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An Economic Approach to Size of a Renewable Energy Mix in Small Islands

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Abstract: The importance of renewable energy exploitation reduces the energy dependence on fossil fuels. Despite technological progress, in several remote areas and small islands the energy production is nowadays dominated by the utilization of fossil fuels. With new, increasingly stringent laws on polluting emissions and the need to lower production costs, it is necessary to exploit as many renewable sources as possible. In order to implement these considerations, it was decided to study renewable energy production. The study was carried out by estimating the energy production on a monthly and annual basis considering a mix of three plants, namely marine, solar, and wind. Simulations on wave production were carried out on a new device developed by the research team at the University of Palermo. In order to be able to perform these simulations, input climate data are required. These data are normally available in literature or obtainable by using specific GIS tools. As criterium, the Levelized Cost of Energy, normally applied to a single technology, is extended to the entire energy mix. Minimizing this parameter, the best solution is individuated, and capable of supplying 50% of the summer electrical load with renewable energy sources. The results carried out from a case study based in aeolian islands show that the solar production reaches 10.2%, the wind production reaches 45.47% and sea wave production reaches 3.04%. In this way, the diesel production decreases to 41.29%. This method can be easily applied for several small islands, estimating for several sites the ability to reduce the energy production from fossil fuels.

Keywords: small islands; optimal sizing; sea wave; renewable energy; LCOE

Citation: Milone, D.; Curto, D.; Franzitta, V.; Guercio, A.; Cirrincione, M.; Mohammadi, A. An Economic Approach to Size of a Renewable Energy Mix in Small Islands. *Energies* **2022**, *15*, 2005. https://doi.org/10.3390/en15062005

Academic Editors: Galih Bangga and Len Gelman

Received: 28 January 2022
Accepted: 7 March 2022
Published: 9 March 2022

1. Introduction

After Kyoto Protocol, the European Union promoted the installation of plants supplied by Renewable Energy Sources (RES), introducing specific policies [1]. With the recent ratification of the "Paris agreement", the signatory countries agreed on common goals to preserve the environment, limiting the CO_2 emissions in order to contain the global warming below 1.5 °C [2].

Due to the diffusion of RES, the unitary cost for the installation of power plants has been progressively reduced, assuming nowadays the same range of fossil fuels plants [3]. From an environmental point of view, the adoption of RES reduces the emissions of pollutants and greenhouse gases, improves the air quality, and decreases the energy dependence on fossil fuels [4].

The main results are linked to the electrical sector, since most of the RES technologies are designed to produce energy (like photovoltaic panels, wind, and hydro turbines) [5]. Secondly, RES plants are also spreading in the indoor heating sector (for example, solar thermal panels or low temperature geotherm) and in the transport sector (essentially biofuel).

Analyzing the energy sector in one European Country, in 2019 the Italian Energy production was satisfied with the following mix: 46.32 TWh hydropower, 20.20 TWh wind power, 23.69 TWh solar, 176.17 TWh fossil fuels, 6.08 TWh geotherm, and 38.14 TWh imported from other countries, thus renewable energy sources covered 35.1% of the Italian energy demand [6].

Despite the progress for the exploitation of RES, reaching important results around the world, small islands and remote regions are affected by an energy production entrusted to old technologies, powered by fossil fuels [7,8]. In the world, a lot of small islands have proposed RES plants to supply the energy demand. In Canary Island a study has been carried out to produce 100% of energy from RES [9]. In Pico and Faial islands, Azores have been studied to perform a 100% power energy supply by RES. In this context, the mixed scenario is composed of wind, solar, hydro, and biomass generation [10]. The Faroe Islands are another example of fossil-dependent islands being transformed into full-powered RES islands, with an energy mix composed of wind, solar, and hydro power production [11]. This paper highlines a particular lack in some similar simulations. The software often used for this aim is "homer". This tool does not allow the calculation of wave energy production. For this reason, the research team wanted to implement simulations that would allow this energy source to be taken into account. Jones Silva and Alexandre Beluco similarly performed possible simulations with homer and then integrated the studies by considering wave energy production separately [12].

Focusing on small islands, these places show several common peculiarities [7,13]:

- High seasonal variation of inhabitants and therefore energy consumption.
- Significant annual growth of the energy demand.
- Lack of innovation and development of the local grid.
- Low use of renewable energy sources.
- High fuel cost due to the small size of the plants and importation from mainland.
- Limited freshwater resources.
- Tourist–environmental priorities.

Therefore, energy production on small islands can no longer be tied to fossil fuels alone. In this context, the adoption of RES represents a valid solution, making the most of small islands being energetically autonomous.

In this specific context, a few years ago (14 February 2017) the Italian Government, through the Economy Ministry, published a new law to support renewable energy sources in small islands. The central idea is the transformation of small Italian islands into open air laboratories where sustainable and innovative energy solutions can be tested [14].

The decree promotes the introduction of renewable energy sources in 20 small Italian islands, indicating the current energy demand, the targets of energy production from RES by 31 December 2020, and the financial incentives [15].

As an example, in the case of Lampedusa (a small island at south of Sicily), Annex I of the decree indicates a current energy demand of 37.66 GWh/y (based on diesel engines) and sets the installation of 2.14 MW of RES electrical power plant. For the thermal energy production, the decree prescribes the installation of 2370 m^2 of solar thermal panels. In addition, Article 6 introduces the possibility to realize "Integrated innovative projects", including in this group the offshore plants supplied by RES and in particular the exploitation of oceanic energies.

The decree has been in force for more than a year, but it was only at the beginning of 2018 that the Authority published guidelines regarding methods and timing. However, since the objectives are also retroactive (the already installed and functioning plants contribute to the target), it is interesting to monitor where each island is compared to the targets by 2020.

Table A1 in Appendix B and Figure 1 display data about electrical plants supplied by RES for each small island, considering the actual number and target set.

The island of Vulcano is the only one that reached half of the target for installation of RES (using photovoltaic panels), while all the others are well below 50%. For example, the islands of Salina, Panarea, Filicudi, and Alicudi do not have any RES plant.

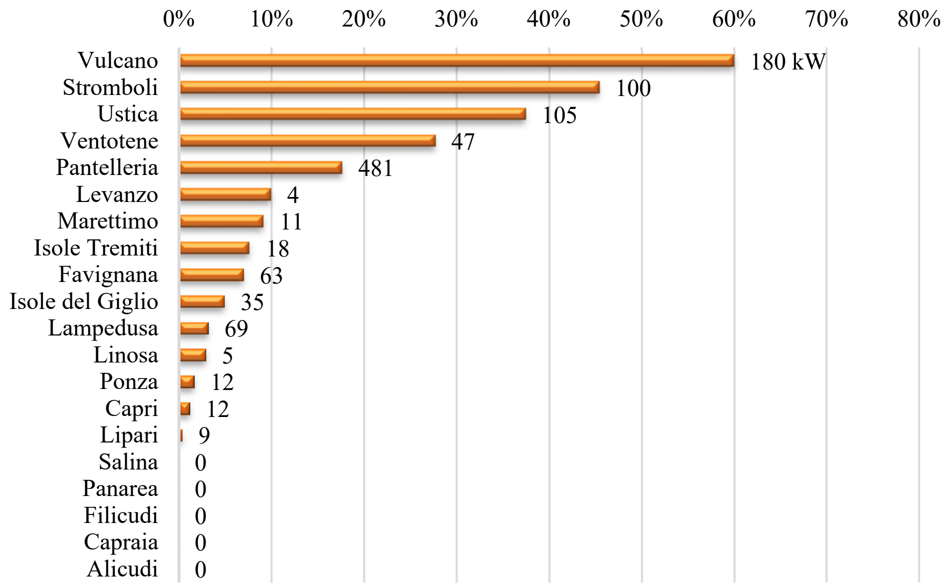

Figure 1. Finalization of target MISE 2020.

