Desalination in small islands: the case study of Lampedusa (Italy)

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***Abstract*—Desalination represents a common solution to overcome the water scarcity in small island. A case study is presented, considering the island of Lampedusa, located at south of Sicily (Italy). As many small islands in the middle of the Mediterranean Sea, Lampedusa presents a small standalone electrical grid, entrusted to old diesel engines. For more, the renewable energy sources are extremely underdeveloped in this territory. Lampedusa is regularly affected by water scarcity, so freshwater is produced by desalination plant and sometimes transported by boat from Sicily. As sustainable solution, the paper firstly analyses the energy demand for desalination and then proposes the installation of a renewable energy mix, based on sea wave, wind and solar. For the exploitation of the first source, an innovative technology in development step at the Department of Energy of Palermo University is presented.**

Keywords—Sea Wave; Point Absorber; Desalination; Renewable Energy Mix

I. Introduction

Water is an indispensable good for human life [1]. It is necessary for several purposes in the modern society. Water is used to irrigate fields and raise livestock. In other sectors, water is used as energy carrier, to heating and cooling the operating machines, to run thermoelectric and hydroelectric power plants. Finally, water is used to quench the population, for ensure personal hygiene and environmental cleaning [2], [3].

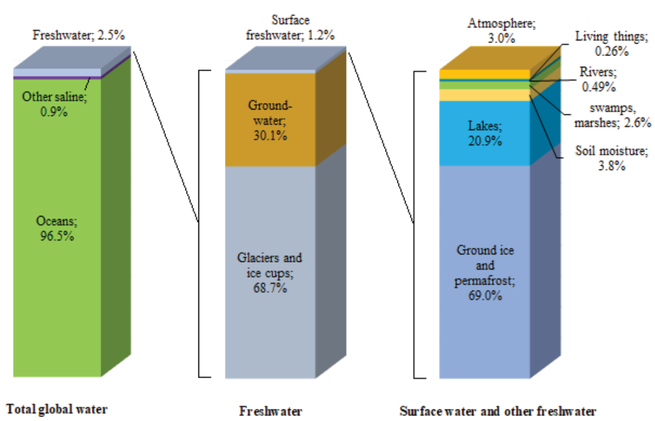

Fig. 1. Water distribution on Earth's surface

An enormous amount of water is available on the Earth. Statistics report that about 71.1% of the Earth's surface is covered by water, generating an estimated volume of 1.36×10^9 km^3. Despite this, a limited ratio (2.5%) is composed by freshwater, since the greatest part is composed by the salt water of seas and oceans (96.5%) and brackish water (0.9%), as shown in Fig. 1. Considering only freshwater, about 68.7% is frozen in glaciers and ice caps, about 30.1% is ground water, so only the 1.2% of freshwater is localized on the Earth's surface [4]. Finally, a limited amount of water is concentrated in rivers (0.49%) and lakes (20.9%). So, in conclusion, the freshwater directly usable represents only 64.17 ppm of the total water on the Earth (about 87.3×10^3 km^3).

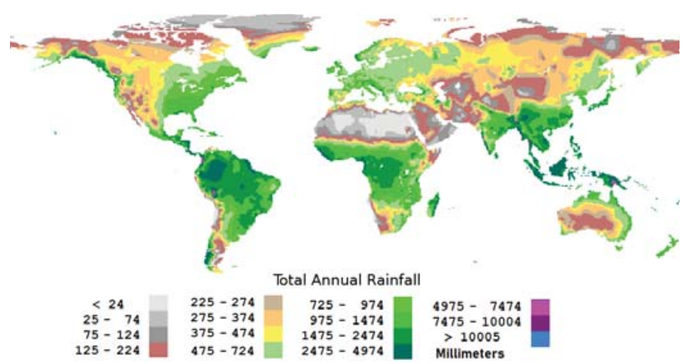

Fig. 2. Total annual rainfall around the world

Rivers and lakes are refilled by rainfalls, that are irregularly distributed around the world, as shown in Fig.2. Several regions, as Middle Africa, South America, India, Indonesia, are characterized by high values of precipitation, over 3000 mm/y. In other areas, as Middle East, western part of North America, Australia, north part of Asia, the precipitations are limited, with values ranging from 100 to 500 mm/y. Finally, regions, as North Africa, are affected by a severe water scarcity, with rainfalls lower than 100 mm/y.

