Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2012.715423

51 (2013) 1205–1218
January

Taylor & Francis
Taylor & Francis Group

A multicriteria analysis for the optimal desalination–RES system. Special focus: the small Greek islands

Emilia Kondili[a,*], John K. Kaldellis[b], Mina Paidousi[a]

[a]*Optimisation of Production Systems Laboratory, Technological Education Institute of Piraeus, 250 P. Ralli and Thivon Av., 122 44, Athens, Greece*
Tel./Fax: +30 210 5381430; email: ekondili@teipir.gr
[b]*Soft Energy Applications and Environmental Protection Lab, Technological Education Institute of Piraeus, PO Box 41046, 12201 Athens, Greece*

Received 23 March 2012; Accepted 18 July 2012

ABSTRACT

The coupling of renewable energy sources (RES) with desalination has the potential of providing a sustainable potable water source, especially in arid areas with limited water resources. During the design stage a RES–desalination process combination suitable for the particular application needs to be selected. The factors that should be considered for such a selection include the local RES potential, the compatibility of the desalination process with a certain renewable energy source, its effectiveness with respect to energy consumption, the amount of fresh water required in combination with the range of applicability of the various desalination processes, the seawater treatment requirements, the capital cost of the equipment, the land area required or could be made available for the installation of the system. The main aim of the present research is to find out how RES can optimally be combined with desalination technologies in small and medium size islands, through the development of a suitable selection methodology. To that effect a multicriteria analysis model is developed with special attention to the selection of the evaluation criteria and the weighting factors of these criteria in the final evaluation of the various alternative combinations of RES with desalination technologies. The criteria include technological, environmental, economic and location specific aspects of each alternative desalination–RES application scenario.

Keywords: Wind/PV/geothermal desalination; Reverse osmosis; Pair-wise criteria comparison; Aegean Sea islands

1. Introduction—scope and objectives of the work

Water shortage in the world is one of the most crucial social and environmental issues of our time. Many regions of the world have serious discrepancies between water demand and supply and one of eight people in the world has no access to safe drinking water. Among the solutions being suggested, many world countries are increasingly turning to desalination of brackish and sea water in their effort to match the increasing demand with the available natural resources. The desalination industry has responded well to the increasing demand and is constantly evolving by reducing the costs and reliably producing water of very high quality (Figs. 1 and 2, [1]).

*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

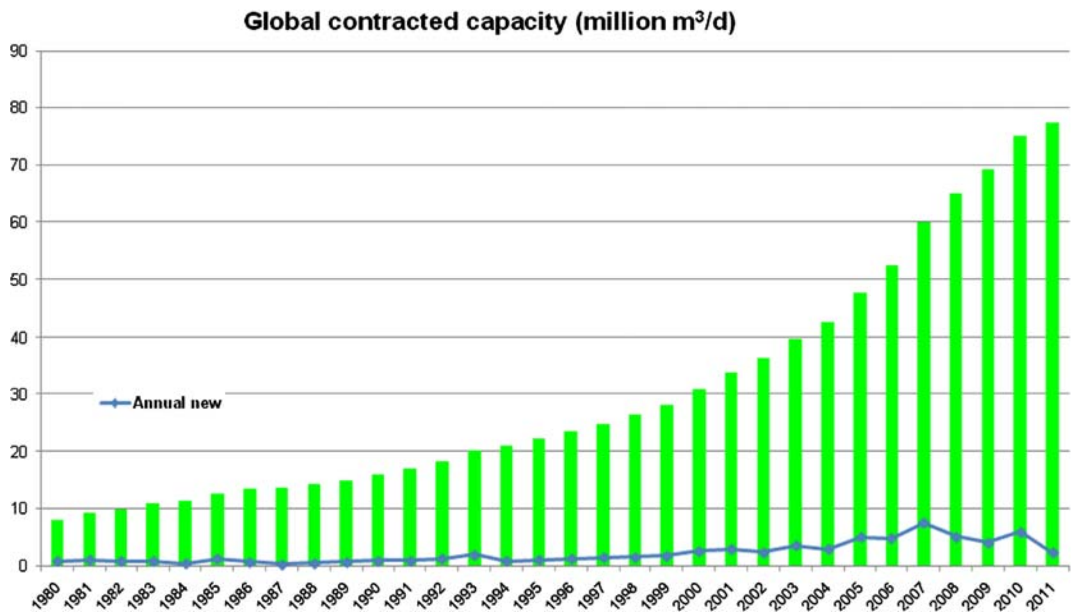

Fig. 1. Global contracted desalination capacity [1].

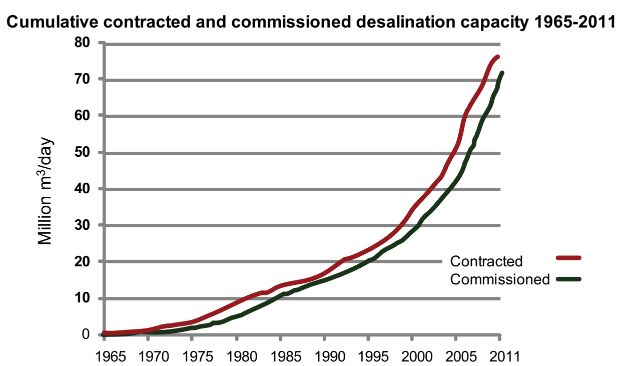

Fig. 2. Contracted and commissioned desalination capacity [1].

Most innovations in desalination technology focus on reducing the energy demand, since this is associated with high operating costs. However, desalination processes will always require considerable amounts of energy. If conventional energy sources are used, they contribute to climate change, which, in turn, affects the water cycle and intensifies the original problem that desalination was intending to solve [2].

Desalination techniques may be classified into: (i) phase-change or thermal processes and (ii) membrane or single-phase processes. Either way, seawater desalination processes require significant quantities of energy to achieve separation of salts from seawater. Apart from satisfying the energy demand, if desalination is accomplished by conventional technology, environmental pollution would be a major concern as burning of substantial quantities of fossil fuels would be required. Therefore, renewable energy sources (RES) coupled with desalination offer a promising prospect for covering the fundamental needs of power and water, especially in remote regions.