Very recently, the European Union created the Clean Energy for EU Islands Secretariat in order to facilitate the energy transition from fossil fuels to RES. In this project, 26 European islands have been selected, three of which are Italian (Favignana, Salina, and Pantelleria) [16].

In conclusion, the aim of this work is the proposal of a renewable energy mix in order to satisfy the environmental target imposed by the decree 14 February 2017 in Aeolian Islands. With this purpose, a simplified approach is presented. This method can be easily replied in other small islands, thanks to the limited number of inputs. These data are normally available in literature or obtainable by using specific GIS tools. The results show that it is possible to exploit the solar source for a total of 10%, wind source 45.5%, and 3% tidal source, reducing fossil consumption by 41%. These results support the avoidance of fossil fuel production as emissions of pollutants are simultaneously reduced. Some similar studies have been carried out. In this way, Tran et al. stated that the LCOE study is influenced by life cycle carbon, the assessment of which is considered [17].

The paper is divided in the following parts: Section 2 presents the simplified approach adopted and developed by the authors, used to estimate the monthly and annual energy production. From an economic point of view, the best energy mix is determined, introducing the Levelized Cost of Energy as an indicator. Section 3 presents the technologies selected for the exploitation of renewable energy sources. Section 4 analyses the As-Is scenario of the case study. Finally, Section 5 reports the proposal of the renewable energy mix for Aeolian archipelago, analyzing the economic and environmental benefits.

2. Methods

With the goal being to size a renewable energy mix, a simplified approach is required, evaluating the potential energy production from each source. In this section, the authors report the main equations used to estimate the monthly energy production from solar, wind, and sea wave sources using climatic data.

To individuate the optimal energy mix, a Levelized Cost of Energy (LCOE) is introduced. As is better defined in the following section, the authors express through this parameter the minimal selling price of energy able to cover the initial investments and the annual operative and maintenance costs for the renewable energy plants and the annual operative and maintenance costs of existing power plants, supplied by fossil fuels [3].

2.1. 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}:

$$E_{PV} = n_{PV} e_{PV} = n_{PV} \sum_{i=1}^{12} Re_{PV,i} = n_{PV} \sum_{i=1}^{12} \overline{H}_{T,i} S_{PV} \eta_{PV} d_i \tag{1}$$

The annual energy production of a PV plant can be expressed by the sum of the monthly energy production $e_{PV,i}$. In more detail, the equation considers the perpendicular component of the monthly average daily solar radiation $\overline{H}_{T,i}$ into 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 d_i per month.

Climate data of solar radiation normally refers to the horizontal plane, considering the average conditions of cloudiness and atmospheric clarity. In the case of unshaded tilted surface, solar radiation can be evaluated by Equation (2), according to the model proposed by Liu Jordan [18]:

$$\overline{H}_{T,i} = \overline{H}_b \overline{R}_b + \overline{H}_d \left(\frac{1 + \cos\beta}{2} \right) + \overline{H}_\rho \left(\frac{1 - \cos\beta}{2} \right) \tag{2}$$

where $\overline{R}_b$ represents the monthly average of the ratio between the direct solar radiation to the tilted surface and the solar radiation $\overline{H}_b$ to the horizontal surface, $\overline{H}_d$ is the diffused solar radiation to the horizontal surface, β is the tilt angle of surface, $\overline{H}_\rho$ is the solar radiation diffusely reflected from the ground, given by Equation (3) [19].

$$\overline{H}_\rho = \rho_g \left(\overline{H}_b + \overline{H}_d \right) \tag{3}$$

where ρ_g is the ground albedo. In the simplified case of surface sloped to equator and installed in the northern hemisphere, the term $\overline{R}_b$ is given by [20]:

$$\overline{R}_b = \frac{\cos(\psi - \beta)\cos\delta + \sin(\psi - \beta)\sin\delta}{\cos\psi\cos\delta\cos(w_s) + \sin\psi\sin\delta} \tag{4}$$

where ψ is the latitude of the place where the device is installed, δ is the solar declination, ω_s is the sunset hour angle for the tilted surface, determined by the following condition:

$$\omega_s = \min \begin{bmatrix} \cos^{-1}(-\tan\psi\tan\delta) \\ \cos^{-1}(-\tan(\psi - \beta)\tan\delta) \end{bmatrix} \tag{5}$$

2.2. Wind Source

The availability of wind source is usually described through the Weibull distribution, reported in Equation (6) [21]:

$$f(v) = \frac{k}{\lambda} \left(\frac{v}{\lambda} \right)^{k-1} \exp\left[-\left(\frac{v}{\lambda} \right)^k \right] \tag{6}$$

where the term $f(v)$ represents the probability that the wind speed v is measured. The Weibull distribution introduces two coefficients: k is the dimensionless shape parameter, λ is the scale parameter, having the same unit of a wind speed. These constants are deeply related to the morphology of the measuring site and the height above the ground. Typically, the term λ ranges between 1.2 and 2.75 in most conditions around the world [21,22].

In the case of preliminary energy assessment, several GIS (Geographic Information System) tools can be used, obtaining results from data collected over a long period in a few measuring stations.

Since the Weibull distribution is normally used to model the annual availability of wind source, in this case an alternative approach is preferred [23].

In detail, the availability of wind source can be reported by introducing a discretized number of wind speed classes and reporting each of them as the corresponding number of hours when that speed class was measured [24].

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

$$E_W = n_W e_W = n_W \sum_{i=1}^{12} e_{W,i} = n_W \sum_{i=1}^{12} \sum_{j=1}^{n} h_{j,i} c_p(v_j) \tag{7}$$

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, $h_{j,i}$ is the number of hours when the j-th wind class v_j. is measured, and $c_p(v)$ represents the power output of a chosen wind turbine as function of wind speed.

