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Responding to water challenges in Greece through desalination: energy considerations

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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 article also discusses the use of renewable energy sources as a means for reducing the energy intensity of desalination.

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Introduction

Economic development and social well-being depend on two vital resources, energy and water, the links between which are both complex and significant: energy production requires large quantities of water, and supplying water requires significant amounts of energy. The analysis of the "water–energy nexus" demands an integrated view of the production and consumption chains of each resource (Marsh, 2008, presents a depiction of the water–energy nexus complexity), focusing on the core operational components, i.e. infrastructure and technologies (Scott et al., 2011).

Particularly for the water supply chain, there is a pressing need to map energy demand along the stages, as the energy intensity of each stage depends on the input water quantity and quality. Overall, the stages of the water supply chain tend to become more energy-demanding over time (Schumacher, 2007). Energy intensity can increase with growth in water demand, extraction of water from deeper bores, longer interbasin water transfers, stricter water quality standards, and greater restrictions on wastewater discharge. Despite all this, there are options for improving energy efficiency. For example, as highlighted by the European Innovation Partnership for Water (EIPW, 2015), there is significant potential for increasing energy use efficiency in water supply systems by introducing low-energy technologies in water and wastewater processes and increasing the use or efficiency of renewable resources.

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The energy intensity of a water supply chain can vary depending on the sources of water (type, seasonal availability, quality) and end-user characteristics (infrastructure, consumption patterns). The anticipated impacts of climate change on water resources (IPCC, 2014), the increased competition among users, and the "loop effect" of the energy–water interlinks are expected to lead to a 35% increase in energy consumption by 2035. This could in turn lead to an 85% increase in water consumption and thus energy requirements for water treatment and distribution (International Energy Agency, 2012; Rodriguez, Delgado, DeLaquil, & Sohns, 2013). Given these interlinkages, it is important to analyze the energy–water relationship, particularly in water-scarce regions.

In water-scarce regions, three main supply management approaches are followed: (1) transferring water from areas of relative abundance to areas of relative scarcity; (2) intensive use of available resources; and (3) use of alternative water resources (e.g. desalination, wastewater reuse). All three result in an increase in the energy intensity of the water system, leading to high cost of water, either for consumers or governments. Thus, any improvements in the efficiency of water and energy use may lead to benefits for the environment as well as reductions in the cost of water provision paid by consumers or governments.

This article discusses the energy-for-water links in Greece, focusing on the most water-scarce regions of the country, the arid and semi-arid islands of the Aegean Sea. On these islands, desalination currently offers the most effective solution for meeting public water demand, though it is one of the most energy-intensive methods (together with transport and conveyance). Syros Island, located at the centre of the Cyclades island complex, is used as a case study to demonstrate the links between water production and energy consumption, and the need to increase energy use efficiency in the isolated water systems of the Greek Islands.

The water system of the Greek islands: energy considerations

The problem of scarcity

Greece is characterized by the longest coastline in Europe, at roughly 14,000 km. The country has about 2,500 islands (see Figure 1), with a total area of 21,580 km^2. The population of the islands is estimated at 1,633,433 (EL.STAT., 2012).

The climate on the Greek islands is Mediterranean (wet winters and dry summers), with low annual precipitation (less than 400 mm, especially for the Aegean Islands; Hellenic National Meteorological Service, 2015). The low precipitation, in addition to the geological formations, makes the storage of surface or groundwater of sufficient quantity and quality impossible on some islands. Moreover, the seasonal summer peak in water demand (due to irrigation and tourism), the high water losses due to leakages in old distribution networks, the absence of integrated water management systems and the degradation of aquifers due to over-pumping all intensify water-scarcity problems and tend to create local water deficiencies (Table 1).

Water deficiency problems are addressed in different ways according to the special characteristics of each island. The current practices for domestic water supply, according to Nokas (2002), are: (1) desalination of sea or brackish water using reverse osmosis (RO) and/or thermal technologies; (2) water transfer from the mainland or nearby islands on tanker ships; (3) large reservoirs, dams and tank-lakes that store surface and rain water; and (4) boreholes.

Figure 1. Map of Greek islands and island complexes.

Table 1. Island complexes in Greece (EL.STAT., 2012).

