DESALINATION IN GREEK ISLANDS BY USING RES

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EXTENDED ABSTRACT

Water scarcity is a perennial problem in Greek islands that remains unsolved for most. The issue is often dealt with using water transfers from the mainland by tanker ships subsidized by the Greek government. As a result, the cost of water can be as high as 10€/m^3. This problem emerges as a combination of factors associated with the supply and demand of water. In terms of supply, most of the islands are small dry rocky formations with limited precipitation during the year, with water wells that produce brackish water unsuitable for consumption. In terms of demand, the most critical parameter affecting the water shortage problem is the high demand during the summer months, a byproduct of seasonal tourism. Although some islands can satisfy water demand during winter, the water quality is not as good as that of the mainland. Moreover, even during winter the local resources are insufficient in some islands, so the supply is augmented using tanker ships.

Desalination is viewed as a suitable long term solution to the water shortage problem, although a number of technical and feasibility aspects need to be examined before a solution can be deemed applicable. The selection of desalination method to be applied in each island is critical, as it affects both feasibility and technical aspects. Recently, the Greek Government invited experts and stakeholders in a public dialogue on the feasibility and technical aspects concerning the installation of reverse osmosis desalination units in 15 islands in the Cyclades and the Dodecanese Prefectures.

Reverse osmosis is the technology proposed in this the present work. The possibility of satisfying desalination energy needs by using renewable energy is a very promising option in Greek Islands which have significant resources (high wind speed and solar radiation) that peak concurrently with the water demand.

The present work estimates water cost in each island by examining a number of alternative configurations and operational rules. The most important factor that determines the feasibility of a desalination plant is low utilization, as the common design practice has been to focus on satisfying peak water demand in the summer (high installation cost), while during the rest of the year the water production is limited. The high installation cost with limited annual water production can result in high water cost; however the use of renewable energy can reduce operational costs and even provide a supplementary income through the sale of the electrical energy surplus. Additional factors that can influence the installation cost and can be adjusted are the number of desalination units and their capacity, the period and length of operation and the renewable energy system configuration.

Keywords: Desalination, Renewable energy, Greek islands, Water and Energy production

1. INTRODUCTION

Water desalination is a practice that can solve the perennial problem of water scarcity in Greek islands. Most of the islands have limited water production as the precipitation is low and the local geological formations are not adequate to store sufficient quantities of potable water. Thus, only a portion of the annual demand can be covered through local resources, mostly during the winter, when the water demand is lower. Water scarcity not only affects the standard of living of the local populations, but also sets back island development in terms of tourism, industry and agriculture.

Although the water shortage problem is common to most islands, the applicable solutions for each are different, according to the local attributes (Litti, 2008). Desalination is a mature solution that can be applied to the majority of islands in order to address the water shortage problem. Reverse osmosis is a preferred desalination method, as it is easy to install and operate and the specific energy needed per cubic meter is low (4 kWh/m^3 for a modern reverse osmosis unit for sea water with energy recovery).

Electrical energy is primarily needed for desalination, and is available to the desalination unit through the local grid. In most of the Greek islands that face water shortage problems, the local grids are small, isolated networks with diesel engines as the primary power source (Stefopoulou, 2008). Electrical energy demand patterns in the islands coincide with those for water demand. The high electrical energy demand during the summer and low demand during the winter require the public power corporation (PPC) to invest in high capacity units with low annual utilization. The local authorities address the water problem with water transfers from the mainland (or from other islands).

Desalination can be used to cover water needs, and by using renewable energy to cover the energy needs of the desalination process, water production becomes clean and sustainable. The renewable sources that can be used most easily are solar and wind energy. Desalination energy demands are covered by renewable energy production and the surplus is supplied to the grid. If the renewable energy is not sufficient to cover the demand, then energy is obtained through the grid.

The configuration that solves the design problem is that which minimizes the water cost from the investor point of view. A configuration is defined by a set of design parameters such us the desalination capacity, the photovoltaic installed power etc. For this reason, a software tool was developed using hourly simulation to identify the best configuration by examining a large amount of realistic design parameters. The simulation procedure will be obligatory for licensing this type of investments, according to the “Regulation of License for Energy Production by RES” (Annex 2) of the Greek Energy Authority.

