# *Evaluation of the optimal renewable electricity mix for Lampedusa island: the adoption of a technical and economical methodology*

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## Abstract

Worldwide, the majority of small islands not connected to the main grid is still dependent on fossil fuels. From an economic and environmental point of view, this condition is no more sustainable given the high costs for electricity generation and the high level of pollutant emissions. Furthermore, the dependence on fossil fuel represents a risk for the security of the supply of several small developing Countries since they are obliged to import those resources from foreign Countries. The introduction of renewable energy sources in small islands represents a valid solution to solve these problems. In this context, the paper investigates the case of Lampedusa, a small Italian island whose electrical power system is currently totally supplied by diesel power plants. In the paper, the authors investigate the transition toward an economically and technically feasible generating system based on solar, wind and sea wave plants, to achieve specific targets of decarbonization. Commercial technologies are adopted for the exploitation of solar and wind sources, while sea wave plants are based on an innovative device, currently under development at the University of Palermo. A mathematical model is proposed to find the optimal energy mix that can satisfy a fixed share of annual electricity production from renewables, considering the Levelized Cost of Electricity. Finally, the proposed solution is analyzed in order to check the dynamic stability of the power system. The paper shows that, for replacing the 40% of the current electricity demand of Lampedusa, an optimal energy mix comprising 1509 kW from photovoltaic plants, 2100 kW from wind turbines and 640 kW from wave energy converters is needed. In this way, the actualized cost for the electricity production could be reduced to 0.260 €/kWh from the current value of 0.282 €/kWh.

## Keywords

Renewable Energy; Small Islands; Grid Stability; Mediterranean Sea; Sea Wave; LCOE.

## 1 Introduction

In the race to improve the world energy sustainability, the European Union promoted the installation of technologies supplied by Renewable Energy Sources (RES), introducing incentives to simplify their spreading and diffusion (Meleddu and Pulina, 2018).

Thanks to RES, the reduction of pollutants and greenhouse gases emission is obtained for both a lower use of fossil fuels and a better management of local natural resources (Fuldauer et al., 2019; Joseph and Prasad, 2020).
A recent report from IRENA shows that, in less than 20 years, the RES installed power worldwide is practically tripled, from 753.95 GW in 2000 to 2350.76 GW in 2018. RES are concentrated mainly in Asia (1023.5 GW, 43.54%), Europe (536.4 GW, 22.82%) and North America (366.5 GW, 15.59%) (IRENA, 2018).
However, huge investments are required for the energy transition from fossil fuel to RES (Kutan et al., 2018).

Despite the spreading of RES around the world, several remote areas and the major part of small islands are still equipped with power plants almost entirely based on fossil fuels both in Europe, as shown in (Cannistraro et al., 2017) and in other regions, as shown in (Liu et al., 2018) where the case of Maldives is discussed. Considering also the Small Islands Developing States (SIDS), the electricity demand to supply all these communities is estimated equal to 52690 GWh/y, and is mainly based on fossil fuels (Blechinger et al., 2014).

In particular, small islands show several peculiarities in the energy sector (Majidi Nezhad et al., 2019, 2018):

- presence of electrical grids not connected to the mainland, that is a common condition in the entire Mediterranean Sea.
- high seasonal variation in inhabitants, especially in touristic destinations.
- annual growth of the energy demand, especially in developing countries.
- limited utilization of RES, especially for the preservation of the landscape.
- high fuel cost due to the need to import it from the mainland or far foreign Countries.
- limited freshwater reserves, so desalination plants sometimes are required.

Focusing on Europe, there are 362 islands, having at least 50 permanent residents, and other 286 with fewer inhabitants (Zafeiratou and Spataru, 2018).
To increase the energy independence from fossil fuels, several projects have been promoted, proposing specific energy mixes according to local availabilities, such as Samsø (Denmark) (Marczinkowski and Østergaard, 2019), Faroe Islands (Katsaprakakis et al., 2019), Cozumel Island (Mexico) (Mendoza-Vizcaino et al., 2016), Canary Islands (Spain) (Gils and Simon, 2017; Rusu, 2014), Azores (Portugal) (Alves et al., 2019; Stenzel et al., 2017), Maldives (Liu et al., 2018) and Reunion Island (France) (Selosse et al., 2018).
The literature on RES penetration in small island is mainly focused on commercial technologies such as wind plants and photovoltaic (PV) systems. As an example, Notton reported statistics on the electricity generation in several French islands (located in different parts of the world), considering the installation of power plants supplied by wind and solar sources (Notton, 2015).
Kougias et al. investigated a potential energy mix based on solar, wind, fossil fuel and a battery storage system to supply several small Greek islands (Rhodes, Lesvos, Chios, Karpathos and Patmos) in the Aegean Sea, close to Turkey (Kougias et al., 2019).
Geothermal, hydropower and biomass are sometimes considered to improve the sustainability of the energy sector (Bueno and Carta, 2006).
Sea wave energy potential has been also investigated in the last decade, thanks to several peculiarities, such as the great regularity and huge availability, especially in the case of small islands where the energy demand is limited. As an example, in (Bozzi et al., 2014), the energy production and the performance characteristics of three wave energy converters are estimated for two of the Italian locations. In (Monteforte et al., 2015) the authors carry out an estimation of wave energy potential in Sicily (Italy). In (Lavidas and Venugopal, 2017) an high-

resolution wave atlas for nearshore energy production at the Aegean Sea is provided, while in (Sierra et al., 2014) the wave resource around Menorca island (Spain) is assessed. Several solutions have been proposed but still no consolidated technologies are commercially available. In (Majidi Nezhad et al., 2018) four wave converters (Wave Star, Oyster, Wave Dragon and Archimedes Wave Swing) are compared, assuming the Sicilian coast as case study while in (Rusu and Guedes Soares, 2013) two Pelamis farm configurations are considered in the Portuguese coast.

To improve the energy sustainability of about 20 Italian small islands, the Italian Government has recently issued two decrees promoting the introduction of RES and the realization of projects able to affect the energy efficiency of the final uses. In detail, the Italian Ministry of Economic Development issued Decree 14 February 2017 fixing the amount of RES devices to install in 20 small islands by December 31, 2020 (Ministero dello Sviluppo Economico, 2017). The energy goals are modulated according to annual electricity production.

As an example, in the case study reported in this paper, the Decree proposes for Lampedusa the installation of 2.14 MW from RES and 2370 m$^2$ of solar thermal panels. In addition, the Article 6 suggests the installation of “Integrated innovative projects”, including also the exploitation of oceanic energies.

Decree n. 340 of 14 July 2017, issued by the Italian Ministry of Environment, Land and Sea, establishes a fund of 15 M€ for the realization of projects devoted at lowering the primary energy consumption of final users in small islands (Italian Ministry of the Environment and for Protection of the Land and Sea, 2017).

In order to achieve the goal fixed by the Italian Government for small islands, in this paper the authors propose a method for finding the optimal renewable energy mix, composed of solar, wind and sea wave energy. Commercial technologies are considered to exploit solar and wind sources while, in the case of sea wave, an innovative technology is presented. The method is applied to the case of the island of Lampedusa (Italy), located in the middle of the Mediterranean Sea.

Various methods are present in the literature for performing similar analyses. As an example, in (Zhang and Zheng, 2019) the authors consider five indicators for assessing renewable energy integration in the Beijing-Tianjin-Hebei Region. The authors consider the importance of the presence of flexible resources for the integration of renewables and evaluate both technical and economic indicators. In (de Santoli et al., 2019) a GIS-based approach is presented, based on the elaboration of queried maps and tables with percentages of electricity consumptions covered by local RES, identifying the most critical and suitable areas for the installation of new RES plants in Lazio. In (Alves et al., 2019) the RES potential of Pico and Faial islands is characterized by modeling some scenarios with EnergyPLAN.

In this paper, we propose an approach for a deeper analysis of RES feasibility in small islands considering not only the energy and environmental issues but also the problem of grid stability due to the reduction of system’s primary reserve and inertia.

The main novelty of the paper is a two phases-approach presenting at first, a preliminary choice of the optimal energy mix to install, based on the calculation of the Levelized Cost of Electricity (LCOE) and, subsequently, a dynamic stability analysis in the presence of the identified energy mix in various operating conditions for assessing the technical feasibility of the installation of RES plants from the point of view of grid security.

The model proposed for the identification of the optimal energy mix requires a limited amount of climatic data that are available in the literature or obtainable from specific GIS tools. This makes the method easy-to-apply and, being based on the calculation of the LCOE, is relevant for industries that tend to invest in RES in small islands.

Moreover, the best energy mix found by the proposed method is furthermore investigated, analyzing the frequency stability problem of the local grid. This is another important characteristic of the approach presented in this paper given that this kind of analysis is fundamental for all power systems not connected to the main grid, characterized by low inertia and high variability of RES.

Indeed, power electronics-based RES generators, if not suitably controlled, contribute to the reduction of the power systems regulation reserve and inertia and, consequently, to the increase of the Rate of Change of Frequency (RoCoF) creating possible instabilities (Favuzza et al., 2018a, 2018b).

Thus, in this paper, a methodology is reported to analyze how the increase of power generation from RES can affect the stability of a small island not supplied by the main grid. In detail, the power systems inertia is evaluated by considering typical summer and winter week profiles of the energy demand delivered by the local company in the absence and in the presence of RES. Two case studies, suggested by the Levelized Cost of Electricity (LCOE) analysis, are analyzed and the lowest inertia state is individuated. Finally, 24 failure conditions are simulated in NEPLAN environment, analyzing the dynamic transient stability to verify the robustness of the local grid in the presence of RES.

