

Simulation of electricity supply of an Atlantic island by offshore wind turbines and wave energy converters associated with a medium scale local energy storage

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Abstract

The problem of sizing an electricity storage for a 5000 inhabitants island supplied by both marine renewables (offshore wind and waves) and the mainland grid is addressed by a case study based on a full year resource and consumption data. Generators, transmission lines and battery storage are accounted for through basic simplified models while the focus is put on electricity import/export budget. Self-sufficiency does not seem a reasonable goal to pursue, but partial autonomy provided by renewable sources and a medium size storage would probably be profitable to the island community.

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1. Introduction

Marine renewables like tidal current and wave energy devices will come to the market in a near future in Europe [1], pushed by the commitment of most of these countries to supply a large part of their energy from renewables by 2010. For such intermittent sources the coupling with a local energy storage is often necessary in order to regulate the energy output flow. This is a routine procedure when one deals with small-scale installations of a few kilowatt like small wind turbines or photovoltaic cells installed to provide electricity in isolated sites. It is less common in large-scale plants of dozens of megawatt, which are most often connected to the main grid, acting then as a storage of infinite capacity.

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In the present case study, we have evaluated by numerical simulations the benefit of coupling a medium scale electric storage to offshore wind turbines and wave energy converters, in order to supply electricity to a French island community. The case is virtual, no such project being planned today, but the simulations were performed by using real resource data (wind and waves) over a whole year (1999) and also the recorded data of the electricity demand of this island community.

In the study, we systematically varied the storage capacity, and the power installed at sea, considering three cases: offshore wind farm only, wave energy only, or a mixed solution combining these two resources. From our results we could predict the resulting flux of electricity between the island and the mainland in the time-domain, on a one-hour time step sampling. So, from this case study, we are now able to size the required electricity storage with respect to an energy management strategy which should be chosen by the island community as, for instance: self-sufficiency with regard to the utility network, or balancing the input and output electricity fluxes to a certain level, depending on economic parameters as kilowatt hour price, or any other choice of local energy management strategy.

2. The data

The data used for this study are related to the French island of Yeu, which is located 20 km off France west coast, near Nantes. The data shown in Fig. 1 are the actual wind and wave resource data over one full year (1999) on this site. Global electricity consumption of the island

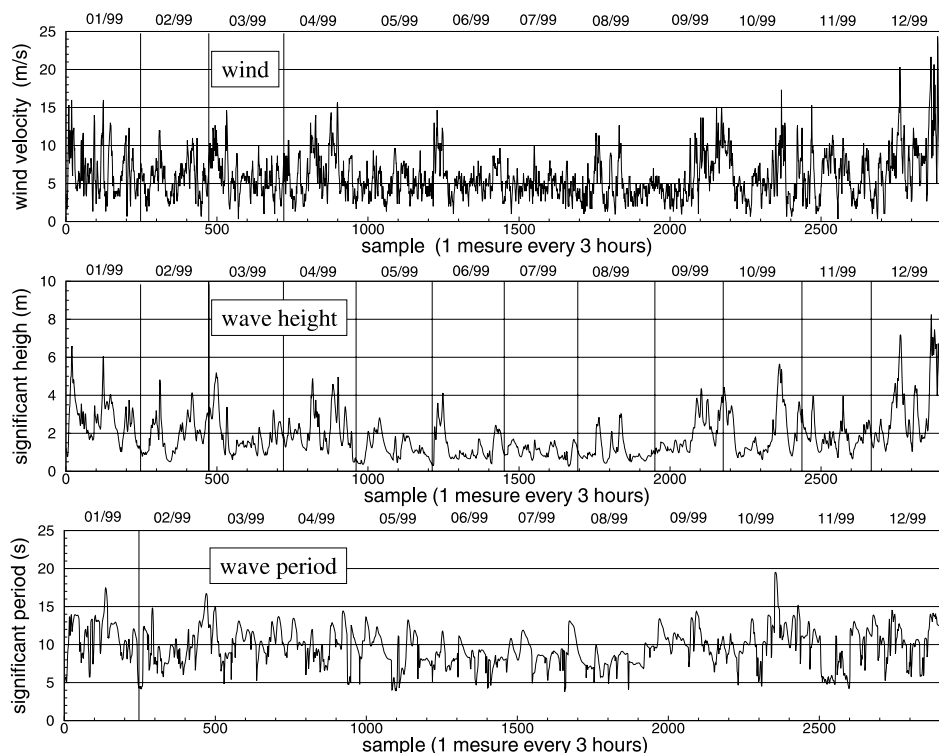


Fig. 1. Time evolution of wind velocity (top), significant wave height (middle) and significant wave period (bottom).

community is shown in Fig. 4 (top). These data sets were post processed to sample them on a one-hour time step basis.

