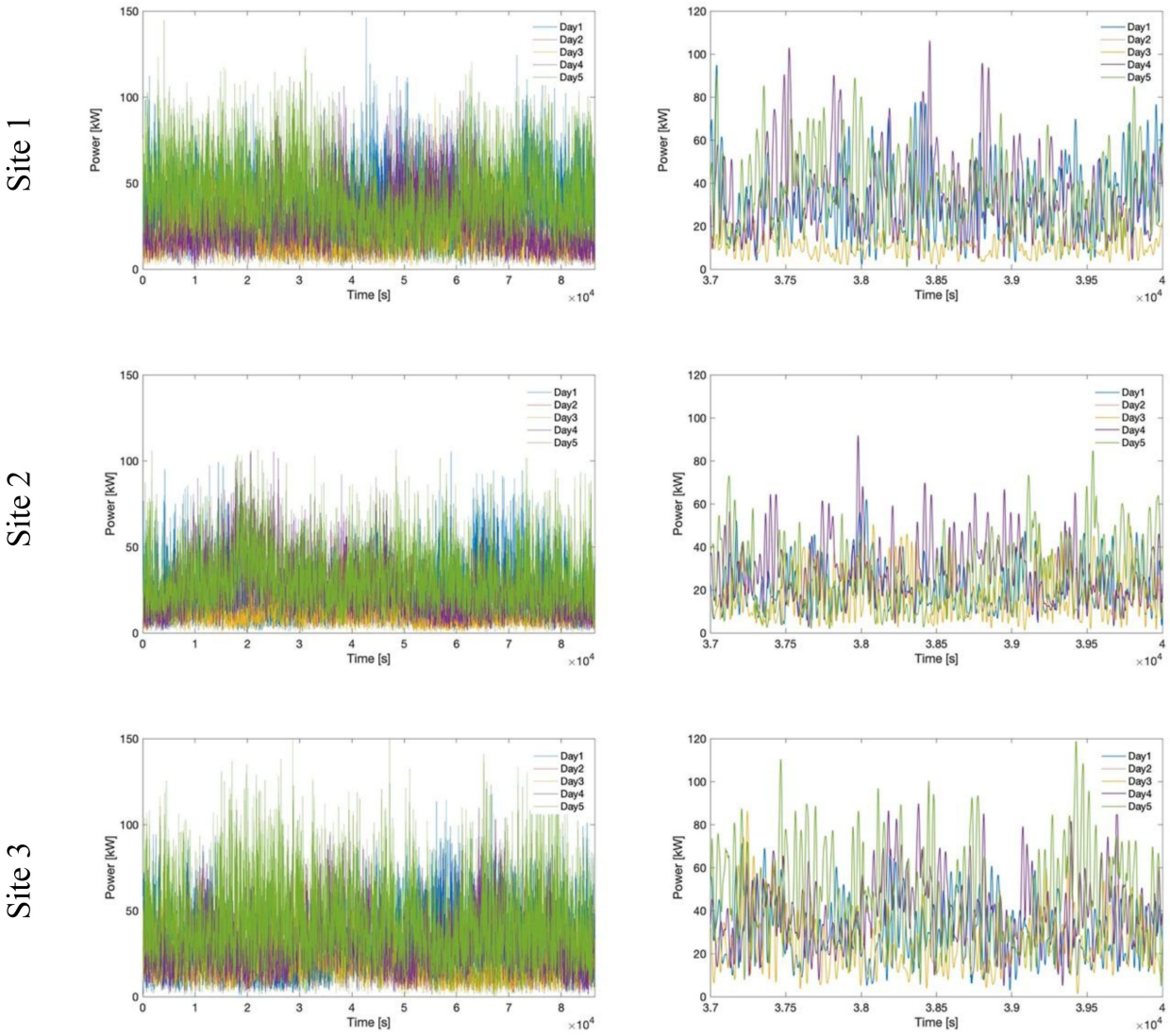


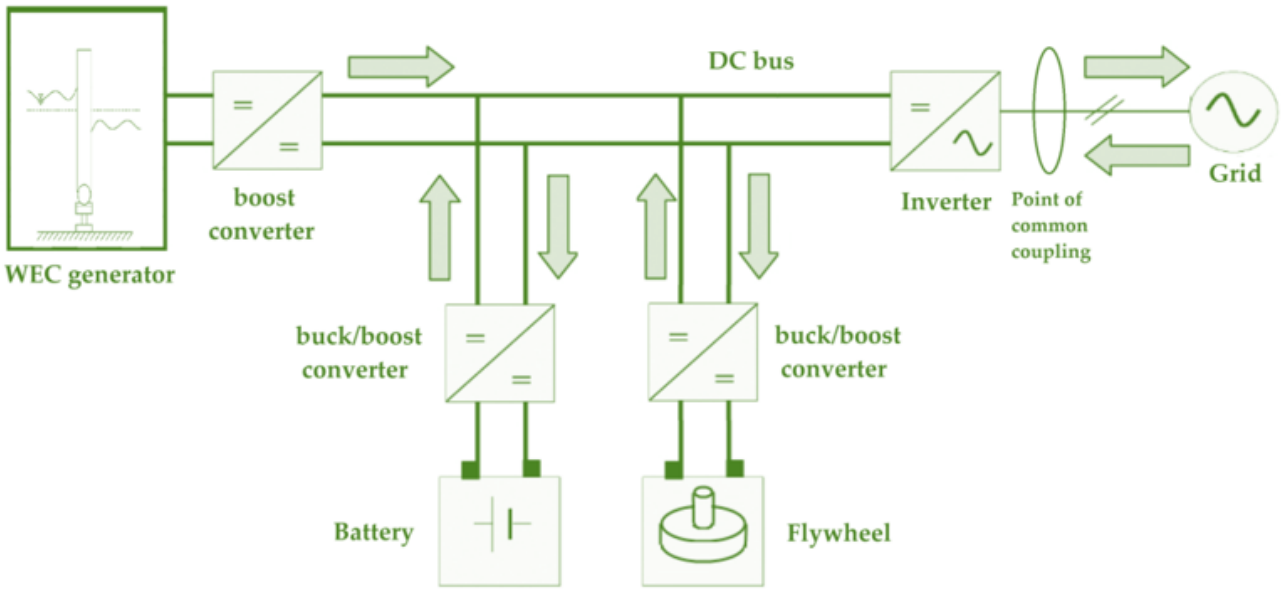
Figure 8. Comparison of power profiles for all selected days and sites.

Figure 10 describes the SPSA algorithm iterative procedure for the optimal solution determination. It moves from an initial estimation of the parameters vector ($\hat{\theta}$) and the definition of the loss function ($y(\theta)$).

