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Aiding water production in isolated islands using integrated renewable energies sources

Mariasole Cipolletta, Valeria Casson Moreno*, Elisa Dallavalle, Barbara Zanuttigh, Valerio Cozzani

Alma Mater Studiorum - Università di Bologna, Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali, via Terracini 28, 40131 Bologna, Italy
*valeria.cassonmoreno@unibo.it

Worldwide, several locations are characterized by abundance of natural energy sources, prone to be converted in power for electricity generation and process-related duties. However, the discontinuity of such renewable energy sources (RES) coupled with their conversion difficulties, results in moderate advantages when a steady power demand has to be satisfied using a single energy source. To overcome the forehead mentioned limitations, profitable renewable energy harvesting can be reached by exploiting multiple RES at once. Such possibility is, in principle, very versatile, thanks to the modularity of the integrated power generation plant, that can be designed based on the energy availability and investment options.

In the present work, the approach of integrating multiple RES was used to assess the technical feasibility of harvesting solar (via photovoltaic panels) and wave energy (via wave energy converters) to supply a desalination unit for the production of irrigation water in Tenerife (Canary Islands, Spain). The available energy from RES was evaluated through the elaboration of weather-climate hourly data, offered by open-access databases. Then, the proper conversion technologies were selected and single production curves were obtained. The integrated system was conceptually designed overlapping the hourly power generations; its performance was assessed with respect to possible duties of the desalination unit. The self-sustainment level of the integrated system was evaluated by calculating the percentage of time that RES can cover the requested power. Based on this, the selection of the most sustainable RES mixing was set, determining, in turn, the final productivity of the desalination facility. The results demonstrated that the integration of different RES represents a reliable and environmentally sustainable solution, especially for remote areas dependent on fossil fuels importation.

1. Introduction

Worldwide many small islands located far from continents experience lack of sources in terms of materials, fossil energy sources and/or natural elements. When these shortcomings occur simultaneously, these regions become totally dependent on importations with consequent skyrocketing of life cost for their inhabitants (WorldData.info, 2020).

The increasing development and employment of renewable energy sources (RES) open the way for novel considerations, in addition to clean energy exploitation and avoided CO_2 emissions: firstly, the decentralization of power generation and secondly, the opportunity of reducing the dependence from fossil fuels vendors (Lozano *et al.*, 2019).

It’s the case of the Canary Islands, that historically suffer from water scarcity due to climate characteristics and reduced underground sources (Rosales-Asensio *et al.*, 2020); furthermore the energy panorama of the archipelago is still dominated by fossil fuels purchase for the 92% (Gobierno de Canarias, 2017), with electricity prices touching the 0.26 €/kWh (Schallenberg-Rodríguez and García Montesdeoca, 2018) vs. 0.20 €/kWh €/kWh of the Spanish peninsula (GlobalPetrolPrices, 2020).

Nevertheless, for this geographical location the potential of marine energy was diffusely studied and resulted extremely promising for wind and wave power conversion (García, 2019). Thus, this location was chosen for the present case study to demonstrate a possible application of RES integration aimed at aiding water supply.

Among the Canaries, Tenerife island was considered: besides being an increasingly populated and touristic island (CityPopulation, 2020), the agricultural sector is of paramount importance in the overall economics because of the favorable cultivation conditions of many sub-tropical crops. This island alone covers the 42% of the banana production of the seven Canary Islands, exporting 90% of the products to the Spanish mainland, with a cultivated area of 3775.5 ha (Gobierno de Canarias, 2020). In Tenerife, climatic conditions causes that 7 over 9 fields ask for irrigation (Gobierno de Canarias, 2020). Thus, although the level of spring waters is slightly higher than in the rest of the archipelago (Consejo insular de Aguas de Tenerife, 2020), environmental policies foresee the reuse of abundant wastewaters in irrigation and farming: to this purpose and also for desalination systems, RES employment is strongly recommended (Gobierno de Canarias, 2017).

Therefore, in this study the possibility to energetically self-sustain a desalination unit for wastewater treatment was explored starting from a defined set of solar and wave technologies, whose integration can lead to the sustainable production of irrigation water for a typical exotic crop. The most water-demanding fruit-crop, i.e. banana *Musa acuminata C.* (FAO, 2020), was selected in order to quantify the maximum surface that would benefit from this RES-based system..

Electrodialysis (ED) technology is here assumed for the core operation as it is more employed than reverse osmosis (RO) with low-salinity entering liquids (brackish waters); being characterized by low pressure, ED also reduces the energy inputs (Schallenberg-Rodríguez, Veza and Blanco-Marigorta, 2014). Real plant data showed that ED is able to lower salts concentration (from 1200 mg/L to 300 mg/L) and to remove turbidity, with a specific energy request of about 0.9 kWh/m^3 (Veza, 2001).