Complex	Number of islands	Population	Water balance (Special Secretariat for Water [SSW], 2013–14)
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

Domestic use of surface water is limited to the largest islands; the majority of the Aegean Islands use groundwater from boreholes and/or desalinated water from brackish or seawater desalination plants. In many cases, water is transferred by tankers from the mainland or from nearby islands to assist water supply. Despite being costly and unsustainable, this practice remains popular due to the unwillingness of some public officials to adopt alternative solutions such as desalination.

Desalination: an energy-intensive water source

In the 1960s, when it was understood that water transport was not cost-effective, desalination was identified as a potential tool for addressing water scarcity on the Greek islands. The first attempts at desalination involved the use of solar still collectors filled with seawater.

Heat provided by the sun evaporates the water, separating it from salt and other impurities. The vapour is condensed on an inclined glass surface at the top of the collector, and the distilled water is collected in the edge. From 1964 to 1973 five solar still systems of different sizes were installed on the islands of Symi, Kastelorizo, Kimolos, Aegina and Patmos. Their individual water production was approximately 3 L per day per m^2 of collector area. The projects failed for various reasons, including unskilled personnel, operation malfunctions due to bad design (at the early installations), the lack of maintenance programmes (Deligiannis & Belesiotis, 1995), and conflicts of interest with water tanker owners (success in the operation of desalination plants would result in significant reduction in the quantities of water they transferred).

The second attempt at using desalination was in Syros in 1969–70 with the construction of a thermal multi-stage flash unit of 1200 m^3 daily capacity. The desalination unit operated with fuel oil and was in operation until 1984, by which time several technical problems had emerged, mostly due to scaling in the heat exchangers. The technical problems, in combination with the high cost of spare parts and the cost of oil, led to the transition towards RO (Vakondios, 2015).

In 1977–78, an electrodialysis reversal plant with daily capacity of 15,000 m^3 was installed on the island of Corfu for the treatment of low-salinity brackish water (up to 2000 ppm). Its operation was halted due to functional problems after a few years (Dafnis, 2005). Its specific energy consumption was 1.7 kWh/m^3 (Arnold, 1979).

The first RO units for public water supply were installed on the islands of Ithaca and Mykonos in 1981–82. The actual specific energy consumption of the Ithaca RO plant was 15 kWh/m^3, and the installed power of the unit was 510 kW. Since these first installations, RO has been the preferred technology for water desalination; it has been used for more than 30 years for public water supply, and privately by hotels and luxury houses. The reasons for the adoption of RO are: (1) modular operation to meet seasonal variations in demand; (2) relatively low water needs; (3) compact design; (4) fast installation (2–3 months); (5) low energy consumption relative to other desalination methods; and (6) easy operation.

Presently, the total installed desalination capacity (for public use in the islands) is around 52,000 m^3/day, distributed among 30 islands (Figure 2), with 9000 m^3/day brackish water feed and 43,000 m^3/day seawater feed. The majority of the desalination units are installed on islands with autonomous electrical energy production grids (22 of the 30 islands), and the rest are on islands that are interconnected with the mainland's electrical grid through underwater cables. The rate of desalination development was quite low until the early 2000s, but rose rapidly prior to the Athens Olympic Games in 2004 (Figure 3). Around 10 islands are expected to install desalination plants, with a total capacity of 11,000 m^3, in the coming years.

The energy consumption of RO units is high and takes place almost exclusively in three pump stages (pumping water from the sea to the desalination plant; pretreatment and desalination; and product water forwarding to the distribution tank). Over the years, great advances have been made to reduce energy consumption through the use of more efficient energy-recovery devices. Today, all desalination units (even small units producing around 100 m^3/day) use efficient and reliable energy-recovery devices to significantly reduce energy use. The specific energy consumption for selected desalination units installed on the islands is presented in Figure 4 from data acquired from manufacturers and local water companies (Culligan Hellas SA, personal communication on technical characteristics of existing