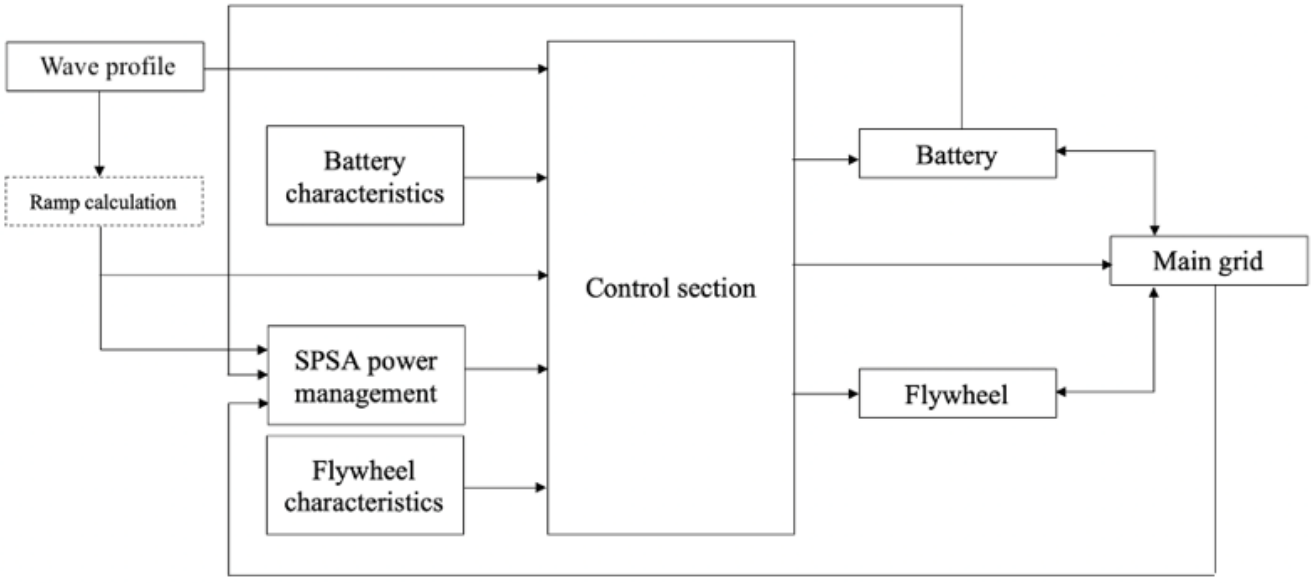
The optimal solution is searched iteratively. At each iteration the algorithm coefficients a_k, c_k are updated (A, a, c, α, γ values are set as visible in Table 5 to ensure calculation convergence according to literature[40,41]) and all the parameters of vector $\hat{\theta}$ are simultaneously perturbed. Thus two estimates ($\hat{\boldsymbol{\theta}}_{\boldsymbol{k}}^{\pm}$) of the parameters vector are determined. These estimates are used to evaluate the gradient of the loss function, $g_k(\hat{\theta}_k)$. The updated estimation ($\hat{\theta}_{k+1}$) of the parameters vector is assessed in consideration of $g_k(\hat{\theta}_k)$ and a_k. The loss function is evaluated in reference to $\hat{\theta}_{k+1}$ and the convergence condition is checked.

The iterative calculation is stopped when the convergence conditions (or the maximum iterations number) is achieved, and the final update of the initial estimate is provided as the optimisation problem solution. This corresponds to a vector of parameters which ideally brings the gradient of the loss function, $g_k(\hat{\boldsymbol{\theta}}_{\boldsymbol{k}})$, to zero or to a convergence threshold.

Similarly to the power management strategy proposed by the authors in 46, the problem formulation here presented implements through Equation (4)–Equation (8) the SPSA algorithm. This implementation aims to the real-time calculation of the optimal shares of power exchanged with the flywheel, the battery and delivered to the grid in managing the oscillating wave power profile. Specifically, the SPSA algorithm manages the difference between the current value of the wave power and the previous value of the power injected at the PCC



a)



b)

Figure 9. a) DC bus electrical architecture layout of the considered system; **b**) outline of the implemented Simulink model.

(ΔP as expressed in Equation (4)) sharing it among the battery (q_{batt}), the flywheel (q_{fw}) and the grid (q_{grid}). Consequently the instantaneous exchanged power values can be determined according to Equation (5), permanently taking into account maximum battery and flywheel capacity and power. To ease the smoothing process, the difference ΔP is pre-processed using a moving average filter with a one-hour window length.

$$\Delta P = P^{t}_{wave} - P^{t-1}_{grid} \tag{4}$$

$$\begin{aligned} P^{t}_{batt} &= q_{batt} \cdot \Delta P \\ \boldsymbol{P^{t}_{fw}} &= \boldsymbol{q_{fw}} \cdot \boldsymbol{\Delta P} \\ P^{t}_{grid} &= q_{grid} \cdot \Delta P \end{aligned} \tag{5}$$

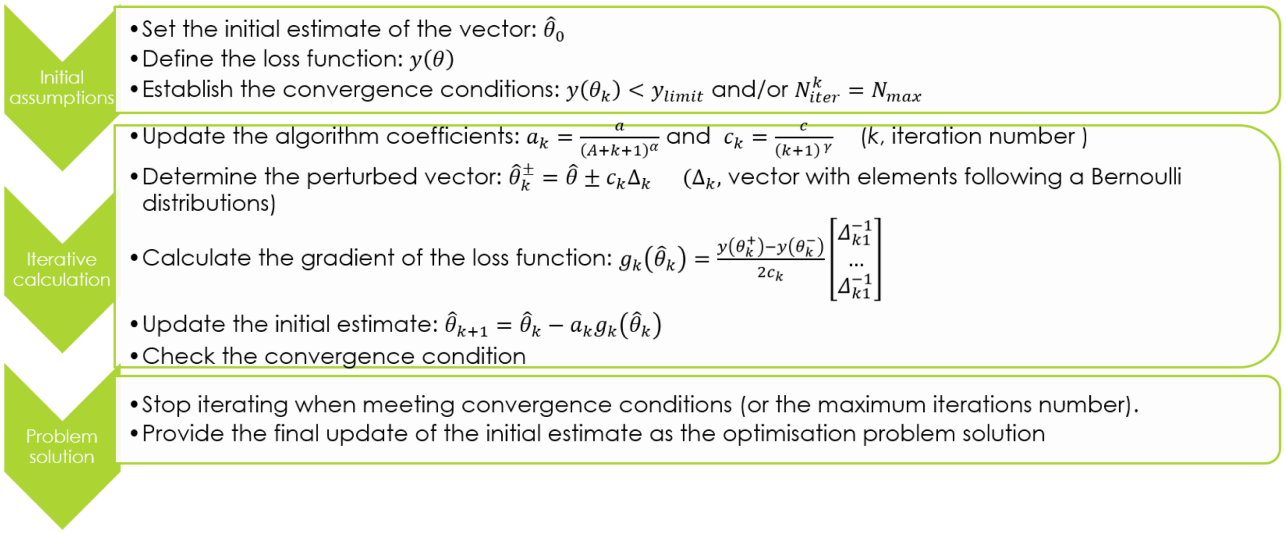


Figure 10. Simultaneous Perturbation Stochastic Approximation (SPSA) algorithm description.

Table 5. Algorithm parameters.

Parameter	Value
A	10
a	2.1127e^{-5}
c	1e^{-5}
α[37,47]	0.602
γ[37,47]	0.101
Maximum iterations	100

The target is the smoothing of both power profiles sent to the grid and managed by the battery (extending its lifetime[22,35]). This is achieved thanks to flywheel ramping capability and fast response, exploited to compensate the fast variations of produced power, while smoothing the profiles imposed to the battery. The corresponding mathematical formulation implements a multi-object loss function of the SPSA algorithm, as indicated in Equation (6) in terms of the weighted sum of two objectives.

$$y^k(\theta) = w_1 \cdot y_1^k(\theta) + w_2 \cdot y_2^k(\theta) \tag{6}$$

Where:

1. The smoothness of the power profile exchanged with the grid is modeled through Equation (7) as the ratio between the power delivered to the grid at the current (t) and previous (t-1) timestep.

$$y_1^k(\theta) = \left(\frac{q_{grid} \cdot \Delta P}{P_{grid}^{t-1}} \right)^2 \tag{7}$$

2. Similarly, Equation (8) expresses the smoothness of the battery power profile.

$$y_2^k(\theta) = \left(\frac{q_{batt} \cdot \Delta P}{P_{batt}^{t-1}} \right)^2 \tag{8}$$

3. $w_1 = w_2 = 0.5$, that is the same relevance is considered for the two objectives.

Starting from an initial estimate of vector θ, the q shares are iteratively determined, following the SPSA principle illustrated in Figure 10. Specifically, q_{batt} and q_{grid} are calculated according to the SPSA algorithm, while q_{fw} results imposing the power balance. The convergence condition is imposed accordingly with the loss function expressed by Equation (6). Furthermore, 100 is fixed as the maximum number of iterations to avoid any loop in the convergence procedure.

5. Hybrid energy storage system sizing

The sizing procedure mainly follows two stages:

- a first assumption in reference to both storage devices is made starting from the cumulative distribution of the power ramp calculated according to Equation (3). It is noted that the storage devices are customized one at a time, aiming to avoid/minimize saturation in power and capacity; so, the flywheel rating (both in power and capacity) is adjusted first, assuming a very large battery, since the flywheel is more adequate to fast response operation (i.e. power smoothing). The capacity and maximum power of the flywheel are determined so that the saturation objective is achieved. Further, the capacity of the battery is adjusted (so, considering the C-rate also the power), following the same objective in terms of saturation.