About 5000 persons live here all year long, but the island population increases by a factor 6 during summer holidays. That can explain why, the electricity demand is as important in summer and in April (Easter holiday) as in winter (due to house heating). During this sample year (1999), the average annual power demand was about 4.16 MW and the peak power was recorded at 11.9 MW. This island is connected to the mainland grid by a three submarine cables rated 10 MW each.

The top Fig. 1 shows the wind speed recorded at 55 m height. As expected in this country, the velocity of the wind is higher in autumn and winter than in summer. The year average velocity is about 5.84 m/s and the maximal velocity is 24.3 m/s.

Medium and bottom Fig. 1 show, respectively, significant amplitude (H_s) and period (T_s) of the wave climate at a point few kilometers offshore Yeu island (data provided by LNHE). As expected, wave period and wave height are smaller in summer. As the wave power per meter of wave front can be estimated by: $\bar{P} = 0.57 H_s^2 T_z$ kW/m (with $T_z = T_s/1.2$), the wave energy resource is naturally smaller in summer. The yearly average incident wave power is evaluated at about 25.8 kW/m. For this site, the prevailing sea state is: $H_s = 1$ m, $T_s = 10$ s resulting in a mean incident power of 4.75 kW/m.

3. Offshore energy generators

Offshore farms of wind turbines and wave energy generators were considered here. They were modelled by simple basic input/output models which are described below. Losses in transmission lines, transients, hysteresis phenomena, ..., were not accounted for in this first simplified modelling of the global dynamics of this complex system.

3.1. The wind turbine model

In Fig. 2, the solid line shows the normalized power curve of a real device (from the manufacturer) and the dashed line is a simplified linear approximating power curve used in this study. When the wind velocity is lower than 4 m/s the turbine is stopped and the power output is zero. For wind velocity greater than 25 m/s, the turbine is put in survival condition and the power

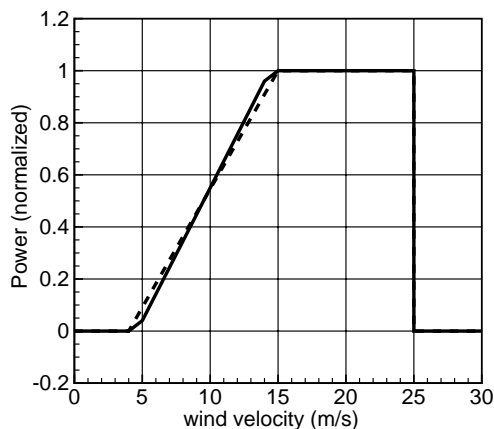


Fig. 2. Wind turbine: normalized power curve.

is also set to zero. For velocity between 15 and 25 m/s, the output power is the rated power of the turbine. In the simulations, we worked with a normalized power curve instead of a precise type of turbine, in order to vary easily the installed power of the virtual offshore park as a parameter. With this model of wind energy device and by using wind data depicted in previous section, a generic 10 MW wind farm provides 21.52 GWh on this site. The predicted power output of this farm over the full year is shown in the middle cell of Fig. 4.

3.2. The wave energy device

The wave energy device used here is a 250 kW version of the SEAREV floating system, currently under development at ECN [3]. As wind turbine power curves give the power output as a function of wind velocity, the average power matrix of a wave energy device (Fig. 3) allows to predict power output for each given sea state characterized basically by the two variables (H_s , T_s): significant wave height and period. The primary wave energy output being naturally fluctuating, we have to work here with average values. The average power output is indeed lower than the installed power, due to long periods of under rating running of the devices. By reducing the rated power of the wave energy converters and installing more converters the global the capacity factor (i.e. the annual energy production expressed in term of hours at rated output) is increased. The maximal average power that the current device can provide is about 0.9 times the installed power. For the prevailing sea state (1 m, 10 s), the normalized average power output (i.e. average power output/rated power) is about 0.39.

