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Market potential of renewable energy powered desalination systems in Greece

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Abstract

The present work analyzes water management strategies based on advanced desalination schemes powered by renewable energy sources. The framework for developing a decision procedure, which monitors water shortage problems and identifies the availability of renewable energy resources to power desalination plants, is presented. Cost of alternative solutions, taking into account energy cost or profits by energy selling to grid, is estimated. Emphasis is given to the market forces and the relationship of technology prices and market potential. A case study for the Aegean Islands in Greece is presented.

Keywords: Desalination; Renewable energy; Reverse osmosis; Water market potential

1. Introduction

The development of alternative methods and solutions for tackling water shortage problems and the evaluation of the capabilities and limitations of these alternatives requires a reliable assessment of the available and exploitable water resources and accurate estimation of current and future water needs.

Traditional supply-side techniques aiming to meet the increasing water needs may induce severe environmental impacts as there is a tendency to reach hydrological limits by the depletion of aquifers or the salination of coastal aquifers, and to disturb natural ecosystems by the reduction of surface run-off and the desiccation of wetlands. Drilling in groundwater aquifers, damming and diversion of rivers, inter-basin water transfer, construction of surface water collection systems and enormous financial investments on expanded

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water networks are common and widely used methods falling under this heading [1].

Desalination, compared to conventional supply-side intervention, has an advantageous position in terms of economic costs and environmental impact. The major drawback of desalination schemes is the large energy requirements that traditionally are supplied by conventional energy forms (fossil fuels and electricity). Amongst the various desalination techniques, reverse osmosis (RO) has been widely used during the last years, mainly due to the development of the membrane technology and its low energy requirements compared to other desalting processes. Electrodialysis (ED) processes have also shown attractive results in serving freshwater production, especially in cases that the feed water is of low salinity, as in brackish water applications.

During the last decade, the applicability and reliability of renewable energy sources (RES) powered desalination systems have been extensively discussed as an innovative approach to desalinate water economically and in an environmentally friendly manner [2–7]. Furthermore, the results of numerous research programs have shown that RES/desalination systems could be economically competitive with the conventionally powered ones or other possible solutions, especially in remote arid regions where electricity production costs are high and where appropriate and adequate RES potential exists [8–10]. Wind and solar energy have been found to be the most effective and economic RES for powering RO and ED desalination systems provided that the control mechanisms of the plants are able to sufficiently manage the intermittent nature of these energy sources [11–14]. Based on those findings, the identification of the potential market for RES powered desalination schemes is the next natural step for the evaluation of their expected contribution in solving water shortage problems.

The focal point of the present work lies in the development of a method to evaluate the potential market for RES powered desalination systems. The method comprises the investigation of water shortage problems, the assessment of economically exploitable RES potential, the evaluation of advanced RES/desalination schemes, and the comparison of those schemes with traditionally used supply-side intervention in order to quantify the available market potential of RES-powered desalination for fresh water supply. Emphasis is given to the argument that a greater acceptance of market forces is necessary for an efficient solution to current and future water problems.

In Section 2 the developed method is presented and in Section 3 the case study of the evaluation of market potential in Greece is presented. In Section 4 conclusions derived from the method and the case study in Greece are discussed.

2. Method

The proposed method for the evaluation of the market potential for RES-powered desalination systems is based on the following steps:

- Identification of areas facing water shortage problems through the analysis of water demand and supply balance
- Evaluation of available and economically exploitable RES potential taking into account the geographic distribution of RES
- Site selection for the installation of a RES/desalination plant taking into account possible restrictions on appropriate land availability
- Definition of the characteristics of typical RES/desalination schemes based on the estimated water shortage problem and the availability of RES potential
- Analysis of the economic viability of possible RES/desalination investments

Fig. 1 presents the basic outline of the method for the evaluation of the market potential of RES-powered desalination systems.

