Desalination and Water Treatment
www.deswater.com
51 (2013) 695–701
January
Taylor & Francis
Taylor & Francis Group

doi: 10.1080/19443994.2012.714523

Photovoltaic-based combined electricity and clean water production for remote small islands

Dimitrios Tiligadas[a], Emilia Kondili[b], John K. Kaldellis[a,*]

[a]*Department of Mechanical Engineering, Lab of Soft Energy Applications & Environmental Protection, TEI of Piraeus, P.O. Box 41046, Athens 12201, Greece*
Email: jkald@teipir.gr; www.sealab.gr
[b]*Department of Mechanical Engineering, Optimisation of Production Systems Lab, TEI of Piraeus, 250 P. Ralli and Thivon Av., Athens 1224, Greece*

Received 12 March 2012; Accepted 18 July 2012

ABSTRACT

Most remote small islands of the Mediterranean area suffer from insufficient and high-cost electricity generation as well as significant water scarcity, considerably hindering the local development activities. The problem is much more pressing during the summer period due to the increased touristic activity. On the other hand, the entire Mediterranean region has significant solar potential, which is almost unexploited. In this context, the current paper investigates the opportunities of combined electricity and clean water production on the basis of the available solar potential. To that effect the currently proposed energy system comprising of photovoltaic (PV) generators and energy storage is combined with a small desalination unit. Actually, the maximization of the properly defined solar energy "value" is attempted on the basis of an appropriate allocation and planning of the PV generators either for covering directly the electrical demand of the local society or by providing the energy required for the seawater desalination process. According to the results obtained from the application of the proposed solution to a representative small Aegean Sea island, the production cost of both electricity and clean water through the desalination plant are favorably compared with the respective cost of the already existing electricity and water supply solutions.

Keywords: Stand-alone; Desalination; Energy autonomy; Solar potential

1. Introduction

Most remote small islands of the Mediterranean area suffer from insufficient and high-cost electricity generation as well as significant water scarcity, considerably hindering the local development activities [1,2]. The problem is much more pressing during the summer period due to the increased touristic activity. Actually, in the numerous Aegean Archipelago islands the electricity demand is hardly covered by the existing thermal power stations, based mainly on internal combustion engines that present extremely high electricity generation costs [3] that even exceed 250€/MWh_e, see also Fig. 1.

Additionally, all these small islands suffer from significant water deficit [4], thus 50% up to 100% of the required fresh water is transferred at a very high cost, even approaching 10€/m^3. More precisely, the problem becomes intense for the Cyclades and

*Corresponding author.

Presented at the International Conference on Desalination for the Environment, Clean Water and Energy, European Desalination Society, 23–26 April 2012, Barcelona, Spain

Dodecanese complexes, where in 2008, more than 1.8 Mm^3 of fresh water were transported and more than 10 M€ were spent for that purpose (at an average cost of approximately 6 €/m^3), see Fig. 2. On the other hand, the entire Mediterranean region has significant solar potential (Fig. 3), which still remains largely unexploited. To this end, it must be noted that solar irradiance is maximum during the summer period, i.e. when maximum water and electricity demand are also encountered.

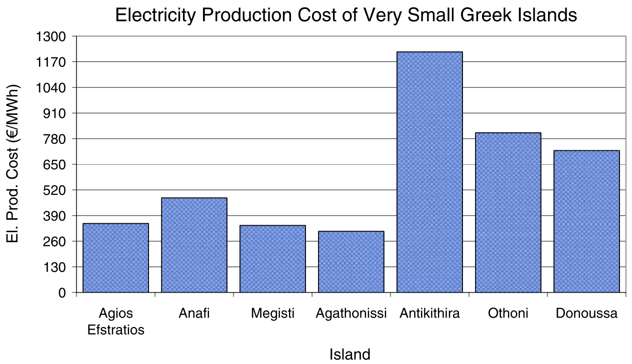

Fig. 1. Electricity production cost of very small Greek islands.