The objective of the present work is to develop a methodology based on Multicriteria Analysis for the most appropriate RES–desalination combination selection for small islands, especially in cases where there may be more than one alternative feasible options.

2. RES-based desalination: state of the art

2.1. *Analysis and design issues*

The use of renewable energy sources for the operation of desalination plants is a feasible and environmentally compatible solution in areas with significant RES potential. The main driving forces for applying RES in desalination plants are:

- the continuous technological advancements in RES systems and their cost reduction,
- the seasonal variability in water (and energy) demand, usually occurring in areas with high renewable energy availability, e.g. the islands,
- the limited availability of conventional energy supply in remote areas,
- the technological advancements being achieved in desalination systems,
- the need for elimination of the environmental impacts of conventional desalination systems, and
- the relative easiness of the plant's operation and maintenance compared to conventional energy ones.

Renewable energy based desalination has been under intensive research in recent years. A significant number of various units for seawater and brackish water, employing different technology combinations have been installed worldwide. Commercial desalination systems (MED, multi-effect distillation; MSF, multi-stage flash; RO, reverse osmosis; VC, vapor compression) driven by renewable energies have been built. Most of them are small capacity systems and have been developed within the framework of R&D or international cooperation projects. Among the renewable energies suitable for driving a seawater reverse osmosis (SWRO) system, wind energy is the most cost-effective option. If adequate wind resources are not available, the use of solar photovoltaic energy is recommended for small capacity plants and solar thermal energy is recommended for the medium–large capacities. If electricity generation is not demanded, it is recommended to drive the SWRO by means of a solar organic Rankine cycle [3].

The thermal energy sources are most often used with distillation desalination, while wind and photovoltaic solar energy are commonly paired with reverse osmosis desalination. The combined choices of energy and process take advantage of matching the type of energy with the type of process (thermal vs. mechanical). The RO systems can use seawater or brackish water as the feed source and are typically small to medium plants. Overall, the energy source most often being used has been solar energy (70% of market) and RO holds the majority (62%) of the renewable energy desalination market. Solar-powered desalination is possibly the most promising alternative energy choice and both distillation and membrane plants have been designed and operated. In particular, countries already advanced in conventional RO desalination, such as Spain, Italy, and Saudi Arabia, have successfully implemented solar photovoltaic energy and seawater RO, with a permeate production capacity in the range of 0.5–120 m^3/day. In Spain a large scale plant has been built; a wind farm (four wind generators) has been combined with a seawater RO plant (5000 m^3/day) in Gran Canaria, Canary Islands [4].

EU is very much interested in the implementation of RES in desalination and the implementation of these technologies. To that effect, there are funded projects that attempt to promote these ideas, such as the PRODES that promotes the market development of renewable energy desalination in Southern Europe (Promotion of Renewable Energy for Water production through Desalination) [5] (ProDes Project, 2010).

Various criteria should be taken into account for the best coupling of RES with desalination, related to the specific location characteristics, the expectations and needs that the unit is intended to cover, the infrastructure and, in particular, energy availability in the specific area as well as other economic parameters that need to be considered.

In fact this is a major decision-making issue, part of the wider problem of infrastructure planning. The selection of the most promising solution not only will solve a particular problem under consideration but will also create good prospects for the further implementation of this approach to the water and energy needs satisfaction.

2.2. Energy use in water desalination

All desalination processes use energy, which is the largest cost component in the operation of a desalination plant and offers the greatest potential for further efficiency improvement and cost reduction. In fact, energy consumption is considered as the main reason that desalination has not yet been as widely applied as it would be expected. The share of energy cost in the overall cost varies with the plant, its operation parameters and location, as it is shown in Figs. 3 and 4, for thermal and membrane processes, respectively.

In any desalination process, the energy consumption depends on a variety of factors, including:

- the technology being used,
- the seawater salinity,
- the ability of the system for energy recovery,
- the operation temperature for membrane processes,
- the performance ratio,
- the temperature difference etc., for thermal processes.

Table 1 evaluates the combinations of desalination and RES according to certain energy-related criteria.

In Table 2, the possible combinations of RE with desalination technologies along with their most important characteristics are indicated [2].

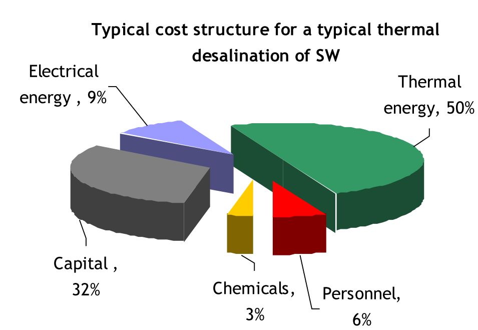

Fig. 3. Typical cost structure of thermal seawater desalination [6].

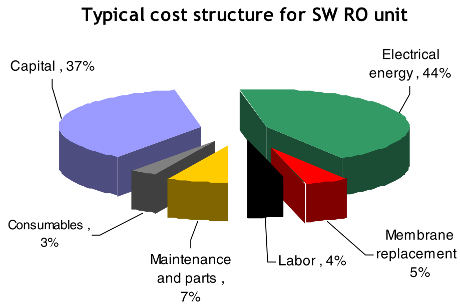

Fig. 4. Typical cost structure of RO seawater desalination [6].

3. Examples and applications of RES based desalination in small islands

Desalination using renewable energy is undergoing a rapid development nowadays. The most likely market for coupling renewable energy with desalination is for small communities in remote locations where there is no power grid connection or where energy is expensive. In the context of the utilisation of the more established renewable energy sources, i.e. the sun (thermal and PV), and the wind, stand-alone desalination systems have been widely discussed. Even if one focuses on one particular renewable source and a specific desalination method, there may still be many options available in terms of the final system configuration (Fig. 5). There is very strong research interest in this specific area. Many research teams work in specific technical issues or in integration and optimisation aspects of the combination between RES and desalination [7–15]. However, as far as implementation is concerned, many small scale and rather experimental projects have been installed but there is no serious experience from industrial scale projects.