## 2 Methodology

The proposed mix of RES considered in this study is composed of solar, wind and sea wave. Fixing the share of annual electricity production from RES equal to the target established for the island, a mathematical model is used to find the best energy blend with the lowest LCOE. This parameter, reported in Eq. (1), represents the minimal selling price for electricity to cover the initial investment cost and the annual operative and maintenance costs of the entire electrical system (Branker et al., 2011; González-Roubaud et al., 2017).

$$LCOE * \sum_{i=1}^{n} \frac{E_i}{(1+\tau)^i} = TLCC \tag{1}$$

The Total Life Cycle Cost (TLCC) is the sum of all the costs associated with the selected technology in its entire life, practically, the initial investment and the annual operative and maintenance costs of the system (Short et al., 1995). The term $E_i$ represents the annual electricity production (or saving) from the power plant. Indeed, this parameter is normally referred to a single technology and is commonly available in the literature (IRENA, 2017). In the energy scenario based on RES, considering an expected life equal to 20 years, Eq. (1) can be adapted into Eq. (2):

$$LCOE = \frac{\sum_{i=1}^{20} E_f c_f \left(\frac{1+\varepsilon}{1+\tau}\right)^i + C_{r,0} + \sum_{i=1}^{20} \frac{C_{r,A} + C_{f,A}}{(1+\tau)^i}}{\sum_{i=1}^{20} \frac{E_d}{(1+\tau)^i}} \tag{2}$$

where:

$$\begin{cases} E_f = E_d - \left(P_{sw} h_{e,sw} + P_w h_{e,w} + P_{pv} h_{e,pv}\right) \\ C_{r,0} = P_{sw} c_{sw,0} + P_w c_{w,0} + P_{pv} c_{pv,0} \\ C_{r,A} = P_{sw} c_{sw,A} + P_w c_{w,A} + P_{pv} c_{pv,A} \end{cases}$$

$E_d$ represents the annual energy demand, $\varepsilon$ and $\tau$ are the inflation rate for the energy sector and the monetary interest rate, respectively. $E_f$ is the expected annual electricity production from the existing power plant in order to balance the energy demand and the production from

RES. Consequently, $E_f$ can be expressed as the difference of the annual energy demand and the annual electricity production from sea wave ($P_{sw}h_{e,sw}$), wind ($P_w h_{e,w}$), and solar sources ($P_{pv}h_{e,pv}$). Each term is given by the product of the installed power from each source ($P_{sw}$, $P_w$, $P_{pv}$) and the annual equivalent working hours ($h_{e,sw}$, $h_{e,w}$, $h_{e,pv}$), i.e. the number of hours per year required to produce the entire annual electricity production if the system works at the rated power. This parameter depends on the chosen technologies and the local climatic conditions. The initial investment cost $C_{r,0}$ can be expressed as the sum of the initial investment costs for sea wave $P_{sw}c_{sw,0}$, wind $P_w c_{w,0}$ and solar $P_{pv}c_{pv,0}$, each one expressed as the product of the installed power and the unitary cost of each technology. The same approach is applied to the annual operative and maintenance costs for the energy mix $C_{r,A}$. Finally, the term $C_{f,A}$ represents the annual operative and maintenance cost for the existing diesel generators (except the fuel expenditure). The equations to determine these parameters are below reported.

The annual electricity production $E_{pv}$ can be evaluated through Eq. (3), summing the monthly electricity production $E_{pv,i}$:

$$E_{pv} = \sum_{i=1}^{12} E_{pv,i} = \sum_{i=1}^{12} I_{T,i} S_{pv} \eta_{pv} t_{d,i} \tag{3}$$

The availability of solar source is expressed by the monthly average daily total solar radiation $I_{T,i}$ into the plane of photovoltaic panels (PVP). The main parameters are the area of PVP $S_{pv}$, the average energy efficiency $\eta_{pv}$ and the number of days $t_{d,i}$ per month. The exploitation of the solar source can be realized using commercial silicon PVP. In Table 1, the data of the selected photovoltaic panel are reported (Mitsibishi Electric, 2017).

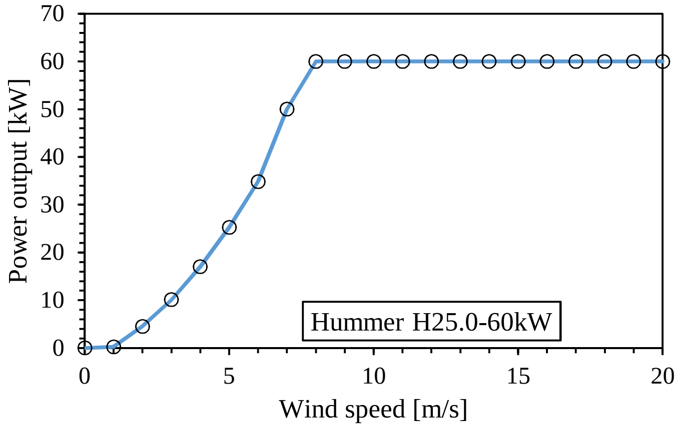
Table 1. Main parameters of photovoltaic panels.

| **Model** | **PV-MLU255HC** |
|---|---|
| Number of cells per panel | 120 |
| Maximum power rating | 255 W$_p$ |
| Open circuit voltage | 37.8 V |
| Short circuit current | 8.89 A |
| Module efficiency | 15.4% |
| Dimensions | 1625x1019x46 mm |
| Weight | 20 kg |

The annual electricity production from wind $E_w$ can be evaluated, defining several wind speed classes and the corresponding number of hours $t_{j,i}$ when a wind speed class $v_j$ is measured, as reported in Eq. (4).

$$E_w = \sum_{i=1}^{12} E_{w,i} = \sum_{i=1}^{12} \sum_{j=1}^{n} \psi(v_j)\, t_{j,i} \tag{4}$$

In detail, the wind speed is discretized in several bins per each month, so the availability of wind source is expressed indicating for each month the number of hours when a wind class is measured. The function $\psi(v)$ expresses the power output of the chosen wind turbine, as a function of the wind speed. This relation and other data are available in the datasheet of the turbine builder, as reported in Figure 1 (HUMMER, 2019).



| Model | H25.0-60kW |
|---|---|
| Nominal power | 60 kW |
| Cut-in wind speed | 2.5 m/s |
| Nominal wind speed | 7.5 m/s |
| Cut-out wind speed | 20 m/s |
| Rotor diameter | 25 m |
| Rotor area | 490.87 $m^2$ |
| Voltage | 660 V (DC) |
| Current | 90.91 A (DC) |
| n. blades | 3 |

Figure 1. Data of the selected wind turbine.

The sea wave energy source is described by the wave power flux $\varphi$, i.e. the average power available in a unitary length of a wave front. In deep water, the wave power flux is given by Eq. (5) (Emmanouil et al., 2016):

$$\varphi = \frac{\rho g^2}{64\pi} H_s^2 T_e \tag{5}$$

introducing the significant wave height (trough to crest) $H_s$, the energy period $T_e$, the seawater density $\rho$.

These data are obtained from a measuring campaign, analyzing the wave spectrum (Holthuijsen, 2007). The estimation of the electrical energy production from a wave energy converter $E_{sw}$ is given by Eq. (6):

$$E_{sw} = \sum_{i=1}^{12} E_{sw,i} = \sum_{i=1}^{12} \varphi_i d_C \eta_{sw} \eta_{hy} t_{h,i} \tag{6}$$

considering the monthly average sea wave energy flux $\varphi_i$, the equivalent hydraulic diameter $d_C$ of the wave energy converter, the average electrical efficiency $\eta_{sw}$ of the device, the hydraulic efficiency $\eta_{hy}$ of power take-off and the number of hours in the i-th month $t_{h,i}$.

For the exploitation of sea wave, the authors considered a Wave Energy Converter (WEC) that is in design step at the laboratories of the Engineering Department of the University of Palermo (Franzitta et al., 2017).

This system is composed of two floating buoys, as shown in Figure 2. The central one is fixed to the seabed, thanks to a mooring system. The external buoy is able to move up and down, running the linear generators that are installed inside the central buoy.

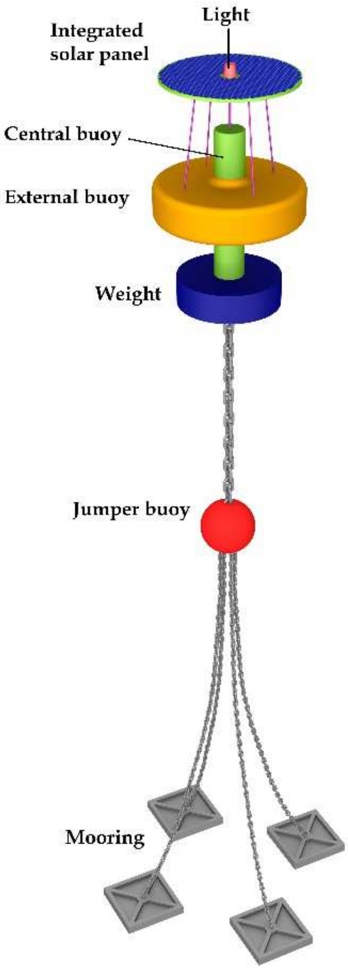


Figure 2. External view of the wave energy converter.

The annual equivalent working hours $h_{e,sw}$, $h_{e,w}$, $h_{e,pv}$ are obtained by Eq. (7):

$$h_{e,pv} = \frac{E_{PV}}{P_{pv,rated}} = \frac{\sum_{i=1}^{12} I_{T,i} S_{pv} \eta_{pv} t_{d,i}}{P_{PV,rated}}$$
$$h_{e,w} = \frac{E_w}{P_{w,rated}} = \frac{1}{P_{w,rated}} \sum_{i=1}^{12} \sum_{j=1}^{m} \psi(v_j) t_{j,i} \tag{7}$$
$$h_{e,sw} = \frac{E_{sw}}{P_{sw,rated}} = \frac{1}{P_{sw,rated}} \sum_{i=1}^{12} \varphi_i d_C \eta_{sw} \eta_{hy} t_{h,i}$$

Since the main goal of the paper is the individuation of the best energy mix from an economic point of view, the authors define the following parameters:

- $r$ is the ratio between the annual electricity production from RES and the annual demand.
- $a_{pv}$ is the ratio between the annual electricity production from photovoltaic panels and the annual electricity production from RES.
- $a_w$ is the ratio between the annual electricity production from wind and the annual electricity production from RES.

Thus, by using the definition of $r$, $a_{pv}$ and $a_w$ and the equivalent working hours from each RES ($h_{e,sw}$, $h_{e,w}$ and $h_{e,pv}$), after few manipulations the LCOE is be finally evaluated by Eq. (8):

$$LCOE = (1-r)\frac{c_f k_1}{k_2} + r\left[\frac{1-a_{pv}-a_w}{h_{e,sw}}\left(\frac{c_{sw,0}}{k_2}+c_{sw,A}\right)+\frac{a_w}{h_{e,w}}\left(\frac{c_{w,0}}{k_2}+c_{w,A}\right)+\frac{a_{pv}}{h_{e,pv}}\left(\frac{c_{pv,0}}{k_2}+c_{pv,A}\right)\right]+\frac{C_{f,A}}{E_d} \qquad (8)$$

where

$$\begin{cases} k_1 = \sum_{i=1}^{20}\left(\frac{1+\varepsilon}{1+\tau}\right)^i \\ k_2 = \sum_{i=1}^{20}\frac{1}{(1+\tau)^i} \end{cases}$$

It is interesting to observe that in Eq. (8) there are only three variables: $r$, $a_{pv}$ and $a_w$. Indeed, the annual equivalent working hours can be evaluated only one time, according to Eq. (7), thus these parameters are considered constant in the optimization phase. The other inputs of the problem are the specific costs to install ($c_{sw,0}$, $c_{w,0}$, $c_{pv,0}$) and maintenance of all RES technologies ($c_{sw,A}$, $c_{w,A}$, $c_{pv,A}$), the annual energy demand $E_d$, the discount rate for money $\tau$ and the inflation rate for the energy sector $\varepsilon$.