- The second stage, resulting in the final sizing of the HESS components (in particular the flywheel) implies a sensitivity analysis performed relatively to the power ramp mitigation capability, varying the flywheel maximum power. As it emerges from Figure 11, there is a point on each graph where the flywheel is able to ensure a maximum power ramp mitigation towards the grid. It is remarked that the trends plotted in Figure 11 correspond the 90% threshold value of the CDF evaluated for the power ramp. It can also be observed as for values lower than 20 kW flywheel power, the power ramp at the PCC is too high and by increasing the flywheel power it can still be mitigated. Furthermore, for flywheel power values larger than 33 kW, the power ramp reduction at the PCC is insignificant, the power ramp conveyed to the flywheel being approximately constant for all the three investigated sites. The resulting final sizing of the HESS is presented in Table 6. It is noteworthy that the differences in terms of battery capacity are correlated with the total amount of energy generated over one year, as discussed in Section 3.1. Site 2 and Site 3 exhibit, in fact, the lowest and the largest annual energy production respectively.

6. Discussion

Following the sizing process, the power smoothing performance towards the grid, related to coupling the HESS to the wave energy plant, is assessed for all three sites. The power

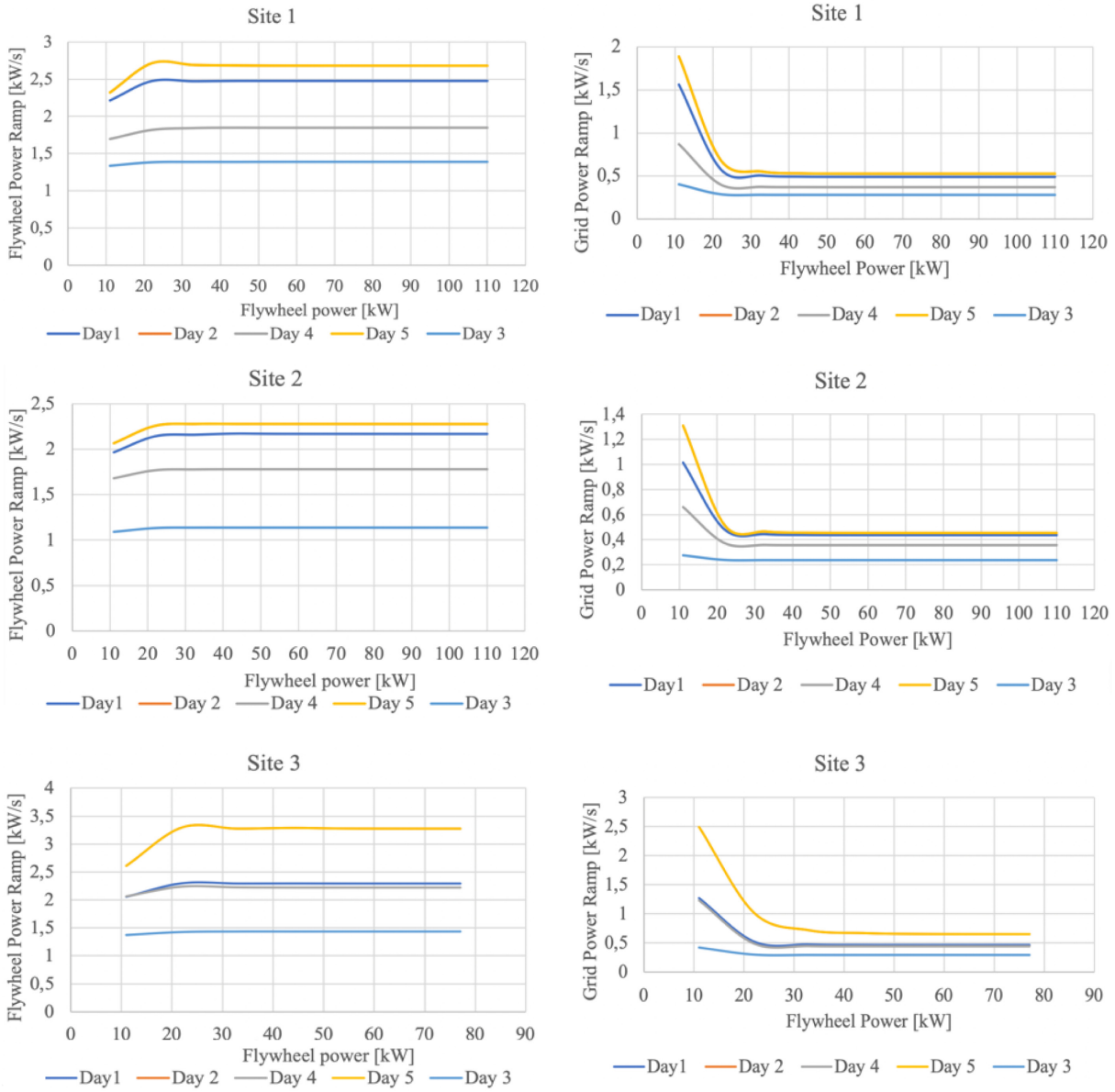


Figure 11. Sensitivity analysis in reference to flywheel sizing; all trends correspond the 90% threshold value of the CDF evaluated for the power ramp.

management strategy implemented is based on the simultaneous perturbation stochastic approximation principle, as detailed in 46,48.

Figure 12 depicts the power profile at the PCC compared to the original one generated by the wave converters. The right side shows a detailed comparison between the wave and the grid power in a random interval from Day 1 (characterized by the maximum bandwidth). It is remarked that the fluctuations are substantially reduced.

Figure 13 quantifies the smoothing of the fluctuation achieved towards the grid thanks to the HESS coupling with wave energy converters and the implemented stochastic power management

Table 6. Hybrid energy storage system (HESS) components final sizing.

	Site 1		Site 2		Site 3	
	Power [kw]	Capacity [kWh]	Power [kw]	Capacity [kWh]	Power [kw]	Capacity [kWh]
Flywheel	33	2.1	33	2.1	33	2.1
Battery	66	22	60	20	72	24

