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Wind desalination for the Island of Mykonos in Greece: a case study

George Xenarios[a], Panagiotis Papadopoulos[b], Eftihia Tzen[b,*]

[a]*School of Electrical and Computer Engineering, Division of Industrial Electric Devices and Decision Systems, National Technical University of Athens, NTUA, Athens, Greece*
[b]*Centre for Renewable Energy Sources & Saving, CRES 19th km Marathonos Ave, GR-19009 Pikermi, Greece Tel. +30 210 6603361; Fax: +30 210 6603301; email: etzen@cres.gr*

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ABSTRACT

The Greek island of Mykonos belongs to a large group of islands in the Aegean Sea, which suffers from poor natural water resources. On the other hand, it is one of the windiest places in Europe. In the last decades, the exploitation of wind potential to produce potable water through desalination has been considered as a promising alternative for standalone or grid-connected units. In this paper, a methodology for the design of a wind desalination system that matches the needs of the local society are discussed. The existing, grid-connected, seawater reverse osmosis plant, producing 4,500 m^3/day, is considered as the basis for the analysis. A series of common commercial wind turbines were examined to suit the site characteristics and energy demands. The target is to cover the energy needs of the desalination unit exclusively from wind energy. The work was performed under the terms of a diploma thesis, and the ultimate scope is to illustrate the benefits of the use of renewable energy sources in desalination units in the Greek islands, where electricity is covered by environmentally unfriendly, noncost effective autonomous power stations and the provision of fresh water remains an unsolved problem.

Keywords: Reserve osmosis; Wind turbines; Seawater desalination

1. Introduction

The island of Mykonos has an area of 85.4 km^2 and is located in the middle of the Aegean Sea (Fig. 1), about 93 nautical miles away from the port of Piraeus. Concerning local climate, Mykonos suffers from limited available natural water resources, since the average annual rainfall is only 380 mm, which demonstrates the significance of the water scarcity problem [2]. On the other hand, very strong winds hit the island especially during summer. Due to its high wind potential, Mykonos is also known as the “island of winds.”

Today, Mykonos is a municipality with approximately ten thousands of inhabitants, most of whom live in the largest town, known as *Chora*. For many decades, despite its small size, it has emerged one of the most popular tourist destinations in Greece, since it tends to concentrate itself the 10% of the total foreign tourism in the country. The touristic development of the island started mainly at 1970s and continues till today with 90% of the economic activity

*Corresponding author.