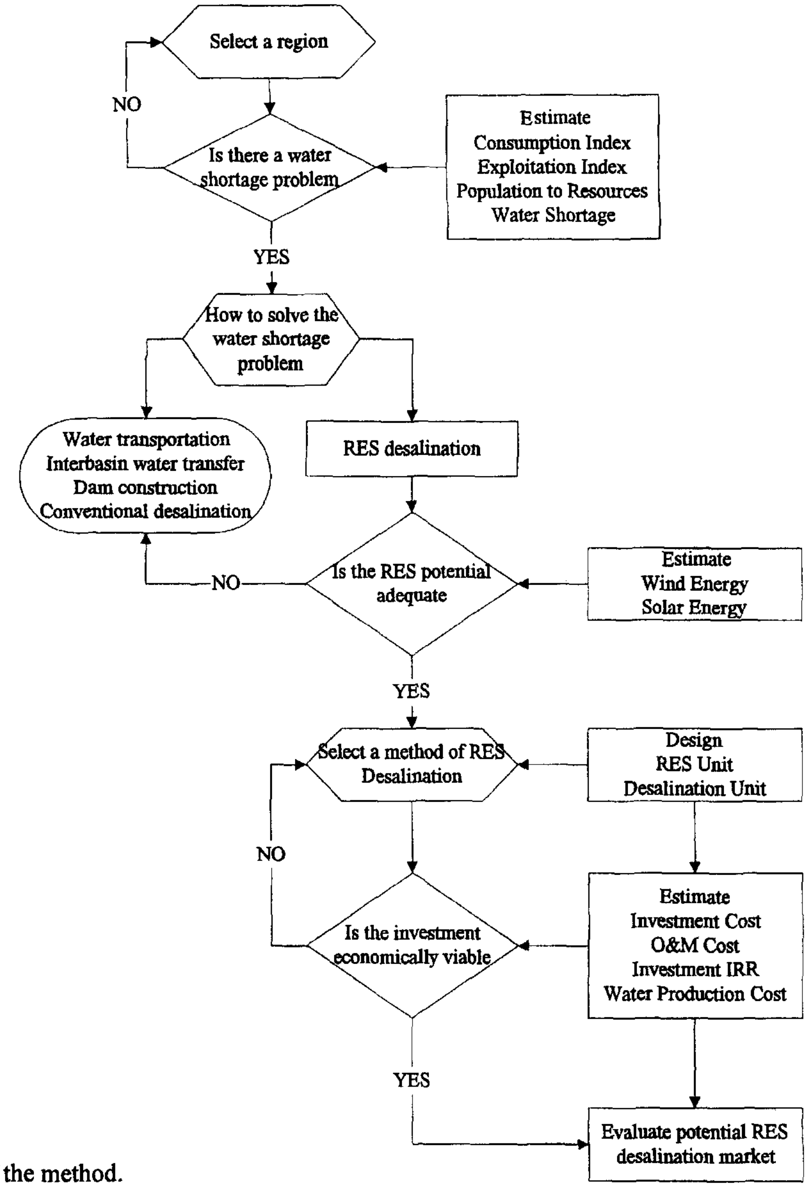

Fig. 1. Overview of the method.

2.1. Identification of areas facing water shortage problems

Areas facing water shortage problems are identified by evaluating the available total and stable natural water resources, assessing the water demand for domestic, agricultural and industrial uses and calculating indices indicative of the water problem size.

The identification of areas under water stress conditions is conducted in two steps. In the initial step, a rough geographical analysis in the level of hydrologic departments (large hydrologic watersheds) is used to identify the regions that lack adequate natural water resources. In the next step, for the regions which currently face severe water shortage problems, the actual water demand and

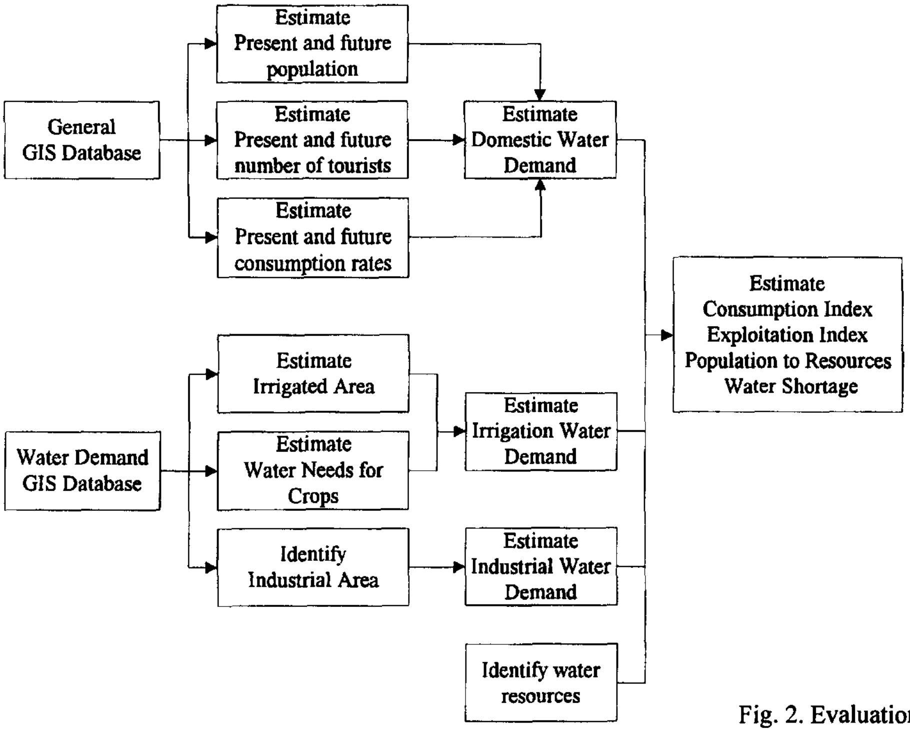

Fig. 2. Evaluation of water supply/demand.

supply is estimated and the annual distribution of water shortage is analyzed.

Fig. 2 presents the algorithm for the evaluation of water supply/demand situation. Water demand in the domestic sector is estimated using water consumption rates for various consumers, estimated on the basis of region type, socio-economic criteria, water distribution network condition, price of water and availability of water resources [8, 10]. Irrigation water requirements for the most important crops are estimated taking into account the specific crop evapotranspiration. In regions where the necessary climate data are not available, average consumption rates for each crop are used for the determination of irrigation requirements [15, 16]. The estimation of industrial water demand is based on water consumption data for main industrial consumers [8, 10].

Areas facing considerable water scarcity problems are determined by the use of indices such as the *Consumption Index, Exploitation Index* and *Population to Resources Ratio* [17]. The consumption index is defined as the ratio of total water demand to the total available water resources and represent a draft measure of the water shortage. Depending on the characteristics of the region, values of the consumption index over 80% indicate possible water shortage problems, and values over 130% indicate severe water stress conditions. The exploitation index is defined as the ratio of total water distribution to the total stable water resources and is a measure of the exploitation degree of the available natural resources. Values of the exploitation index over 80% indicate severe water stress conditions, and values over 100% indicate that non-regional or non-conventional water resources are used (e.g., water transfer from other basins, desalination).

2.2. Evaluation of RES potential

The evaluation of the available and exploitable RES potential is based on meteorological data that define the theoretical wind and solar energy potential, as well as on restrictions imposed by the RES unit siting that introduce constraints for RES exploitation.

