Chapter 9

Responding to Water Challenges Through Desalination: Energy Considerations

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Additional information is available at the end of the chapter

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Abstract

Desalination technology and reverse osmosis in particular, is used by several island authorities in Greece to address water scarcity. However, this is a highly energy-intensive technique, requiring the consumption of significant quantities of fossil fuels. The case of Syros island is presented to demonstrate the strong water-energy link in the operation of desalination plants. The use of renewable energy sources as a means for reducing water cost from desalination is also discussed. A simple algorithm to calculate estimating water costs with renewable energy sources (RES) is presented and is applied in the island of Patmos and in Hermoupolis, Syros island.

Keywords: desalination, reverse osmosis, RES-powered desalination, hybrid energy systems, water scarcity, water-energy nexus

1. Introduction

Economic advancement and prosperity depend on the significant resources of energy and water, the links between which are equally complex and important: energy production necessitates significant quantities of water, and water supply requires great amounts of energy. The study of the "water-energy nexus" demands a holistic view of the production and consumption chains of each resource [1] presents a view of the complexity of the water–energy nexus), focusing on the core operational components, i.e., infrastructure and technologies [2].

Energy requirements along the stages of the water chain depend on the quantity and quality of water and usually increase over time [3]. Energy intensity will increase with growth in water demand, as abstraction of water is carried out from deeper boreholes with lengthy interbasin water transfers, strict water-quality standards, and limitations on wastewater discharge. Despite all this, there are opportunities for improving energy efficiency. According to the European Innovation Partnership for water [4], there is an important potential for increasing the efficiency of energy use in water supply systems by using low-energy technologies in water treatment and wastewater cleaning processes. Also, the use of renewable resources is beneficial for the total energy efficiency of these systems.

The sources of water (in terms of type, quality, and seasonal availability) and the end-use characteristics (such as consumption patterns and infrastructure) play an important role on the energy intensity of the water supply chain. An increase of 35% in energy consumption is expected by 2035 due to the impacts of climate change on water resources [5], the increased competition among water users, and the "loop effect" of the energy-water interlinks. This might cause 85% increase in the water consumption and thus extra energy requirements are needed for water distribution and treatment [6, 7]. As these interlinkages are established, the quantification of the energy-water relationship is a priority issue, particularly in water-scarce regions.

In water-scarce areas, the main supply management methods are (1) water transports from areas with abundant water sources to areas with water scarcity; (2) intensive use of the available resources; and (3) use of nonconventional water resources (e.g., wastewater reuse, desalination). All these supply methods cause an increase in the energy consumption for water supply and as a consequence, the cost of water is higher either for consumers or governments. Thus, any improvements in the energy use and the efficiency of water supply may lead to profits for the environment as well as important reductions in the cost of water.

In this chapter, the water–energy nexus is presented with emphasis in remote areas. The island of Syros, located in the Cyclades island complex, is used as a case study to demonstrate the links between energy consumption and water production and the need to increase energy-use efficiency in the isolated water and electrical energy systems of the Greek islands. The desalination option with RES is explored through modeling, and as a case study, Hermoupolis in the island of Syros and Patmos island is selected. The rich history of all the desalination methods that have been applied in the Greek islands is also described in brief.

2. The water system of the Greek islands

Greece has the longest coastline in Europe, approximately 14,000 km. The country has about 2500 islands (**Figure 1**), with a total area of 21,580 km^2. The islanders are estimated to be 1,633,433 [8].

The climate on the Greek islands is typical Mediterranean (dry summers and wet winters), with relatively low precipitation (less than 400 mm per year, especially for the Aegean islands [9]). The storage, surface, or groundwater of sufficient quality and quantity is impossible on some islands due to the low precipitation and the geological formations. Furthermore, there is a peak in water demand on the summer period (due to tourism and irrigation), the water losses are high due to the leakages in the old distribution networks, the aquifers are degraded due to over-pumping, and above all, an integrated water management system is

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Figure 1. Map of Greek islands and complexes.

absent in most of the islands. These facts intensify the problems of water scarcity and create water deficiencies in the local areas (**Table 1**).

In each island, the specific conditions shape the approach used to address water deficiency problems. The current practices for domestic water supply according to Ref. [10] are: (a) desalination of sea or brackish water, (b) water transfer from the mainland at high cost (about 10 €/m^3), (c) dams, and (d) boreholes. The state officials regard desalination as an appropriate long-term settlement to the water-shortage problem.

Complex	Number of islands	Population	Population water balance [11]
Dodecanese	24	191,084	Negative
Ionian	17	211,954	Positive
Cyclades	28	118,000	Negative
North Aegean	14	202,360	Negative
Sporades	7	16,792	Negative
Saronic	7	63,467	Negative

Table 1. Island complexes in Greece [8].

3. Energy-intensive water desalination

Desalination was first introduced into Greek islands during 1960s, based on solar still collectors. Five systems of various sizes were installed until 1973, without great success, mainly due to operational breakdowns, poor maintenance [12], and conflicts of interest with the water tanker owners. The success in operation of these desalination units would result in a significant decline in the quantities of water they transferred to the islands.

In 1969, a multistage-flash system was installed in Syros, powered by fuel oil. The high cost of fuel in addition to mechanical problems led to the shift toward RO [13]. The next desalination attempt took place in the island of Corfu in 1977. A reverse electrodialysis (ED) plant with a daily capacity of 15,000 m^3 was installed for the treatment of low-salinity brackish water (up to 2000 ppm). The operation of this desalination plant ceased due to functional problems happened after few years [14]. Its specific energy consumption was 1.7 kWh/m^3 [15].

Before the Syros RO installations, the first RO units for the public community water supply were installed in 1981–1982 in the islands of Ithaca and Mykonos. The reasons for the domination of RO are: (1) compact design, (2) relatively low water needs, (3) modular operation to meet seasonal and diurnal variations in demand, (4) easy operation, (5) relatively low-energy consumption comparing to other desalination methods, and (6) fast installation (2–3 months).

Currently, the total capacity of the installed desalination units (for public use in the islands) is about 60,000 m^3/day spread over 39 islands (**Figure 2**) with 9000 m^3/day of brackish water feed, and 51,000 m^3/day of seawater feed. Very small islands of Pserimos and Rho are not included in the map of **Figure 2**. Most desalination units are located on islands, which are not connected to the mainland electricity grid (31 out of 39 islands), and the rest are installed on islands that are interconnected to the main grid, through underwater cables. The rate of development of new desalination units was quite low until the early 2000s, but rose very fast prior to the Athens Olympic Games in 2004 (**Figure 3**). In the coming years, almost five more islands are about to install and operate desalination plants.

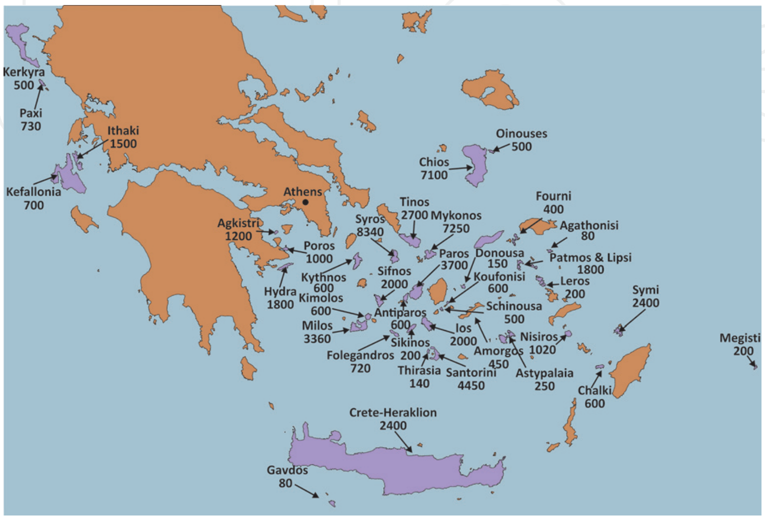

Figure 2. Desalination units in the Greek islands ([13, 16–22]; TEMAK SA, personal communication).