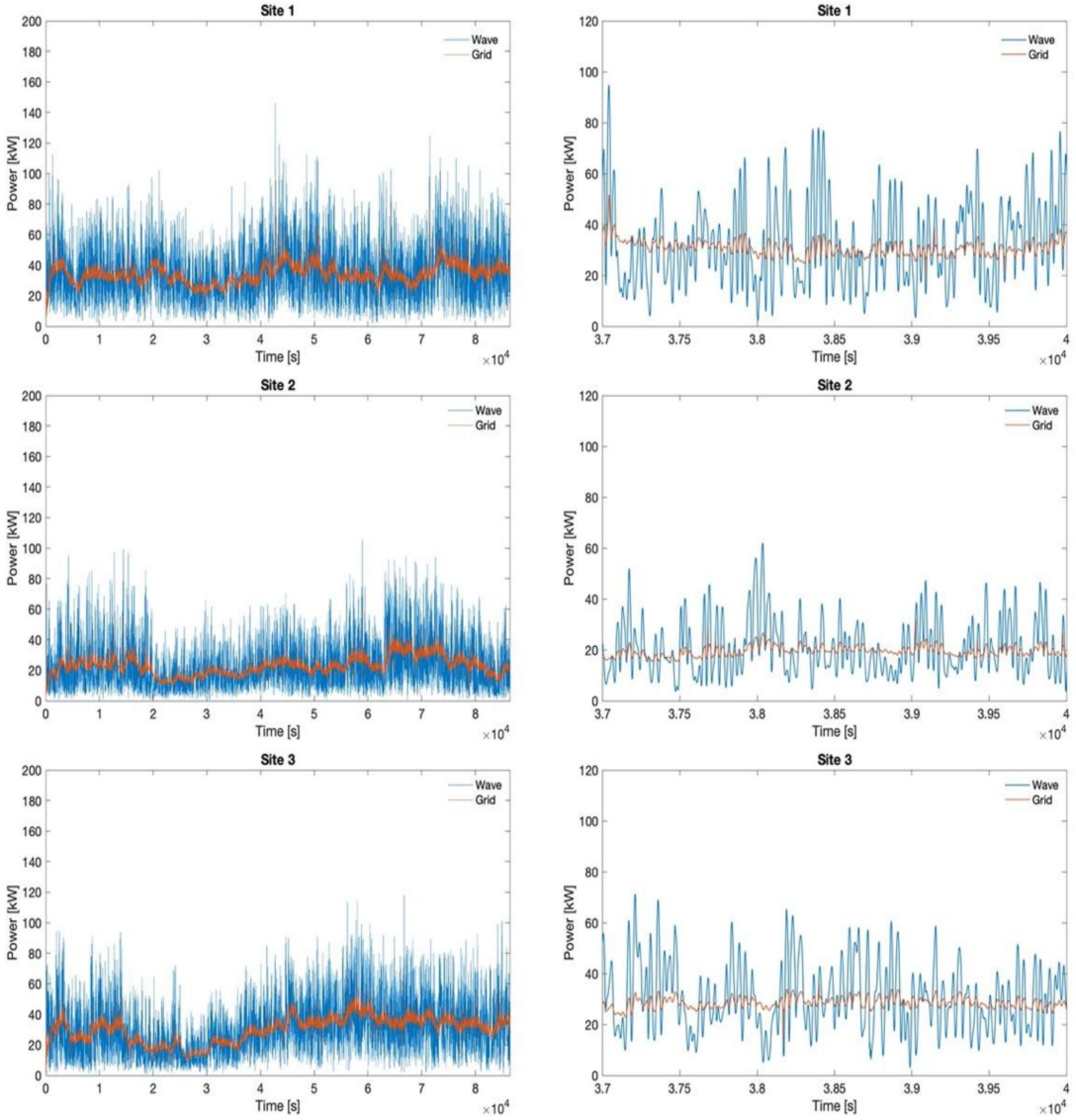


Figure 12. Original wave profile and smoothed grid profile for all sites in day 1.

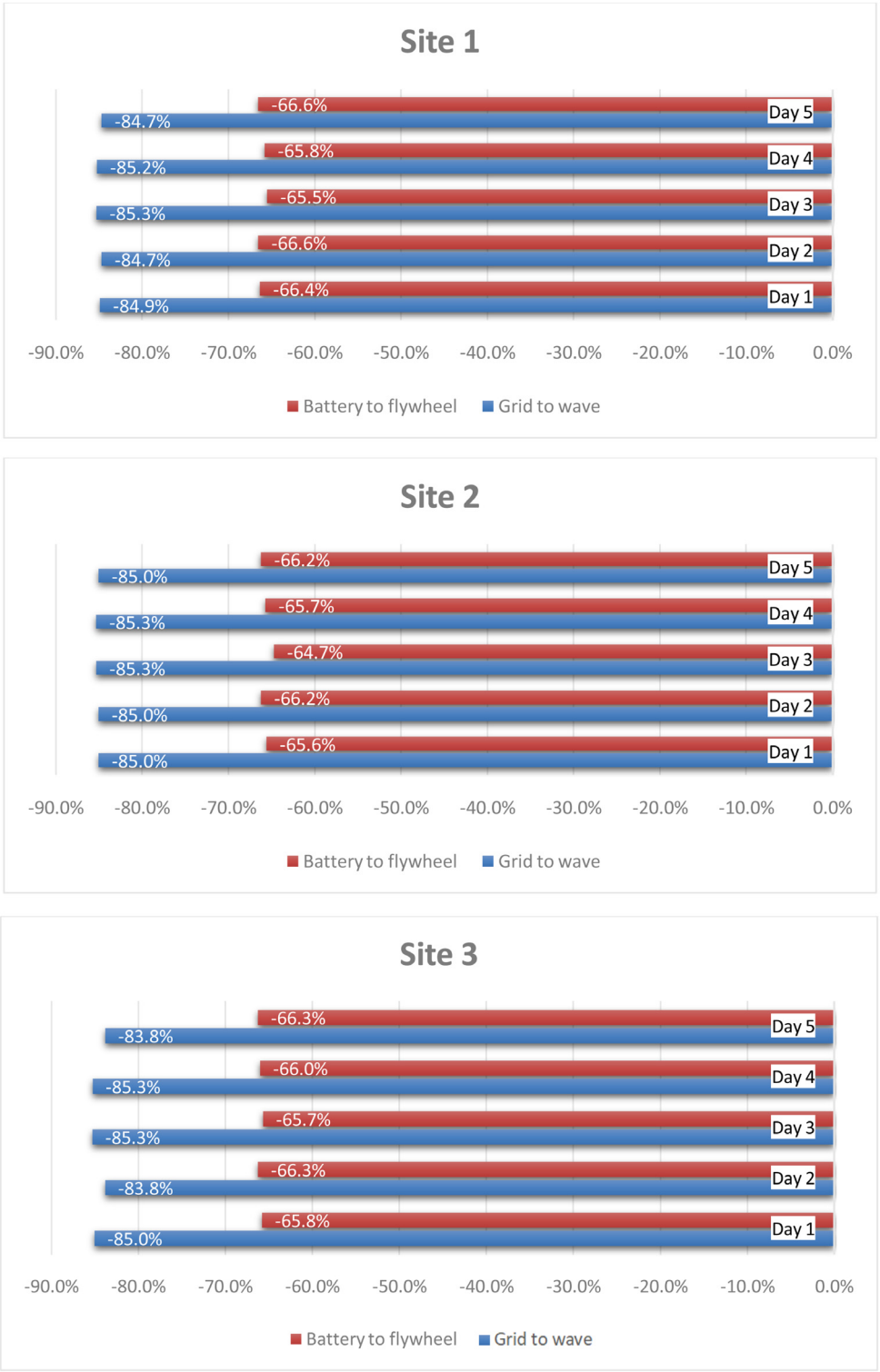


Figure 13. Power ramp reduction.

algorithm. The evaluation is made in reference to the 90% CDF threshold. Moreover, a comparison is conducted also between the battery and flywheel, to demonstrate the reduction in fluctuation of the battery input power profile with respect to the flywheel one. The latter is obtained thanks to different management of the two devices in terms of operating modes, implemented according also to their technical features and restrictions. It can be noticed that the results are uniform,

the HESS (with the implemented power management algorithm) achieving approximately the same performances in all three sites under all considered operating conditions.

The energy exchanges are evaluated below under the simulated conditions for all three sites. Based on the results of absorbed and released energy by the battery and flywheel, their operational efficiencies are determined. An average battery efficiency of 97% is found over all conducted simulations, while a 79.5% efficiency is evaluated for the flywheel. For what concerns the ratio between the wave energy produced and the amount processed by the HESS, it is emphasized that it varies within a range of 5% among the three sites, specifically between 78% and 83%. Regarding the global energy losses, the total energy delivered to the grid amounts, as the average value among the three sites, to 94.7% of the wave converters production, thus with an average energy penalty of 5.3%. These values are consistent with the operation energy efficiency determined for the battery and the flywheel, considering that only 17–22% (taking into all the three sites) of the produced energy is managed by the HESS being not directly delivered to the grid.

7. Conclusions

Among the RES, wave energy arouses a broad interest in research because of its very high theoretical potential. Even if only few of the WEC technologies have reached commercial maturity, many efforts are addressed to increase the efficiency of generation, one of the greatest issues is related to the grid connection. Therefore, many research activities deal with ESS integration with renewables in order to improve power quality and grid safety. In this work, flywheel-Li-ion battery HESS is employed for power smoothing towards the grid, aiming to maximize power generation and, at the same time, reducing harmful fluctuations for grid stability. The advantages of SPSA power management on HESS allow a reduction of more than 80% of power oscillations at the PCC, with an average energy penalty slightly higher than 5%. Furthermore, simulations demonstrate that flywheel features can extend Li-ion battery lifespan, decreasing battery solicitations of more than 64% with respect to flywheel fluctuations.

Data availability

Underlying data

The National Oceanic and Atmospheric Administration WAVEWATCH III model data used in this study is available here: https://polar.ncep.noaa.gov/waves/ensemble/download.shtml

The Climate Forecast System Reanalysis (CFSR) dataset used in this study is openly available upon registration here: https://rda.ucar.edu/datasets/ds093.1/#!access

Zenodo: An effective solution to boost generation from waves: benefits of HESS integration to wave energy converter in grid-connected systems. https://doi.org/10.5281/zenodo.5993310[49].