2.3. Sea Wave Source

To describe sea wave energy exploitation, it is necessary to introduce the wave power flux φ_m. that represents the average power produced by a length unit of wave front. Considering off-shore sea wave exploitation, the wave power flux can be calculated by Equation (8) [25]:

$$\varphi_m = \frac{\rho g^2}{64\pi} H_s^2 T_e \tag{8}$$

where H_s represents the significant wave height (though to crest), T_e is the energy period, and ρ is the seawater density. In detail, H_s is the mean wave height of the highest third of the waves [26]. A more recent definition considers the significant wave as four times the standard deviation of the surface elevation or equivalently as four times the square root of the zeroth-order moment of the wave spectrum [27]. As regards the wave energy period, it is defined as the variance-weighted mean period of the one-dimensional period variance density spectrum [28]. Analytically,

$$T_e = \frac{m_{-1}}{m_0} = \frac{\int f^{-1} S(f) df}{\int S(f) df} \tag{9}$$

The energy period is usually evaluated from the peak period T_p, multiplying for a coefficient α. This parameter is function of the wave spectrum shape. A common value is 0.86, obtained in the case of Pierson Moskowitz spectrum [29].

In conclusion, the production of energy generated by a set of devices installed at the same site (E_{SW}) can be evaluated by using Equation (10):

$$E_{SW} = n_{SW} e_{SW} = n_{SW} \sum_{i=1}^{12} e_{SW,i} = n_{SW} \sum_{i=1}^{12} \overline{\varphi}_{m,i} D_C \eta_{SW} h_{m,i} \tag{10}$$

The terms in this equation are 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.

2.4. Levelized Cost of Energy

In the previous paragraphs, a simplified approach was reported in order to evaluate the potential energy production from different renewable energy sources. In this section, the authors introduce an economic approach usable to individuate the optimal energy mix.

In detail, a Levelized Cost of Energy (LCOE) for an energy mix is presented [30,31]. As introduced before, this parameter expresses the minimal selling price of electricity, covering the initial investments and the annual operative and maintenance costs for the new installed capacity supplied by renewable energy sources and the annual operative and maintenance costs of existing power plants supplied by fossil fuels [32,33].

Equation (11) suggests the general definition of LCOE, introducing the Total Life Cycle Cost (TLCC) that represents the sum of the initial investment and the annual operative and maintenance costs of the system [34]. The term E_i represents the energy output in the i-th year due to the realization of power plant.

$$LCOE \times \sum_{i=1}^{n} E_i = TLCC \tag{11}$$

This equation can be analyzed in any power generation system [3,31,32,35–37]. The authors extend this approach to an entire energy mix, composed by different technologies. Therefore, in this case the parameter LCOE can be obtained from the following economic balance, where the discounted cash flow is introduced. Equation (12) has been adapted to the specific case study, where three renewable energy sources are considered.

$$LCOE \sum_{i=1}^{n} E_d = E_F c_F \sum_{i=1}^{n} \left(\frac{1+\varepsilon}{1+\tau} \right)^i + I_0 + (C_{m,R} + C_{m,F}) \sum_{i=1}^{n} \frac{1}{(1+\tau)^i}$$
where
$$\begin{cases} E_F = E_d - (E_{SW} + E_W + E_{PV}) \\ I_0 = I_{0,SW} + I_{0,W} + I_{0,PV} \\ C_{m,R} = C_{m,SW} + C_{m,W} + C_{m,PV} \end{cases} \tag{12}$$

Several parameters are introduced in Equation (12). In detail, is the annual energy demand, E_F is the annual electricity production from existing power plant (fossil fuel) in the renewable energy mix scenario. This term represents the difference between the annual energy demand and the annual energy production from the renewable energy sources E_{SW}, E_w, E_{PV} (sea wave, wind, and solar sources). The specific cost for the energy production from fossil fuel is expressed by the term c_F.

The parameters ε and τ are the inflation rate for energy sector and the monetary interest rate, respectively. The initial investment I_0 is expressed as a sum of the initial investment for sea wave $I_{0,WF}$, wind $I_{0,W}$, and photovoltaic panels $I_{0,PV}$. The same approach can be applied to the annual operative and maintenance costs for the renewable energy mix $C_{m,R}$. Finally, the term $C_{m,F}$ represents the annual operative and maintenance cost for the existing diesel engines (do not considering the fuel expenditure). To simplify Equation (12), the authors introduced the following assumptions:

- The initial investment is assumed to be directly proportional to the installed capacity, introducing a unitary cost for each technology ($c_{0,SW}$ for sea wave converter, $c_{0,W}$ for wind turbine, and $c_{0,PV}$ for PV plant).
- The annual operative and maintenance costs can be expressed as fraction of the initial investment, introducing the parameters μ_{SW}, μ_W, μ_{PV}.

In these hypotheses, the Levelized Cost of Energy can be evaluated through Equation (13):

$$LCOE = \frac{E_F c_f \sum_{i=1}^{n} \left(\frac{1+\varepsilon}{1+\tau} \right)^i + I_0 + (C_{m,R} + C_{m,F}) \sum_{i=1}^{n} \frac{1}{(1+\tau)^i}}{n \ E_d}$$
where
$$\begin{cases} E_F = E_d - (n_{SW} e_{SW} + n_W e_W + n_{PV} e_{PV}) \\ I_0 = n_{SW} p_{SW} c_{SW} + n_W p_W c_W + n_{PV} p_{PV} c_{PV} \\ C_{m,ren} = n_{SW} p_{SW} c_{SW} \mu_{SW} + n_W p_W c_W \mu_W + n_{PV} p_{PV} c_{PV} \mu_{PV} \end{cases} \tag{13}$$

The equation introduces the rated power of the wave energy converter (p_{SW}), the wind turbine (p_W), and PV plant (p_{PV}).

According to Equation (13), it is easy to observe that LCOE 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 LCOE of the entire energy mix. However, some constrains are required:

- Each source must annually produce almost 5% of the total renewable energy production.
- n_{SW}, n_W, and n_{PV} must be natural numbers and bounded above according to the size of the island.

In order to repay the maintenance of the existing power plant, the monthly electricity production from renewable sources must be limited to 90%. In this way, producing 10% of the demand will allow the necessary earnings for maintenance purposes. Therefore, in conclusion the proposed approach is a case of constrained multivariable single objective optimization problem [38].

3. Technologies for the Renewable Energy Mix

3.1. Wave Energy Converter

This article was developed with the intention of promoting the production of energy from renewable sources in small districts such as the Aeolian Islands. In particular, it demonstrates that producing energy from wave power is possible. For this reason, the engineering department of the University of Palermo decided to optimize a system called point absorber. This machine is called this because it consists of two buoys that run in relative motion independently of the direction of the wave. Since the device is essentially composed of buoys, the environmental impact is very limited [39,40]. Its geometric and technical structure means that most of the components are submerged and not visible. This aspect allows the device to be considered unobtrusive to the eye. In addition, it is possible to use the upper surfaced buoy as a normal signaling buoy, with the addition that it is capable of producing electricity.

The external buoy (green in Figure 2) has the task of transferring the vertical motion caused by wave movement to the central buoy to which it is mechanically connected (yellow buoy in Figure 2). The central buoy is characterized by high inertia, due to a weight installed at the bottom of the machine. In addition, the entire device is anchored to the seabed, using a chain connected to another buoy, known as a jumper, and finally four moorings resting on the seabed to prevent the system from drifting.