Different production capacities for the desalination unit were considered and the corresponding power demands compared with the RES integrated system's output. The optimal productivity searched is the one enabling a high-level of energetic self-sustainment using RES only. Furthermore, the observation of energies involved enables the discussion about possible back-up systems aimed at valley filling; similarly, opportunities for storage systems for peak shaving can be regarded.

2. Methodology

The methodology applied in this study consists of the following steps: (i) data collection, (ii) evaluation of available renewable power, (iii) conversion system selection and power output calculation, and (iv) performance assessment of the integrated RES system.

2.1 Data collection

First, meteo-climatic data were collected from region-specific datasets in order to represent the actual RES potential in Tenerife. To assess the yearly repeatability of climatic conditions, the time-span analyzed was 20 years for both sources, from 1999 to 2018.

The variables needed for the evaluation of solar irradiation are the surface net solar irradiation H_h [J/m^2], the direct irradiation H_{bh} [J/m^2] and the ground albedo α [rad] (all referred to a horizontal capturing surface). They were all retrieved as hourly series from "Copernicus Climate Data Store" provided by the European Centre for Medium-range Weather Forecasts, through the reanalysis dataset "ERA5" (ECMWF, 2020). The sea states information was obtained from the SIMAR dataset, where hourly data arrays reporting the significant wave height H_s, its energy period T_e and the wave direction ϴ are available (Puertos del Estado, 2020).

For both RES, the locations considered for climate data retrieval are reported in Table 1.

Table 1. Geographical coordinates of the points considered for solar and wave data retrieval.

Source points	Latitude	Longitude
Solar irradiation	28°50' N	16°25' W
Wave power	28°45'N	16°00'W

2.2 Evaluation of available natural power from the selected RES

Solar-related variables were re-worked according to the regulation UNI 8477 (UNI Standards, 1983) in order to evaluate the total solar irradiation H [J/m^2] on a generally inclined and oriented surface. Eq. 1 reports the core final step of the procedure, where R [-] is the total gain of incident energy, resulted from previous calculations.

$$H = R \cdot H_h \qquad \text{Eq. 1}$$

Similarly, wave data were processed in order to calculate P_w [kW/m], the available wave power per unit of crest length according to Eq. 2:

$$P_w = (\rho_{sea\,water} \cdot g^2 \cdot H_s^2 \cdot T_e)/64 \cdot \pi \qquad \text{Eq. 2}$$

where $\rho_{sea\,water}$ is the sea water density (1.025 kg/m^3) and g is the gravitational acceleration (m/s^2).

2.3 Evaluation of renewable power production

From the previous step, the study is restricted to a reference year whose climatic parameters are representative (i.e. average) of the studied decades.

Then, in order to estimate the attainable hourly renewable power production, suitable conversion technologies were selected for each RES.

For the case of solar power, a photovoltaic (PV) panel characterized by average-performances was selected and a limited land area of 100 m x 100 m (1 ha) was considered for the installation. The small extension is believed to properly represent the solar potential in Tenerife while not exceeding in land-use, taking into account either the scarce free spaces in the island (Cabildo de Tenerife, 2019)The orientation of the panels was optimized (in terms of azimuth and inclination angles) to maximize the power production..

More in details, the hourly power generation of the solar park P_{PV} is calculated through Eq. 3, known the irradiation power PH [kW/m^2] and the converter's characteristics, namely the available capturing area A_{PV} [m^2], the nominal efficiency η_{PV} [-] and the relative efficiency f_{PV} [-] (expressing the influence of panel temperature and incident irradiation).

$$P_{PV} = (PH/I_{REF})\ A_{PV} \cdot \eta_{PV} \cdot f_{PV} \qquad \text{Eq. 3}$$

where I_{REF} is the reference instantaneous irradiation of 1 kW/m^2.

For what concerns the conversion of wave energy into electricity, offshore floating Wave Energy Converters (WECs) were found to be a feasible solution, because of (i) the very deep seabed and (ii) the visual impact of the devices in a touristic island. For each WEC, the ranges of operative conditions for (H_s and T_e) together with the power output P_{WEC} (H_s, T_e) are provided by the constructors in form of power matrices (Kofoed *et al.*, 2006). Thus, for each hourly sea state, the power produced can be calculated by means of the power matrix.

2.4 Assessing the performance of the integrated system

In this final step, the renewable power productions by PV panels (P_{PV}) and by WECs (P_{WEC}) are combined in order to obtain the integrated power generation.

