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Improved methodology for the optimal mixing of renewable energy sources and application to a multi-use offshore platform

Elisa Dallavalle [a,*], Barbara Zanuttigh [a], Pasquale Contestabile [b], Alessandro Giuggioli [c], Davide Speranza [c]

[a] University of Bologna, Viale Risorgimento 2, 40136, Bologna, Italy
[b] Università degli Studi della Campania "Luigi Vanvitelli", via Roma 29, 81031, Aversa, Italy
[c] Eni spa, Via Felice Maritano 26, 20097, San Donato Milanese, Italy

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ABSTRACT

The increase of Renewable Energy (RE) production to fight the climate crisis is posing new technological and financial challenges, due to the availability and variability of RE Sources (RES). These challenges can be addressed by selecting the most suitable mix of RES to optimise power production, to assure grid resilience and to promote local energy use. To facilitate the selection of such combination, this paper presents an original methodology that allows to compare mixing scenarios with different RES, also in presence of batteries and backup system. It simultaneously optimises the energy surplus with respect to the eventual external electrical load and the missing energy with respect to the same electrical load. This method, which can cope with isolated or plugged-to-grid systems, is here applied to a novel case study, an oil&gas platform under decommissioning, located in the Adriatic Sea (Italy). The RE production from wind, wave and solar panels is supposed to support other activities for the platform reuse, such as aquaculture, monitoring and mineral deposition. In this case, solar energy is providing the greatest contribution to the optimal mix in terms of production, while wave energy assures the most relevant contribution in terms of continuity.

1. Introduction

The need for adaptation to climate change and for independence from fossil fuels demands the exploitation of Renewable Energy Sources (RES) and the increase of Renewable Energy (RE) in the grid energy mix. The variability and uncertainty of RES, however, requires resilient power grids, facing the peaks and the transients. The selection of the RE mix to be integrated in the power system is therefore of outmost importance to accomplish the established RE targets while minimizing the technical impacts.

Studies about the optimal mix for the energy system at national scale, to define the target levels for sustainable development, are available for many countries [1]. proposed a linear optimisation model, comprising several economic, environmental and technical aspects, to determine the optimal mix for the energy system in the Czech Republic [2]. showed the application of the WITCH model [3] to the decarbonisation scenario, considering different storage technologies, carbon tax values, grid requirements and costs.

Recently, the interest in the technical issues to be overcome at local scale (i.e. grid scale) prompted works on case studies related to the integration of specific RES to support specific activities or to be plugged into specific grids [4]. first proposed a methodology for the optimal RE mix from different available technologies (hydro, wind and photovoltaic) considering the variability of the RE mix and the target share of RE in Portugal [5]. investigated a 100% solar-plus-wind only scenario for Morocco, by adopting a mismatch energy modelling approach with the objective of minimizing the required storage capacities [6]. proposed an optimisation model that minimizes the construction, operation and management costs, the fuel cost and the carbon emission cost while satisfying minimal demand requirement, maximal annual installation potential and RE standard constraints [7]. analysed the advantages and disadvantages of different RE mixes to meet local island requirements, finding that the addition of alternative RES and of alternative storage systems may lead to a feasible electricity price [8]. combined different RES to supply the energy demand of a desalinisation plant, setting up a methodology to maximise the energy production and the integrated

* Corresponding author.
E-mail addresses: elisa.dallavalle3@unibo.it (E. Dallavalle), barbara.zanuttigh@unibo.it (B. Zanuttigh), pasquale.contestabile@unicampania.it (P. Contestabile), alessandro.giuggioli@eni.com (A. Giuggioli), davide.speranza@eni.com (D. Speranza).

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energy plant operational time, based on the electrical load to be supported.

In this context, this paper aims at proposing a procedure for the optimal RES mixing that can be applied whatever the components of the system considered and that can provide the optimum balance among different RES, not only in terms of operational time and continuity, but also in terms of amount of energy production. This method is based on the preliminary work by Ref. [8] and it will be here applied to an innovative case study, seeking to test technologies for the potential reuse of offshore platforms.

The PlaCE (Offshore Platform Conversion for Eco-sustainable Multiple Uses) project [9], working under the National Operative Programme (PON) on research and innovation and funded by the Italian Ministry of Research and University, aimed at boosting the Blue Growth sector at local and national scale and was based on an oil and gas (O&G) platform in the Adriatic Sea whose operational life has ended. Here, an integrated installation was set-up to produce energy by solar panels and to reuse it locally for the operation of the technologies for platform maintenance. The integration of other RES, i.e. wind and waves, will be investigated in this particular case (an isolated system with very limited energy requirements) through the proposed original methodology for the optimal mixing, significantly different from what was tested by Ref. [8].

The paper structure is as follows. Section 2 describes the methodology. Section 3 presents the case study, an O&G platform in the Adriatic Sea, including an overview of the PlaCE project, and identifies the different activities that could be carried out at the platform. Also, the available wind, wave and solar energy potentially present at the platform location are analysed. In section 4, the potential energy production for each RES and the required electrical loads are assessed. Section 5 applies the developed methodology for the optimal mix to the case study, discussing its exportability in different situations. Conclusions are drawn in Section 6.

2. The methodology for the selection of the optimal mix

This Section presents the original methodology for the selection of the optimal mixing, starting from the overview of its steps (Sub-section 2.1), including the fundamentals (Sub-section 2.2), outlining the results (Sub-section 2.3) and discussing the advantages (Sub-section 2.4).

2.1. Overview of the method

The methodology is synthetically described in Fig. 1.

The method consists of three main steps, starting from a preliminary evaluation of the RES availability and of the energy needs at the considered location, continuing with the definition of the technical characteristics of the system and concluding with the procedure for the optimal RES mixing. Specifically, the steps are the following.

1. Step 1. Assessment.

In this step, the assessment is twofold, since it involves on one side the assessment of the available RES at the site and on the other side the assessment of the energy required by co-located activities.

The activities to be performed in this step include therefore.

- the identification of the available RES which could be combined together at the site;
- the identification of the available RES datasets and the retrieval of climatic information with the minimum time interval (e.g., hour);
- the retrieval of hourly data of available RES;

and

- the identification of the energy consuming activities to be powered by RES within the considered system;
- the calculation of the total hourly energy demand (i.e. the same time interval for which RES data are available).

2. Step 2. Design.

In this step, the most suitable devices for energy conversion are selected, based on the specific location requirements and on different specific procedures for each considered RES; then, for each selected device, the power curves or matrices are retrieved and the produced RE is calculated. Specifically, the hourly produced energy is obtained for each device by combining the hourly available RES data and the power curve or matrix.

The technical characteristics of the additional components of the system, including the eventual storage systems (e.g. batteries), the backup system and the possibility of grid connection, are also selected.

3. Step 3. Optimisation.

In this step, the optimal RES mixing is evaluated, considering the defined technical characteristics of the system components, such as batteries and backup system. The main criteria for the optimisation, depending on the specific site conditions, consist of.

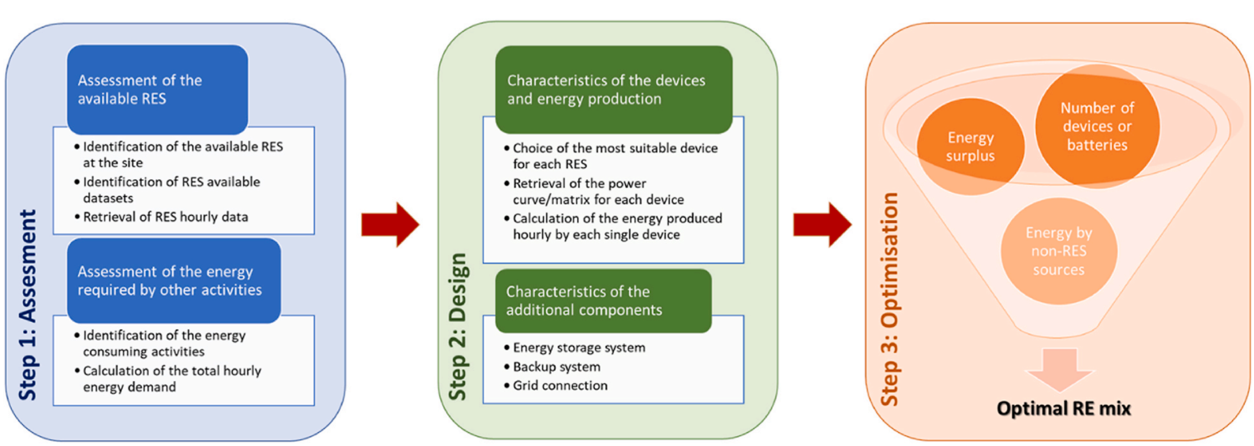

Fig. 1. Overview of the methodological steps.

- the minimisation of the energy surplus, in absence of grid connection, or its balancing in case of plugged-to-grid systems;
- the minimisation of the required energy by sources different from RES, given the maximum available marine space for offshore installations;
- the minimisation of the number of devices given the number of batteries or vice versa.

The methodology is described in more detail in the following Sub-Sections.

2.2. Fundamentals

The method requires as input.

- the hourly data of available energy from RES,
- the production curve of the selected devices for RE conversion,
- the hourly energy demand of the co-located activities,
- the technical characteristics of the additional components of the system (e.g. batteries).

The data type of hourly available energy depends on the RES considered in the analysis (e.g. wave height and period; wind speed at turbine height; solar irradiance per unit area, see Section 3.4). From this data, it is possible to obtain the hourly energy produced from the selected device for each resource, through different procedures (see for example [8]; for wave and solar energy, and [10]; for wind energy) which also depend on the considered RES. For example, in the case of Wave Energy Converters (WECs), a power matrix usually relates the wave height and period to the produced power; in the case of wind turbines, a power curve relates the wind speed at the turbine height to the produced power; photo-voltaic (PV) panels characteristics, as efficiency and installation angle, can provide the produced energy from the solar irradiance (see Section 4.1).

The hourly values of the produced energy from each RES can be added together, obtaining an hourly value of total available energy E_a, which can be compared hour per hour with the energy required by the co-located activities E_r. The co-located activities may include for instance an offshore transportation hub, a floating greenhouse, aquaculture, fish farming, tourism (through a rig-to-reef experience or a recreational hub).

The energy balance can be hour per hour verified, and the hourly energy surplus or hourly energy missing can be therefore calculated, either neglecting or considering the presence of storage systems (see Sections 5.1 and 5.2).