This project contains the following underlying data:

- Flywheel_power_ramp_site_1.csv (flywheel power saturation data for site 1)
- Flywheel_power_ramp_site_2.csv (flywheel power saturation data for site 2)
- Flywheel_power_ramp_site_3.csv (flywheel power saturation data for site 3)
- Grid_power_ramp_site_1.csv (grid power saturation data for site 1)
- Grid_power_ramp_site_2.csv (grid power saturation data for site 2);
- Grid_power_ramp_site_3.csv (grid power saturation data for site 3);
- Statistics_power.csv (data relating to Figure 4 for the three considered sites);
- Statistics_bandwidth.csv (bandwidth data relating to Figure 4 for the three considered sites);
- Statistics_ratio.csv (ratio data relating to Figure 4 for the three considered sites).
- Statistics_ramp.csv (power ramp data relating to Figure 4 for the three considered sites).#

Extended data

Zenodo: An effective solution to boost generation from waves: benefits of HESS integration to wave energy converter in grid-connected systems. https://doi.org/10.5281/zenodo.5993310[49].

This project contains the following extended data:

- wave_sim.mat (in this file the main simulations data are saved and can be opened through the free software GNU Octave, loading it in the workspace with the command: load ‘wave_sim.mat’. The profiles of Figure 8 can be reproduced in GNU Octave loading wave_sim.mat and plotting the following files: day1_S1, day2_S1, day3_S1, day4_S1, day5_S1, day1_S2, day2_S2, day3_S2, day4_S2, day5_S2, day1_S3, day2_S3, day3_S3, day4_S3, day5_S3).
- 1hour_profile.mat (in this file the hourly power profile of site 1 is saved and can be opened through GNU/Octave loading it in the workspace with the command: load ‘1hour_profile’).
- pdf_site1_data.mat (in this file the data related to the probability density function of site 1 are saved and can be opened through GNU/Octave loading it in the workspace with the command: load ‘pdf_site1_data’).
- pdf_site2_data.mat (in this file the data related to the probability density function of site 2 are saved and can be

opened through GNU/Octave loading it in the workspace with the command: load 'pdf_site2_data').

- pdf_site3_data.mat (in this file the data related to the probability density function of site 3 are saved and can be opened through GNU/Octave loading it in the workspace with the command: load 'pdf_site3_data').

- Smoothing_site_1.mat (in this file the data of the smoothed power and generated power relating to site 1 are saved and can be opened through GNU/Octave loading it in the workspace with the command: load 'Smoothing_site_1.mat').

- Smoothing_site_2.mat (in this file the data of the smoothed power and generated power relating to site 2 are saved and can be opened through GNU/Octave loading it in the workspace with the command: load 'Smoothing_site_2.mat').

- Smoothing_site_3.mat (in this file the data of the smoothed power and generated power relating to site 3 are saved and can be opened through GNU/Octave loading it in the workspace with the command: load 'Smoothing_site_3.mat').

Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

Acknowledgements

The H2020 IMAGINE project is acknowledged for providing generated power profiles corresponding to specific sea states. The project I.Ph.D.@UNIPG is also acknowledged.

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Version 2

Reviewer Report 10 May 2024

https://doi.org/10.21956/openreseurope.17795.r39296

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The paper introduces a novel strategy aimed at enhancing power quality within wave energy converters through the integration of hybrid energy storage systems. While the simulation results exhibit promising outcomes, a critical evaluation reveals several areas warranting enhancement, notably in terms of methodological depth, comprehensive cost analysis, and rigorous energy sizing evaluation. Overall, the manuscript presents some insights, yet it requires substantial refinement to meet the rigorous standards expected. Strengthening technical rigour and addressing identified shortcomings are imperative steps toward elevating the manuscript's scholarly contribution. In general, the study fails to provide sufficient details for replication, hindering the reproducibility of the results. A better presentation of dynamical models involved, for simulation and assessment, related, for example, to the flywheel and DC bus, must be included. Find below some crucial comments and concerns:

- To the best of this reviewer's knowledge, the use of supercapacitors is more common in the literature than flywheels. A cost analysis, a concrete and specific analysis to support the decision of considering flywheels, i.e. a mechanical-based energy storage system, must be provided.

- It is worth noting that the reference provided for the literature review on WEC systems (Reference 5) is outdated (2010), overlooking the significant advancements that have occurred in WEC technology over the past 15 years. Updating this reference to include more recent studies would ensure a more comprehensive review of the current state-of-the-art in WEC systems: Please update this reference with a more recent study.

- The power synthesis in Fig. 3 is confusing. Have waves been synthesised for each of the points (Fig 1) using the PW spectrum? Then, based on the synthesised waves, are power profiles, such as the one shown in Fig. 3, estimated? If so, what variables of peak period, significant height, etc., are considered? This aspect is presented very loosely, and needs to be reinforced. Just in case, and given the subsequent sections in the manuscript, if this procedure is related to the effect introduced by the flywheel, this is not realistic at all.

- The following paragraph (before Eq. (3)) "The differences among the three vectors are analysed for each site, considering as a principal comparison criterion the distribution...". It is not clear how you plan to smooth and 'ramp' the power profile. In essence, what's the plan for physically dissipating the power profile? What's the benefit or requirement for this procedure? The expression Eq. (3) is a filtered version of the power profile, how is this definition made? This aspect must be clarified.

- There is a misuse of the term bandwidth (Fig 4), which must be related to spectral bandwidth (Hz or rad/s), however the manuscript considers this terms as a power measure. Correct and clarify this crucial aspect.

- There is no model presented for the Li-io battery nor the flywheel. This aspects make the study impossible to replicate or assess.

- No model is presented for the Li-ion battery or the flywheel. This aspect makes the study impossible to replicate or assess. This has to be discussed and explained in the manuscript. At a minimum, there should be a discussion to support the decision to omit the inclusion of a mathematical model. Similarly, the DC bus is not explained, including its efficiency factor.

- What are the columns in Figs. 8 and 12? Please, and in general, Figures must be clearly explained, presented, and discussed.

- Can the authors provide more detailed information on the efficiency of the HESS connected power converter and how it impacts the overall performance of the system?

- How was the cost and energy density comparison between different storage systems, specifically Li-ion batteries and supercapacitors, conducted, and what were the key findings?

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
No

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
No

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Control systems; dynamical systems; Wave Energy Systems.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 26 October 2023

https://doi.org/10.21956/openreseurope.17795.r34906

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Marzio Barresi
Politecnico di Milano, Milan, Italy

Luigi Piegari
Polytechnic University of Milan, Milan, Italy

Several comments of this reviewer have been neglected (or rejected).

Even if the paper is improved, the reviewers remain of their original idea that some parts could be better explained (e.g., the SoC diagrams could have been added to the results, the proposed sizing procedure is not optimal, i.e. a smaller FESS could give the same advantages, ...).

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Power electronics for renewables, batteries and automotive, electrical drives, electrochemical storage modeling

We confirm that we have read this submission and believe that we have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however we have significant reservations, as outlined above.

Author Response 07 Nov 2023

Federico Gallorini

Below further details are provided according to the specific comments of the reviewers, relative to the need of integration of SoC diagrams obtained in simulation and details relative to the flywheel sizing with particular reference to its maximum power. SoC profiles, obtained through simulation in reference to the day 1 (similarly to what depicted in Figure 12) for all the investigated sites, can be integrated in the Results section. Figure 13 can be added to the manuscript.

Figure 13 [a], [b], [c]. Instantaneous battery SoC and flywheel speed for: a) site 1, b) site 2 and c) site 3 in day 1.

With regards to flywheel sizing, it is highlighted as it doesn't follow an optimization procedure, being implemented based on the methodology described in Section 5 and illustrated in Figure 11. Specifically, a sensitivity analysis on power ramp at the PCC varying flywheel maximum power is performed for all the investigated 5 days for all the sites. As evident from Figure 11, grid power ramp (in terms of 90% CDF assessed on the basis of the simulated power ramp profiles relative to the investigated 5 days for each site) reduces increasing flywheel maximum power (starting from 11 kW) and it stabilizes at around 33 kW for all the considered days in the three sites. A further increase over such a power does not contribute to a further reduction in the grid power ramp; this indicates that higher flywheel powers are unnecessary for the studied application.

Competing Interests: No competing interests were disclosed.

