Selection of a renewable energy mix by using economic and environmental criteria. A case study in the Mediterranean Sea

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Abstract— **Despite technological progress and the ever more stringent laws on polluting emissions, in several remote areas and small islands the energy production is still dominated by the utilization of fossil fuels. This article discusses the feasibility of a mixed system of renewable sources (wind, photovoltaic and wave energy) to be implemented in Favignana, considering alternatively the minimization of the energy costs and estimation of the CO_2 emission of the proposed energy mix. The study was carried out by estimating the energy production on a monthly and annual basis considering a mix of three renewable sources. This method can be easily applied for several small islands, estimating the ability to reduce the energy production from fossil fuels.**

Keywords—***renewable energy, sea wave, wind, photovoltaic plants, small islands***

I. Introduction

In recent years the European Union has defined international agreements and policies to achieve the balance between greenhouse gas emissions and their removal in the second half of the century, thus contributing to limit the global warming and achieve the objectives set by Green European Deal [1]. The promotion of renewable energy mixes to combat CO_2 emissions is one of the most relevant issues in the European panorama implemented through directives. First of all, the Directive 2009/28/EC was emitted for the promotion of the use of Renewable Energy Sources (RES). After almost a decade, the Directive (EU) 2018/2001 of the European Parliament and of the Council amended the previous directive [2], [3].

In Italy, with the National Integrated Plan for Energy and Climate (PNIEC) objectives have been established to incentivize the increment of the share of energy produced from renewable sources. Through the decree, the introduction of renewable energy sources is promoted in twenty small Italian islands, where the objectives of energy production from RES within the time limit of 31/12/2020 and the financial incentives are indicated in [4].

For example, in the case of Favignana (a small island west of Sicily) Annex I of the decree indicates a current energy demand of 15.47 GWh/y (based on diesel engines) and provides for the installation of 900 MW of power plants supplied by RES. As regards the production of thermal energy, the decree provides for the installation of 1,070 m^2 of solar thermal panels. Furthermore, article 6 introduces the possibility of creating "Integrated innovative projects", including in this group also offshore plants powered by RES, and particularly the exploitation of ocean energies.

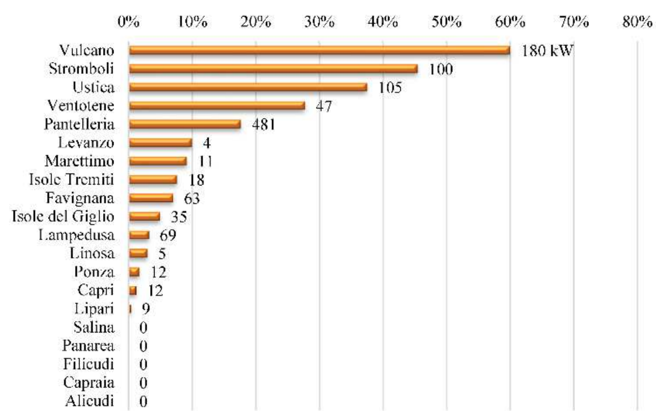

Fig. 1. Finalization of target MISE 2020

The guidelines on the methods and timing were published only at the beginning of 2018, one year after the entry into force of the decree. It is interesting to monitor the objectives achieved by each island compared to the 2020 targets. Fig. 1 shows the electrical system data provided by RES for each small island, considering the actual number and the set objective. Among the small Italian islands, Favignana has not reached the 10% quota. The proposed work aims to identify an energy mix that can contribute to the achievement of the objectives proposed for 2030 by the Ministerial Decree of 14 September 2017. The subsequent ARERA resolution no. 558/2018 established specific incentive tariffs for the strengthening of each island.

This method includes the use of data available in the literature or obtainable through the use of GIS tools. Energy saving is proposed in relation to the reduction of CO_2 emissions.