Fixing the desired share of renewable electricity production, there are only two degrees of freedom to the problem ($a_{pv}$, $a_w$), thus the economic optimization is realized in order to find the best energy mix. The two degrees of freedom are varied in a discretized way, and the evaluation of LCOE is performed for each condition. It is important to underline that this parameter is based on the estimation of annual electricity production. Since each RES has a different trend during the year, some energy mixes could involve an hourly production trend incompatible with the network's balance. This problem is basically more relevant during winter when the electricity production from wind and sea wave are maximal and the energy demand minimal.

To avoid this condition, the evaluation of LCOE introduces the following constraints on the renewable energy mix:

- each source must produce almost 10% of the total renewable electricity production, in each month in order to justify the adoption of this energy source.
- the total renewable electricity production from RES must not exceed a specific ratio $z$ of the monthly electricity demand, to guarantee a minimal electricity production from fossil fuels, compensating the maintenance cost of the existing power plant.
- considering the load profile during a typical summer day (highest energy demand) and winter day (lowest energy demand), the difference between electricity production from RES and demand must be positive in order to balance the electrical grid by using the local power plant, avoiding the requirement of an energy storage system.

To avoid the hourly verification of all possible mixes and reduce the computational burden, a maximal share $z$ of monthly electricity production from RES has been introduced. Consequently, the check of RES production is applied to the monthly scale, according to Eq. (9):

$$E_{sw,i} + E_{w,i} + E_{pv,i} \leq zE_{d,i} \tag{9}$$

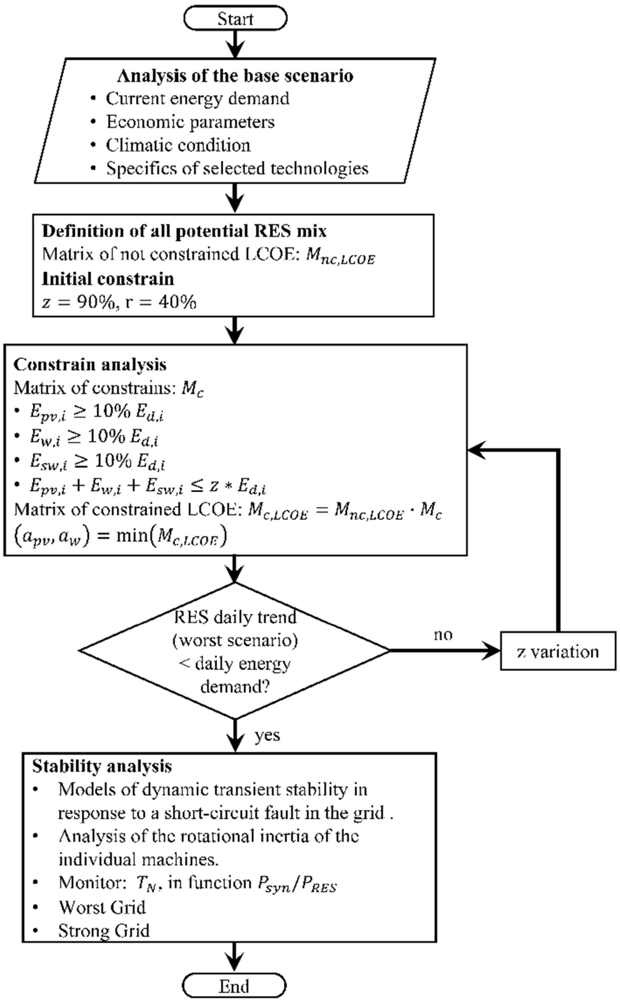


Figure 3. Flow chart of the methodology.

As shown in the flow chart reported in Figure 3, the parameter $z$ is evaluated with an iterative approach. It assumes firstly the value of 90% in order to evaluate preliminarily the matrix of constrains. Overlapping the matrix of constraints to the not constrained LCOE matrix, it is possible to identify the best condition, i.e. the RES mix corresponding to the lowest LCOE. This condition is consequently verified, considering the hourly trends of energy demand and production from RES. If the proposed energy mix exceeds the energy demand in some hours of the day, the parameter $z$ is reduced and consequently the matrix of constrains is calculated again and overlapped on the not constrained LCOE matrix to find the new best energy mix. After a few iterations, the best energy is finally obtained, verifying the hourly compatibility with the local energy demand.

After the selection of the best energy mix, the grid stability analysis is finally performed.

## 3 Case Study

Lampedusa is a small Italian island, located between Sicily and North Africa, about 113 km from Tunisia and 205 km from Sicily. It covers a surface of about 20.2 km$^2$ and a coastline of about 26 km.

The power system is isolated from the main national grid. The local medium voltage network is composed of 69 nodes, 39 kiosk and 13 pole-mounted (10 kV/400 V) substations. The annual electricity production is about 36.2 GWh. The trend of the daily electricity production is reported in Figure 4 (Di Silvestre et al., 2016).

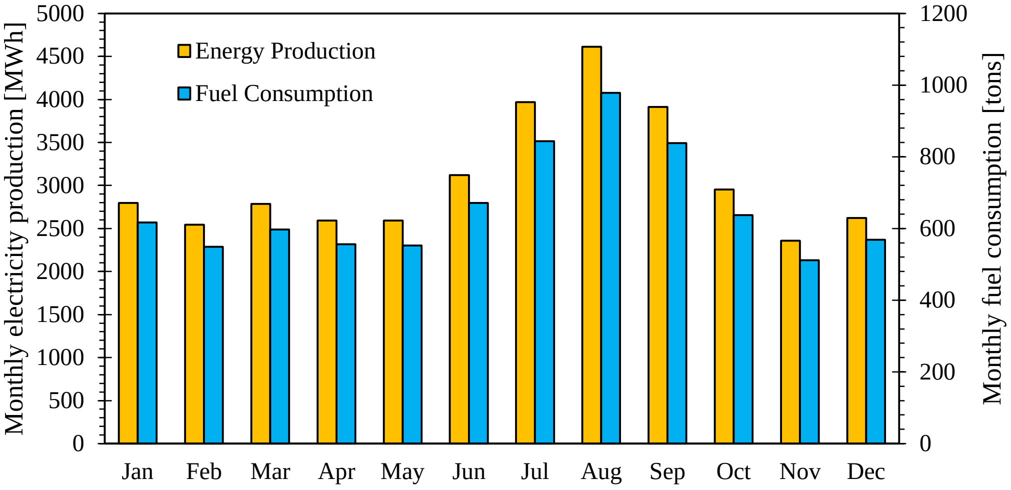


Figure 4. Monthly electricity production and corresponding fuel consumption (2014).

As shown in Figure 4, the energy consumption varies significantly from summer to winter. This is a typical situation in small islands whose touristic flows during summer have a great impact on the energy demand.

The local electrical grid is supplied by a power plant, composed of eight diesel generators (with a total installed power of 22.5 MVA) as shown in Table 2. Data are provided by the local producer. The generators work with different scheduling according to the hourly electrical load.

Table 2. Rated power of diesel generators installed in Lampedusa.

| **Identification** | **Rated power [kW]** | **Inertia constant [s]** |
|---|---|---|
| G1 | 4100 | 2.85 |
| G2 | 1328 | 1.51 |
| G3 | 1470 | 1.53 |
| G4 | 2800 | 2.41 |
| G5 | 1893 | 2.01 |
| G6 | 2998 | 2.52 |
| G7 | 2935 | 2.47 |
| G8 | 5040 | 2.91 |

A boat service refills regularly the fuel tanks of the local power plant. This solution is not sustainable from an environmental point of view, because of the emission of $CO_2$ and pollutants due to the diesel combustion in the local power plant. Figure 5 represents the structure of the local medium voltage network (Lo Brano et al., 2016).

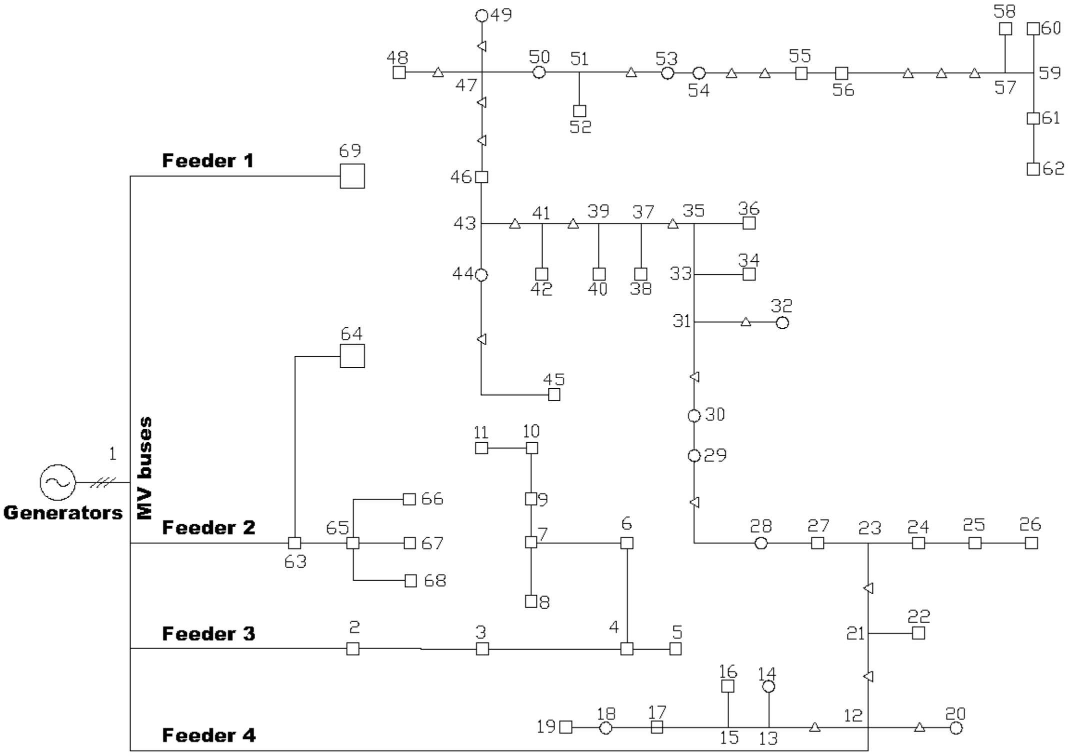


Figure 5. Layout of the medium voltage network of Lampedusa island.