Figure 2. Point absorber device.

The tests underlying the paper were carried out on a device consisting of the outer buoy with a diameter of ten meters and the inner buoy with a diameter of two meters. The conversion from mechanical to electrical energy is handled by linear generators located in the central buoy. The working stroke is equal to four meters. The maximal power output is equal to 80 kW. In order to comply with the rules at sea, a flashing signal light has been installed at the top of the point absorber to be recognizable by all vessels encountering it.

3.2. Wind and Solar

In the case of the devices required to harness wind and solar power, a decision was made to opt for commercially available solutions. The wind turbines chosen are of the three-axis horizontal type with a power of 30 kW, 60 kW, and 200 kW. The graphs of power output as wind speed function are reported in Figure A1 in Appendix A. Main data are reported in Tables A1 and A2.

The technology using solar exploitation is provided by monocrystalline silicon panels whose technical data are shown in Table A3 [41].

4. The Case Study

In the Mediterranean Sea, most of the small Italian islands are equipped with standalone electrical grids, not linked to the mainland, as the local energy demand is limited. Despite the technological progress in the energy generation from renewable energy sources, small islands are supplied by diesel engines. Big fuel tanks are periodically refilled, using boats from the mainland. Prolonged bad weather conditions represent a significant risk for energy security.

As example, the authors analyze the Aeolian Islands. It is an Italian archipelago, situated in the Tyrrhenian Sea (north of Sicily) and composed of different islands, of which the largest are Alicudi, Filicudi, Lipari, Panarea, Salina, Stromboli, and Vulcano (see Figure 3). The last two islands are famous active volcanos, characterized by sulfurous fumaroles, hot springs, and volcanic muds. Eruptions occasionally occur.

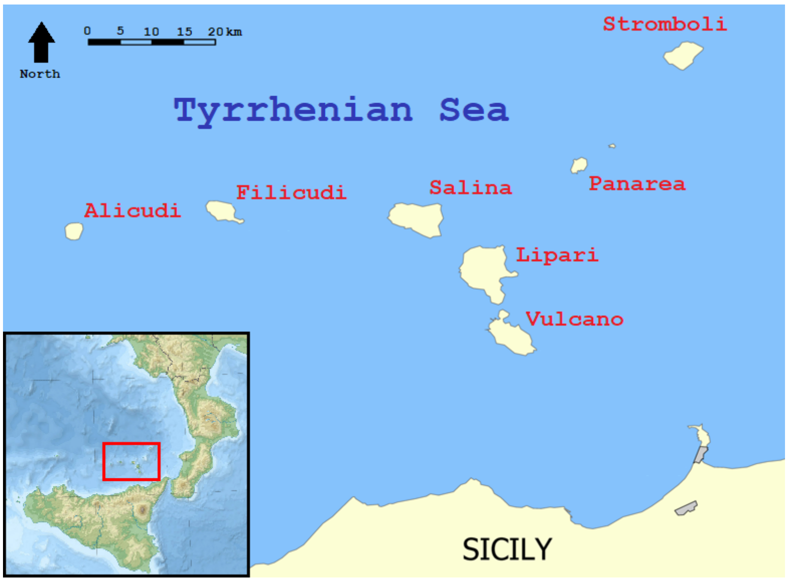

Figure 3. Aeolian Islands in the Tyrrhenian Sea (Italy).

From an economic point of view, the Aeolian Islands live on tourism, especially in summer, attracting up to 200,000 visitors. A ferry service connects the Aeolian Islands to Sicily.

The archipelago presents a Mediterranean climate, characterized by a mild winter, dry summer, and temperate middle seasons.

As regards the administration, all islands are part of Lipari's municipality, expect the island of Salina, which is divided in three municipalities (Leni, Malfa, and Santa Marina Salina).

Some statistics on Aeolian islands are reported in Table A4 [42]. As shown, Lipari is the most populated island. All islands are affected by water scarcity, and for this reason some of them are equipped with desalination plants. Fresh water is also transported by boat from Sicily.

As introduced before, the electrical energy production is realized through diesel engines. In Lipari, the power plant is owned by the private society "Società Elettrica Liparese S.r.l.", producing about 34.8 GWh/y. In the other islands, the power stations are owned by the Italian company "Enel Produzione S.p.A.", producing about 25.3 GWh/y in Aeolian Islands. Given the high costs for energy production, an incentive is paid to electrical energy producers in small islands by all Italian consumers through the item ARIM in energy bills. In detail, the energy producer in Lipari receives an incentive equal to 284.40 €/MWh for the electrical energy production [43]. In the case of "Enel Produzione" the incentive mechanism is more complex, as the incentive is contained in the general item "dispatching charge" ("Oneri di Dispacciamento" in Italian).

The utilization of renewable energy sources is very limited in the Aeolian Islands, and instead they have availability of solar and wind sources. To increase the energy sustainability of the archipelago, the Majors of the Aeolian Islands signed specific agreements, such as the SEAP (Sustainable Energy Action Plan), the Islands Plan ("Patto delle Isole" in Italian), and Mayors Plan ("Patto dei Sindaci" in Italian) [44]. These actions are encouraged by the European Union with the goal to increase the energy efficiency in small islands, reduce the energy dependence from fossil fuels, and consequently the emissions of CO_2.

In this context, the paper proposes a renewable energy mix, tailored to the case of the Aeolian Islands, considering the local energy demand and three different energy sources: wind, solar, and sea wave. As introduced in the previous sections, the exploitation of wind and solar sources is entrusted to commercial technologies (wind turbines and photovoltaic panels), while for the utilization of sea wave source, an innovative device has been presented. As known from literature, sea wave shows several peculiarities, like [45,46]:

- a more regular energy production in comparison with other aleatoric renewable energy sources.
- limited visual impact, promoting the installation along the coastline (in Italy offshore wind turbines are absent, as the visual impact could discourage local tourism) [47].
- high energy potential in comparison with the local demand, especially in small islands.

According to the national objectives for the promotion of energy production from renewable, Table A5 shows the targets imposed to the Aeolian Islands and the current installed plants.

As the limited extension of the electrical grid, pilot plants have been tested in the Aeolian Islands. As shown in Figure 4, in 1984 a photovoltaic park (monocrystalline silicon) was installed in Vulcano, having a rated power of 180 kW and an energy efficiency of 9% [48].

Figure 4. PV plants in Vulcano [48].

On the other volcanic island (Stromboli), a hybrid power system (HPS) was installed in 2004 [48]. The system comprises a 100 kW PV plant and a diesel generator (160 kW), both connected to the local grid at Ginostra, suppling 140 homes. The energy overproduction during autumn is used by the local desalination plant.

5. Results

The above-mentioned mathematical model has been applied to the Aeolian islands, taking into account the electrical production from renewable energy sources like solar photovoltaic, wind, and sea wave [49]. The better solution is based on the evaluation of LCOE as a function of the number of the devices installed for the utilization of wind, solar, and sea wave energies. GIS software made it possible to retrieve climate data to study the energy production of islands [23].