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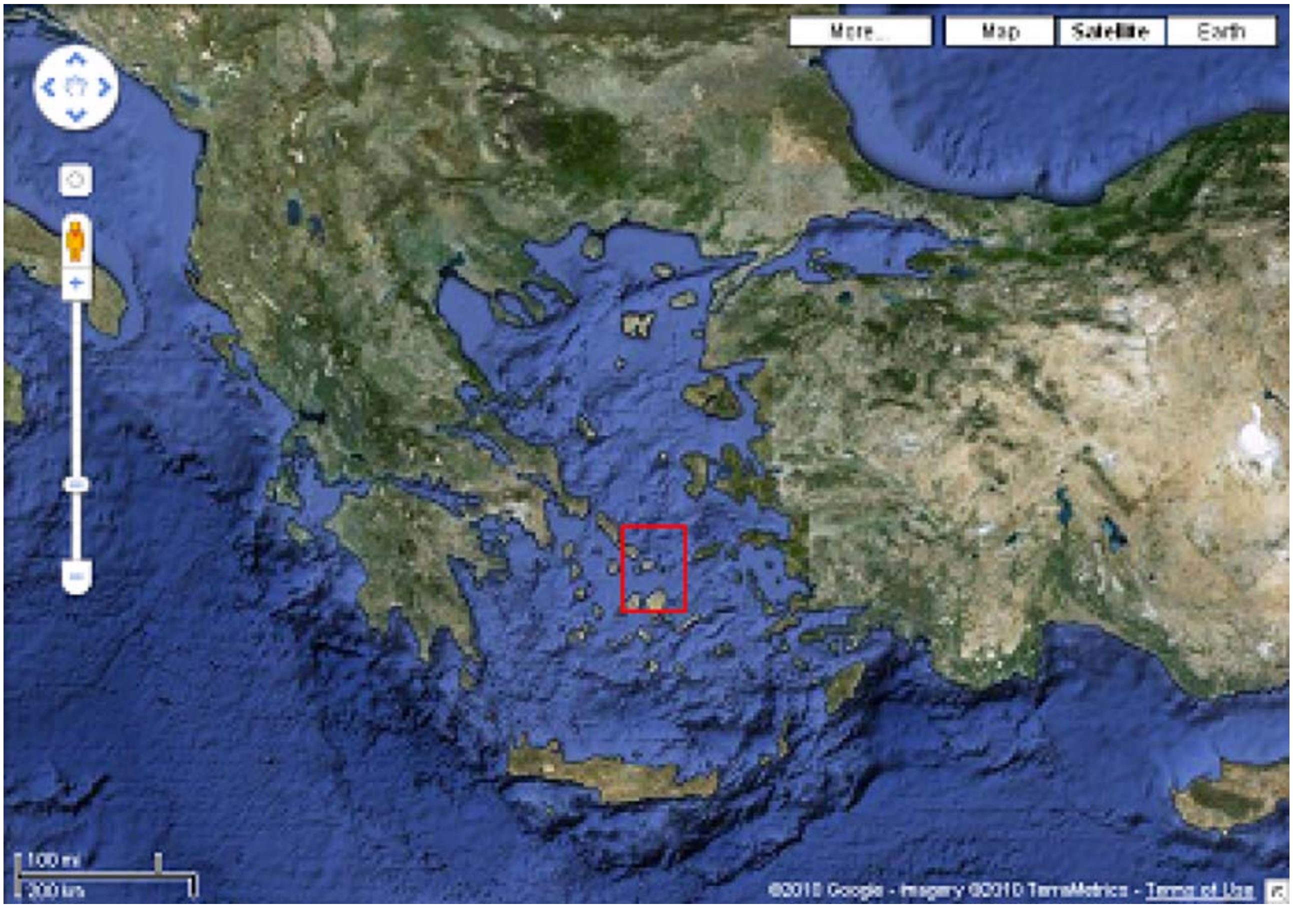

Fig. 1. View of Greece, [1].

in the region based directly or indirectly to tourism. Every year around 1.5 million tourists visit the island, mainly during spring and summer period.

Since late 1980s, the continued growth of tourism, the excessive residential development along with the extremely high cost of transporting water from the mainland, urged local authorities to take the decision to install one of the first desalination plants in Greece. In 1989, a seawater reverse osmosis (SWRO) plant of 1,200 m^3/day ($2 \times 600\,m^3$/day) installed and operated successfully for many years. Moreover, in 2001 and 2008, two seawater Reverse Osmosis (RO) plants of 1,800 m^3/day and 4,500 m^3/day were installed, respectively. The 4,500 m^3/day RO unit is the largest installed desalination unit for municipal use in Greek islands.

In recent years, the process of RO has become increasingly important compared with other desalination processes. Some of the reasons for this trend are the low specific energy consumption of this process and the considerable progress made in membrane technology. However, RO remains energy intensive technology, and the operation of RO units in the Greek islands constitutes essential load that burden significantly their local autonomous power supply systems.

The use of wind energy technology is a reliable alternative for electricity production to cover the needs of RO plants, especially in regions with plenty of wind. The state of the art shows that wind–RO plants provide a technically promising option in water-scarce regions with plenty of wind, either through autonomous or grid-connected systems.

The main scope of the present work is to outline the basic requirements and rules for the proper design of a wind desalination plant, address the technical barriers, and examine the economic and environmental benefits. As an example, a preliminary energy study has been performed considering the parallel operation of the large RO unit in Mykonos island, with wind turbine technology. To elaborate this study, data from the conventional 4,500 m^3/day ($3 \times 1{,}500$ m^3/day) SWRO unit [3] were considered as basis, and certain types of common commercial wind turbines are examined in the range between 800 kW and 2 MW. Several energy

Fig. 2. View of Mykonos where the areas of the dams, desalination plants, and tanks are marked [1].

calculations were accomplished, taking into account different scenarios for the operation of the desalination plant. For the estimation of the electricity production from wind turbines, one-year time series wind data of Mykonos have been used, measured through a 10 m-high meteorological mast. The most representative of the examined scenarios is selected to be presented in the following.