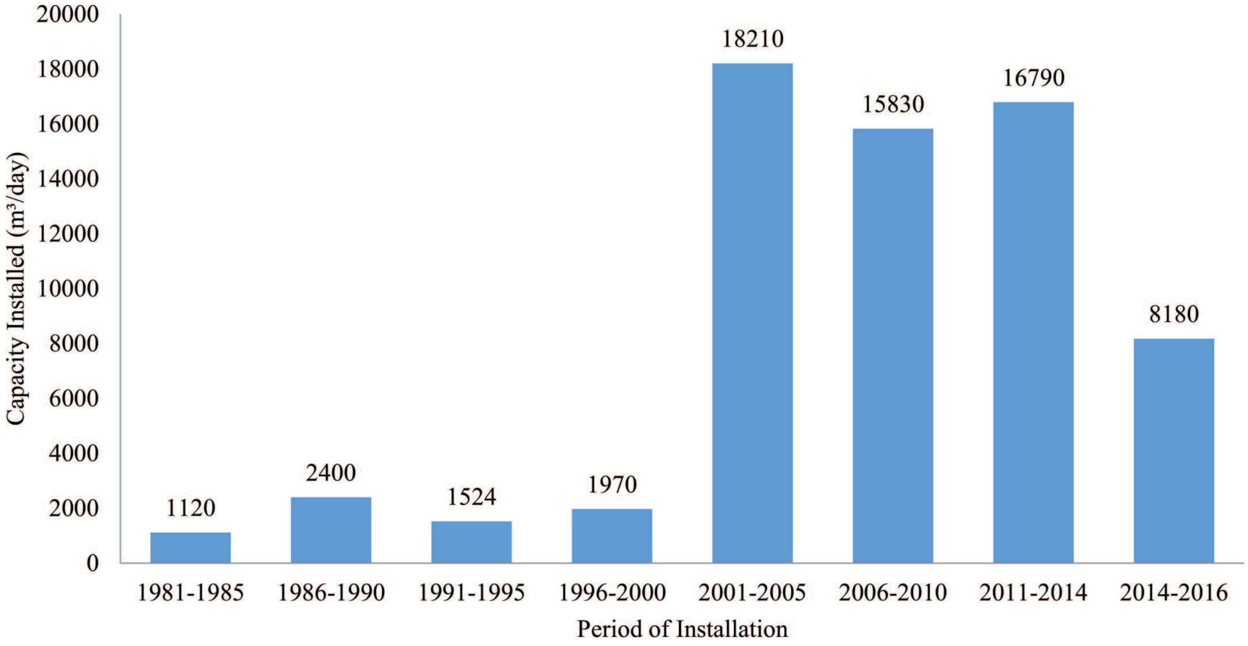

Figure 3. Desalination facilities in Greece, 1981-2014 ([13, 16–22]; TEMAK SA, personal communication).

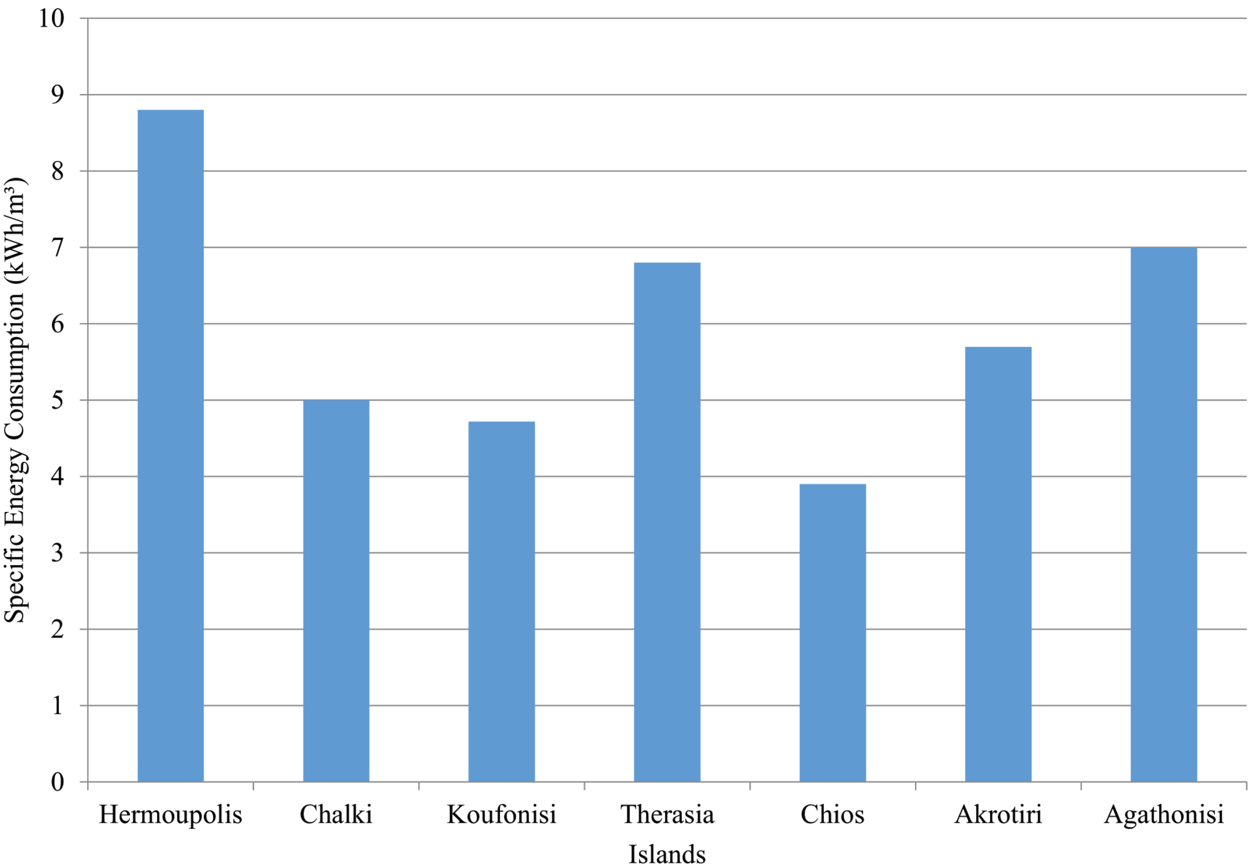

Figure 4. Specific energy consumption of Greek desalination plants (Syros WSSC, personal communication, 2014; TEMAK SA, personal communication, 2014).

The specific energy consumption for a number of desalination units installed on the islands is presented in **Figure 4**. These data were acquired through the desalination manufactures and local water companies (TEMAK SA, personal communication, 2014; Culligan Hellas SA, personal communication on technical characteristics of existing desalination units, 2014). Both high pressure and booster pumps are included in these data.