Figure A2 shows the annual availability of wind source for the main Aeolian Islands. According to the data reported above, wind speed assumes greater values during winter and summer.

Table A7 shows the monthly solar radiation data [50]. Finally, Table A8 reports the average values of wave energy flux and the location of the measuring point with respect the island [51].

The authors designed the renewable energy mix based on wind, solar, and sea wave, considering the availability of these sources (described in the Figure and Table above reported) and applying the mathematical model reported in the previous sections.

For solar photovoltaic and wind conversion [52], the authors considered commercial devices with power curve and efficiency noted, while wave energy potential is calculated using the prototypal devices (Point Absorber) realized by the University of Palermo [53,54].

The Evaluation of LCOE in the Case Study

The mathematical model reported above has been used to evaluate the Levelized Cost of Energy (LCOE) as a function of the numbers of installed sea wave converters n_{SW}, wind turbines n_W, and photovoltaic plants n_{PV}. The best solution is obtained by the minimization of LCOE, considering all constrains introduced above.

The method can be implemented in an Excel sheet. The input data are represented by climatic data and parameters related to the chosen technologies, like rated power, extension, energy efficiency, etc. The optimization can be performed by a GRG nonlinear solver.

This method was applied to the Aeolian islands. Focusing the attention on Lipari island, it is possible to show, using data from the literature, that energy consumption is equal to 34.8 GWh [15]. With regard to the cost for energy production through diesel engines, it assumed equal to the sum of PUN (National Single Price, in Italian "Prezzo Unico Nazionale") [55] and the incentive established by the Italian Authority for Energy [43].

As the mathematical model considers the cost for energy production and operative and maintenance cost, the first term is assumed equal to the 90% of the total annual expenditure. In conclusion, the energy cost by diesel engines is reduced by the same amount with respect to the sum of PUN and the incentive. The maintenance cost for diesel engines is assumed to be independent by the annual energy production from fossil fuel and equal to 10% of the current annual expenditure for the energy production by diesel engines. All economic parameters are reported in Table A8.

In detail, the unitary cost for the installation of photovoltaic panels and wind turbines and the related annual operative and maintenance cost are extrapolated by recent reports of IRENA [3]. The economic consideration related to sea wave exploitation has been focused on by authors in other papers [56].

Figure 5 shows the potential energy production from the proposed energy mix in comparison with the energy demand, whose trend has been modelled in similitude using the annual trend of other Aeolian Islands [42].

The graph demonstrates that the meeting of energy demand and energy production from renewable energy sources is very complex. Not considering the installation of energy storage system, the renewable energy mix capacity is limited by the energy demand during winter, according to the conditions imposed above.

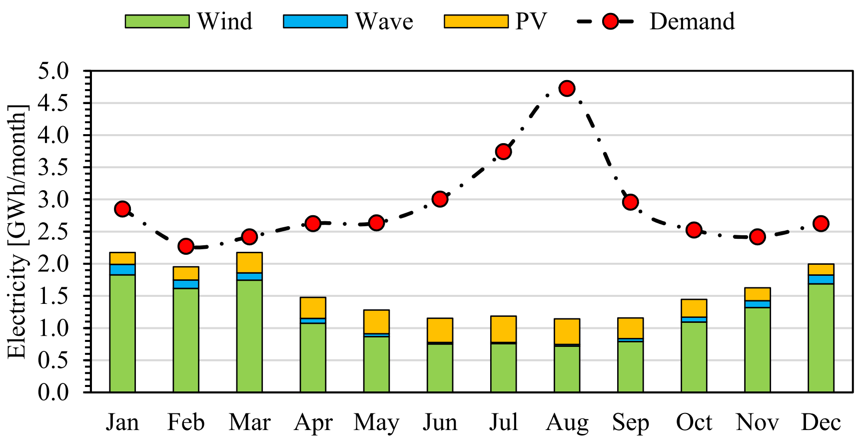

Figure 5. Energy demand and potential renewable energy production in Lipari Island.

Given the significant increase of energy demand during summer, three solutions could be applied if the share of renewable energy production is further increased:

- Increase the installed power and introduce of an energy storage, saving the energy surplus during winter and exploiting it during summer (for example, hydrogen storage).
- Increase the installed power from RES, accepting to stop a part during winter.
- Interconnect all small islands to Sicily. In this way, the energy produced and consumed is managed by a larger and more secure grid, reducing balancing problems.

The LCOE approach has been applied to the other Aeolian Islands. The results are reported in Table A9. The authors considered the realization of building integrated photovoltaic plants (each one with a rated power of 3.3 kW_p), the utilization of 200 kW wind turbines in Lipari, 30 kW in Alicudi, and 60 kW in the other islands, and finally, the installation of several wave energy converters. As regards the economic parameters, the Aeolian Islands have used the same unitary costs as Lipari, as more accurate data are not available.

In the cases of Alicudi and Filicudi, sea wave energy source is not considered, as a single wave converter is too big in comparison with the desired share of energy production. The annual energy production from the proposed energy mix is reported in Figure 6, considering each island.

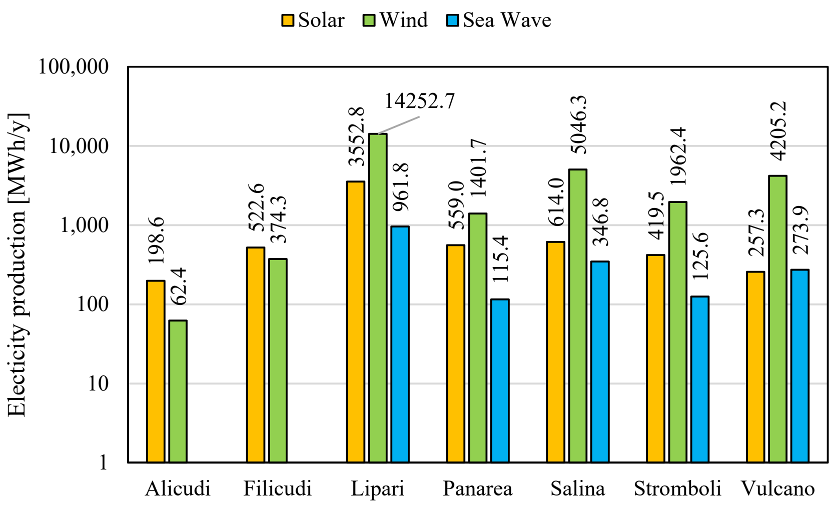

Figure 6. Total electrical production from RES in the Aeolian Islands.

Figure 7 shows the annual average share of energy production in the Aeolian Islands for each energy source. The proposed mix is able to cover 58.7% of the energy demand by using RES.