2. Description of water and energy conditions

2.1. Water conditions

In Mykonos, the last two decades, large projects concerning water production and water storage are realized to fulfill the continuously increase in water demand in the island. Two dams, with a total water storage capacity of approximately 4 million cubic meters, were built in Marathi and Ano Mera and supplied by their natural streams. The purpose of the projects was the utilization of surface runoff so as to meet needs of water supply and irrigation. Additionally, in 2001 and 2008, two SWRO plants of 1,800 and 4,500 m^3/day were installed, respectively.

The desalinated water is stored into tanks of 200 m^3 water capacity, and is transported, through tight tube, to the central tanks of Mykonos town, (Fig. 2). The water system of Mykonos town is powered exclusively by the central tanks. The tanks have a total storage capacity of 8,000 m^3 and their supply comes mainly from the desalination plants, the dam of Marathi and, in emergency cases, from tankers. The mixing of the water from the several water sources resulting in the supply of nonpotable water to the water network of Chora.

For the pricing of water, the Municipal Enterprise for Water and Sewage of Mykonos[1], (DEYAM), follows a nonuniform pricing policy, in which the price of water ranges with the amount of consumption (Table 1).

The above prices reveal the importance of water in the island; however, price is not always the optimum

[1]The main players of water supply and sewerage issues are the Athens Water Supply and Sewage Company (EYDAP SA) for the capital of Greece and the Municipal Enterprises for Water and Sewage (DEYAs) for the rest of the mainland and for the islands.

Table 1
Pricing of water consumption (€/m^3), [4]

Water Consumption (m^3)	Pricing (€/m^3)
0–30	0.73
31–50	1.06
51–100	1.39
101–150	1.63
151–200	2.12
≥201	2.44

The above prices are charged with a fixed charge of 0.97€/month, a special duty on consumption and VATs (VAT on consumption, VAT on fixed charge, and VAT on special duty) [4].

motivation for water management and water sustainability.

2.2. Mykonos Power System

Mykonos island belongs to the noninterconnected Aegean islands, although it is intended to be connected to the mainland power system within the present decade. Based on data from the Public Power Corporation (PPC), in 2011, the island's electricity needs covered by an autonomous power station (APS) of 65.27 MW installed power and the energy produced from these units was 5.52157 MWh [5]. A major drawback of such autonomous power systems is the high electricity production costs due to their dependence on the international gas prices.

Regarding the use of renewable energy sources (RES), two wind turbines are currently in operation with a total capacity of 1.2 MW. The installed capacity of photovoltaics is 20 kW$_p$ [5]. According to PPC, for 2011, the energy produced from the wind turbines was 361.89 MWh while from PVs was of 0.69 MWh, resulting in a total of 362.58 MWh, which corresponds to a contribution of 6.2% on the total electricity production of the island.

3. Technical description of the 4,500 m^3/day SWRO plant

The 4,500 m^3/day SWRO unit studied in this work consists of three individual subunits of 1,500 m^3/day product water capacity, each (Fig. 3). All the units use FilmTec spiral-wound membranes (SW30HRLE-400i), and operate at a recovery of 38.8%. The units have the same design, which is shown in Fig. 4. The salinity of the feedwater in Aegean is around 42,500 ppm TDS. Each unit consists of 15 pressure vessels with seven modules in each one, leading to a total number of mem-

Fig. 3. The 4,500 m^3/day SWRO of Mykonos island.