4. Desalination with renewable energy sources

Renewable energy powered desalination offers noteworthy benefits in comparison to use conventional energy supply. Although desalination systems with renewable energy have increased installation costs, they have lower operating costs due to the fact that costly fuel oil used in most islands is avoided. During the summer period, higher wind speed and solar radiation occur while water demand is also higher, and thus these have been identified as possible energy sources for supporting desalination systems in general and in the Greek islands especially.

Annual mean wind speed in most areas varies from 5 to 7 m/s, but it can be much higher in some areas. Annual solar radiation varies from 1400 to 1700 kWh/m^2, and in the islands of Milos, Nisyros, Kimolos, and Thira have high-enthalpy geothermal fields. Since the installation of solar stills, several attempts have been made to use renewable energy for desalination, both on pilot and commercial systems. The Greek state has promoted desalination systems powered by renewable energy by prioritizing the licensing procedure for the installation of the renewable systems.

A desalination unit with geothermal energy as an energy source with capacity of 80 m^3/day using multi-effect distillation (MED) technology was installed in the framework of a European project and operated effectively for demonstrations in the island of Kimolos in 1997–1998 [23]. The water production cost was estimated at € 1.7/m^3. However, at the end of the project, the desalination unit was abandoned. A very small RO unit with a capacity of 4.8 m^3/day, powered by a stand-alone 15 kW wind turbine, was installed as a pilot system in Therasia in 1997.

Hydriada, a floating RO desalination unit (80 m^3/day) with power supplied by a wind turbine and photovoltaics, was launched in 2007. It was a promising prototype designed to meet the potable water needs of 300 inhabitants in a small and arid island. Iraklia, a suitable island in Cyclades was selected as a pilot area. Early technical problems emerged and were compounded by the indifference of the local authority and the high maintenance costs, and thus the project was abandoned [24].

In the island of Milos, a successful desalination unit was constructed during 2007–2009 using wind energy supply. Three similar RO units with a total capacity of 3360 m^3/day and very low specific energy consumption (approximately 3.5 kWh/m^3) were powered by a 850 kW wind turbine. A supervisory control and a data acquisition system were installed to assist and to optimize the operation of the RO units and the wind turbines as both the RO unit and the wind turbine are connected into the island's autonomous power grid. Optimization is accomplished by the use of operation modes depending on climate conditions, the potable water demand forecasting, and the level of the water tanks. One more important innovation of this project was its ownership status: the wind turbine and the desalination unit are private investments, and they work under contract agreement with the island municipality for supplying water.

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A promising mechanical vapor compression (MVC) desalination system with the exploitation of wind energy (330 kW) was built in the island of Symi in 2009. The installed system was not successful due to important technical problems that caused very low water production. This system was stand-alone, with specific energy consumption of about 14.5 kWh/m^3 [25]. Its operation ceased in 2011 due to a fire and it was never repaired. An autonomous RO unit of 8 m^3/day was installed in 2013 on the very small island of Strogyli with the use of 20 kWp photovoltaics as power source. The unit provides potable water to a small army camp.

5. The case of Syros island: comparing the operation and energy costs of desalination

The urban water supply in Syros is covered mainly by desalinated water. The island power grid is autonomous and the electrical energy supply relies on diesel fuel transferred from the mainland. Currently, there are 13 RO units distributed in five regions (**Figure 5**). According to the Syros Water Company (Syros Water Supply and Sewerage Company [26] personal communication) and the Hellenic Electricity Distribution Network Operator [27], more than 11% of the electricity produced in the island is used for potable water production and the total desalination power demand, when plants are running at full capacity is 5.2% of the conventional installed power production units.

These plants require 2.08 MW of power and the cost of energy is the primary operating cost for the Water Supply Company. The total operational cost is estimated at about €1.2–1.6/m^3. The contribution of energy to the water cost is €0.7 m^3 (about 45%), with an average energy cost of €0.086/kWh [12].

The following indicators will be used to assess the energy-for-water nexus: (a) energy consumption per volume of water sold, (b) energy cost per volume of water sold, and (c) energy

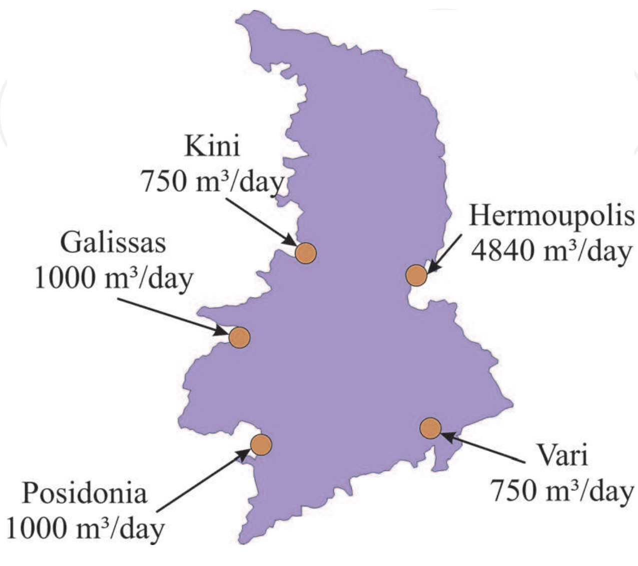

Figure 5. Desalination units in Syros.

consumption per capita. These analyses take into account only the desalination plant of Syros capital, Hermoupolis, for which the required input data are available. For comparison purposes, similar results are presented for the two major water supply systems in Greece (**Table 2**), the Athens, and the Thessaloniki water supply systems.

5.1. Assessment indicators

The energy consumption per volume of water sold is presented in **Figure 6** for three water energy systems. The Athens water system has a value 0.75 kWh/m^3, Thessaloniki's water system has twice that, and Hermoupolis about 15 times. The cost of energy also follows such

	Hermoupolis DEYA Syrou	Athens EYDAP	Thessaloniki EYATH
Population served	13,400	4,500,000	1,000,000
Water production (hm^3)	1.05	385.5	89.7
Water billed (hm^3)	0.89	337	66.3
Annual per capita consumption (m^3/year)	66.6	74.9	66.3
Energy consumption (GWh)	10	251	119
Reference year or period	2010–2013	2009	2008
Energy cost (€/kWh)	0.086	0.089	No data (assumed same as Athens)
Data sources	[27]	[28, 29]	[29, 30]

Table 2. Data used for the calculation of the assessment indicators.

