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Harnessing wind and wave resources for a Hybrid Renewable Energy System in remote islands: a combined stochastic and deterministic approach

Evangelos Moschos[a,]*, Georgia Manou[b], Panayiotis Dimitriadis[b], Vasileios Afentoulis[a], Demetris Koutsoyiannis[a], Vasiliki K. Tsoukala[b]

[a] *Laboratory of Harbour Works, Department ofWater Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens, Iroon Polytechniou 5, 15780 Athens, Greece.*

[b] *Laboratory of Hydrology and Water Resources Utilization, Department of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens, Iroon Polytechniou 5, 15780 Athens, Greece.*

Abstract

Wind and wave resources enclose an important portion of the planet's energy potential. While wind energy has been effectively harnessed through the last decades to substitute other forms of energy production, the utilization of the synergy between wind and wave resource has not yet been adequately investigated. Such a hybrid energy system could prove efficient in covering the needs of non-connected remote islands. A combined deterministic and stochastic methodology is presented in a case study of a remote Aegean island, by assessing a 100-year climate scenario incorporating uncertainty parameters and exploring the possibilities of fully covering its energy demands.

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Keywords: renewable energy; wind energy ; wave energy ; HRES ; pumped storage; stochastic modeling ; numerical modeling ;

1. Introduction

Remote island residents do not enjoy the privilege of connection to the main electrical grid, that inhabitants of cities do. This creates significant problems for the most cases, where power is generated from oil-fueled plants, from

* Corresponding author. Tel.: +30 695 662 7248.
E-mail address: cv12050@mail.ntua.gr

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dependency to oil market and prices [1], to inability to cover energy demand peaks, if the stored fuel is not enough. Hybrid Renewable Energy Systems (HRES) have been planned or installed in various locations. Such systems provide a sustainable alternative to wasteful oil-based energy production and carbon emissions, as well as self-sufficiency of the local communities [2]. Combined wind and wave energy utilization is examined here, in a HRES model suitable for non-connected, remote islands, with high availability of these resources. While wind energy technology is in commercial stage, marine/wave energy technology is currently in an early stage, from research to pre-demonstration on full scale. A wide variety of Wave Energy Converters (WECs) exist today; each technology uses different solutions to absorb energy from waves and can be applied depending on the water depth and on the location [3].

The case of the Aegean Sea belongs to the low-energy areas of Europe, thus wave energy converters have not been developed, while at the same time the large wind potential has not been fully harnessed. Nevertheless, several studies have shown the potential of both WEC installation and combined wind and wave resource utilization in the area of the Aegean Sea. Lavidas and Venugopal [4] created a 35-year wave energy atlas of the Aegean, on which they tested the energy production and performance of different WEC technologies. Furthermore, Friedrich and Lavidas [5] tested a combined HRES system consisting of a wind turbine, a WEC and a diesel generator at the island of Astypalaia, which is also examined in this study, evaluating the assets of combined wind and wave resource management. Finally, Ioannou et al. [6] simulated an HRES system in Donoussa, another remote Aegean island, consisting of a wind turbine and an overtopping WEC, providing a sustainable system with fully autonomy from the grid.

The selected case study area is Astypalaia, a Greek island in the south-eastern Aegean Sea. The island has about 1,300 inhabitants and it extends in an area of 96.9 km^2. Astypalaia has more than 20,000 visitors per year, creating high energy demand in the summer period. Today the electric energy demand is covered by an oil-fuelled thermal station, as the island is not connected to the energy distribution grid of the mainland and there are no renewable energy installations in the area. According to records from 2014 to 2015, the island's mean annual demand was 6,250 MWh. The peak hourly demand was 2.2 MWh (occurred on 14/08/2015 at 21:00) and the minimum was 0.23 MWh [7,8].

2. Modeling of wave climate

2.1 Wind and wave historical data

Measurements of wind and wave resources exist only in a few locations of the Aegean Sea. For the examined island, wind and wave data are unavailable on-spot, due to its remote location. For this reason, past wind and wave climate in the surrounding area of the island needs to be modeled and reconstructed. The historical data are then used as input in a numerical model to simulate a 7-year scenario for the years 2005 until 2011, in order to obtain time-series of wind and wave resources in the position of installation of the HRES. Wave data are obtained through the HCMR's (Hellenic Center for Marine Research) Poseidon buoy network [9]. The POSEIDON system is a real-time monitoring and forecasting system for the marine environmental conditions in the Aegean Sea. The Santorini and Mykonos buoys are picked out, being the most proximate to the location of Astypalaia; their location can be seen in Figure 1(a). For the operation of the numerical model, the parameters of Significant Wave Height, Spectral Peak Period, Wave Direction, as well as the Wave Directional Spreading are needed. The Poseidon buoys record, among others, these parameters on a 3-hourly basis. The short data availability as well as the big gaps in the measured time series of the buoys, create a limit in the available measured time period. Thus, time-series for the period between 2005-2011, in which consistent measurements are available, are isolated and the small gaps that exist in this period are filled through a high order auto-regressive model. Hence, the 3-hourly time series is obtained, which is used as input for the spectral wave model. For the same time period (2005-2011) reconstructed wind data is obtained through the ERA-Interim model, produced by ECMWF [10]. The data is obtained in a grid form with a 6-hourly time interval and a spatial analysis of 0.125 degrees, consisting of the u and v components of the wind velocity, at a 10 meter altitude. Furthermore, the matching of the ERA-Interim data with the wind data measured by the Poseidon buoys is validated. These wind data account both for the input to the wave numerical model as well as the raw data for the wind resource.