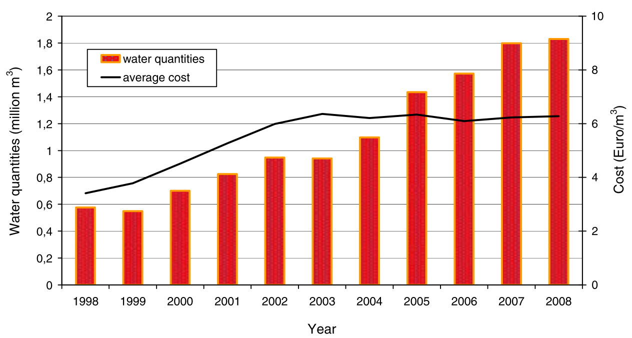

Fig. 2. Water imports and average transportation cost evolution for the Cyclades and Dodecanese island complexes.

In this context, the current paper investigates the opportunities of combined electricity and clean water production on the basis of the available solar potential. To that effect, the proposed power system, comprising of photovoltaic (PV) generators and energy storage, is combined with a small desalination unit [5]. Actually, maximization of the properly defined solar energy "value" is attempted on the basis of an appropriate methodology for the allocation and planning of the PV generators either by covering directly the electrical demand of the local society or by providing the energy required for the seawater desalination process.

The proposed methodology is accordingly applied for a typical small-scale island in order to demonstrate the advantages of such a solution without however disregarding any drawbacks accompanying such an innovative effort to satisfy—on the basis of PV generators—electricity and fresh water demand at the same time.

2. Position of the problem

Water and energy (electricity) are two of the most important elements of human life, strongly affecting

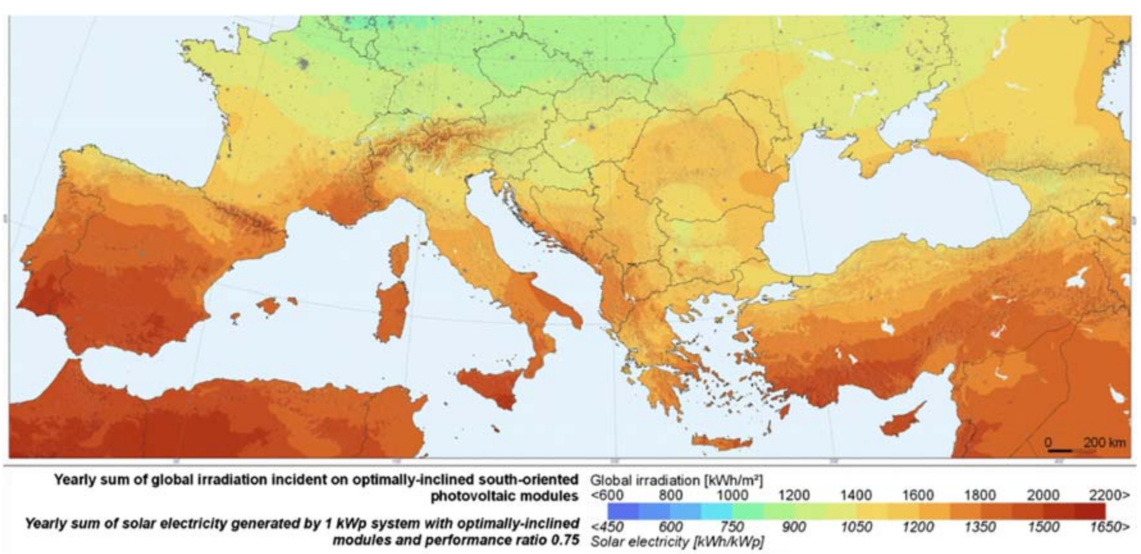

Fig. 3. Mediterranean region solar potential [6].

the development of any society. The social and economic status of the modern world depends on the sustainable supply of both energy and water [7]. To this end, most islands of the Mediterranean Sea face water shortage and low quality-high production cost of electricity provided. Note that the water shortage problem being more acute during summer months, i.e. when significant increase in water demand occurs, is currently faced by high cost water transportation [8].