2 METHODOLOGY

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

2.1 Desalination Unit

Desalination capacity ($Q_{cap} - m^3/day$) is one of the design parameters. The energy needed for producing a cubic meter of fresh water is called specific energy ($Sp - kWh/m^3$) and is given for a specific desalination unit and water salinity. Thus, the average power that is needed during normal operation is:

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

The hours of operation of the desalination unit each day with respect to the daily water demand can be derived as:

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

The min operator denotes that hours of operation needed for each day cannot be more than 24hr. 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 are a critical factor for the exploitation of the renewable sources. If the renewable source is solar power, then the best operation strategy is to operate the unit in the hours around noon (**Figure 1**).

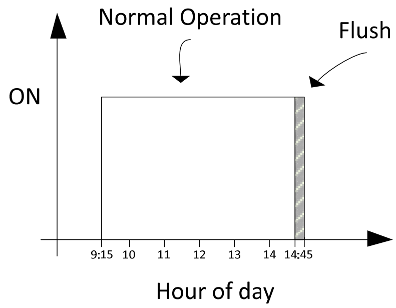

Figure 1: Reverse osmosis operation schedule (example)

If the renewable source is the wind, then the hour of the day when the desalination plant can produce water with high wind energy penetration depends on the micro scale of the location of the power plant. In most cases, it is windier during the afternoon. The desalination production distribution is noted as $OP(t)$ and gives the percentage of operation for every hour t for one year ($OP(t)$ is 100% when the desalination unit works for an hour without start and stop, 0% when the desalination is not working at all, and a value among 0% and 100% if the desalination starts or stops in this hour). Also, desalination will remain in operation $(fm - hr)$ for cleaning the membranes (flushing) just after the end of daily normal operation.

The energy needs for desalination every hour (t) is given by

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

2.2 RES System

The renewable power production system can be photovoltaic, wind turbines or both.

2.2.1 Photovoltaic Model

The photovoltaic installed power is a design parameter $\left(N_{pv} - kWp\right)$.

The mean energy produced by a photovoltaic array is given by:

$$E_{PV}(t) = \eta_{inv} \cdot \eta_{loss} \cdot N_{PV} \cdot \frac{H(t)}{H_{ref}} \cdot T\ (kWh) \tag{4}$$

Where $H(t)$ is the mean hour solar radiation for every hour (t) in (kWh/m^2), T is the duration of the simulation step (usually $T = 1hr$), H_{ref} is the standard test condition reference radiation $(1000W/m^2)$ and η_{inv} and η_{o_eff} are the inverter efficiency and overall efficiency respectively. The effect of temperature on module efficiency is not taken into account.

2.2.2 Wind Energy Conversion System Model

The total installed power of the wind turbines is a design parameter $(N_{WEC} - kW)$. The mean energy produced by the wind energy conversion system is given by:

$$E_{WEC}(t) = \eta_{loss} \cdot P_{WEC}\big(V(t)\big) \cdot T\ (kWh) \tag{5}$$

Where $P_W\big(V(t)\big)$ is the power produced by the wind energy system for the wind speed $V(t)$. In the simple case of a single wind turbine the power from the WEC system is the power curve of the wind turbine:

$$P_{WEC}\big(V(t)\big) = N_{WEC} \cdot f(V(t)) \quad (6)$$

Where, $f\big(V(t)\big)$ is a normalized wind curve that gives the percentage of nominal power produced.

2.2.3 Energy Flow Algorithm

For a simulation step, where desalination is starting up or shutting down, the total energy of the renewable energy source that is available is equal to the percentage of time that desalination is operating for this step. Thus:

$$E_{RES_{av}}(t) = \big(E_{WEC}(t) + E_{PV}(t)\big) \cdot OP(t) \quad (7)$$

The energy produced from renewable sources when the desalination plant is not operating is:

$$E_{rest}(t) = E_{WEC}(t) + E_{PV}(t) - E_{RES_{av}}(t) \quad (8)$$

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

$$E_{NET}(t) = E_{RES_{av}}(t) - E_{DES}(t) \quad (9)$$

If $E_{NET}(t) \geq 0$, then there is renewable energy not exploited from the RO unit and is available for the grid

$$E_{Togrid_{av}}(t) = E_{NET}(t) + E_{rest}(t) \quad (10)$$

If $E_{NET}(t) < 0$, then there is additional energy needs that have to be covered from the utility grid

$$E_{Fromgrid}(t) = E_{NET}(t) \quad (11)$$

According to Greek legislation for desalination by RES, there is an upper level of the amount of energy that can be infused into the grid. This is a percentage (a_{inf}) of the energy produced during the hour. Thus the energy that can be sold to the grid is:

$$E_{Togrid}(t) = \min\big(E_{Togrid_{av}}(t), \big(E_{WEC}(t) + E_{PV}(t)\big) \cdot a_{inf}\big) \quad (12)$$