As shown in the following Fig.3, the population is tendentially concentrated in temperate areas and along the coastline. We can observe that Fig. 2 and Fig. 3 show an interesting overlap: population is distributed in areas with medium values of precipitation (500-2500 mm/y). The only

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significative exception is represented by Middle East Area, where population density is quite high, with a limited availability of freshwater.

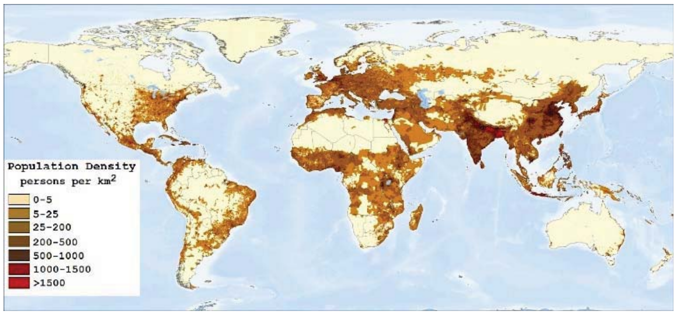


Fig. 3. Population density around the world

Nevertheless, around the world several areas show a chronically water scarcity, essentially for two reasons (see Fig. 4): absence of freshwater availability or poverty that obstructs the realization of specific infrastructures [5], [6].

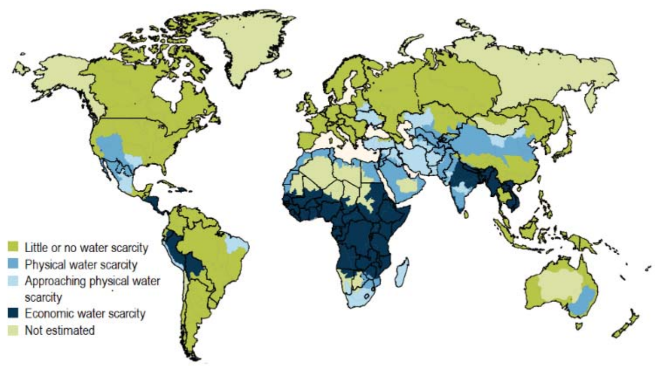


Fig. 4. Water scarcity in the world

The picture is based on the following definitions [7]:

- ***Little or no water scarcity.*** Water resources relative to use are abundant, with less than 25% of water from rivers withdrawn for human purposes.
- ***Physical water scarcity.*** Water resources development is approaching or has exceeded sustainable limits. More than 75% of river flows are withdrawn for agriculture, industry, and domestic purposes.
- ***Approaching physical water scarcity.*** More than 60% of river flows are withdrawn. These basins will experience physical water scarcity in the near future.
- ***Economic water scarcity.*** Human, institutional, and financial capital limit access to water, despite the resource could potentially satisfy the local human demands. Water resources are abundant relative to water use, with less than 25% of water from rivers withdrawn for human purposes, but malnutrition exists.

In the case of water scarcity, if salt water or brackish are available, a solution is represented by desalination process [8]–[10].

Several technologies have been developed in the past. A simple classification can be realized considering the working principle used in the process: phase transition or diffusion through semipermeable membranes [11], [12].

In the first group, we can find the ***Multi Effect Distillation*** (MED), the ***Multistage Flash Distillation*** (MFD) and the ***Mechanical Vapor Compression*** (MVC). Both MED and MFD technologies need a thermal input to generate vapor from salt water. Vapor is then condensed producing a demineralized water. Both technologies are optimized thanks to the utilization of heat recovery exchangers, working at decreasing pressure and temperature, reducing the energy demand to vaporize water.