The objective of this work is to identify the optimal configuration, design and operation of an integrated system based on the solar energy exploitation in order to face the clean water and electricity demand of small remote islands in the Mediterranean area. During this simulation procedure, the daily and seasonal fluctuations of electricity demand along with the periodical/variable behavior of the solar irradiance seriously bound the solar energy participation in the small islands' energy balance, while on top of these, additional operational limits are also set by the local grid and the reverse osmosis (RO) desalination plant operators in order to protect their equipment from long-term operation, near or below the corresponding technical minima.

In this context, the main idea of the present work is to design (specify equipment, production and storage systems and also decide on their sizing) a renewable energy plant and a RO desalination plant in order to:

(1) Cover the electricity and water demand of a remote area (given the electrical load and water demand profile).
(2) Develop a tool/methodology for the optimal operation of the integrated water-electricity covering system. This means that this "tool" will be able to determine for how many hours per day will the power plant provide electricity to the users, for how many hours will it operate to charge the energy storage and for how many hours will it also provide energy (and how much energy) to the desalination plant.

Certainly, the entire operation of the system is expected to exhibit different optimal conditions under different circumstances with each of the various parameters of the system playing a very significant role. In this context, the methodology is currently applied to a specific case study, while at this point one should keep in mind that the combined operation of a renewable energy-based power station and a desalination plant for fresh water production is still scarce [9], comprising a very small portion (about 0.02%) of the total desalination capacity.

3. Proposed solution

In order to ameliorate the current situation in the numerous remote, very small-scale islands of the Mediterranean area and achieve energy and water autonomy, the application of a combined PV-RO system is examined. The proposed configuration comprises of a PV generator, an appropriate energy storage facility and a desalination unit, which is able to provide the necessary fresh potable water quantities (see Fig. 4).

More precisely the proposed configuration includes [10] the following:

- A PV generator, consisting of "z" PV panels, with a total peak power "$N_{PV\text{-}peak}$".
- A DC/DC charge controller of "N_{cc}" rated power.
- An appropriate energy storage system (ESS), namely lead-acid batteries, of total capacity "Q_{ss}", operation voltage "U_b" and maximum depth of discharge "DoD_L".
- A DC/AC inverter of maximum power "N_{INV}" able to meet the consumption peak load demand.
- A properly sized seawater desalination plant of daily capacity "Q_o".
- A water storage reservoir of storage capacity "V_{res}", able to store the required potable water quantities for a given time period "d_w".

During the long-lasting operation of the proposed system, the following situations may appear:

- The energy production "E_{PV}" of the PV plant is higher than the total energy demand "E_{dem}" (both consumption and desalination needs), i.e.

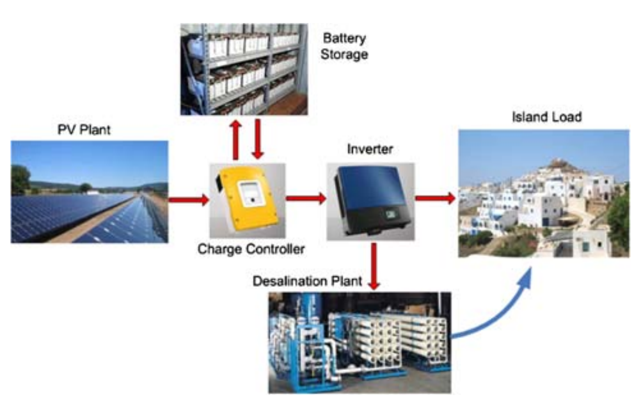

Fig. 4. Schematic presentation of the proposed solution.

$E_{PV} > E_{dem}$. In that case the energy surplus is forwarded either for producing clean water which is accordingly stored in the existing water reservoir or to the ESS. If both storage systems are full the excess energy is forwarded to low priority loads.

- The energy production from the PV plant is lower than the total energy demand (both consumption and desalination needs) ($E_{PV} < E_{dem}$). In that case energy from the ESS is used in order to cover the energy deficit.

It should be noted that in the current analysis emphasis is given in order to eliminate the contribution of the existing local thermal power station. Therefore, the ESS must be able to meet the energy deficit and to support the desalination unit to cover the water demand during the entire year period.