2.2 Spectral wave model

The third-generation spectral wave model MIKE 21 SW [11] is set-up and calibrated to adapt to the conditions of the south-eastern Aegean island complex and the offshore area near Astypalaia. The simulated domain covers 35.4°-38.2° N Latitude and 25.2°-27.5° E Longitude. The bathymetry of the area, obtained from the HNHS (Hellenic National Hydrographic Service) [12] with a 15" spatial resolution, is interpolated in an unstructured triangular mesh. Coastline data is also obtained from the HNHS and smoothed for the triangulation of the mesh. The model consists of a land boundary to the east, while measured wave data from the Poseidon buoys are the input conditions from two open boundaries. The time-series of the Santorini buoy is used as input data for the southern boundary, while the time-series of the Mykonos buoy is used as input data for the northern boundary. Initial bathymetry and mesh of the model area, as well as the open boundaries and the buoy locations, are illustrated in Figure 1(a). Spectral and spatial discretization of the domain of MIKE 21 SW is done by cell centered finite volume method. The governing equations of the model are briefly analysed by Sorensen [13]. Additionally, the model simulates the effects of wind growth, wave to wave interactions, wave mechanisms such as wave-breaking, shoaling, refraction, diffraction and dissipation due to bottom friction and white capping. A fully spectral formulation based on the wave action conservation equation is used in the model run, as well as quasi-stationary solution scheme with a 15 minute time-step, to handle big computational needs.

2.3 Model results

The model results are presented as a 2-dimensional grid time-series in the nearshore area of Astypalaia and in time-series in several examined points for installation of a Wave Energy Converter, both onshore and offshore. In all outputs hourly time-series of Wave Power (P), Significant Wave Height (H_s), Mean Wave Period (T), Mean Wave Direction (M_{dir}) and Wind Speed at 10 meters altitude (U_{10}) and direction are obtained. Figure 1(b) depicts the mean Wave Power in the 7-year modeled period in the nearshore area of the island. As can be seen in Figure 1(b) the northern side of the island has access to a higher wave energy potential, which reaches a mean value near 5 kW/m nearshore and up to 6 kW/m in offshore areas close to the island. Comparing nearshore and offshore possible positions through their output time series, a nearshore position is chosen in this study for the installation of the WEC and a HRES combining it with wind turbines, in order to have the ability to use beneficial processes such as pumped storage, as discussed later. The point of installation of the WEC, located on the nearshore area with access to wave energy of 5 kW/m (yellow contour), can be seen on the 7-year Mean Wave Power map in Figure 1(c).