A wind atlas is used to select and isolate areas with adequate wind speed. Additional maps are used to exclude areas of hard accessibility or areas near populated towns, airports and archaeological sites. The remaining areas are candidate sites with favorable conditions for the installation of wind turbines [18]. Solar radiation measurements in meteorological stations are used for the evaluation of solar energy potential in the areas of interest using interpolation methods [19].

2.3. Site selection and design of appropriate RES/desalination systems

The site selection for the installation of a RES/desalination plant is based on the results of the previous methodology steps. The sites for the installation of a RES-powered RO plant are selected after taking under consideration restrictions on desalination and RES unit siting. For the desalination unit the restrictions concern the maximum allowable distance from the feed water resource (sea or brackish water spring) and the maximum allowable altitude difference. For the RES unit the restrictions concern the minimum energy resource (wind speed in the case of wind energy and solar radiation in the case of solar energy) the topographic characteristics of the site for the installation of the power unit that have to be uniform and the minimum distance of the power unit from the desalination unit.

The rated capacity of the desalination plant is selected in order to cover the peak water demand that has been estimated. Given the specific energy consumption per unit of produced water, the power consumption at the rated capacity of the desalination plant is determined by Eq. (1):

$$P_{RO} = SP_{RO} C_r / 24 \tag{1}$$

The energy flows from the RES unit to the desalination plant, as well as the energy flows from and to the electrical grid, are estimated on an annual basis. The Weibull distribution and the power curve of the selected wind turbine are used to estimate the energy produced by wind generators.

The total annual energy consumed by the desalination plant is estimated by Eq. (2):

$$E_{RO} = SP_{RO} \cdot D_{TOT} \tag{2}$$

The annual energy production of the wind turbines is calculated by Eq. (3):

$$E_T = 8760 \cdot N_{WT} \cdot \int_0^{U_{CUTOUT}} P(U) \cdot p(U) \mathrm{d}(U) \tag{3}$$

Assuming that the wind turbines can provide the desalination plant up to P_{RO}, we can define the maximum annual wind energy that the desalination plant can absorb by Eq. (4):

$$E_{WT-RO} = 8760 \cdot N_{WT} \cdot \left[\int_0^{U_{PRO}} P(U) p(U) \mathrm{d}U + \int_{U_{PRO}}^{U_{CUTOUT}} P_{RO} p(U) \mathrm{d}U \right] \tag{4}$$

The installed wind turbine power is selected in order to cover the energy needs of the RO desalination unit. In case that the wind speed is weak ($U<U_{PRO}$) and the power from the wind turbines is not adequate for the operational requirements of the desalination unit, the additional necessary energy is obtained from the electrical grid. In case that the wind speed is high ($U>U_{PRO}$) the excess energy from the wind turbines is sold to the electrical grid.

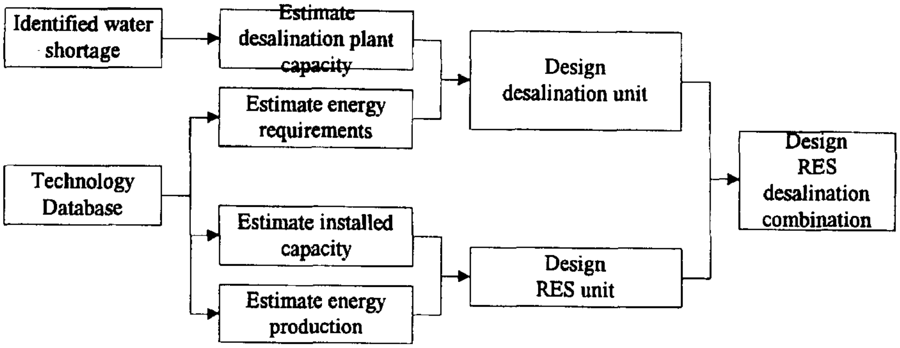

Fig. 3. Design of the appropriate RES/desalination plant.

The type and number of the wind turbines that are used in each of the above-mentioned cases is defined by an iterative approach which tests various wind turbine models and decides on the one that covers sufficiently the energy needs of the desalination unit.

Fig. 3 presents the algorithm for the design of the appropriate RES/desalination plant.

2.4. Financial analysis and market penetration

The financial analysis of a RES/desalination plant is based on the estimation of total investment, operational and maintenance cost of the potential RES/desalination scheme, the energy and water production costs and the calculation of the internal rate of return (IRR) for the RES/desalination investment.

The total investment cost for a wind/RO plant consists of the investment costs for the wind turbines and the desalination unit. The investment cost of the RES unit includes preliminary and engineering costs, design costs and permits, field works and road construction costs, foundation costs, wind turbines transportation and installation costs, grid connection costs and land cost. The operational and maintenance costs of the RES unit include personnel and consumables, services and travel expenses. The investment of the RO unit includes the costs of pre-treatment equipment (filters, pumps and chemicals), high pressure pumps, membrane modules and energy recovery devices. The operational and maintenance costs of the RO unit consist of labor, spare parts, chemicals and membrane replacement [8, 9].

The water production cost is calculated by Eqs. (5) and (6):

$$WPC = \frac{(TIC_{WT} + TIC_{RO}) \cdot R + (M_{WT} + M_{RO}) + 0.7 \cdot EL_{PR} \cdot (E_{WT} - E_{RO})}{D_{TOT}} \tag{5}$$

$$R = \frac{r}{1 - (1+r)^{-N}} \tag{6}$$

The financial analysis of a wind/RO installation is based on the IRR which is estimated by Eq. (7):

$$IRR = d: \sum_{i=1}^{N} \frac{D_{TOT} \cdot W_{PR} + (E_{WT} - E_{RO}) \cdot EL_{PR} \cdot 0.7 - M}{(1+d)^{i}} = TIC \tag{7}$$

The specific investment cost for a given IRR is calculated by Eq. (8).