If we define (Eq. (1)):

$$\Delta E_i = E_{a,i} - E_{r,i} \qquad \text{Eq. 1}$$

where $E_{a,I}$ is the available energy at hour i (depending on the number and type of selected RES and related devices) and $E_{r,i}$ is the required energy at hour i (depending on the energy consuming activities), in the first case (absence of storage systems, storage capacity set to zero), ΔE_i is detected either as energy surplus (if $E_a > E_r$) or energy missing (if $E_a < E_r$).

In the second case, if a storage system (e.g. battery system) is present, in order to calculate the energy amount inside the batteries at each hour, the following procedure can be used (Eq. (2)):

$$E_{b,i} = \begin{cases} E_{b,max}, \left(E_{b,i-1} + \Delta E_i\right) \geq E_{b,max} \\ E_{b,i-1} + \Delta E_i, 0 < \left(E_{b,i-1} + \Delta E_i\right) < E_{b,max} \\ 0, \left(E_{b,i-1} + \Delta E_i\right) \leq 0 \end{cases} \qquad \text{Eq. 2}$$

where: $E_{b,i}$ is the energy in the batteries at hour i, with $0 \leq E_{b,i} \leq E_{b,max}$; $E_{b,max}$ is the maximum batteries capacity; $E_{b,1} = E_{b,max}$ (batteries are initially full).

The energy surplus $E_{s,i}$ at hour i and the energy missing $E_{m,i}$ at hour i can be respectively calculated through Equations (3) and (4):

$$E_{s,i} = \begin{cases} \Delta E_i - \Delta E_b, E_{b,i} = E_{b,max} \\ 0, E_{b,i} < E_{b,max} \end{cases} \qquad \text{Eq. 3}$$

$$E_{m,i} = \begin{cases} E_{b,i-1} + \Delta E_i, E_{b,i} = 0 \\ 0, E_{b,i} > 0 \end{cases} \qquad \text{Eq. 4}$$

where: $\Delta E_b = E_{b,i} - E_{b,i\text{-}1}$

This calculation is carried out for each hour for the whole period considered (one typical year, in this case study: $i_{max} = 8760$) and all the $E_{s,i}$ values are added up, as well as all the $E_{m,i}$ values, to obtain the total (annual, in this case) energy surplus (Eq. (5)) and energy missing (Eq. (6)):

$$E_{s,y} = \sum_{i=1}^{8760} E_{s,i} \qquad \text{Eq. 5}$$

$$E_{m,y} = \sum_{i=1}^{8760} E_{m,i} \qquad \text{Eq. 6}$$

Also, it is possible to obtain the hours when there is a lack of RES supply (i.e. number of hours when $E_{m,i} \neq 0$) and to compare the total energy surplus and energy missing in different scenarios, by varying the number of devices (i.e. $E_{a,i}$) or the number and kind of batteries, if present (i.e. $E_{b,max}$).

2.3. Results of the method

Based on the data provided, known the structure of the system, by varying the number of devices or batteries, the proposed methodology allows to achieve different results, reported in the following.

In absence of energy storage systems, the method allows to maximise the time during which the power threshold is instantly satisfied by the available RES. This parameter, called t_{RES}, is complementary to t_{LS}, that is the time during which a backup system is needed. This kind of analysis can be applied in the case of plugged-to-grid systems which don't need the use of batteries, see for example [8]; where an integrated system of PV panels and WECs was designed to provide energy to a desalination plant in Tenerife in the most continuous way possible, with no redistribution of the energy through storage systems. In this case, the energy surplus was supposed to be directly transferred to the electrical grid and a backup system assured a constant power threshold in case of lack of RE production.

On the other side, in presence of batteries, the instantaneous energy peaks can be smoothed out and the energy surplus can be redistributed when RES production is insufficient. The method allows in this case to simultaneously optimise the amount of energy surplus and the amount of missing energy with respect to the external electrical load required by the co-located activities. This is the case of isolated systems, disconnected from the electrical grid, like many offshore platforms. In this situation, the proposed method allows to identify the different combinations of devices which set at zero the missing energy and minimize the energy surplus.

Thus, in the most general case, i.e. a system connected to the grid and equipped with a storage system and a backup system, the method allows to identify the various combinations of devices which ensure the best balance of energy surplus and missing energy.

Also, considering the inverse problem, once selected the number and kind of devices, the method can provide the minimum number of batteries allowing to continuously meet the energy requirements with no lack of supply and therefore no need of backup systems.

2.4. Advantages of the method

Differently from what reported by Ref. [8]; the upgraded method here proposed makes it possible to determine the optimal RES mixing not only on the basis of the instant meeting of the energy demand hour by hour through the available RES, as in the case of the maximisation of t_{RES}, but also considering the overall amount of available and required energy, which can be balanced by means of a storage system. The different RES combinations can be analysed in more detail, also identifying the ones which allow to continuously satisfy the energy requirements for 100% of the hours, with no need of fossil-based backup systems.

The method is therefore even more generally applicable and can provide personalized outputs based on the characteristics of the system and on the user's specific needs. The method can thus be applied regardless of.

- the number and kind of RES considered and the trend of the energy production of the devices;
- the number and kind of energy-consuming activities considered and the trend of the energy requirements over time;
- the fact that the examined integrated system is isolated or connected to the grid;
- the presence or absence of storage systems.

Hence, the methodology turns out to be a useful tool for the conceptual design of hybrid systems of any kind.

3. The case study

This Section presents an overview of the case study, including the PlaCE research project framework (Sub-section 3.1), the description of the Viviana platform, selected as the PlaCE demonstration site, and of the ongoing experimental activities related to the project (Sub-section 3.2), the potential research and economic activities to be integrated at the Viviana platform (Sub-section 3.3), and the analysis of the available RES (Sub-section 3.4).

3.1. The context: the PlaCE project

About 6500 O&G offshore installation are present around the world and many of these infrastructures are approaching to the end of their operational life. As regards the Adriatic Sea only, about 100 gas platforms have been installed over the last 50 years by the Italian Oil Company Eni [11], at least 40 of which will have to be removed in the next few decades [12]. However, the effect of decommissioning activities is still largely unknown. Regulations of complete removal assume that restoring the seabed, bringing it back to its original state before the installation, represents the most environmentally-sound decommissioning option. However, these structures are capable of supporting abundant and diverse marine communities also of regional significance [13,14]. Therefore, some obsolete structures were left in place as artificial reefs, as in the case of the Gulf of Mexico, and reused especially for diving and tourism activities.

In this context, the PlaCE project, a national project funded by the Italian Ministry of University and Research, aimed at investigating cutting-edge technologies and solutions for the sustainable reuse of offshore platforms, starting from a demonstration project, the Viviana platform, located in the Adriatic Sea in front of the Abruzzo region coastline.

In particular, in view of a future possible reutilisation of offshore platforms within the framework of a new and eco-sustainable economy, a platform life-extension strategy was tested, based on a mineral deposition technology under low voltage electrolysis of seawater to protect the coated structures from corrosion [15,16]. This technology is already used for coral reef restoration and it has already been tested for rust protection of big structures in the North Sea.

Other breakthrough activities of the project included experiments of innovative eco-sustainable strategies of aquaculture based on integrated shellfish and holothurians farming, design and development of innovative systems for RE generation to support multi-purpose platform activities, cost-benefit analyses and business scenarios.

3.2. The Viviana O&G platform within the PlaCE project

The PlaCE project considered the Eni Viviana platform, a structure at the end of its operational life, as a demonstration site to test the various project activities. The Viviana platform (Fig. 2) is a monotubular steel structure without grid connection, located in the Adriatic Sea, 9 km away from the Abruzzo coast, in the province of Teramo, on a depth of about 20 m (42.656403°N; 14.155051°E). With a height of 19 m above

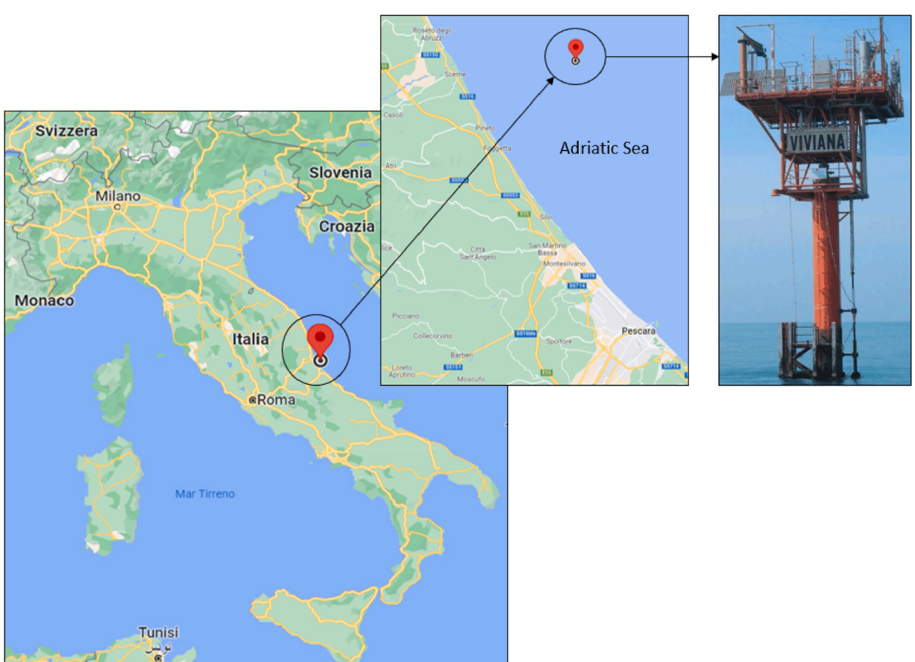

Fig. 2. To the left, map of the location of the Viviana platform. To the right, view of the Viviana platform.

Fig. 3. Installation of the PV panels on the new deck of the Viviana platform.

sea level and a horizontal surface of about 8 × 8 m, the platform was built in 1998 and has been under decommissioning since 2018. The activities required for the platform reuse, including the modification of the deck layout, started in December 2020 and were completed in February 2021.

The RE installation included 12 SunPower Maxeon3/400 PV panels [17], covering an area of about 21 m^2 on the platform deck (Fig. 3). The solar energy production of the plant has been at least about 8.6 kWh/day in December, i.e. the month characterised by the lowest irradiation. The produced energy is locally stored by means of 24 SMG/S 1440 2V batteries for a total storage of about 69 kWh. A Power Management System shifts the power supply from the PV panels to the batteries at night and in low irradiation conditions.

The RE system should also have included a WEC, specifically an OPT PB3 type buoy [18], already under testing at the Amelia platform operated by Eni [19], but its deployment at the Viviana platform couldn't take place due to operational implications.

Other activities included: a mineral deposition experiment for the platform maintenance and the development of a monitoring system through an innovative drone.