As already noted, the main concept of the present analysis is the exploitation of the available solar potential using the appropriate number of PV panels in order to cover the electricity and water demand in a remote island network. Thus during the proposed analysis the following main steps are followed:

(1) Selection of the PV panels and the battery bank characteristics and accordingly estimation of the annual energy yield of the PV plant: In order to estimate the energy produced by the PV plant, hourly solar radiation and ambient temperature data are used [11,12].
(2) Determination of the operation planning of the seawater RO desalination unit: Several different scenarios of water production are examined (e.g. rated capacity of 6, 9, 12, 15 m^3/h), fulfilling the criterion of 100% water autonomy of the remote island [13].
(3) Estimation of the total load demand: The total load demand is estimated on an hourly basis, comprising the sum of the electricity demand of the local community and the electricity needs of the RO desalination unit.
(4) Estimation of the energy balance and ESS state of charge: With the use of the developed computational algorithm, the energy balance is calculated on a given time step (e.g. on an hourly basis).
(5) Financial evaluation: A preliminary economic evaluation of the proposed PV-RO configuration is carried out focusing on the calculation of the IRR values for a 25-year period [14,15]. Besides, the electricity generation and the clean water production costs are estimated. However, a more detailed financial analysis is required, including also an appropriate sensitivity analysis.

4. Application results

In order to obtain a first idea about the abilities of the proposed methodology, a typical case study is currently investigated and the results can be summarized below. Actually, the tiny island of Anafi, located at the southeast edge of the Cyclades complex (Fig. 5), has been selected. The island's population is approximately 250–300 inhabitants and its area is about 40 km^2.

The annual electricity generation during the last decade is about 1 GWh. During the same period, the lowest electricity consumption occurred in April and May (i.e. 60 MWh), whereas the highest in August (i.e. 160 MWh) due to the increase of tourism.

Furthermore, the peak load demand varies between 400 and 500 kW (recorded usually on the 15 August) and the minimum load demand was 50 kW (recorded during April). At the same time, the small thermal power station of the island consists of five (similar) internal combustion engines of total rated capacity 670 kW, with a mean specific fuel consumption of 240 g/kWh and an electricity production cost of about 500 €/MWh.

The island of Anafi faces also a complete lack of fresh water and thus the water needs are currently being covered exclusively by transported quantities. Taking into consideration the daily needs of the permanent population for fresh water and assuming also an increase of the population during summer, the total annual water needs of the island are found to be almost 20,000 m^3.

To this end, considering the high solar potential of Anafi and the fact that the water is transported to the island by ships, the application of a combined PV-RO

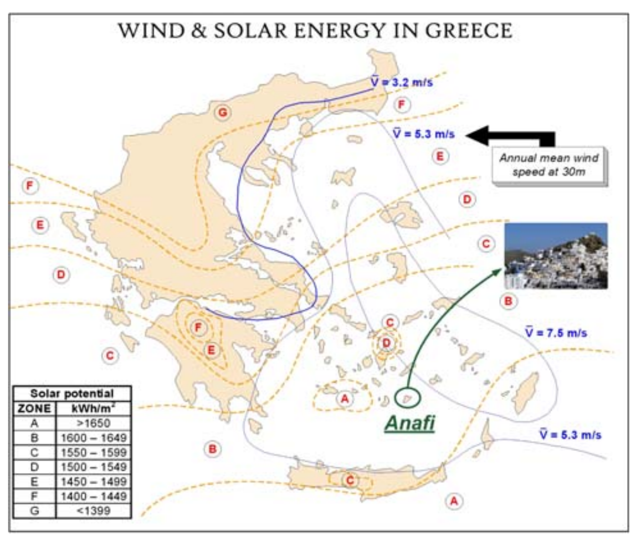

Fig. 5. A map of Greece and the island of Anafi.

system, in order to achieve energy and water autonomy, is examined.

4.1. PV generator sizing on the basis of electricity demand

Applying the proposed algorithm in order to cover the electrical load demand of the island one may find the energy autonomy combinations of the PV-ESS system in Fig. 6. For the simulation of the system's operation, 250 W monocrystalline PV panels with a nominal efficiency of 13% at standard conditions have been used.

