A tool for the design of desalination plants powered by renewable energies

D. Voivontas, K. Misirlis, E. Manoli, G. Arampatzis, D. Assimacopoulos*, A. Zervos

Chemical Engineering Department, Sector II, National Technical University of Athens,
9, Heroon Polytechniou, Zografou Campus, Athens GR-15780, Greece
Tel. +30 (1) 772-3218; Fax +30 (1) 772-3155; email: assim@chemeng.ntua.gr

Abstract

A unified approach for the evaluation of alternative renewable-energy-powered desalination systems and their comparison on the basis of the economics of the associated investments is presented. The proposed method works out a preliminary plant design, evaluates the energy flows and calculates the water cost and the expected water selling price. The energy needs of the desalination processes and the energy production by the renewable energy technologies are estimated using simplified models. The size and type of the back-up power units (energy storage, grid connection or diesel generators) are identified. The expected water selling price is estimated, taking into account the water production cost and the investment profitability index. The computer-aided design tool that has been developed proposes technology combinations that guarantee the desalination energy needs and provides the means to compare the alternative options on the basis of economic indicators. Results on alternative RE–desalination combinations are presented in order to select the optimum solution for a specific case study. The effect of critical design parameters on the water selling price is analyzed for a wind-powered reverse osmosis plant.

Keywords: Renewable energy; Desalination; Water price; Financial analysis; Software application

1. Introduction

Renewable energy sources (RES) represent one promising option for the considerable energy needs of desalination processes. Especially in remote and arid regions where the use of conventional energy (fossil fuels, electricity) is costly or not available, RES-powered desalination plants may be an attractive alternative. In most cases fresh water scarcity co-exists with abundant RES potential.

Stand-alone RES-powered desalination

*Corresponding author.

schemes are selected mainly for remote areas where a grid connection is impossible or very expensive and water demand is usually rather low. The main desirable features for these systems are low cost, low maintenance requirements, simple operation and, of course, very high reliability. On the other hand, grid-connected plants are preferred for medium- or large-scale plants. Grid connection provides the plant with the energy needed at periods of low RES energy supply while offering the possibility of selling excess energy to the local grid.

The selection of the optimum combination of RES and desalination technologies in a specific region is based on resource availability and the technical compatibility and maturity of processes. Numerous RES–desalination combinations have been identified and tested in the framework of ongoing research for innovative desalination processes [1–9]. Detailed assessments of available and exploitable water resources and water needs have been carried out in the framework of research programmes [10–12] taking into account current and future trends of economic development and environmental and socioeconomic factors. Moreover, the market potential for RES desalination in specific regions has been identified, based on the combined evaluation of water shortage problems and RES potential with the objective to determine economically competitive options for RES-powered desalination [13–15].

Although various methods to assess the economic viability of specific desalination plants powered by RES have been presented, there is still a need for a unified approach which can assess alternative RE–desalination combinations and compare them on the basis of the economic results of the associated investments. In the present work, a method is proposed for the preliminary plant design and evaluation of water production cost. The profitability index [16,17] is used for the estimation of the expected water selling price on the basis of the overall

discounted water cost. A computer-aided design tool, which implements user-defined RE–desalination combinations, has been developed. The tool proposes technology combinations that guarantee the desalination energy needs and provide the means to compare alternative options on the basis of economic indicators. The tool provides all the necessary information to the user for the selection of the optimum power matching between the intermittent RES supply and the steady energy demand of desalination processes.

2. The design approach

There is no straightforward way to select the appropriate RE–desalination technology for a specific case. Rather an iterative approach is most probably to be followed, involving careful assessment of available options in meeting the regional water demand and the economic viability of the selected solution. The decision-maker handles information such as feed water quality and quantity, desalinated water specifications, type and size of the available RES potential and commercial maturity of the technology in order to decide on operational characteristics of each candidate solution. Furthermore, candidate options are screened through constraints such as site characteristics and financial requirements and compared in order to select the optimum solution.

The overall design algorithm is presented in Fig. 1. The first step of the proposed approach involves the definition of a list of alternative technology arrangements which can satisfy the targeted water demand. In the next step, a detail design of each candidate option is made to determine the plant capacity, the structure of the power unit, and the operational characteristics. The final step pursues a financial analysis of the investment associated with the selected RES desalination combination. The investment and operational costs are analytically estimated and
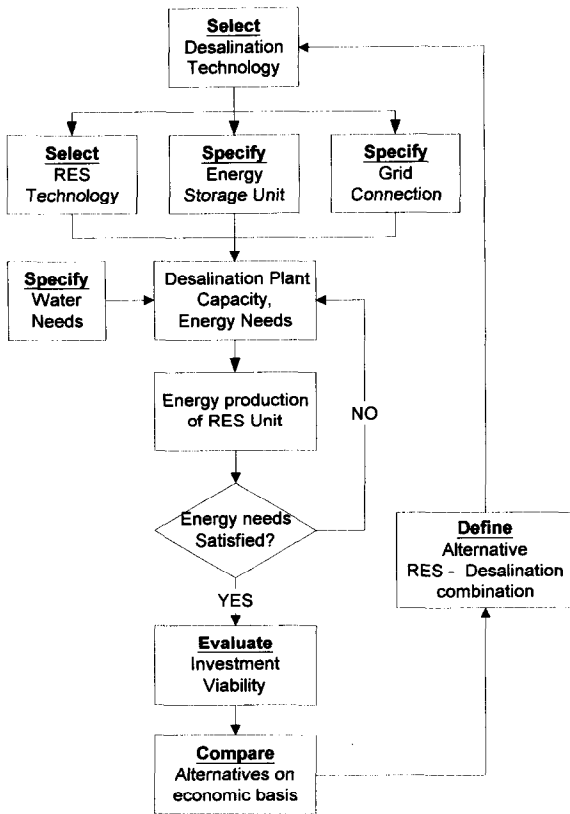
Fig. 1. RES–desalination design algorithm.

the expected water selling price is evaluated on the basis of the overall discounted water cost. The expected water selling price is used for comparison among alternative RES desalination options as well as different schemes to cover water shortages such as transportation of water, construction of dams or conventional desalination systems.