As for the mineral deposition technology, the test was carried out on two identical steel structures, placed on the sea bottom close to the Viviana platform. One of the structures was electrified in order to validate the carbonate deposition due to low voltage induction while the other one was used as control site to verify the physico-chemical effects on the structure integrity and the level of colonisation by marine organisms. The two 3.15 m high structures had a 1.2 × 1.2 m square footprint. Their surface foundations consisted of two tubular beams placed orthogonally to each other. They were both equipped with 10 cylindrical cathodes installed by means of a quick release system to facilitate their removal during the various monitoring phases. On the electrified module there was a central anode consisting of a PVC cylinder covered with a titanium alloy mesh. The installation of the structure is shown in Fig. 4. The performance of the mineral deposition technology based on low voltage (i.e. constant value of 2.5 V) was investigated, starting from September 2021. The mineral deposits on the cathodes after half a month is shown in Fig. 4.

The actual platform energy consumption is therefore very low, about 1.9 kWh/day, only 45 Wh/day of which are needed for the mineral deposition experiment. The system docking station absorbs on an average 600 Wh/day. Finally, an amphibious drone developed within the PlaCE project, in view of a possible future use at the platform, was tested in the Gulf of Naples and its electricity demand is reported in Section 4.2.2.

3.3. *Identification of promising economic activities for the reuse of an offshore platform*

The hypothetical reuse of an offshore platform may include different economic activities, such as fish farming, creation of an offshore maritime hub, set-up and maintenance of a floating greenhouse, creation of an offshore tourist site, that may be powered by local energy production systems. The combination of activities to be exploited in the multi-use marine area may be judged following some objective criteria and ranked using available literature metrics [20]. For the purpose of this research, the activities are considered in the following and shortly discussed without ranking. Details of the Viviana platform were used as a benchmark on which to scale all the evaluations performed in this study.

In the rather warm Mediterranean Sea, fish farming is the most promising offshore activity from an economic point of view, due to the use of mature and reliable technologies and to the mild water temperature [10]. The water depth at Viviana platform is unfortunately insufficient for fish farming as the gabions should be submerged of at least 10 m based on the present national legislation, but it can be suited for smart aquaculture installation, where mussels can autonomously grow and are periodically collected, without any specific requirement besides the periodic travels to and from the platforms. However, the shift of aquaculture from nearshore to offshore may cause a relevant social opposition at regional scale due to the many operating traditional factories. An example of a successful demonstration of smart aquaculture and wind farms is provided by the Edulis project case study in the North Sea [21]. For the scope of the paper, i.e. the identification of the optimal mixing, we will not consider this activity further as it does not require any power supply and therefore it does not introduce any change of the external electrical loads.

Another promising option would be either to leave the platform foundation in the sea, without disturbing the colonisation and the attracted mammals, or to build an artificial reef in the area close the

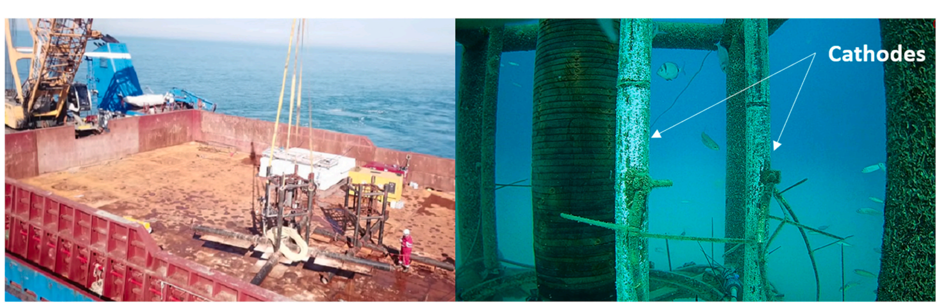

Fig. 4. Installation phase of the structure for the mineral deposition experiment (to the left) and view of the cathodes showing the mineral deposits on its surfaces after ½ month (to the right).

platform and let it become a novel biodiversity source. Given the tourist relevance of the Paguro wreck off the coast of Ravenna [22,23], approx. 400 km North of Viviana, an offshore platform could become an area of high scuba diving interest. Considering the Viviana platform, its 9 km distance from shore and the speed of typical diving boats of about 15 kn, the platform can be reached in about ½ hour. Even in this case, the inclusion of this platform reuse does not require any power supply and therefore it is not detailed further. The more complex business of creating an offshore recreational hub, including an hotel and an adventure park, such as in the RIG project [24], recently launched in Saudi Arabia, is not considered because of the potential conflicts with active environmental associations.

The mild Adriatic Sea cannot lead to marine renewable energy production comparable to the Atlantic Ocean or to the North Sea. Available wave energy is about 1/10 the available wave energy in the Atlantic Ocean, for which most of the devices are designed. Moreover, the wave energy technology is far from being economically viable. Wind energy instead is highly reliable but, after SOFIA project [25], it is considered feasible in case of average wind speed 3 times greater than the average wind speed at Viviana. Tidal energy has to be disregarded because of the negligible tidal range and of the low-speed currents. However, for the purpose of this research, both wind and wave energy production will be assessed (see Section 4) and combined with the solar energy, already installed at Viviana, to test the optimal mix methodology in a wider range of conditions and to verify the promising integration of energies that prevail during storms (wind, waves) with energies that are maxima during good weather (sun). The development of a combination strategy of different RE technologies, in order to provide constant power supply to the platform reuse activities, was in fact one of the main goals of the PlaCE project, with the overarching aim of extending the procedure to any decommissioned platform.

3.4. The climate conditions

In order to supply power to Viviana platform, three different available RES were considered: waves (Sub-section 3.4.1), wind (Sub-section 3.4.2), and sun (Sub-section 3.4.3). Twelve years of climate data were analysed, specifically the period between January 2005 and December 2016. Data were taken from open databases, considering the location of the platform.

3.4.1. Wave resource

Wave energy analysis was performed starting from twelve years of hourly wave data (2005–2016) extracted from the open database ERA5 [26]. In this database, wave data (significant wave height H_s, peak wave period T_p and wave direction) are provided with a resolution of 0.5° × 0.5°. The grid point selected for the analysis is the closest to Viviana platform, in particular the point of coordinates 42.5°N, 14.5°E.

The probability of occurrence of each combination of H_s and wave direction is reported in Table 1. As is typical of the Adriatic Sea, the H_s-Direction matrix shows that three direction intervals are more frequent, specifically 90°–120°, 330°–360° and 0°–30°; moreover, the highest and more energetic waves ($H_s > 4$ m) come from the directions 0°–60°.

By grouping the data based on H_s and T_p, the most common wave conditions were identified (Table 2). In particular, as expected in the Adriatic Sea, the most frequent waves are characterised by $H_s < 1$ m; furthermore, in over 61% of cases, H_s is lower than 0.5 m. The most frequent T_p interval is 2.5–4 s. The available wave power is therefore very low the majority of the time.

The wave power associated to each sea state can be calculated through Eq. (7):

$$P_w = \frac{\rho g^2 H_s^2 T_e}{64\pi} \qquad \text{Eq. 7}$$

where P_w is the wave power per unit crest length (kW/m), T_e is the energetic period assumed to be $0.9T_p$, $\rho = 1.025$ kg/m^3 is the water density and g is the gravitational acceleration.

P_w was calculated at hourly level for each wave condition over the whole period considered, obtaining that the average annual value of available wave power over the twelve years is $P_{y,m} = 1.33$ kW/m. Considering the individual years, the average available power P varies between −17/+26% $P_{y,m}$, ranging from a minimum of 1.1 kW/m in 2006 up to a maximum of 1.67 kW/m in 2012 (Fig. 5).

Looking at the individual seasons separately, over the entire period, P results to be almost equal to $P_{y,m}$ in Spring and Autumn, but considerably different in Summer and Winter: in fact, 2.35 kW/m are available on average during Winter (i.e., 77% more than $P_{y,m}$), 1.31 kW/m during Spring (1% less than $P_{y,m}$), 0.43 kW/m during Summer (67% more than $P_{y,m}$) and 1.22 kW/m during Autumn (8% less than $P_{y,m}$). Summer and Autumn values of P are rather constant over the years, while a greater variability is observed in Winter and Spring (Fig. 6).

3.4.2. Wind resource

Wind energy analysis was performed starting from twelve years of hourly data (2005–2016) extracted again from the open database ERA5 [26]. Differently from wave data, wind data (wind speed components in eastern and northern directions at 10 m height) are provided with a resolution of 0.25° × 0.25°. Despite the presence of grid points closer to Viviana platform, the point selected for the wind data analysis is the same used for the wave data analysis, in particular the point of coordinates 42.5°N, 14.5°E.

Wind data are provided at the reference height $z_0 = 10$ m above s. w. l. Considering the height of the wind turbine here selected for the analysis (Section 4.1.2), the wind velocities were therefore transferred to the hub height $z_{hub} = 31$ m through Eq. (8) [10]:

$$v_{hub} = v_0 \frac{\ln\left(\frac{z_{hub}}{m}\right)}{\ln\left(\frac{z_0}{m}\right)} \qquad \text{Eq. 8}$$

where v_{hub} is the wind velocity at the turbine height $z_{hub} = 31$ m; v_0 s the velocity at the reference height $z_0 = 10$ m; $m = 2 \times 10^{-4}$ is the surface roughness parameter in the open sea.

The annual variability of v_{hub} is reported in Fig. 7. The mean wind speed remains stable at around 4 m/s and most of the data are in the range 2–6 m/s.

3.4.3. Solar resource

Solar energy analysis was performed starting from twelve years of hourly data (2005–2016) extracted from the open database PVGIS [27], where only onshore data are available. Therefore, the grid point considered for the analysis has the same latitude of Viviana platform but different longitude, specifically 42.656°N, 14.035°E. Given the PV mounting type (fixed, in this case) and the optimal slope and Azimuth (60° and 0° respectively at the Viviana platform), the database provides the hourly values of G_i (W/m^2), that is the irradiance per unit area. Moreover, given the PV technology (specifically, crystalline silicon) and the system losses (assumed to be 14%), the database provides P (W), that is the power produced by a solar plant of given peak power. A unit peak power value was considered for subsequent further processing.

The monthly and seasonal variability of the available power is shown in Fig. 8 and in Table 3. No significant variations are reported for the average seasonal irradiance during the examined years. Also, interestingly, the irradiance is almost equivalent in Spring and in Summer.

Table 1
Probability of occurrence (%) for each combination of significant wave height H_s (m) and direction (°N) calculated over 12 years (2005–2016).