The amount of energy that cannot be infused to the grid, is dumped

$$E_{Dump}(t) = E_{Togrid_{av}}(t) - E_{Togrid}(t) \quad (13)$$

The annual energy demand for the desalination is:

$$E_{DES_{an}} = \sum_{t=1}^{8760} E_{DES}(t) \quad (14)$$

The renewable energy collected in one year is:

$$E_{RES_{an}} = \sum_{t=1}^{8760} (E_{WEC}(t) + E_{PV}(t)) \quad (15)$$

And the annual energy that is not exploited by the reverse osmosis unit is:

$$E_{NEXP_{an}} = \sum_{t=1}^{8760} E_{Togrid_{av}}(t) \quad (16)$$

2.2.4 Energy Indicator

In order to evaluate the performance of the desalination system by using renewable sources it is important to use indicators. The indicator “Renewable to Energy Demand” (RW) gives the percentage of the renewable energy used for water production to the total energy used (equal to energy demand):

$$RW = \frac{E_{RES_{an}} - E_{NEXP_{an}}}{E_{DES_{an}}} \quad (17)$$

2.2.5 Economic Evaluation

Economic evaluation of a reverse osmosis water production plant with renewable energy can identify profitable and optimal configurations.

2.2.5.1 Water Cost

The water cost per m^3 can be calculated from:

$$WC = \frac{(IC_{EN} + IC_{RO}) \cdot R + OM + EC - ES}{WP} \quad (18)$$

Where:

- IC_{EN} is the installation cost of the power system

$$IC_{EN} = IC_{WEC} + IC_{PV} \quad (19)$$

  - o IC_{WEC} is the cost of the WEC system
  - o IC_{PV} is the cost of the PV system
- IC_{RO} is the reverse osmosis installation cost
- R is the annuity factor

$$R = \frac{i}{1 - (1 + i)^{-n}} \quad (20)$$

  - o i is the interest rate
  - o n is the duration of the investment
- OM is the annual operation and maintenance cost that contains consumables (CN), (filters, spare parts), chemicals for post treatment and pretreatment (CHM), membrane replacements (MR), labor (LB) and insurance (IN).

$$OM = CN + CHM + MR + LB + IN \quad (21)$$

- EC is the annual cost of energy

$$EC = EC_{SP} \cdot \sum_{i=1}^{8760} E_{Fromgrid}(t) \quad (22)$$

  - o EC_{SP} is the specific cost of energy $(€/kWh)$
- ES is the income from energy sale

$$ES = ES_{SP_{PV}} \cdot \sum_{i=1}^{8760} E_{Togrid}(t) \cdot f_{PV}(t) + E_{SP_{WEC}} \cdot \sum_{i=1}^{8760} E_{Togrid}(t) \cdot (1 - f_{PV}(t)) \quad (23)$$

  - o $ES_{SP_{PV}}$ is the specific price of energy from photovoltaics $(€/kWh)$
  - o $ES_{SP_{WEC}}$ is the specific price of energy from wind turbines $(€/kWh)$
  - o $f_{PV}(t)$ is the contribution of the photovoltaic system to the renewable energy mixture

$$f_{PV}(t) = \frac{E_{PV}(t)}{E_{WEC}(t) + E_{PV}(t)} \quad (24)$$

- WP is the annual water production

$$WP = \cdot \sum_{i=1}^{8760} \frac{Q_{cap}}{24} \cdot OP(t) \quad (25)$$

3 CASE STUDY

3.1 Model Inputs

3.1.1 Water Demand

The islands studied in this work are presented in Table 1, along with their annual water transportation for the year 2008 and the minimum and maximum monthly quantities (Ministry data). The fluctuation from the minimum water that was transported to the maximum can be up to 15 times more for the island of Sikinos.

Based on analysis of historical data on the water transportation needs, for the design, an assumed increase of 20% on water demand will be taken into account.