According to the results obtained it is obvious that as the PV generator peak power increases, the energy storage capacity decreases. This phenomenon is more intense for low PV generator rated power and finally an asymptotic behavior is achieved, since after a specific point the increase of the PV peak power does not cause any further decrease of the energy storage capacity. The optimum combination may result after taking into consideration the appropriate optimization criteria.

4.2. Sea water RO desalination operation planning

After analyzing the water demand of the local community and taking into account that:

- The water demand during winter months is 100 L/cap/day.
- The water demand during spring and autumn months is 120 L/cap/day.
- The water demand during summer months is 150 L/cap/day.
- The population during summer months is tripled (800–900 people).

One may demonstrate in Fig. 7 the expected monthly water demand profile for the small island under investigation. According to the data of Fig. 7 June, July, and August have the higher water demand, of about 3,800 m^3. The corresponding mean daily water consumption is approximately 125 m^3.

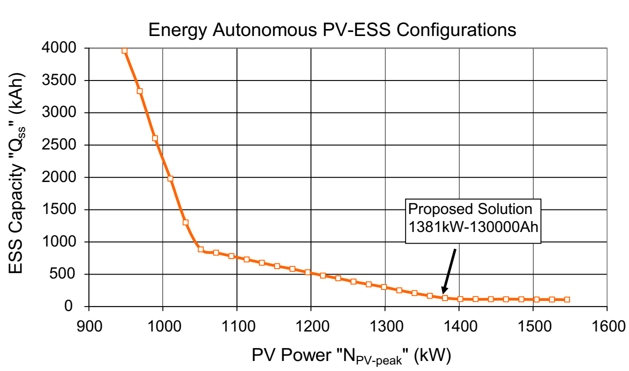

Fig. 6. Energy autonomous combinations of PV-ESS for electricity production.

Consequently the minimum RO desalination capacity should be higher than 5 m^3/h. In the current analysis the minimum desalination capacity is assumed to be 6 m^3/h, taking into account a safety factor in order to guarantee that the RO unit can meet the local water demand.

Subsequently and taking into account that:

- Water production can be adjusted to the demand and energy availability within a range of 12.5–100% of the nominal output of the RO unit.
- Membranes used are sensitive to frequent start-stop [16].

Four different scenarios of water production are examined in the present work, with hourly capacity production equal to 6, 9, 12, and 15 m^3/h (+50, +100, +150% of the minimum desalination capacity) respectively. Furthermore, the criterion of fulfilling 100%

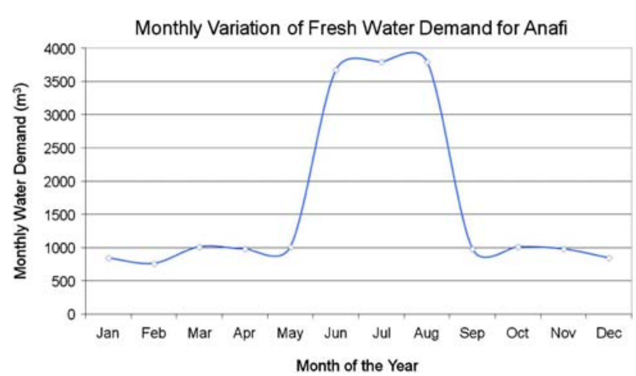

Fig. 7. Monthly water demand variation in Anafi.

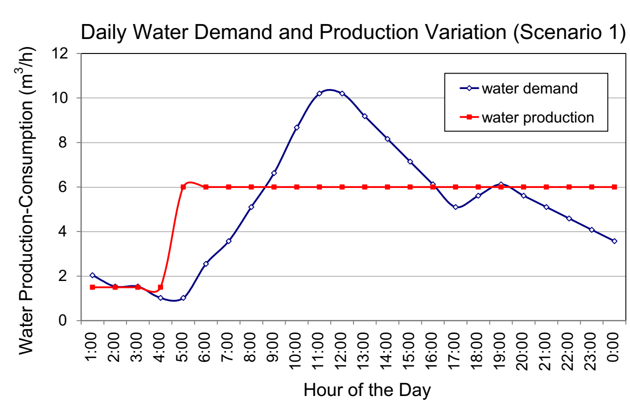

Fig. 8. Hourly water production-demand pattern (Scenario 1).

water autonomy is considered, while for each scenario the water production–demand analysis is carried out on an hourly basis. In Fig. 8 one may find the hourly water demand-production balance for a typical summer day for the minimum RO desalination unit (i.e. nominal capacity 6 m^3/h).