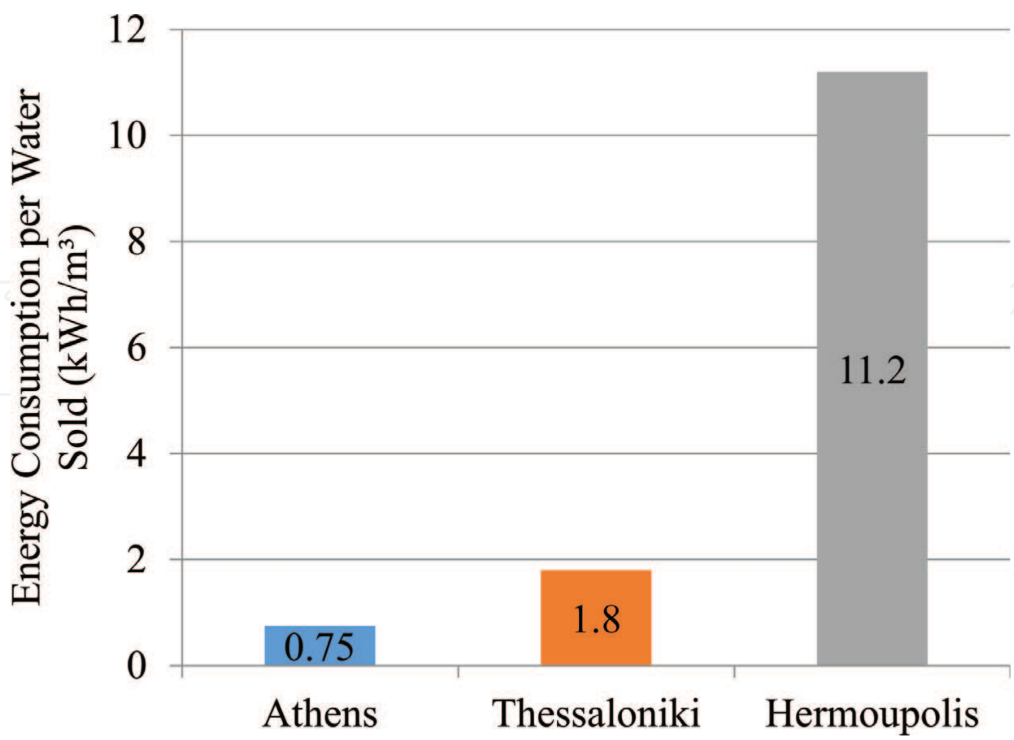

Figure 6. Energy consumption per volume of water sold in the water supply systems of Hermoupolis, Athens, and Thessaloniki [27–30].

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a pattern, as seen in **Figure 7**. Similar ratios between water systems also apply for the case of the per capita energy demand for water supply. Syros has a value 14 times than that of Athens and more than twice that of Thessaloniki (**Figure 8**).

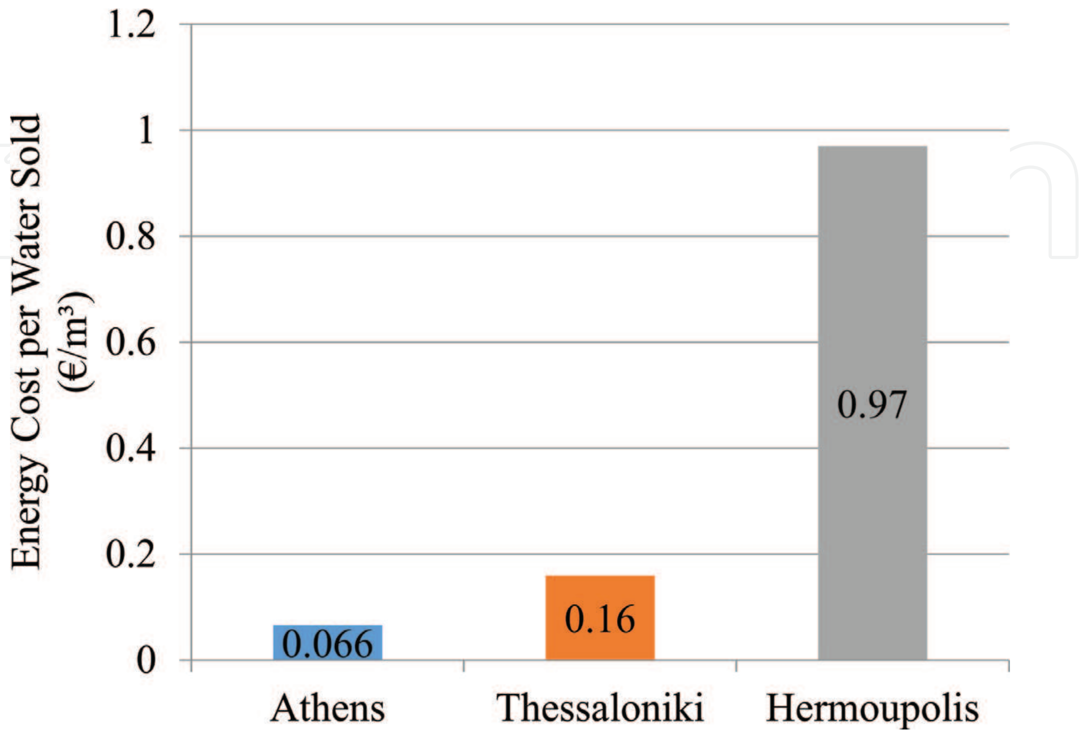

Figure 7. Energy cost per volume of water sold in the water supply systems of Hermoupolis, Athens, and Thessaloniki [27–30].

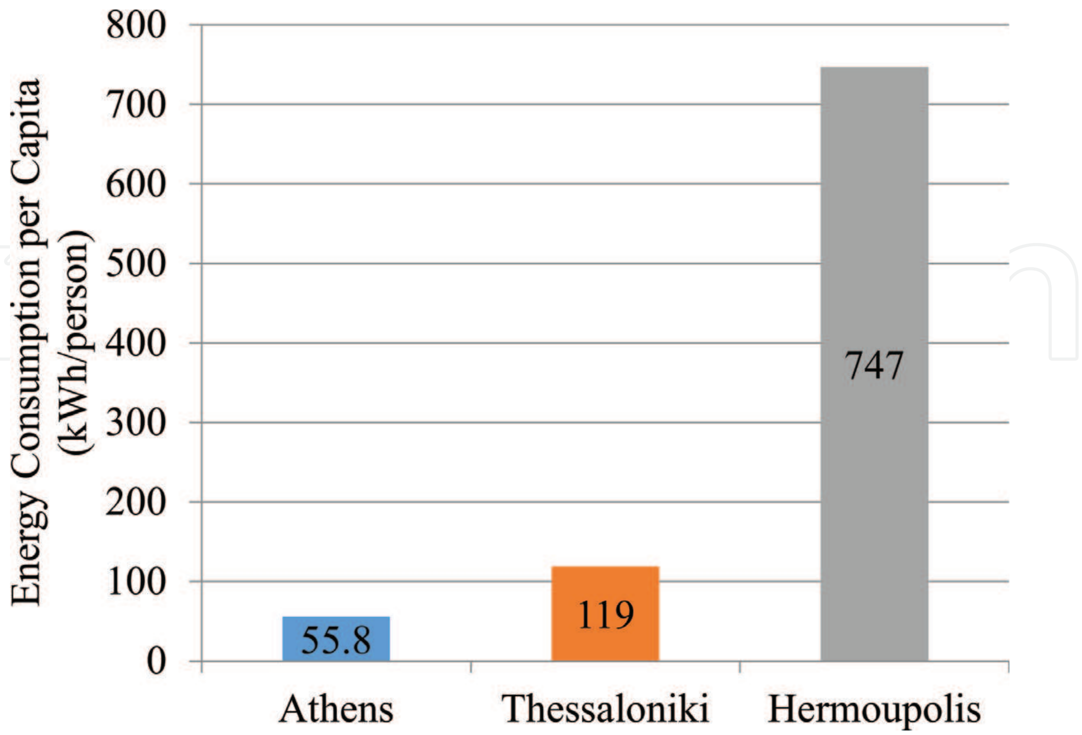

Figure 8. Energy consumption per capita in the water supply systems of Hermoupolis, Athens, and Thessaloniki [27–30].