An innovative RES Desalination Application: The Floating Autonomous Environmental Friendly and Efficient Desalination Unit (FAEFEDU)

The Floating Autonomous Environmental Friendly and Efficient Desalination Unit (FAEFEDU) is separately described as a distinct and interesting application of RES based desalination. It is designed to produce potable water from sea water by generating its own power through wind turbines on board. The unit sits on a special floating 20×20 m platform with a height of 8 m for a cylinder and a 22-m tower and can adapt to any weather conditions (Fig. 6, [9]). The maximum water production is more than 70 m^3 per day (at rated wind speed)—enough for the needs of about 300 people. In addition, because the unit is autonomous, it is not required to be connected to the national electrical grid. Since the unit is portable, it can be stationed away from populated centres and be placed wherever needed, on a seasonal basis for instance, to service the needs of islands that have an enlarged population during summer months. In addition, the unit can be repositioned to take advantage of changing weather conditions. The unit has been co-financed by the European Fund for Regional Development and domestic national funds.

4. Criteria for the selection of RES based desalination technology combination

4.1. RES–desalination technologies: general issues

In this section, the criteria that guide either explicitly or implicitly the selection of the optimal RES–desalination system are extracted and classified in groups. This classification will in fact determine later on the evaluation of each different proposed solution.

Table 1
Evaluation of various RES in desalination applications [2]

Criterion	Solar thermal energy	Photovoltaic	Wind energy	Geothermal energy
Suitability for powering desalination plants	Well suited for desalination plants requiring thermal power (3)	Well suited for desalination plants requiring electrical power (3)	Well suited for desalination plants requiring electrical power (3)	Well suited for plants requiring thermal power (3)
Site requirements and resources availability	Typically good match with need for desalination (3)	Typically good match with need for desalination (3)	Resources is location-dependent (2)	(1) Resources limited to certain location
Continuity of power output	Output is intermittent (energy storage required) (1)	Output is intermittent (energy storage required) (1)	Output intermittent (energy storage required) (1)	Continuous power output (3)
Predictability of power output	Output is relatively unpredictable (2)	Output is relatively unpredictable (2)	Output is very stochastic / fluctuates (1)	Output is predictable (3)

Marking index: 3: excellent compliance with criterion, 2: good compliance with criterion, 1: poor compliance with criterion.

Table 2
Possible combinations of RES with desalination technologies, main characteristics [2]

	Typical capacity (m^3/day)	Energy demand	Water generation cost	Technical development stage
Solar Still	<0.1	Solar passive	1–5 €/m^3	Applications
Solar MEH	1–100	Thermal: 100 kW h/m^3 Electrical: 1.5 kW h/m^3	2–5 €/m^3	Applications/ advanced R&D
Solar MD	0.15–10	Thermal: 100 kW h/m^3	8–15 €/m^3	Advanced R&D
Solar CSP	>5,000	Thermal: 100 kW h/m^3 Electrical: 1.5 kW h/m^3	1.8–2.2 €/m^3	Advanced R&D
PV-RO	<100	Electrical: BW: 0.5–1.5 kW h/m^3 SW: 4–5 kWh/m^3	BW 5–7 €/m^3 SW: 9–12 €/m^3	Applications/ advanced R&D
PV-EDR	<100		8–9 €/m^3	Advanced R&D
Wind-RO	50–2,000	Electrical: BW: 0.5–1.5 kW h/m^3 SW: 4.5–5 kW h/m^3	<100 m^3/day BW 3–5€/m^3 SW 5–7€/m^3>1,000 m^3/day 1.5–4 €/m^3	Applications/ advanced R&D
Wind-MVC	<100	Electrical: SW: 11–14 kW h/m^3	4–6 €/m^3	Basic research

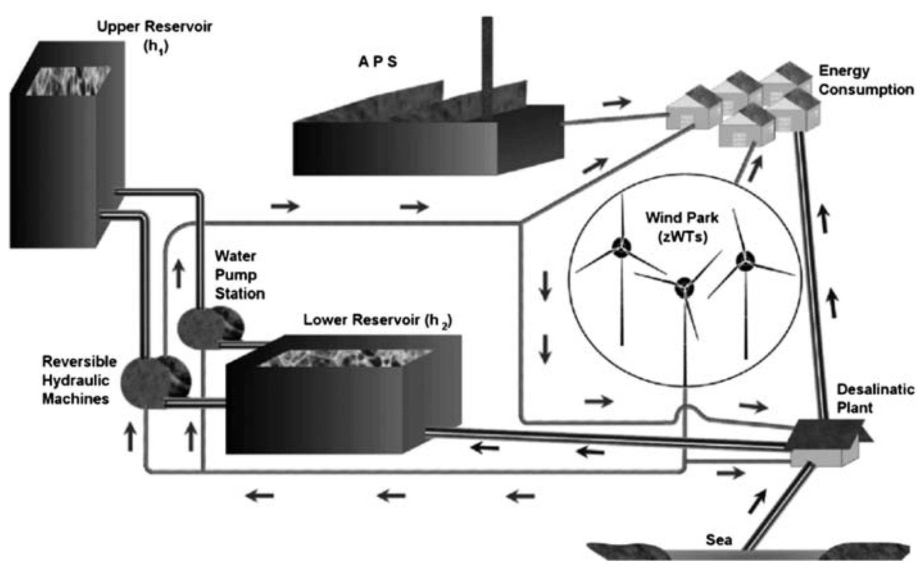

Fig. 5. Possible configuration of wind-based desalination plant [8].