2.1. Design of the RES–desalination unit

The capacity of the desalination plant and the daily and seasonal operation are determined by the water demand. The desalination process is selected taking into account the capacity of the plant, the feed water quality and the product water requirements. The plant capacity, the feed salinity as well as operating characteristics of the plant determine the energy requirements of each desalination process. Appendix 1 describes the models for the evaluation of the energy needs of desalination processes.

The most challenging problem associated with the implementation of RES-powered desalination plants is the optimum matching of the intermittent RES power output with the steady energy demand for the desalination process. Power management and demand-side management are the two options available to solve this problem. In the first case, an appropriately controlled hybrid RES unit that is able to provide a steady energy output is used, and it is sized at the nominal power demand of the desalination process. In the second case, the desalination process operates only when the energy output of the RES unit is able to cover the energy demand. The cost analysis and comparison among alternative RES–desalination combinations can point out the optimum solution for a specific case. The energy balance between energy production from RES and auxiliary energy sources and the energy demand of desalination processes is used for determining the capacity of the energy unit.

The algorithm for the analysis of the energy flows for the entire unit and the determination of auxiliary energy supply needs is outlined in Fig. 2. The RES potential and the available area for the installation of the RES unit determine the maximum capacity of the power unit and the energy production. The energy produced from the RES unit varies according to the RES potential, and only when it reaches the desalination plant power requirements is it supplied to the desalination plant. The energy produced in periods of low RES availability and the fraction of the RES energy that is not needed for the desalination plant are dumped or sold to the grid. The fraction of desalination plant energy needs that is not covered by the RES unit is provided by auxiliary energy sources (grid, diesel generators, energy storage).
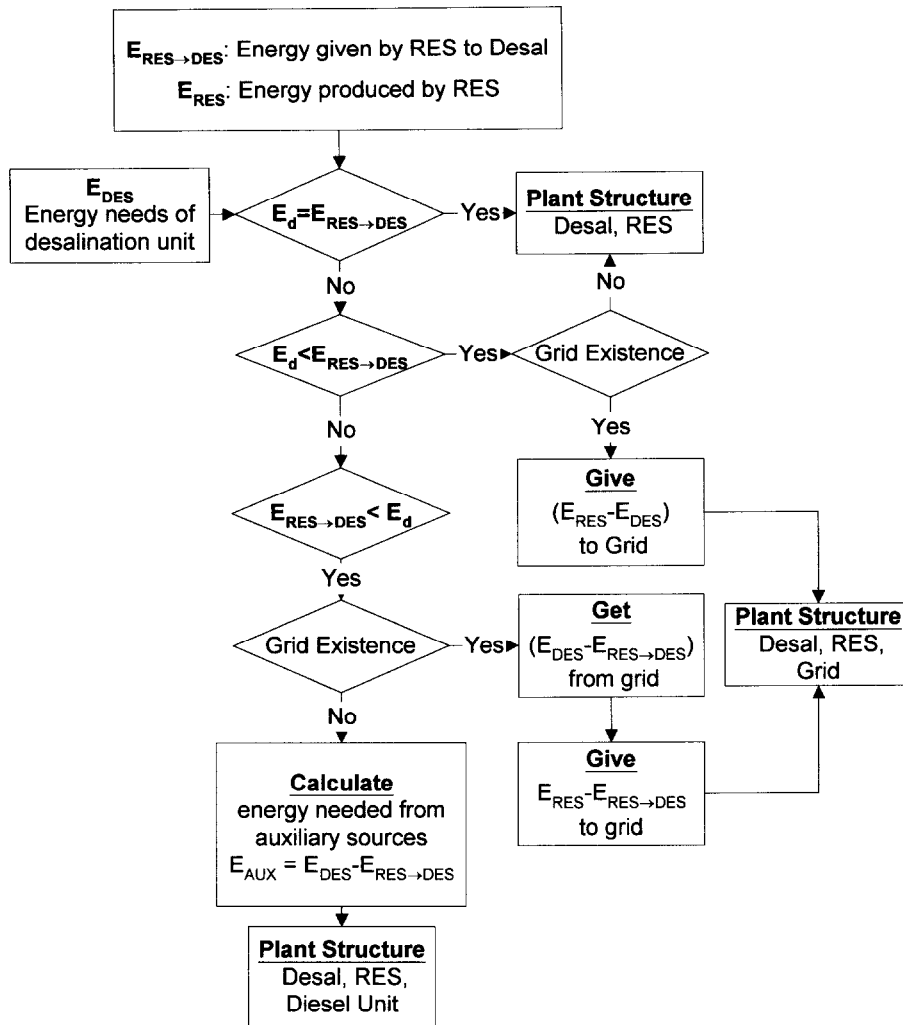
Fig. 2. Algorithm for estimating annual energy flows and plant size.

