INTERNATIONAL JOURNAL OF HEAT AND TECHNOLOGY

ISSN: 0392-8764
Vol. 34, Special Issue 2, October 2016, pp. S379-S386
DOI: https://doi.org/10.18280/ijht.34S227

A publication of IIETA

IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

http://www.iieta.org/Journals/IJHT

Nexus Water & Energy: A Case Study of Wave Energy Converters (WECs) to Desalination Applications in Sicily

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ABSTRACT

The recent studies about interactions among energy and water are considered as a new field of research. As almost all energy generation processes require significant amounts of water, and water requires energy for treatment and transport, so these two resources are inextricably linked.
The main aim of this work is a presentation of the use of renewable energy for desalination plants in Sicily: in particular exploitation of wave energy into electrical energy necessary for water treatment.
Desalination is the most energy intensive water treatment technology but it could be solution for many problems in water supply for areas with chronic debt of water.
In this study we find three section: in the Section I we propose the state of art of renewable energy system for water desalination applications, in Section II we present an experimental evaluation of wave energy power in Mediterranean and the description of WEC prototype realized by Department of Energy of University of Palermo. In the final Section III we describe a case study of sustainable integrated system WEC and desalination plant.

Keywords: Desalination, Water, Renewable energy, Wave Energy.

1. INTRODUCTION

The studies about interactions among energy and water are considered as a new and recent field of research.

The procedure applied in the present article are the result of previous application made in different technical fields that show a good replicability [1]–[4].

In general, electrical energy processes require one huge amounts of water, anyway water needs energy for treatment and transport, so these sources are inextricably joined. This relation is called “energy-water nexus”.

It emerged from an understanding that natural resources are beginning to limit, to a substantial degree, economic growth and human well-being goals. As population and economies grow many regions of the world experience water and energy security challenges that must be addressed now.

In the next 20 years, towns in developing countries will increase their population as the demand of 70 million more people each year. Recently FAO’s studies describe that by 2050, nine billion people will want a 60 percent increase of water in agricultural production and a 6 percent increase in already-strained water withdrawals [5]

In addition to this, over 1.3 billion people worldwide still lack access to electricity; most of them live in sub-Saharan region or East-Asia [6]. About 2.8 billion people live in areas of high water scarcity and 1.2 billion live in areas of water deficiency [7].

Other interesting aspect regard primary energy production and electricity production in Asia where new analysis describe an incredible increase. For example, Latin American countries, increased production will come from non-conventional sources and the amount of electrical energy produced will be fivefold so the direct consequences will be the increase of fresh water [7].

Water is an essential element for energy. Energy depends on water – for power generation, the extraction, transport and processing of fossil fuels, and the irrigation of biofuels feedstock crops – and is vulnerable to physical constraints on its availability and regulations that might limit access to it.

Water is necessary to produce all forms of energy. For primary fuels, water is used in resource extraction, irrigation of biofuels feedstock crops, fuel refining and processing, and transport. In power generation, water provides cooling and other process-related needs at thermal power plants; hydropower facilities harness its movement for electricity production.

These uses can, in some cases, entail significant volumes of water. Additionally, they can have adverse effects on water quality via contamination by fluids that contain pollutants or physical alteration of the natural environment.

The global demand for water is assumed to grow for all major water use sectors, with the largest proportion of this growth occurring in countries with developing or emerging economies as India or China.

Another interesting aspect is energy requirement for supplying and treating water. In particular, it is necessary for the water provision: pumping and treatment. In literature, desalination is defined as the most energy all-out water process.

Desalination is a process purifies saline water so in general means to remove salt [8] from seawater or generally saline water.

Their disadvantage is their high salinity of ocean. The energy cost of treating low salinity seawater is about ten times greater than a typical freshwater source. Desalination is therefore an appropriate option only when there are no other sources or the cost of energy for transporting water is very high.

However, the desalination industry is working on reducing energy costs. The International Desalination Association has a goal of achieving a 20% energy reduction by 2015, and some companies have started to experiment with using renewable energy for desalination. Anyway, recent economic and technical problems could effect a delay to reach the aim.

So desalination represents one the most case of water and energy interconnections and in particular, the principal aim of this work is its application using renewable energy.

As above mentioned, desalination is the most energy intensive water treatment technology but it could be solution for many problems in water supply for areas with chronic debt of water.