Conversely, the MVC technology needs a mechanical energy input to run a vapor compressor, that is used to increase the vapor pressure, inducing its condensation. Thanks to the increase of vapor temperature, the heat from condensing vapor is used to produce other vapor from salt water.

Other more recent technologies are based on water diffusion through semipermeable membranes. These include the ***Electro Dialysis Reversal*** (EDR) and ***Reverse Osmosis*** (RO). The first uses an electric current through electrodes to confine the dissolved ions in specific regions, delimited by the cationic and anionic ion exchange membranes, removing ions from salt water and producing freshwater [13], [14].

In RO technology, pumps are used to pressurize salt water in order to overcame the osmotic pressure, generated by the different ions concentration of salt water and freshwater at the two sides of the semipermeable membrane [15]. So, the semipermeable membranes are used as a filter, extracting freshwater from salt water.

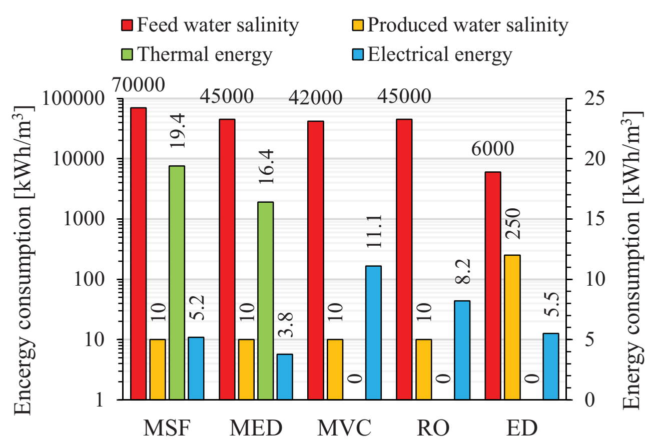


Fig. 5. Water scarcity in the world

Fig. 5 shows a comparison between the desalination technologies, before introduced. The red bars represent the maximal salinity concentration that can be used as feed water. From this point of view [16], MSF accepts the maximal level of salinity (about 70000 ppm). Except for ED that requires a salinity concentration lower than 6000 ppm, the other technologies accept a salinity concentration up to 45000 ppm. All technologies are able to produce freshwater with a salinity concentration about 10 ppm, exception for ED, that usually produces freshwater with a salinity concentration equal to 250 ppm. Finally, as regard the energy consumption, MSF and MED are the most energy consuming technologies, requiring thermal (to produce vapor) and electrical energy (to run pumps). The other technologies require only electricity.

A sustainable solution to produce freshwater is represented by desalination plants supplied by renewable energy sources [17], [18]. This new approach could be tested in small islands affected by water scarcity [19]. In this context, many examples can be found around the world. Focusing the attention on the Mediterranean Sea, several small islands show a chronical water scarcity, especially in summer season, as the very limited rainfall and the increasing of freshwater demand due to the tourist's arrivals.

In order to overcome the water scarcity, some small Sicilian islands have been equipped by desalination plants, in the last two decades. However, the current situation shows a strong energy dependence from fossil fuel, that is regularly transported by boat from Sicily, as the very limited installation of technologies powered by renewable energy sources.

The following Table I reports the main data of desalination plants installed in small Sicilian islands [20]. The data represent the average values in the period 2001-2008.

TABLE I. DESALINATION PLANTS IN SMALLER SICILIAN ISLANDS

Islands	Technology	Average annual production [m^3/y]	Average specific costs [€/m^3]	Average annual costs [€/y]
Pantelleria Sataria	EDR - RO	580,157	3.291	1,909,328
Pantelleria Maggiuluvedi	EDR - RO	197,506	3.157	623,532
Lampedusa	MVC	221,990	3.689	818,971
Linosa	MVC	99,381	5.336	530,258
Lipari	MVC	937,565	4.422	4,146,013
Ustica	MVC	215,667	6.303	1,359,348

Desalination technologies could be supplied by renewable energy sources, in order to increase the environmental sustainability. Among the renewable energy sources, sea wave energy represents an interesting solution to supply areas having a long coastline in comparison with the extension of their territory and, of course, a favourable sea wave climate. This condition can be a strong point for the small islanded communities in the Mediterranean Sea, reducing the energy dependence from fossil fuel and using a renewable energy source available in the territory.