Version 1

Reviewer Report 28 July 2022

https://doi.org/10.21956/openreseurope.15154.r29630

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The paper is an interesting example of how a hybrid energy storage system including a Li-ion battery and a flywheel has been developed and implemented with the purpose of reducing power oscillations produced by WEC system and sent to the grid.

Dynamic simulations were carried out in MATLAB® Simulink environment considering three different wave power profiles.

Obtained results demonstrate how the proposed HESS and the implementation of the SPSA power management coupled to a WEC allow a reduction of more than 80% of power oscillations at the Point of Common Coupling (PCC).

Comments are the following:

- Author presents only one drawing for only one WEC system in Fig.2. It may be interesting to include in the section "Introduction" several concepts for wave energy conversion and the principle of energy conversion that can use a Hybrid Energy Storage System (HESS).

- The efficiency of HESS connected power converter is missing. This data shall be included for maintaining the readership of the Journal.

- Cost and Energy density of FESS shall be presented, as shown on pg. 4 for SCs.

- The sizing of energy storage is not clear, this data shall be added that could show the purpose of the study is fully covered using FESS/HESS.

- Power converters control modelling and used topologies are also missing in the study. It would be beneficial for the readers to have this information available.

- Li-ion batteries are being complemented with Flywheel energy storage, this study lacks the information about the SOCs of the batteries and the power losses during the operation.

- Efficiency of the DC-DC power converter could be presented in buck and boost mode for the three sites investigated.

- Authors write “In this paper, HESS consisting of a Li-ion battery and a flywheel is coupled to a Wave Energy Converter (WEC) that operates in grid connected mode”.

It is interesting what the model of flywheel-Li-ion battery HESS looks like. Constriction and

connection principal to WEC.

- Authors write on Page 3 “The Power Take-Off (PTO) subsystem, which converts the captured wave energy (by the prime mover) into electricity. The most common typologies are: hydraulic PTO, electro-mechanical PTO, linear generators, air turbine and low head water turbine”.

Technical aspects: for example how to connect flywheels to linear generators? From my point of view, it is almost impossible to do. But even if it succeeds, it will be a complicated mechanical system that takes resources and becomes costly.

- It is good to adjust the scale in Fig.12 so that empty spaces are not so large.
- The authors have laid out in a very reasonable manner how simulations demonstrate that flywheel features can extend Li-ion battery lifespan, decreasing battery solicitations of more than 64% with respect to flywheel fluctuations.
- The article referenced some relevant references on HESS. However few more references shall be included showing the HESS studies (Li-on Batteries/SCs/Flywheel/Fuel Cells).
- An overall overview of the Electrical power system used in this study shall be included.

The paper presents an interesting approach to reducing power fluctuations. It is a good platform for evaluating offshore experiments.

Data is provided in Matlab. However, reproducing the experiment in more detail would significantly improve the paper. The paper is relevant for indexing.

We confirm that we have read this submission and acknowledge that it is of an acceptable scientific standard.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
No

If applicable, is the statistical analysis and its interpretation appropriate?
I cannot comment. A qualified statistician is required.

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Wave power systems for renewable energy conversion; HESS and Grid Integration; Power quality, Flickers and transients analysis at the PCC; linear and rotational wave

energy converters; electromechanical design

We confirm that we have read this submission and believe that we have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 01 Aug 2023

Linda Barelli

POINT TO POINT ANSWERS TO REVIEWERS The paper is an interesting example of how a hybrid energy storage system including a Li-ion battery and a flywheel has been developed and implemented with the purpose of reducing power oscillations produced by WEC system and sent to the grid. Dynamic simulations were carried out in MATLAB® Simulink environment considering three different wave power profiles. Obtained results demonstrate how the proposed HESS and the implementation of the SPSA power management coupled to a WEC allow a reduction of more than 80% of power oscillations at the Point of Common Coupling (PCC). Comments are the following:

- Author presents only one drawing for only one WEC system in Fig.2. It may be interesting to include in the section "Introduction" several concepts for wave energy conversion and the principle of energy conversion that can use a Hybrid Energy Storage System (HESS).

We considered this suggestion in the review process of the manuscript

- The efficiency of HESS connected power converter is missing. This data shall be included for maintaining the readership of the Journal.

We included it as follows: “Moreover, considering the specific application, under the assumption of connecting the components in a common DC bus, a buck/boost converter with efficiency of 0.95 was taken into account for both storage units.”, in Section 4.1.

- Cost and Energy density of FESS shall be presented, as shown on pg. 4 for SCs.

Ok, we added the costs related to FESS.

- The sizing of energy storage is not clear, this data shall be added that could show the purpose of the study is fully covered using FESS/HESS.

Table 6 reassumes the final sizing of the HESS components, according to the methodology developed, as described in Section 5.

- Power converters control modelling and used topologies are also missing in the study. It would be beneficial for the readers to have this information available.

The aim of this preliminary study is to demonstrate the benefits introduced by HESS coupling to WECs. A schematic view of the electrical architecture is added in Figure 9a. Anyway, the design and control of the converters is out of the scope of the presented work and must be implemented in a future paper.

- Li-ion batteries are being complemented with Flywheel energy storage, this study lacks the information about the SOCs of the batteries and the power losses during the operation.

The HESS was modeled according to previous refs of the Authors (such as https://doi.org/10.3390/en11020396). Specifically, Flywheel is a low-speed mechanical flywheel, and it is implemented taking into account the aerodynamic and bearing losses in reference to the current rotational speed. The Li-ion battery is instead modeled by means of real measurements of open circuit voltages and internal resistances during

charge/discharge at varying the state of charge. It is defined in Section 4.1 according to reviewers' suggestions: "Specifically, the Li-ion battery and flywheel are implemented on the basis of their governing equations. Further details on the HESS implementation can be found in [1], [41-42]. Regarding the battery, open circuit voltage and internal resistance data were gathered by the authors, varying the state of charge in both charging and discharging phases, through a dedicated experimental campaign and implemented in the Simulink model. For what concerns the flywheel, the instantaneous delivered/absorbed power is computed taken into account the instantaneous aerodynamic and friction power losses according to the current flywheel speed value. " As regards SOCs of the HESS, the Authors avoided to put many figures in the paper to improve the readability with a focus on the power smoothing aspects introduced by HESS since several simulations were carried out. Nevertheless, SOC trends can be found in the additional data at the link http://www.doi.org/10.5281/zenodo.5993310.

- Efficiency of the DC-DC power converter could be presented in buck and boost mode for the three sites investigated.

As previously described, the efficiency of the buck/boost converters is fixed at 0.95 for both the operating modes.

- Authors write "In this paper, HESS consisting of a Li-ion battery and a flywheel is coupled to a Wave Energy Converter (WEC) that operates in grid connected mode". It is interesting what the model of flywheel-Li-ion battery HESS looks like. Constriction and connection principal to WEC.

According to reviewers' suggestion, a schematic view of the electric connection to the WEC and the overall architecture is reported in Figure 9a.

- Authors write on Page 3 "The Power Take-Off (PTO) subsystem, which converts the captured wave energy (by the prime mover) into electricity. The most common typologies are: hydraulic PTO, electro-mechanical PTO, linear generators, air turbine and low head water turbine". Technical aspects: for example how to connect flywheels to linear generators? From my point of view, it is almost impossible to do. But even if it succeeds, it will be a complicated mechanical system that takes resources and becomes costly.

The flywheel is not directly connected to the linear generator. The HESS (i.e., consisting of FESS and BESS) is interfaced with the WECs by means of a common DC bus. Therefore, HESS operates absorbing/delivering power to the electric power produced by the WEC, without any interference with the PTO of the latter.

- It is good to adjust the scale in Fig.12 so that empty spaces are not so large.

We adjusted Figure 12 according to the suggestion.

- The authors have laid out in a very reasonable manner how simulations demonstrate that flywheel features can extend Li-ion battery lifespan, decreasing battery solicitations of more than 64% with respect to flywheel fluctuations.

Although this aspect is out of the paper's scope, the Authors already demonstrated that HESS consisting by flywheel and Li-ion battery, thanks to the peak-shaving function operated by flywheel towards the battery, can strongly extend the battery lifespan, as found in our previous works: 1) https://doi.org/10.1016/j.energy.2019.02.143, 2) https://doi.org/10.3390/en12163138, 3) 10.1016/j.est.2020.102050.