The case study for our work is Sicily, in fact in the end of the 20th century, the island had the problem of aridity, so to respond of water demand, there were the planning of various desalination plants for different uses as civil, agricultural and industrial uses.

As for Sicilian climate, northern part has often been helped by the presence of mountain chains which have significantly contributed to the water needs, in the southern part of Sicily the availability of water sources has been continuously worsening [9] due to a decrease in rainfall.

In Sicily, the biggest desalination plants were installed in Gela and Porto Empedocle from 1974 onwards. Today six other plants are operating in Sicily: one in Trapani and the others on the five islands of Lampedusa, Linosa, Pantelleria, Ustica and Lipari. So the principal innovation of this work is using wave potential in Mediterranean sea (near islands as Pantelleria or Ustica) to nurture desalination plants [10].

The paper will be divided into three section: the first will be a presentation of state of the art of seawater desalination using renewable energy source, in the second we will describe a possible integration of wave energy to desalinate (a presentation of prototype realized by DEIM) and in the final section a real application near Pantelleria.

2. DESALINATION DRIVEN BY RENEWABLE ENERGY

The Desalination represents an important choice of water supply for areas with chronic debt of water.

In general, we could identify different technologies adopted as multistage flash distillation (MSF), multieffect distillation (MED) and vapour compression (VC), reverse osmosis (RE) and electrodialysis (ED). MSF and MED systems work decreasing temperature and pressure (cycle made up by various steps) MSF plant operates through the development of vapour from seawater or brine due to a sudden pressure reduction when seawater enters to an evacuated chamber. [11]. Another process used is reverse osmosis that requires electricity or shaft power to drive the pump that increase the pressure of the saline solution to that required.

The main system adopted s are MSF and RO, in particular the values are 44% and 42% of worldwide capacity. The MSF process signifies more than 93% of the thermal process production, while RO plants are more than 88% of membrane processes production [11].

Recent studies analyze an innovative combination among renewable energy source and desalination in fact it exhibits an interesting chance, or even the only way to offer a secure source of fresh water in arid regions that have high renewable energy resources.

Renewable energies for use in desalination processes include wind, solar thermal, photovoltaic and wave energy.

We could distinguish into two classifications: the first category consists of distillation processes driven by heat coming the renewable energy plans, while the second includes reverse osmosis or multistage flash distillation that need electricity or mechanical energy produced by Renewable energy system. The Fig. 1 describes this classification in detail

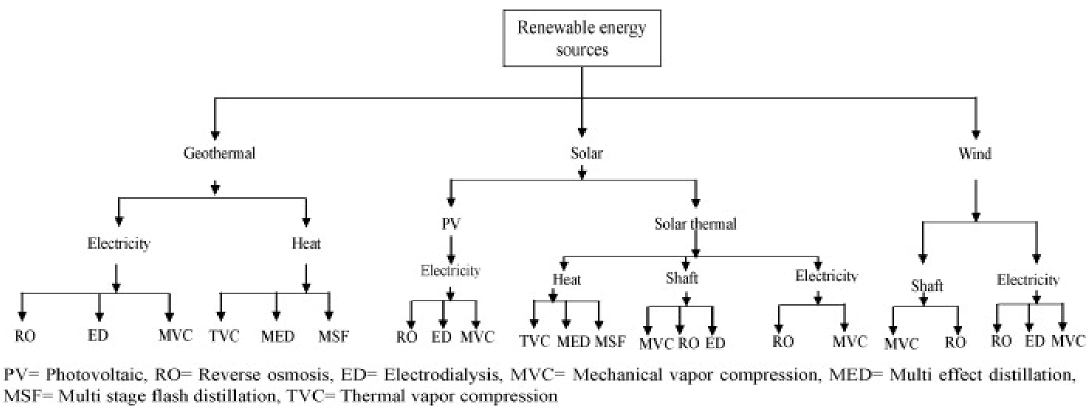

Figure 1. Combinations technologies of RES and desalination methods [12]

In this section we present a short state of art of this possible integration.

As for solar thermal energy is one of the most promising applications of renewable energy for seawater desalination. A solar distillation system can include two separated devices:

the solar collector and the conventional distiller that is called "indirect solar desalination" [11], in fact, these processes normally are composed by a commercial desalination plant combined to high consumption or particular solar thermal collectors.