Sea wave is currently a "new entry" in the extensive green energy discussion [10], [21]. Several studies and researches have been investigated the sea wave energy potential, in order to select the optimal sites and design a system able to exploit this energy source [22].

For the exploitation, many technologies have been proposed in the last years; some of them have been also tested in the open sea. Various classifications can be realized, considering several criteria, for example the orientation of device respect the wave front, the working principle, the distance from the coastline, the position respect the sea level, etc.

The most common classification is based on the orientation of device respect the direction of sea wave propagation, defining the following categories [23], [24]:

- ***attenuator*** that is a floating device which operates parallel to the wave direction and rides effectively the waves;
- ***point absorber*** that is a structure able to absorb energy from all directions through its movements;
- ***overtopping*** device captures water as waves break into a storage reservoir;

For the exploitation of sea wave, the Department of Energy of Palermo University is designing an innovative device, briefly descripted in the following sections. The system is based on linear generators, electrical machines able to transform directly the mechanical energy introduced as linear motion into electricity.

The main objective of this paper is the proposal of a renewable energy mix to supply a desalination plant in a sustainable way. As case study, a small Sicilian island, Lampedusa, is analysed. Starting with the evaluation of electrical demand of desalination plant, the authors suggests an integrated system able to produce electrical energy, using simultaneously solar, wind and sea wave sources.

II. THE CASE STUDY

Lampedusa is a small Italian island located at south of Sicily, in the middle of the Mediterranean Sea, about 167 km from Tunisia and 205 km from Sicily, as shown in Fig. 6. The island, with triangular shape, has a surface about 20.2 km^2 and a coastline about 26 km.

Fig. 6. Lampedusa's location in the Mediterranean Sea

As other Mediterranean small islands, Lampedusa presents a small standalone electrical grid [25].

The electricity production is entirely entrusted to the local power station. The electrical energy is produced by a traditional power plant owned by the society "S.EL.I.S. LAMPEDUSA" [26]. The power station is entrusted to eight diesel engines, with an installed power of 22.5 MW. The annual production is about 36.8 GWh (data of 2015), concentrated mainly in summer season [27]. Fig. 7 shows the annual trend of the monthly electrical production and the corresponding diesel consumption.

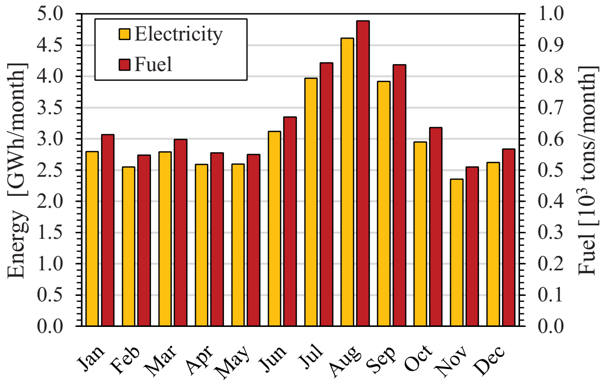


Fig. 7. Electricity production and fuel consumption in Lampedusa power station

As reported in the graph, the energy demand changes significantly during the year, reaching the maximum value in August (about 4613 MWh/month) and the minimum value in November (about 2355 MWh/month), with a ratio equal to 1.96. The fossil fuel is regularly transported by boat from Sicily, so prolonged adverse weather conditions represent an important risk for the energy supply of the island. For more, the renewable energy sources are extremely underdeveloped in this territory, as the environmental constraints which make complex the use of sources, like wind or photovoltaic panels (except the installation in an integrated solution with buildings) [28].