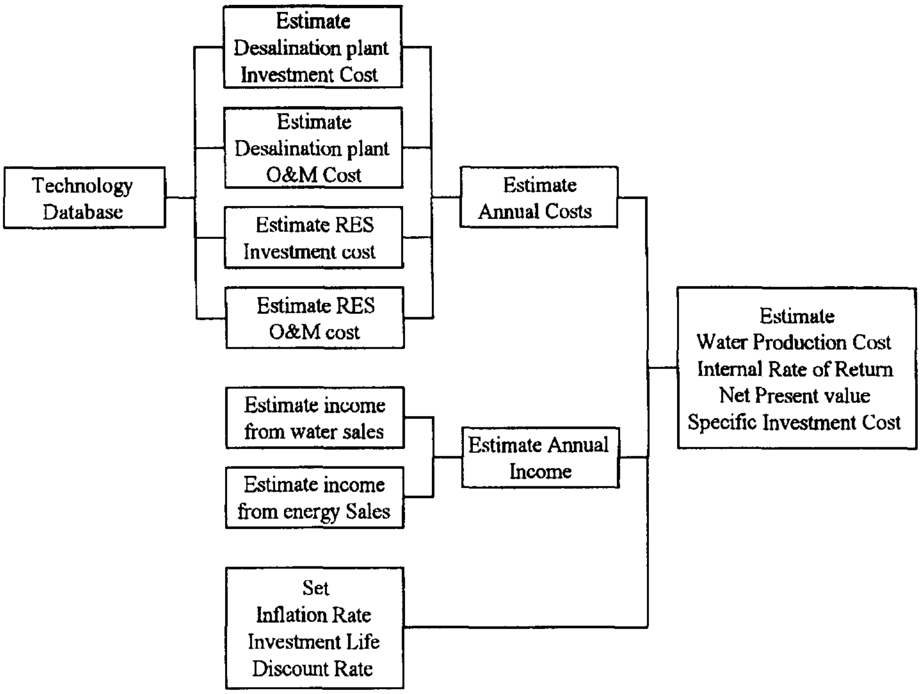

Fig. 4. Financial analysis of a RES/desalination plant

$$SC = \sum_{1}^{N} \frac{\dfrac{D_{TOT} \cdot W_{PR} + (E_{WT} - E_{RO}) \cdot E_{PR} - M}{(1 + IRR)^{N}}}{D_{TOT}} \tag{8}$$

The potential investments that have been identified in the previous steps are ranked according to the specific investment cost for various discount rates, and the cumulative water production is estimated for all investments. The results are graphed and compared to the current specific investment cost. The investments that are economically viable, with a specific cost higher than the current one, are considered as the contribution of RES desalination to the confrontation of water shortage problems of the region under examination and represent the potential market of RES powered desalination.

Fig. 4 presents the algorithm for the financial analysis of a RES/desalination plant.

3. Case study — results

The developed method was used for the identification of the Greek regions that face water shortage problems and the evaluation of water demand and availability for the period 1991–2011. The water supply for this period is considered to be stable, and the future demand for potable water is estimated on the basis of demographic growth of permanent population and tourists.

3.1. Databases

The implementation of the various steps of the developed methodology requires a large amount of different groups of data accommodated in a GIS environment which is used for the application of the method. The necessary data stored and handled by the GIS are:

- Maps of the administrative boundaries and the location of populated areas in Greece

- Data on permanent and non-permanent population and cultivated and irrigated areas for the most important crops
- Domestic water consumption rates for permanent and non-permanent population and irrigation water consumption rates for the most important crops
- Map with the industrial areas and relative industrial water consumption data
- Maps of the boundaries of hydrologic departments and hydrologic basins and data on precipitation height, water run-off, surface and groundwater resources
- Map of the most important brackish water springs and data on flow rate, water quality, and current and future exploitation plans for each spring
- Digital map with wind speed data and meteorological data on average monthly sunshine duration and air temperature
- Map of altitude lines, slope lines, airports, archaeological sites, roads and the electric grid network
- Data on technical characteristics; energy production; and investment, operational, maintenance and other costs for wind turbines
- Data on technical characteristics, energy requirements and various costs for RO technologies.

3.2. Identification of areas facing water shortage problems

The areas with the greatest water scarcity problems are the Aegean Islands. The existing data on population and hotel units were used for the estimation of potable water requirements on each island of the Prefectures of Cyclades and Dodecanese. The water consumption rate for permanent population was determined as 150 l/person/d. The same rate for tourists was assumed as 200 l/d.

The available data on water supply in each island combined with the estimated water needs were used for the evaluation of the Consumption Index, the Exploitation Index and the "Population to Resources" ratio. The values of these indices indicate the islands where serious water shortage problems occur. Fig. 5 presents the consumption index of the islands of Cyclades and Dodecanese.