If the energy supplied by RES meets the energy requirements of the desalination unit, then there will be no energy from the auxiliary energy sources. An auxiliary energy supply system can be used in this case to make up for periods of low RES availability. In the case where the maximum available RES energy is not adequate to cover the energy needs, a grid connection or diesel generator is necessary. The size of the diesel generator and the energy flows to and from the grid are determined in order to cover the power shortage.

The energy production from RES as well as the energy flows from the RES unit to the desalination plant are estimated by simplified models. In the case of wind-energy-powered desalination plants, the mean annual wind speed and the k-Weibull distribution are the main site-specific inputs necessary for the evaluation of energy production. The main technology related

inputs are the height and the power curve of the selected wind turbines. In the case of PV-powered desalination plants, the solar radiation in the specific region as well as the efficiency of the PV cells are the main necessary inputs for the evaluation of energy flows to and from the grids. Details on the modelling of the renewable energy converters are given in Appendix 2.

2.2. Financial evaluation

The financial analysis of the proposed investment involves the estimation of capital and operational costs, the estimation of the overall water discounted cost and the evaluation of the expected water selling price.

The profitability index (PI) is defined as the net present value of the investment per unit of initial capital investment [Eq. (1)] and provides a measure of the minimum profitability margin, which determines the difference of discounted cost and selling price. Positive values of the PI indicate that the investment is viable while negative values indicate that the overall discounted costs are higher than the expected water selling price.

$$PI = \frac{NPV}{C_{INV}} \qquad (1)$$

The net present value (*NPV*) of the investment is calculated by

$$NPV =$$

$$\frac{SP_W * Q_W + SP_E * Q_E - C_{INV} * CR - C_{O\&M}}{R} \qquad (2)$$

The overall discounted water cost is a function of the initial investment and the operational and maintenance costs of the RES-powered desalination plant. Both the desalination unit and the RES unit costs are taken into account in the estimation of the water production cost. In the

case that the plant is grid connected, the potential revenues from power sales have to be excluded from the analysis because a fraction of the plant costs is covered by those revenues and does not influence the water cost [Eq. (3)].

$$DC_W = \frac{C_I * R + C_{O\&M} - SP_E * Q_E}{Q_W} \qquad (3)$$

The PI is used to calculate the expected water selling price based on the overall discounted cost of the RES–desalination system. Taking into account Eqs. (1)–(3), the water selling price can be estimated from Eq. (4).

$$SP_W = \frac{C_I * R}{Q_W} * PI + DC_W \qquad (4)$$

The comparison among alternative RES–desalination schemes is based on the estimated water selling price or the overall discounted costs. Moreover, estimated water prices can be compared to the actual water selling prices in order to specify whether the proposed investment is competitive towards conventional methods of water supply. The variation of water selling price with the PI helps the decision-maker to identify the selling price that best matches the economic requirements from the investment. The graph of the water selling price vs. the PI is a straight line, in accordance with Eq. (4). The slope of the line depends on the initial investment, the financing parameters of the investment (lifetime, discount rate) and the plant capacity. Higher slopes represent more attractive investments since a small increase of the selling price leads to a substantial increase of the profitability index and consequently to the net present value. Higher PI values lead to high revenues and consequently more profitable investments. On the other hand, lower PI values lead to lower consumer water

prices, making the proposed investment competitive with alternative options to cover water demand.

3. Software implementation

The tool implements the proposed method in four sequential steps. Each step is presented in a specific form and the user has the option to review the results and repeat the calculations at any step. The tool starts with the form presented in Fig. 3. The user defines different RES desalination combinations by selecting the desired desalination process and the renewable energy source that will be used. Moreover, the

grid connection and the use of diesel generators or storage units can be determined in order to generate a series of alternative RES desalination plant structures. In the initial form the user defines the costs for all desalination processes and RE technologies as well as the financial parameters of the investment.

The second step presents the energy requirements of the selected desalination process and provides the option to the user to alter the specific energy demand or re-estimate the energy requirements using different design variables. Fig. 4 presents the form for the definition of the specific energy requirements of the selected desalination process. Fig. 5 presents the form for

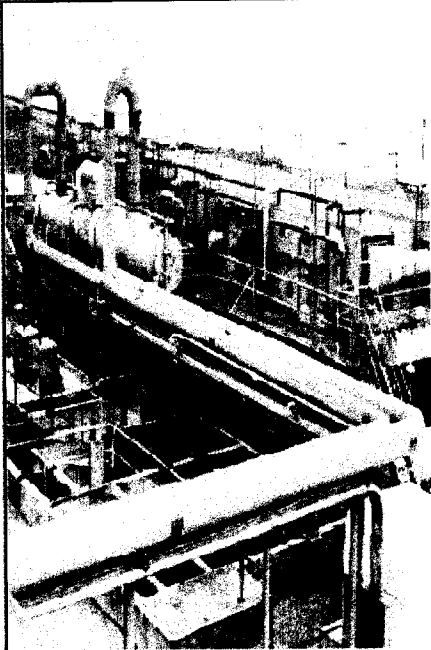Fig. 3. RES–desalination plant configuration.

the analytical estimation of reverse osmosis (RO) energy requirements. Fig. 6 presents the design variables for the estimation of vapour compression energy needs. In both cases the capacity of the desalination plant has been defined in the first step of the design procedure.