II. METHODS

To identify the optimal energy mix, in a previous work of the authors, an economic criterium was introduced [5]. The idea was the minimization of the levelized cost of energy produced by an energy mix, composed by solar, wind, sea wave and the existing diesel plant. In this paper, the CFP (Carbon Footprint) of the entire energy mix is introduced.

The need to control emissions of greenhouse gases as set out in the Kyoto Protocol requires ongoing careful consideration and evaluation of energy consuming activities [6], [7]. Many activities can result in the emission of more than one of the greenhouse gases. CFP is a methodology for computing the total relevant emissions of greenhouse gases for specific applications.

CFP is a measure of the greenhouse gas emissions (i.e. the global warming impact) and, as better defined in the following paragraph, the authors express it starting from the evaluation of CO_2 emissions that are produced in the life cycle of these technologies during the production and execution phase and those produced by the use fossil fuels to satisfy the energy demand.

Photovoltaic (PV) panels convert solar radiation into electricity, thus, the power generation during their lifetime does not require any fossil fuel as input. However, large amounts of energy are necessary during production, especially for the refinement of the silicon feedstock and the crystallization processes [8]. Wind plants and systems that exploit sea waves, like all other renewable energy sources, also have an impact and an environmental cost, which must be identified and estimated [9].

CFP is calculated starting from the impact of CO_2 emissions deriving from fossil fuels used to produce the energy necessary for the construction, installation, maintenance and decommissioning of systems that exploit renewable energy.

A. Solar source

If all photovoltaic (PV) plants have the same specifics (installed power, orientation, etc.), the annual energy production solar radiation E_{PV} is given by the product of the annual energy production of a single PV plant and the number of operating PV plants n_{PV}:

$$E_{PV} = n_{PV} e_{PV} = n_{PV} \sum_{i=1}^{12} e_{PV,i} = n_{PV} \sum_{i=1}^{12} H_{T,i} S_{PV} \eta_{PV} t_i \tag{1}$$

The annual energy production of a PV plant can be expressed by the sum of the monthly energy production $e_{PV,i}$. More in details, the equation considers the perpendicular component of the daily solar radiation $H_{T,i}$ on the plane of photovoltaic panels, the surface of photovoltaic panels S_{PV}, the average energy efficiency η_{PV} of the system and the number of days t_i per month.

Climate data of solar radiation are normally referred to the horizontal plane, considering the average conditions of cloudiness and atmospheric clarity.

B. Wind source

The availability of wind source can be expressed by using the parameters k and λ of the Weibull distribution. Despite this probability density function is usually used to model the entire year, it is also possible to evaluate the previous parameters, by considering each month [10], [11].

In this case, Eq. 7 can be introduced to evaluate the annual electrical energy production E_W from a wind farm:

$$E_W = n_W e_W = n_W \sum_{i=1}^{12} e_{W,i} = n_W \sum_{i=1}^{12} \sum_{j=1}^{n} c_p(v_j) pdf_i(v_j) \Delta v$$
$$pdf_i(v_j) = \frac{k_i}{\lambda_i} \left(\frac{v}{\lambda_i}\right)^{k_i - 1} e^{-\left(\frac{v}{\lambda_i}\right)^{k_i}} \tag{2}$$

where e_W is the annual energy production from a wind turbine, $e_{W,i}$ represents the energy production in i-th month from the same turbine, n_W is the number of installed wind turbines, and $c_p(v_j)$ represents the power output of a chosen wind turbine as function of wind speed.

C. Sea wave source

The sea wave energy source is usually described, introducing the wave power flux φ_m that represents the average power produced by a length unit of wave front. In deep water, the wave power flux can be evaluated by Eq. 3 [12], [13]:

$$\varphi_m = \frac{\rho g^2}{64\pi} H_s^2 T_e \tag{3}$$

where H_s represents the significant wave height (though to crest), T_e the energy period, ρ the seawater density. In detail, H_s is traditionally defined as the mean wave height of the highest third of the waves [14].