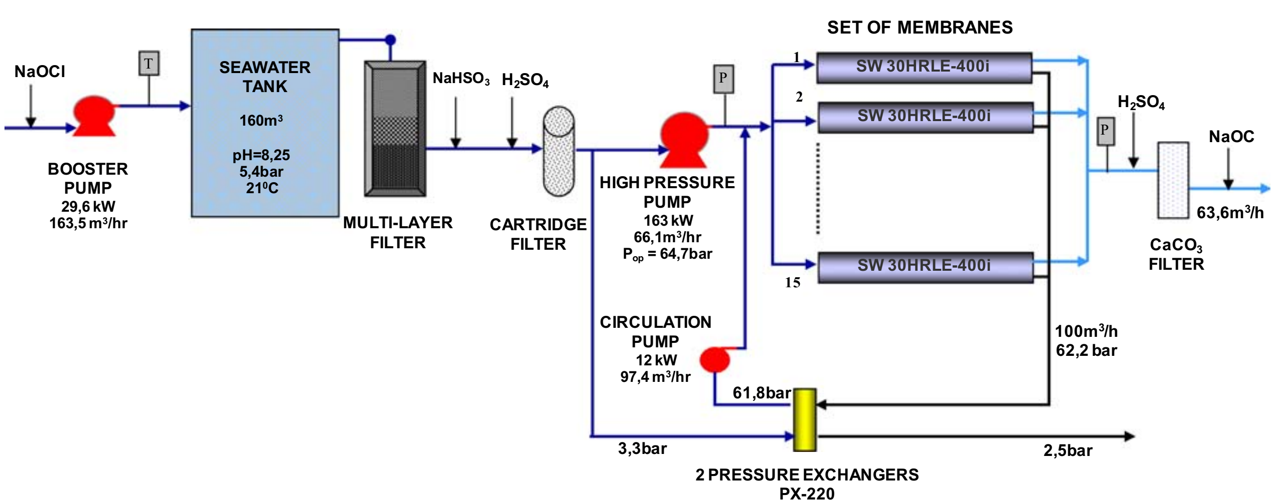

Fig. 4. Flow diagram of the SWRO unit, Mykonos island.

branes equal to 105. The feed flow rate is 163.6 m^3/h and the pressure of operation is around 64 bar [3].

The pretreatment system consists of filtration (multilayer filters and cartridge filters) and addition of chemicals (chlorination and dechlorination of the feedwater with the use of NaOCl, $NaHSO_3$, respectively, and addition of H_2SO_4 for pH correction. The post treatment procedure contains enrichment and sterilization of the produced water, as described in the flow diagram, in Fig. 4. Regarding the energy requirements, the main loads of each unit are the booster pump and the high-pressure pump.

The booster pump is centrifugal type made of stainless steel AISI 316L and has a nominal power of about 30 kW. The high-pressure pump has nominal power of 163 kW and feed flow rate at 163.6 m^3/h. The produced water capacity of each unit is 63.6 m^3/h, while the expected yearly water production is 532.500.0 m^3. The high-pressure pump includes a high efficient energy recovery device. The energy recovery device is a pressure exchanger of PX220 type ($2 \times$ PX220 at each RO unit). The efficiency of the energy recovery device is estimated at 94%. A total energy saving of 52% on the energy consumption have been considered. Table 2 presents the main loads and energy requirements of each RO unit.

According to the table above the total specific energy consumption of each RO unit is estimated at around 3.2 kWh/m^3.

4. Description of the wind study

4.1. Description of the examined system

For the needs of the study, a hypothetical wind desalination system is considered as shown in Fig. 5. For the WT, common commercial WT types are used ranging from 800 kW to 2 MW. The total installed capacity of the desalination unit of 4,500 m^3/day is equal to 613.8 kW.

The idea is to select a proper WT size to match the energy demands of the desalination unit, in order to form a RES-desalination system that "virtually" works without consuming power from the conventional engines of the APS. Both the WT and the desalination unit will be grid connected most probably at a different connection point of the grid. The desalination unit will consume energy from the grid but the total annual energy consumption will be compensated by the annual energy that the WT has supplied to the grid. As a basis for the rest of the study, the "worst-case" scenario of full operation of the desalination unit for one year is considered.

4.2. Wind data analysis

One-year wind data from a 10 m-high meteorological mast installed by CRES were used as reference wind series and shown in Fig. 6. The mast position does not necessarily match the WT installation position. However, for simplification reasons, it is considered that the wind characteristics of the island remain more or less the same and no significant error is introduced in the analysis. The data are 10-min average values measured by a dedicated data logger.

The analysis of the data, performed with *WindRose Software* [6], shows an excellent wind potential of almost 9 m/s annual average. The average wind speed per month and the annual wind rose are presented in Fig. 7, while the yearly data distribution are shown in Fig. 8. The available wind data were used for the selection of a proper WT type and for the estimation of the expected wind energy production.