The two hourly power series are summed up and the outcome (P_{RES}) is compared with different duties (P_D) of the desalination facility. The hours in which the integrated system was able to sustain the desalination plant request, hereafter Functioning Time (FT), were calculated as per Eq. 4.

$$FT = \sum_{i=1}^{n} h_i \ : \ \ P_{RES}(h_i) = P_{PV}(h_i) + P_{WEC}(h_i) \geq P_D \qquad \text{Eq. 4}$$

where h_i is the i-th hour and n is the total number of hours in the year considered (i.e.8784, being 2016 a leap year).

An analysis of the single RES contribution to the duty and of the overlapping time was performed by introducing the Single Functioning Time (respectively indicated as SFT_{PV} and SFT_{WEC}) and the Combined Functioning Time (CFT), as depicted in Eq. 6:

$$SFT_{r_1} = \sum_{i=1}^{n} h_i : \ \left(P_{r_1}(h_i) \geq P_D \quad \wedge \quad P_{r_2}(h_i) = 0\right) \qquad \text{Eq. 5}$$

where r_1 and r_2 indicate the two RES considered in this study.

$$CFT = \sum_{i=1}^{n} h_i : \ (P_{PV}(h_i) + P_{WEC}(h_i) \geq P_D \ \wedge \ \ P_{PV}(h_i) > 0\, P_D \ \wedge \ \ P_{WEC}(h_i) > 0) \qquad \text{Eq. 6}$$

In order to guarantee a high level of self-sustainment by RES, the final desalination plant capacity was set as the maximum for which the FT is higher than 90 %, i.e. for a maximum Non-Functioning Time (NFT) lower than 10 %.

Irrigable areas were finally quantified starting from banana daily water need in the growth period (covering 300-365 d/y), considering the grass evapotranspiration in arid areas and with average temperatures over 25 °C, as in the hottest season in Tenerife. This value, amounting to 9 mm_{H2O}/d, was increased of a 20 % because of the crop's specificity (FAO, 2020).

3. Results and discussion

3.1 Available wave and solar energy

The study of meteo-climatic parameters led to the quantification of the available natural potential for each RES, namely the solar irradiation on a flat surface (H) and the available wave power (P_W). Table 2 reports the statistic parameters related to the yearly average powers obtained for the investigated period. Yearly values of H are very stable throughout 20 years, while wave power can undergo substantial variations, thus to exemplify the assessment procedure, year 2016 was selected as representative for both RES.

Table 2. Statistical results of available powers from RES over the analysed 20 years and in the reference year.

	Solar irradiation H *[W/m^2]*	**Available wave power P_W *[kW/m]***
Max	188	27
Min	179	12
Average	185	18
Standard Deviation (S)	2.2	3.3
SDV %	1.2 %	17.4 %
In 2016	186	20

3.2 RES conversion outputs

If for solar energy the choice of the PV system is independent from the irradiation level, for wave energy the feasibility of a WECs installation is strongly dependent on typical wave climate (Rusu, 2014). Since waves are characterized by high T_S and low steepness in the examined oceanic region, the Wave Dragon (WD) overtopping device appears the most feasible option. Specifications of the devices chosen are reported in Table 3, while monthly energy outputs for the reference year are displayed in Figure 1.

Table 3. Characteristics of the selected WEC and PV panels.

Device	**PV panel** (Canadian Solar, 2020)	**WEC** (Kofoed *et al.*, 2006)
Name	CanadianSolar CS6K 270P	Wave Dragon
Type	Poly-crystalline	overtopping
Nominal Power (kW)	0.27	4000
Nominal efficiency (%)	16.8	not definable
Weight (kg)	24	22,000,000
Dimensions (m x m)	0.99 x 1.65	260 x 150

Yearly energy generation from the selected PV area is limited when compared with the WD's one (3.2 vs 13.2 GWh/y) as well as power trends, running with averages of 365 kW and 1506 kW, respectively for the solar park and the wave farm. The percentage of hours in which the conversion systems produce energy, amount to 49 % for solar panels and to 85 % for the WD.