3.3. Site selection

The site selection for the installation of a RES/desalination plant is based on the identification of areas under water stress conditions, the evaluation of exploitable RES potential, and the evaluation of available sea and brackish water resources to feed desalination plants for each region. In islands where the consumption index takes high values (over 130%) the installation of a RO desalination unit powered by wind energy is examined. The sites for the installation of a wind-driven RO plant are selected after taking under consideration the following restrictions:

For the desalination unit:

- Maximum distance from the coast: 500 m
- Maximum altitude: 100 m

For the wind turbines:

- Minimum wind speed in areas under examination: 6 m/s
- Maximum distance from the desalination plant: 500 m
- Areas near archaeological sites, airports, towns are excluded from further analysis
- Areas with difficult access (high altitude and steep slope) are also excluded

For the RES/desalination matching:

- Maximum distance between RES unit and desalination unit: 500 m

Fig. 6 presents the process for the selection of the appropriate site for the installation of a RO desalination unit in the island of Antiparos. One selected area is in the NW side of the island and

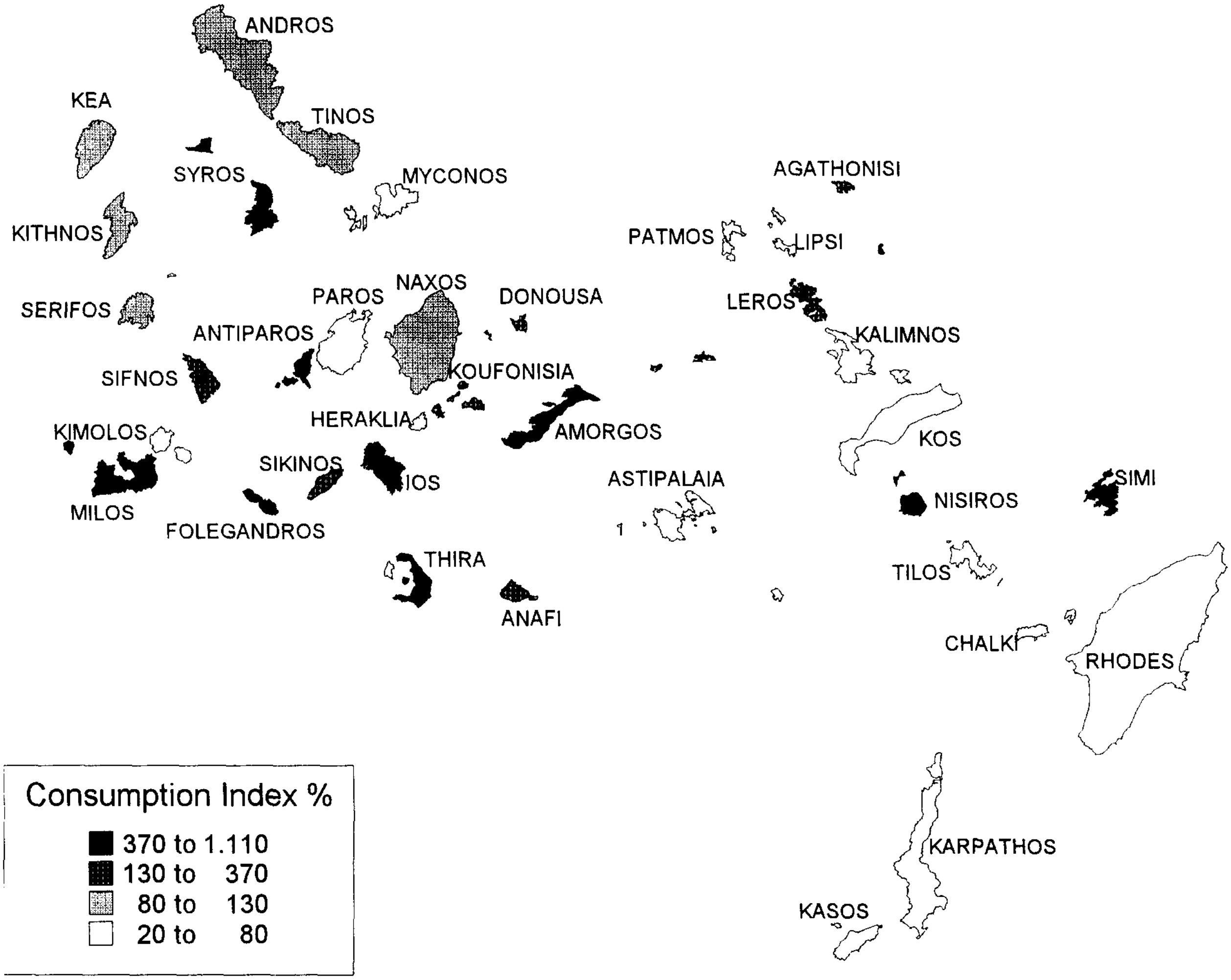

Fig. 5. Consumption Index for the Aegean Islands.

another in the SE side. The final selection is determined with additional criteria, such as the existence of a road in the SE side that could make easier the access.

According to legal restrictions, the maximum RES power that can be installed in an autonomous electrical system of an island cannot be more than 30% of the maximum power needs in the island. In case that the extra amount of energy produced by the wind turbines is bigger than the electrical power which is allowed to be provided to the grid, then the wind park is autonomous. Otherwise the wind generators are connected to the grid and the extra produced energy is sold to the PPC in order to improve the economic efficiency of the desalination unit.

3.4. Market potential

Table 1 presents the investment and operational cost of a wind/RO installation and the sale prices of water and electricity. Fig. 7 presents the capacity of the desalination plants in the islands that face water-shortage problems. Fig. 8 presents the required wind turbine capacity. Fig. 9 presents the IRR of the investment in each island.