As discussed earlier, some of the factors to be considered for selecting desalination process and the corresponding energy source for a particular application include [10]:

- The amount of fresh water required in a particular application (i.e. the plant's capacity) combined with the applicability of the various desalination-processes.
- The seawater treatment requirements, i.e. the feed's water salinity.
- The technical infrastructure of the area (e.g. road access, network).
- The local regulations concerning the land use and the land area required, or could be made available, for the installation of the integrated energy and desalination unit.
- The remoteness of the area and the availability of grid electricity.
- The suitability and effectiveness of the process with respect to energy consumption.

Fig. 6. Floating desalination unit [9].

- The capital cost of the equipment.
- Robustness criteria and simplicity of operation.
- Low maintenance, compact size and easy transportation to site.
- Acceptance and support by the local community.
- Organisational capability at local level with relatively simple training.

The geographic location of a final site where an autonomous desalination system unit can be installed has a strong influence on the success of such a project. If the desalination unit is not located in the most favourable position, the competitive advantages of the process may be wiped out. Considerable care must be exercised in selecting the unit site and many different factors must be considered. Collection of the basic data and evaluation are the essential steps for the identification of sites [11].

Table 3 makes a synthesis of the most critical parameters and choices that affect the feasibility and financial attractiveness of a RES-based desalination project. In parallel, the implications of the economic and environmental criteria are discussed in more detail in the following sections.

What is important and the added value of the present work is that there are two different problems concerning the selection of a RES–desalination system for a certain area. One is the technical problem of suitably combining a certain type of renewable energy with a desalination technology, independently of the location and specific demands (e.g. PV is combined with RO, wind energy can be used efficiently on condition that the average wind velocity is above 5 m/s and, for stand-alone wind energy driven desalination units with a reported cost of fresh water produced ranged from 1.5 to 3.5 €/m^3 [9]). The other problem is whether such a combination provides a good solution for a certain and specific application. These considerations are the origin of the criteria classification as they are presented in Section 4.4.

4.2. *Criteria—economics: parameters affecting economics of desalination*

Concerning the economic evaluation and the determination of the main parameters for basic RES based desalination plants, a conclusion of all the efforts being made is that there is no specific and generally applicable tool for determining the cost of such a unit. Many parameters, being technical, environmental and social are very site-specific. As a general rule, a

Table 3
Parameters affecting economics of RES-based desalination plants

Parameters affecting economics of RES-based desalination plants	Comments
The desalination technology (thermal, RO)	In general, RO units have lower investment cost but high operation and maintenance costs
The plant's capacity	Large capacity units are more expensive but the water unit cost is lower
The energy requirement of the desalination plant	This is determined by (1) the water supply salt concentration; (2) the coupling of the energy and the desalination system
The feed water salinity	BWRO is generally cheaper than SWRO
The location that the RES system and the desalination plant will be installed	Required siting, altitude, infrastructure preparation costs
The configuration of the energy system	Main design decision determining the operation and the cost of the unit
The water storage capacity	Design parameter determining the operation of the unit
The distribution of the available power (e.g. the wind speed distribution, solar radiation, etc.)	It affects the size, the configuration and, therefore the investment cost

seawater RO unit has low capital cost and significant maintenance cost due to the high cost of the membrane replacement. The cost of the energy used to drive the plant is also significant.

A detailed financial analysis leading to the estimation of detailed and precise financial indices should be carried out in case private investments are attempted. In this case, the investor will possibly undertake the cost of the project expecting to benefit from the selling of water, either in the free market or in the municipality it belongs to (e.g. case of a Greek island Milos desalination plant, [9]). It is expected that many such private investments will take place in the next years, especially in areas with water shortage and financial activities in the field of tourism.

Example of a private RES Desalination investment in Milos island, Greece [9]

In the general case, the factors that are taken into account in water production cost include the investment cost (i.e. cost of land, cost of the energy system, cost of the desalination unit, cost of the energy storage system) and the operating cost, including the manpower, chemicals and energy costs (the latter being usually the most important component) as well as the maintenance, spares and membranes replacement costs.

A wind-based desalination unit has been installed in a Greek island called Milos and belonging in the Cyclades complex (Fig. 7). The plant has been operating since summer 2007. The unit has a capacity of 3,000 m^3/day. At the moment it operates in a daily production of 2,000 m^3 of potable water. This is a private investment that has been subsidised by the state. The water is sold to the municipality of Milos, in a continuous effort to solve the urgent water shortage problem, especially during the summer months. The contract that has been signed between the private company and Milos Municipality refers to a water selling price of almost 1.8 €/m^3. The entire plant includes the desalination unit, a wind turbine of 600 kW, the storage tanks (capacity 3,000 m^3) and the remote control system.

Fig. 7. Milos wind-based desalination plant.

The siting of the unit in a very touristic island as Milos could be a major problem, mainly because of the optical and noise disturbance. Therefore, the unit has been located on a hill that is not apparent from most of the island's villages.

4.3. Criteria—environmental impacts of RES-based desalination plants

Desalination plants cover the needs of remote areas in water. Usually they are implemented as a result of an analysis and alternative solutions evaluation amongst various possible solutions for water supply. For example, in several Greek islands, fresh water requirements are covered by the construction of large dams or ground reservoirs or desalination plants. In smaller islands, the only available solution is the transport of fresh water by ship, with high costs and improper hygienic conditions. All these water supply methods cause a spectrum of environmental impacts, more or less serious depending on the type of the project, its location and scale.

The main environmental impacts of an RO desalination plant are the following:

- Noise disturbance.
- Optical disturbance.
- Land use.
- Interference with public access in the coast.
- Discharge of brine—a concentrated salt solution that may be hot and may contain various chemicals on coastal or marine eco-systems or, in the case of inland brackish water desalination, on rivers and aquifers.
- The intensive energy use and the consequent emissions of greenhouse gases in the production of electricity and steam needed to power the desalination plants in case the energy provided is from the grid and fossil fuels are used to generate it. Certainly this last environmental impact is eliminated in most cases when the energy source is renewable.

Furthermore, concerning the siting of the desalination units, their location definitely needs to be very close to the sea. The area required is minimal for Reverse Osmosis units; however, it is quite big in cases of thermal desalination methods.