About the economic aspects, it is interesting to underline that electricity production in small islands shows higher costs than in the mainland for several reasons (Liu et al., 2018):

- the local power plant is significantly oversized to have enough backup power in the case of failure.
- the energy demand varies considerably during the year, due to arrivals in the touristic season.
- the small size of the power system increases the cost of fuel transportation and the operative and maintenance costs.

With the liberalization of the Italian energy sector in 2009, an incentive UC4 (now collapsed inside the incentive $A_{rim}$) was introduced in the electricity bills to cover the higher costs for the electricity production in small islands. In this way, who lives in small islands purchases electricity at the same price as the mainland. It is estimated that this incentive generates an income of 70 M€/year, of which about 13 M€/y for Lampedusa, to cover the higher costs of electricity generation in all small islands supplied by small private companies (Legambiente, 2018).

To increase the environmental and economic sustainability of the energy sector, in the next section a renewable energy mix is proposed and sized using the mathematical model before introduced. The stability problem is consequently analyzed.

### 3.1 Minimization of LCOE

The RES mix is selected according to the economic parameter LCOE seen in Eq. (8). The function shows three degrees of freedom: the share of electricity production from the RES mix $r$ respect the total energy demand, the ratio of electricity production from photovoltaic panels ($a_{pv}$) and wind turbines ($a_w$) respect to the RES production. Climatic data have been collected, by using specific GIS tools. In detail, Figure 6 shows the annual trend of the wind source, considering 9 wind speed classes and reporting the number of hours when each speed class is measured. These data are based on a specific weather model having a resolution of 30 km (meteoblue, 2019).

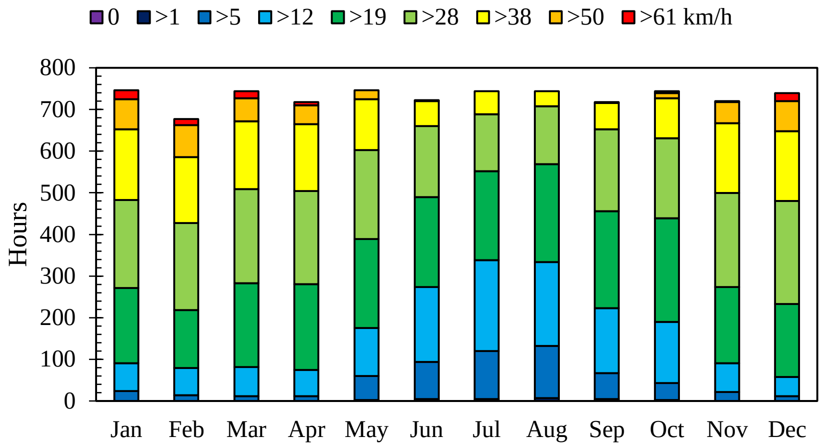


Figure 6. Availability of wind source by wind speed classes.

As regards the sea wave energy source, the monthly average power flux trend is reported in Figure 7 (ENEA, 2019). In the same graph, the solar source is represented by the monthly average daily solar radiation on horizontal surface and a tilted surface (31°) (JRC European Commission, 2017).

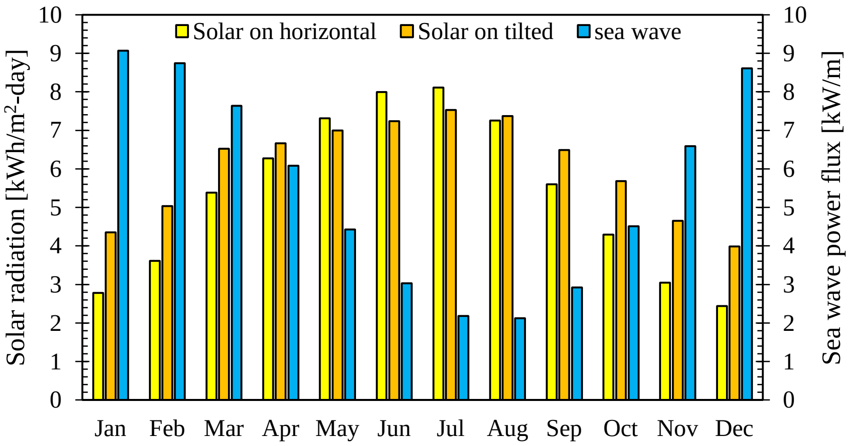


Figure 7. Solar radiation on horizontal and tilted surface (31°) and sea wave power flux.

About the existing power plant, the mathematical model splits the annual costs in two items: a term related to the fuel consumption to produce energy and the latter to fixed expenditure (maintenance, worker salaries, etc.). Assuming that the trend reported in Figure 4 was the same also in 2015, the evaluation of the average price for fuel consumption has been evaluated as weighted average of the monthly average price of oil with a low concentration of sulfur (less than 1%) published by the Italian Ministry of Economic Development (Italian Ministry of Economic Development, 2019).

The total income of the local producer is given by product of the annual electricity production and the total selling price of energy. Thus, the fixed costs are evaluated as the difference of the total income and the estimated expenditure for the fuel consumption. About the cost for electricity production using traditional generators, it assumed equal to the sum of NUP

(National Unique Price) (GME, 2019) and the incentive established by the Italian Authority for Energy (ARERA, 2018).

About RES, the unitary cost for the purchase and installation and for the operative and maintenance operations of each RES technology can be obtained from literature (IRENA, 2018). About sea wave, the economic parameters have been considered by the authors in previous researches (Franzitta et al., 2016).

The discount rate for energy sector has been evaluated by the authors, considering the entire data bank (from January 1996 to December 2019) on the monthly average price of oil with a low concentration of sulfur (Italian Ministry of Economic Development, 2019). About the discount rate for money, data are available in literature (Caporale and Gil-Alana, 2019).

Recent statistics indicate an annual electrical energy consumption equal to 36.8 GWh in Lampedusa (Ministero dello Sviluppo Economico, 2017). All data are reported in Table 3.

Table 3. Values of main economic parameters.

| Parameters | Symbols | Values |
|---|---|---|
| Annual energy demand | $E_d$ | 36863 MWh/year |
| Electricity cost by diesel engines | $c_f$ | 0.205 €/kWh |
| Inflation rate for energy | $\varepsilon$ | 2.99% |
| Monetary interest rate | $\tau$ | 1.14% |
| Unitary cost to install 1 kW of PVP | $c_{pv,0}$ | 1231 €/kW |
| Unitary cost to install 1 kW of wind turbines | $c_{w,0}$ | 1310 €/kW |
| Unitary cost to install 1 kW of sea wave | $c_{sw,0}$ | 5020 €/kW |
| Unitary O&M cost for 1 kW of PVP | $c_{pv,A}$ | 18 €/kW-year |
| Unitary O&M cost for 1 kW of wind turbines | $c_{w,A}$ | 50 €/kW-year |
| Unitary O&M cost for 1 kW of WEC | $c_{sw,A}$ | 75 €/kW-year |
| Annual O&M cost of diesel engines | $C_{f,A}$ | 2,830,659 €/year |
| Equivalent working hours of PVP | $h_{e,pv}$ | 1953.2 h/year |
| Equivalent working hours of wind | $h_{e,w}$ | 4982.6 h/year |
| Equivalent working hours of sea wave | $h_{e,sw}$ | 2419.5 h/year |

Considering the climatic data above reported, the mathematical model is applied considering a RES share set to 40%. The remaining two free degrees of freedom are varied in a discretized way from 0 to 100%, as shown in Table 4, obtaining the LCOE as function of the share of solar and wind production.

Table 4. LCOE (€/MWh) as function of photovoltaic and wind ratio (%), without constrains.

| | $a_{pv}$ | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $a_w$ | **0** | **5** | **10** | **15** | **20** | **25** | **30** | **35** | **40** | **45** | **50** | **55** | **60** | **65** | **70** | **75** | **80** | **85** | **90** | **95** | **100** |
| **0** | 304 | 302 | 300 | 298 | 296 | 294 | 292 | 290 | 288 | 286 | 283 | 281 | 279 | 277 | 275 | 273 | 271 | 269 | 267 | 265 | 263 |
| **5** | 302 | 300 | 297 | 295 | 293 | 291 | 289 | 287 | 285 | 283 | 281 | 279 | 277 | 275 | 273 | 271 | 269 | 267 | 265 | 262 | |
| **10** | 299 | 297 | 295 | 293 | 291 | 289 | 287 | 285 | 283 | 281 | 279 | 276 | 274 | 272 | 270 | 268 | 266 | 264 | 262 | | |
| **15** | 297 | 295 | 293 | 291 | 288 | 286 | 284 | 282 | 280 | 278 | 276 | 274 | 272 | 270 | 268 | 266 | 264 | 262 | | | |
| **20** | 294 | 292 | 290 | 288 | 286 | 284 | 282 | 280 | 278 | 276 | 274 | 272 | 270 | 267 | 265 | 263 | 261 | | | | |
| **25** | 292 | 290 | 288 | 286 | 284 | 281 | 279 | 277 | 275 | 273 | 271 | 269 | 267 | 265 | 263 | 261 | | | | | |
| **30** | 289 | 287 | 285 | 283 | 281 | 279 | 277 | 275 | 273 | 271 | 269 | 267 | 265 | 263 | 260 | | | | | | |
| **35** | 287 | 285 | 283 | 281 | 279 | 277 | 275 | 272 | 270 | 268 | 266 | 264 | 262 | 260 | | | | | | | |
| **40** | 284 | 282 | 280 | 278 | 276 | 274 | 272 | 270 | 268 | 266 | 264 | 262 | 260 | | | | | | | | |
| **45** | 282 | 280 | 278 | 276 | 274 | 272 | 270 | 268 | 265 | 263 | 261 | 259 | | | | | | | | | |
| **50** | 279 | 277 | 275 | 273 | 271 | 269 | 267 | 265 | 263 | 261 | 259 | | | | | | | | | | |
| **55** | 277 | 275 | 273 | 271 | 269 | 267 | 265 | 263 | 261 | 259 | | | | | | | | | | | |
| **60** | 275 | 273 | 270 | 268 | 266 | 264 | 262 | 260 | 258 | | | | | | | | | | | | |
| **65** | 272 | 270 | 268 | 266 | 264 | 262 | 260 | 258 | | | | | | | | | | | | | |
| **70** | 270 | 268 | 266 | 263 | 261 | 259 | 257 | | | | | | | | | | | | | | |
| **75** | 267 | 265 | 263 | 261 | 259 | 257 | | | | | | | | | | | | | | | |
| **80** | 265 | 263 | 261 | 259 | 257 | | | | | | | | | | | | | | | | |
| **85** | 262 | 260 | 258 | 256 | | | | | | | | | | | | | | | | | |
| **90** | 260 | 258 | 256 | | | | | | | | | | | | | | | | | | |
| **95** | 257 | 255 | | | | | | | | | | | | | | | | | | | |
| **100** | 255 | | | | | | | | | | | | | | | | | | | | |

The share of electricity production from sea wave represents the complementary part to 100% of the sum of the share of electricity production from PVP and wind turbines.