Hs/Dir	0°–30°	30°–60°	60°–90°	90°–120°	120°–150°	150°–180°	180°–210°	210°–240°	240°–270°	270°–300°	300°–330°	330°–360°	∑
0–0.5	8.93%	5.98%	7.78%	15.71%	3.56%	1.02%	0.33%	0.20%	0.21%	0.35%	2.18%	15.30%	61.55%
0.5–1	4.91%	1.71%	1.53%	6.39%	2.03%	0.30%	0.02%	0.01%	0.01%	0.03%	1.00%	7.62%	25.57%
1–1.5	2.64%	0.63%	0.38%	1.65%	0.65%	0.04%	0.00%	0.00%	0.00%	0.01%	0.26%	1.99%	8.25%
1.5–2	1.23%	0.31%	0.11%	0.52%	0.19%	0.00%	0.00%	0.00%	0.00%	0.00%	0.06%	0.46%	2.89%
2–2.5	0.63%	0.12%	0.06%	0.15%	0.02%	0.00%	0.00%	0.00%	0.00%	0.00%	0.02%	0.14%	1.13%
2.5–3	0.21%	0.04%	0.02%	0.04%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.05%	0.38%
3–3.5	0.09%	0.01%	0.01%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.02%	0.15%
3.5–4	0.02%	0.02%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.07%
4–4.5	0.00%	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%
4.5–5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
∑	18.67%	8.85%	9.89%	24.47%	6.47%	1.36%	0.35%	0.21%	0.23%	0.39%	3.54%	25.58%	**100.00%**

Table 2
Probability of occurrence (%) for each combination of significant wave height H_s (m) and peak period T_p (s) calculated over 12 years (2005–2016).

Hs/Tp	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	∑
0.5	4.24%	12.85%	11.46%	13.05%	9.26%	5.60%	2.51%	1.19%	0.78%	0.40%	0.11%	0.08%	0.02%	0.00%	0.00%	0.00%	0.00%	61.55%
1	0.00%	0.00%	0.26%	1.40%	3.15%	6.14%	6.32%	3.53%	2.29%	1.19%	0.56%	0.42%	0.23%	0.06%	0.03%	0.01%	0.00%	25.57%
1.5	0.00%	0.00%	0.00%	0.01%	0.03%	0.28%	1.27%	2.21%	2.18%	1.13%	0.61%	0.28%	0.15%	0.08%	0.01%	0.01%	0.01%	8.25%
2	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.02%	0.15%	0.72%	0.92%	0.64%	0.25%	0.10%	0.07%	0.02%	0.00%	0.00%	2.89%
2.5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.02%	0.18%	0.56%	0.23%	0.07%	0.05%	0.01%	0.00%	0.00%	1.13%
3	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.10%	0.17%	0.06%	0.03%	0.01%	0.00%	0.00%	0.38%
3.5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.03%	0.08%	0.03%	0.00%	0.00%	0.00%	0.15%
4	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.02%	0.04%	0.00%	0.00%	0.00%	0.07%
4.5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%
5	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
∑	4.24%	12.85%	11.72%	14.45%	12.44%	12.02%	10.12%	7.09%	6.00%	3.83%	2.58%	1.46%	0.73%	0.35%	0.08%	0.04%	0.01%	**100.00%**

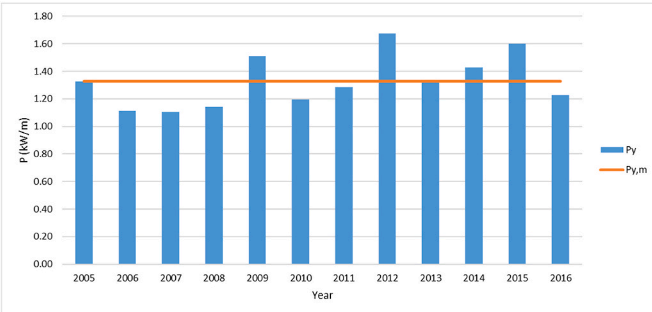

Fig. 5. Average available wave power P calculated on an annual basis (P_y) and over the entire period ($P_{y,m}$).

4. Assessment of the reuse activities at the Viviana platform

Based on the observations made in Section 3, the activities considered for the evaluation of the possible reuse of the Viviana platform, and specifically for the application of the optimal RE mixing methodology, are the on-site renewable power generation from different sources (Sub-section 4.1) and the experimental activities of the mineral deposition technique and environmental monitoring performed through innovative devices (Sub-section 4.2).

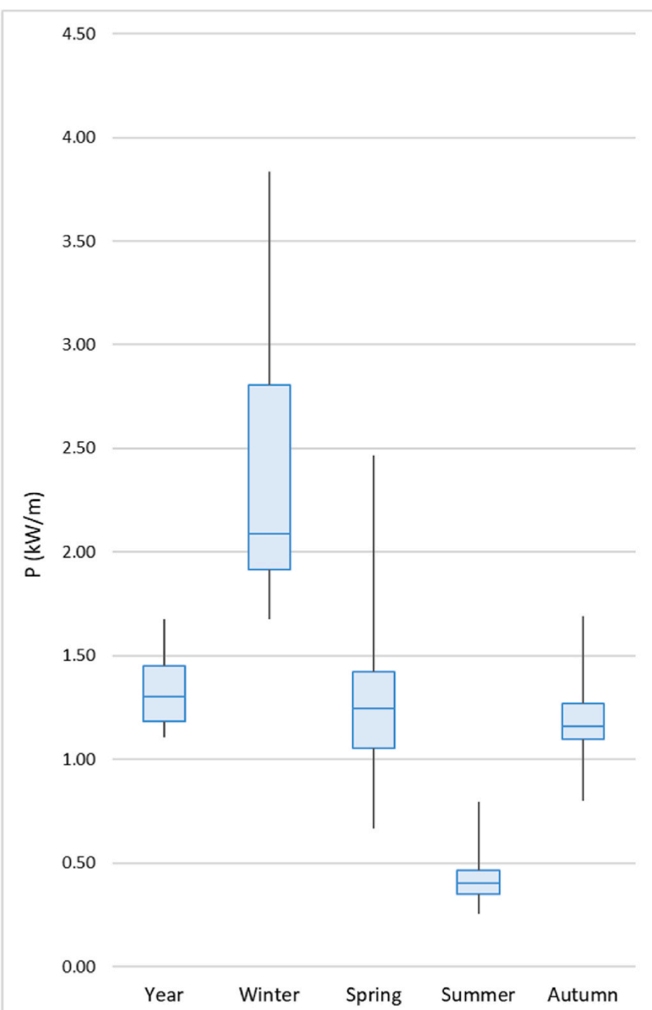

Fig. 6. Box plots of the annual and seasonal available wave power P (years 2005–2016).

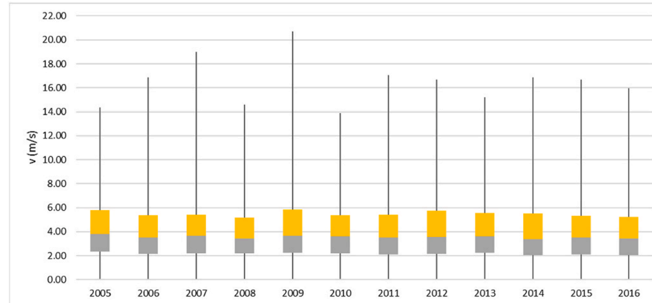

Fig. 7. Box plots of the wind velocity at the hub height (31 m above s. w.l.).

4.1. Renewable energy production

This Section describes the devices selected for the analysis of the RE integration and quantifies their production. The technical characteristics of each selected device, i.e. the WEC, the wind turbine and the PV panels, are publicly available online. Specifically, in Sub-section 4.1.1 the chosen WEC is described and the potential wave energy production is reported, while Sub-sections 4.1.2 and 4.1.3 report the wind and solar energy production respectively.

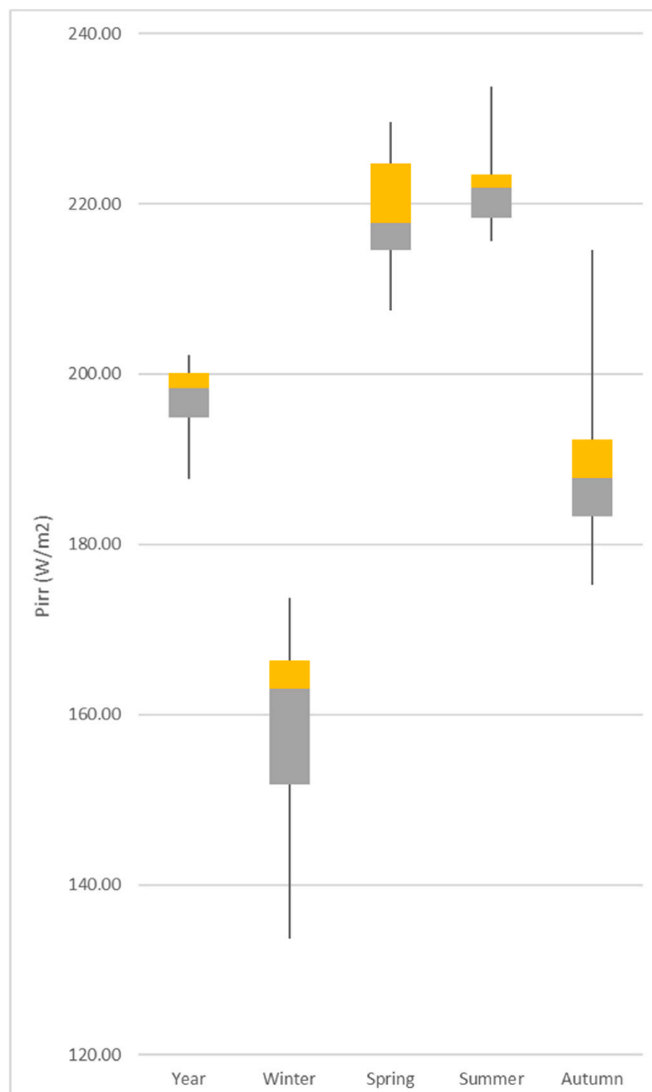

Fig. 8. Box plots of the seasonal irradiance per unit surface (years 2005–2016).

Table 3
Monthly average solar irradiance per unit surface (W/m^2).