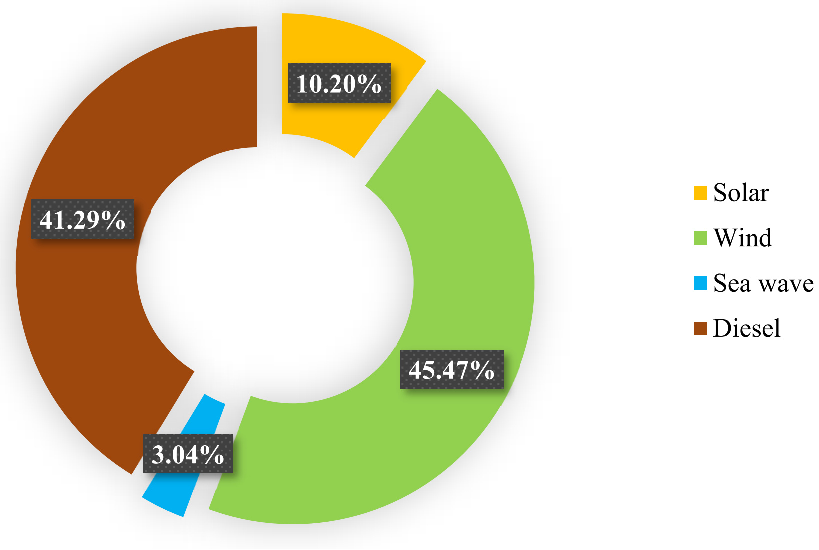

Figure 7. Share of each source in Aeolian Islands Energy Scenario.

The application of the renewable energy mix, above reported, can produce an annual economic saving equal to 6.5 million of euros in all Italian energy bills and avoid the emission of 25,593 tons of CO_2 per year. Thus, the introduction of a RES mix in Aeolian Islands can generate economic and environmental benefits. It is important to evaluate that the LCOE approach is a study that underlines the feasibility of RES installation considering the only power generation depending on the cost of energy. The study presented, focusing on this aspect, carried out a renewable energy production using an energy mix. A lot of problems related to this kind of energy production, such as studying grid stability and energy storage systems, are not included in the LCOE study. Therefore, it must be emphasized that they are processed separately.

6. Conclusions

An algorithm has been presented in order to individuate the best renewable energy mix, considering economic aspects. This technique is able to estimate, in a simplified way, the monthly and annual electrical energy production from each renewable energy source.

The method has been applied to the Aeolian Islands, a small Italian archipelago in the Mediterranean Sea. The case study is an example of standalone electrical systems, entrusted to diesel engines. The authors proposed a renewable energy mix based on solar, wind, and sea wave in order to increase the environmental sustainability of the energy sector.

The renewable share has been chosen according to the current legislations, in particular the decree 14 February 2017 that obligated small Italian islands to produce a significant share of energy from RES.

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

The authors estimated an annual avoided expenditure for the energy generation in Aeolian Islands equal to 6.5 million of euros if the proposed RES mix is realized. From an environmental point of view, 25,593 tons of CO_2 per year can be avoided.

In conclusion, the model can be improved with other terms like the addition of other renewable energy sources or energy storage systems.

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 scenarios can be identified:

- Stop several plants supplied by RES during winter.
- Add a seasonal energy storage in order to store the energy surplus produced during winter and consume it during summer (for example, using hydrogen as an energy carrier).
- Interconnect the Aeolian Island to Sicily in order to simplify the balancing problem of local energy demand and production.

In future works, the authors desire to analyze these three scenarios in order to demonstrate the optimal solution. In any case, results reported in this paper can easily be applied to the other small islands in the Mediterranean Sea, as they have similar climatic and economic conditions. This approach will be implemented by modifying the boundary conditions of the islands considered. In this way, it is simply to estimate the power plant mix, which could be installed according to the needs of the site.

Author Contributions: Conceptualization, D.C. and V.F.; methodology, D.M. and M.C.; software, D.C. and A.M.; validation, V.F., D.C. and A.G.; writing—original draft preparation, D.C. and A.M.; writing—review and editing, A.G. and D.C.; project administration and funding acquisition V.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received FFR_D26_PREMIO_GRUPPO_RICERCA_2020_ DI_UNIPA_funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: The work presented is carried out thanks the technical and operational support of Engosys Enterprise. The research on sea wave harvesting is promoted by the Italian project "Ondaflex" (PO FESR Sicilia 2014/2020), financed by Sicilian Region.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviation

Sigle	**Description**
Capex	Capital Expenditure
EU	European Union
FER	Fonti di Energia Rinnovabile, Italian acronym equivalent to RES
GIS	Geographic Information System
HPS	Hybrid Power System
IRENA	International Renewable Energy Agency
LCOE	Levelized Cost OfEnergy
Opex	Operating Expense
PUN	Prezzo Unico Nazionale, Italian acronym of National Single Price
PV	Photovoltaic panel
RES	Renewable Energy Sources
SEAP	Sustainable Energy Action Plan
SEL	Società Elettrica Liparese S.r.l.
TLCC	Total Life Cycle Cost
Latin Symbols	**Description**
$c_{m,R}$	Total operative and maintenance cost for the renewable energy mix
$c_{m,W}$	Total operative and maintenance cost for wind farm
$c_{m,SW}$	Total operative and maintenance cost for wave energy farm
$c_p(v)$	Power output function of wind speed
$c_{p,max}$	Maximal power output from a wind turbine
c_{PV}	Unitary cost to install 1 kW of photovoltaic panels
c_w	Unitary cost to install 1 kW of wind turbines
c_F	Electricity cost from diesel engines
$c_{m,F}$	Operative and maintenance cost diesel engines (except fuel expenditure)
$c_{m,PV}$	Operative and maintenance cost for photovoltaic plants
c_{SW}	Unitary cost to install 1 kW of wave energy farm

D_C	Hydraulic equivalent diameter of the external buoy of DEIM point absorber
d_i	Number of days per month
E_d	Annual energy demand
E_i	Annual energy production in the i-th year
E_F	Annual energy production from diesel engines
E_{PV}	Annual electrical production from photovoltaic plants
e_{PV}	Annual electrical production from a photovoltaic plant
$e_{PV,i}$	Monthly electrical production from a photovoltaic plant
E_w	Annual electrical production from wind
e_W	Annual electrical production from a wind turbine
$e_{W,i}$	Monthly electrical production from a wind turbine
E_{SW}	Annual electrical production from a sea wave farm
e_{SW}	Annual electrical production from a sea wave energy converter
$e_{SW,i}$	Monthly electrical production from a sea wave energy converter
f	Wave frequency
$f(v)$	Probability density function of wind speed
g	Standard acceleration due to gravity
$\overline{H}_b$	Monthly average of direct daily solar radiation
$\overline{H}_d$	Monthly average of diffused daily solar radiation
$h_{m,i}$	Number of hours in the i-th month
$\overline{H}_\rho$	Monthly average of daily solar radiation diffusely reflected from the ground
H_s	Significant wave height
$\overline{H}_{T,i}$	Monthly average of total daily solar radiation
$h_{j,i}$	Number of hour when the j-th wind class is measured
I_0	Total initial investment for the new energy mix
$I_{0,PV}$	Initial investment for photovoltaic plants
$I_{0,W}$	Initial investment for the wind farm
$I_{0,SW}$	Initial investment for the sea wave energy farm
k	Dimensionless shape parameter of Weibull distribution
$LCOE$	Levelized Cost of Energy
m_{-1}	Spectral moment of order -1
m_0	Spectral moment of order 0
n_{SW}	Number of DEIM points absorbers
n_{PV}	Number of photovoltaic plants
n_W	Number of wind turbines
P_{PV}	Total installed power from photovoltaic panels
P_W	Total installed power from wind source
P_{SW}	Total installed power from sea wave source
p_{PV}	Rated power of a single photovoltaic plant
p_W	Rated power of a wind turbine
p_{SW}	Rated power of a sea wave energy converter
$\overline{R}_b$	Monthly average of the ratio between the direct solar radiation to the tilted surface and the solar radiation
$S(f)$	Variance of wave frequency, function of frequency
S_{PV}	Generic photovoltaic plant surface
t	Observing period in wind measurement
T_e	Wave energy period
$TLCC$	Total Life Cycle Cost
T_p	Wave peak period
v	Wind speed
v_j	Wind speed class
Greek Symbols	**Description**
α	Conversion factor of peak period to energy period
β	Tilt angle of photovoltaic panels
δ	Solar declination
ε	Inflation rate for energy
η_{PV}	Average electrical efficiency of photovoltaic plant
η_{SW}	Average energy efficiency of DEIM point absorber
λ	Scale parameter of Weibull distribution
μ_{PV}	Ratio of annual O&M cost on initial investment for photovoltaic plants