Table 2
Main loads of each 1,500 m^3/day RO unit

Equipment	Nominal power kW	Flow rate (m^3/h)
Booster pump	29.6	163.5
High-pressure pump	163	66.1
Circulation pump[a]	12	97.4
Total installed power	204.6 kW	
Yearly hours of RO operation (h)		8,520
Aver. yearly water production (m^3)		532.500.0
Estimated annual energy consumption (kWh)		1.743.192
Total spec. energy consumption (kWh/m^3)		3.27
Price of electricity (€/kWh)		0.08
Total annually cost of electricity (€)		139.455.36

[a]A circulation pump is required to move water through the high-pressure loop. The circulation pump provides a pressure boost to compensate for friction losses in the membranes, the PX unit, and the associated piping.

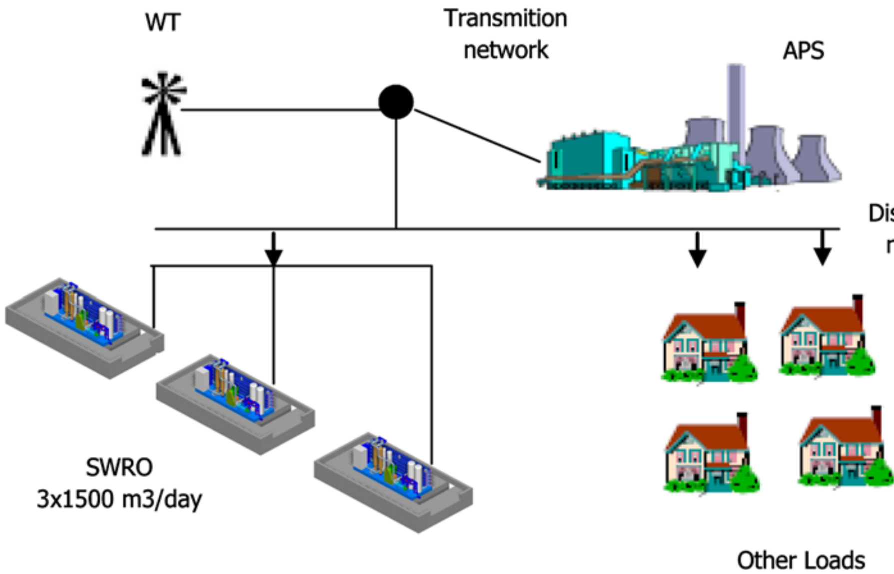

Fig. 5. Schematic diagram of the examined system.

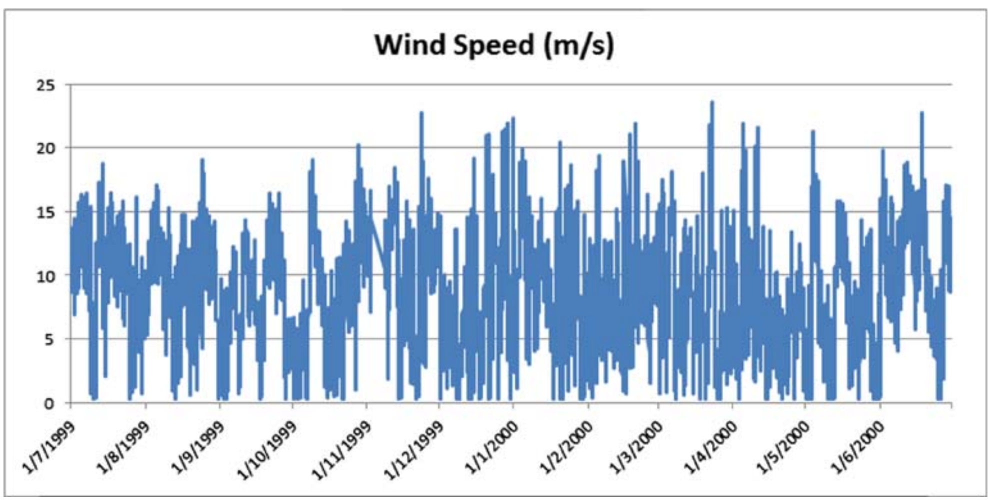

Fig. 6. One-year wind time series used in the analysis.

4.3. Description of the methodology

The size of the proposed wind desalination system depends on technical and financial parameters.

For the sizing of a desalination unit, the main parameters under consideration are the water needs of the local society, the energy as well as the budget availability.