Month	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Jan	170	126	188	152	100	118	145	183	149	119	164	163
Feb	179	175	184	219	188	158	196	168	165	192	171	181
Mar	226	185	214	214	211	212	211	252	197	233	199	199
Apr	239	223	251	231	208	206	234	220	241	213	234	232
May	217	225	215	208	234	205	228	217	203	205	228	213
June	214	214	212	202	195	208	211	225	209	206	221	206
July	220	231	232	222	229	220	215	226	227	207	228	216
Aug	214	218	231	244	231	234	247	251	232	234	221	232
Sept	210	228	228	205	209	216	238	204	239	207	215	218
Oct	183	215	163	213	195	164	187	193	196	191	152	175
Nov	133	201	161	152	172	165	156	136	144	171	189	164
Dec	139	147	125	120	113	147	157	152	162	147	177	178
$P_{m,y}$	195	199	200	199	190	188	202	202	197	194	200	198

Table 4
Main features of the AquaBuOY device. The original model [29] is compared with the downscaled version for the Viviana platform and with the PowerBuoy device [31].

	Original AB	Scaled AB	PB3
Available power (kW/m)	29	1.33	–
Water depth min (m)	46	13	20
Water depth max (m)	76	22	1000
Float diameter (m)	6	1.75	2.65
Float draught (m)	2.5	0.73	–
Float mass (ton)	71	1.76	–
Spar diameter (m)	4	1.17	1
Spar lenght (m)	30	8.74	10.18
Internal water mass (ton)	382	9.46	–
Total draught approx. (m)	32.5	9.47	8.67
Total mass approx. (ton)	453	11.22	10
Rated power (kW)	250	3.34	3
Hs min (m)	1	0.29	–
Hs max (m)	5.5	1.60	–
Tp min (s)	6	3.24	–
Tp max (s)	17	9.18	–

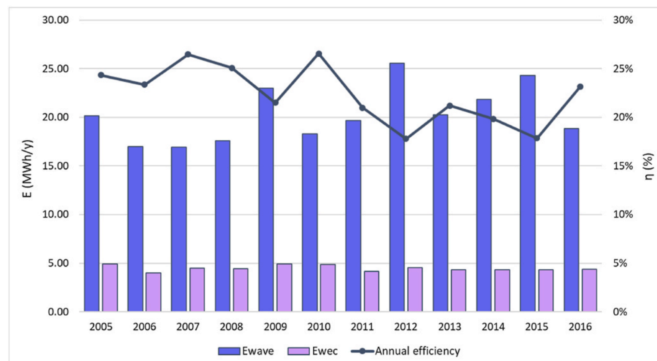

Fig. 9. Annual available and produced wave energy at the Viviana platform.

4.1.1. Wave energy

The possible wave energy production at Viviana platform was analysed in the case of a wave energy converter of the kind point absorber, AquaBuOY (AB hereinafter), whose power matrix is available in literature [28,29] and which is similar in shape, size and working principle to the PB3 device, tested in parallel to the PlaCE project at the Eni Amelia platform, also located in the Adriatic Sea, where it produced over 2 MWh/y [30]. Considering the climate conditions of the Adriatic Sea and specifically at the Viviana platform (Section 3.4.1), a point absorber WEC appears to be the most suitable choice, since it can harvest energy from every direction.

From Table 4, where the main characteristics of the AB are reported, it is apparent that the device could not be installed in its original size at Viviana platform, where the seabed depth is 20 m, and it is thus necessary to scale it. The procedure, reported by Ref. [20]; consists in scaling the WEC applying the Froude similarity starting from the typical climate (specifically the average available wave power per unit length). The new dimensions and power features (reported again in Table 4) are almost equivalent to the ones of the PB3 actually installed and working in the Adriatic Sea, thus verifying the scaling criterion. As reported by Ref. [32] and by Ref. [33]; it was also necessary to scale the AB operating ranges, being the climate of the Adriatic Sea completely different from the original AB operational climate. The scaled power matrix is shown in Table 5. The fact that the scaled-AB doesn't produce energy in case of waves characterized by $H_s > 1.60$ m does not affect the overall estimate of the produced wave energy, since over 95% of waves at Viviana platform is characterized by $H_s < 1.5$ m (Table 2).

Based on the scaled power matrix, the produced wave energy was calculated for each hour of the data range (2005–2016) and an average annual value $E_{y,m} = 4.47$ MWh/y was obtained. Considering the single years, the produced energy varies between ± 11% $E_{y,m}$, ranging from a minimum of 3.98 MWh/y and a maximum of 4.95 MWh/y. The annual wave energy production therefore shows a lower variability than the available energy, being the WEC not operational during peak periods (Fig. 9). The same difference can be observed on a seasonal basis in Fig. 10, where the variability of the seasonal values of the available and

Table 5
Scaled-AquaBuOY power matrix in kW.

Hs/Tp	2.70	3.24	3.78	4.32	4.86	5.40	5.94	6.48	7.02	7.56	8.10	8.64	9.18
0.29	0.00	0.08	0.08	0.15	0.16	0.15	0.13	0.11	0.09	0.00	0.00	0.00	0.00
0.44	0.00	0.16	0.23	0.33	0.36	0.36	0.31	0.27	0.20	0.17	0.14	0.12	0.09
0.58	0.00	0.32	0.40	0.59	0.65	0.63	0.55	0.45	0.37	0.31	0.26	0.21	0.16
0.73	0.00	0.49	0.63	0.89	1.03	0.98	0.86	0.73	0.57	0.52	0.43	0.35	0.26
0.87	0.00	0.72	0.91	1.32	1.48	1.42	1.23	1.03	0.84	0.68	0.57	0.47	0.36
1.02	0.00	0.00	1.24	1.80	2.03	1.92	1.68	1.40	1.15	0.94	0.79	0.65	0.51
1.17	0.00	0.00	1.63	2.27	2.65	2.49	2.19	1.85	1.50	1.32	1.11	0.89	0.67
1.31	0.00	0.00	0.00	2.98	3.34	3.19	2.78	2.31	1.90	1.54	1.30	1.06	0.83
1.46	0.00	0.00	0.00	3.34	3.34	3.34	3.34	2.86	2.34	1.90	1.61	1.32	1.03
1.60	0.00	0.00	0.00	3.34	3.34	3.34	3.34	3.34	2.82	2.30	1.94	1.59	1.23

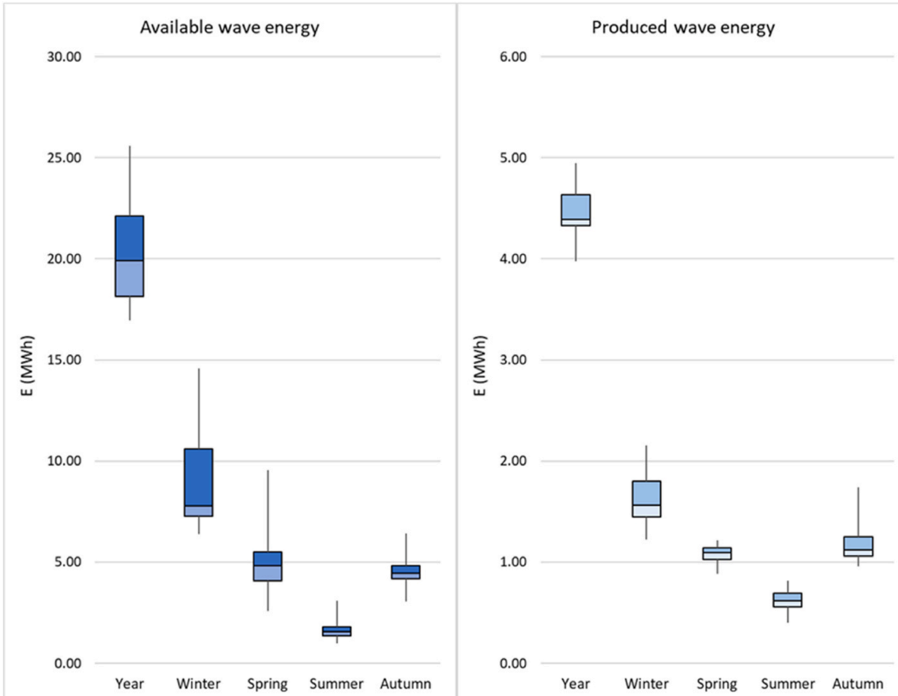

Fig. 10. Box plots of seasonal wave energy production and available wave energy at the Viviana platform (years 2005–2016).

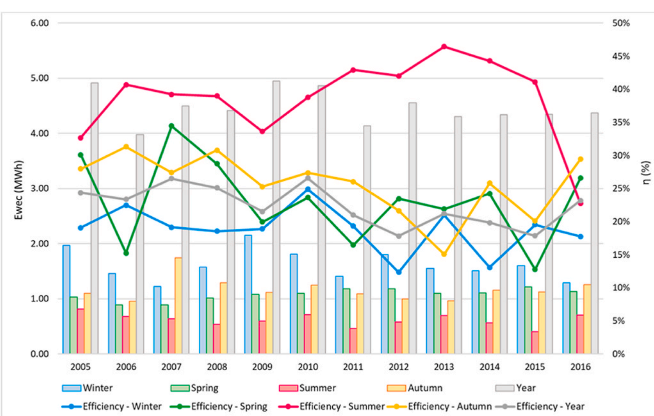

Fig. 11. Annual and seasonal trend of wave energy production and WEC efficiency at the Viviana platform.

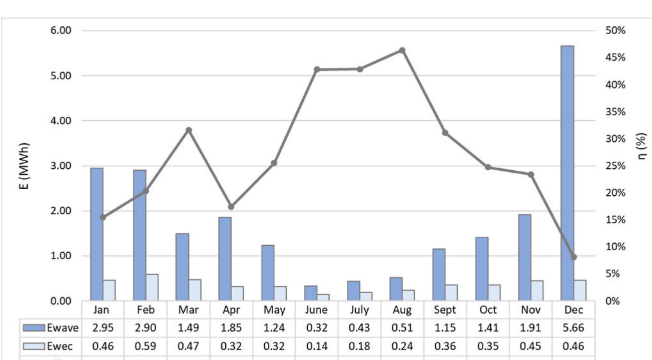

Fig. 12. Monthly available and produced wave energy at the Viviana platform for a typical year (2014).

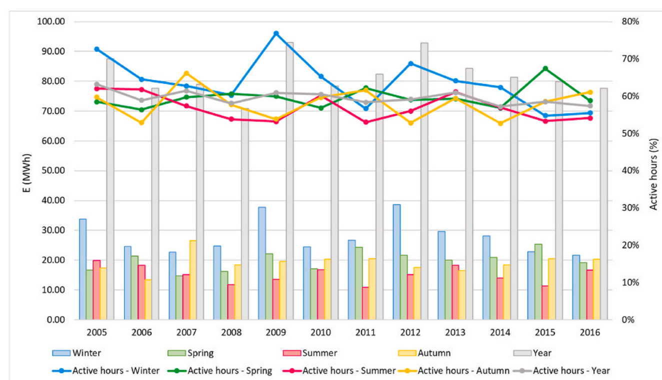

Fig. 13. Annual and seasonal trend of wind energy production and wind turbine active hours at the Viviana platform.

produced wave energy is represented through their quartiles. On average, 1.61 MWh (36% $E_{y,m}$) are produced during Winter, 1.08 MWh (24% $E_{y,m}$) during Spring, 0.61 MWh (14% $E_{y,m}$) during Summer and 1.17 MWh (26% $E_{y,m}$) during Autumn. Fig. 11 summarizes the results on both annual and seasonal level.