Thus, the estimation of the energy production of a wave energy farm (E_{SW}) can be evaluated by using Eq. 4:

$$E_{SW} = n_{SW} e_{SW} = n_{SW} \sum_{i=1}^{12} e_{SW,i} = n_{SW} \sum_{i=1}^{12} \varphi_{m,i} D_C \eta_{SW} h_{m,i} \tag{4}$$

considering the monthly average sea wave energy flux $\varphi_{m,i}$, the equivalent hydraulic diameter D_C of the wave energy converter, the average energy efficiency η_{SW} of the device, the number of devices n_{SW} installed in the wave farm and the number of hours in the i-th month $h_{m,i}$. In the equation, the term $e_{SW,i}$ represents the monthly electrical production from a sea wave energy converter, while e_{SW} represents the annual electrical production.

D. CFP (Carbon Footprint)

In a previous article the authors selected the energy mix by using LCOE as a criterium [5], [15]. The formula was now modified to move from an economic approach to an environmental approach. This article aims to verify whether an economic approach is comparable to an environmental one or whether the results are antithetical.

$$LCOE = \frac{E_F c_F \sum_{i=1}^{n} \left(\frac{1+\varepsilon}{1+\tau}\right)^i + I_0 + \left(C_{m,R} + C_{m,F}\right) \sum_{i=1}^{n} \frac{1}{(1+\tau)^i}}{\sum_{i=1}^{n} E_d}$$

where:

$$\begin{cases} E_F = E_d - (E_{SW} + E_W + E_{PV}) \\ I_0 = i_{0,SW} p_{SW} n_{SW} + i_{0,W} p_W n_W + i_{0,PV} p_{PV} n_{PV} \\ C_{m,R} = c_{m,SW} p_{SW} n_{SW} + c_{m,W} p_W n_W + C_{m,PV} p_{PV} n_{PV} \end{cases} \quad (5)$$

Several parameters are introduced in Eq. 5, in detail E_d is the annual energy demand. The annual electricity production from existing power plant (fossil fuel) E_F is obtained as a difference between the energy demand and the expected production from the renewable energy sources, respectively E_{SW}, E_w, E_{PV} (sea wave, wind, and solar sources). The cost for the electricity production from diesel engine is expressed by the term c_F. The amount I_0 represents the investment to build the energy mix, thus three contributions are considered, by using unitary costs ($i_{0,SW}$, $i_{0,W}$, $i_{0,PV}$), the rated power of the selected technologies (p_{SW}, p_W, p_{PV}), and the proposed number of devices (n_{SW}, n_W, n_{PV}).

Considering the environmental impacts, a Carbon Footprint (CFP) for an energy mix was presented [16], [17]. This parameter is a methodology for computing the total relevant emissions of greenhouse gases for specific applications starting from the impact of CO_2 emissions deriving from fossil fuels used to generate the energy necessary for the construction, installation, maintenance and decommissioning of systems that exploit renewable energy. This concept is normally applied to a single technology in literature [18], [19], [20]. The authors extend this approach to an entire energy mix, composed by different technologies. So, in this case the parameter CFP can be obtained from the following calculation of CO_2 emissions, where the CO_2 emission factor is identified starting from studies on the life cycle assessment of the systems (LCA). Eq. 7 has been adapted to the specific case study, where three renewable energy sources are considered.

$$CFP = \frac{CFP_0}{n} + CFP_m + CFP_F$$

Where

$$\begin{gathered} CFP_0 = CFP_{0,PV} p_{PV} n_{PV} + CFP_{0,SW} p_{SW} n_{SW} + CFP_{0,W} p_W n_W \\ CFP_m = CFP_{m,PV} p_{PV} n_{PV} + CFP_{m,SW} p_{SW} n_{SW} + CFP_{m,W} p_W n_W \\ CFP_F = (E_d - e_{PV} p_{PV} n_{PV} + e_{SW} p_{SW} n_{SW} + e_W p_W n_W) c_{c,f} \end{gathered} \quad (6)$$