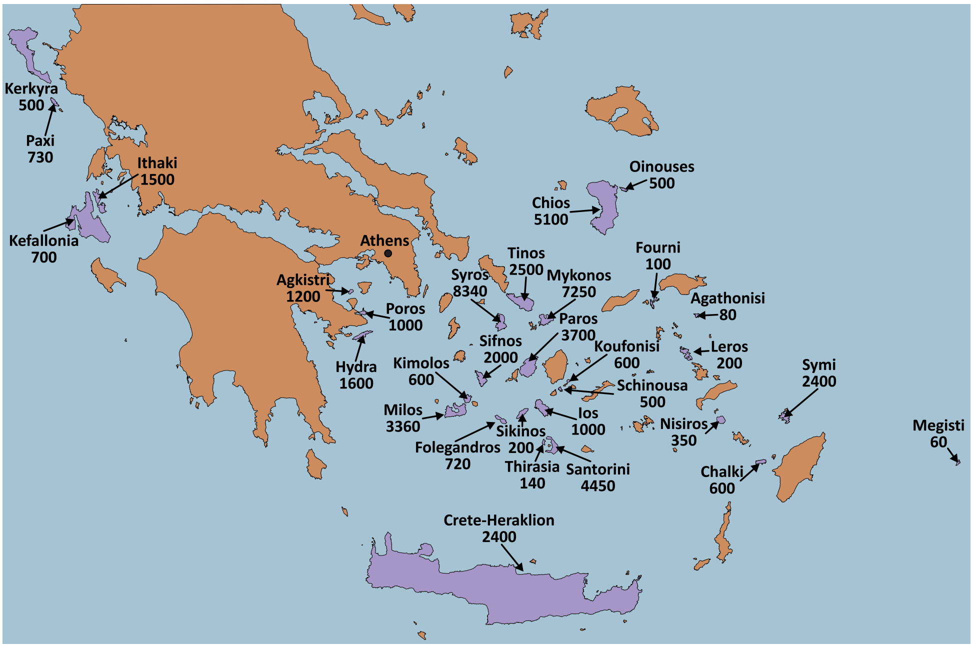

Figure 2. Desalination units in the Greek islands (Cuenca, 2012; Dagkalidis, 2009; Dalmira, 2013; imerisia.gr., 2009; Kampourakis, 2013; Karagiannis & Soldatos, 2007; sychem.gr., 2011; TEMAK SA, personal communication, 2014; Vakondios, 2015; Ventouris, 2013).

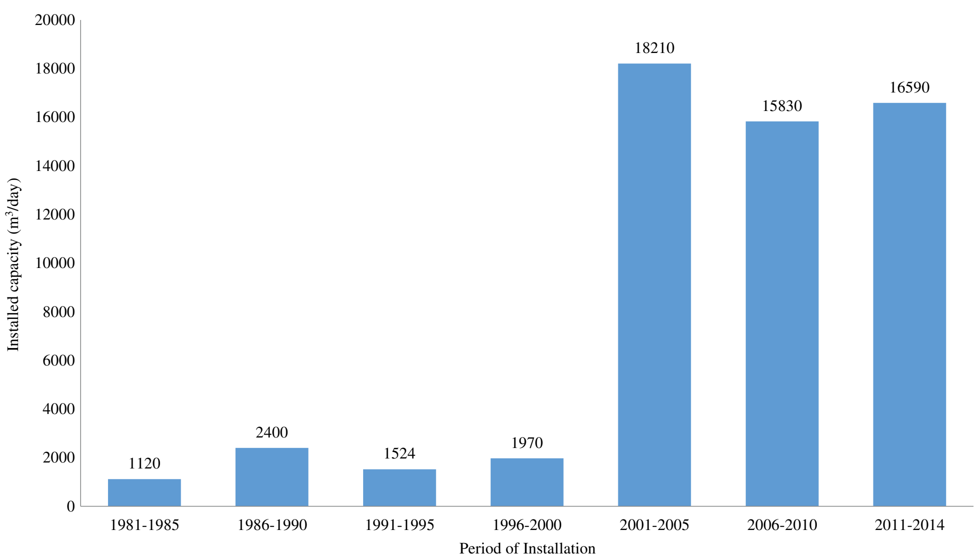

Figure 3. Desalination facilities in Greece, 1981–2014 (Cuenca, 2012; Dagkalidis, 2009; Dalmira, 2013; imerisia.gr., 2009; Kampourakis, 2013; Karagiannis & Soldatos, 2007; sychem.gr., 2011; TEMAK SA, personal communication, 2014; Vakondios, 2015; Ventouris, 2013).