The third step presents the capacity and structure of the energy production unit and the user can alter the capacity of the RES unit and estimate the new energy production. The form for the presentation of the wind park configuration is shown in Fig. 7. Wind speed and the k-Weibull parameter are site-specific characteristics. A database with the technical characteristics and the power curves of specific wind turbines is

available, and the user may select the most appropriate wind turbine model. The available list presents the model and the nominal capacity of each wind turbine.

In the final step the design results of the selected RE–desalination combination are presented. The final form presents the plant characteristics, the cost analysis and the investment appraisal results. The plant characteristics form gives details on plant capacity, energy production from RES and auxiliary energy sources and characteristics of the RES unit. Fig. 8 presents the results of the energy balance estimation. In the cost analysis form (Fig. 9), the costs of all components of the desalination and

Fig. 4. Energy requirements of the selected desalination process.
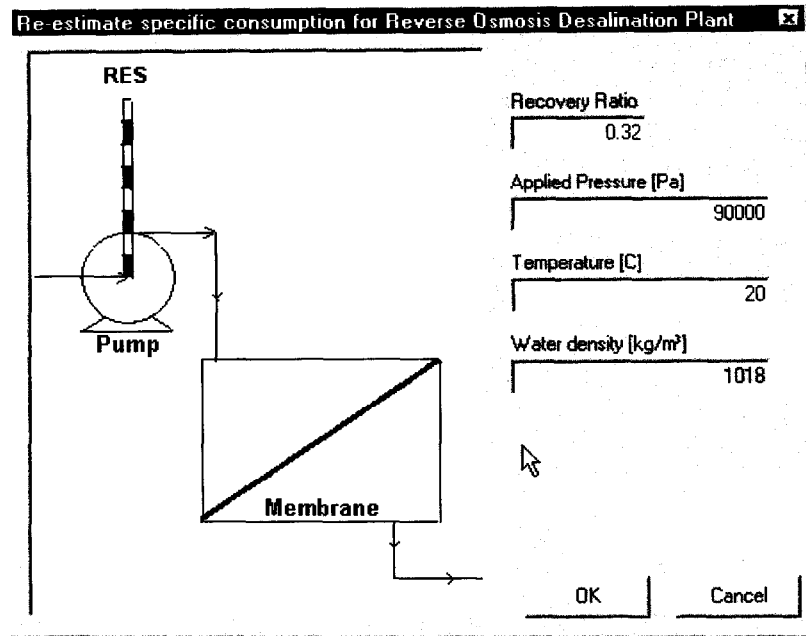
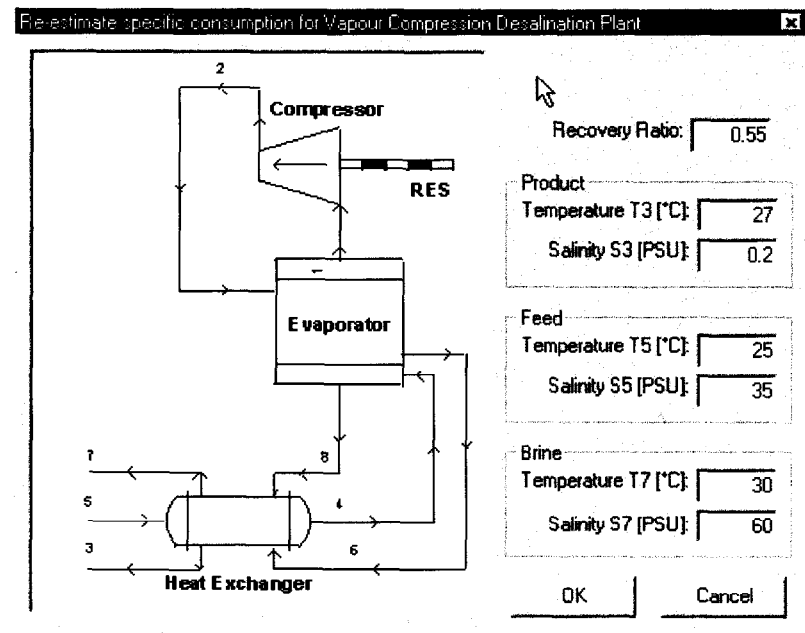Fig. 5. Estimation of energy requirements for reverse osmosis.
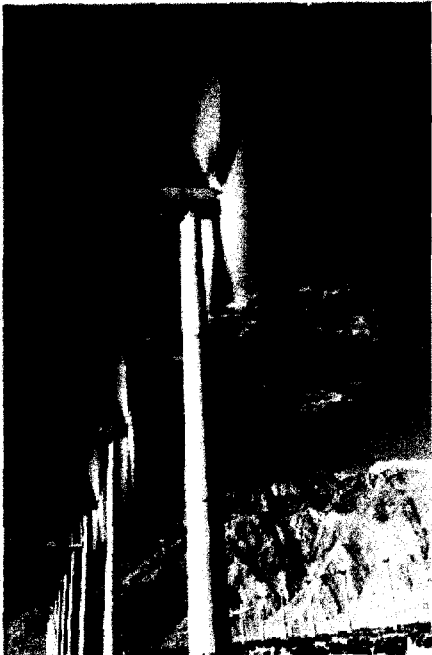
Fig. 6. Estimation of energy requirements for vapour compression.