The evaluation of all economic parameters considers a linear relation with the installed power of each RES. As a consequence, Table 4 reveals the following features:

- In the case of not constrained matrix, LCOE assumes lowest value using only the renewable energy source with high equivalent working hours and low Capex and Opex (see $a_w = 100\%$).
- About sea wave, this technology is at a development step, thus the initial investment is higher in comparison with the other two sources. Consequently, in the case $a_w = 0\%$ and $a_{pv} = 0\%$ LCOE assumes the highest value.
- The greatest part of the values reported in Table 4 is lower than the cost for the electricity production from fossil fuel (0.282 €/kWh, given by the sum of NUP and incentive). This aspect means that the adoption of different RES mixes can reduce the sum of all costs to produce electricity in small islands in comparison with the as-is scenario.
- The choice of the optimal energy mix is not influenced by the change of operative and maintenance cost to produce electricity from fossil fuels.

The mathematical model introduces several constrains:

- Each renewable energy source must annually produce at least the 10% of the total electricity production from RES.
- The monthly share of electricity production from RES must not exceed the parameter $z$, in order to guarantee a minimal electricity production from the existing power plant and balance the electrical grid. At the same time, $z$ is calibrated in order to avoid the case that the electricity production exceeds the electricity demand in order to avoid the installation of an energy storage.

Table 5. Matrix of constrains for the renewable energy mix.

| | $a_{pv}$ | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $a_w$ | **0** | **5** | **10** | **15** | **20** | **25** | **30** | **35** | **40** | **45** | **50** | **55** | **60** | **65** | **70** | **75** | **80** | **85** | **90** | **95** | **100** |
| **0** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **5** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| **10** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | |
| **15** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | |
| **20** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | |
| **25** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | | | | | |
| **30** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | | | | | | |
| **35** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | | | | | | | |
| **40** | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | | | | | | | | |
| **45** | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | | | | | | | | | |
| **50** | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | | | | | | | | | | |
| **55** | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | | | | | | | | | | | |
| **60** | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | | | | | | | | | | | | |
| **65** | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | | | | | | | | | | | | | |
| **70** | 0 | 0 | 0 | 0 | 1 | 0 | 0 | | | | | | | | | | | | | | |
| **75** | 0 | 0 | 0 | 0 | 0 | 0 | | | | | | | | | | | | | | | |
| **80** | 0 | 0 | 0 | 0 | 0 | | | | | | | | | | | | | | | | |
| **85** | 0 | 0 | 0 | 0 | | | | | | | | | | | | | | | | | |
| **90** | 0 | 0 | 0 | | | | | | | | | | | | | | | | | | |
| **95** | 0 | 0 | | | | | | | | | | | | | | | | | | | |
| **100** | 0 | | | | | | | | | | | | | | | | | | | | |

To simplify this evaluation, a worst scenario is considered, in which the renewable energy mix produces the maximal potential energy output: photovoltaic panels according to the hourly solar radiation, wind and sea wave at rated power. According to this analysis, $z$ is evaluated equal to 0.53. Table 5 shows the RES mixes that satisfy all the conditions above reported, using a Boolean representation. The value 1 is referred to the energy mixes that are compatible with all constrains above reported. Thus, multiplying the values reported in Table 4 and Table 5, the constrained LCOE matrix is finally obtained (see Table 6).

Table 6. Constrained LCOE matrix for Lampedusa.

| | $a_{pv}$ | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $a_w$ | **0** | **5** | **10** | **15** | **20** | **25** | **30** | **35** | **40** | **45** | **50** | **55** | **60** | **65** | **70** | **75** | **80** | **85** | **90** | **95** | **100** |
| **0** | | | | | | | | | | | | | | | | | | | | | |
| **5** | | | | | | | | | | | | | | | | | | | | | |
| **10** | | | | | | | | | | | 279 | | | | | | | | | | |
| **15** | | | | | | | | | | 278 | 276 | | | | | | | | | | |
| **20** | | | | | | | | | | 276 | | | | | | | | | | | |
| **25** | | | | | | | | | 275 | 273 | | | | | | | | | | | |
| **30** | | | | | | | | 275 | 273 | 271 | | | | | | | | | | | |
| **35** | | | | | | | | 272 | 270 | | | | | | | | | | | | |
| **40** | | | | | | | 272 | 270 | 268 | | | | | | | | | | | | |
| **45** | | | | | | 272 | 270 | 268 | | | | | | | | | | | | | |
| **50** | | | | | | 269 | 267 | 265 | | | | | | | | | | | | | |
| **55** | | | | | | 267 | 265 | | | | | | | | | | | | | | |
| **60** | | | | | 266 | 264 | 262 | | | | | | | | | | | | | | |
| **65** | | | | | 264 | 262 | | | | | | | | | | | | | | | |
| **70** | | | | | 261 | | | | | | | | | | | | | | | | |
| **75** | | | | | | | | | | | | | | | | | | | | | |
| **80** | | | | | | | | | | | | | | | | | | | | | |
| **85** | | | | | | | | | | | | | | | | | | | | | |
| **90** | | | | | | | | | | | | | | | | | | | | | |
| **95** | | | | | | | | | | | | | | | | | | | | | |
| **100** | | | | | | | | | | | | | | | | | | | | | |

As shown in Table 6, according to all constrains, the best energy mix to cover the 40% of the annual electricity demand is composed by 70% wind, 20% solar and 10% sea wave. Consequently, the following Eq. (10) are used to obtain the power to install for each source, considering the parameters already described above.

$$P_w = rE_d \frac{a_w}{h_{e,w}} \qquad P_{pv} = rE_d \frac{a_{pv}}{h_{e,pv}} \qquad P_{sw} = rE_d \frac{1 - a_w - a_{pv}}{h_{e,sw}} \tag{10}$$

Table 7. Proposal of energy mix for Lampedusa.

| | | Solar | Wind | Sea wave |
|---|---|---|---|---|
| Power to be installed | [kW] | 1509 | 2100 | 640 |
| Rated power of device | [kW] | 3 | 60 | 80 |
| n. device | [-] | 503 | 35 | 8 |
| Annual electricity production | [MWh/year] | 2947.4 | 10463.4 | 1548.5 |

Considering that each selected technology supplied by RES has a fixed rated power, the final values of installed powers are obtained rounding the number of required devices to achieve the desired electricity production. The details of the RES mix are reported in Table 7.

In Figure 8, the electricity demand and production show different trends: the first one has a peak in summer, while the latter in winter. For this reason, the share of electricity production by RES oscillates from 23.1% in August to 53.3% in April and 53.0% in November.

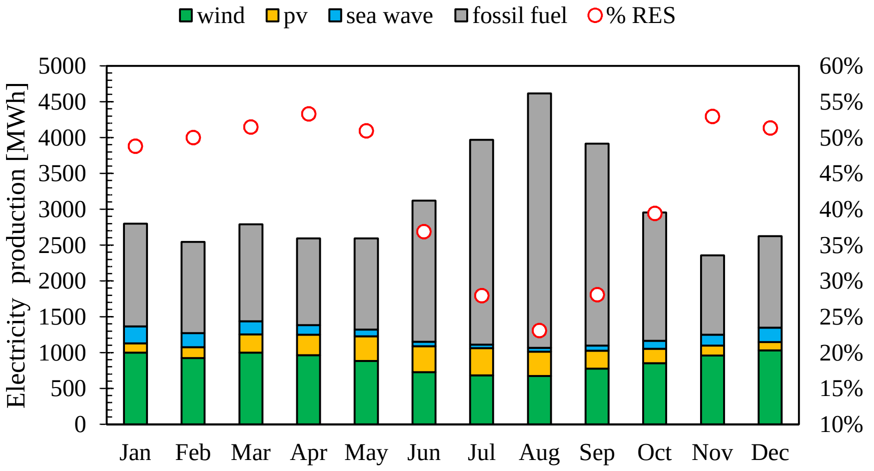


Figure 8. Electricity demand and potential renewable electricity production.

In order to replace the 40% of the current electricity demand, the best energy mix from an economic point of view requires the installation of 1509 kW of photovoltaic panels (subdivided into 503 small roof-integrated plants), 2100 kW of wind turbines (35 wind plants) and 640 kW of wave energy converters (8 devices). In this way, the estimated annual electricity production is equal to 2947.4 MWh/year for solar panels, 10463.4 MWh/year for wind turbines analyzed and 1548.5 MWh/y for sea wave energy converters.

The energy mix can reduce the energy price to 0.260 €/kWh from the current value equal to 0.282 €/kWh (data of 2015). An avoided annual expenditure in all Italian energy bill equal to 0.797 million euros (a reduction of 7.67 % of the current expenditure) is estimated thanks to the reduction of electricity production from fossil fuels.

From an environmental point of view, the fuel consumption is reduced by 3170 tons of oil, corresponding to an avoided emission of 9963 tons of $CO_2$ per year.

Since sea wave technology is still at prototypical step, an alternative simulation was also investigated, removing the constrain on the minimal electricity production from this energy source. In this case, the proposed energy mix includes 40 wind turbines, producing the 80% of RES production, and 503 PVP (same value of previous simulation); therefore, the entire sea wave electricity production should be entrusted to wind turbines. The same environmental results could be achieved. From an economic point of view, the annual avoided expenditure is equal to 0.973 million euros, due to the lower investment to realize this energy mix. The LCOE is consequently reduced to 0.255 €/kWh.