5.2. Monthly energy consumption

Water consumption in Syros is high during summer, due to the tourism. For instance, consumption during August is around 85% higher than in February (**Figure 9**). The same

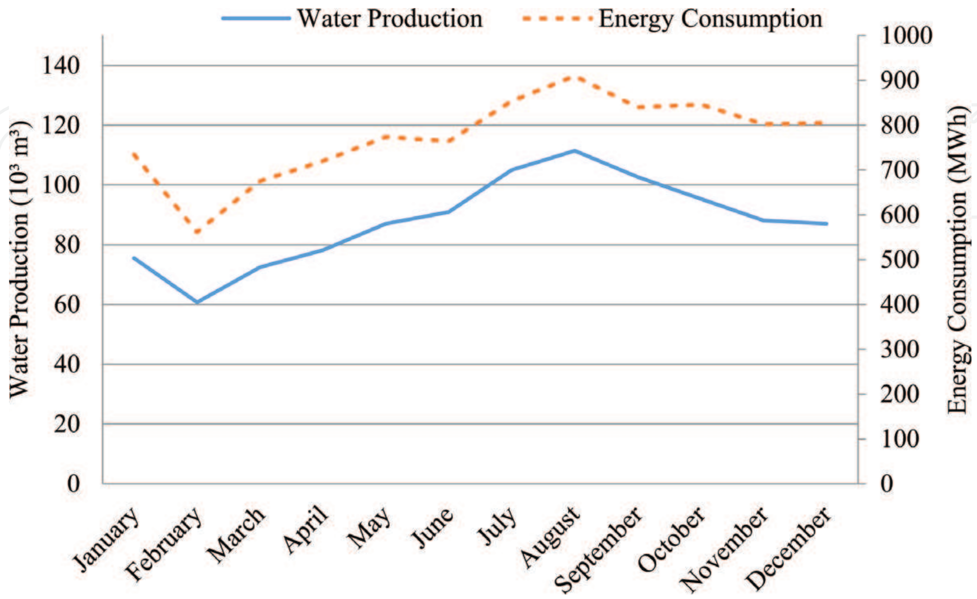

Figure 9. Monthly water production and energy consumption for the Hermoupolis desalination plant (average values for 2010–2013) [27].

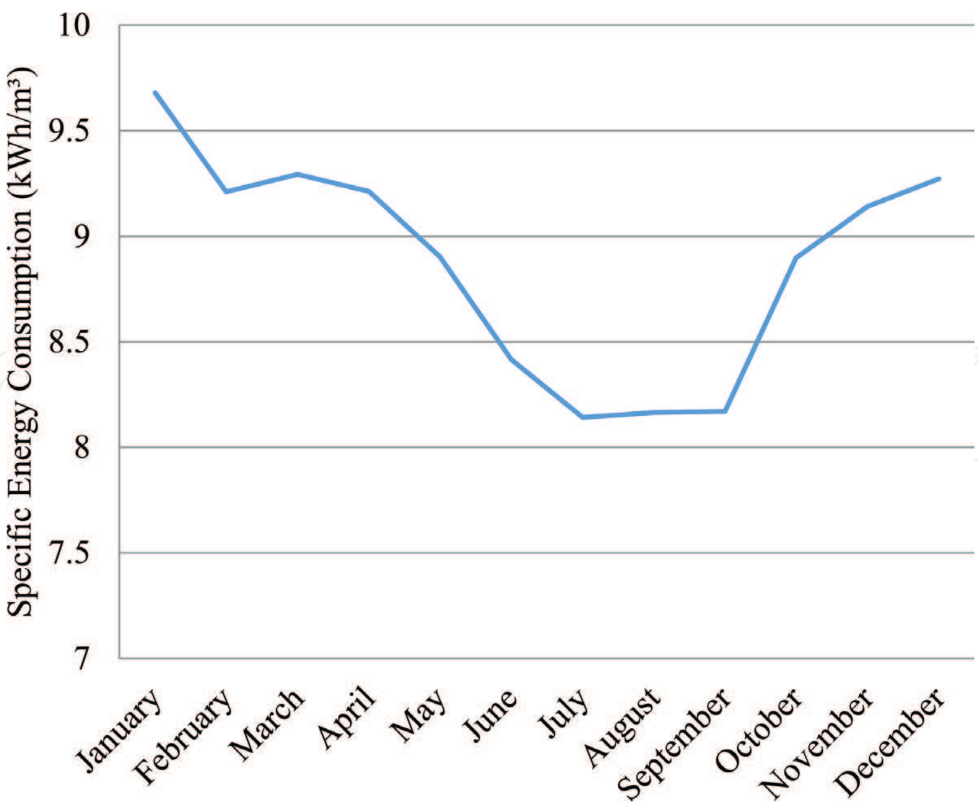

Figure 10. Specific energy consumption of the desalination units in the Hermoupolis desalination plant (average values for 2010–2013) [27].

pattern applies to the energy consumption of the desalination. However, the desalination process is significantly more efficient in the summer period (**Figure 10**). Specific energy for the Hermoupolis plant is 8.1 kWh/m^3 in August and 9.7 kWh/m^3 in February, a reduction of 16.5%. This reduction can be credited to three main factors which are as follows: (i) the units operate continuously during summer, with less start-and-stop cycles, (ii) the temperature of the seawater during summer period is high, affecting properties such as viscosity and lowering the energy demand of the high-pressure pump [31], and (iii) as the Hermoupolis desalination plant comprises several desalination units, each one with different capacities and specific energies, making extensive use of the unit with the lower specific energy also lowers the specific energy of the desalination plant as a whole.

6. Satisfying energy needs by using RES: a design methodology

A method for assessing the desalination system with RES is presented in the following section. In most cases, the desalination systems are interconnected with the electrical grid of the island, where the energy mix is dominated by diesel or heavy oil and a small percentage is covered by RES or other sources. Some islands are interconnected with the mainland and thus the energy mix contribution comes from lignite, natural gas, and RES.

The renewable sources considered in the present study are solar and wind energy. Energy demand for desalination is covered by the produced renewable energy and the excess is supplied to the grid. If the renewable energy is not sufficient to cover the demand, then energy is obtained through the grid.

The optimal configuration is the one that minimizes the water cost from the investor point of view. A configuration is defined by a set of design parameters such as the desalination capacity, the photovoltaic installed power, etc. A methodology, using hourly simulation, was developed to identify the optimum configuration. The islands to be examined are Syros and Patmos.

6.1. Design methodology

6.1.1. Water demand

Water demand can be derived from real historical data, from average monthly values or from other sources. The developed methodology requires daily water demand values throughout the year. However, if only monthly average data are available, then it can be assumed that water demand is the same for every day (Q_{daily}) of the month.

6.1.2. Desalination unit

Desalination capacity (Q_{cap} in m^3/day) is one of the design parameters. The specific energy demand (Sp in kWh/m^3) is a specification parameter of a given desalination unit and water salinity. Thus, the average power that is needed during normal operation is as follows:

$$P_{des} = Sp \cdot \frac{Q_{cap}}{24\text{ hr}}(\text{kW}) \tag{1}$$

The hours of operation of the desalination unit per day can be derived as follows:

$$T_{op} = \min\left(\frac{Q_{daily}}{Q_{cap}/24\text{ hr}}, 24\text{ hr}\right)\ (\text{hr}) \tag{2}$$

The min operator denotes that hours of operation needed for each day cannot be more than 24 hr. The desalination might not be able to fully cover the demand and in this case, there is a water demand deficit. The operating hours of the desalination unit is a critical factor for the exploitation of the renewable sources. In case of solar energy, the best strategy corresponds to the operation of the unit in the period around noon (**Figure 11**). In case of wind energy, then the optimum period depends on the micro scale of the location of the power plant (in most cases, the afternoon is the windiest time).