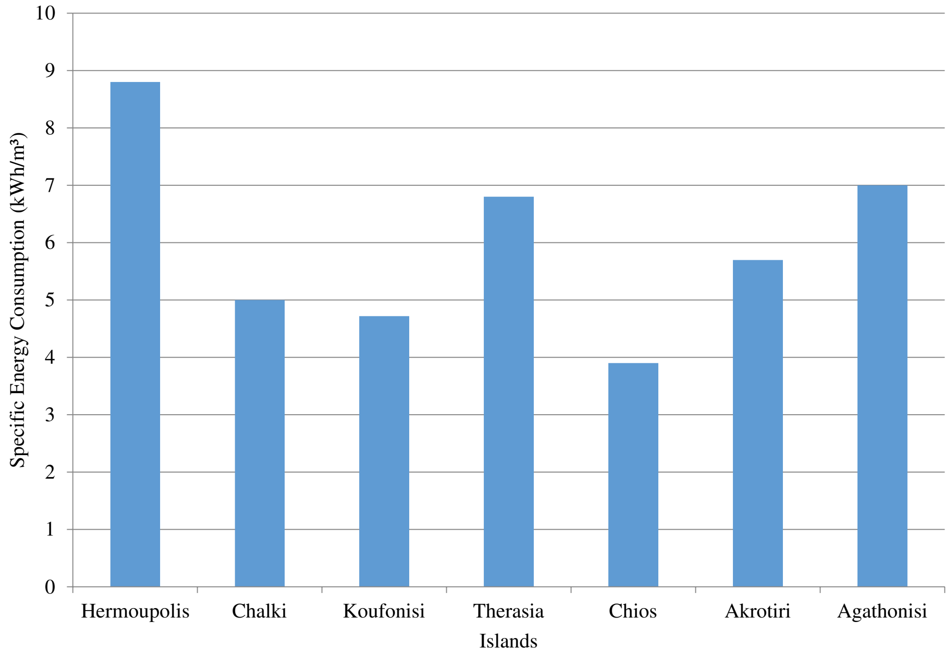

Figure 4. Specific energy consumption of selected desalination units in Greece (TEMAK SA, personal communication, 2014; Syros WSSC, personal communication, 2014).

desalination units, 2014; TEMAK SA, personal communication, 2014). Both booster and high-pressure pumps are included in the calculations.

In Chios, Koufonisi and Chalki, the specific energy consumption is estimated at less than 5 kWh/m^3. In Thirasia, Agathonisi and Akrotiri, this value is higher due to the small size of these plants (installed capacity less than 250 m^3/day), making auxiliary energy consumption relatively more important. In Hermoupolis, the capital of Syros Island, the actual recorded specific energy consumption is 9 kWh/m^3. This high value is attributed to the use of older-technology energy-recovery equipment, installed before 2002, when pressure-exchanger technology was expensive and technologically immature.

The case of Syros Island: comparing the operation and energy costs of desalination

The urban water supply in Syros consists mainly of desalinated water. The island has an autonomous grid, and the electrical energy supply relies on diesel fuel. Currently, there are 13 RO units distributed in five areas (Figure 5). Twelve of these use the mature and reliable, but also less efficient, Pelton wheel turbines as energy-recovery devices, and one uses the more advanced pressure exchanger. The total capacity of all the plants is 8340 m^3/day, with individual capacities ranging from 250 to 2000 m^3/day. According to the Hellenic Electricity Distribution Network Operator (HEDNO, 2012) and the Syros Water Company (Syros Water Supply and Sewerage Company [Syros WSSC], 2014), more than 11% of the total electricity produced in the island is used for water production, and the desalination power demand when plants are running at full capacity is 5.2% of the conventional installed power.

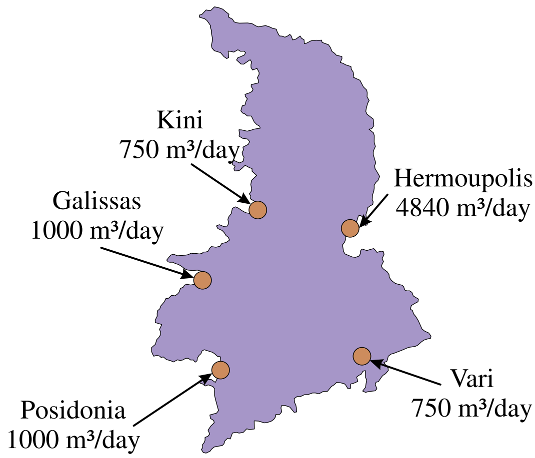

Figure 5. Location and capacity of desalination plants in Syros Island.