3.1.2 Meteorological Data

The data needed for the simulation are the wind speed and the solar radiation in hourly time series for the duration of the year. Due to the fact that the availability of such detailed data is limited, mean monthly values for the wind speed and the solar radiation were used and transformed to hourly time series according to the methodology of Homer Software. The initial mean monthly data are from public databases for the closest area available.

Table 1: Water transported in the selected islands for 2008

Island	Annual Transportation (m^3)	Min Monthly (m^3)	Max Monthly (m^3)
Amorgos	25400	700	4500
Koufonisia	42600	1300	8500
Irakleia	15700	600	3000
Folegandros	53900	1300	10000
Sikinos	22800	400	6000
Therasia	12100	400	2000
Donoussa	2500	0	600
Leipsoi	41200	1500	7000
Megisti	63900	3800	9300
Patmos	172500	4500	30000
Halki	63500	3000	9000
Pserimos	3500	200	400
Arki	6600	0	1500

3.1.3 Cost Values

3.1.3.1 Installation Cost

The desalination unit installation cost (IC_{RO}) is given approximately in Table 2, according to the capacity of unit. These costs were retrieved through market research. The cost of the PV system was calculated as a fixed price of $3000€/kWp$.The installation cost of the WEC system is estimated at $1500€/kW$.

Table 2: Desalination cost as a function of the capacity

Daily Capacity (m^3)	Cost (€)	Daily Capacity (m^3)	Cost (€)
50	80000	350	305000
150	200000	550	380000
200	230000	600	400000
300	280000		

3.1.3.2 Operation and Maintenance Cost

In this analysis the operational and maintenance cost is a sum of parameters as is noted in equation (21). These costs are either fixed or depend on the water production.

- Labor is a fixed cost and for 1 person in a small desalination plant is estimated at $LB = 25000€$ per year. When the annual water production is low, then labor cost is a very important factor to the water cost.
- Chemicals cost is variable and depends on the water production. The specific cost of the chemical is estimated from $0.02\ \$/m^3$ (Wilf) to $0.05\ \$/m^3$ (Vince, 2008) but in some cases can be as high as $0.23\ \$/m^3$ (Lamei, 2008). For the Greek islands a value of $0.065\ €/m^3$ is proposed (Karagiannis, 2007). Thus the chemical costs are $CHM = 0.065 \cdot WP$.
- Membrane cost is the most difficult to estimate due to the fact that 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 can be vary from 3 years 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 $0.04€/m^3$ to $0.34€/m^3$ (Avlonitis,

2003). In this study membrane replacement cost will be an average $0.15€/m^3$ which agrees with data from real plants in similar areas (Dagalidis, 2009). $MR = 0.15 \cdot WP$.

- Consumables and other costs will be taken equal to $CN = 0.04 \cdot WP$ (Dagalidis, 2009 and Wilf)
- Insurance will be $IN = 0.05 \cdot (IC_{EN} + IC_{RO})$ per year (Vince, 2008).

3.1.3.3 Energy and other costs

The cost of energy is per kWh $EC_{SP} = 0.1 \frac{€}{kWh}$, the feed in tariff for PV is $ES_{SP_{PV}} = 0.45 \frac{€}{kWh}$ and from WEC is $ES_{SP_{WEC}} = 0.09 \frac{€}{kWh}$. The life time of the investment is $n = 20\ yr$ and interest rate is $i = 4\%$.

3.1.4 Other Inputs

The specific energy consumption for reverse osmosis can be from $3.5\ kWh/m^3$ for very efficient systems with energy recovery (e.g RO unit in Milos Island) to $9\ kWh/m^3$ for systems without energy recovery. In this analysis the specific energy will be $Sp = 4.5\ kWh/m^3$ which is an average value for modern systems in the Greek islands. The flushing duration will be 15 minutes ($fm = 0.25\ hr$).

3.2 Results

3.2.1 Conventional Energy

The tool developed for this analysis can provide economic performance results for each island. Figure 2 depicts the levelized water cost with and without labor cost as a function of the installed capacity for two representative islands. The Cover Ratio (Annual Water Production/Annual Water Demand) and the Capacity Factor (Annual Water Production/365*Capacity) are also depicted. The water cost results for each island are presented in table 3.