We find a great number of pilot plant located in world:

•Gran Canaria, Spain where a 10 m^3/day-MSF plant driven by low concentration solar collectors;

•Al Azhar University in Gaza: a small experimental pilot plant, an MSF of 4-stages driven by solar thermal collectors and PVcells to drive the auxiliary equipment.

One possibility is the connection among photovoltaic technology and reverse osmosis system. The high cost is addressed to PV cells. However, the principal aim is reducing initial investment, because the PV energy is competitive with fossil fuels when it's possible optimize parameters as the plant capacity or the distance to the electricity grid.

One more possibility of adopting PV is a connection with electrodialysis. The ED process has more advantages than RO, for example is more convenient for brackish water desalination in remote areas.

A few of pilot plants of ED processes combined to PV by means of batteries have been implemented.

In this case we find different examples as Cituis West, Jawa, Indonesiaa (Brackish water 1.5 m^3/h supported by 25 kWp), Concepción del Oro, Mexicob (Brackish water 1.5 m^3/day and 2.5 kWp), North west of Sicily, Lampedusa Island, Italy (sea water 3+ 2 m^3/h and 100 kWp).

As regards wind power, usually it's been integrated to RO process. In consideration of this technology is the system that needs the more moderate energy demand and coastal areas have a high availability of wind power resources, a lot of researchers have defined wind-powered desalination is one of the most promising alternatives for sustainable energy desalination.

A further study is the direct union of a wind energy system and a RO unit by means of shaft power. Experimentation in this area has been made up at the Canary Islands Technological Institute. Other works studied the use of wind power directly with an MVC and ED [13].

As regards geothermal energy, it can be utilized as a power input for desalination. Energy from the earth is normally extracted with ground heat exchangers. These are made of a material that is extraordinarily durable but allows heat to pass through it efficiently. Low-temperature geothermal waters in the upper 100 m may be a reasonable energy source for desalination In general, the price of geothermal desalination is as low as the price of large multi-effect dual-purpose plants. One more opportunity that could be studied is the use of high-pressure geothermal power directly as shaft power on desalination. Moreover, there are commercial membranes that withstand temperatures up to 60°C, which permits the direct use of geothermal brines for desalination [13].

In conclusion, we find a new recent possible integration among wave energy and desalination.

The oceanic energy is expressed as the waves, the tides and the thermal gradient of the sea. Their nominal power are 0.5, 240 and 40 MWe, respectively. Nowadays, there are very few facilities of wave and tide energy conversion to electricity.

Not only RO, but also distillation processes were connected to wave-power systems.

The advantages of such a system would be the availability of a more regular energy source than wind power.

One most famous example is desalination pilot plant (DPP) installed on Garden Island, Western Australia.

The Desalination Pilot Plant (DPP) has been developed to complement the Perth Project by leveraging the CETO wave energy hydraulic system infrastructure being installed at the site.

CETO units will supply hydraulic energy to a standard Seawater Reverse Osmosis (SWRO) desalination facility via mechanical coupling to the Perth project's hydraulic system, with a permeate, or potable water, production capacity of up to 150 m3/day. Fig. 2 describes a short description of whole scheme.

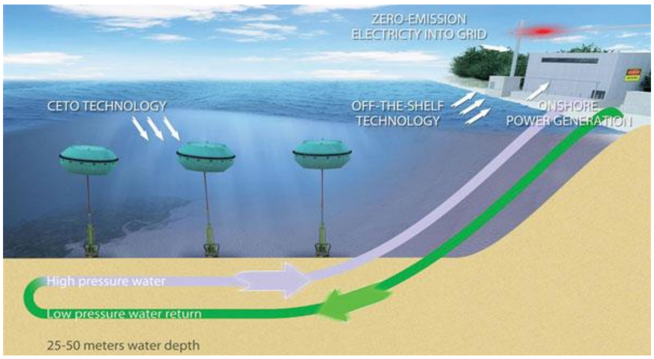

Figure 2. CETO technology and DPP [14]

3. SEA WAVE ENERGY POTENTIAL AND DESALINATION PLANT IN SICILY

T Recent studies defined exploitation from sea wave as one of the most talent among the renewable energy. It is approximated that in the imminent period it will have one huge increase because these electrical devices used become more complete. In general, these generators are called Wave Energy Converters (WECs).