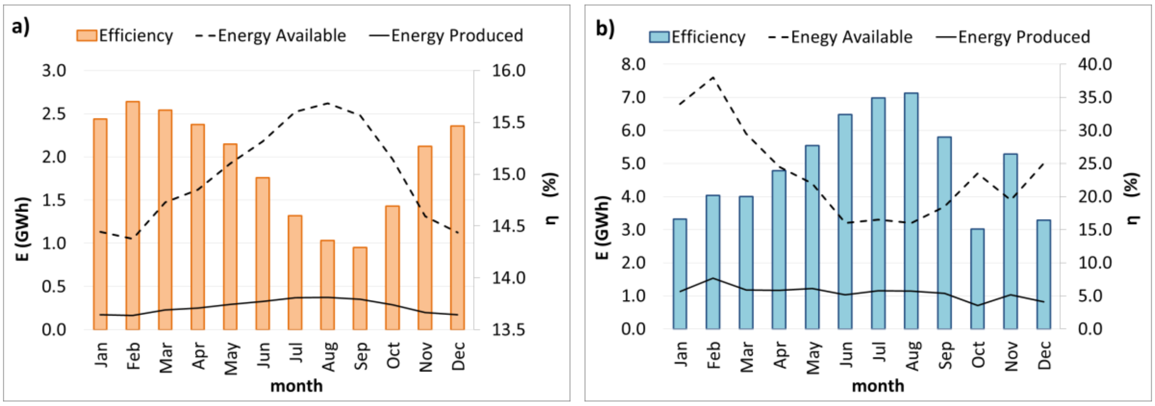

Figure 1. Energy generation performances of the selected renewable energy converters in Tenerife (year 2016): a) solar park of 10'000 m^2 of PV panels; b) the Wave Dragon overtopping device.

3.3 RES integration results

To find the maximum desalination capacity associated to a RES self-sustainment Functioning Time above 90 %, several water productivities were considered and the corresponding power requests compared with the integrated power outputs obtained in the previous step. The duties, representing desalination capacities ranging from 5000 to 20000 m^3/h, are reported in the x-axis of Figure 2. For each option, the contributions of single RES and their combination to satisfy the power demand are reported on the primary y-axis, while the NFT% is displayed on the secondary y-axis.

Power demand was variated to progressively meet the FT%. When decreasing the power duty below 311 kW (corresponding to 8300 m^3/d of desalinated water), FT% reaches the set threshold of 90 %. As a result, this optimal RES set can perform the daily irrigation of banana crops over an area of 768'500 m^2. In the 880 hours during which the power demand is not satisfied, the maximum missing power is equal to the nominal power of the plant (i.e. 311 kW) and the energy missing throughout a year amounts to 256 kWh. On the contrary, energy surplus (i.e. when $P_{RES} > P_D$) sum up to 13.9 GWh.

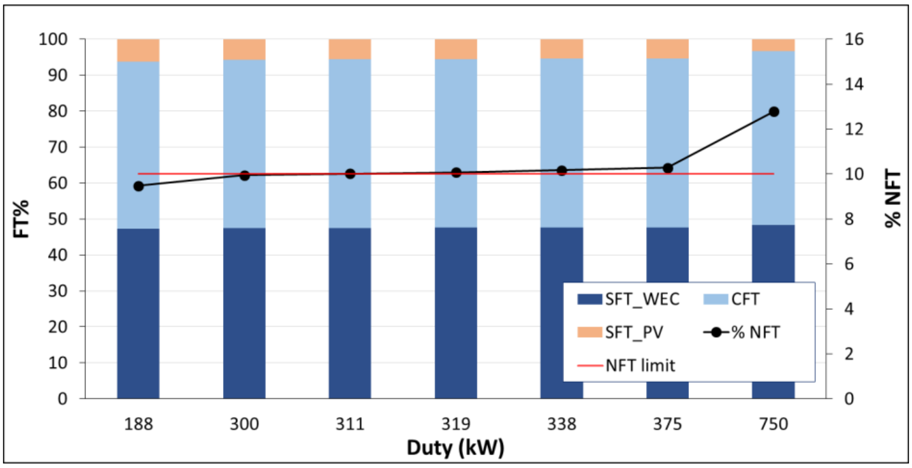

Figure 2. Power response of the RES integrated system supporting different desalination duties: NFT=non-functioning time; FT= functioning time split into SFT_{WEC} and SFT_{PV} (single RES functioning time) and combined functioning time (CFT).

4. Conclusions

This work developed a conceptual design of a self-sustained energy production system based on integrated RES, aimed at producing water for agricultural purposes in Tenerife (Canary Islands). The integrated RES system is based on 1 ha of PV panels and 1 Wave Dragon device, targeted to satisfy the power duty of a wastewater treatment plant for 90 % of its functioning time, in order to reduce as much as possible, the dependence from back-up systems. The study identified a desalination capacity of 8300 m^3/d as the maximum one at which the previous condition can be verified. The implementation of such facility would produce enough water for the equivalent daily irrigation of a banana cultivation of approximately 0.77 km^2. It's worth noticing that the PV farm extension is only 1.3 % of the total crop area. Finally, the analysis of the performance of the RES integrated system revealed that for the defined set-up the maximum power lack is 311 kW, which can be easily provided by a small-size gas turbine or other flexible back-up systems. Alternatively, on the base of economic convenience, energy storage systems can be regarded for valley filling, consuming a minor part of the abundant energy surplus. Furthermore, the results suggest the possible advantages in connecting the RES integrated system to the national grid in order to sell the energy surplus.

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