For the selection of the most suitable WT that fits the needs of the desalination plant, certain criteria may be examined such as:

- *Site wind conditions*: Wind measurements of at least one year are required to estimate the available wind energy on an annual basis as well as the wind turbulence intensity. Based on these measurements, the proper WT class and size will be decided.
- *Site characteristics*: Topographical conditions, roughness length, land availability, existing roads, ground slopes, natural, or other obstacles.
- *WT power control*: The connection of the WT in an APS requires that the selected WT has inherent power control capability in order to adjust its power output depending on the restrictions imposed by the APS.
- *Energy balance*: The energy production of the selected WT should fulfill the energy demands of the desalination plant.

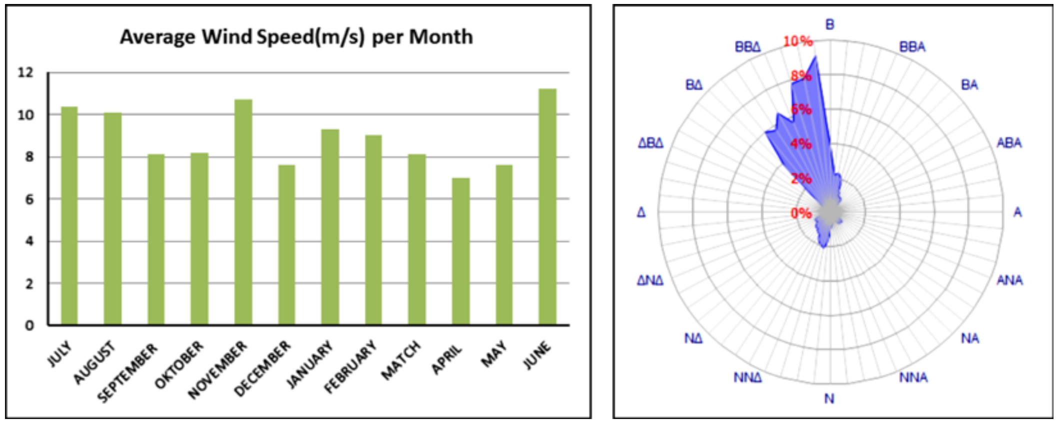

Fig. 7. Measured wind speeds per month and annual wind direction.

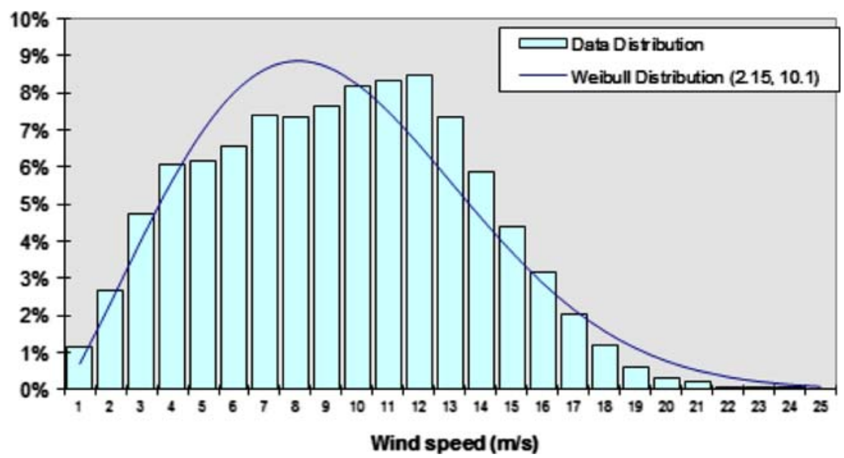

Fig. 8. Measured wind speed data distribution.

- *Financial criteria*: The available budget will finally define the exact size of the WT that will be used. Additional transportation costs should be also taken into account. The feed-in tariff is the critical parameter for the effectiveness of the studied investment.

4.4. Case study

In the examined example case, the main criterion was to cover the energy demands of the desalination plant. The study was performed through the following steps:

Step 1. Determination of the energy production of selected wind turbines (WTs)

For the estimation of wind energy production, common commercial WTs are considered, through their power curves available by the manufacturers.

A graphical method, using polynomial trend lines of wind speed sections to approximate the power curves of the WTs is used as the basis for the study. This method will be referred a "Built-in Method" in the rest of the paper. For verification purposes, the results are compared to those of the widely used *WindRose Software*, showing acceptable correlation.