Given that the remote areas mainly requiring desalination plants are the islands that have very limited land availability, this last issue may become a serious obstacle for favouring desalination in the selection of a water supply method. However, other infrastructure projects such as dams and ground reservoirs are even worse in the environmental impacts and the land use. As an approach to face land use problems, an innovative project has taken place a few years ago in Greece, namely the development of a so-called Floating Desalination Unit described above.

4.4. *Synthesis of criteria groups for the optimal RES based desalination plant*

According to all the above considerations, the criteria may be classified into various different categories/groups, each group including a number of sub-criteria. More specifically the groups of criteria for the selection of the most suitable RES–desalination combination in each specific case and their corresponding attributes are as follows:

1. Technological availability and suitability

- Simplicity of operation
- Energy demand and the effectiveness of the process with respect to energy consumption
- Robustness and reliability
- Maintenance needs
- Compact size
- Commercial availability of the technology
- Site characteristics required
- Infrastructure required
- Requirements for specialised personnel
- Produced water quality
- Easy transportation to site

2. Environmental/Land use

- Effluents/waste produced
- Visual impact
- Noise
- Land requirement
- Compatibility with other land uses (recreation and tourism)

3. Economic issues

- Investment cost
- Operation/maintenance cost (€/m^3 water produced)

4. Location specific characteristics

- Demographic and geographical characteristics
- Tourist activity-water seasonal demand-need for continuous water availability
- Personnel availability and organisational structure
- Harmonisation with the natural and human environment
- Funding opportunities
- Private investors interest

5. Energy—RES availability and quality

- Specific RES potential—availability
- RES cost
- RES operational requirements and characteristics
- Local power availability from the local network

5. RES-based desalination in the Greek small islands

For the vast majority of Greek islands, water resources are quite restricted, thus deteriorating the quality of life of the habitants. Besides, in several islands salt water intrusion into the aquifers has been observed. In fact, the water reserves are not adequate to cover the needs of the islands, especially during summer, when the population may be even ten times more than the normal. For these reasons the majority of small- and medium-sized Aegean Archipelago islands have a significant clean water deficit, especially during the summer, while in several cases almost 50–80% of the fresh water needed is transferred by boat at a very high cost [12].

The best solution for the islands' water supply problem depends on a number of parameters, such as the water needs and their time and quantity distribution during a year, the infrastructure of the island, its size and morphology, economic activities, population and its seasonal fluctuation, as well as the extent of the water shortage. A solution that has already been implemented in various cases is the construction and

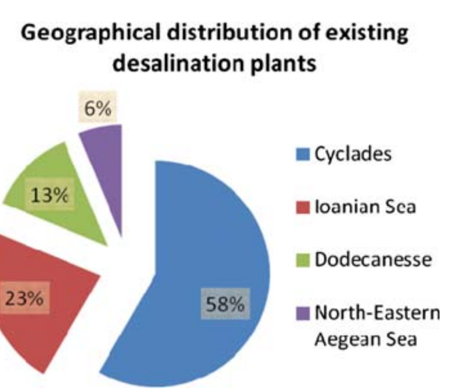

Fig. 8. Geographical distribution of the island desalination plants.

operation of desalination plants. A significant number of desalination plants have already been developed and operate in the Greek islands for the solution of water shortage problems. Their geographical distribution is shown in Fig. 8. The significant renewable potential of the area, which is up to now partially exploited, can substantially contribute to meet the energy requirements of appropriately designed desalination plants at reasonable cost [12–16].

The small Greek islands, with less than 1000 inhabitants, have also serious water deficit problems. In these cases, major water supply projects such as dams, ground reservoirs are not justified and, on the other hand, the islands do not have the infrastructure required for their constructions. These islands expand all over the Aegean Sea (mainly) in the complexes of Cyclades, Dodecanese, in the North Eastern Aegean Sea region and are the following: Agathonisi, Agios Efstratios, Anafi, Chalki, Donoussa, Folegandros, Heraklia Inousses, Kasos, Kimolos, Koufonissia, Lipsi, Nisiros, Schinoussa, Sikinos, Symi, Tilos, Psara (Fig. 9).

Selection of the most appropriate RES–desalination combination should be made in any case such a system is planned but in particular when:

- There is a serious interest for investments in the specific area. In this case, the suitability of the selected energy and desalination system will need to be evaluated in terms of profitability.
- When funding schemes are designed, in many cases the development and implementation of these innovative water supply solutions is encouraged with partial financial support from national or European programmes. In this case it is also very important to identify the most appropriate schemes.

Fig. 9. Many small islands belong in Cyclades Island complex.

6. The implementation of multi-criteria analysis

The method being used in the work is the classical weighted sum multicriteria analysis. In this simple multiobjective optimization method, a set of criteria is escalated into a single objective by multiplying each criterion with a user supplied weight being determined by its relative importance. The innovative element of the multicriteria optimization in the present work is that groups of criteria are considered instead of single criteria. This means that each criteria group includes many other considerations and the grade given in each criterion is in fact the synthesis of many sub-criteria.

The method consists of five steps:

1. *Defining the decision context:* In the present case the most suitable RES–desalination combinations for a certain island are defined.
2. *Identify the options:* This means that the possible alternative solutions that will be evaluated need to be identified. In the wider context of the problem under consideration, all the RES–desalination alternative combinations could be examined. However, as a matter of fact not all of them are appropriate; therefore, a selection of three of them will be made in the present case in order to indicate the methodology; namely, the PV-RO combination, the Wind-RO and the Geothermal-based desalination. In the general case, in this step all the feasible and promising combinations are considered. The methodology may be used for any island. In the present case, the method will be applied in three small Aegean islands, namely the islands of Agios Efstratios, Anafi and Kimolos. All of them are very small and have limited or no water resources.
3. *Identify the objectives and the criteria that reflect the value associated with the consequences of each option:* The groups of criteria and the corresponding subcriteria have already been defined above. The other important issue of the method is the determination of the relative weight of each subcriterion.
4. *Scoring the alternative scenarios against the criteria:* The first step when applying a Multi Criteria Analysis is to assess the consequences of a scenario for each criterion. This is accomplished by describing the consequences and scoring on a scale from 1 to 10 against each criterion, either by using a function

between a physical quantity (parameter) and the corresponding consequences, or by using a matrix which converts the verbal judgments into numerical measures on a scale 1–10. In some cases one criterion can be further analysed to sub-criteria (decision tree) as it happens in the present study. Sub-criteria are used in the same way as criteria. This aspect of the model allows the possibility to assess interactions between various different attributes of the problem.