TABLE II. WATER DEMAND IN LAMPEDUSA IN THE PERIOD 2009-2011

Water consumption [m^3/month]				
Month	**year 2009**	**year 2010**	**year 2011**	**average**
January	24948	39366	22568	28960.7
February	30891	29615	31688	30731.3
March	27529	39198	33528	33418.3
April	44452	38183	35704	39446.3
May	47611	35349	36868	39942.7
June	55754	44841	45301	48632.0
July	60786	49361	45667	51938.0
August	62892	62875	44602	56789.7
September	45742	45151	41351	44081.3
October	37466	43054	29940	36820.0
November	32501	41401	24213	32705.0
December	35772	28048	26105	29975.0
Total	***506344***	***496442***	***417535***	***473440***

As introduced in the previous section, Lampedusa is regularly affected by water scarcity, so a desalination plant was installed in 1973. Recently, the MVC desalination units (see Table I) has been replaced with new RO units. So, the current configuration is composed by two RO units having a nominal flow of 450 m^3/day and a smaller unit of 50 m^3/day [29]. Sometimes freshwater is also transported by boat from Sicily [30]. Some statics about the freshwater demand are reported in Table II. Data are referred to the period 2009-2011. Average values are also reported.

The desalination plant uses electrical energy generated by the local power plant, consuming fossil fuel. The objective of the authors is evaluating the electrical energy demand in order to size properly a renewable energy mix based on solar, wind and sea wave.

So, as first step, considering a specific energy consumes for the fresh water production equal to 8.2 kWh/m^3, as shown in Fig. 5, the annual energy consumption for desalination is estimated equal to 3.88 GWh/year.

III. SEA WAVE ENERGY CONVERTER

In this section an innovative device for the exploitation of sea wave source is presented. According the classification reported in the introduction, this system can be classified as Point Absorber, thanks to the fact that is able to exploit the sea wave source, independently of wave direction.

This technology is currently in development step at the laboratory of Department of Energy, Information Engineering and Mathematical Model of Palermo University.

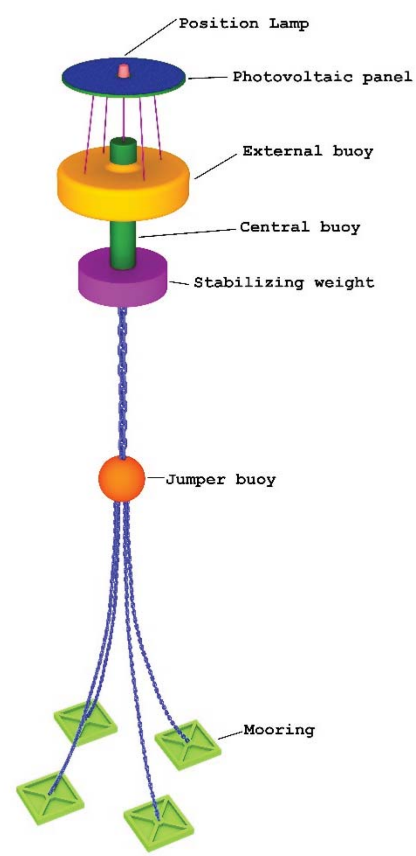


Fig. 8. External view of wave energy converter.

The system, depicted in Fig. 8, is essentially composed by two floating buoys, assembly in order to have the axial symmetry, necessary to exploit sea wave independently of wave direction. The external buoy is bounded to the central buoy through a bar, allowing the generation of a vertical motion according the sea level [31].

The central buoy is fixed to seabed through moorings, maintaining the position of the entire system. Furthermore, in order to reduce the vertical oscillation, the central buoy is equipped with a cylindrical ballast, increasing the inertia of the system and the hydrodynamic resistance. In this way, it is possible generate a differential vertical motion between the central and the external buoys. This motion is converted into electricity by eight linear generators installed inside the central buoy [32]. The system in the picture has an external diameter of 10 meters, with a rated power of 80 kW. Optionally, the WEC can be equipped with photovoltaic panels in the upper part of the central buoy (about 71 m^2), increasing the electrical output and regularizing the electrical production during the year.

IV. Simulations

The sizing process of the Renewable Energy Mix (REM) is realized to satisfy the electrical energy demand for desalination.