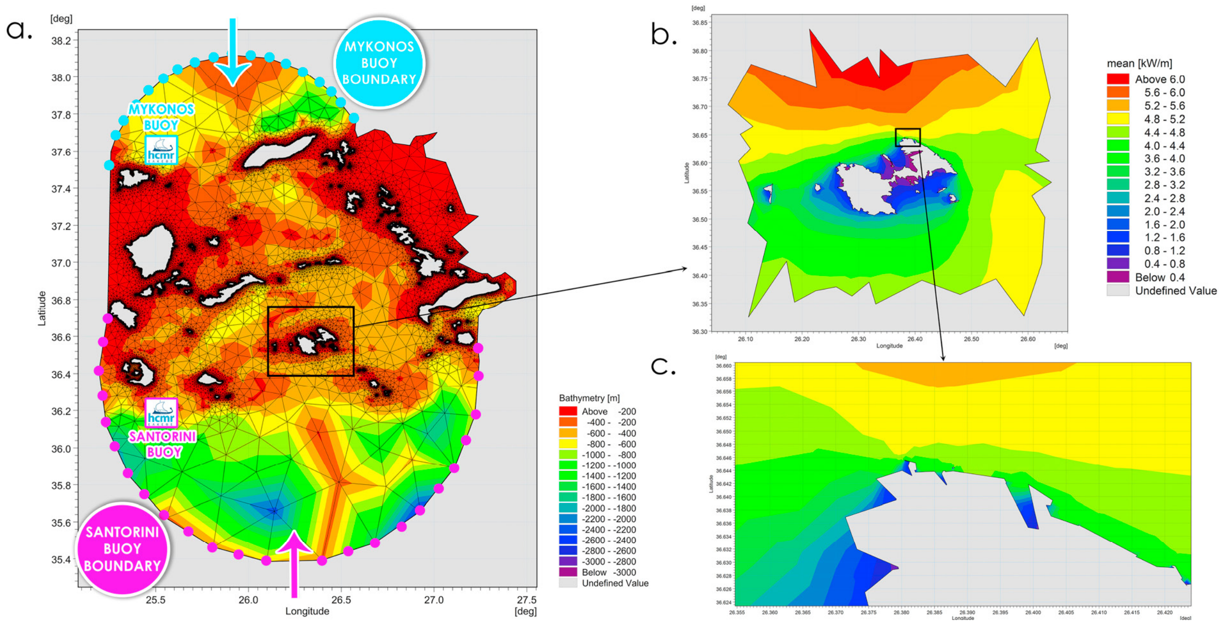

Figure 1. (a) Initial bathymetry and mesh of the MIKE 21 SW model. Location of buoys and open boundaries; (b) Mean Wave Power [kW/m] results around Astypalaia from MIKE 21 SW model; (c) Mean Wave Power [kW/m] results around the WEC installation point.

3. 100-year stochastic estimation of wind and wave resource

A stochastic methodology is chosen for the purposes of this study, in order to estimate a 100-year long scenario of wind and wave energy resource in the area where the HRES will be installed. Time-series generated through this methodology (called "synthetic" from now on) provide an assessment of reality by modeling uncertainty and randomness, rather than a deterministic "prediction". The statistical characteristics, as well as the periodicities and the correlations of the time-series obtained through the ECMWF re-analysis for wind resource, and MIKE 21 numerical modeling for wave resource (called "original" from now on), are preserved through this methodology, and a depiction of one of the infinite possible random future scenarios is received. For 100-year time-series of Significant Wave Height H_s [m] and Mean Wave Period T_m [s], for the wave resource, and Wind Speed U_{10}[m/s*]* at 10-meter altitude, for the wind resource, are generated through the following methodology.

The internal periodicities are a common characteristic of hydrometeorological processes. For the generation of the synthetic time-series we implement the methodology of Dimitriadis and Koutsoyiannis [14], which is suitable for double periodic processes, such as the ones examined in this study. In particular, the applied methodology preserves the double cyclostationarity (diurnal and seasonal) of a process through the hourly-monthly marginal distributions, including intermittent characteristics, such as probability of zero values, as well as the dependence structure of the processes through the climacogram, which represents a plot of the variance of the scaled-averaged process as a function of scale [15]. For the dependence structure we apply a Hurst-Kolmogorov (HK) model [16] based on the empirical climacogram of each process. More specifically, the climacograms of the three variables show a Hurst coefficient value of approximately 0.72 with a more complex autocovariance structure than the simple HK model and thus a simplified autocovariance structure is used. Finally, for the generation scheme the CSAR (Cyclostationary Sum of finite independent AR(1) processes) [17] algorithm is used. The algorithm is capable of generating any length of time-series following an HK behavior or various other processes, with arbitrary distributions of each internal stationary process of the double cyclostationary process.

Cross-correlation is significant between wind and wave resource, due to the physical processes of wind generated waves. For a combined estimation of the two resources that is followed by this study, empirical cross-correlation between U_{10} and H_s must be accounted for and preserved by the stochastic model. Because of the dependence of wave generation on wind phenomena, the availability of the two resources follows a common pattern on the time scale, with wave resource incoming on a small time-lag after wind resource. To present this effect, wind and wave resource values are selected from an August monthly window, normalised by subtracting their monthly mean value and dividing with their standard deviation; the normalised values are depicted in Figure 2(a). First order cross-correlation factor between H_s and U_{10} is calculated approximately at 0.75, a particularly high value, which is also caused by the inner-model dependency between the two parameters. Additionally, due to the fact that Wave Power is directly proportional to the square of Significant Wave Height and the Mean Wave Period, the cross-correlation between the values of H_s and T_m is significant when simulating wave energy production, and is therefore also preserved [18].

The distributions of the characteristic values of wind and wave resources are also preserved in the synthetic time-series. According to Ochi [19], the Significant Wave Height follows either a Log-normal or a Weibull distribution, while the Mean Wave Period follows a Log-normal distribution. The two parameter Weibull distribution is applied for H_s values, and the two-parameter Log-normal distribution is applied for the T_m values. Finally, for the wind-speed U_{10} the two-parameter Weibull distribution is also applied, suitable for small return periods, which are of interest in wind energy production and management [20]. In Figures 2(b) to 2(d) the histograms of the original time-series are presented with a distribution curve fitting on them. As deducted from Figures 2(d) and 2(b), depicting T_m and U_{10} values, the distributions seem to have an overall well fitting, whereas in Figure 2(c), depicting H_s values, it should be noted that a Weibull curve fits better on the maximum data, while a Log-normal curve offers an improved fitting on average values (where $H_s < 0.8$). For reasons of model simplicity, out of the two distributions, only the Weibull distribution has been used.