Table 3: Desalination costs for Greek islands without renewable energy

Island	With Labor Costs				Without Labor Costs		
	Minimum		CR=1		Minimum		CR=1
	Cost (€/m³)	Capacity $(m3/day)$	Cost (€/m³)	Capacity $(m3/day)$	Cost (€/m³)	Capacity $(m3/day)$	Cost (€/m³)
Amorgos	2.34	100	2.42	200	1.27	50	1.60
Koufonisia	1.85	300	1.89	350	1.20	50	1.40
Irakleia	3.15	100	3.51	150	1.42	50	2.08
Folegandros	1.66	300	1.67	400	1.20	50	1.28
Sikinos	2.68	150	2.73	250	1.39	50	1.82
Therasia	3.47	50	3.58	100	1.45	50	1.86
Donoussa	12.30	50	12.30	50	3.95	50	3.95
Leipsoi	1.81	200	1.87	300	1.20	50	1.36
Megisti	1.46	300	1.51	400	1.10	200	1.19
Patmos	1.12	750	1.18	1250	0.97	550	1.06
Halki	1.46	300	1.48	350	1.11	250	1.16
Pserimos	8.98	50	8.98	50	3.02	50	3.02
Arki	5.21	50	6.01	100	1.95	50	2.85

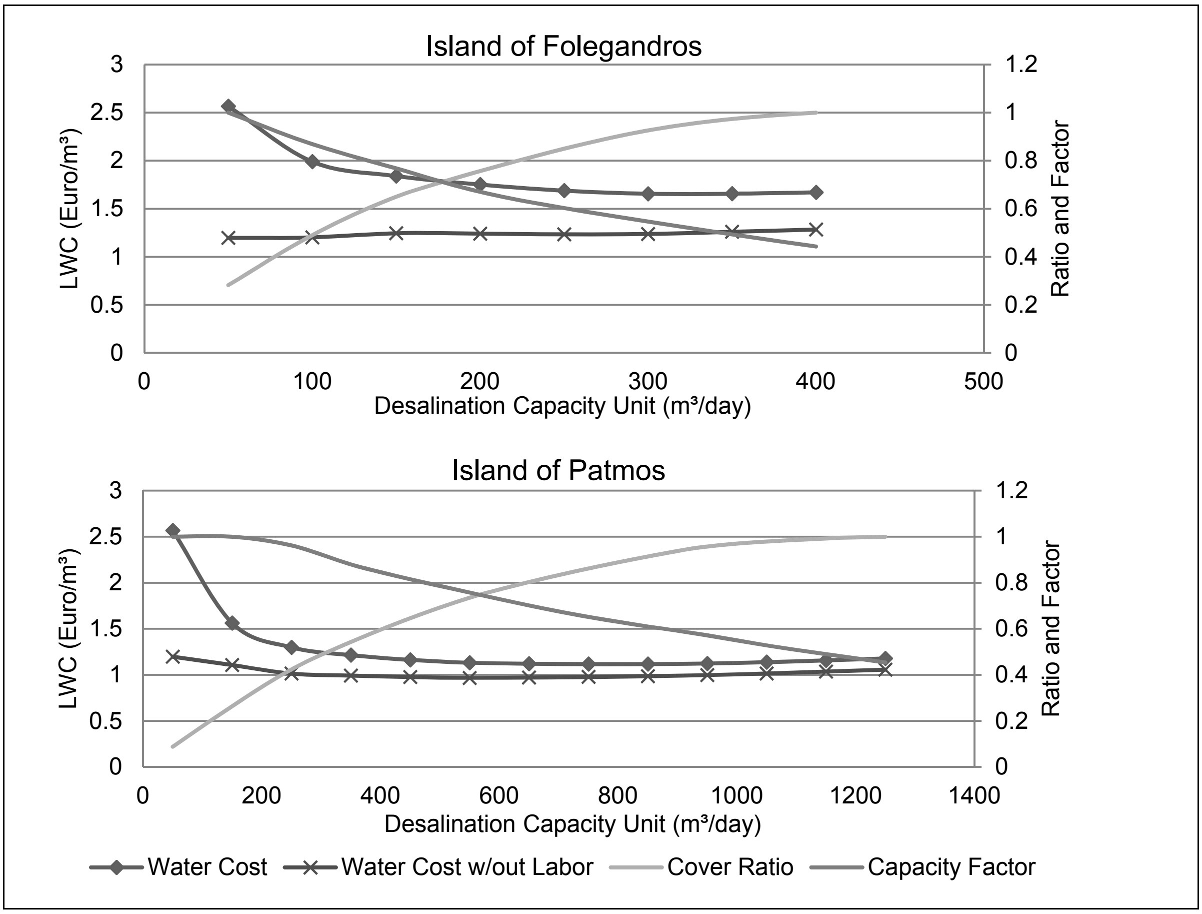

Figure 2: Levelized water cost (with and w/out labor cost) and indicative ratios as a function of the desalination capacity for the islands of Folegandros and Patmos