More precisely, for this specific RO configuration, the desalination plant should operate at 1.2 m^3/h (20% of the nominal capacity) during winter (December, January, February). In spring and autumn (March to May and September to November respectively) the desalination plant operates at 20–25% of the nominal hourly capacity (1.2 and 1.5 m^3/h respectively). Finally, during summer it operates for four hours (early morning) at 25% (1.5 m^3/h) and for the rest of hours at 100%.

As it is rational the desalination plant should basically operate during the high solar radiation periods in order to absorb electrical energy directly from the PV generator and not through the system batteries. Besides, no seasonal water storage strategy has been adopted, while the water reservoir capacity is less than 500 m^3, providing water autonomy for four consecutive days.

4.3. Energy results related to the combined water and electricity production

Recapitulating, for each of the four scenarios of water production the operation of the seawater RO desalination plant is simulated for one-year period, using different combinations for PVs' rated power and energy storage capacity. As depicted in Fig. 9, PVs' rated power increases inversely to the energy storage capacity till the point at which the increase of the PVs' rated power does not cause any further decrease of the energy storage capacity.

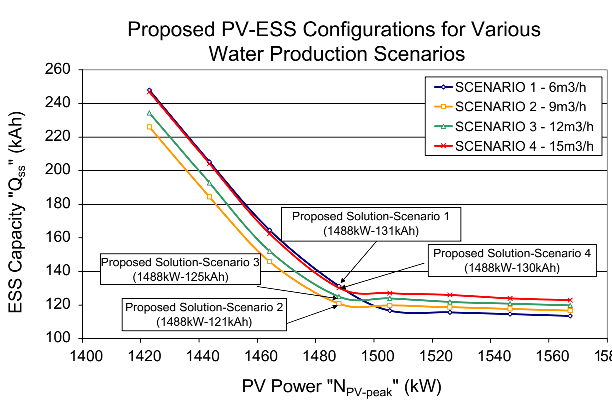

Fig. 9. Proposed configurations for combined electricity and water production.

The currently selected PV-RO configurations result based on the condition of achieving 100% energy and water autonomy with the minimum required PV panels' rated power and ESS capacity. Depending on the water production scenario selected and for PVs' rated power ranging between 1,423 and 1,567 kW, four different configurations arise (see Fig. 9).

As far as the preliminary financial evaluation of the proposed solution is concerned, the electricity production cost of the proposed system is found equal to 340 €/MWh, while the water production cost is found approximately 1.5 €/m^3. Further analysis including optimum sizing of the proposed installation is expected to reduce remarkably the above-mentioned values. On the other hand, it should be mentioned that the above costs are considerably lower than the current ones, i.e. 500 €/MWh and 7 €/m^3, respectively. As far as the IRR of the investment is concerned, after 25 years of the plant's operation, it is estimated slightly higher than 10% (depending on the selected water production scenario), based on current market selling prices for each kWh produced (Law 3734/2009). Nowadays, the corresponding capital cost values fluctuate between 6 and 8% in the local market. Note that water selling prices are considered to vary between 2 and 4 €/m^3, while the price of 3 €/m^3 is used for the above-mentioned IRR value.

5. Conclusions

In the present study the possibility of covering the total electricity and water needs of a small non-interconnected island through the application of a combined PV-RO system is investigated. Based on the results of the parametric analysis carried out, the proposed configuration comprises of a PV generator (1.5 MW), an appropriate energy storage facility (around 140,000 Ah) and a desalination unit able to produce up to 15 m^3 of fresh water per hour (or 360 m^3 per day).