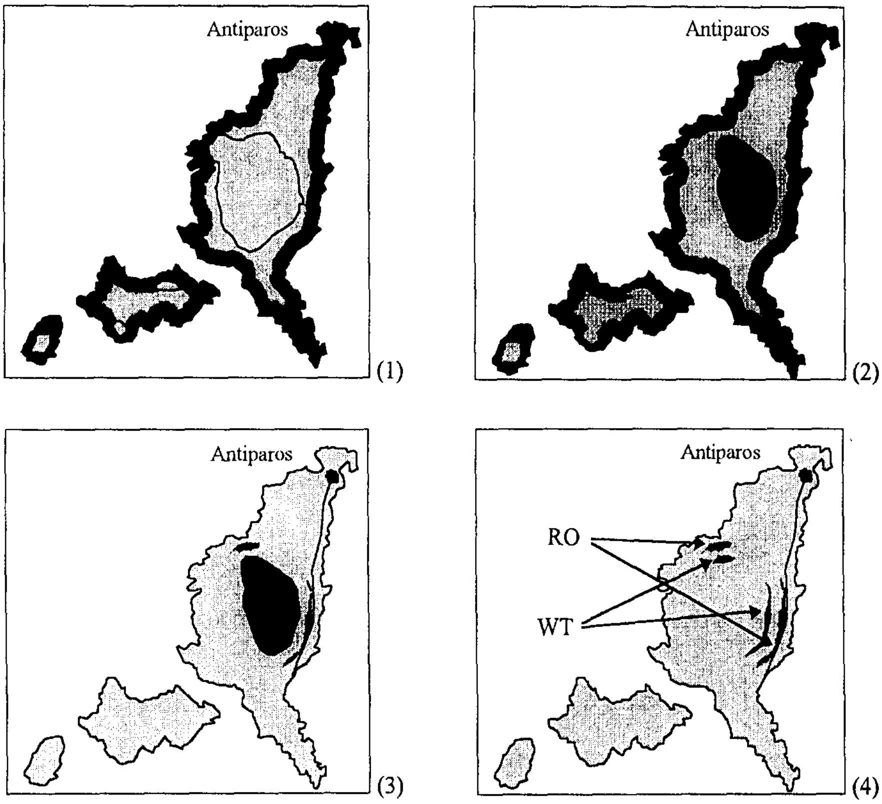

Fig. 6. Site selection of desalination units and wind turbines in the island of Antiparos. (1) Selection of desalination unit sites with distance less than 500 m from the coast and altitude less than 100 m. (2) Selection of wind turbines sites with average wind speed over 6 m/s. (3) Selection of the possible sites for the installation of the desalination unit with distance less than 500 m from the sites with appropriate wind speed. (4) Selection of the possible sites for the installation of the wind turbines with distance less than 500 m from the possible sites for the installation of the desalination unit.

Table 1
Economic analysis of a RO desalination plant powered by wind turbines

Total investment cost of wind turbines, ECU per installed kW	1300
Total investment cost of RO plant, ECU per produced m^3/d	2000
Operational and maintenance cost of wind turbines, % of total investment cost	2.5
Spare parts of the RO unit, ECU/m^3/y	0.06
Labor costs for the RO unit, ECU/m^3/y	0.11
Membrane replacement for RO unit, ECU/m^3/y	0.13
Chemicals for RO unit, ECU/m^3/y	0.15
Lifetime of investment, y	20
Water selling price	Differs upon case
Electricity selling price, ECU/kWh	0.056

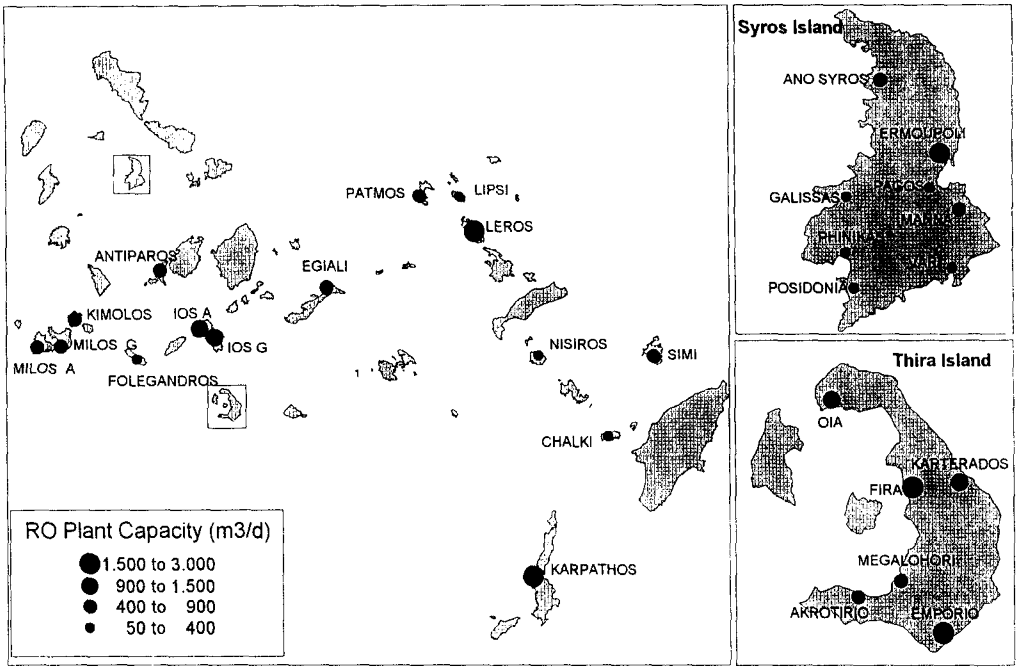

Fig. 7. Required capacity of desalination units.