4. Evaluation of Wave Energy Converters

For this study, two nearshore Wave Energy Converters (WECs) are evaluated, in order to compare their energy production output, which is channelled in the HRES. Hence, we compare an overtopping-type WEC with the Wave Star WEC, both of which are installed in nearshore positions. The criteria of the selection of the two WECs is their adaptability to the Aegean wave climate.

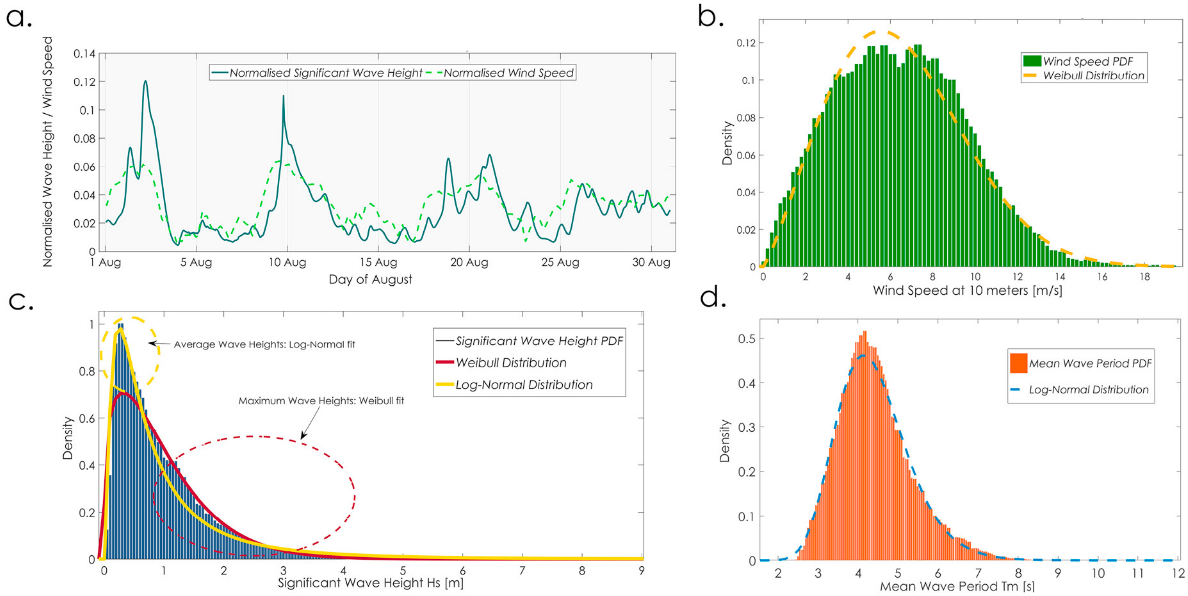

Figure 2. (a) A monthly (August) window of normalised wind and wave resources. Distribution fitting for (b) Wind Speed at 10 meters (U_{10}); (c) Significant Wave Height (H_s); (d) Mean Wave Period (T_m)

4.1 Wavestar WEC

The Wave Star, is a prototype WEC, produced by Wave Energy, currently installed for testing and demonstration by Roshage pier, near Hanstholm at the west coast of Denmark. The machine consists of two rectilinear arrays of closely spaced floaters, located on both sides of a long bottom-standing steel structure that is aligned with the dominant wave direction, and houses a hydraulic PTO consisting of a high-pressure-oil hydraulic circuit equipped with hydraulic motors [21]. The commercial Wave Star WEC rates 600 kW power by employing 20 floaters, while the testing prototype installed at Hanstholm contains only two floaters and rates 110 kW power.

The energy production of the Wave Star is calculated through the power matrix given by the manufacturer. Figure 3(a) shows the power matrix for the 600 kW Wave Star. For each value of (H_s, T_m), a bin is matched from the matrix, and an energy production value is returned, allowing to calculate the hourly energy production time-series, from a known hourly time-series of H_s and T_m. For values of H_s above 3 meters, the WEC operates in storm protection mode in which no energy is produced. As observed in Figure 3(a) of the power matrix, the WEC functions optimally when the H_s values vary between 2.5–3 m, and T_m values vary between 4–9 s. Because the wave climate of the Aegean Sea contains much lower H_s values, a downscaling approach is chosen, through which a rough estimation of the energy production of a WEC, adapting to the wave climate of the area can be obtained [22]**.** By applying a Froude criterion, the scale λ is calculated through the equation (1) provided below, where P_{wec} is the power rating of the prototype Wave Star WEC (600 kW) and $P_{wec,d}$ the power rating of the downscaled WEC. The power matrix for the downscaled machine can be then calculated, by multiplying the power values by the scale of power $(\lambda)^{7/2}$, the H_s values by the scale of length λ and the T_m values by the scale of time $(\lambda)^{0.5}$ [23]. The relation of the downscaled with the prototype values is given in equations (2) and (3). To fill the upper rows of the power matrix until H_s values of 3 meters, a linear extrapolation method is used. The power matrix of the downscaled, 250kW Wave Star WEC is illustrated in Figure 3(b). Through this methodology, the annual energy production for three different WEC power ratings of 200, 250 and 300 kW are calculated, resulting in an annual production of 608, 698 and 787 MWh and capacity factors of 34.32%, 31.87% and 29.91% respectively.