In order to simplify the balancing problem between generation from REM and energy demand from desalination plants, the authors consider the following criteria:

- ***Annual energy balance.*** REM is sized to balance the annual energy production from REM and the electricity demand for desalination;
- ***Monthly energy balance.*** During winter the energy production exceeds the electricity demand for desalination. The energy surplus can be used to reduce the production of local power plant, satisfy a part of local energy demand of final users. During summer, the REM isn't enough to cover completely the energy demand for desalination, so the deficit will be satisfied by the local power plant.

The first step is to define the electrical energy demand for desalination during the year. The second step represents the sizing of REM, considering the available renewable energy sources.

The annual electrical consumption for desalination E_d can be evaluated through Eq. 1, considering the monthly average water consumption Q_i in Lampedusa (see Table II) and the specific energy consumption ξ fixed to 8.2 kWh/m^3 (see Fig. 5).

$$E_d = \sum_{i=1}^{12} Q_i \xi \tag{1}$$

The evaluation of the electrical production from renewable energy system is performed introducing the following equations.

$$E_{sw} = \sum_{i=1}^{12} \varphi_{m,i} D_b n_c \eta_{sw} \tau_i \tag{2}$$

The equation analyses the electrical production from sea wave E_{sw}, considering the following terms: $\varphi_{m,i}$ is the average wave energy flux, D_b is the external diameter of the wave energy converter, n_c is the number of wave energy converter installed, η_{sw} is the electrical efficiency of the device, τ_i is the interval considered.

As regard the electrical production from solar E_{pv}, Eq. 3 introduces a similar approach [33][34]:

$$E_{pv} = \sum_{i=1}^{12} H_{m,i} S_{pv} \eta_{pv} \tag{3}$$

Where $H_{m,i}$ is the monthly solar radiation, S_{pv} is the total surface covered by photovoltaic panels, η_{pv} is the average electrical efficiency of photovoltaic panels.

Sea wave and solar sources are graphically reported in the following Fig. 9, considering respectively the monthly average sea wave flux [35] and the monthly solar radiation [36].

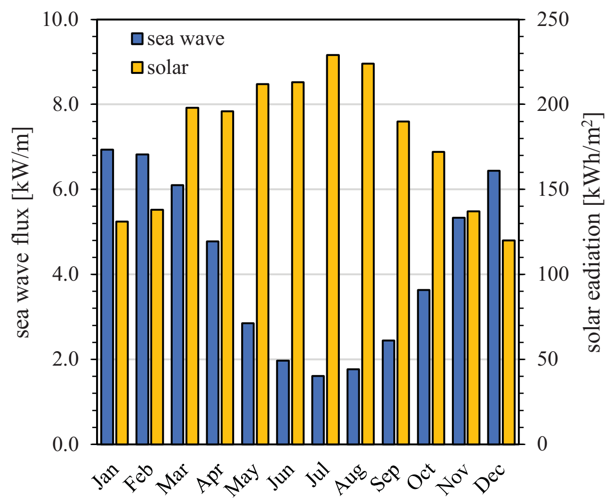


Fig. 9. Sea wave and solar sources in Lampedusa

Finally, the evaluation of annual electrical production from wind power E_w, it is estimated through the Eq. 4:

$$E_w = \sum_{i=1}^{n} f_i \int_{v_{cut-in}}^{v_{cut-off}} \frac{K_i}{\lambda_i} \left(\frac{v}{\lambda_i}\right)^{K_i - 1} e^{-\frac{v}{K_i}} c_p(v) dv \tag{4}$$

Where f_i is the annual occurrence that wind flows from a specific direction, K_i and λ_i are the two parameters used in the Weibull distribution, modelling the wind source for each direction, v is the wind speed and, finally, $c_p(v)$ is the power coefficient of wind turbine, function of wind speed and usually graphically available in the datasheet of wind turbines.

Wind source is graphically reported in Fig. 9, showing the interval (expressed in day) when a specific wind class is registered [37].