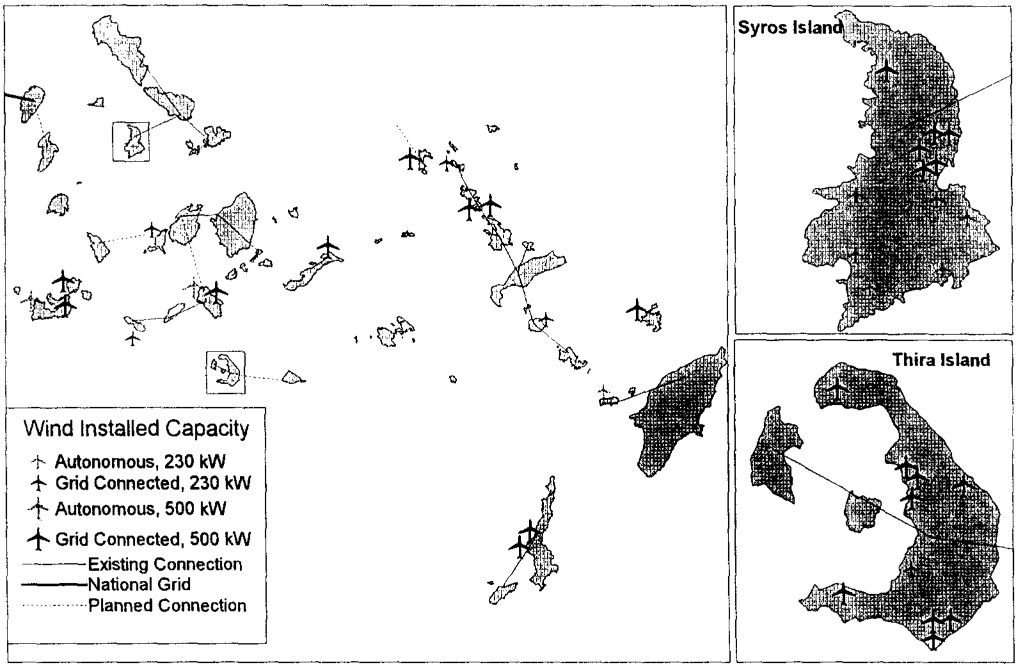

Fig. 8. Electrical grid of Aegean Islands and required capacity of wind turbines.

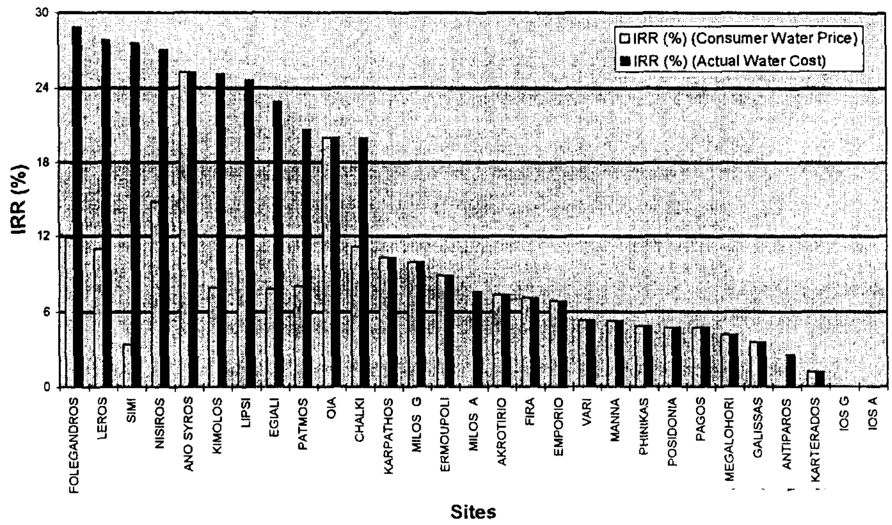

Fig. 9. Internal rate of return of investments.

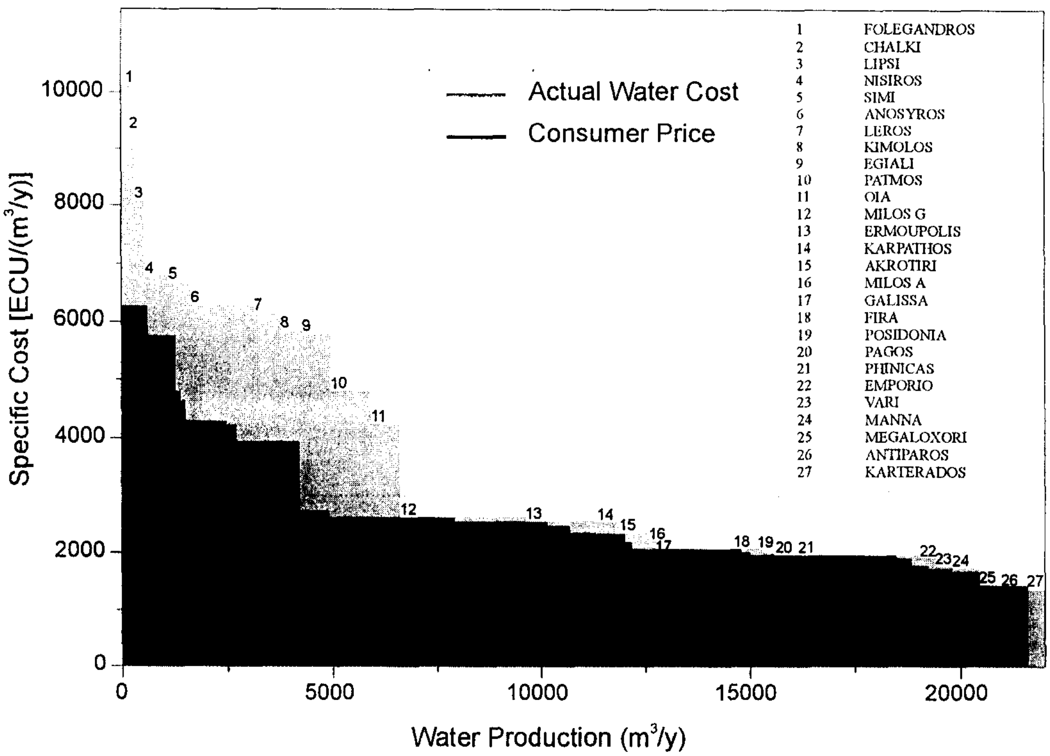

Fig. 10. Market penetration of desalination units at internal rate of return of 12%.