Preliminary cost estimates indicate the attractiveness of the proposed system in comparison to the current situation, especially from the local community point of view. However, a more detailed economic analysis is required in order to obtain a more accurate estimate of costs, including also the socio-economic benefits of such systems as they contribute to regional development and reduce harmful emissions related with the fossil fuels combustion.

Recapitulating and according to the results obtained from the application of the proposed solution to a representative small Aegean Sea island, the production cost of both electricity and clean water through the desalination plant are favorably compared with the respective and already existing electricity and water supply solutions. Therefore, the idea could be developed and implemented in the small islands or other remote communities of the Mediterranean area and offer them electricity and fresh water at a relatively rational cost.

References

[1] J.K. Kaldellis, D. Vlachou, K. Kavadias, An integrated renewable energy solution for very small Aegean Sea islands, Proceedings of the Renewable Energies for Islands International Conference, Chania, Crete, Greece, 2001.
[2] C.A. Balaras, M. Santamouris, D.N. Asimakopoulos, A.A. Argiriou, G. Paparsenos, A.G. Gaglia, Energy policy and an action plan for renewable energy sources (RES) for the Hellenic islands of the north Aegean region, Energy 24(4) (1999) 335–350.
[3] J.K. Kaldellis, D. Zafirakis, Present situation and future prospects of electricity generation in Aegean Archipelago islands, Energy Policy 35(9) (2007) 4623–4639.
[4] J.K. Kaldellis, E. Kondili, The water shortage problem in Aegean Archipelago islands. Cost-effective desalination prospects, Desalination 216(1–3) (2007) 123–128.
[5] J.K. Kaldellis, D. Zafirakis, EI. Kaldelli, E. Kondili, Combined photovoltaic and energy storage systems. An integrated electrification solution for small islands, Int. J. Environ. Technol. Manag. 10(2) (2009) 123–149.
[6] European Commission Joint Research Centre-Institute for Environment and Sustainability. Solar radiation and PV maps—Europe (Africa), 2012. Available from: http://re.jrc.ec.europa.eu/
[7] I.C. Karagiannis, P.G. Soldatos, Current status of water desalination in the Aegean Islands, Desalination 203(1–3) (2007) 56–61.
[8] E. Mathioudakis, V. Belessiotis, E. Delyannis, Desalination by using alternative energy: Review and state-of-the-art, Desalination 203(1–3) (2007) 346–365.
[9] D. Herold, A. Neskakis, A small PV-driven reverse osmosis desalination plant on the island of Gran Canaria, Desalination 137(1–3) (2001) 285–292.
[10] E. Kondili, J.K. Kaldellis, D. Tiligadas, Wind-based combined electricity and clean water production for remote islands, Proceedings of the World Renewable Energy Congress -WRECXI, Abu Dhabi, United Emirates, 2010.
[11] J.K. Kaldellis, D. Zafirakis, E. Kondili, Optimum sizing of photovoltaic-energy storage systems for autonomous small islands, Int. J. Elec. Power Energ Syst. 32(1) (2010) 24–36.
[12] J.K. Kaldellis, P. Koronakis, K. Kavadias, Energy balance analysis of a stand-alone photovoltaic system, including variable system reliability impact, Renew. Energy 29(7) (2004) 1161–1180.
[13] J.K. Kaldellis, K. Kavadias, J. Garofalakis, Renewable energy solution for clean water production in the Aegean Archipelago Islands, Proceedings of the Mediterranean Conference on Policies and Strategies for Desalination and Renewable Energies, Santorini, Greece, 2000.
[14] J.K. Kaldellis, D. Zafirakis, Kaldelli El, K. Kavadias, Cost-benefit analysis of a photovoltaic-energy storage electrification solution for remote islands, Renew. Energy 34(5) (2009) 1299–1311.
[15] J.K. Kaldellis, K.A. Kavadias, E. Kondili, Renewable energy desalination plants for the greek islands, technical and economic considerations, Desalination 170(2) (2004) 187–203.
[16] A. Ghobeity, A. Mitsos, Optimal time-dependent operation of seawater reverse osmosis, Desalination 263(1–3) (2010) 76–88.