Fig. 7. Wind energy unit configuration.

RES unit are presented. Moreover, a graph with the discounted water production cost as function of the desalination plant capacity can be given. The investment appraisal form (Fig. 10) presents the water selling price, the internal rate of return and net present value of the investment as well as a graph of the PI as a function of the water selling price.

Plant capacity represents the most important design parameter since it affects the selection of both the desalination and energy production processes as well as the size of the energy production unit. In order to have a flexible way to modify this parameter, the tool provides the option to alter the value of the plant capacity throughout the design procedure and update the results of all calculations. The user has the option to alter the percentage of the water needs that are covered by the RES-powered desalination plant, ranging from 1 to 200%, and update the results of the design procedure. Water needs coverage lower than 100% means that the desalination plant is used in combination with an alternative option to cover the water demand. Values higher than 100% mean that the plant is oversized in order to cover possible water needs that have not been identified or to make up for future or seasonal demand higher than the one predicted.

```
┌─────────────────────────────────────────────────────────────────────────┐
│ System Design                                                             │
├───────────────────────────────────────────────────────────────────────── │
│                                         Presenting Results for  100  ⬍ % of demand │
│                                                                           │
│  Plant Size  Cost Analysis  Investment Appraisal                          │
│                                                                           │
│  ┌─Water Data────────────────────────┐  ┌─Energy Data──────────────────┐  │
│  │ Capacity of desalination plant: [ 1000 ] m³/day │ Nominal power of RES converter: [ 920 ] kW │
│  │        Water demand: [ 1000 ] m³/day │ Energy produced by RES: [ 3301167 ] kWh │
│  │ Water produced only by RES: [ 592 ] m³/day │ Energy needs of desalination plant: [ 2865870 ] kWh │
│  │       Exploitation factor: [ 59 ] % │ RES used by desalination unit: [ 1697336 ] kWh │
│  │                                     │      RES to grid: [ 1603830 ] kWh │
│  └─────────────────────────────────────┘  └───────────────────────────────┘ │
│                                                                           │
│  ┌─Other──────────────────────────────┐  ┌─Auxiliary non-RES energy sources─┐ │
│  │                                     │    Diesel generator power: [ 0 ] kW │
│  │  Information on RES Park  RES Park   │   Energy supplied by diesel: [ 0 ] kWh │
│  │                                     │   Energy supplied by the grid: [ 1168533 ] kWh │
│  │            Parameters  Parameters   │      Power of storage cells: [ 0 ] kW │
│  │                                     │ Energy available from storage cells: [ 0 ] kWh │
│  └─────────────────────────────────────┘  └───────────────────────────────┘ │
│                                                                           │
│  ┌─Description───────────────────────────────────────────────────────┐   │
│  │ Desalination Process: Reverse Osmosis, Renewable Energy Source: Wind │  │
│  └─────────────────────────────────────────────────────────────────┘   │
│                                                                           │
│                          Cancel      <Back     Next      Close            │
└───────────────────────────────────────────────────────────────────────────┘
```
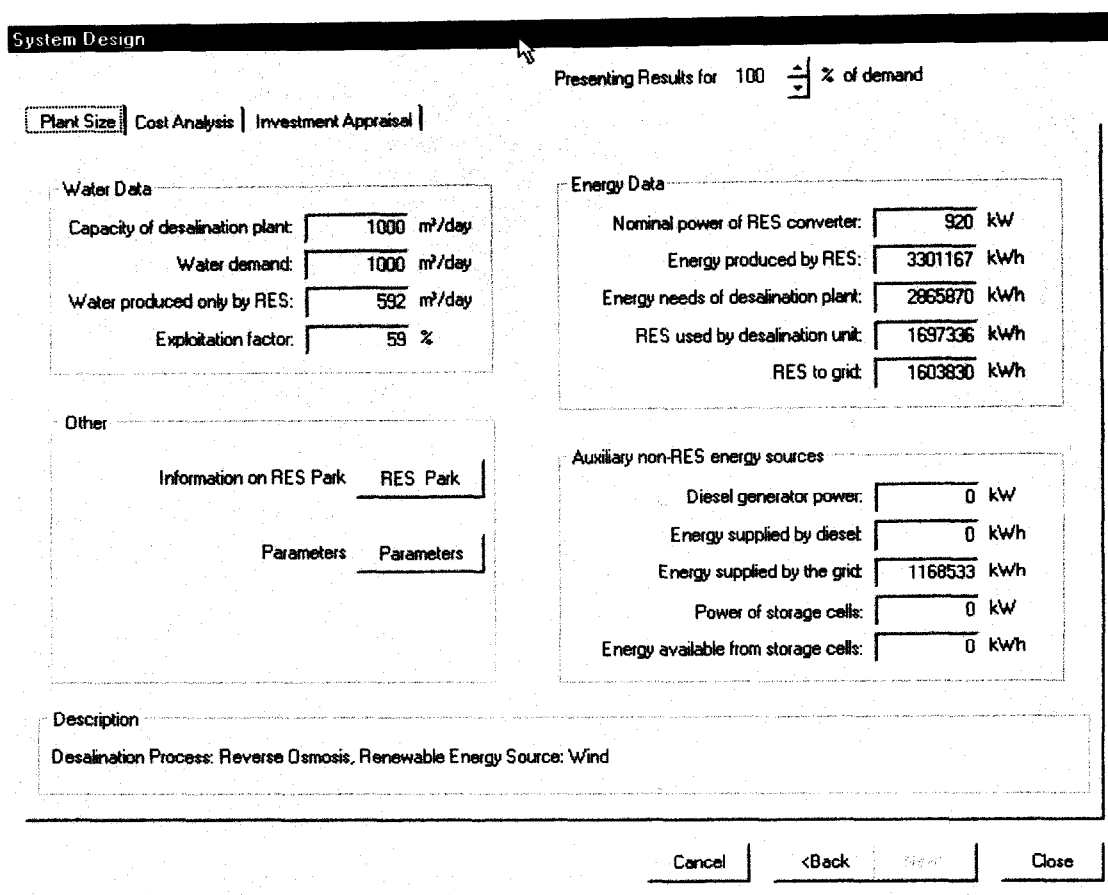
Fig. 8. Water production and annual energy flows for the RES–desalination plant.