Eq. 6 adopts the same approach of Eq. 6. The term CFP_0 represents the emissions of CO_2 for the construction and installation of plants supplied by RES. This term can be expressed as sum of the CO_2 emission linked to the installation investment for sea wave $CFP_{0,SW}$, wind $CFP_{0,W}$ and photovoltaic panels $CFP_{0,PV}$. The same approach can be applied to the annual expected emissions for the maintenances of RES ($CFP_{m,SW}$, $CFP_{m,W}$ and $CFP_{m,PV}$). Finally, the term CFP_F represents the annual emissions of CO_2 due to the production of electrical energy by using the existing diesel engines.

According to Eq. 6, it is easy to observe that CFP is linearly dependent on the numbers of wave converters, wind turbines and PV plants. Indeed, the energy production of each technology depends only on climatic data and the rated power of the selected technologies.

Thus, the terms n_{SW}, n_W and n_{PV} can be variated in order to minimize the CFP of the entire energy mix. However, some constrains are required:

- n_{SW} , n_W and n_{PV} must be natural numbers and bounded above according to the size of the island.
- By considering a reference day for each month, the expected hourly production of electrical energy from RES must not exceed the average energy demand in order to avoid (or at least minimize) the requirement of and energy storage system [21].

So, in conclusion the proposed approach is a case of constrained multivariable single objective optimization problem [22], [23].

III. Technologies for the Renewable Energy Mix

In previous papers, the authors described a sea wave energy converter developed by the Energy Department of Palermo University. Since the device is essentially composed by buoys, the environmental impacts are very limited [24]. In fact, the system does not contain any fluid that can be dispersed in the sea. The greatest part of the device is submerged, so the visual impact is perfectly equivalent to a common buoy used to delimit reserved areas. So, the point absorber could be used as marking buoy and, obviously, as power plant, producing electrical energy from the sea wave.

The maximal power output is equal to 80 kW [25]. For safety in navigation, a red light in the upper part of the WEC is used to makes it visible up to several nautical miles away.

For the exploitation of wind and solar sources, the authors consider the installation of commercial technologies. Regarding the wind source, the selected technology is a horizontal axis wind turbine, having rated power of 60 kW.

The paper proposes also the utilization of solar radiation, considering the installation of roof top integrated photovoltaic panels. Plants having a rated power of 4.5 kW are considered.

IV. The Case Study

In the Mediterranean Sea, the greatest part of small Italian islands is equipped with standalone electrical grids, not linked to the mainland, as the limited local energy demand. Despite the technological progress in the energy generation from renewable energy sources, small islands are supplied by diesel engines. As example, the authors analyze the Favignana island. Egadi is an Italian archipelago, situated between the Tyrrhenian Sea and composed by different islands, of which the largest are Favignana, Levanzo, Marettimo. (see Figure 2).

The production and distribution of electricity on the island of Favignana is entrusted under concession to SEA S.p.a. (Favignana electricity company) producing about 15 GWh per year. The energy demand is currently entrusted to 7 diesel generators with rated power ranging between 1290 kVA and 1800 kVA for a total diesel generation capacity of 12.0 MVA. The hourly demand varies significantly during the year, from 0.75 MW in the night during winter to 5 MW in the midday in August.

As the high costs for the energy production, an incentive is paid to electrical energy producers in small islands by all Italian consumers through the item ARIM in energy bills. The document proposes a mix of renewable energy sources, adapted to the case of the Egadi Islands. Considering three different energy sources: wave motion, wind and solar. The exploitation of wind and solar sources is entrusted to commercial technologies (wind turbines and photovoltaic panels), while an innovative device was presented for the use of the sea wave source [26].