$$\lambda_L = \left(\frac{P_{WEC,d}}{P_{WEC}}\right)^{2/7} \quad (1) \qquad L_{WEC,d} = \lambda_L\, L_{WEC} \quad (2) \qquad T_{WEC,d} = (\lambda_L)^{0.5}\, T_{WEC} \quad (3)$$

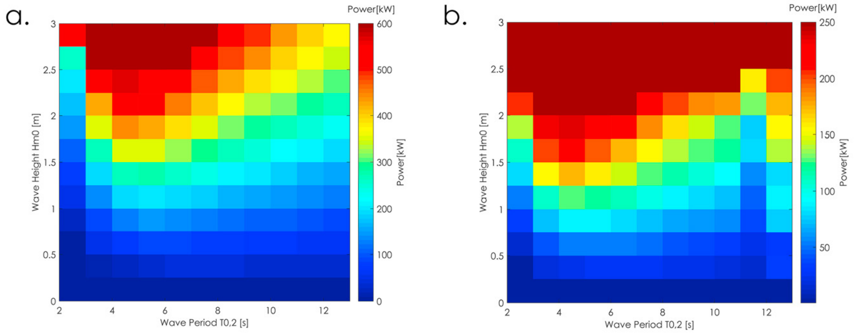

Figure 3. Power matrices of (a) the prototype 600 kW Wave Star WEC; (b) the downscaled 250 kW Wave Star WEC

4.2 Overtopping WEC

Overtopping WECs are installed into nearshore or offshore structures and function by collecting water through overtopping and wave run-up processes and feeding it in a low-head turbine. Different types of Overtopping WECs (OWECs) have been tested both in laboratory conditions and also on-site, suggesting alternative layouts. It has been shown that OWECs containing multiple reservoirs at different heights, such as the SSG, provide a better overtopping discharge, and therefore produce more energy [24].

In this study, a 4-reservoir OWEC is modeled. Its layout can be seen in the cross-section displayed in Figure 4(a). The reservoir heights $R_{c,j}$ are $R_{c,1}$ = 0.5 m, $R_{c,2}$ = 1.50 m, $R_{c,3}$ = 2.50 m and $R_{c,4}$ = 4.00 m. The depth at the point of installation is 15 meters, while the foundation height, on which the concrete structure is built, is 10 meters. The OWEC is equipped with 5 Kaplan Turbines, two of them installed in the lowest reservoir, and the other three on the rest of the reservoirs.

Kofoed [25] has experimentally derived a methodology of calculating the discharge in each reservoir, for a multi-reservoir OWEC. The rate of discharge relative to the vertical height is derived from the following equation [26]:

$$\frac{dq}{dz} = \sqrt{g \cdot H_{m0,t}} \cdot A \cdot e^{B \cdot \frac{z}{H_{m0,t}}} \cdot e^{C \cdot \frac{R_{c,1}}{H_{m0,t}}} \qquad (4)$$

where ${dq}/{dz}$ represents the rate of variation of the overtopping discharge, per unit of width, relative to a vertical coordinate z, measured upward from the still water level, $H_{m,0,t}$ represents the Significant Wave Height and g represents the gravitational acceleration. The three empirical coefficients A, B and C refer to a standard layout, with d_r/h =1 and slope θ_j = 30°–35° and take values of A = 0.197, B = -1.753 and C = -0.408.

By integrating equation (4) between the crest levels $R_{c,j}$ and $R_{c,j+1,}$ the amount of water entering the j-th reservoir is estimated:

$$q_{ov,j} = \int_{R_{c,j}}^{R_{c,j+1}} \frac{dq}{dz} dz = \sqrt{g \cdot H_s^3} \cdot \frac{A}{B} \cdot e^{C \cdot \frac{R_{c,1}}{H_{m0,t}}} \cdot \left(e^{B \cdot \frac{R_{c,j+1}}{H_{m0,t}}} - e^{B \cdot \frac{R_{c,j}}{H_{m0,t}}}\right) \qquad (5)$$

Total discharge for the j-th reservoir is obtained by multiplying equation (5) with the OWEC length. Energy production, proportional to discharge, drop height and total hydraulic efficiency can be then calculated.

$$Q_{ov,j} = q_{ov,j}\, L \quad (6) \qquad\qquad P_j = Q_{ov,j}\, R_{c,j}\, g\, \eta \quad (7)$$

where η accounts for total hydraulic efficiency of the OWEC assumed as 0.30 -signifying the product of the efficiency of various functions- and g represents the gravitational acceleration.