The water scarcity problem that the islands of Cyclades and Dodecanese face creates a market of about 25,000 m^3/d of water produced by wind powered desalination plants.

The cost of equipment for each investment is calculated by Eq. (8) in order to estimate the percentage of this water market that can be covered by investments with an IRR greater than 12%. In the next step, all the investments are arranged in a descending order according to the equipment cost per product unit and the total production of water is estimated. Fig. 10 presents the equipment cost per product unit in relation to the total production of water for the whole of the current market in the Aegean Islands. The dotted line represents the current commercially available equipment cost per product unit.

Fig. 10 shows that a water market of about 4500 m^3/d can be covered by investments with an IRR bigger than 12%, if the selling price of water is the one that consumers currently pay. This market is increased up to 5500 m^3/d, if the selling price of water represents the actual cost of water. In any case however the equipment cost of RES powered desalination units must be further decreased, if wind powered desalination plants are to cover a higher portion of the available potable water market.

4. Conclusions

The developed method has been able to propose an alternative option to solve water shortage problems by selecting the proper RES/desalination combination using technical and economic criteria. Moreover, the market penetration limits of the selected solution has been evaluated under various economic scenarios. The information derived from the case study are of primary importance for authorities concerned with water management and water policy. The obvious future step is the development of decision support system for the implementation of the method with the objective to make it easily handled and applied to various regions even from non experts.

The estimation of the water needs in Greece has pointed out that the Aegean Islands are the most arid areas in Greece because the existing water resources are limited and the water demand is increased due to their tourist development.

The evaluation of the available and economically exploitable RES potential presented that the wind energy is abundant in most of the Aegean Islands that face water shortage problems. Wind-powered RO desalination plants can operate economically in most of the arid Aegean Islands because of the high wind potential that improves the economics of the desalination plant due to additional income from the electricity sales.

The market for RO applications using RES can be considered as favorable in the South Aegean Sea islands and can promote the further development of RES-powered desalination technologies in Greece although significant technology cost reduction is necessary in order for this option to contribute a larger portion of water demand.

5. Symbols

C_r	—	Daily production of the unit
D_{TOT}	—	Annual water production of the desalination unit
E_{WT}	—	Annual produced energy by wind turbines
E_{RO}	—	Annual energy consumption of the desalination unit
$E_{WT\text{-}RO}$	—	Annual produced wind energy consumed by the desalination plant
EL_{pr}	—	Electricity selling price
M	—	Total operational cost of wind turbines and desalination plant
N	—	Lifetime of the investment equal to 20 years
N_{WT}	—	Number of wind turbines
$p(U)$	—	Wind speed distribution

P_{RO} — Energy consumption of the desalination unit at rated capacity
$P(U)$ — Power curve of wind turbine
r — Discount rate
SC — Equipment cost per product unit
SP_{RO} — Specific consumption per unit of produced water
TIC — Total investment cost of wind turbines and desalination plant
U_{cutout} — Maximum wind velocity for the operation of the wind turbine
U_{Pro} — Wind velocity corresponding to produced energy P_{RO}/N_{WT} from the wind turbine power curve
W_{pr} — Water selling price
WPC — Water production cost

References

[1] J. Winpenny, Managing Water as an Economic Resource, Routledge, New York, 1994.
[2] N. Ishimaru, Desalination, 98 (1994) 485.
[3] D. Infield, Solar Energy, 61(3) (1997) 415.
[4] C.T. Kiranoudis, N.G. Voros and Z.B. Maroulis, Desalination, 109 (1997) 195.
[5] J. Kabouris, G.C. Contaxis, N. Zouros, M. Tortoreli and K. Perrakis, Proc., EWEC'94, 1994, pp. 1050–1055.
[6] R. Robinson, G. Ho and K. Mathew, Desalination, 86 (1992) 9.
[7] C.G. Warfel, J.F. Manwell and J.G. McGowan, Solar & Wind Technol., 5(5) (1988) 549.
[8] PRODESAL, Towards the large-scale development of decentralised water desalination, Final Report, EEC, DG XII, APAS RENA CT94-0005, 1996.
[9] K.G. Rados, D. Assimacopoulos and A. Zervos, Proc., MED Conference, Santorini, 1996.
[10] REDES, Decision support system for the integration of renenergies into water desalination systems, Final Report, EEC, DG XII, APAS RENA CT94-0058, 1996.
[11] O.A. Hamed, E.I. Eisa and W.E. Abdalla, Desalination, 93 (1993) 563.
[12] A. Hanafi, Desalination, 97 (1994) 339.
[13] J.F. Manwell and J.G. McGowan, Desalination, 94 (1994) 229.
[14] R.K. Suri, A.M.R. Al-Marafie, A.A. Al-Homoud and G.P. Maheshwari, Desalination, 71 (1989) 165.
[15] R.G. Allen and W.O. Pruitt, J. Irrigation and Drainage Engineering, 117(5) (1992) 758.
[16] M.E. Jensen, R.D. Burman and R.G. Allen, Evapotranspiration and irrigation water requirements, ASCE Manuals and Reports on Engineering Practice. No. 70, 1989.
[17] ECOTEC, Research and technological development for supply and use of freshwater resources – Sast Project No 6, Monitor-SAST Activity, DG Information Technologies and Industries, and Telecommunications, Commission of the European Communities, 1992.
[18] D. Voivontas, D. Assimacopoulos, A. Mourelatos and J. Corominas, Renewable Energy, 13(3) (1998) 333.
[19] D. Voivontas, G. Tsiligiridis and D. Assimacopoulos, Solar Energy, 62(6) (1998) 419.