However, both scenarios are almost equivalent if the grid stability is investigated. Thus, although the installation of sea wave energy converters represents a suboptimal solution from an economic point of view, the first energy mix is considered in the following section in order to obtain useful results for a potential installation of first pilot plants.

### 3.2 Grid stability evaluation

Power systems security is based on frequency stability in relation to the inertia and kinetic energy variation of the synchronous area for each typical hour during the year. Two scenarios are verified in this study considering two different hourly production trends from RES during a typical week in summer and in winter. The transient stability is analyzed considering an imbalance due to the sudden load lack following a short circuit occurring at bus 65 located at two kilometers from the power plant. The fault occurs at the simulation time “1 second”. The procedure performed for the study is described below (Favuzza et al., 2018a):

- The typical load profiles are obtained according to two different contributions from RES defined in the Scenario A and Scenario B below explained.
- For each scenario, typical summer and winter weeks are investigated, in order to evaluate the power system inertia at each hour, considering the contribution from RES. The inertia constant of the power system in operation is determined according to Eq. (11), below reported:

  $$T_N = \frac{\sum_1^n T_i \, . \, A_{n,SG,i}}{\sum_1^n A_{n,SG,i} + \sum_1^n A_{n,RES,i}} \tag{11}$$

  where $A_{n,SG,i}$ and $T_i$ are, respectively, the nominal apparent power and the inertia constant of the i-th synchronous generator in operation at the considered hour and $A_{n,RES,i}$ is the nominal apparent power of the i-th RES generator at the same hour. In the case of RES generator $T_i$=0 s.

  To evaluate the number of active generators, the real daily operating plan of the diesel engines provided by the utility is considered.
- Based on Eq. (11), the hours corresponding to the maximum and minimum inertia constants of the power system are found for the winter and summer weeks. For those hours the non-synchronous penetration level (NSPL) is calculated (Advanced Flow, 2015), defined as the measure of the non-synchronous generation for the instantaneous simulated scenarios time, expressed in percentage according to Eq. (12):

  $$NSPL = \frac{P_w + P_{pv} + P_{sw}}{P_w + P_{pv} + P_{sw} + P_{syn}} \tag{12}$$

  where $P_{syn}$ is the power produced by synchronous generators.
- As introduced before, the fault is simulated at the time step $t = 1s$ in the hours when the power system inertia is maximum and minimum.

The two scenarios considered in the analysis are below reported.

**Scenario A** or **Worst scenario**. This case study models the worst condition for the local electrical grid. The hourly electricity production trend from RES defined as $P_{res}$ is obtained, assuming sea wave and wind power productions equal to their rated power for every hour, while PV plants produce according to the daily trend of solar radiation. The parameters considered for Scenario A are represented in three events with different penetrations of RES production to the power system:

- Event A0: $P_{res}$ is 100% in service for every hour.
- Event A1: $P_{res}$ is 88% in service for every hour, with the condition that must participate in the electricity production during each hour, at least one synchronous generator.
- Event A2: $P_{res}$ is 88% in service for every hour, with the condition that must participate in the electricity production during each hour as minimum two active synchronous generators.

The comparison between the typical load profiles (delivered by the local energy producer) and the RES penetration according to each event on the island every hour are reported in Figure 9.

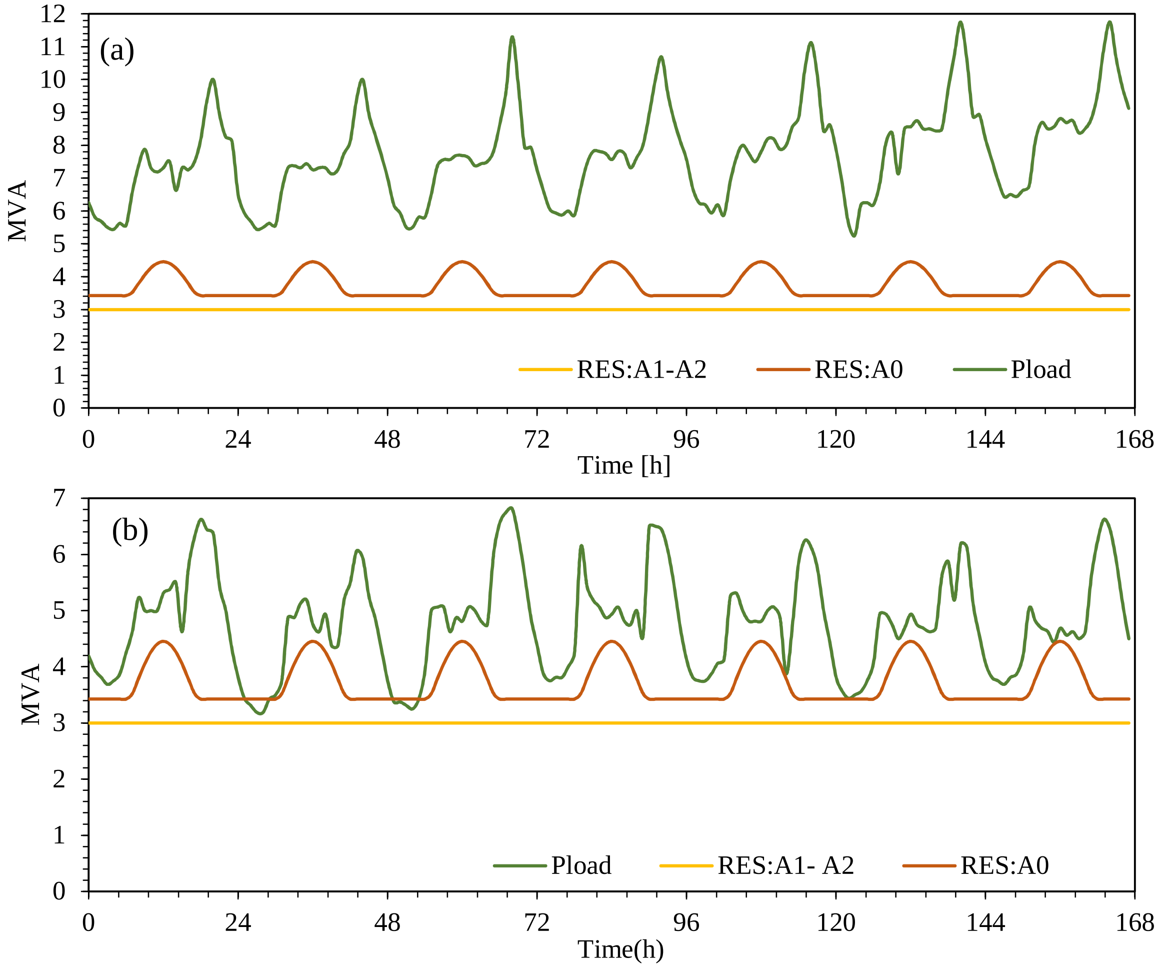


Figure 9. Scenario A: Typical load profile with RES penetration:
a) one summer week and b) one winter week.

**Scenario B** or **Probabilistic scenario**. This case study introduces a more realist condition, evaluating the hourly energy producibility by considering the data collected in two different years about sea wave, wind and solar radiation, and assuming for each source the condition that corresponds to the maximal electricity production. The parameters considered for Scenario B are represented in three events with different penetration percentages from the RES production to the power system:

- Event B0: $P_{res}$ is 100% in service for every hour.
- Event B1: $P_{res} \leq 3MVA$ with the condition that must participate in the electricity production during each hour, at least one synchronous generator.
- Event B2: $P_{res} \leq 3MVA$ with the condition that must participate in the electricity production during each hour as minimum two active synchronous generators.

The comparison between the typical load profiles (delivered by the local energy producer) and the RES penetration according to each event on the island every hour are reported in Figure 10.

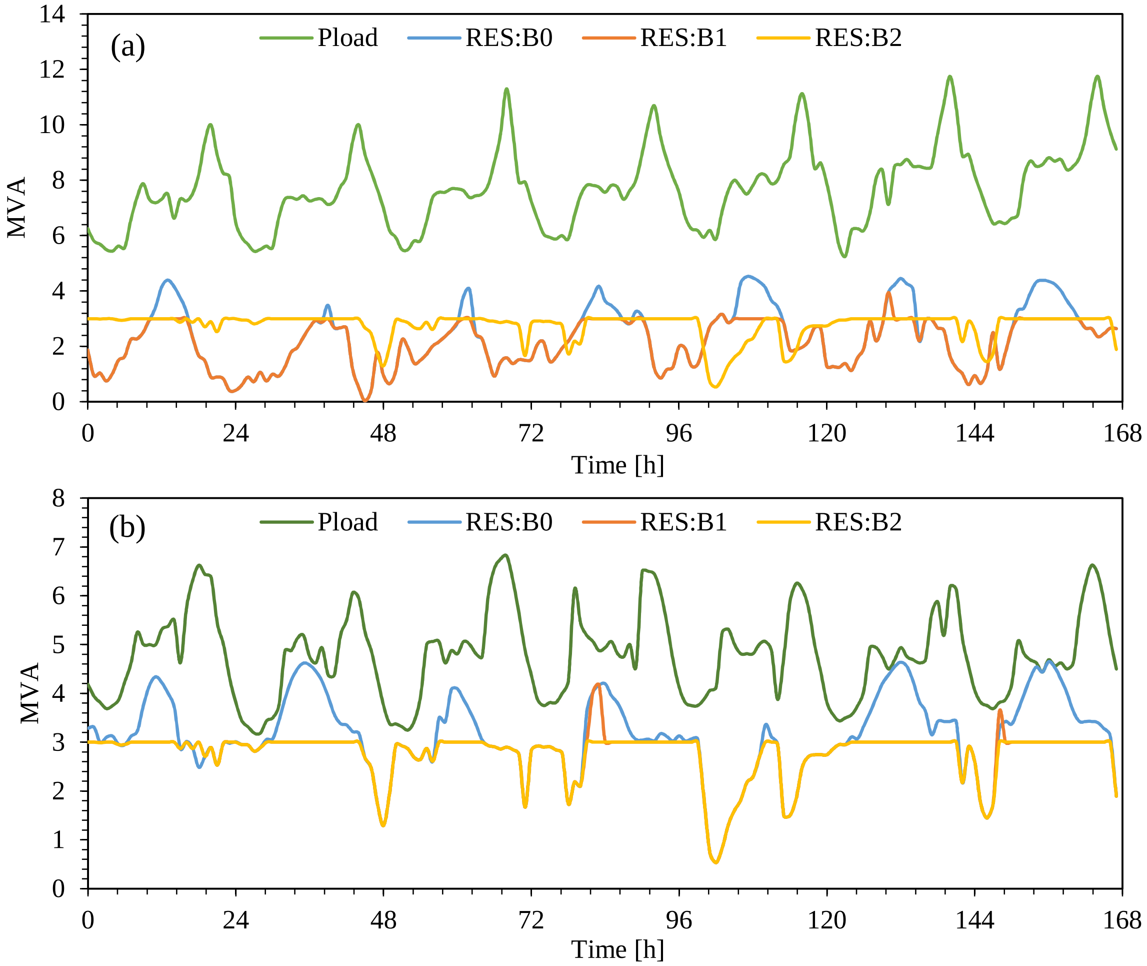


Figure 10. Scenario B: Typical load profile with RES penetration:
a) one summer week and b) one winter week.