Fig. 12 shows the energy produced monthly for a typical year. Again, the monthly trend of the energy produced by the scaled-AB does not always follow the trend of the available wave energy, since it depends on the operating ranges of the chosen device, which is non-operational with the highest waves. The efficiency results in fact higher during Summer, when scaled-AB can take advantage of the majority of the waves, and lower during Winter, when waves are higher and fall outside the operating range of the device.

Beyond the actual production rate, the monthly trend of the produced wave energy is consistent with the PB3 fluctuations in energy generation, as per private communication. Also, the estimate of the energy produced by AB does not account for the actual system efficiencies and losses, thus slightly overestimating the production. Since detailed information about AB efficiencies is not available, the theoretical values obtained for the produced wave energy will be considered

Table 6
Average wind speed at hub height (31 m above s.w.l.), total energy production and percentage of active hours of Libellula 60i at the Viviana platform.

Year	Average v_{hub} (m/s)	E (MWh/y)	Active hours (%)
2005	4.23	87.59	63%
2006	4.01	77.68	59%
2007	4.05	79.07	61%
2008	3.88	70.95	58%
2009	4.26	93.00	61%
2010	4.02	78.48	61%
2011	4.06	82.41	58%
2012	4.24	92.87	59%
2013	4.13	84.29	61%
2014	4.01	81.34	57%
2015	4.03	79.82	59%
2016	3.96	77.70	57%
Max.	4.26	93.00	63%
Average	4.07	82.10	60%
Min.	3.88	70.95	57%

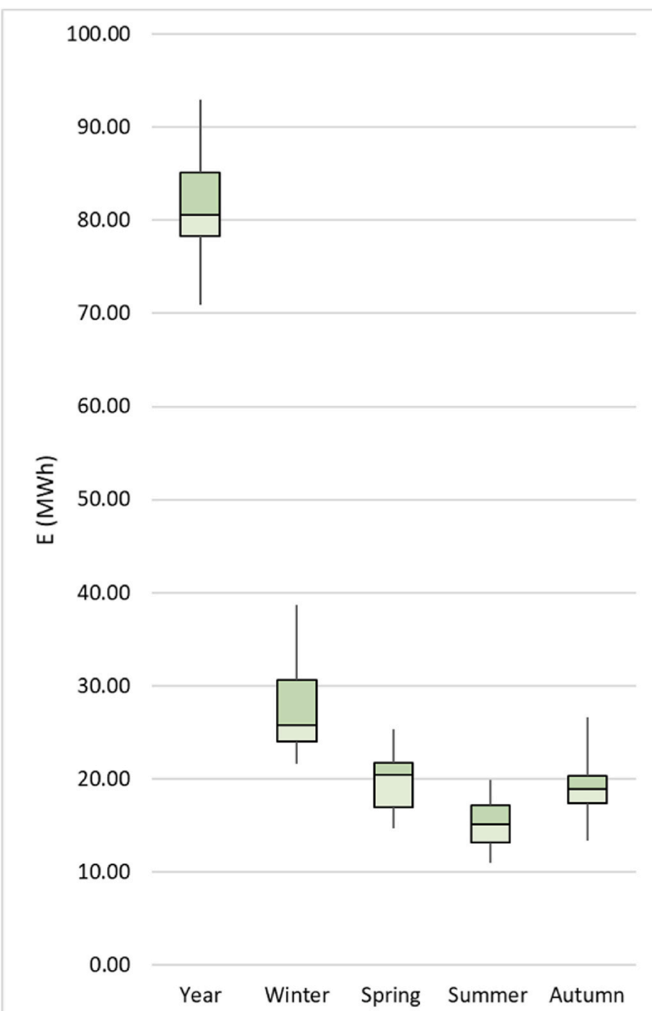

Fig. 14. Box plots of seasonal wind energy production at the Viviana platform (years 2005–2016).

in the following analysis.

4.1.2. Wind energy

Libellula wind turbines [34] were selected for the analysis, since they ensure the best price/performance ratio in the Italian small wind field. In particular, the model Libellula 60i was chosen, whose main features are available online [35,36]). Specifically, a 31 m height and 19 m diameter turbine was considered.

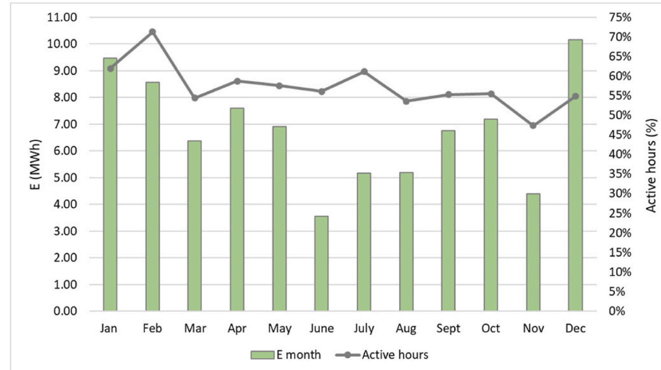

Fig. 15. Monthly trend of wind energy production and wind turbine active hours at the Viviana platform for a typical year (2014).

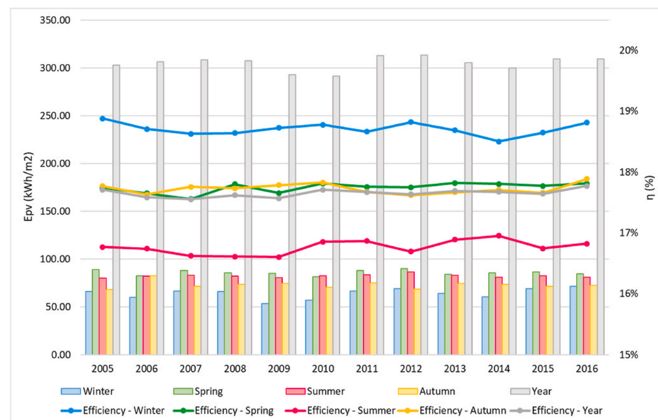

Fig. 16. Annual and seasonal trend of solar energy production and PV panels efficiency at the Viviana platform.

The hourly producibility analysis shows that the turbine is operational 60% of the hours on average, with little variability through the years (Fig. 13). Despite the constant trend of the active hours, the annual energy production is mainly related to the average wind speed and its variation is therefore more significant, also in case of small changes in average wind speed (Table 6).

Looking at the individual seasons separately, the energy production reaches its maximum in Winter and its minimum in Summer in most of the years, as well as the active hours (Fig. 13). The season with the greater production variability is Winter, when extreme wind episodes more frequently occur (Fig. 14).

Even on a monthly basis, a high energy generation does not necessarily relate to a high number of active hours (Fig. 15). The maximum production occurs in Winter, usually December–January, while the minimum production frequently occurs in June.

4.1.3. Solar energy

The analysis of the solar energy production was carried out considering the PV panels that were actually installed at Viviana platform within the PlaCE project (Sub-section 3.2), the high-efficiency SunPower Maxeon3, characterized by a nominal power of 400 W and a surface of 1.77 m^2. Specifically, twelve panels were installed on the deck with a total area of 21 m^2. The main features of the chosen solar panels are available online [37].

The producibility analysis was carried out per unit area. Fig. 16 shows that producibility and efficiency of the solar plant remain stable throughout the years. Interestingly, the energy generation is frequently

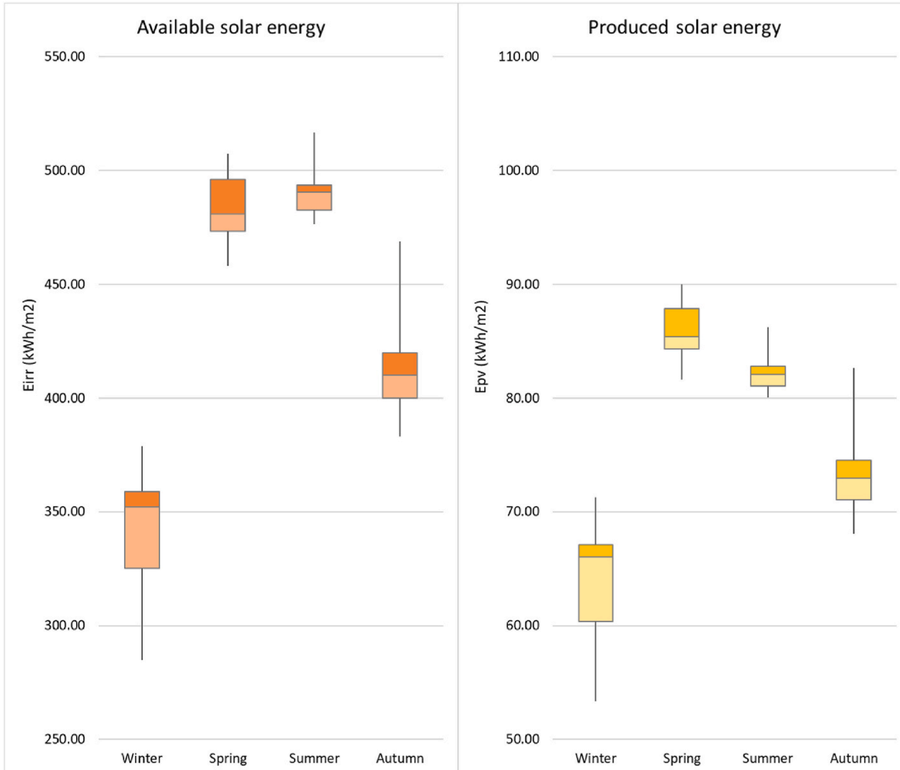

Fig. 17. Box plots of seasonal solar energy production and available solar energy at the Viviana platform (years 2005–2016).