4. Case study

4.1. Design of alternative RE–desalination options

The software tool has been used to identify and design the most appropriate RES-powered desalination plant in the case of a seawater desalination plant. The capacity of the desalination plant is 1000 m³/d. The mean annual wind speed considered for the case study is 6.4 m/s, and the annual solar radiation on a tilted surface is 1680 kWh/m². The objective of the case study is to select the RES–desalination technology

combination that best matches the conditions of the specific region.

Six alternative combinations of desalination process and renewable energy technologies have been evaluated. The desalination processes that can be used for seawater are reverse osmosis (RO) and vapour compression (VC). Electrodialysis (ED) is not used for seawater desalination and is excluded from further analysis. The RES technologies that have been evaluated are wind turbines (WT) and photovoltaics (PV), either grid connected or stand-alone. The high energy needs of vapour compression and the high

Fig. 9. Cost analysis.

PV costs indicate that this combination is not expected to be economically competitive with the rest of the available options and is excluded from further analysis. The operating pressure of the RO plant is 90 bar and the recovery ratio is 0.32. The recovery ratio for the VC plant is 0.55 and the salinity of the feed and product streams is presented in Fig. 6. In the cases of grid-connected desalination plants, the installed capacity of RES units does not exceed the maximum allowable limit that ensures the stability of the grid.

Table 1 presents the energy balance for the selected RES–desalination combinations. The existence of the grid connection provides the option to direct the excess energy to the grid during high wind energy availability and to get the required energy during low wind energy availability. For non-grid-connected plants, a diesel generator covers the energy demand during low energy production while excess energy produced during high wind energy production is rejected. In the case of PV-powered plants, the capacity of the power unit has been selected to meet the energy requirements of the desalination process. This option implies that the desalination plant operates only when adequate solar energy is available.

The overall discounted water cost for each of the selected RES–desalination combinations is estimated according to the investment and operational costs in Table 2 [1]. A lifetime of 15 years and a discount rate of 8% are assumed.
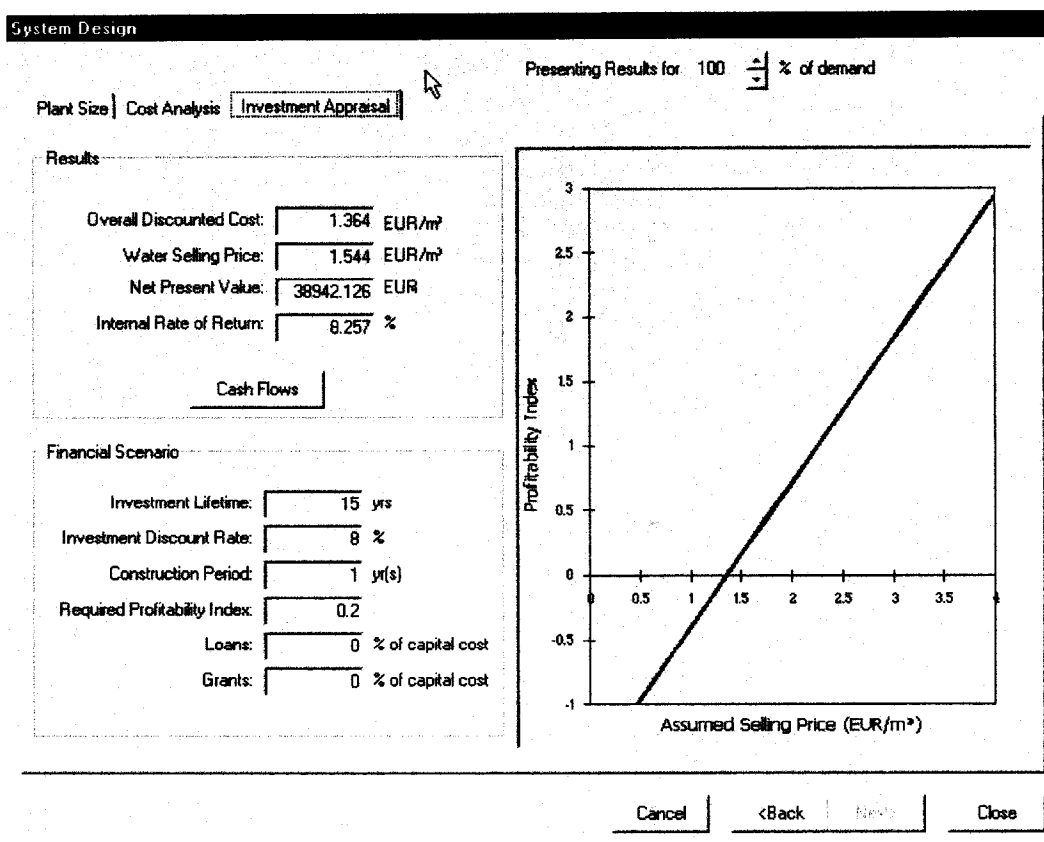
Fig. 10. Investment appraisal.