Wave energy devices need large investment of money throughout the process of producing a valid device: overcoming successive steps that can lead them to validate their concepts, build and test prototypes and optimize parameters with the final outcome of a successful product that can be deployed in arrays and sold.

The current panorama with many concepts being patented in every country can be confusing; some technologies have the potential of being successful, whereas many others will not pass the concept phase. An interesting research on wave energy conversion is excellent in countries near oceans, where the wave energy potential is a big resource. In Europe, most of the pilot plants are located along the Atlantic coast in countries such as Ireland, Portugal, Spain, Norway and the UK [17].

Energy accessibility is one of the most important aspect to determine a wave energy production, but high energy potential usually includes uncommon wave during extreme events. In flat opposition, other characteristics or physical aspects regard semi closed sea as Mediterranean where is possible a minor availability, but interesting researches are addressed to optimize wave energy extraction. For example, some studies demonstrated a wave energy production along Italian coasts. As mentioned before, sea wave information, about fundamental features as its temporal and spatial variability and of its distribution or different sea states, is necessary to WECs' realization

Therefore, thanks to the large amount of information taken from these wave buoys, wave atlases along the Italian coastline were realized, in which the values of wave power and the average wave energy offshore are exposed. These reference books of the Italian coasts are elaborated with local wave parameters measured by buoys sat in Mediterranean [18] [19]. Wave buoys represent the best and direct measure of wave parameters.

On the other hand, there are some drawbacks. In fact, time series obtained from buoys definite local wave climate and sometimes present large data gaps caused by momentary collapse of the buoy or by habitual keeping operations. Wave energy resource is strongly connected to the bathymetry: a greater water depth increases wave potential due to the lower friction losses. On the other side, a less water depth decreases wave potential. According to this, all wave buoys are located offshore, several kilometers from the coastline. Moreover, fetch represents an important characteristic too. It is the distance where the wind blows: a large fetch should be preferred, because it defines a more intense and regular wave climate. Focusing on the Sicilian coastline, all these studies have allowed the creation of this wave power map [20], in which the red flags represents the measuring buoys.

The minimum wave power potential is identified along the coasts of Catania, in which values vary from 2.1 kW/m to 3 kW/m. Along Palermo's coasts the values are higher, included between 3.1 kW/m and 4 kW/m, while the higher ones are referred to Mazara del Vallo, where average wave power is bigger than 5.1 kW/m.

The use of third generation wave model allowed the creation of further wave power maps, which are characterized by a higher resolution. Therefore, the presence of these maps represents an important breakthrough not only in the description of wave power along the Sicilian coastline, but also in the assessment of the production of electrical energy from sea wave through the use of WECs. Moreover, the implementation of the GIS technology (Geographic Information System) will increase the feasibility of the installation of Wave farm. This instrument is able to include different data in a specific geographic map, such as the placement of protected areas with the distribution of wave power. In this way, we are able to know exactly the usable areas for exploitation of wave energy and the ones where this exploitation should be avoided.

3.1 Methodology and Sicilian wave power evaluation

P In this work a study of the wave energy potential along the Sicilian coast was performed using data acquired by sea wave buoy such as DEIM Buoy [21] and a third generation ocean wave model. Particularly, the potential wave map was obtained thanks to the large amount of data that came from the wave buoys of the Rete Ondametrica Nazionale (RON). In 1989, it was originally composed by 8 pitch-roll buoys, but in 2007 the total number of wave buoys was of 15. These buoys are able to record different parameters, such as Significant wave height Hs [m], Peak period T_p [s], Average period T_m [s], and Average wave direction Φ_m. At first, recording period was about 3 hours, then (with the replacement of all the wave buoys with more technological ones) was about every 30 minutes. In this way, RON was able to describe wave climate with a higher time resolution (but the spatial resolution remained still low). In deep waters, Wave power P can be obtained through H_s and T_e data [22]:

$$P = \frac{\rho g^2}{64\pi} H_S^2 T_e \tag{1}$$

in which ρ is seawater density (equals to 1025 kg/m^3) and Te represents the Energetic period [s], equals to the Peak period multiplied by a constant, which depends on the exact collocation of the buoy. Finally, average wave energy can be obtained summarizing every sea state wave energy (fig. 3).