μ_W	Ratio of annual O&M cost on initial investment for wind turbines
μ_{SW}	Ratio of annual O&M cost on initial investment for wave energy farm
π	Pi constant
ρ	Seawater density
ρ_g	Ground albedo
τ	Monetary interest rate
φ_m	Sea wave power flux
$\overline{\varphi}_{m,i}$	Monthly average of sea wave power flux
ψ	Latitude of the considered place
ω_s	Sunset hour angle for the tilted surface

Appendix A

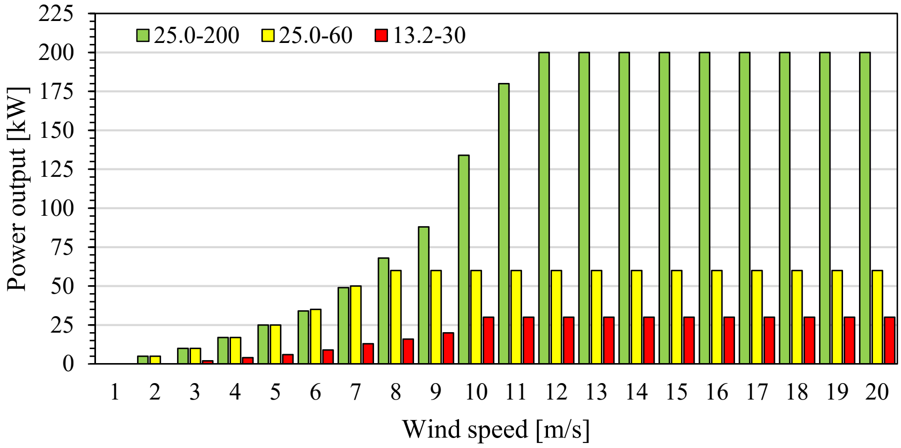

Figure A1. Power output of wind turbine as function of wind speed [57–59].

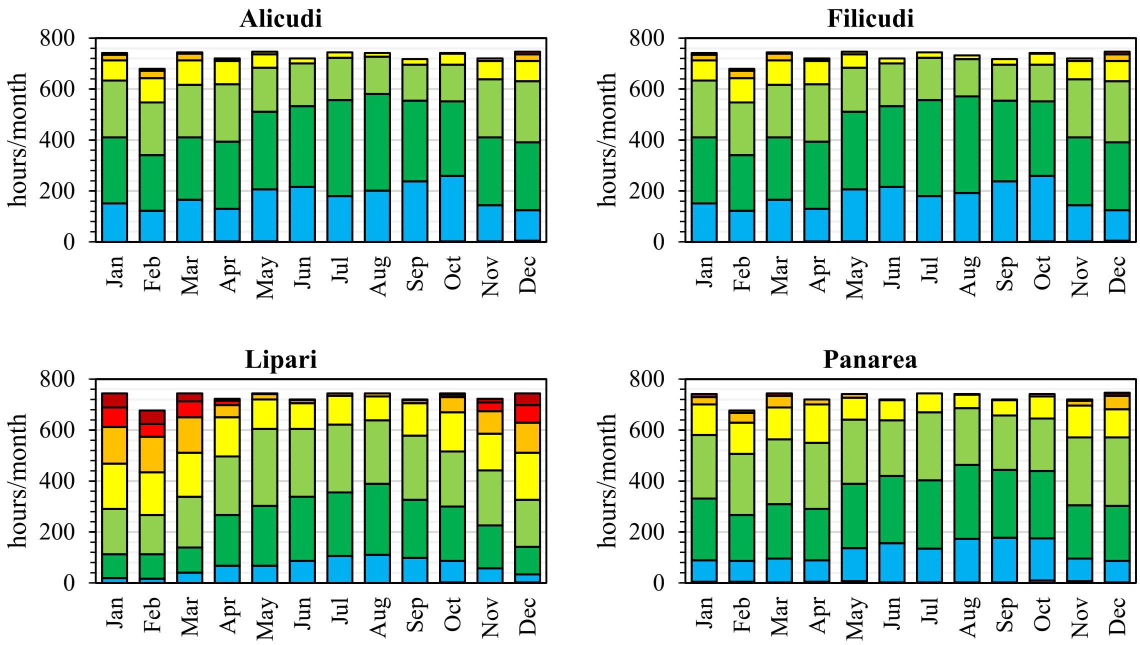

Figure A2. *Cont*.

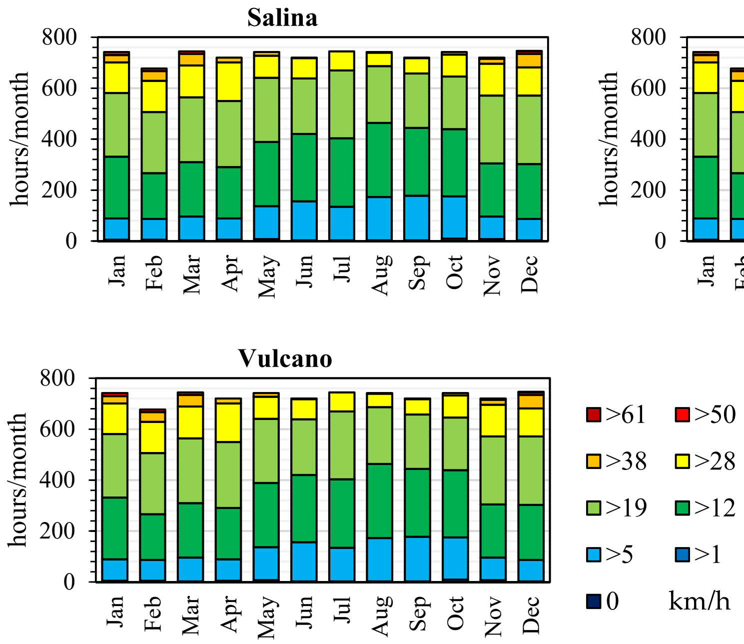

Figure A2. Availability of wind source for each island during the year.