5. *Calculating the relative importance weights of the criteria:* The overall preference score for each alternative is given by a function that multiplies its score on a criterion by the weight of the criterion, then does the same for all the criteria and finally sums the products. For better understanding of the scoring process, criteria are categorised into five groups. The relative importance of these groups is expressed by weights. In this case, Table 4 shows the weight factors that have been assigned to the groups of criteria.

The above weights have been suggested since it is believed that the technological considerations have already been taken into account straight from the beginning, since the combinations to be examined will be relevant to these specific applications.

On the other hand, implementation success is mainly dependent on the compatibility of the unit with the specific location and the possibility to afford the investment and the operation of the unit. Finally, energy issues are very significant as well, since the whole installation and idea relies on the RES suitability and availability in the certain place.

In parallel, the results' sensitivity in the values of the above weights should be analysed in the "sensitivity analysis", where different values will be given to these weights.

Assigning weights to the sub-criteria within each group is another critical success factor of the proposed method. In many decision-making problems, we may find that all criteria do not equally contribute to reaching the overall objective. Weights, which express the relative importance of criteria, may be derived by:

- Pair-wise comparison of the criteria and formulating a matrix showing the values generated by the pair-wise comparisons.

The method of pair-wise comparison of the sub-criteria within each group has been applied in the present work [17,18]. The relative weights of each sub-criterion compared to the others are determined according to the relevant importance of one criterion as thought by the designer. Definitely all these weights have a subjective element; therefore the sensitivity analysis plays a very important role.

Table 4
Weights of the groups of multicriteria analysis

	Suitability	Weight (%)
I	Technological/operational	10
II	Environmental/land use	20
III	Economic	20
IV	Location characteristics	30
V	Energy use	20
	Total	100

Table 5
Matrix comparing technological/operational criteria

	Technological/operational criteria	1	2	3	4	5	6	7	8	9	10	11	Total	Weight (%)
1	Simplicity of operation	1	0.5	1	2	2	0.5	0.5	0.5	2	1	2	13	9.5
2	Energy demand and the effectiveness of the process with respect to energy consumption	2	1	2	1	2	1	1	2	2	1	2	17	12.5
3	Robustness, maintenance needs	1	0.5	1	1	2	1	0.5	1	2	0.5	2	12.5	9.2
4	Reliability	0.5	1	1	1	1	1	1	2	2	1	2	13.5	9.9
5	Compact size	0.5	0.5	0.5	1	1	0.5	1	1	2	0.5	1	9.5	7.0
6	Commercial availability of the technology	2	1	1	1	2	1	1	1	2	1	2	15	11.0
7	Site characteristics required	2	1	2	1	1	1	1	1	2	0.5	1	13.5	9.9
8	Infrastructure required	2	0.5	1	0.5	1	1	1	1	1	0.5	1	10.5	7.7
9	Requirements for specialised personnel	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	1	0.5	1	7	5.1
10	Produced water quality	1	1	2	1	2	1	2	2	2	1	2	17	12.5
11	Easy transportation to site	0.5	0.5	0.5	0.5	1	0.5	1	1	1	0.5	1	8	5.9
	Total												136.5	100

Table 6
Matrix comparing environmental/land-use criteria

	Environmental/land use criteria	1	2	3	4	5	Total	Weight (%)
1	Effluents/waste produced	1	2	2	1	2	8	28.6
2	Visual impact	0.5	1	2	0.5	1	5	17.9
3	Noise	0.5	0.5	1	0.5	1	3.5	12.5
4	Land requirement	1	2	2	1	1	7	25.0
5	Compatibility with other land use (recreation and tourism)	0.5	1	1	1	1	4.5	16.1
	Total						28	100

Table 7
Matrix comparing economic criteria

	Economic criteria	1	2	Total	Weight (%)
1	Investment cost	1	2	3	66.7
2	Operation/maintenance cost	0.5	1	1.5	33.3
	Total			4.5	100

The following Tables 5–9 show the relative weights of each of the subcriteria for each criterion group. The weights have been determined, as mentioned above, by considering each pair of subcriteria separately and assigning value expressing the significance of one subcriterion related to another one that it is compared with.

1. *Combining the weights and scores to derive an overall value (Weighted Scores) for each alternative scenario for the calculation of the total objective function:* The sum of the weights of each criteria group is multiplied by the relevant weighting factor of the corresponding criteria group.
2. *Ranking alternative scenarios:* The alternative with the highest overall weight is the most favourable one. Finally, the alternatives are ranked in a relevant order of preference from the most suitable to the least suitable one.

Table 9
Matrix comparing energy use characteristics

	Energy demand-availability	1	2	3	4	Total	Weight (%)
1	RES potential-availability	1	2	2	2	7.00	35.2
2	RES cost	0.5	1	0.33	0.5	2.33	11.7
3	RES operational characteristics	0.5	3.03	1	2	6.53	32.9
4	Local power station adequacy	0.5	2	0.5	1	4.00	20.1
	Total					19.86	100.0

7. Example for the implementation of the method—case study

The method wil be applied for three Aegean Sea islands, namely the islands of Agios Efstratios, Anafi and Kimolos (Fig. 10). Anafi and Kimolos belong to the Cyclades complex, while Agios Efstratios is in the Northern part of the Aegean Sea.