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

	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	2010–13	2009	2008
Energy cost (€/kWh)	0.086	0.089	No data(assumed same as Athens)
Data sources	Syros WSSC (2014)	EYDAP, Athens Water Supply & Sewerage Company (2011); Georgalas (2010)	EYATH, Thessaloniki Water Supply & Sewerage Company (2010); Georgalas (2010)

The 13 desalination units have a total installed power of 2.08 MW (only booster and high-pressure pumps). The cost of energy is the main operating cost for the Syros Water Supply Company, which estimates the total operational cost at €1.2–1.6/m^3. The participation of energy in the cost of water is €0.7/m^3 (about 45%), with an average energy cost of €0.086/kWh (Vakondios, 2015). Energy production is subsidized in order to offer consumers an electricity rate similar to that of the mainland. Thus, the real cost of energy is higher than what is billed, and the participation of energy in the cost of water can be as high as €1.7/m^3, which is roughly 240% of the billed energy for water production.

The energy-for-water connection is described using three indicators (energy consumption per volume of water sold, energy cost per volume of water sold, and energy consumption per capita), including both the water supply and wastewater treatment processes in the analysis. The present analysis concerns only the desalination plant of Hermoupolis, for which the required data are available. For the purpose of this comparison, the same results are given for the two major water supply systems in Greece (Table 2): the Athens water supply system, which relies exclusively on fresh surface water; and the Thessaloniki water supply system, which is based on a mix of fresh groundwater and fresh surface water.

Assessment indicators

Figure 6 presents the energy consumption per volume of water sold in the three water systems (water supply and treatment). Athens has a specific energy consumption of 0.75 kWh/m^3, Thessaloniki has twice that, and Hermoupolis' consumption is 15 times that of Athens, at 11.2 kWh/m^3. The cost of energy follows a similar pattern, as shown in Figure 7. Similar ratios also apply for the case of energy demand for water supply per capita. The value in Syros is 14 times that in Athens, and more than twice that in Thessaloniki (Figure 8). The assessment indicators showcase how the source of water affects the demand for energy, with desalination plants having the highest demand.

Monthly variation of specific energy consumption

Water demand on the Island of Syros is higher during the summer period, mainly as a result of tourist influx. For example, water production in August is about 85% higher than in February

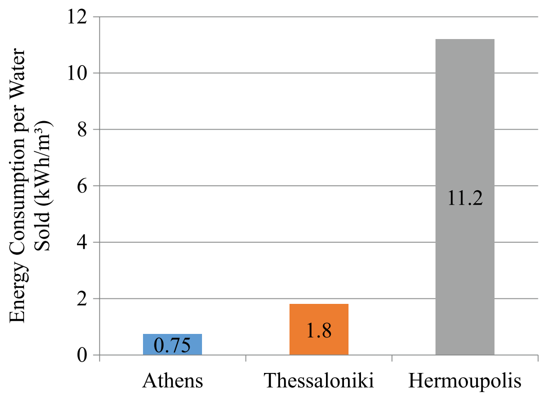

Figure 6. Energy consumption per volume of water sold in the water supply systems of Hermoupolis, Athens and Thessaloniki (Syros WSSC, 2014; EYDAP, Athens Water Supply & Sewerage Company, 2011; EYATH, Thessaloniki Water Supply & Sewerage Company, 2010; Georgalas, 2010).

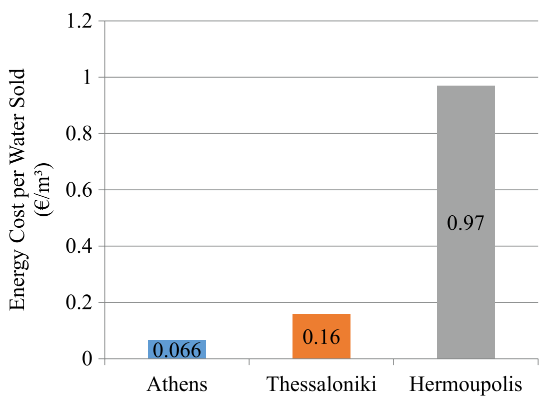

Figure 7. Energy cost per volume of water sold in the water supply systems of Hermoupolis, Athens and Thessaloniki (Syros WSSC, 2014; EYDAP, Athens Water Supply & Sewerage Company, 2011; EYATH, Thessaloniki Water Supply & Sewerage Company, 2010; Georgalas, 2010).