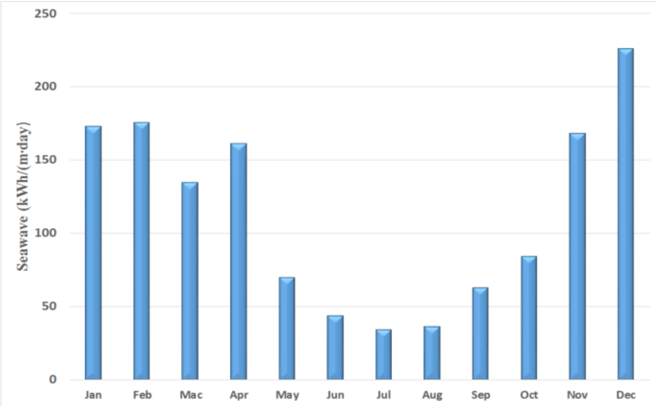

Figure 3. Evaluation of sea wave energy in Sicily for year 2013

3.2 Wave Energy Converter by DEIM

F In this paragraph we expose the electricity production scenario from marine waves along the Sicilian coastline, due to the use of an innovative conversion device nowadays in the design phase by DEIM department of *University of Palermo* [23]. This is a new device called Point Absorber (shown in Fig. 4) in which will be able to transform wave energy in electrical energy directly, without the use of intermediate devices or polluting fluids. Every Point Absorber presents a nominal power of 80 kW, consisting of 8 linear generators of 10 kW each one, and had an external diameter of 5 meters. The working stroke of the translators is about 4 meters: so, the WEC will be able to exploit the most energetic sea state too. Moreover, thanks to the high performance of the linear generators, the overall efficiency of this WEC will be about 50 %.

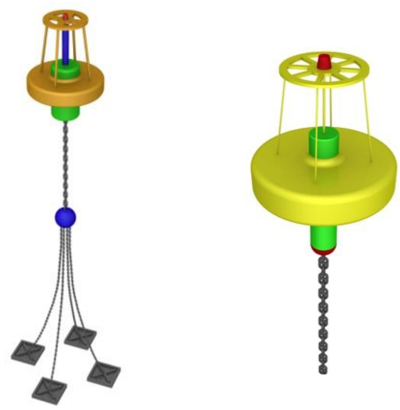

Figure 4. Model design of wave energy converters

The Permanent Magnet Generator (PMG) is a bilateral generator with two stators. The main material is "laminated" iron that is it's made up by overlapping of a lot of sheets (126 as exact number), with a thickness of 0.5 mm. This choice is justified to cut down the eddy current and other losses.. As for its design, the first and last three slots have a width of 8 mm while internal slots have a width of 12 mm because they must contain two winding, 13.5 mm teeth are built, except the first and last tooth that measure 7 mm. We use two tables made up by bakelite, used for coming together the stator block.. There are 32 holes to 10 mm. The Fig. 5 does an internal view of this new device.

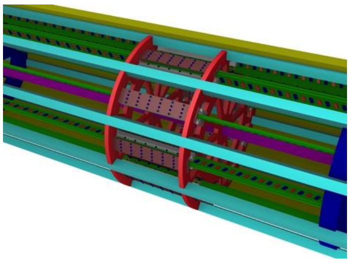

Figure 5. Internal view of DEIM Point Absorber

As for the translator is realized by an alternating assembly of 40 permanent magnets that interspersed with soft iron pole pieces mounted on a bakelites sheet. The material used is Neodymium– Iron–Boron (Nd–Fe–B), the arrangement is in pairs such that opposing magnetomotive forces (mmfs) drive the flux through the soft iron. In the end, the coil material used is copper and in particular is copper wire of diameter 0.5 mm. The coils have 375 turns of rectangular shape with an average size of 85x135 mm. Each coil has a weight of 278 g. We identify 72 coils that are arranged in 36 in each side of the armature (coils A and coils B). Tab.1 describes all technical data.