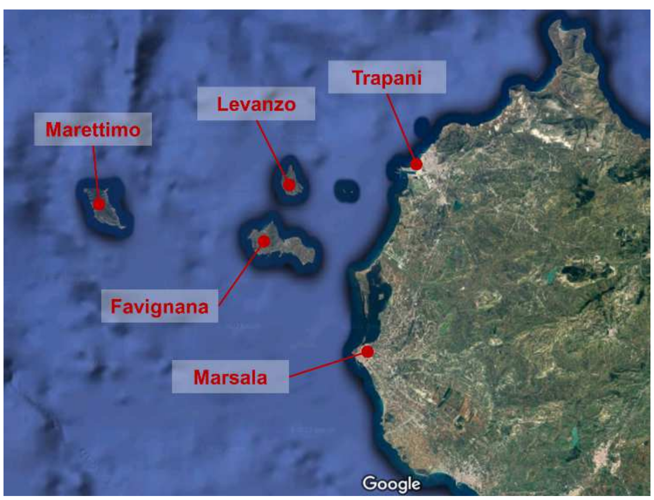

Fig. 2. Egadi Island in the Tyrrhenian Sea (Italy)

V. RESULTS

The selection of the best mix was performed by using both criteria: the minimization of LCOE and the minimization of CFP, in order to find the number of the devices installed for the utilization of wind, solar and sea wave energies. In order to evaluate renewable energy scenario, climate data have been collected. In detail, wind speed data were extracted from the weather station of Trapani Fulgatore, from SIAS measuring network [27]. Data were processed in order to obtain the Weibull coefficients in the each month (see Fig. 3).

Solar radiation was extracted by using PVGIS [28]. Finally, wave data were collected from the Italian wave measuring network (RON), considering the buoy of Mazara del Vallo [29].

The Authors designed the renewable energy mix based on wind, solar and sea wave, considering the availability of these sources applying the mathematical model reported in the previous sections.

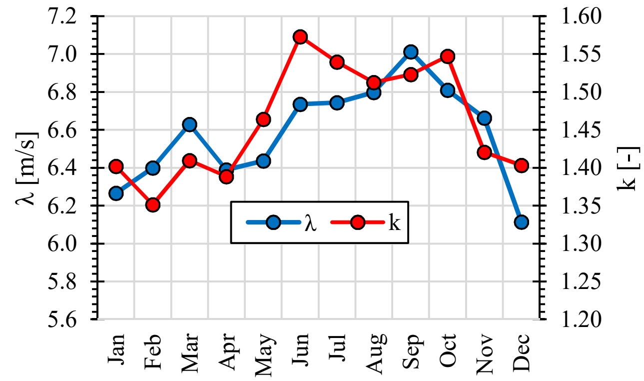

Fig. 3. Coefficients of Weibull distribution per each month

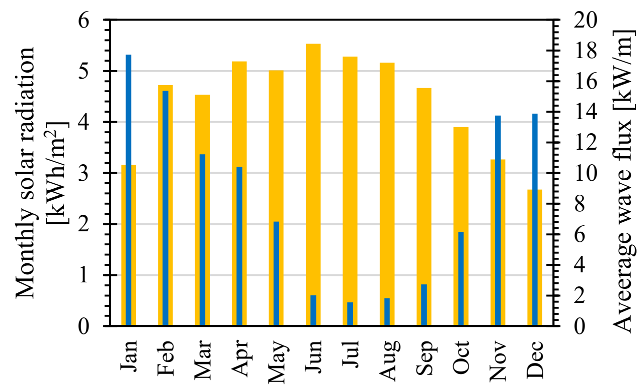

Fig. 4. Coefficients of Weibull distribution per each month

The method was implemented in an Excel sheet, considering monthly and hourly data. The input data are represented by climatic data, the specifics of the selected technologies, the unitary costs and the specific emissions.

This method was applied to Favignana. With regard to the cost for energy production through diesel engines, it assumed equal to the current prize for fuel (without excise), according to the data available to the Italian Ministry of Environment and Energy Security [30]. About the unitary costs for the installation and maintenances of RES plants, data were obtained from IRENA report [31].