Through the above equations, an optimization model is set up, considering values of OWEC length L, and total installed power P_{inst} in the Kaplan turbines. With an hourly wave height time-series in the OWEC installation point, total discharge per reservoir is calculated, adding to total OWEC discharge. The hourly produced energy values are filtered through the maximum hourly production limit of the installed turbine power, and a minimum production limit of 10% of the installed turbine power. An optimal value of 75 meters for the OWEC length is obtained this way, which is the size of a typical breakwater. In similar fashion with the Wave Star calculations, three OWEC with total power ratings of 200, 250 and 300 kW each, spread through the Kaplan turbines, are simulated, resulting in annual energy production values of 649, 706, 747 MWh and capacity factors of 37.04%, 32.25% and 28.42% respectively.

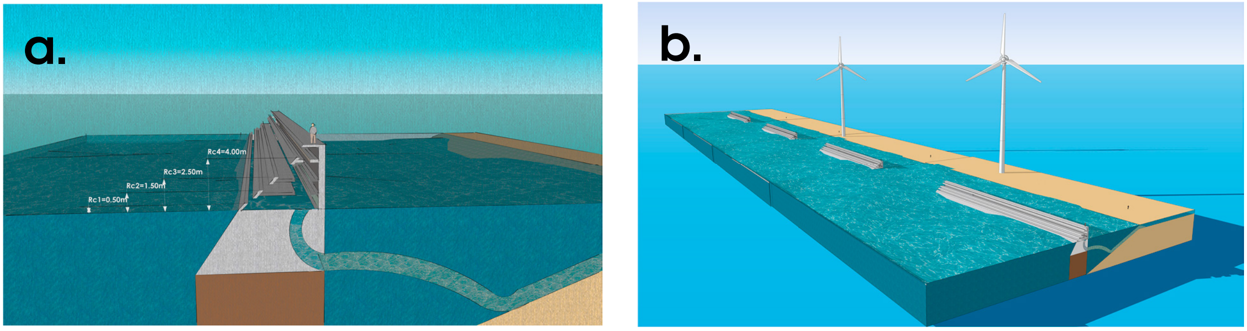

Figure 4. (a) Schematic representation of the Overtopping Wave Energy converter simulated in this study; (b) Schematic representation of the Hybrid Renewable Energy System designed for the case study, containing two wind turbines and four overtopping wave energy converters.

5. A Hybrid Renewable Energy System for remote islands

5.1 Setting up the HRES and monthly analysis

A hypothetical stand-alone HRES (Hybrid Renewable Energy System) is set-up and simulated, to evaluate its sustainability in covering all of the energy demands of the island of Astypalaia. From the 100-year hourly synthetic time-series depicting a stochastic estimation of the wind and wave climate in the HRES installation area, 100-year hourly energy production time series are calculated. Based on the energy demand data for the years 2014-15 a 100-year energy demand synthetic time-series has been produced by Koskinas et al. [27], an annual window of which is displayed in Figure 5(a). For wind and wave resource, a 100-year synthetic time-series is produced through the methodology described in section 3. To harness the wind resource, a DW 52/54 wind turbine by EWT is selected, with a power rating of 500 kW and hub height of 75 meters. The wind resource time-series is extrapolated to the hub height at 75 m, using the logarithmic law, assuming neutral atmospheric stability conditions. Through the power curve of the wind turbine, the wind energy time-series is calculated. Regarding the WECs, the performance of the two types modeled above, in terms of annual energy production, is approximately similar, while a 250kW power rating seems to have an optimal efficiency. By evaluating additional parameters such as the adaptability to the wave climate, the availability of data for calculating the cost of the WEC and the simplicity of the WEC construction, the OWEC seems to outperform the Wave Star, and therefore a 250 kW OWEC-type is selected for the HRES simulation. The wave energy time-series is calculated through the aforementioned methodology, through the initial resource time-series.

Through evaluation of the demand needs, a HRES combining energy inputs from two 500 kW Wind Turbines and four 250 kW Overtopping WECs is considered. The total 1MW of wind turbines produces a mean 5.56 GWh annually, whereas the total 1MW of installed OWECs produces a mean 2.83 GWh annually. Figure 4(b) provides a graphical representation of the HRES. In Figure 5(b) the mean monthly energy production based on wind and wave resource, along with the mean monthly energy demand, through the 100 modeled years, are displayed. The mean monthly probability of failure through the 100-year simulation is 35%. Additionally, it is observed in the same figure that during August, the energy demand has a maximum value, while during May, energy production based on both wind and wave resource, has a minimum value. The HRES fails to cover energy demands on these two months for all the years of the simulated period. Covering the energy deficits of May and August is therefore an important parameter for the sustainability of the renewable system.