3.2.2 Renewable Energy

The island of Folegandros will be examined as a typical case with a proposed desalination capacity of $400m^3/day$. Figure 3 displays the levelized water cost and figure 4 shows the indicator "Renewable to Energy Demand" as the installed capacity of renewable energy increases.

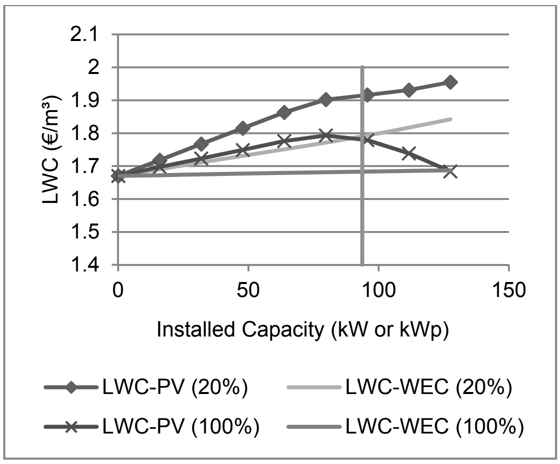

Figure 3: Levelized water cost for the island of Folegandros as a function the installed renewables. The percentage denotes the infusion level to the grid.

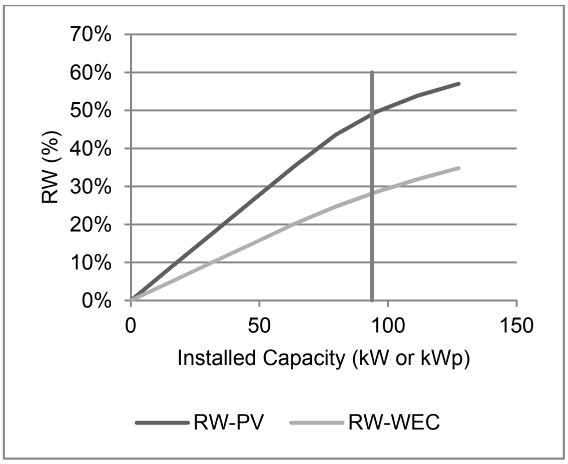

Figure 4: The indicator "Renewable to Energy Demand"

The vertical line in figures 3 and 4 denotes an installation limit according to law restrictions.

4 Discussion

As can be derived from the graphs and table 3, desalination cost is strongly affected by labor cost for islands with limited water production and this make the units not feasible. Minimum water cost occurs for desalination capacity that cannot fully cover the demand (CR<1) but in most cases water price increases by less than 0.1€/m^3 from minimum water cost when all the demand is covered (CR=1).

The impact of renewable sources to water cost, in general, is negative because the cost increases. This is due to the low cost of conventional energy, the high cost of renewable energy and finally, the legal restrictions in selling the renewable energy surplus. At infusion level 20%, the use of renewable energy increases water cost. At 100% infusion, the wind energy conversion system gives steady water cost making this solution feasible (as this is subject to the site wind speed). With 100% infusion, the use of photovoltaics incurs a high water cost, although the excess of energy subsequently increases and the profit from that lowers the water cost, which however remains higher than that without photovoltaics. This trend is observed in the other islands as well.

Figure 4 shows that with the use of photovoltaics, water is produced with more renewable energy than with the same installed power of wind energy. This occurs because of the timing in water production which is set around noon in areas where there is sun through most of the year. In addition, both the curves of photovoltaics and wind energy decline after a certain installed power, which indicates that the exploitation of the renewable energy will be less (per unit of installed power).

5 Conclusion

In this analysis a powerful tool was developed to analyze the economic and energy behavior of desalination systems in Greek Islands with the option of renewable energy. In most of the cases examined, water cost was estimated at 3 to 5 times less than the water transportation cost. Although the use of renewable energy tends to increase the cost of water, this increase is small, and in some cases it could produce extra profit (in cases where there are no legal restrictions).

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