The hourly distribution of energy requirements for desalination is given by Eq. (3):

$$E_{DES}(t) = OP(t) \cdot P_{DES}(\text{kWh}) \tag{3}$$

where $OP(t)$ is the desalination production distribution, representing the percentage of operation for each hour t of the year ($OP(t)$ is 100% when the desalination unit is in operation for an hour without breaks, 0% when the desalination is not operating at all, and a value between 0 and 100% in other cases).

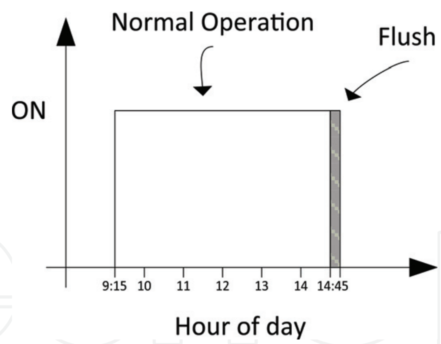

Figure 11. Reverse osmosis operation schedule (example).

6.1.3. Photovoltaic model

The installed power of the photovoltaic (PV) system is a design parameter, denoted by P_{PV} (kWp) and the energy produced by a PV array, in a given hour t, is given by:

$$E_{\text{PV}}(t) = \eta_{inv} \cdot \eta_{oeff} \cdot P_{\text{PV}} \cdot \frac{\overline{G}_T(t)}{G_{STC}} \cdot 1\text{ hr} \quad (\text{kWh}) \tag{4}$$

where $\overline{G}_T(t)$ is the mean hour solar radiation for every hour in (kWh/m^2), G_{STC} is the standard test condition reference radiation (1000 W/m^2), η_{inv}, and η_{oeff} are the inverter efficiency and overall efficiency respectively.

6.1.4. Wind energy conversion system model

The total installed power of the wind turbines is also a design parameter (P_{WEC} in kW). The energy produced by the wind energy conversion (WEC) system in a given hour t, is given by:

$$E_{WEC}(t) = \eta_{oeff} \cdot P_{WEC}(V(t)) \cdot 1 \text{ hr} \quad (\text{kWh}) \tag{5}$$

where $P_{WEC}(V(t))$ is the power produced by the wind energy system for wind speed $V(t)$. In the case of a single wind turbine, the power from the WEC system is given by the power curve of the wind turbine.

6.1.5. Energy management scheme

The scheme concerning the energy flows is quite simple. There is no sale of extra electrical energy to the grid, but net metering method is applied with annual clearance.

The renewable energy consumed by the RO unit is the sum of the wind turbine energy and photovoltaic energy produced during the operating time of the unit:

$$E_{RESav}(t) = (E_{WEC}(t) + E_{PV}(t)) \cdot OP(t) \tag{6}$$

The energy produced from renewable sources when the RO unit is not operating is as follows:

$$E_{rest}(t) = E_{WEC}(t) + E_{PV}(t) - E_{RESav}(t) \tag{7}$$

The energy difference among the available renewable energy and energy needed for desalination is as follows:

$$E_{NET}(t) = E_{RESav}(t) - E_{DES}(t) \tag{8}$$

If $E_{NET}(t) \geq 0$, then the renewable energy is not fully exploited by the RO unit. Therefore, the total amount of renewable energy that can be infused into the grid is.

$$E_{Togridav}(t) = E_{NET}(t) + E_{rest}(t) \tag{9}$$

If $E_{NET}(t) < 0$, then there are additional energy needs and they are going to be covered from the grid.

$$E_{Fromgrid}(t) = |E_{NET}(t)| \tag{10}$$

Due to technical limitations or legislation, there is an upper limit to the amount of energy that can be infused into the grid, depending on the relation between the conventional and RES energy production in the island. Thus, the energy that can be infused to the grid will be

$$E_{Togrid}(t) = \min\left(E_{Togridav}(t), E_{gridS}(t)\right) \tag{11}$$

E_{gridS} is the RES margin of the autonomous grid system.

The annual energy demand for the desalination is

$$E_{DESan} = \sum_{t=1}^{8760} E_{DES}(t) \tag{12}$$

and the renewable energy collected in one year is

$$E_{RESan} = \sum_{t=1}^{8760} \left(E_{WEC}(t) + E_{PV}(t)\right) \tag{13}$$

6.1.6. Economic evaluation

Economic evaluation will allow the identification of the most profitable and optimal configurations with the use of water cost as the main decision parameter. The levelized water cost (WC) per cubic meter can be calculated as:

$$WC = \frac{(IC_{EN} + IC_{RO}) \cdot R + OM + EC}{WP} \tag{14}$$

where: IC_{EN} is the installation cost of the power system.

IC_{RO} is the reverse osmosis installation cost.

R is the annuity factor (n is the life time of the investment and i the interest rate):

$$R = \frac{i}{1 - (1+i)^{-n}} \tag{15}$$

OM is the annual operation and maintenance cost that contains consumables (CN), (filters, spare parts), chemicals for posttreatment and pretreatment (CHM), membrane replacements (MR) and labor (LB):

$$OM = CN + CHM + MR + LB \tag{16}$$

EC is the annual cost of energy and EC_{SP} is the specific cost of energy (€/kWh):

$$EC = EC_{SP} \cdot \max\left(\left(\sum_{t=1}^{8760} E_{Fromgrid}(t) - \sum_{t=1}^{8760} E_{Togrid}(t)\right), 0\right) \tag{17}$$

WP is the annual water production:

$$WP = \sum_{t=1}^{8760} \frac{Q_{cap}}{24\ \text{hr}} OP(t) \tag{18}$$

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6.2. Case study

The installation of renewable energy systems for covering water demand will be examined for the city of Hermoupolis in the island of Syros and for the island of Patmos. As detailed above, Hermoupolis has high energy needs for water production; therefore, the introduction of RES technologies could be beneficial in minimizing the cost of the water. The island of Patmos still covers its water needs by water transports and local drills. However, two units of 600 m^3 each have already been installed and are planned to be operational in the near future.

6.2.1. Model inputs

6.2.1.1. Water demand

Monthly water production for Hermoupolis is given in **Figure 9**. Maximum water demand for Patmos, according to a recent public tender, was estimated at 236,000 m^3 per year, but not all of the demand will be covered by the desalination. Thus, an estimation can be derived from the amount of water that was transferred to the island by tanker ships, according to Special Secretariat for Water. For 2014, this value was 68,654 m^3. Due to the lack of monthly distribution data, we can assume that the profile is the same as the previous years (monthly data exists). Also, due to the rebound effect on desalination, the water produced by desalination can be up to 20% more than water transferred. However, the case of covering all water needs through desalination will be examined.

6.2.1.2. Meteorological data

The data needed for the simulation are the wind speed and the solar radiation as hourly time series for 1 year. For Hermoupolis, the average wind speed at wind turbine height is 6.5 m/s and the total solar radiation at the photovoltaic inclination is 1847 kWh/m^2. As the island of Patmos is an important site of cultural heritage, the wind energy option is not examined. The annual solar radiation is 1935 kWh/m^2.

6.2.1.3. Installation cost

Total cost has been estimated at 2.082 M€ using data from the Syros Water Service [32]. The installation cost of the reverse osmosis unit in Patmos installation was estimated at 0.739 M€. The specific cost of the photovoltaic system was calculated for a fixed price of 1200 €/kWp and the installation cost of the wind turbine system is estimated at 1500 €/kW.