Agios Efstratios (Fig. 11) is in the Northern part of the Aegean Sea. It has a permanent population of 400 inhabitants and an area of almost 45 km^2. Very good

Table 8
Matrix comparing location specific characteristics

	Location specific criteria	1	2	3	4	5	6	Total	Weight (%)
1	Geomorphology of the island	1	0.5	1	2	1	1	6.5	16.0
2	Tourist activity—seasonal demand—need for continuous water availability	2	1	2	2	0.5	0.5	8	19.8
3	Personnel availability and organisational structure	1	0.5	1	2	1	1	6.5	16.0
4	Compatibility with the local human and natural environment	0.5	0.5	0.5	1	0.5	0.5	3.5	8.6
5	Funding opportunities	1	2	1	2	1	1	8	19.8
6	Private investors interest	1	2	1	2	1	1	8	19.8
	Total							40.5	100

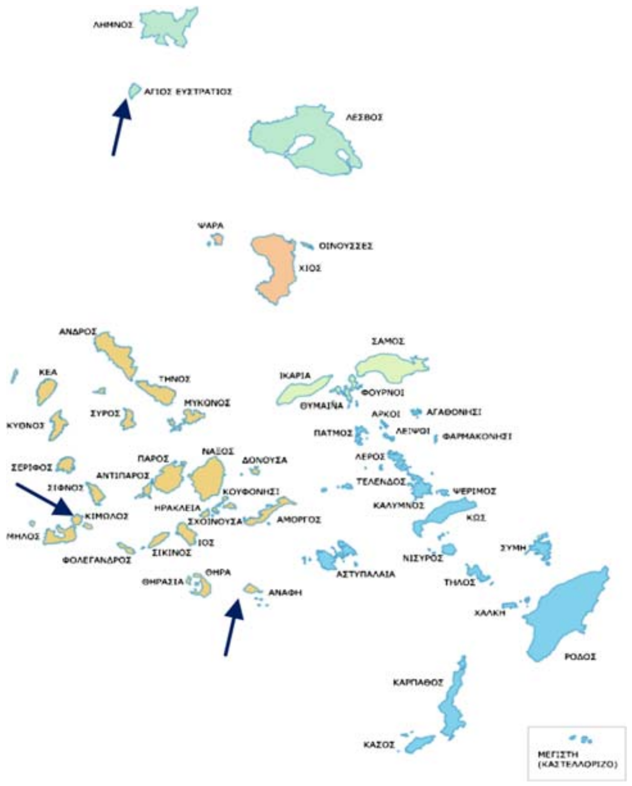

Fig. 10. Map of Greek islands indicating the islands of Ag. Efstratios, Anafi, Kimolos.

Fig. 11. The Island of Agios Efstratios.

wind potential exists in the island. Furthermore, Agios Efstratios has been suggested to become "Green Island", with energy autonomy and local production of potable water and a series of projects in this direction have already started to be designed.

Fig. 12. The Island of Anafi.

Anafi is in the Southern part of Santorini (Fig. 12). It has almost 300 permanent inhabitants. There are no local water resources and most of the water demand is covered through water transfer by boats. Its total area is 383 km^2 and the total coast line is 38 km. In general the island is mountainous and has a warm desert climate (in fact it is the only island along with Santorini in Europe with such climate). During the summer there are many tourists and the water needs are increased. Anafi, as most of the Aegean islands has very significant solar energy potential.

Kimolos is very close to Milos Island (Fig. 13). It has almost 770 permanent inhabitants and area of 375 km^2. During the summer this number gets at least two times an as much. Kimolos has medium enthalpy geothermal. It mainly covers its water needs with ship water transfer and water transfer from the adjacent island of Milos.

Fig. 13. The Island of Kimolos.

Table 10
Most appropriate combination of RES–desalination systems in the selected Aegean Sea islands with the corresponding weights of the criteria groups, case 1

Criteria groups	Weights (%)		Scores of the solutions, case 1		
			Agios Efstratios	Anafi	Kimolos
Technological/operational	10	Wind-RO	6.9	5.6	6.5
Environmental	20	PV-RO	5.1	6.0	5.1
Economic	30	Geothermal	0	0.0	7.7
Location	20				
Energy	20				

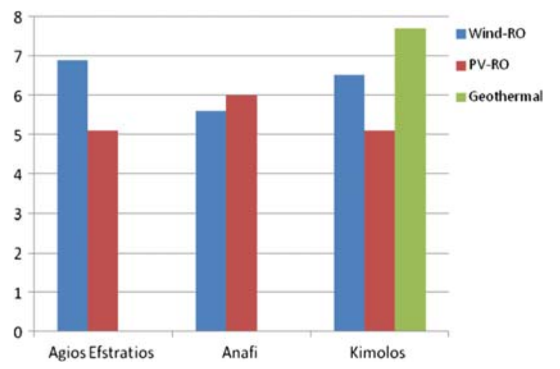

Fig. 14. Scoring of three islands for three alternative RES–desalination combinations (case 1).

The evaluation of the three suggested solutions (Wind-PV, Solar—PV and geothermal desalination) is done with the implementation of the method as described above.

Table 10 and Fig. 14 show the results of the method's implementation. The scoring of each sub-criterion has been done according the characteristics of each specific technology along with the special features of the island under consideration. In fact the geothermal desalination option has not been considered for the islands of Agios Efstratios and Anafi since there is not such an energy available in these two islands.

Most of the Aegean Sea islands have very good wind and solar potential. The difference may be made according to the peculiarities of the specific location (visual impact, land, etc.). In case another form of RES is available, i.e. geothermal fields in Kimolos, then the specific RES is the most prominent solution.

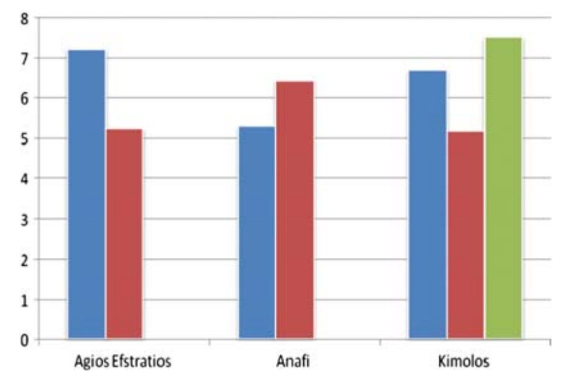

Fig. 15. Scoring of three islands for three alternative RES–desalination combinations (case 2).