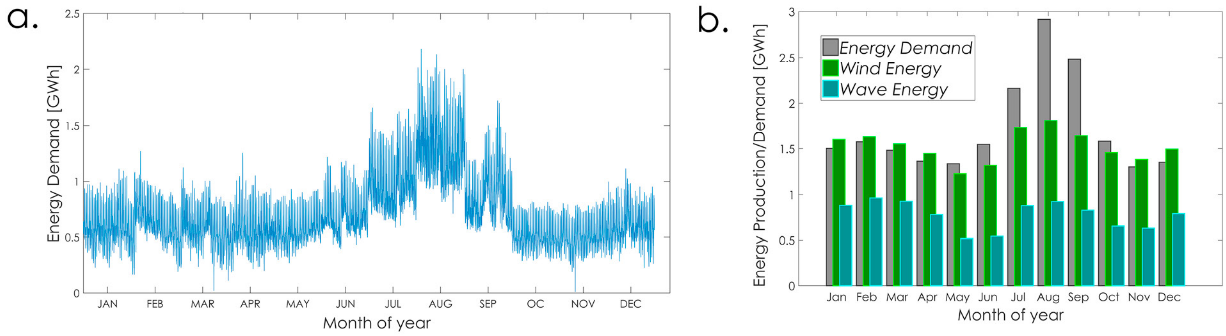

Figure 5. (a) An annual window of energy demand in Astypalaia; (b) Mean monthly energy production and demand by the simulated HRES in Astypalaia, for the 100-year scenario.

5.2 Adding pumped storage and simulating a 100-year risk analysis

A main disadvantage of Renewable Energy resources is that they cannot be used for on-demand energy production. Thus, a renewable energy system needs a supportive on-demand energy production source or an energy storage system to cover peak daily and monthly demands. In the simulated HRES, an average of 54% of the days through the 100 years are covered fully by utilizing the wind and wave energy resource, without any complementary system. To achieve full autonomy of the HRES, a pumped storage system is proposed as a feasible and economic addition, utilizing surplus energy resource, in order to cover peak demands. The pumped storage system stores the surplus energy collected through the OWEC in water discharge values, by channeling it in a reservoir through a pump, fed with the surplus wind energy. Due to the fact that peaks of wave resource arrive at the same time periods with peaks of wind resource (with a small hourly lag), as discussed in section 3, it is assumed for the simulation of this study, that the wind surplus is always enough to feed the pump. A pump efficiency factor of 75% is estimated. By simulating the HRES with a pumped storage system, the capability of the system to fully cover 100% of the daily hourly demands through the year is examined.

By storing the surplus wave energy (the surplus of wind is not saved), a 100-year hourly simulation is run, in which the hourly deficits are covered by the stored surpluses. The total yearly surpluses and deficits for each of the 100 simulated years are calculated and presented in the risk analysis graph of Figure 6. The annual probability of failure of the pumped storage system is 24%, while the measure and frequency of surplus values exceeds significantly the measure of deficit values, which implies sustainability of the HRES system. The worst-case scenario can be located through years 32-34 with a total 3-year deficit of 700MWh. It should be noted here, that the modeled 100-year scenario includes a randomness factor, therefore all real developments would vary, nevertheless agree with the statistical properties of the estimation, making the conclusions from the modeled scenario reliable.

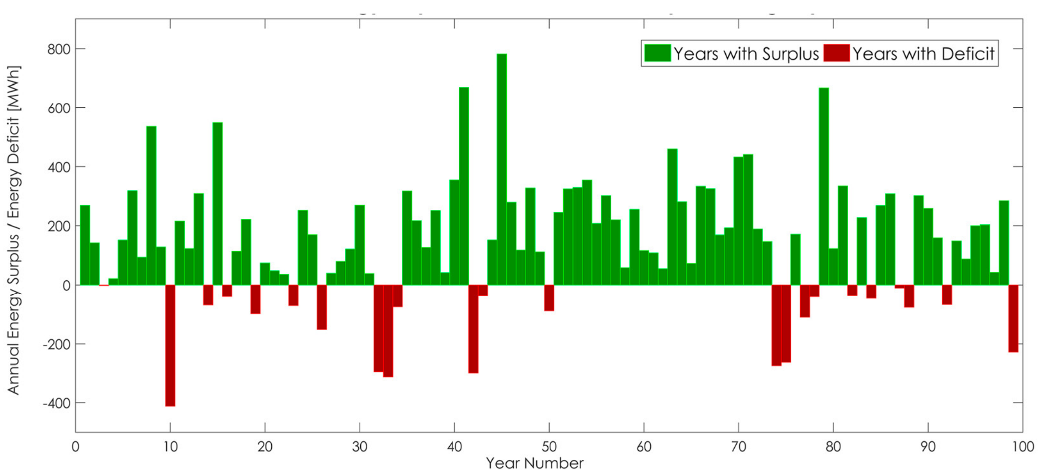

Figure 6. Annual surpluses and deficits in the HRES simulation for a 100-year scenario