- The article referenced some relevant references on HESS. However, few more references shall be included showing the HESS studies (Li-on

Batteries/SCs/Flywheel/Fuel Cells).

We added refs. [31-35] as other noteworthy studies on hybrid energy storage systems.

- An overall overview of the Electrical power system used in this study shall be included.

As previously mentioned, a schematic overview of the electrical power system is reported in Figure 9a.

- The paper presents an interesting approach to reducing power fluctuations. It is a good platform for evaluating offshore experiments.
- Data is provided in Matlab. However, reproducing the experiment in more detail would significantly improve the paper. The paper is relevant for indexing.

We already provided and explained all the data for simulation reproduction, as annexed to the paper.

Competing Interests: No competing interests were disclosed.

Reviewer Report 12 April 2022

https://doi.org/10.21956/openreseurope.15154.r28907

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Luigi Piegari
Polytechnic University of Milan, Milan, Italy
Marzio Barresi
Politecnico di Milano, Milan, Italy

The paper deals with the use of hybrid energy storage systems with wave energy converters to improve the power quality of wave generators.
Even if the idea is interesting, in the opinion of the reviewers, the paper does not completely achieve the claimed goals. It is worth noting that several data are provided in Matlab environment. Nevertheless, the minimum data to reproduce the experiment should be explained in the text, since using data already produced is very difficult and time-spending.

The major points that should be addressed are detailed in the following:

- The efficiency of the storage units is given as a final data but it is not clear how it has been obtained. Indeed, there is no detailed model of the storages. The model used to simulate the storage units and their efficiencies should be provided.

- A cost analysis is necessary to understand the results. Indeed, for the data reported in the paper, FESS is much less efficient than batteries. Therefore, the additional cost related to energy losses should be accounted for to verify if this solution is better than using a bigger battery substituting it at the end of life.

- the size of the FESS is established only based on the power ramp. The battery power is obtained to complement the required power. There is no information about the energy sizing of each storage. This is very important to understand if the storages can accomplish their mission without being fully charged or discharged. The analysis of the state of charge during the simulated days should be added to the paper.

- Other sizing procedures should be studied and results compared with the proposed one. Indeed, the optimal size of flywheel and batteries could be different from the one obtained with the simple procedure proposed in the paper (i.e. FESS power = required power ramp).

- BESS and FESS need a power converter to connect to the grid. How the efficiency of these converters has been taken into account?

- An overall scheme of the electrical power system plant should be added to the paper.

Some other minor comments are the following:

- FESS can experience problems if subjected to high accelerations. Usually, a platform in the sea can be subjected to these accelerations. Some considerations about the feasibility of using FESS for this application could be interesting.

- Some details about the implementation of the control could improve the readability. For example, are the authors supposing that the power converter can precisely follow the references? How this hypothesis can affect the final results?

- When acronyms are defined uppercase should be avoided (e.g. "*Wave Energy Converters (WECs)*" should be "*wave energy converters (WECs)*").

- In the sections, before starting with subsections, a few sentences to introduce the topic could be added.

- At pag. 4, col. 1, cost and energy density of SCs are compared with those of FESS. For a fair comparison, also the cost and the energy density of the FESS should appear in the text.

- Fig. 8 is difficult to read and its content is not very significant. Probably it could be eliminated leaving space for figures reporting more interesting data (e.g. the SOCs of the HESS during operation, the losses of the storages...).

- In Table 5, "A" (uppercase) is reported twice (with two different values). Likely, one of the two should be "a" (lowercase).

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
No

If applicable, is the statistical analysis and its interpretation appropriate?
I cannot comment. A qualified statistician is required.

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Power electronics for renewables, batteries and automotive, electrical drives, electrochemical storage modeling

We confirm that we have read this submission and believe that we have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however we have significant reservations, as outlined above.

Author Response 28 Apr 2022

Federico Gallorini

POINT TO POINT ANSWERS TO REVIEWER (Reviewer comments in italics)

The major points that should be addressed are detailed in the following:

- *The efficiency of the storage units is given as a final data but it is not clear how it has been obtained. Indeed, there is no detailed model of the storages. The model used to simulate the storage units and their efficiencies should be provided.*

As written in the paper, the described dynamic model was developed and detailed in our previous papers. Specifically, the li-ion battery and flywheel were implemented on the basis of mathematical equations. For what concerns flywheel, the instantaneous delivered or absorbed power was computed taken into account the instantaneous aerodynamic and friction power losses according to the current flywheel speed value. Moreover, considering the specific application, under the assumption of connecting the components in a common DC bus, a buck/boost converter efficiency of 0.95 was taken into account both for battery and flywheel. For sake of clarity, we can add the following part to the “Modeling considerations” section:
“Specifically, the li-ion battery and flywheel are implemented on the basis of their governing equations. Further details on the HESS implementation can be found in [1], [41-42]. For what concerns the flywheel, the instantaneous delivered/absorbed power is computed taken into account the instantaneous aerodynamic and friction power losses according to the current flywheel speed value. Moreover, considering the specific application, under the assumption of connecting the components in a common DC bus, a buck/boost converter efficiency of 0.95 was taken into account for both the storage units.”

- *A cost analysis is necessary to understand the results. Indeed, for the data reported in the paper, FESS is much less efficient than batteries. Therefore, the additional cost related to*

energy losses should be accounted for to verify if this solution is better than using a bigger battery substituting it at the end of life.

Although we understand the importance of a cost analysis of the hybrid energy storage integration in wave energy converters for power smoothing, the paper's main aim is not addressed to such evaluation. Anyway, we already assessed the benefits of flywheel-li-ion battery integration into a renewable power plant in our previous several papers (INS. RIF.). Specifically, flywheel's peak shaving function acting on the battery allows to reduce harmful power spikes strongly enhancing battery lifespan. We proved such results both by applying rainflow cycle counting algorithm (https://www.mdpi.com/1996-1073/12/16/3138; https://doi.org/10.1016/j.est.2020.102050) and conducting experimental tests (https://doi.org/10.1016/j.energy.2019.02.143).

- *The size of the FESS is established only based on the power ramp. The battery power is obtained to complement the required power. There is no information about the energy sizing of each storage. This is very important to understand if the storages can accomplish their mission without being fully charged or discharged. The analysis of the state of charge during the simulated days should be added to the paper.*

The same procedure to determine power and capacity of the HESS components was followed, as reported in the paper, Section 5: **"a first assumption in reference to both storage devices is made starting from the cumulative distribution of the power ramp calculated according to eq. (3). It is noted that the storage devices are customized one at a time, aiming to avoid/minimize saturation in power and capacity; so, the flywheel rating (both in power and capacity) is adjusted first, assuming a very large battery, since the flywheel is more adequate to fast response operation (i.e. power smoothing). The capacity and maximum power of the flywheel are determined so that the saturation objective is achieved. Further, the capacity of the battery is adjusted (so, considering the C-rate also the power), following the same objective in terms of saturation."** Therefore, storage units accomplish their mission without being fully charged or discharged during the daily simulations.

- *Other sizing procedures should be studied and results compared with the proposed one. Indeed, the optimal size of flywheel and batteries could be different from the one obtained with the simple procedure proposed in the paper (i.e. FESS power = required power ramp).*

The presented procedure for sizing was developed for this specific application in order to properly work with the implemented power management algorithm (SPSA). In fact, the power management strategy pursues its objective of reducing power oscillations produced by the WECs and providing a smoothed instantaneous power profile at the point of common coupling. Such an algorithm acts on the instantaneous power ramp of the generation, mitigating the oscillations by means of requiring/providing a certain amount of power to the storage units. Therefore, comparing the sizing procedure of this work with other ones is outside of the paper's purpose.

- *BESS and FESS need a power converter to connect to the grid. How the efficiency of these converters has been taken into account?*

How it is pointed out in the first answer, we assumed an efficiency equal to 0.95 for the HESS converters and it is implemented in the dynamic model acting on the instantaneous power delivered/provided by the storage components, increasing the amount of power sent to the flywheel and battery during their charge and decreasing the power provided by the storage units during their discharge.

- An overall scheme of the electrical power system plant should be added to the paper.

As reviewers suggest, we can provide the electrical architecture of the plant in the paper for sake of clarity (see the following figure). This figure can be added in Figure 9.