6.2.1.4. Operation and maintenance cost

These costs are either fixed or dependent on the water production:

- *Labor* is a fixed cost, in a small desalination plant estimated at $LB = 25000$ € per year and per person. When the annual water production is low, the labor cost is an important factor in the water cost. One person was employed for the RO unit of Patmos and four persons for the unit of Hermoupolis.

- *Chemicals cost* is variable and depends on the water production. The specific cost of the chemicals is estimated from 0.02 to 0.05 $/m^3$ [33], but in some cases it can be as high as 0.23 $/m^3$ [34]. For the Greek islands a value of 0.065 €/m^3^ is proposed [35]. Thus, the chemical costs are $CH = WP \cdot 0.065€/\mathrm{m}^3$.
- *Membrane* cost is the most difficult to estimate, due to the fact that the life span of a membrane depends on many parameters. Proper use of the reverse osmosis system can produce water of potable quality for 5 years or more. In literature and in feasibility studies, the life span of the membrane varies from 3 to 5 years. Water production in the islands is limited and the periodical operation of the reverse osmosis can incur a specific replacement cost that is three times higher. For this reason, membrane cost varies from 0.04 to 0.34 €/m^3[36]. In this study, membrane replacement cost will be an average 0.15 €/m^3, which agrees with data from real plants in similar areas $MR = WP \cdot 0.15€/\mathrm{m}^3$[17].
- *Consumables* and *other* costs: will be taken equal to $CN = WP \cdot 0.04€/\mathrm{m}^3$ [16].

6.2.1.5. Other inputs

The specific energy for Patmos is assumed to be$Sp = 5.5\,\mathrm{kWh/m^3}$ and for Hermoupolis, a monthly specific energy is used (**Figure 10**). The flushing duration will be 15 min ($fm = 0.25$ hr). The cost of electrical energy for Hermoupolis is 0.086 €/kWh according to local data, and for Patmos a value of 0.1 €/kWh was assumed.

6.2.2. Results

The water cost in the island of Patmos, using conventional energy sources, is estimated at $WC = 1.62€/\mathrm{m}^3$. **Figure 12** presents the cost breakdown graph, where it is obvious that all cost components have approximately the same participation in water cost. If the RO unit is sized to produce water to cover all the demand of Patmos, then the water cost drops to $WC = 1.154€/\mathrm{m}^3$.

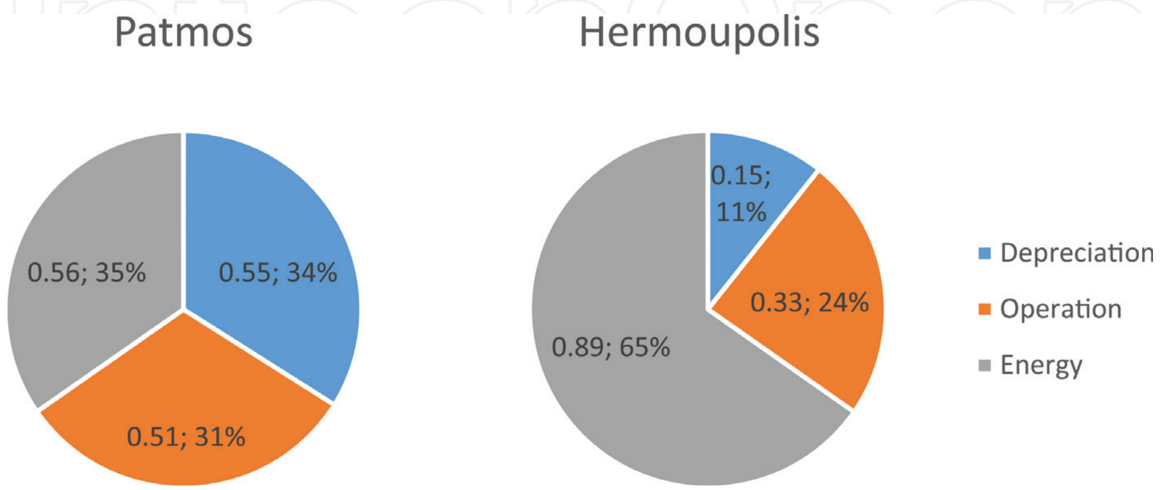

Figure 12. Water cost breakdown into the basic components for Patmos and Hermoupolis.

When installing photovoltaic units in the island of Patmos, water cost reaches a minimum of about 1.52 €/m^3, which can be achieved when the installed power of the photovoltaic system is about 200 kWp (**Figure 13**).

Water cost in the city of Hermoupolis is estimated at 1.26 €/m^3, but the contribution of each cost component is different. Energy contributes 61% of the total water cost (**Figure 12**).

The installation of photovoltaics minimizes water cost to the value of 1.16 €/m^{3}for a photovoltaic power plant of 2.3 MW The reduction in water cost is 0.1€/m^3 (the same as is in Patmos). On the other hand, when installing wind turbines, the water cost can be as low as 1.12 €/m^{3}for total wind turbine installed power of 1750 kW. In **Figure 14**, the water cost is presented versus the installed power of each technology.

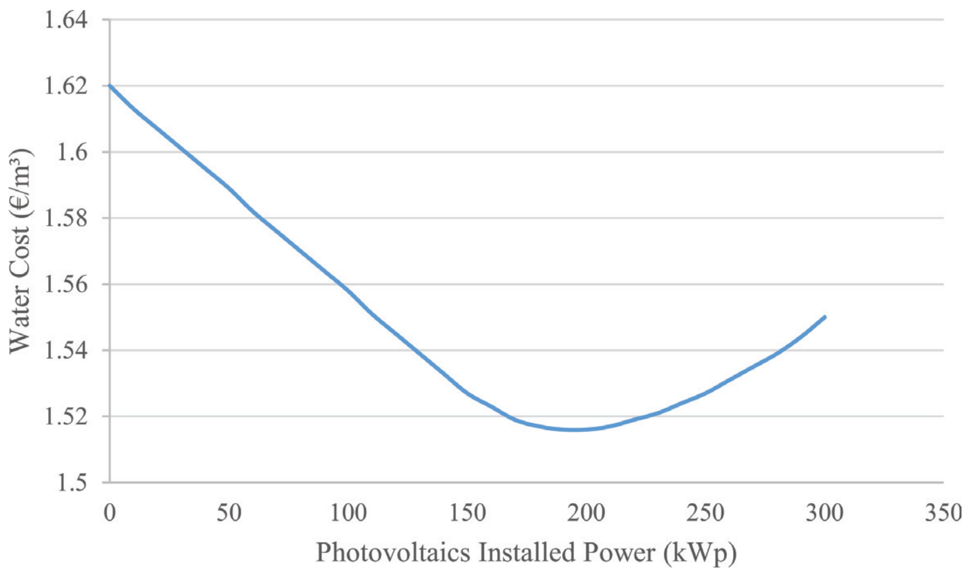

Figure 13. Water cost versus photovoltaic install power for Patmos.