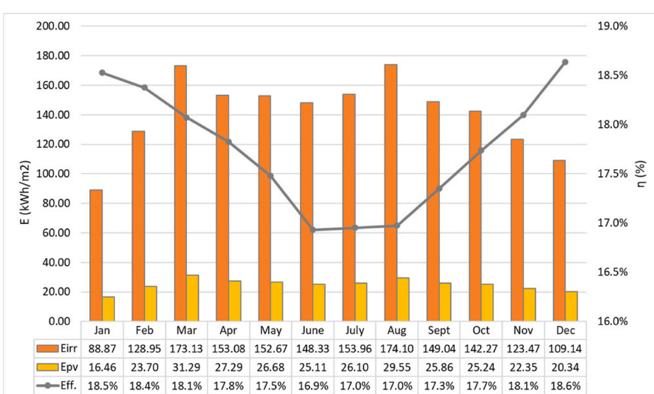

Fig. 18. Monthly available and produced solar energy at the Viviana platform for a typical year (2014).

higher in Spring than in Summer, although the available energy is of course higher during Summer (Fig. 17). In fact, the efficiency reaches its minimum in Summer and it is higher in Spring, while the maximum efficiency occurs in the Winter. On a monthly basis, the maximum production is usually achieved in March, April or May and in July or August (Fig. 18).

4.2. Energy-consuming ancillary activities at the Viviana platform during PlaCE

The ancillary activities tested at the Viviana platform, which need to be powered by RES, are essentially the structural maintenance (Sub-section 4.2.1) and the environmental monitoring activities (Sub-section 4.2.2). The estimated energy demand of the platform is finally reported in Sub-section 4.2.3.

Table 7
Electrical load required for the mineral deposition activity extended to the entire submerged surface of the structure.

Total submerged area (m^2) =	140
Current density (A/m^2) =	1.06
Voltage (V) =	2.5
Required power (W) =	371
Daily energy request (kWh/day) =	8.9

4.2.1. Structural maintenance

Periodic maintenance of the structure has to be carried out to assure its integrity. The mineral deposition technique (Sub-section 3.2) can significantly contribute by protecting the submerged part of the platform from corrosion. The experiment could be transferred to the protection of surfaces of any extension by means of a wire mesh equipped with.

- spacer elements (in high density polyethylene or similar), in order to keep the mesh from the structure to be protected (which constitutes the cathode) a few centimetres away. The spacers are arranged at a mutual distance of a few tens of centimetres, compatibly with the morphological complexity of the structure;
- a further network of electric cables (with mesh sizes also different from that of the support wire mesh) to which titanium alloy “sinkers” (or similar) are fixed and electrically connected, placed at a suitable distance (depending on the electrical components) from each other, and which constitute the anode of the electrolytic system.

Such network should be able to create a sort of homogeneously distributed electrolytic cell along the entire structure. The possibility of defining the dimensions of the meshes of the net and the diameter of the cable allows to adapt the net to the dimensions of the structure or to that of the elements of which it is made.

The estimation of the energy consumption for the mineral deposition activity was made on the basis of recent field experiment in the

Table 8
Hourly consumption trend at the Viviana platform in a day, expressed in kWh, for each considered activity.

Time	Mineral deposition	Fixed consumption	Drone	Docking station	AUV	Total
00	0.37	0.08	0.00	0.025	1.43	1.90
01	0.37	0.08	0.00	0.025	1.43	1.90
02	0.37	0.08	0.00	0.025	1.43	1.90
03	0.37	0.08	0.00	0.025	1.43	1.90
04	0.37	0.08	0.30	0.025	1.43	2.20
05	0.37	0.08	0.30	0.025	1.43	2.20
06	0.37	0.08	0.30	0.025	1.43	2.20
07	0.37	0.08	0.00	0.025	1.43	1.90
08	0.37	0.08	0.30	0.025	0.00	0.77
09	0.37	0.08	0.30	0.025	0.00	0.77
10	0.37	0.08	0.30	0.025	0.00	0.77
11	0.37	0.08	0.00	0.025	0.00	0.47
12	0.37	0.08	0.30	0.025	0.00	0.77
13	0.37	0.08	0.30	0.025	0.00	0.77
14	0.37	0.08	0.30	0.025	0.00	0.77
15	0.37	0.08	0.00	0.025	0.00	0.47
16	0.37	0.08	0.30	0.025	0.00	0.77
17	0.37	0.08	0.30	0.025	0.00	0.77
18	0.37	0.08	0.30	0.025	1.43	2.20
19	0.37	0.08	0.00	0.025	1.43	1.90
20	0.37	0.08	0.00	0.025	1.43	1.90
21	0.37	0.08	0.00	0.025	1.43	1.90
22	0.37	0.08	0.00	0.025	1.43	1.90
23	0.37	0.08	0.00	0.025	1.43	1.90
TOT	**8.90**	**1.86**	**3.60**	**0.60**	**20.00**	**34.96**

Mediterranean Sea [16]. The characteristics of the system and the estimated energy request, assuming to extend the experiment to the total submerged area of the Viviana structure, are reported in Table 7.

Being the energy demand for this activity constant over time, the daily consumption was evenly distributed over 24 h and an hourly energy request of 0.37 kWh was obtained.

4.2.2. *Monitoring systems*

Within this study, it was supposed to make use of additional instruments on the platform in order to perform environmental monitoring, in particular an innovative amphibious drone and a hypothetical Autonomous Underwater Vehicle (AUV) to be resident at the bottom of the platform.

The amphibious drone [38] was developed within the framework of the PlaCE project by the University Federico II of Naples in collaboration with the start-up Neabotics. One mission has a maximum duration of 40 min and requires 900 Wh. The full charging process takes 3 h. For the purpose of this study, it was supposed to carry out the maximum possible number of missions during daytime, which is equal to 4 missions a day, considering the abovementioned timeframe. It was also assumed that every mission is always led at the same time of the day throughout the year, independently from the light hours. The drone consumption trend is thus constant, with an energy demand of 0.3 kWh per hour of charge (Table 8).

Also, a hypothetical AUV device was considered in this study with the goal of automatically performing environmental monitoring activities and underwater inspection of offshore installations. The considered model requires 20 kWh for a 10-h mission. In this study, it was supposed to carry out a mission every day during daytime for the whole year. The energy consumption for the recharge was therefore assumed to be uniformly distributed over the remaining 14 h, resulting in an hourly energy request of 1.43 kWh mainly during night-time, for the whole year (Table 8).

4.2.3. *Daily trend of consumption*

Excluding the mineral deposition experiment, the fixed energy consumption registered at Viviana platform has been equal to 1.86 kWh/day on average. This electrical load and the daily energy request of the docking station were equally distributed over 24 h, resulting in an additional hourly energy demand of 0.08 kWh and 0.025 kWh respectively. The overall trend in daily consumption, considering all the activities, is reported in Table 8.

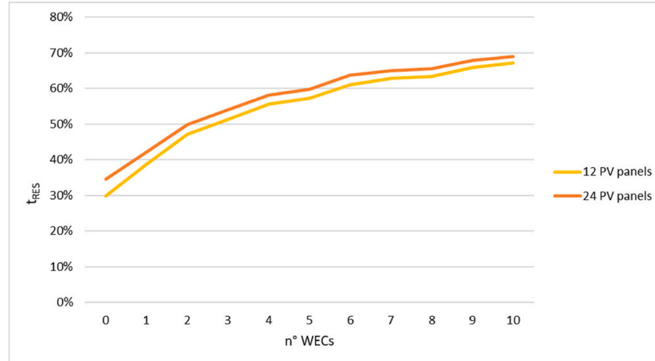

Fig. 19. Number of hours per year when the energy demand is instantly met through renewable energies only, plotted as a function of the number of WECs, in absence of wind turbines (year 2014).

The energy demand results to be higher during the night, when the AUV is supposed to be charging at its docking station. Considering to store the solar energy available during daytime and/or to integrate the PV panels system with different renewable energy sources is thus of great importance.

5. Assessment of the optimal energy mix at the Viviana platform

In this Section, the proposed method for the identification of the REs optimal mixing is applied to the case study of the Viviana platform, firstly in case of absence of storage systems (Sub-section 5.1) and subsequently considering the presence of batteries (Sub-section 5.2).

5.1. *Preliminary assessment without storage systems*

An initial evaluation of the optimal RES mixing was at first made according to the general t_{RES} criterion (see Sub-section 2.3), neglecting the presence of the batteries that store and release energy when necessary. This method was applied in order to carry out a preliminary sensitivity analysis of the parameter t_{RES} with respect to the number of RE devices, known the energy demand. The analysis was performed for a typical year, specifically the 2014. The main results are presented in Fig. 19, Figs. 20 and 21.

Fig. 20 shows that t_{RES} doesn't increase much by varying the number of wind turbines from 1 to 3 and remains constant for a higher number of turbines. The comparison of Figs. 19 and 20 also shows that, based on t_{RES} only, and therefore without considering the presence of storage systems, at least 6 WECs are needed in order to guarantee the same energy coverage as one single wind turbine. Finally, Fig. 21 shows that, in none of the cases considered, an increase in the number of the PV panels beyond 18–30 produced a significant increase in the energy coverage. Considering that the existing deck could support up to 30 PV panels, further expanding the deck in order to install a number of PV panels greater than 30 wouldn't be a sustainable solution.

Given the annual available and requested energy at Viviana, 24 PV panels or 18 PV panels combined with 1 WEC or 12 PV panels combined with 1 wind turbine are necessary and sufficient to meet the energy demand of the platform (in the latter case with a significant energy surplus). Thus, based on previous results, it was decided not to consider the installation of a higher number of WECs or wind turbines in the following. The main outcomes are reported in Table 9. Although t_{RES} is considerably higher in case of installation of a wind turbine instead of a WEC, and therefore t_{LS} (representing the hours of lack of RE supply) is

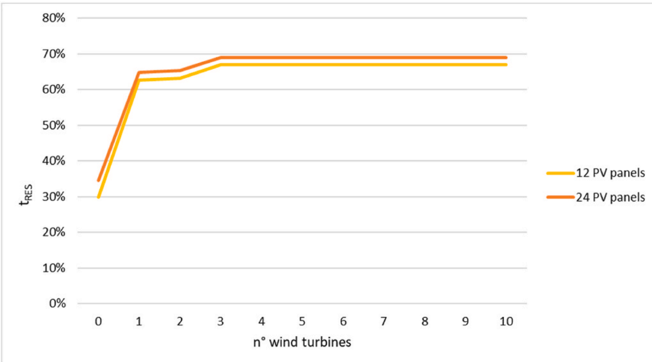

Fig. 20. Number of hours per year when the energy demand is instantly met through renewable energies only, plotted as a function of the number of wind turbines, in absence of WECs (year 2014).