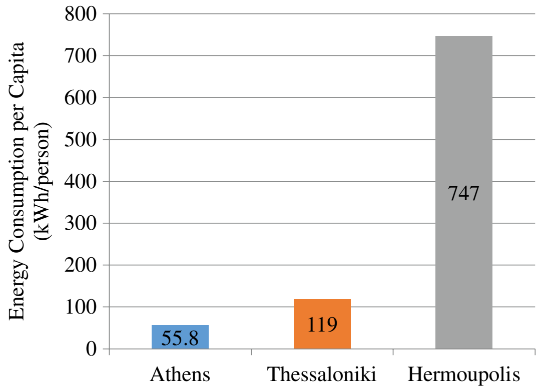

Figure 8. Energy consumption per capita in the water supply systems of Hermoupolis, Athens and Thessaloniki (Syros WSSC, 2014; EYDAP, Athens Water Supply & Sewerage Company, 2011; EYATH, Thessaloniki Water Supply & Sewerage Company, 2010; Georgalas, 2010).

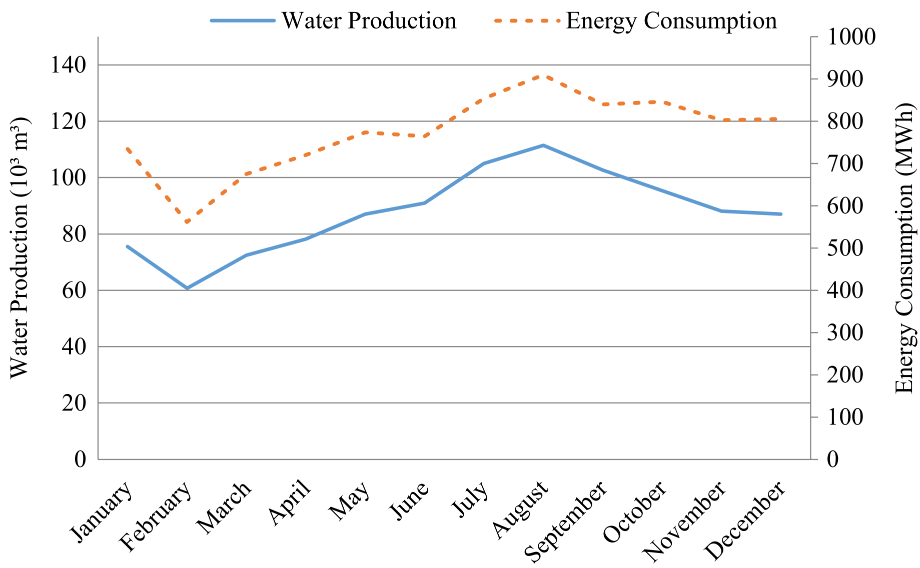

Figure 9. Monthly water production and energy consumption for the Hermoupolis desalination plant (average values for 2010–2013) (Syros WSSC, 2014).

(Figure 9). Similar variability applies to the energy consumed by the desalination plant. In February, the energy required is only 560 MWh, but in August it increases by 62.5%, to 910 MWh (Figure 9). This difference shows that the desalination process is more efficient in summer than in winter (Figure 10). Desalination specific energy for the Hermoupolis plant is about 8.1 kWh/m^3 in August and 9.7 kWh/m^3 in February, a reduction of about 16.5%. This reduction is attributed to three main factors: (1) the desalination units are working continuously during the summer period, minimizing start-and-stop cycles and consequently the energy-consuming cleaning process; (2) the higher temperature of seawater during summer changes water properties such as its viscosity, lowering the specific energy demand of the

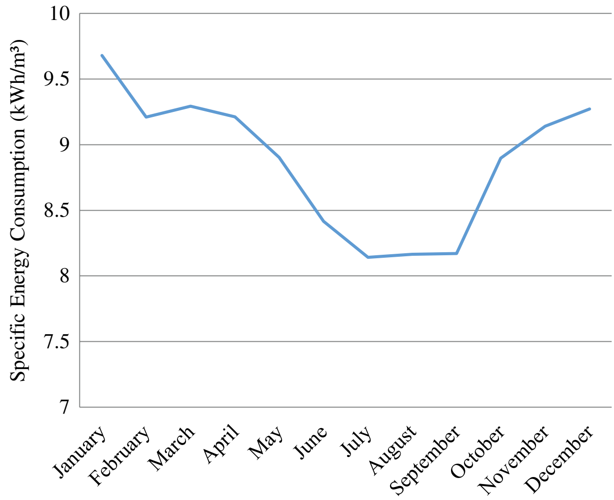

Figure 10. Specific energy consumption of the desalination units in the Hermoupolis desalination plant (average values for 2010–2013) (Syros WSSC, 2014).

high-pressure pump for the desalination process (Water Reuse Association, 2011); and (3) as the Hermoupolis desalination plant consists of several desalination units, each 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.