Table 1
Energy balance for the 1000 m³/d RES–desalination units

RES–desalination combination	Desalination energy needs (MWh/y)	RES energy production (MWh/y)	Nominal installed power (kW)	RES energy used by desalination (MWh/y)	Grid energy used by desalination (MWh/y)	RES energy to grid (MWh/y)
RO–WT–G	2866	3301	920	1697	1169	1604
RO–WT–NG	2866	3301	920	1697	0	0
VC–WT–G	5641	5777	1610	3235	2406	2542
VC–WT–NG	5641	5777	1610	3235	0	0
RO–PV–G	2866	2809	1968	2809	57	0
RO-PV-NG	2866	2809	1968	2809	0	0

Table 3 presents the estimated overall discounted cost and the expected water selling price for each of the selected RES–desalination combinations and a desalination unit capacity of 1000 m³/d. The overall discounted water cost is lower in the case of the grid-connected wind-powered RO plant due to the revenues from power sales to the grid. The PV-powered RO plant is the scheme with the higher discounted costs due to the high PV costs, and there is no substantial difference between the grid- and non-grid-connected option. This is due to the selected PV unit capacity, which exactly matches the energy requirements of the RO plant and, consequently, the energy flow from the PV unit to the grid does not substantially affect the plant economics.

The water selling price has been estimated assuming a PI of 0.2, which is considered adequate for an investment with very low operating and maintenance costs. One of the criteria to select the most applicable combination for the region under consideration is to compare the expected water selling price to the price that consumers already pay. In most Aegean Islands, which face severe water shortage problems, the only available alternative to cover water demand is water transportation by ships. The cost of this option ranges from 2.9–3.5€/m³ but is subsidized, resulting in water prices in the range of 1.5–1.7 €/m³. Comparing the RE–desalination water cost with the non-subsidized cost of water transportation, most of the RE–desalination alternatives are competitive on economic terms. Only

Table 2
Investment and operational costs of RES–desalination plants

Desalination process	Initial investment (€/m³)	Consumables (€/m³)	Labour (€/m³)	Maintenance (€/m³)
Reverse osmosis	1600	0.25	0.2	0.05
Vapour compression	2500	0.15	0.2	0.08
Electrodialysis (brackish water)	328	0.13	0.2	0.01

Renewable energy technologies	Equipment (€/kW)	Installation (€/kW)	Maintenance (€/kW)
Wind turbines	750	500	32
Photovoltaics	4000	153	10

Table 3

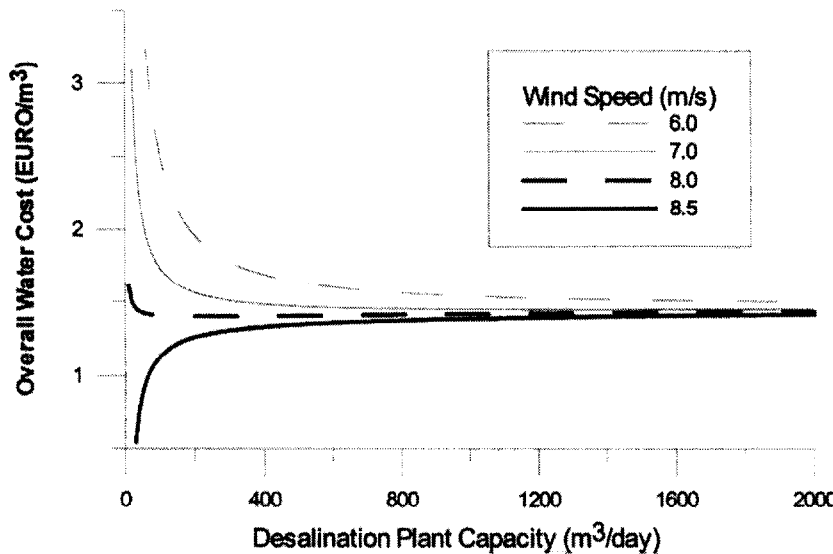| Res–desalination combination	Estimated discounted water cost (€/m³)	Expected water selling price (€/m³)	Subsidized water prices (€/m³)
RO–WT–G	1.50	1.68	
RO–WT–NG	1.69	1.87	
VC–WT–G	2.13	2.42	1.5–1.7
VC–WT–NG	2.44	2.74	
RO–PV–G	3.15	3.78	
RO–PV–NG	3.14	3.76	

Fig. 11. Effect of wind speed on the overall discounted water cost for the grid-connected wind-powered RO plant.

the wind-energy-powered RO plant is economic-ally competitive when the comparison is based on the subsidized water price.