Considering the energy produced by RES and the load profiles in Figures 9 and 10, the inertia of the system is evaluated hour by hour for the two typical weeks, by using Eq. (11). Results for each scenario are reported in Figure 11.

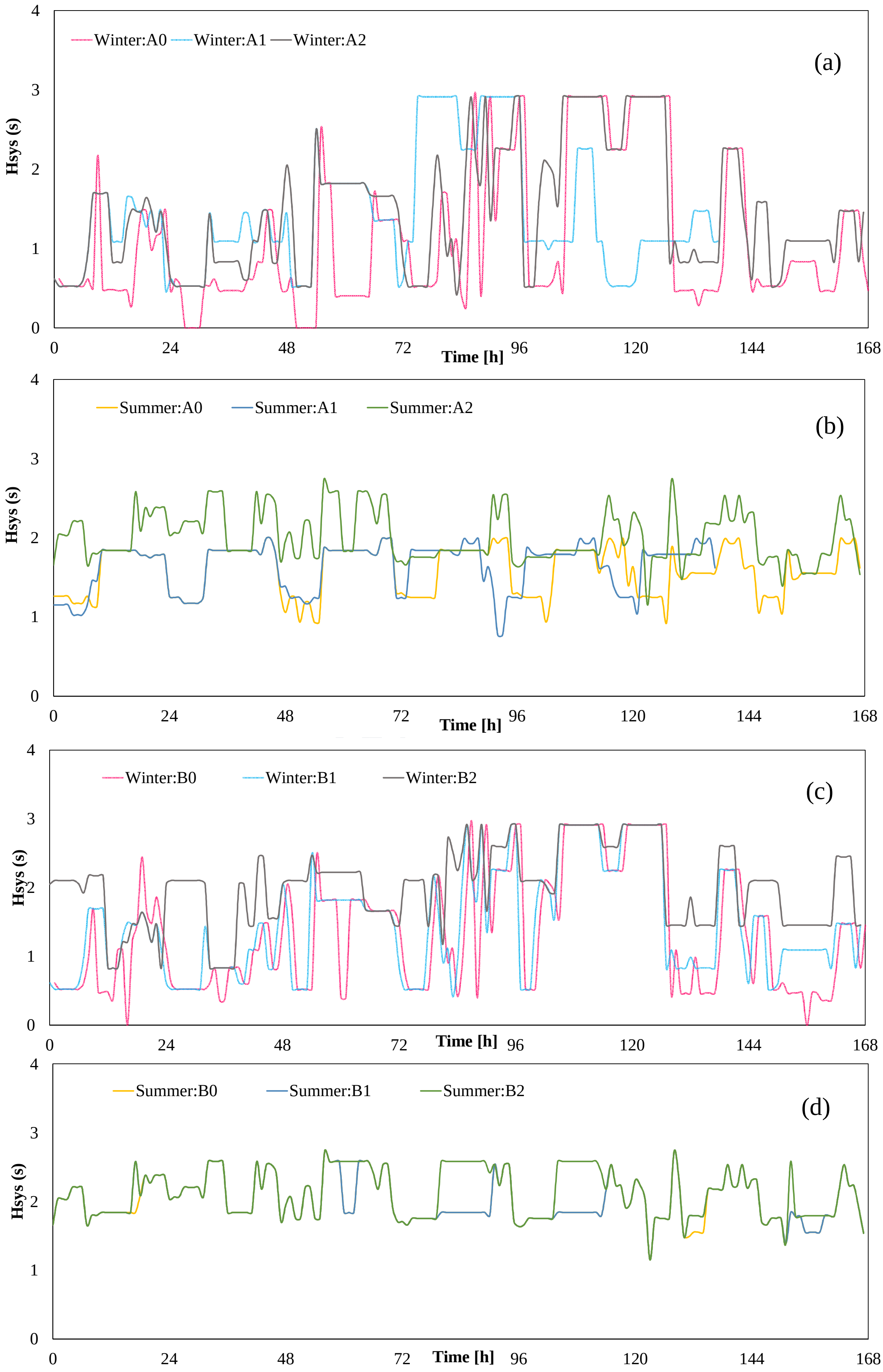


Figure 11. Trend inertial response in RES presence: (a) Scenario A, Winter; (b) Scenario A, Summer; (c) Scenario B, Winter; (d) Scenario B, Summer

Figure 11 shows how the system inertia constant $T_{N,}$ evaluated by Eq. (11), varies along a summer and winter week. The figure shows the inertia trend for all the examined cases as the production from RES varies.

In particular, the system inertia constant decreases due to fact that the production from RES increases and the number of the synchronous generators in operation consequently decreases.

Besides the number of synchronous generators in operation for each hour, the sum of the rated apparent powers of the synchronous generators influences the value of the inertia.

The trends in Figure 11 show that the values of the inertia are included in the range 0-2.75 s. This means that in some situations, characterized by a high share of renewables, all synchronous generators are disconnected from the grid and the inertia goes to zero. This happens, in particular, when renewables are 100% in service for every hour.

Table 8 reports 24 different power system states corresponding to the minimum and maximum inertia of the system, evaluated according to Eq. (12). Each state is identified by a code, whose structure is the following

$$\#code = x_1 x_2 . x_3 . x_4$$

where:

$\boldsymbol{x_1}$ indicated the scenario (A or B)

$\boldsymbol{x_2}$ indicates the event (0, 1, 2)

$\boldsymbol{x_3}$ indicates the value of the inertia constant of the system (1 for minimum inertia; 2 for maximum inertia)

$\boldsymbol{x_4}$ indicates the season (1 for summer and 2 for winter).

Table 8. Simulated events overview.

| Simulation | Active Generators | NSPL | $T_N$ [s] |
|---|---|---|---|
| A0.1.1 | G4 | 58% | 0.54 |
| A0.1.2 | - | 100% | 0.00 |
| A0.2.1 | G4-G8 | 43% | 1.48 |
| A0.2.2 | G8 | 100% | 2.34 |
| A1.1.1 | G7 | 54% | 0.57 |
| A1.1.2 | G3 | 74% | 0.30 |
| A1.2.1 | G4-G8 | 38% | 1.48 |
| A1.2.2 | G8 | 87% | 2.34 |
| A2.1.1 | G3-G7 | 45% | 0.67 |
| A2.1.2 | G1 | 20% | 0.92 |
| A2.2.1 | G7-G8 | 45% | 1.70 |
| A2.2.2 | G1-G8 | 59% | 2.75 |
| B0.1.1 | G5-G7 | 26% | 0.91 |
| B0.1.2 | - | 100% | 0.00 |
| B0.2.1 | G4-G7-G8 | 13% | 1.71 |
| B0.2.2 | G8 | 86% | 2.34 |
| B1.1.1 | G5-G7 | 26% | 0.91 |
| B1.1.2 | G3 | 75% | 0.31 |
| B1.2.1 | G4-G7-G8 | 13% | 1.71 |
| B1.2.2 | G8 | 34% | 1.29 |
| B2.1.1 | G5-G7 | 26% | 0.92 |
| B2.1.2 | G3-G5 | 55% | 0.51 |
| B2.2.1 | G4-G7-G8 | 13% | 1.71 |
| B2.2.2 | G1-G8 | 61% | 2.75 |

For the 24 cases in Table 8, a dynamic stability analysis is performed by Neplan. The disturbance occurs at $t = 1s$ and the observation window is set equal to 10 seconds. The grid frequency oscillation is represented for the 24 cases in Figure 12.