Applying this model of wave energy device to the wave data depicted in Section 2, a 10 MW wave farm would deliver 21.42 GWh/year. The predicted power output over the year is shown in the bottom part of the Fig. 4. So the global production efficiency is equivalent, at this site, for the wave farm as for the wind turbine farm.

3.2.1. The electricity storage and transmission lines models

In this study, we were primarily interested by the difference between the real dynamics of time domain consumption curves and offshore renewable energy production. So we keep a very

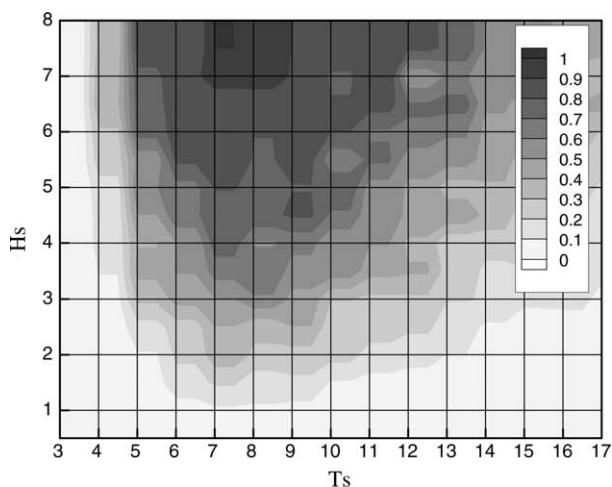


Fig. 3. Wave energy device: normalized power matrix.

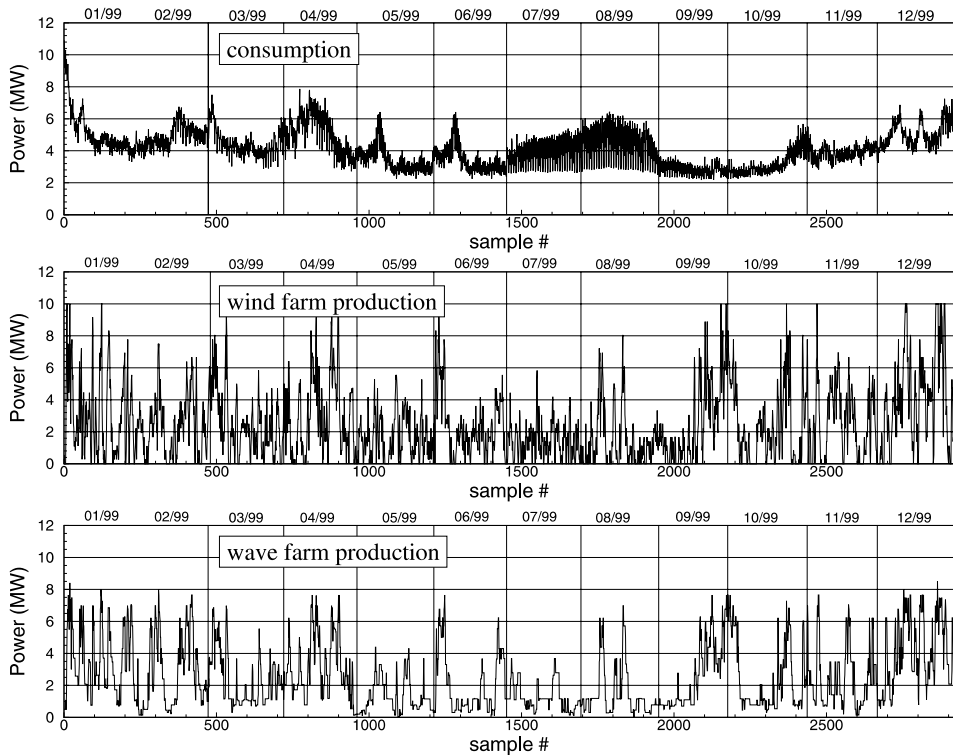


Fig. 4. Electricity consumption (top); 10 MW offshore wind farm production (middle); 10 MW wave farm production (down).

basic modelling for the transmission and storage components. Unlike a previous more sophisticated approach to a similar problem in Ref. [2], we have considered here a ‘perfect’ electricity storage model with no loss in input neither in output. This virtual electricity storage is indeed unrealistic, but because our goal here was only to compare the global efficiency of different configurations, we considered this assumption as valid. We also supposed that transmission lines are perfect (no loss).