5.3 HRES sustainability discussion

From the results of the risk analysis and the illustrated scenario of Figure 6, the HRES is evaluated on its ability to cover all of the non-connected island's energy demand with zero dependency on oil-based energy production. In such manner, the pumped storage system requires a significantly large reservoir in order to store the volumes required to cover the inter-annual deficits, which are 700MWh in the worst-case period. The required area to construct such a reservoir constitutes the major drawback of the proposed system. To solve this, an additional component of either storage or on-demand energy production could be further simulated and added to the HRES. One such storage alternative is adding a battery, which can also store the wind energy surplus and through this cover daily and monthly peak deficits. The main disadvantages of a battery are the high cost and low life-cycle. Alternatively, on-demand energy production could be covered by either biomass conversion or a diesel generator. Biomass counts as a carbon-free, renewable energy source, found through the island community's disposable organic matter. On the other hand, diesel generators are commonly used in HRESs due to their efficiency and their widespread energy source.

Overall, the sustainability of the system in the case study is considered satisfactory. The prevailing wind and wave conditions in the months of July and August, combined with the stored energy of the surpluses of previous months, allow for high August energy demands, attributed to tourism and temperature rise, to be covered. Additionally, low HRES energy output on the months of May and June can be covered by resources stored in winter months.

6. Conclusions

In this study, a wind and wave resource based HRES consisting of two 500kW Wind Turbines, four 250kW Overtopping Wave Energy Converters and a pumped storage system has been simulated, to cover the energy demand of a remote, non-connected island. The wind and wave resources in the case study area of Astypalaia have been simulated for a historical period of 7 years. Historical data were drawn from the ECMWF Era-Interim re-analysis for wind resource and HCMR Poseidon buoy network for the wave resource. These data served as input to the spectral wave numerical model MIKE 21 SW to assess a 7-year wind and wave climate around the island. The model results time-series were the base of a stochastic modeling, to estimate a 100-year scenario of wind and wave energy resource availability. Through a CSAR algorithm hourly synthetic time-series were produced, preserving the periodicities, distribution of the resource significant values, as well as the cross-correlation between the values. Furthermore, because of the immaturity of marine energy technology, two types of WECs were compared, to choose the most suitable one for the Aegean climate. Finally, the sustainability of the system has been simulated through a risk analysis of the 100-year scenario, examining daily, monthly and yearly energy coverage of a synthetic energy demand time-series. Through the risk analysis, it is extracted that the simulated HRES is overall sustainable, possibly providing energy autonomy to the island of Astypalaia. This case study contains significant limitations, regarding the parameters taken into account by the modeling procedures of either natural, environmental, social or economic aspect. While the methodology followed here provides a reliable assessment of the sustainability of such system, it is far from consisting a recipe for immediate implementation, for which further investigation is advised.

Modeling climate dependent renewable resources requires an accurate reproduction of the deterministic mechanisms of physical processes as well as the quantification of the uncertainty factor, present in all multivariate systems. A combined deterministic and stochastic modeling serves for such an approach, reproducing historical data around the area of interest through numerical modeling tools and expanding random possible future scenarios with a stochastic methodology [28]. A long simulation (large number of years) increases the reliability of the modeled system. This way, possibilities rather than certainties are produced, which are the criteria that a system like a HRES can be evaluated on its probability of failure.

Wind and wave resources are suitable for renewable energy management, especially in the case of non-connected, remote islands where they are available on high amounts. One such case is that of the islands of the Aegean, examined in this study, the methodology of which, could be replicated for various places around the world. The mature wind energy technology combined with the much more immature marine energy technology, can constitute an alternative system to photovoltaic or combined HRESs like wind/hydro or wind/PV systems. The advances in wave energy utilization, as well as the improvement of the synergy between wind and wave energy converter technology could prove crucial for the sustainability of such systems. For the case of the Aegean, the construction of a WEC adaptable to its climate could serve for this case. Furthermore, the adoption of renewable energy policies by the local and national authorities can minimize wasteful fossil fuel products and provide self-sufficiency to local communities of the islands, especially for the ones not connected to the national grid. Regardless, critical social, organizational and economic factors, essential for planning and implementing an effective renewable resource management, can prove key ingredients to substitute expendable oil based energy production.

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