Appendix B

Table A1. Target for the electrical capacity in each Italian small island.

Islands	Target Set (Electrical Capacity) Defined by MISE	Islands	Target Set (Electrical Capacity) Defined by MISE
Vulcano	300	Lampedusa	2140
Stromboli	220	Linosa	170
Ustica	280	Ponza	720
Ventotene	170	Capri	1000
Pantelleria	2720	Lipari	2110
Levanzo	40	Salina	580
Marettimo	120	Panarea	130
Isole Tremiti	240	Filicudi	80
Favignana	900	Capraia	180
Isole del Giglio	700	Alicudi	20

Table A2. Main data of selected wind turbine [57–59].

Model	Hummer H13.2–30 KW	Hummer H25.0–60 KW	Hummer H25.0–200 KW
Cut-in wind speed	3.0 m/s	2.5 m/s	2.5 m/s
Rated wind speed	10 m/s	7.5 m/s	11.5 m/s
Cut-off wind speed	25 m/s	20 m/s	20 m/s
Survival wind speed	50 m/s	50 m/s	50 m/s
Rated power	30 kW	60 kW	200 kW
Rotor diameter	13.2 m	25 m	25 m
Rotor area	136.85 m^2	490.9 m^2	490.9 m^2

Table A3. Photovoltaic panels datasheet [41].

Model	PV-MLU255HC
Number of cells per panel	120
Maximum power rating	255 Wp
Open circuit voltage	37.8 V
Short circuit current	8.89 A
Module efficiency	15.4%
Dimensions	1625 × 1019 × 46 mm
Weight	20 kg

Table A4. Main data of Aeolian Island.

Island	Water Supply/ Wastewater Treatment	Inhabitants	Area [km^2]	Electrical Consumption (MWh/y)	Electrical Society
Alicudi	Boat/No	105	5.1	400	Enel Produzione
Filicudi	Boat/No	235	9.5	1400	Enel Produzione
Lipari	Desalination/Yes	11,386	37.6	34,800	SEL SNC Lipari
Panarea	Boat/No	241	3.4	3140	Enel Produzione
Salina	Boat/No	2300	26.4	9160	Enel Produzione
Stromboli	Boat/No	400	12.6	3870	Enel Produzione
Vulcano	Desalination/Yes	733	21	7280	Enel Produzione

Table A5. Installed plants and targets for Aeolian Archipelago.

Island	PV Plants (kW)	Thermal Solar Plants (m^2)	Target of Energy by RES (kW)	Target Thermal Solar Plants (m^2)
Alicudi	-	-	20	20
Filicudi	-	-	80	8
Lipari	79.9	304	2110	2520
Panarea	-	-	130	200
Salina	4	-	580	570
Stromboli	-	100	220	250
Vulcano	-	183	300	470

Table A6. Monthly solar radiation data [kWh/m^2] for each island [50].

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Alicudi	103.9	113.1	178.3	186.6	213.0	217.2	232.8	223.5	177.6	148.5	115.8	96.1
Filicudi	115.6	133.0	196.5	196.5	218.6	218.4	235.0	229.7	192.9	170.5	127.8	105.7
Lipari	107.3	119.8	184.8	189.9	214.5	218.4	237.2	230.3	187.2	161.2	117.3	98.6
Panarea	104.2	117.9	182.0	190.2	213.9	217.5	235.0	228.5	185.4	158.7	111.9	95.8
Salina	89.0	109.2	171.1	186.9	213.3	217.5	236.2	229.7	178.8	148.5	99.9	78.4
Stromboli	83.7	103.6	169.9	192.3	215.1	220.5	238.7	231.3	183.0	147.3	94.2	76.3
Vulcano	113.5	126.0	190.0	192.3	215.5	218.4	234.1	230.7	189.6	167.7	124.2	105.1

Table A7. Wave energy flux [kW/m] [51].

	Point: Lat./Long.	Jan.–Mar.	Apr.–Jun.	Jul.–Sep.	Oct.–Dec.
Alicudi	38.56° N/14.32° E	7.13	2.17	1.37	5.39
Filicudi	38.57° N/14.51° E	6.83	2.08	1.32	5.12
Lipari	38.45° N/18.88° E	4.42	1.42	0.79	3.33
Panarea	38.66° N/15.07° E	5.85	1.80	1.15	4.35
Salina	38.60° N/14.78° E	5.85	1.78	1.16	4.38
Stromboli	38.83° N/15.17° E	6.37	1.99	1.21	4.74
Vulcano	38.36° N/14.87° E	4.60	1.47	0.85	3.48

Table A8. Values of main parameters used in the evaluation on Lipari Island.

Parameters	Symbols	Values
Annual energy demand	E_d	34.8 GWh/y
Electricity cost by diesel engines	c_F	0.311 €/kWh
Inflation rate for energy	ε	5%
Monetary interest rate	τ	1.75%
Unitary cost to install 1 kW of PV panels	c_{PV}	1231 €/kW
Unitary cost to install 1 kW of wind turbines	c_W	1310 €/kW
Unitary cost to install 1 kW of sea wave	c_{SW}	5000 €/kW
Ratio of annual O&M cost on investment for PV	μ_{PV}	0.013
Ratio of annual O&M cost on investment for wind	μ_W	0.034
Ratio of annual O&M cost on investment for wave	μ_{SW}	0.010
Annual O&M cost of diesel engines	$C_{m,F}$	1,824,912 €

Table A9. Proposal of energy mix for the Aeolian Islands.

	Unit	Alicudi	Filicudi	Lipari	Panarea	Salina	Stromb.	Vulcano
n. PV plants	(-)	30	74	521	83	95	65	37
Total PV power	(kW)	99	244	1719	274	314	215	122
PV production	(MWh/y)	198.6	522.6	3552.8	559.0	614.0	419.5	257.3
n. wind turbines	(-)	1	6	26	5	18	7	15
Total wind power	(kW)	30	180	5200	300	1080	420	900
Wind production	(MWh/y)	62.4	374.3		1401.7	5046.3	1962.4	4205.2
n. wave converters	(-)	0	0	11	1	3	1	3
Total wave power	(kW)	0	0	880	80	240	80	240
Total wave prod.	(MWh/y)	0.0	0.0	961.8	115.4	346.8	125.6	273.9
Total RES prod.	(MWh/y)	261.0	896.9	18,767.3	2076.2	6007.1	2507.6	4736.4
RES share	(%)	65.25	64.06	53.93	66.12	65.58	64.80	65.06
LCOE	(€/kWh)	0.217	0.220	0.257	0.210	0.208	0.210	0.212

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