4. Results

Three configurations were considered for the electricity supply of the island by the renewables: an offshore wind farm, a wave farm or a mix of those two sources. The installed power of each one and the storage capacity were the main parameters of the study. The complimentary part of electricity, when needed, is still provided by the utility grid from the mainland through the submarine cables. Left Fig. 5 shows the amount of energy exchanged yearly with the mainland: the island community imports energy when the offshore farms cannot provide enough energy, at the opposite when the amount of energy produced is larger than the demand, the community sells (export) energy in excess to the mainland.

Let us first consider a configuration without electricity storage, but with the constraint of no electricity supply breakdown during the full year.

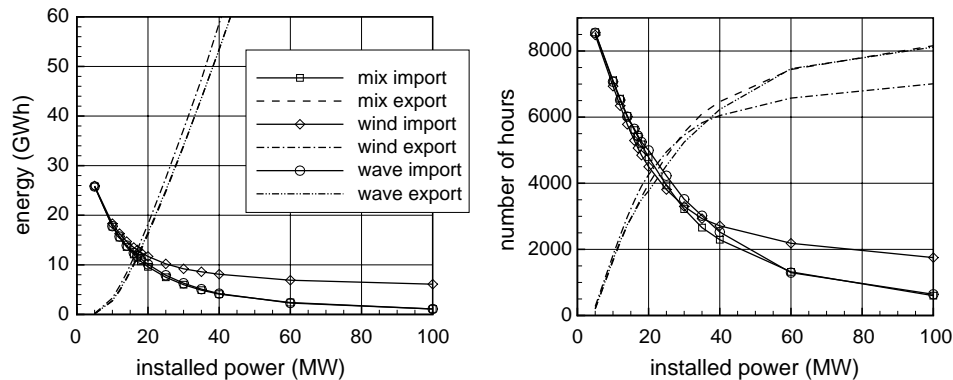


Fig. 5. Electricity exchange with mainland. Solid lines: import (the community buy); dashed lines: export (the community sell).

We observe that curves corresponding to combined sources farm and wave farm are very close whatever the installed power. Whereas input and output energy fluxes are larger with wind generators, this difference increasing with installed power. Whatever the renewable source used, the amount of sold and bought energy are almost equal when the installed power is around 17 MW. A 17 MW wave farm and a 17 MW wind farm provide, respectively, 36.41 and 36.58 GWh, which coincides with the energy consumed yearly (36.4 GWh) by the island community.

The right part of Fig. 5 shows the number of hours spent by the community selling and buying electricity to the mainland grid. The curves cross around an installed power of 22 MW, which is a bit larger than the previous level of equal fluxes (17 MW) for which energy importation duration is larger than exportation duration. This is a clearly consequence of the difference in the dynamics of electricity production from offshore sources and electricity consumption.

The asymptotic behavior of solid lines in Fig. 5 shows that it would not be realistic, in terms of power installed offshore, to seek for complete self-sufficiency of the island; it would necessitates several hundred of megawatt offshore, to provide only 36 GWh/year for the community consumption, and the local grid would not be able to absorb the difference in excess.

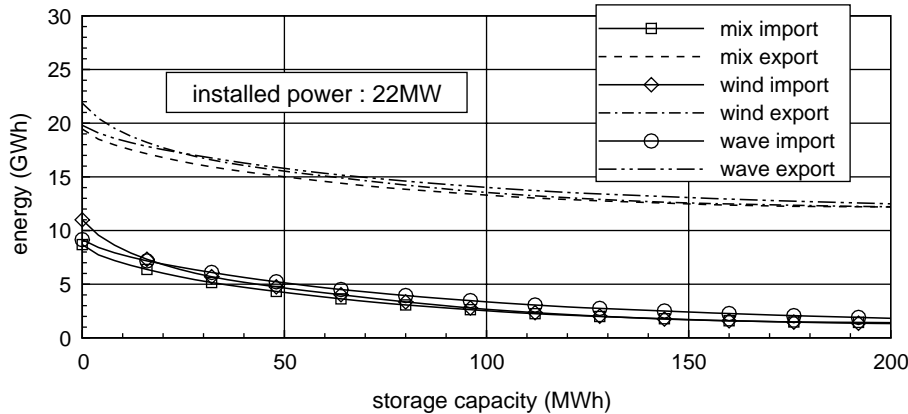


Fig. 6. Annually imported and exported electricity.