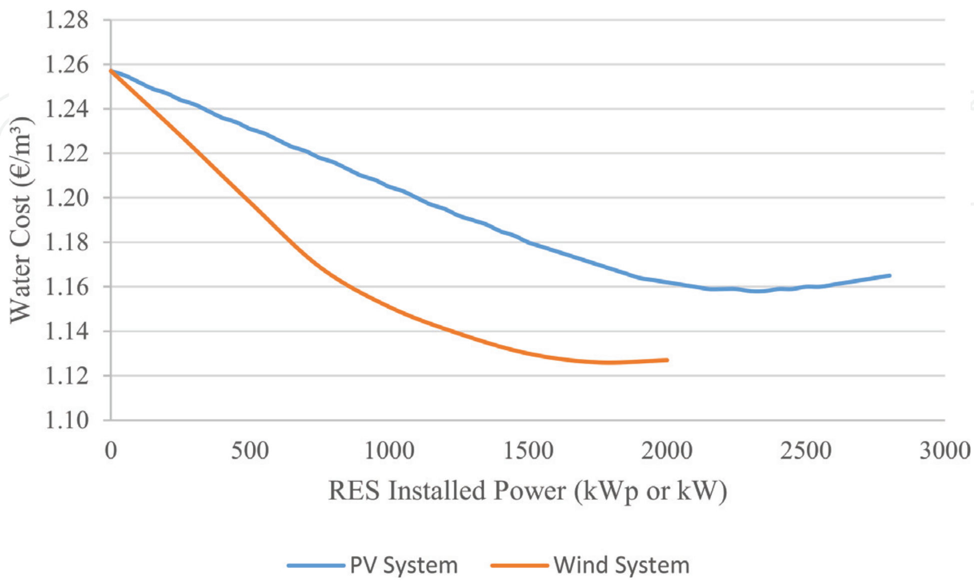

Figure 14. Water cost versus wind and photovoltaic install power for Hermoupolis. One technology each time.

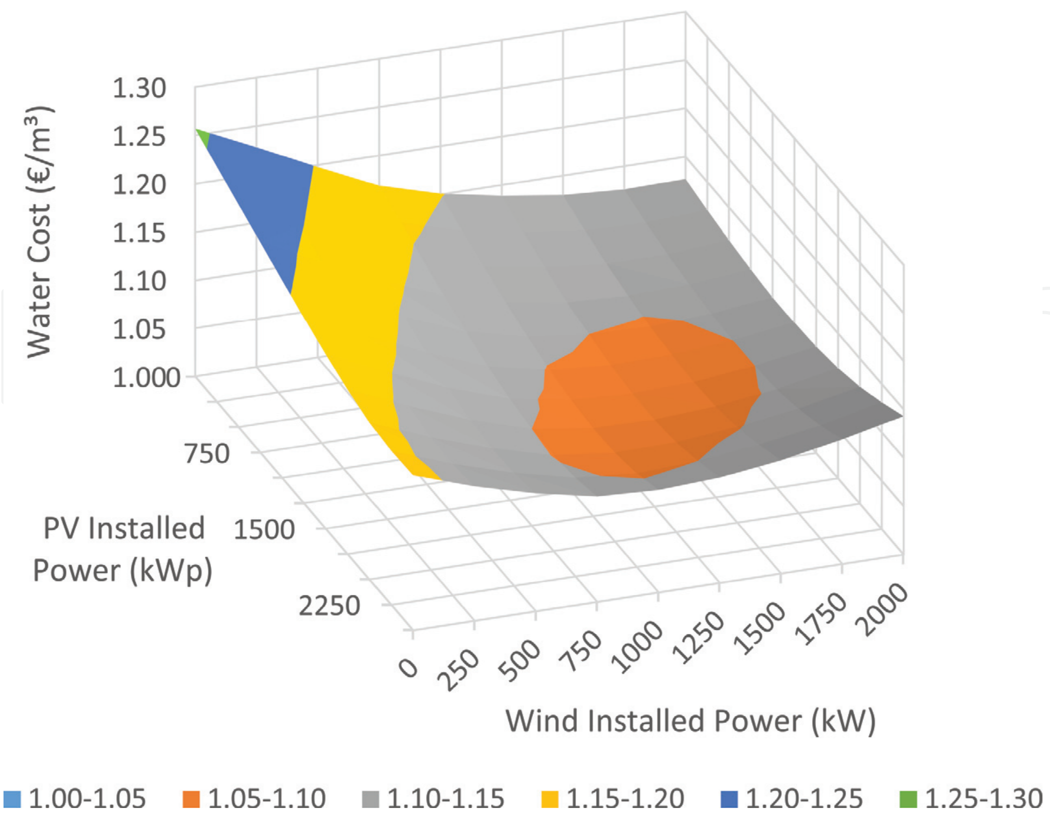

Figure 15. Water cost versus wind and photovoltaic installed power for Hermoupolis when both technologies exists simultaneously.

When both photovoltaics and wind turbines are installed simultaneously, water cost has an absolute minimum value at 1.09 €/m^3, which is 0.17 €/m^3 less than the case with conventional energy. This value can be achieved for various installed power combinations of each technology. The lower values for both the photovoltaics and wind turbine-installed power (which consequently gives the lower installation costs) are for 1250kWp and 1250 kW, respectively (**Figure 15**).

In both cases, an increase in water demand during the next years has not been taken into account; even so, the installation of renewable energy technologies will be beneficial and will make water cheaper due to higher utilization of the desalination units and due to cheap energy sources.

7. Discussion and conclusions

The practice of desalination has been identified as a promising solution to the water scarcity problem of the Greek islands (Cyclades and Dodecanese). The early efforts during the 1960s with the use of solar distillation technology were not successful, as the technical know-how was very limited and maintenance was inadequate. Also, the operational costs (labor) were very high due to the lack of automation technologies. The advances in desalination technology, combined with the need to meet water demand in the rapidly developing tourist areas, enhanced the prospects of desalination as a supplementary or even primary source of potable

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water. Both at the pilot and commercial levels, efforts have been made to improve the performance of desalination technology. Economic considerations and technical limitations are the most important reasons that such efforts are not always successful.

The primary challenge in the desalination practice and specifically in the reverse osmosis technology is the reduction of the energy consumption of the units. As energy is a very high cost factor for desalination, various methods for lowering the specific energy consumption can help decrease the cost of water. Another important option is the use of cheaper energy sources. Renewable energy technologies can offer a feasible way to reduce the pressure on energy systems for water production, and thus developing renewable-energy-powered desalination plants has become a priority in the Greek energy and water sectors. Energy storage is not a practical solution due to its high investment cost and the low lifetime of battery systems, but the net metering method can lower water cost by up to 13.5%. As a state of the art technology, hybrid systems, combined with operation optimization methods, provide appropriate solutions for cheaper energy; however, wind farms and photovoltaic arrays often face disapproval, especially in the tourism-dependent islands, as local inhabitants find that the local esthetic value is reduced. Environmental reasons and land-use conflicts may also prevent the integration of renewable-energy-powered RO systems. To construct efficiently operated, optimal RO desalination powered by renewable energy systems, the state should promote pilot systems through the relevant studies.

Water deficiency in most of the arid islands is treated with water transfers at the expense of the central government. The operation and maintenance cost of the desalination units is subsidized. In an era of economic crisis, this condition may not be feasible and there is a pressing need to move on toward sustainable solutions. Private sector participation, though not always socially acceptable by the locals, has to be examined. Moreover, as water and energy resources are due to face increasing pressure over the next few decades, the evaluation of trade-offs and the encouragement of cross-sector planning will be critical for further development and for their sustainable management.

The Greek experience indicates that constructing and operating RO units is made possible by state support (in the form of subsidies). The energy intensity of RO units remains high. However, RO technology, although with high cost, is reliable and offers potable water of adequate quality and quantity. Therefore, technical and operation policy challenges (including securing adequate funding) should be addressed so that the implementation of RO technology will further enhance energy efficiency and will be a part of an integrated water management system.

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