Some other minor comments are the following:

- *FESS can experience problems if subjected to high accelerations. Usually, a platform in the sea can be subjected to these accelerations. Some considerations about the feasibility of using FESS for this application could be interesting.*

We thank the reviewers for pointing out this issue. Nevertheless, to avoid such problems and, at the same time, to better interface the system with the main grid, the installation of the storage units was assumed to be on the ground.

- *Some details about the implementation of the control could improve the readability. For example, are the authors supposing that the power converter can precisely follow the references? How this hypothesis can affect the final results?*

Since the model simulates a complex integrated system, we did not enter in details concerning the power converters, only considering their efficiencies. Thus, the dynamic model of the power converters was not included.

- *When acronyms are defined uppercase should be avoided (e.g. "Wave Energy Converters (WECs)" should be "wave energy converters (WECs)").*

Ok, we can modify the acronyms according to the reviewers' suggestions if the editor agrees.

- *In the sections, before starting with subsections, a few sentences to introduce the topic could be added.*

As reviewers suggested, we can introduce in the revised version of the paper the topics with a few sentences for the missing sections of the paper.

- *At pag. 4, col. 1, cost and energy density of SCs are compared with those of FESS. For a fair comparison, also the cost and the energy density of the FESS should appear in the text.*

We can add in the revised paper the values both for flywheel and supercapacitors. As indicated in [21], the total project cost is 75,000 $/kWh for SCs and 11,520 $/kWh for FESS.

- *12. Fig. 8 is difficult to read and its content is not very significant. Probably it could be eliminated leaving space for figures reporting more interesting data (e.g. the SOCs of the HESS during operation, the losses of the storages...).*

We think that the figure illustrates the intrinsic characteristics of the wave energy sector and the variability with respect to the sites.

- *13. In Table 5, "A" (uppercase) is reported twice (with two different values). Likely, one of the two should be "a" (lowercase).*

The second row (a) and third row (c) of Table 5 are to be in lowercase.

Competing Interests: No competing interests were disclosed.

Author Response 01 Aug 2023

Linda Barelli

POINT TO POINT ANSWERS TO REVIEWERS The paper deals with the use of hybrid energy storage systems with wave energy converters to improve the power quality of wave generators. Even if the idea is interesting, in the opinion of the reviewers, the paper does

not completely achieve the claimed goals. It is worth noting that several data are provided in Matlab environment. The major points that should be addressed are detailed in the following:

1. The efficiency of the storage units is given as a final data but it is not clear how it has been obtained. Indeed, there is no detailed model of the storages. The model used to simulate the storage units and their efficiencies should be provided.

As written in the paper, the described dynamic model was developed and detailed in our previous papers. Specifically, the li-ion battery and flywheel were implemented on the basis of mathematical equations. For what concerns flywheel, the instantaneous delivered or absorbed power was computed taken into account the instantaneous aerodynamic and friction power losses according to the current flywheel speed value. Moreover, considering the specific application, under the assumption of connecting the components in a common DC bus, a buck/boost converter efficiency of 0.95 was taken into account both for battery and flywheel. For sake of clarity, we added the following part to the "Modeling considerations" section: "*Specifically, the li-ion battery and flywheel are implemented on the basis of their governing equations. Further details on the HESS implementation can be found in [1], [41-42]. For what concerns the flywheel, the instantaneous delivered/absorbed power is computed taken into account the instantaneous aerodynamic and friction power losses according to the current flywheel speed value. Moreover, considering the specific application, under the assumption of connecting the components in a common DC bus, a buck/boost converter efficiency of 0.95 was taken into account for both the storage units.*"

1. A cost analysis is necessary to understand the results. Indeed, for the data reported in the paper, FESS is much less efficient than batteries. Therefore, the additional cost related to energy losses should be accounted for to verify if this solution is better than using a bigger battery substituting it at the end of life.

Although we understand the importance of a cost analysis of the hybrid energy storage integration in wave energy converters for power smoothing, paper's main aim is not addressed to such evaluation. Anyway, we already assessed the benefits of flywheel-li-ion battery integration into a renewable power plant in our previous several papers (INS. RIF.). Specifically, flywheel's peak shaving function acting on the battery allows to reduce harmful power spikes strongly enhancing battery lifespan. We proved such results both applying rainflow cycle counting algorithm (https://www.mdpi.com/1996-1073/12/16/3138; https://doi.org/10.1016/j.est.2020.102050) and conducing experimental tests (https://doi.org/10.1016/j.energy.2019.02.143).

1. the size of the FESS is established only based on the power ramp. The battery power is obtained to complement the required power. There is no information about the energy sizing of each storage. This is very important to understand if the storages can accomplish their mission without being fully charged or discharged. The analysis of the state of charge during the simulated days should be added to the paper.

The same procedure to determine power and capacity of the HESS components was followed, as reported in the paper, Section 5: "*a first assumption in reference to both storage devices is made starting from the cumulative distribution of the power ramp calculated according to eq. (3). It is noted that the storage devices are customized one at a time, aiming to avoid/minimize saturation in power and capacity; so, the flywheel rating (both in power and capacity) is adjusted first, assuming a very large battery, since the flywheel is more adequate to fast response operation (i.e. power smoothing). The capacity and maximum power of the flywheel are determined so that the saturation objective is achieved. Further, the capacity of the battery is*

adjusted (so, considering the C-rate also the power), following the same objective in terms of saturation." Therefore, storage units accomplish their mission without being fully charged or discharged during the daily simulations.

1. Other sizing procedures should be studied and results compared with the proposed one. Indeed, the optimal size of flywheel and batteries could be different from the one obtained with the simple procedure proposed in the paper (i.e. FESS power = required power ramp).

The presented procedure for sizing was developed for this specific application in order to properly work with the implemented power management algorithm (SPSA). In fact, the power management strategy pursues its objective of reducing power oscillations produced by the WECs and providing a smoothed instantaneous power profile at the point of common coupling. Such algorithm acts on the instantaneous power ramp of the generation, mitigating the oscillations by means of requiring/providing a certain amount of power to the storage units. Therefore, comparing the sizing procedure of this work with other ones, it is outside of paper's purpose.

1. BESS and FESS need a power converter to connect to the grid. How the efficiency of these converters has been taken into account?

How it is pointed out in the first answer, we assumed an efficiency equal to 0.95 for the HESS converters and it is implemented in the dynamic model acting on the instantaneous power delivered/provided by the storage components, increasing the amount of power send to the flywheel and battery during their charge and decreasing the power provided by the storage units during their discharge.

1. An overall scheme of the electrical power system plant should be added to the paper.

As reviewers suggest, we provided the electrical architecture of the plant in the paper for sake of clarity (see as Figure 9a). Some other minor comments are the following:

1. FESS can experience problems if subjected to high accelerations. Usually, a platform in the sea can be subjected to these accelerations. Some considerations about the feasibility of using FESS for this application could be interesting.

We thanks the reviewers for pointing out this issue. Nevertheless, to avoid such problems and, at the same time, to better interface the system with the main grid, the installation of the storage units was assumed to be on the ground.

1. Some details about the implementation of the control could improve the readability. For example, are the authors supposing that the power converter can precisely follow the references? How this hypothesis can affect the final results?

Since the model simulates a complex integrated system, we did not enter in details concerning the power converters, only considering their efficiencies. Thus, the dynamic model of the power converters was not included.

1. When acronyms are defined uppercase should be avoided (e.g. "Wave Energy Converters (WECs)" should be "wave energy converters (WECs)").

Ok, we modified the acronyms according to reviewers' suggestion.

1. In the sections, before starting with subsections, a few sentences to introduce the topic could be added.

As reviewers suggested, we introduced the topics with a few sentences for the missing sections of the paper.

1. At pag. 4, col. 1, cost and energy density of SCs are compared with those of FESS. For a fair comparison, also the cost and the energy density of the FESS should appear in

the text.

We added in the paper the total project costs both for flywheel and supercapacitors, as indicated in [21].

1. In Table 5, “A” (uppercase) is reported twice (with two different values). Likely, one of the two should be “a” (lowercase).

We found a mistake in the table. We modified the second (a) and third (c) term of Table 5 with lowercase.

Competing Interests: No competing interests were disclosed.