Within the "Built-in Method," the calculation of the energy produced by a wind turbine for a time Δt requires as inputs:

(1) The knowledge of wind speed at hub height.
(2) The availability of the wind turbine (the percentage of time the machine is in working order).
(3) The power curve of the examined WT.

From each 10-min wind speed value (U_{ref}) at the height of 10 m (H_{ref}), the corresponding wind speed at the hub height of each WT (U_{Hub}) is estimated using the so-called *"exponential law"*:

$$\frac{U_{Hub}}{U_{ref}} = \left(\frac{H_{Hub}}{H_{ref}}\right)^{a} \tag{1}$$

For a more accurate approximation of exponent a at the site of interest, measurements with several anemometers at several height levels above ground are required. In this study, a hypothesis should be made leading to results on the safe side. Taking into account the very high average wind speed as well as the very low measurement height (10 meters), it is safe to consider a low value for exponent a. Two values are considered:

- $\alpha = 0.04$ as a typical, safe approach of wind speed at the height of hub and
- $\alpha = 0.00$ for a conservative approach in case the measurement position is such that wind over speed occurs at low altitudes (height of the anemometer) and stabilizes at higher (the so-called negative wind shear).

To find the 10-min power output (P_W) of the examined WT, a "look-up" table is used based on the 10-min wind speed at hub height. To facilitate this process, the WT power curves were approximated by polynomial trend lines, through *Microsoft Excel*.

The WT power output at every 10-min period is estimated by substituting the wind speed at the hub height in the equation of the polynomial trend line. The process is repeated for one-year period from July 1999 to June 2000.

The expected produced energy for one year (kWh) is then calculated with the following equation:

$$E_W = \sum P_W\Big(U_{Hub}(t)\Big) * AV(t) * \Delta t \tag{2}$$

where P_w: the 10-min power output (kW), which is calculated by the corresponding wind speed at hub height (U_{Hub}) and the power curve of wind turbine, AV: the availability of wind turbine in 10-min level (0 if not in operation or 1 if it is in operation). It should be noted that the availability refers to the time periods when the WT is out of operation due to technical restrictions (damages, maintenance, etc.). For simplification, it is considered as 1 in the study, and Δt: 10-min period expressed in hours (1/6 h).

The power curves of the examined WTs are selected mainly from the manufacturers' websites. The corresponding capacity factor of the examined WTS is calculated using the formula:

$$CF = \frac{E_R\ (kWh)}{P_n\ (kW) * 8760\ (h)} \tag{3}$$

The capacity factor is defined as the ratio of energy which is actually produced by a WT within a one-year period to the energy that could theoretically be generated if it was continuously operated at nominal power.

For verification purposes, the results of "Built-in Method" were compared to the results of *WindRose Software*. The same hypotheses have been made concerning the WT types and wind shear exponent a, and the results verify that the "Built-in Method" provides good energy estimation.

In the next step, results only from the "Built-in Method" are presented.

Step 2: Estimation of the Net Energy Production

The energy calculations within Step 1 refer to the produced energy at the terminals of the examined WT. To estimate the energy that is finally fed into the grid (Net Energy Production), it is necessary to take into account energy losses due to the ohmic losses of the grid as well as the APS technical restrictions (see Table 3).

The total losses are calculated using the equation:

$$LF = (1 - GL) * (1 - AO) * EL \tag{4}$$

where LF: total losses factor, GL: electric grid losses, AO: assistant operations, and EL: percentage of energy losses due to APS restrictions.

The finally injected energy to the grid for one year and the net capacity factor are calculated by multiplying respectively this total losses factor with the produced energy and the capacity factor of any wind turbine:

$$Net\_E_W = LF * E_W \tag{5}$$

where LF: total losses factor and E_W: the expected produced energy of WT.

Table 3
Overall losses factor

Electric grid losses (GL)	0.03
Assistant operations (AO)	0.13
Percentage of energy losses due to APS restrictions (EL)	0.75
Total losses factor (LF)	*0.63*

Table 4
Estimate of annual energy production and capacity factor without and with losses

		$\alpha = 0.00$		$\alpha = 0.04$	
		E (kWh)	Capacity factor (%)	E (kWh)	Capacity factor (%)
WT1 (1.5 MW)	Without losses	8.377.645	63.6	8.835.221	67.1
	With losses	5.280.480	40.1	5.568.893	42.3
WT2 (1.65 MW)	Without losses	8.508.316	58.7	9.083.234	62.7
	With losses	5.362.843	37.0	5.725.217	39.5

Step 3. Selection of a WT that fulfills the demands of the desalination plant

The application of the "Built in Method" to the selected WTs leads in the results presented in Table 4. In this table, 2 out of 16 examined scenarios were selected to be presented, as the most representatives.