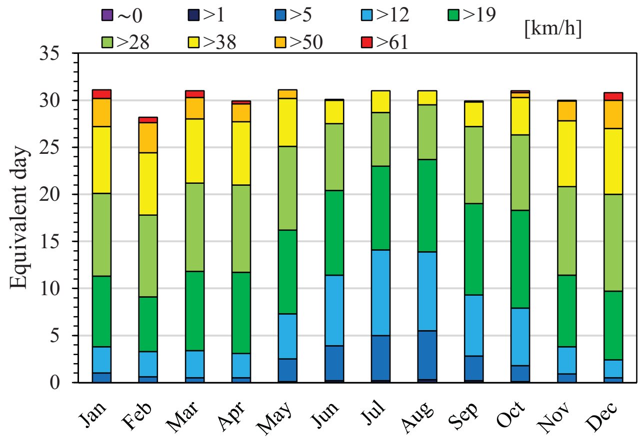
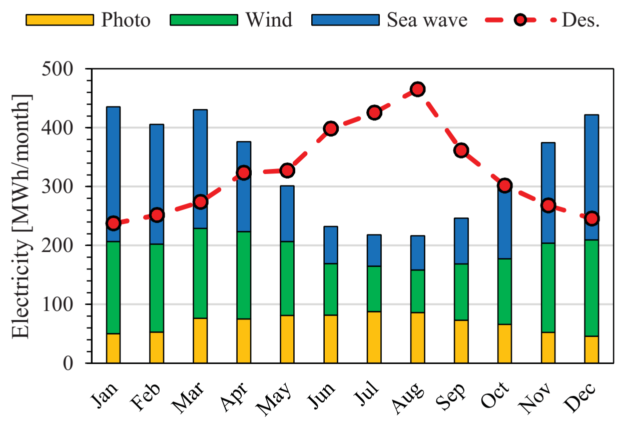


Fig. 10. Wind speed class in Lampedusa

According the mathematical approach previous reported, the authors evaluated the electricity demand for desalination and the annual energy production from the renewable energy mix. Results are reported in Fig. 11.



The sizes of renewable energy mix are reported in Table III. For the exploitation of wind source, the authors consider the installation of five wind turbines, having a rated power of 100 kW. As regard the solar source, the photovoltaic surface takes into account the available area on the roof of desalination power plant and the installable surface on the wave energy converters (as shown in Fig. 8). Finally, the wave energy source can be exploited by 12 point-absorbers, each one having a rated power of 80 kW. Buoys can be assembled in a wave energy farm, in order to simplify the electrical connection to the local grid.

TABLE III. DATA OF RENEWABLE ENERGY MIX

Source	Size	Installed power [kW]	Annual electricity production [MWh/y]
Solar	2742.8 m^2	384	829.4
Wind	5 turbines	500	1490.5
Sea wave	12 buoys	960	1636.8

As introduced before, during winter the electricity production exceeds the energy demand for desalination. The energy surplus could be used to satisfy a part of the local energy demand. Conversely, in summer the renewable energy mix doesn't cover completely the energy demand for desalination. The energy deficit could be covered by local power plant, considering that in the current condition the desalination plant is totally supplied by the local power plant.

Considering the average fuel consumption of local power plant (about 214.4 kg/MWh), the renewable energy mix avoid the consumption of 848.4 tons of diesel, corresponding to the avoided emission of 2682 tons of CO_2.

A solution to reduce the energy surplus and deficit during the year is represented by freshwater storage, in order to accumulate freshwater during winter and using it during summer. Authors evaluated that a total freshwater reserve of 95000 m^3 is enough. Currently five reserves are installed, with a total volume of 20000 m^3 [38]. So, an increase of water reserves is required.

V. Conclusions

A renewable energy mix has been proposed to supply the desalination plant in Lampedusa.

Desalination is a strategic technology to respond to the chronic water scarcity. Renewable energy sources are a real solution to supply this technology in a sustainable way. The case study applied in Lampedusa shows an interesting opportunity to improve the energy efficiency of the process. From an environmental point of view, the renewable energy mix proposed by authors is able to avoid the fuel consumption of 848.4 tons per year of diesel and the corresponding emission of 2682 tons per year of CO_2.

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