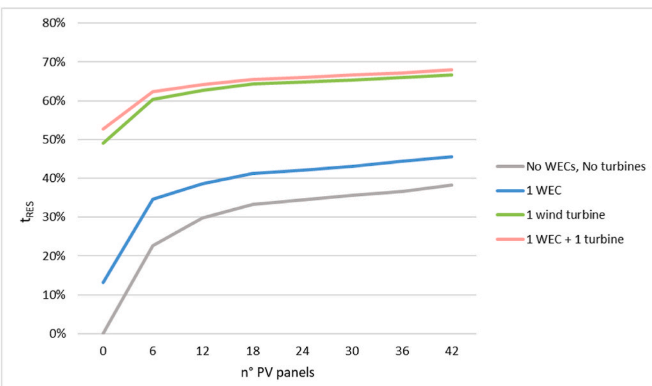

Fig. 21. Number of hours per year when the energy demand is instantly met through renewable energies only, plotted as a function of the number of PV panels (year 2014).

much higher in case of installation of a WEC, the missing amount of energy, that need to be supplied by the backup system, doesn't differ much in the two cases, being the hourly energy demand very low. Moreover, the total annual amount of actually used energy is extremely limited in any case. This indicates that, in each of the examined scenarios and for all RES, the moments when energy is required and the moments when RE is available are not synchronous for most of the year. A further analysis was therefore carried out by applying the upgraded method and considering the presence of the storage system.

5.2. Evaluation of the optimal mixing in presence of storage systems

In the second part of the study, the evaluation of the optimal RE mixing was carried out by applying the optimised methodology and considering the presence of the 24 SMG/S 1440 2V batteries which have actually been installed at the Viviana platform (Section 3.2). In this application, the integrated RES system provides energy to specific co-located activities in absence of grid connection and with a storage

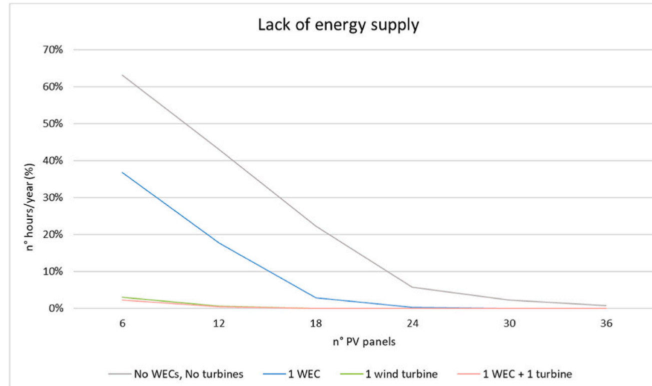

Fig. 22. Hours per year when the energy demand is not met through RES, plotted as a function of the number of devices, considering 24 SMG/S 1440 batteries (year 2014).

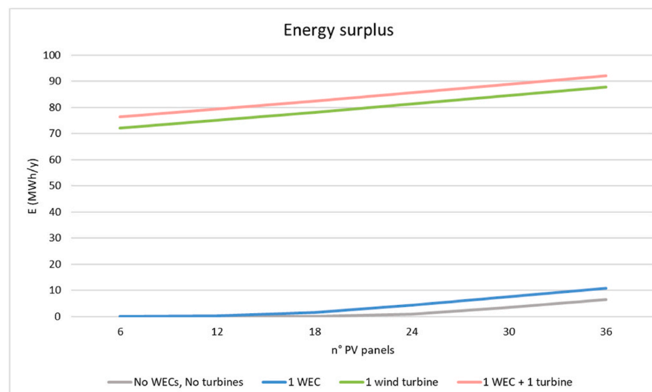

Fig. 23. Annual RE surplus, plotted as a function of the number of RE devices, considering 24 SMG/S 1440 batteries (year 2014).

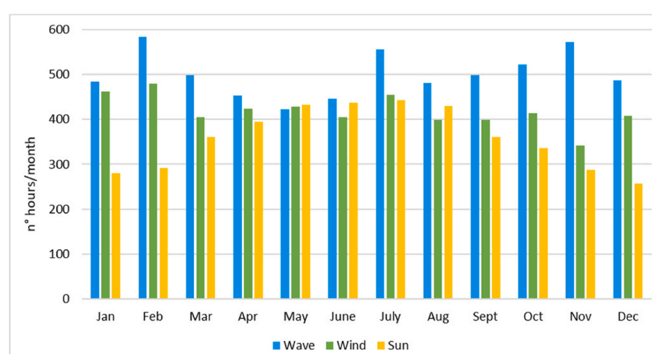

Fig. 24. Hours per month when the different RES are available (year 2014).

Table 9
Main results for the different combinations of RE devices at Viviana platform, with no storage systems (year 2014). t_{RES} = number of hours per year when the energy demand is instantly met through renewable energies only; t_{LS} = number of hours per year when there is a lack of RE supply.

	E (MWh/y)					t_{RES} (%)	t_{LS} (%)
	Available	Required	Surplus (no batteries)	Missing (no batteries)	Actually used	(no batteries)	
1 WEC + 18 PV	13.89	12.76	8.49	7.35	5.41	41.20%	58.80%
0 WECs + 24 PV	12.74	12.76	9.63	9.65	3.11	34.51%	65.49%
1 turbine + 12 PV	87.72	12.76	80.25	5.30	7.46	62.73%	37.27%

Table 10
Main results for the different combinations of RE devices at the Viviana platform, with a storage system comprising 24 batteries (year 2014).

	E (MWh/y)				Hours of no RE supply (24 batteries)
	Available	Required	Surplus (24 batteries)	Missing (24 batteries)	
1 WEC + 18 PV	13.89	12.76	1.53	−0.36	2.89%
0 WECs + 24 PV	12.74	12.76	0.88	−0.83	5.70%
1 WEC + 24 PV	17.08	12.76	4.38	−0.03	0.25%
1 WEC + 30 PV	20.26	12.76	7.53	0.00	0.00%
1 turbine + 12 PV	87.72	12.76	75.06	−0.10	0.67%
1 turbine + 24 PV	94.09	12.76	81.33	0.00	0.00%

system balancing energy peaks and valleys. The results are presented in Fig. 22 and in Fig. 23. Based on the above analysis, the presence of no more than 1 WEC or 1 wind turbine was considered in combination with a system of 18–30 PV panels.

Unlike what was shown by the previous study of the t_{RES} parameter, Fig. 22 shows that the combination of the WEC with a number of PV panels equal or higher than 24 ensures almost the same energy coverage of the wind turbine, thanks to the greater continuity over time of the wave resource with respect to the wind. Fig. 24 shows in fact that, for more than 13% of hours per year, only the wave resource is available, while wind and sun are absent. Additionally, Fig. 23 shows that the wind turbine produces a huge energy surplus if compared to the WEC, with the same number of PV panels and almost the same annual energy coverage from RES.

An advantage of the WEC with respect to the wind turbine therefore emerges from the analysis of this case study. The WEC, in addition to ensuring reduced space requirements and a lower visual and environmental impact, also guarantees the same continuity of the energy supply as a wind turbine when the energy demand is low. This is because, although the total amount of produced energy is lower, its availability is more distributed over time, ensuring an enhanced alternation of energy storage and release from batteries with almost zero surplus.

Based on the previous analysis, the most promising solutions among the different examined RES combinations (summarised in Table 10) are outlined below, depending on the aim of the project.

- If the only objective is to meet the annual energy demand with the minimum number of devices, the installation of 24 PV panels on the deck is an easier and more cost-effective solution than the combination of 18 PV panels and a WEC, given that the energy coverage is similar in the two cases. This solution requires though the use of a backup system for a small part of the time.
- If the objective is instead to make the platform completely energy independent only through RES, 30 PV panels could be combined with 1 WEC or 24 PV panels could be installed together with 1 wind turbine. In the second case, the installation footprint and the visual and environmental impact would be higher and there would be a huge surplus of unused energy. The combination of a WEC with the 30 PV panels would therefore be a more promising option.
- If the platform is not isolated but connected to the electricity grid, producing an energy surplus can prove instead convenient, since it can be used for different purposes elsewhere. In this case, the installation of 1 wind turbine in combination with 24 PV panels could be more beneficial.

It is intended that the use of a higher number of batteries then those installed at the Viviana platform would reduce the number of devices needed. On the other hand, given the combination of devices and the kind of storage system, the method also allows to determine the minimum number of batteries which ensures the continuous satisfaction of the energy demand through RES only. Specifically, in case of installation of 1 WEC combined with 30 PV panels, 19 batteries would be enough to have a constant RE supply, while in case of installation of 1 wind turbine combined with 24 PV panels, 17 batteries would be sufficient.

6. Conclusions

This paper presented an improved methodology to identify the optimal RES mixing for isolated and plugged-to-grid systems. It requires as input: the hourly data of available energy from RES, the production curve of the selected devices, the hourly energy demand of the co-located activities, the technical characteristics of the additional components of the system (e.g. batteries).

This method simultaneously optimises the energy surplus with respect to the external electrical load required by other activities and the missing energy with respect to the same electrical load. It can be applied regardless of the number and kind of RES considered and the trend of the energy production of the devices; the number and kind of energy-consuming activities considered and the trend of the energy requirements over time; the presence or absence of storage systems. It consists of three main steps: the assessment of the local RES availability and of the energy required by the co-located activities; the selection of the energy converters and of the additional system components, with consequent evaluation of the available energy production; the optimisation of the mix based on three main criteria (e.g. number of devices or batteries, management of the energy surplus and production only by RES).

This method was applied to a novel case study, the Viviana platform, an O&G platform at the end of its operational phase and no longer in production, located in the Adriatic Sea, Italy, off the coast of Abruzzo. The platform was tested for the reuse within the national research project PlaCE, including the protection of the structure from corrosion by means of the mineral deposition technique. The case study also included the presence of an amphibious drone and an AUV to be potentially associated to the platform, in order to perform the environmental monitoring. The energy supply for these activities was supposed to be locally generated by a hypothetical integrated system of solar, wave and wind energy devices, since the platform is disconnected from the grid.

The optimal mix of RES for the Viviana platform was investigated by applying the improved method, leading to the following main results. A system of 24 PV panels can provide almost the total energy supply, but a backup system would be needed for part of the time. On the other side, 1 wind turbine, combined with 24 PV panels, could guarantee a constant RE coverage, but with a huge unused energy surplus. The installation of 1 WEC in combination with 30 PV panels would lead to the best energy balance, thanks to the greater continuity over time of the available wave energy with respect to the other resources.

CRediT authorship contribution statement

Elisa Dallavalle: Methodology, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Barbara Zanuttigh:** Conceptualization, Methodology, Resources, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition. **Pasquale Contestabile:** Investigation, Resources, Data curation, Writing – review & editing. **Alessandro Giuggioli:** Validation, Resources, Writing – review & editing, Supervision, Funding acquisition. **Davide Speranza:**

Validation, Resources, Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

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

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