Based on the available data each RO unit requires for its 24 h daily operation 1.743.192 kWh. The estimated annual energy requirements for the 4,500 m^3/day SWRO is 5.229.576 kWh. From the above, it is concluded that the selected WT will produce enough energy to cover the energy demands of the desalination unit on a yearly basis.

5. Restrictions and benefits

The major barrier for the installation of WTs in the Greek islands with APS is the penetration level of the wind energy to the local electricity network. RE sources by their nature are variable energy sources. This leads to the question of how much of the produced energy from RES can be penetrated to the local autonomous network without affect its stability. This difficulty will be solved in the near future with the grid interconnection of the Aegean islands to the more stable electricity network of the mainland.

Besides, there are several financial and environmental benefits from the exploitation of wind energy for the operation of desalination units in Greek islands. The Greek Government in effort to promote the collaboration of the technologies offers priorities on their use. Law 3851/2010 provides priorities, regarding the license procedure of RES projects combined with desalination for the production of potable water or (for) other water use. As mentioned in the Law, the applications for the installation of RES plants which are combined with the installation of water desalinization plants, are examined with absolute priority on condition that the installed capacity of RES does not exceed by 25% of the installed capacity of the desalination unit and that contracts for the distribution of the produced water quantities have been signed between the applicant and the General Secretariat for the Aegean and island policy or with the relevant local authorities (LAs).

Also, as mentioned in the Law, in these cases the duration of the license is determined by the duration of the above mentioned contracts. The judgment concerning the potential inclusion of the RES plants is based on the results of a techno-economic feasibility study which is prepared by the applicant. The electricity produced from the RES plant is recompensed, on an hourly basis, according to the consumption of the desalination plant. The surplus of electricity may be committed to the network up to 20% of the produced power, in accordance to the rules applicable for self-producers.

Regarding the financial benefits, by law[2], for onshore grid-connected wind turbines with installed power more than 50 kW, the selling price of electricity is set at 87.85 €/MWh for the interconnected system and 99.45 €/MWh for noninterconnected islands. Similarly, for grid-connected wind turbines with installed power <50 kW, the selling price of electricity is set at 250 €/MWh either on the interconnected system or noninterconnected islands.

Last but not least, the environmental issues of the use of RES technologies in desalination should be examined and evaluated accordingly. During the operation phase of a wind turbine, air emissions are not released into the atmosphere and do not degrade its quality. In contrast, because of the wind turbine operation, decrease in the total quantities of gaseous pollutants (CO_2, NO_x, particulates, etc.) occurs due to the substitution of electricity generated from conventional fuels of PCC stations, with a corresponding generated from wind energy. Especially, in accordance

[2] Law 3851/2010.

Table 5
Greenhouse gas emissions prevention

Fumes	Emissions (g/kWh)	1.5–1.65 MW WT (kg/kWh)
CO_2	850	4,629,373.7
SO_2	15.50	8,4418.0
CO	0.18	980.3
NO_x	1.20	6,535.6
HC	0.05	272.3
Particles	0.80	4,357.1

with the specific greenhouse gas emissions of power plants in the interconnected system, the production of 1kWh from the operation of a wind farm contributes to prevent release of the following air pollutants (Table 5), [7].

The third column of Table 5 estimates the reduction of greenhouse gas emissions by the energy produced in average values by a wind turbine with nominal power of 1.5–1.65 MW for Mykonos island.

6. Conclusions

Wind energy is a technologically mature, economically competitive, and environment friendly energy choice. Desalination seems to be the most reliable alternative for the production of potable water; however, still remains an energy intensive method. The use of the wind energy technology to cover the energy requirements of desalination is possible and can be easily developed. The overcome of the restriction on the penetration level of the produced energy from RES to the islands' networks, expected to bring a rapid development of both technologies in the Greek islands and especially in small islands of the Aegean Sea.

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