Table 11
Most appropriate combination of RES–desalination systems in selected Aegean Sea islands with the corresponding weights of the criteria groups, case 2

Criteria groups	Weights (%)		Scores of the solutions, case 2		
			Agios Efstratios	Anafi	Kimolos
Technological/operational	10	Wind-RO	7.22	5.3	6.7
Environmental	20	PV-RO	5.25	6.4	5.2
Economic	10	Geothermal	0	0.0	7.5
Location	30				
Energy	30				

Furthermore, Table 11 and Fig. 15 show the results of the method in case the relevant weights between the criteria groups change and both, the location characteristics and the energy get the high percentage of 30% and the economic are reduced to 10%. The ranking between the solutions though does not change.

The method provides the tool to analyse many different cases by changing the scoring of the criteria, the marks in the pair-wise comparison and the weights of the criteria groups. Furthermore, the analysis may be extended to investigate the impact of the pair-wise comparison values in the solution obtained. In addition, the (subjective) scoring of each sub-criterion also influences the value of the objective function and, potentially, the ranking of the solutions. Again the sensitivity analysis will reveal these impacts and the robustness of the suggested solution.

8. Conclusions and significance of the results

A Multicriteria Analysis model for the selection of the most appropriate RES–desalination combination has been developed, taking into account a set of criteria and estimating the corresponding weighting factors including technological, operational, environmental and social and specific location specified criteria.

The proposed work could result in a decision support system for the selection of the appropriate energy desalination system in each specific case, taking into account the basic parameters determining this selection (plant size, capacity, energy availability, infrastructure, investment and operational cost, operation and maintenance capabilities in this specific site). Therefore, it could make a significant contribution in the progress and the successful implementation of RES based desalination systems.

At a later stage of the work, the multicriteria analysis will also be extended to include other water supply solutions, in addition to the desalination, since the desalination may not be the most appropriate water supply solution for some of the islands under consideration and other solutions may be more effective and sustainable. Furthermore, the method will be suitably adapted to include specific considerations for other islands (size of units) by adapting the selection criteria and the corresponding weighting factors.

References

[1] IDA Desalination Year Book 2011–2012, Water Desalination Report. http://www.desalyearbook.com/market-profile/12-new-contracted-capacity (accessed on March 2012).

[2] M. Papapetrou, M. Wieghaus, C. Biercamp, Roadmap for the Development of Desalination Powered by Renewable Energy, Fraunhofer Verlag, Stuttgart, 2010.

[3] B. Penate, L. Garcia-Rodriguez, Current trends and future prospects in the design of seawater reverse osmosis desalination Technology, Desalination 284 (2012) 1–8.

[4] L.F. Greenlee, D.F. Lawler, B.D. Freeman, B. Marrot, P. Moulin, Reverse osmosis desalination: water sources, technology, and today's challenges, Water Res. 43(9) (2009) 2317–2348.

[5] PRODES Project—Promotion of Renewable Energy for Water production through Desalination (contract number IEE/07/781/SI2.499059) [online]. Available from http://www.prodes-project.org (cited 07 September 2010).

[6] V.G. Gude, N. Nirmalakhandan, S. Deng, Renewable and sustainable approaches for desalination: Review article, Renew. Sustain. Energy Rev. 14(9) (2010) 2641–2654.

[7] M. Forstmeier, F. Mannerheim, F. D'Amato, M. Shah, Y. Liu, M. Baldea, M. Stella, Feasibility study on wind-powered desalination. Desalination 203(1–3) (2007) 463–470.

[8] E. Kondili, J.K. Kaldellis, D. Tiligadas, 'Wind-based Combined Electricity and Clean Water Production for Remote Islands', Proceedings, World Renewable Energy Congress—WRECXI, 25–30 September 2010, Abu Dhabi, United Emirates.

[9] E. Kondili, J.K. Kaldellis, in: A. Sayigh (Ed.), Proceedings, World Renewable Energy Congress (WRECX), July 2008, Glasgow-Scotland, UK, pp. 2120–2128.

[10] E. Mathioulakis, V. Belessiotis, E. Delyannis, Desalination by using alternative energy: Review and state-of-the-art, Desalination 203(1–3) (2007) 346–365.

[11] F. Banata, V. Subielab, H. Qiblawey, Site selection for the installation of autonomous desalination systems (ADS), Desalination 203 (2007) 410–416.

[12] J.K. Kaldellis, E. Kondili, The water shortage problem in Aegean Archipelago islands. Cost-effective desalination prospects, Desalination 216 (2007) 123–128.

[13] J.K. Kaldellis, D. Vlachou, K. Kavadias, An integrated renewable energy solution for very small Aegean Sea islands, Renewable Energies for Islands, International Conference, Paper No. 68, Chania, Crete, Greece, 2001.

[14] 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.

[15] J.K. Kaldellis, E. Kondili, K.A. Kavadias, Energy and clean water coproduction in remote islands to face the intermittent character of wind energy, Int. J. Global Energy 25(3,4) (2005) 298–312.

[16] E. Kondili, Hybrid wind energy systems for desalination, in: J.K. Kaldellis (Ed.), Stand-Alone and Hybrid Wind Energy Systems: Technology, Energy Storage and Applications, Woodhead Publishing, Chapter 15, 2010, ISBN 1 84569 527 5, ISBN-13: 978 1 84569 527 9.

[17] R. Ramanathan, Multicriteria Analysis of Energy, Encyclopedia of Energy, 2004, pp. 77–88.

[18] S.D. Pohekar, M. Ramachandran, Application of multi-criteria decision making to sustainable energy planning—A review, Renew. Sustain. Energy Rev. 8(4) (2004) 365–381.