Desalination as a supply option

The per capita annual water consumption for domestic use in Hermoupolis is estimated at 66.6 m^3 (Table 2). This value is almost equal to the water consumption per capita in the city of Thessaloniki, and 12% less than in Athens. It is important, however, to note that there is a significant difference between water use rates by local inhabitants and tourists (about 120 L/day and 200 L/day, respectively), giving the 'misleading message' that even though Syros is lacking in water resources, the consumption is as high as in the urban centres of Thessaloniki and Athens. The summer peak demand increases the per capita consumption, and if the current tourism development pattern continues, new water supply resources (i.e. new desalination plants) may be required. This claim is supported by the fact that water consumption in Hermoupolis increased by 5.6% from 2009 to 2013 (Syros WSSC, 2014).

New desalination plants to meet an increasing water demand will, thus, increase energy requirements of the isolated water systems, if energy efficiency measures are not considered.

Desalination with renewable energy sources

The use of renewable energy for desalination offers significant benefits in comparison to conventional energy systems. Although renewable energy desalination systems have higher installation costs, their operating costs are lower and the cost of expensive fuel oil is avoided. Higher wind speed and solar radiation occur during summer, when the water demand is higher, and thus renewable systems can have lower installed power.

Renewable energy has been identified as one possible energy source for supporting desalination systems in general and in the Greek islands especially due to their high renewable energy potential in the forms of solar, wind, and in certain cases geothermal energy. Mean wind speed varies from 5 to 7 m/s, but in some areas it can be much higher. Annual solar radiation ranges from 1400 to 1700 kWh/m^2, and there are important high-enthalpy geothermal fields on some islands, such as Milos, Kimolos, Nisiros and Thira. Since the introduction of solar stills, numerous attempts have been made to employ renewable energy for desalination, both on pilot and commercial scales. The Greek state has promoted renewable-energy-powered desalination systems by giving priority in the licensing procedure to renewable systems and by providing a higher tariff for renewable energy sold into the grid.

Pilot units

A desalination unit of 80 m^3/day with a geothermal energy source, using multi-effect distillation technology, was constructed in the framework of a European project and operated successfully for demonstrations in Kimolos in 1997–98 (Karytsas, Alexandrou, & Boukis, 2002). The cost of water production was estimated at €1.7/m^3. At the end of the project, however, the desalination equipment was abandoned. A very small stand-alone pilot unit with a capacity of 4.8 m^3/day, powered by a 15 kW wind turbine, was installed in Therasia in 1997 and was in operation for many years. In 1998 a 500 kW wind turbine was installed on the island of Syros to drive a 900 m^3/day RO unit in stand-alone and grid-connected modes. The coupling of the two systems, however, was not achieved.

Hydriada, a floating RO desalination unit (80 m^3/day) with wind turbine and photovoltaics attached, was completed in 2007. It was a prototype designed to meet the water needs of 300 inhabitants on a small, arid island. The island of Iraklia was selected for the pilot application. Early technical problems with the unit, in addition to local-authority indifference and high maintenance costs, resulted in the project's being abandoned (Tsamopoulos, 2014).

Commercial units

A successful desalination plant that exploits wind energy was constructed on the island of Milos during 2007–09. The project consists of three similar RO units with a combined capacity of 3360 m^3/day and low energy consumption (approx. 3.5 kWh/m^3), powered by an 850 kW wind turbine. The RO units and the wind turbine are assisted by a supervisory control and data acquisition system to optimize the operation of the system as both the wind turbine and the desalination power load are connected into the island's autonomous grid. This optimization is achieved by the use of operation scenarios depending on weather and water demand forecasting and the current status of the water tanks. Another innovation of this project is its ownership status: the desalination unit and the wind turbine are private investments, subsidized by the state, and they work under contract partnership with the local municipality for providing water.