The CO_2 emission for the installation of photovoltaic panels and wind turbines and the related annual operative and maintenance cost are extrapolated by recent reports of Life Cycle Assessment (LCA). For the sea wave energy source, the economic parameters have been analyzed by the authors in previous works.

The CFP approach has been applied to the Favignana island. The authors considered the realization of building integrated photovoltaic plants (each one with a rated power of 4.5 kWp), the utilization of 60 kW wind turbines, 50 kW of the installation of several wave energy converters.

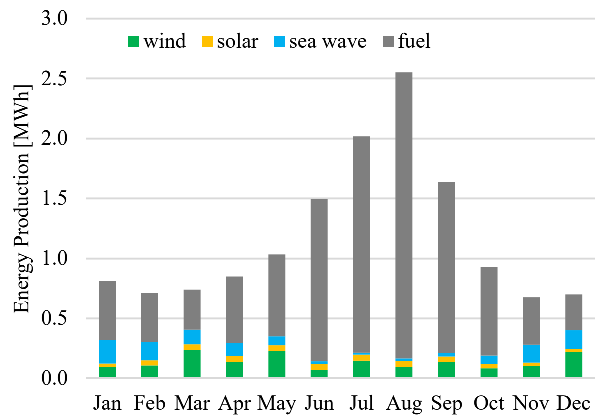

Fig. 5. Trend of the annual energy production from the proposed mix

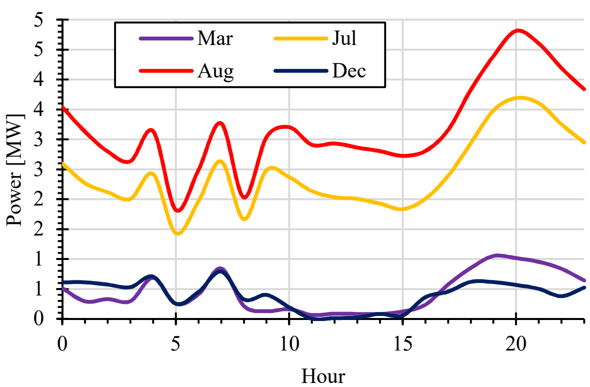

Fig. 6. Hourly trend of the power production from the proposed mix

Figure 5 shows the expected annual production from the proposed energy mix. In detail, fossil fuel will continue to dominate the energy production (76.8%), however, the remaining part will be covered by solar PV (3.5%) wind turbines (11.7%) and sea wave energy (8.0%).

Both criteria suggest the same solution: 69 PV plants, 13 wind turbines and 15 wave energy converter. The expected LCOE is equal to 232.21 €/MWh and the CFP is equal to 496.81 kg CO_2/MWh.

The main reason to the limited share of RES is revealed by Fig. 6: during the winter the energy demand is drastically reduced. As a consequence, if the desired target is to avoid the curtailment of energy production from RES, the number of RES plant is strongly limited.

VI. CONCLUSION

The mathematical model identified the best choice from an environmental point of view thanks to the minimization of the CFP associated to the entire energy mix.

The authors estimated an annual avoided expenditure for the energy generation in Favignana equal to 252 k€ of euros if the proposed RES mix is realized. From an environmental point of view, 2068 tons of CO_2 per year can be avoided.

The case study shows an interesting problem for the sizing of renewable energy mix. As the energy demand is mainly concentrated during summer, the installed capacity should be oversized if a greater share of the energy demand must be covered by RES. Three approaches can be identified:

- Adopt the curtailment of the energy production during winter.
- Add an energy storage.
- Interconnect Favignana to Sicily in order to transfer the energy surplus to Sicily during summer, and take energy during summer, limiting the role of the local power plant.

In future works, the authors desire to analyze these three scenarios, in order to demonstrate the optimal solution. Results here reported can easily replied to other small islands in the Mediterranean Sea. This approach will be implemented modifying the boundary conditions of the islands considered.

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