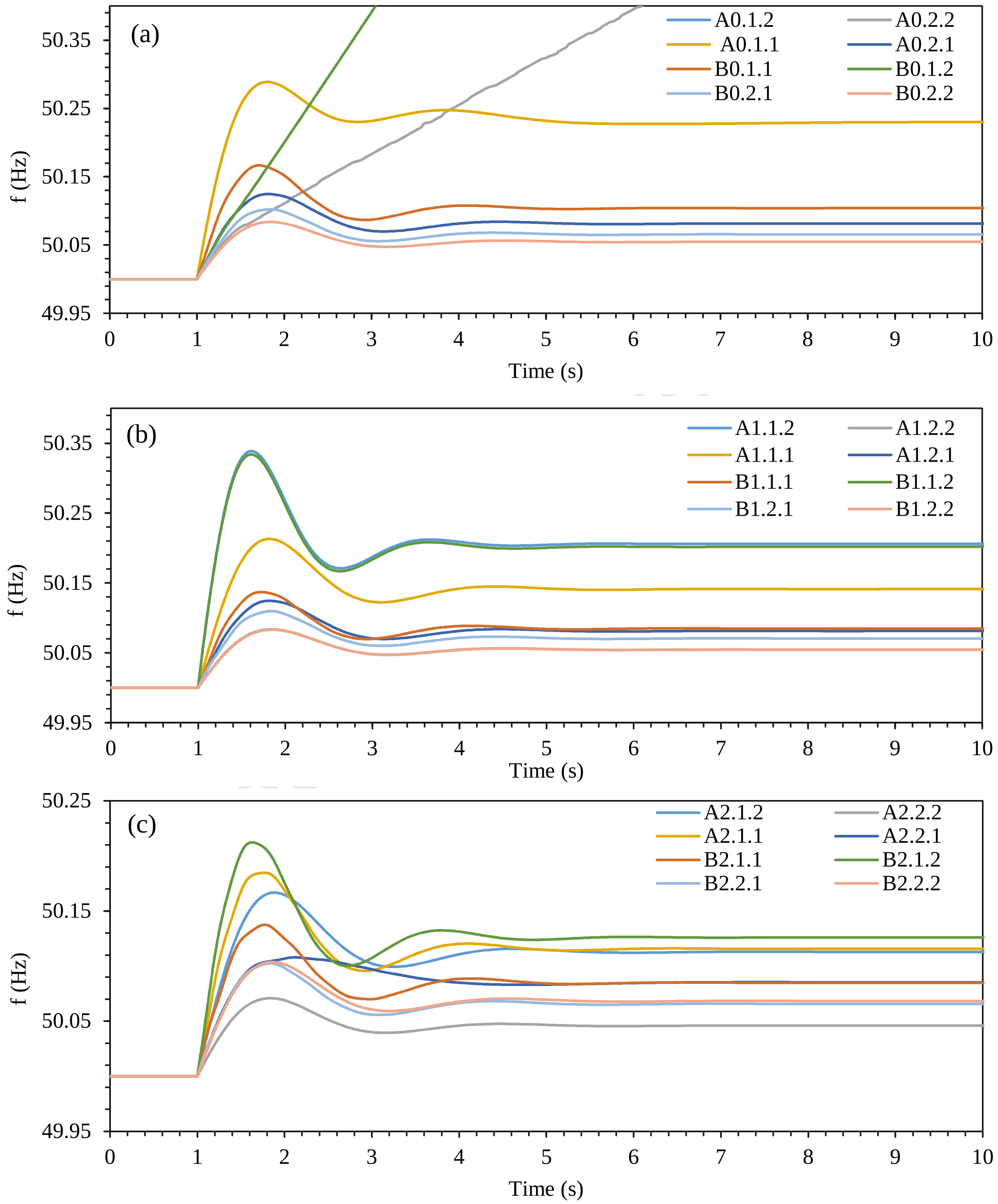


Figure 12. Grid frequency in the case of 3-phase short-circuit in the grid:
(a) Scenarios A0 and B0, (b) Scenarios A1 and B1 and (c) Scenarios A2 and B2.

The trends in Figure 12 show that:

- in all cases the grid frequency shows a typical trend occurring in the case of load loss. In 22 out of 24 cases the frequency initially increases reaching a peak in less than one second due to the unbalance between generation and load. Then, it decreases again reaching a new steady-state value due to the action of the speed regulators of the diesel generators.
- the frequency has greater oscillations when RES contribution is greater than 28% of the synchronous generation and when only one active synchronous generator is working. This is mainly due to lower values of both the system inertia and the primary regulation reserve of the generating systems depending only on the synchronous generators.
- in 22 out 24 cases, the system reaches a new stable condition in less than 10 seconds, therefore in a time interval totally compatible with the grid code. The new conditions area far from the upper frequency limit allowed for the isolated grid (51.5 Hz).
- the system is stable in 22 cases, with limited deviation from the rated frequency, while the upper limit frequency relays (set to 51.5 Hz) detach the synchronous generators in two cases: A0.1.2, B0.1.2.

For a further analysis of the dynamic stability issue, the rate of change of frequency (RoCof) is introduced, according to Eq. (13):

$$RoCoF = \left.\frac{df}{dt}\right|_{t=0+} = \frac{f_o P_k}{2\sum_{i=1}^{n} T_i \, . A_{n,SG,i}} \tag{13}$$

where $f_o$ is the rated frequency and $P_k$ is the power disturbance in the grid (in the examined case the detachment of loads due to the 3-phase short-circuit). Although in Lampedusa RoCoF protections are not present, the analysis is presented for its theoretical value.
The analysis gave the following results:

- number of cases with RoCoF below 2%: 5;
- number of cases with RoCoF between 2% and 3%: 6;
- number of cases with RoCoF exceeding 3% (Maximum limit from ENTSO-E, 2017): 13.

Therefore, 22 of the examined cases are acceptable from the point of view of grid stability. In presence of RoCoF protections, 13 of the examined cases should be further analyzed in order to ensure that, in every possible disturbance event, the system could maintain its stability considering the electricity production from RES in the scenarios above investigated without the intervention of the RoCoF relays.

## 4 Conclusion

A mathematical model has been introduced to investigate a feasible energy mix to supply small islands, considering solar, wind and sea wave sources.
From the environmental point of view, the installation of RES can avoid the emission of 9960 tons of $CO_2$/year and the consumption of 3170 tons of diesel per year. The main limitations to increase furthermore the RES production are related to the seasonal and daily variations of the electricity demand and production.
Since PV plants and modern wind turbine generators are connected through power converters, they do not offer a natural inertial response. This condition can lead to instability issues, thus particular measures for avoiding power blackout must be implemented. For example, power

storage units can be installed both for increasing the RES share and, thanks to specific advanced controls (synthetic inertia, fast frequency regulation and so on) for injecting/absorbing power in the grid and compensating generation of load imbalances. This condition will be examined in future studies.

*Implications for theory and practice*

The presented approach can contribute to a deeper analysis of RES feasibility in small island considering not only the energy and environmental issues but also the problem of grid stability due to the reduction of primary reserve and inertia.

The paper indicates the importance of a dynamic stability analysis after the identification of the optimal energy mix. The issue is even more relevant for small island characterized by high touristic flows that highly impact on the demand profile during the year.

This kind of analysis, normally not performed for not isolated grids, can improve the security of the supply of small islands in the presence of RES, contributing to the reduction of $CO_2$ emissions.

## Abbreviation list

| Sigle | Description |
|---|---|
| GIS | Geographic Information System |
| IRENA | International Renewable Energy Agency |
| LCOE | Levelized Cost Of Electricity |
| NSPL | Non-Synchronous Penetration Level |
| NUP | National Unique Price |
| PVP | Photovoltaic Panels |
| RES | Renewable Energy Source |
| RoCoF | Rate of Change of Frequency |
| SIDS | Small Islanded Developing States |
| TLCC | Total Life Cycle Cost |
| WEC | Wave Energy Converter |

## Nomenclature

### Latin letter

| Symbol | Description |
|---|---|
| $A_{n,RES,i}$ | Nominal apparent power of the i-th RES generator |
| $A_{n,SG,i}$ | Nominal apparent power of the i-th synchronous generator |
| $a_{pv}$ | Ratio of electricity production from PV panels on total RES production |
| $a_w$ | Ratio of electricity production from wind turbines on total RES production |
| $c_f$ | Operative unitary cost to produce electricity using fossil fuel |
| $C_{f,A}$ | Annual operative and maintenance cost for the power plant supplied by fuel |
| $C_{r,0}$ | Total initial investment to purchase and install the renewable energy mix |
| $C_{r,A}$ | Annual operative and maintenance cost for the renewable energy mix |
| $c_{pv,0}$ | Unitary cost to purchase and install 1 kW of photovoltaic panels |
| $c_{sw,0}$ | Unitary cost to purchase and install 1 kW of wave energy converters |
| $c_{w,0}$ | Unitary cost to purchase and install 1 kW of wind turbines |
| $c_{pv,A}$ | Unitary operative and maintenance cost for 1 kW of photovoltaic panels |
| $c_{sw,A}$ | Unitary operative and maintenance cost for 1 kW of wave energy converters |

| Symbol | Description |
|---|---|
| $c_{w,A}$ | Unitary operative and maintenance cost for 1 kW of wind turbines |
| $d_C$ | Equivalent hydraulic diameter of the wave energy converter |
| $E_d$ | Expected annual electricity demand |
| $E_f$ | Expected annual electricity production from fossil fuel |
| $E_i$ | Annual electricity production from a generic energy system |
| $E_{pv}$ | Expected annual electricity production from photovoltaic panels |
| $E_{pv,i}$ | Electricity production from photovoltaic panels in the i-th month |
| $E_{sw}$ | Expected annual electricity production from wave energy converters |
| $E_{sw,i}$ | Electricity production from wave energy converters in the i-th month |
| $E_w$ | Expected annual electricity production from wind turbines |
| $E_{w,i}$ | Electricity production from wind turbines in the i-th month |
| $g$ | Gravity acceleration constant |
| $H_s$ | Significant Height of sea wave |
| $h_{e,pv}$ | Annual equivalent working hours of photovoltaic panels |
| $h_{e,sw}$ | Annual equivalent working hours of wave energy converters |
| $h_{e,w}$ | Annual equivalent working hours of wind turbines |
| $I_{T,i}$ | Monthly average of daily total solar radiation |
| $k_1$ | Constant defined in Eq. (8) |
| $k_2$ | Constant defined in Eq. (8) |
| $P_{load}$ | Total demand of the load |
| $P_{n,SG,i}$ | Nominal Power of the i-th synchronous generator |
| $P_{pv}$ | Power to install from photovoltaic panels |
| $P_{pv,rated}$ | Rated power of a single photovoltaic plant |
| $P_{RES}$ | Renewable energy source power |
| $P_{sw}$ | Power to install from wave energy converters |
| $P_{sw,rated}$ | Rated power of a wave energy converter |
| $P_{syn}$ | Power from synchronous generators |
| $P_w$ | Power to install from wind turbines |
| $P_{w,rated}$ | Rated power of a wind turbine |
| $r$ | Share of electricity production from renewable energy sources |
| $S_{PV}$ | Total surface of photovoltaic panels |
| $t_{d,i}$ | Number of days in the i-th month |
| $T_e$ | Energy period of sea wave |
| $t_{h,i}$ | Number of hours in the i-th month |
| $t_{j,i}$ | Number of hours when the j-th wind speed class is measured in the i-th month |
| $T_i$ | Inertia constant of the i-th synchronous generator |
| $T_N$ | Inertia constant of the system |
| $v$ | Wind speed |
| $v_j$ | j-th wind speed class |

**Greek letter**

| Symbol | Description |
|---|---|
| $\varepsilon$ | Inflation rate for energy |
| $\eta_{hy}$ | Hydraulic efficiency of the wave energy converter |
| $\eta_{pv}$ | Average energy efficiency of photovoltaic panels |

| Symbol | Description |
|---|---|
| $\eta_{sw}$ | Electrical efficiency of the wave energy converter |
| $\pi$ | Pi constant |
| $\rho$ | Sea water density |
| $\tau$ | Monetary interest rate |
| $\varphi_i$ | Monthly average of sea wave power flux in the i-th month |
| $\psi(v)$ | Power output of a wind turbine as function of wind speed |

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