Let us now introduce an ideal electricity storage on the island, with a capacity to be determined by the numerical simulations. The amount of energy exchanged by the island with the mainland grid will indeed decrease when increasing this capacity, as shown for example in Fig. 6 corresponding to three configurations with 22 MW installed offshore. For very small storage capacities, the wind farm curve slope is bigger than the two others, but when the capacity reaches 20 MWh, the exchanges of energy are quite similar whatever the kind of generators installed. The amount of imported energy with combined wind and wave sources always remains smaller than the two others individually, as expected, but only of a few percent. This is analyzed as a consequence of the high correlation between offshore wind and wave energy resources. For large storage capacity, amounts of exchanged energy become very close all together. The difference between exported and imported amount of electricity is constant whatever the installed storage capacity, which is explained by the balance relation

$$\text{production} + \text{import} = \text{consumption} + \text{export}$$

implying that $[\text{export} - \text{import}] = \text{constant}$ for a given production figure.

Whatever the kind of renewable farm used it seems quite impossible and unrealistic to obtain electrical self-sufficiency of Yeu island, with a reasonable installed power. With a 20 MW farm, the self-sufficiency would be obtained with 760 MWh storage capacity (!). Nevertheless, and this is the most interesting conclusion here, it is easy for the community to reach a high level of autonomy with a large excess of electricity likely to be sold to the utility: for example with a 22 MW farm (i.e. five times the averaged electrical power demand of the island and twice the peak demand) and a 50 MWh battery capacity (equivalent to 12 h of averaged consumed power), the community will need to buy about 5 GWh (i.e. only 14% of its current yearly electrical consumption demand) and will be able to export three times as much as this amount of energy to the mainland network. Generalizing this approach by varying the installed power of the offshore farms, either wind, waves or both, we were able to plot the curve in Fig. 7 showing the relation between the excess of electricity produced (i.e. $\text{export} - \text{import}$) likely to be sold to the utility,

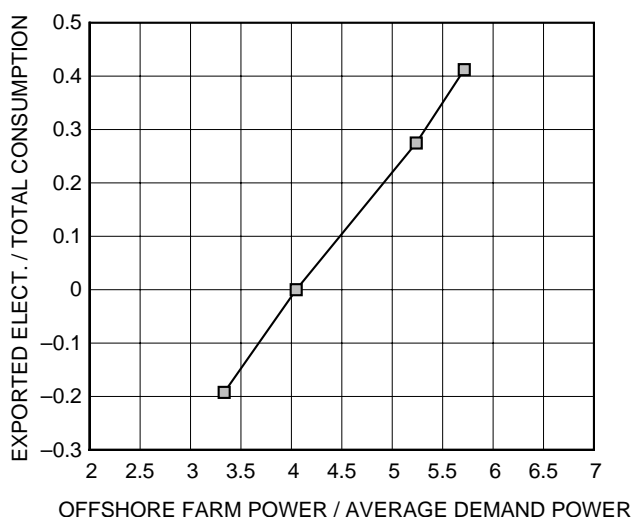


Fig. 7. Excess production ratio versus installed offshore power ratio.

versus the level of power installed offshore (reduced by the average power consumed by the island community).

The very high slope of this line must be interpreted as a favorable sign in favor of such an integrated solution, provided the electricity produced in excess can be exploited financially in order to balance the investment for the electrical storage equipment.

5. Conclusion

In this case study, we have seen that the complementarity between offshore wind turbine and wave energy device is small due to the high correlation between these sources. The level of energy delivered annually are very similar for the same rated power installed at sea. This is encouraging since the model of wave energy power matrix used here is a very preliminary version of the device that we are still optimizing. A third solar source would have been welcome to cope with the summer demand due to tourist rush in this area. Such a complimentary study has been presented in 2004 [4].

It appears that full electrical self-sufficiency from offshore sources cannot be considered as a reasonable goal in the case of Yeu island. But, we have shown that a high degree of energetic independence could be reached by associating to the offshore generators an electricity storage of reasonable capacity range. With such a configuration the ratio of exported over imported electricity could raise up to five or more. This should be accounted for in an economic study to be carried out now, but which was beyond the scope of the present study.

Acknowledgements

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