Table 1. PMG Technical sizes

Permanent Magnet Generator		
Number of Coils	72	-
Number of Turns for each coil	375	-
Length	972	mm
Number of Slot	39	-
Slot Depth	8	
Linear Weight	74.5	Kg
Length	1600	mm
PM Weight	0.203	Kg
Linear Weight	13.1	Kg

3.3 Water resource and desalination plant in Sicily

In the end of the 20th century Sicily had high problem of dryness. Sicilian government/ answer was the construction of a number of desalination plants to satisfy water needs for municipal, rural and industrial demand. While the northern part of Sicily has always been helped by the presence of mountain chains which have significantly contributed to the water needs, in the southern part of Sicily the availability of water sources has been continuously worsening due to a decrease in rainfall [10].

Desalination could be a solution for some of these areas. One summary of the desalination system was carried by different authors [24]. Table 1 and figure 6 describe geographical sites, main technical data and performances of all the desalination plants in Sicily [10].

Figure 6. Geographical distribution of desalination plants [24]

Table 2. Desalination plant :typologies, capacities and energy consumption. Multistage flash distillation (MSF), multieffect distillation (MED) and thermal vapour compression (TVC), reverse osmosis (RE) and electrodialysis (ED) [24]

Plant	Technology	Capacity (actual)	Electricity Consumption
		[m³/y]	[kWh/m³]
Gela	MSF	4.356.000	1-1,2
	MSF	4.356.000	1-1,2
	MSF	4.356.000	1-1,2
	MSF	4.356.000	1-1,2
	MSF	4.356.000	1-1,2
	RO	4.752.000	8-9
Trapani	TVC-MED	2.871.000	2,9
	TVC-MED	2.871.000	2,9
	TVC-MED	2.871.000	2,9
	TVC-MED	2.871.000	2,9
Porto Empedocle	MVC	496.000	11-12
	MVC	496.000	11-12
	MVC	496.000	11-12
Lampedusa	MVC	135.000	-
	MVC	135.000	-
	MVC	15.000	-
Linosa	MVC	77.500	-
	MVC	77.500	-
Pantelleria "Maggiuluvedi"	EDR	135.000	-
	EDR	135.000	-
	RO	60.000	-
Pantelleria "Sataria"	MVC	496.000	-
	MVC	496.000	-
Lipari	MVC	496.000	-
	MVC	496.000	-
	MVC	496.000	-
Ustica	MVC	155.000	-
	MVC	155.000	-
Total		44.267.840	

The table 2 shows a state of the art of desalination plant in Sicily. It is important underline how these plants (MSF, RO, MED, MVC) are now working in the island producing fresh water for a population living in the south and western coast of Sicily. The plants, owned by the Regional Government, were built in different years to face the problem of water supply which has affected the population since the early 1970s [24].

4. CASE STUDY IN PANTELLERIA: AN APPLICATION OF WAVE ENERGY TO DESALINATION PLANT PILOT

Pantelleria has a population of about 7,700 inhabitants in the winter season but as many as 14,000 in summer, pushing electricity consumption to 5,500 kWh/year.

This is generated burning more than 10 million litres of diesel each year at a cost of over 1 euro a litre. With a hybrid system and thanks to the solar installation, fuel consumption is expected to fall by more than 7 million litres a year: that translates into 10.5 million euros a year of cost savings and 20,725 metric tons of CO2 emission reductions

In recent years, this value is increased because the electrical energy produced is used by desalination plant of the island.

The island's drinking water network is supplied by the flow rate produced by two desalination plants "Sataria" and "Maggiuluveddi". In the table 1 we can find some technical specification and data.

These systems have been entrusted by Sicilian government to an operational manager. Sataria plant cleans directly seawater while the second (Maggiuluveddi) purifies brackish water from Valenza well.

Several small-scale solar – powered membrane distillation (MD) demonstration pilot system has been installed in Pantelleria (Fig. 7 Mediras project). This system has a targeted production capacity of 5 [m3/ day] powered simultaneously by solar energy and waste heat from the local diesel power plant. In particular, about 30% of the heat source was provided from the solar panel collectors and 70% from waste heat from a diesel engine [25].

Figure 7. MEDIRAS project MD pilot plant installed in Pantelleria [26]

Another interesting project is the recent installation of four RO (reverse osmosis) produced by PROTECNO srl. The system purifies a total flow of 462.5 m3/h with a total of 11,100 m3/d of water. The water to desalinate is taken directly from the sea, to be subjected to three successive stages: the pre-treatment in ultrafiltration, desalting in reverse osmosis and finally the re-mineralization.