A mechanical vapour compression desalination system using wind energy (330 kW) was constructed in the island of Symi in 2009. This system was not successful due to technical problems that resulted in very low water production. The system was stand-alone, and its specific energy consumption was about 14.5 kWh/m^3 (Bundschuh & Hoinkis, 2012). Operation was halted in 2011 after a fire, and it was never repaired. On the very small island of Strogilli an autonomous RO unit of 8 m^3/day was installed in 2013 with the use of 20-kilowatt-peak photovoltaics. The unit covers the water needs of a small army camp.

Discussion and conclusions

Desalination has been adopted and used extensively as a solution for increasing water supply on the water-scarce Greek islands. Some initial efforts in the 1960s and 1970s using solar distillation plants were unsuccessful, mainly due to limited technical know-how and expertise, insufficient maintenance, and high operation and maintenance costs. Advances in desalination technology, together with the pressing need to meet demand in the rapidly developing tourist destinations, increased the prospects of desalination as a supplementary source of potable water. Both at the commercial and pilot levels, efforts have been made to enhance the performance of desalination. Technical limitations and economic considerations are the main reasons that such efforts were not always successful.

The main technical challenge is the reduction of the energy consumption of desalination units. As energy is a high cost factor for desalination, methods for lowering the specific energy consumption can help reduce costs. Another option is the use of cheaper energy sources. Renewable energy sources can offer a viable way to reduce pressure on energy systems, and thus developing renewable-energy-powered desalination plants is a priority in the Greek energy and water sectors, and a number of incentives are being considered. Energy storage is not a practical solution due to its high investment cost and the low lifetime of battery systems. Hybrid systems, combined with operation optimization schemes, can offer the appropriate solutions; however, wind parks and photovoltaics often face social opposition, especially in the tourism-dependent Greek islands, as locals find that the aesthetic value of the landscape is reduced. Environmental effects and land-use conflicts may also hinder the use of integrated renewable-energy-powered RO systems. Studies and pilot systems should be promoted that will lead to the optimal design and operation of renewable-energy-powered RO desalination systems. Historical data on daily water desalination production patterns and data on renewable energy sources can be used towards improved exploitation of renewable energy for water production.

Water deficiency in many arid and semi-arid islands is addressed with water transfers at the expense of the central government, whereas the operation and maintenance cost of desalination plants is subsidized, as, for social reasons, the true cost of water cannot be fully transferred to the locals (water users). In an era of economic crisis, this situation may not be viable, and there is a need to move from the established to more sustainable solutions. Different forms of private-sector involvement (as e.g. in the case of Milos), though not always socially acceptable, should be examined. In addition, as water and energy resources face increasing pressure over the next few decades, evaluating the trade-offs and encouraging cross-sector planning is crucial for their sustainable management and for development.

The Greek experience shows that building and operating desalination units is made possible by state support (in the form of subsidies). As seen from the comparative analysis presented in this article, the energy intensity of desalination plants remains high. However, RO technology, though costly in energy and financial terms, is reliable and provides adequate quality and quantity of potable water. Therefore, specific technical and policy challenges (including securing adequate funding) should be addressed so that RO technologies can continue to improve energy-efficiency and be part of an integrated water management system on the Greek Islands.

Overall, water supply is a politically sensitive topic on the islands. As a result of the lack of public awareness on water use and the technical problems of the early desalination units, a significant part of the population has formed a negative opinion of desalination systems. The state needs to inform and educate local populations on the long-term benefits of water desalination, while desalination plant owners have to maintain appropriate standards to ensure their efficient operation, taking the local environment into consideration. If social acceptance is achieved, especially in the tourism-dependent Greek islands, where the aesthetic value of the landscape is a crucial element of the local economy, renewable energy (wind parks and photovoltaics) could help in addressing energy challenges. An additional factor that should be addressed is the condition of water networks – poor on most islands and totally absent in many areas – which represents an obstacle for the widespread use of desalination. A flexible, independent public department or agency for the supervision of all desalination units for public supply could be created, in order to secure the application of good practices in all stages of water production, to test the final water quality, and to provide incentives for lowering energy demands. The "success stories" of desalination can be used as examples to promote it.

Water and energy security will be among the policy priorities in the next decades for Greece. Detailed assessments of the energy-for-water nexus for desalination can illustrate the differences between the various systems used in the islands and indicate options (best operational/management practices) for their improvement. Technology innovation will certainly increase energy efficiency; however, inter-regional and international cooperation will be necessary, as the challenge presented by the water-energy nexus is too large for any country, region, development finance institution or implementing agency to tackle alone.

Disclosure statement

No potential conflict of interest was reported by the authors.

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