Although these systems provide high energy savings, it could be a sustainable choice meeting the electricity needs with renewable energy sources as wave energy. Due to its strategic position in the Mediterranean Sea, the Pantelleria Island is a suitable site to produce electrical energy from the wave source.

In literature we find studies about interesting wave energy potential for Pantelleria's coastline. To give an example, ENEA investigated along the island and developed a new simulation software to estimate wave parameters (height or period). In fact, the medium annual extractable power is about 7 kW/m. This is a great value, permitting the intallation of a wave farm in the Mediterranean Sea. In addition, the theoretical annual extractable energy is about 60 MWh/m, while the main direction of the wave front is North-West. Moreover, the significant wave height is less than 4 meters [27].

The "Politecnico di Torino" developed other researches to quantify the average power along Pantelleria's coastline, using a Nortek AWAC buoy, installed at 800 meters from North-West Pantelleria's island. The images below inserted are the results of Politecnico' study (Fig 8 and 9).

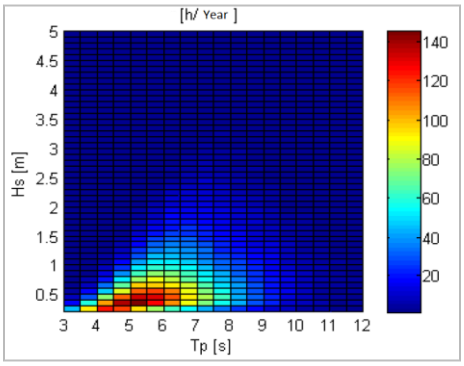

Figure 8. Hourly recurrence measured by Nortek AWAC of Politecnico of Torino[28]

This instrument is able to measure all main parameters that characterize the wave climate, such as Peak period Tp (in seconds), Significant wave Height Hs (in meters), and Main direction (Fig. 8).

The Fig. 9 shows the Scattering Table of extractable energy along North-West coasts of Pantelleria. The maximum annual energy is connected to significant wave height from 1 meter to 3 meter. The average annual wave power estimated by[26] is 7 kW/m.

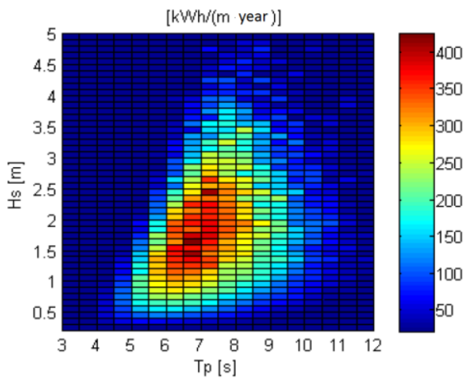

Figure 9. Scattering table of extractable energy along Pantelleria's coasts (Politecnico of Torino) [28]

In DEIM laboratory, several tests of small scale of te electrical devices are performed. the overall conversion efficiency can be fixed equal to 50%, so every Point Absorber [29],[30] is able to produce about 120 MWh/year of electrical energy. These electrical devices [31],[32] will be installed along a line, as represented in Fig. 10. Their direction is normal to the dominant direction of the wave front, so we able to minimize any interference phenomenon. The resulting working rate is about 1,500 h/years. So this value could satisfy electrical energy need of desalination plants that use different technology (MD or RO).

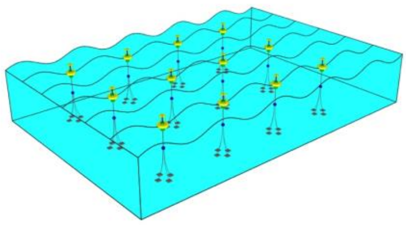

Figure 10. Possible layout and array of WECs farm

5. CONCLUSIONS

This work was born from research field Nexus Water and Energy, in fact desalination represents the best example of interconnection among these different resources. We present a possible integration among desalination plant adopted in Pantelleria (real system or small scale pilot) and wave energy. The island has an average annual wave power of 7 kW/m. If we use WECs above presented, it will convert 120 MWh/year of electrical energy. Due to their fragile environment and the need to protect their resources, islands are natural laboratories for climate change adaptation and integrated solutions concerning energy or water.

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