Fig. 11 presents the overall discounted water cost for different wind speed values in the case of a wind-powered (nominal power 920 kW) grid-connected RO plant. Table 4 presents the electricity production cost for different winds, taking into account the investment and operational costs of the RES unit. For a mean annual wind speed of 6 m/s, the electricity production cost of 0.057 €/kWh is lower than the grid electricity price of 0.063 €/kWh. In this case the RO plant capacity should be the higher in order to maximize the use of the wind energy. Moreover, the electricity selling price of 0.044 €/kWh is lower than the electricity produc-tion cost of 0.057 €/kWh, indicating that it is more profitable to use the wind electricity for desalination than to sell it directly to the grid. For a wind speed of 8.5 m/s, the electricity production cost is lower than the power selling price (and the grid electricity price). In this case the RO plant capacity should be as low as

Table 4
Electricity production cost for the grid-connected wind RO plant

Wind speed (m/s)	Electricity production cost (€/kWh)
6.0	0.057
7.0	0.046
8.0	0.044
8.5	0.040

possible in order to maximize the power sales to the grid.

Fig. 12 presents the water selling price as a function of the PI for the selected RES–desalination combinations. The best options are those for which an increase of the PI produces a small increase to the expected water selling price (the slope of the lines is a function of the energy production by the RES unit and the total invest-ment cost of the plant). Grid-connected wind-energy-powered RO is again considered the best option since, compared to PV-powered RO unit,
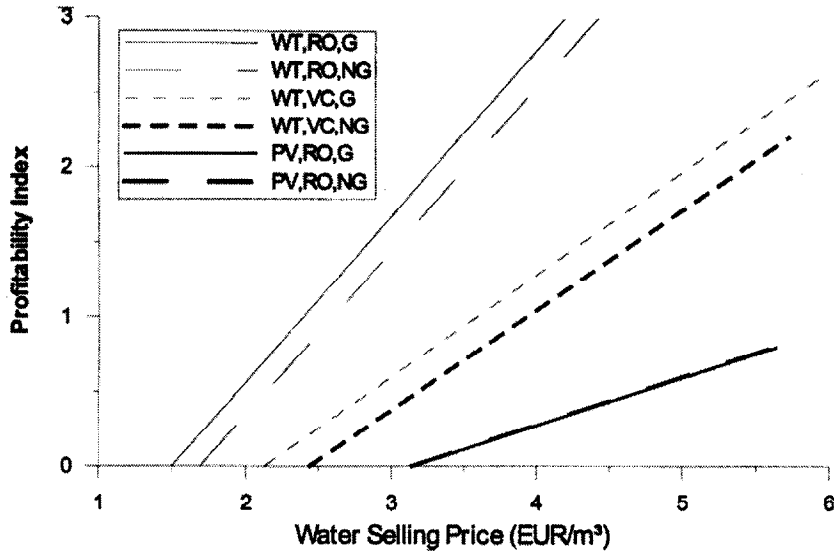
Fig. 12. Water selling price for various combinations of RES and desalination.

Fig. 13. Effect of the desalination plant capacity to the water selling price for the grid-connected wind-powered RO plant.

it presents higher energy production and lower investment costs. Compared to the wind-powered VC plant, the RO is much more attractive due to its lower energy requirements.

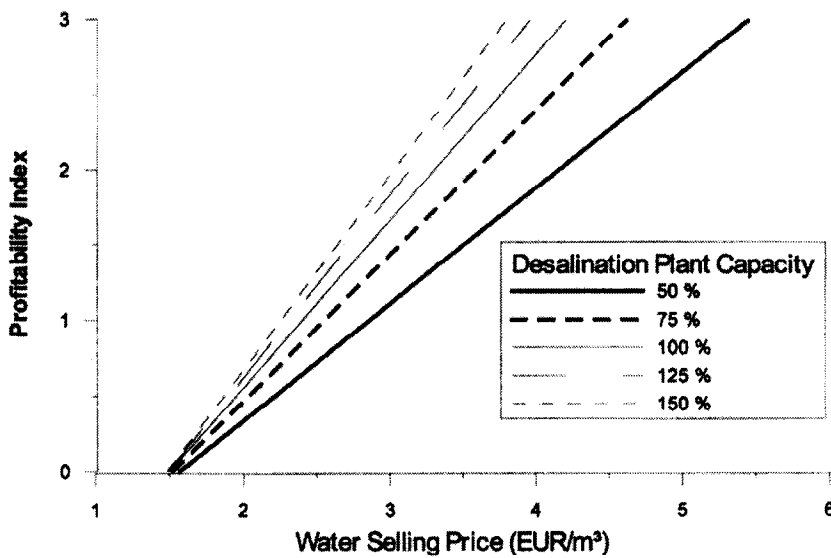Fig. 13 presents the effect of the desalination plant capacity on the water selling price for the grid-connected wind-powered RO unit. The capacity of the wind park is selected to cover the

energy needs of the $1000 m^3$ plant and has not been changed with the desalination plant capacity. Fig. 13 shows that the best option is to increase the desalination plant capacity since the increased revenues from water sales offset the reduction of the power sales revenues.

4.2. Water selling price analysis

The water production cost for most of the RES–desalination schemes is higher than current water prices (Table 3). The RES–desalination scheme with the lower water production cost is the grid-connected, wind-powered RO desalination plant. The expected water selling prices, estimated in order to provide a minimum profitability for the investor (Fig. 12) are well above current water prices (Table 3).

In order for RES-powered desalination plants to be competitive with current water sources in economic terms, the water price should be reduced without affecting the profitability of investments. The options available to reduce the expected water prices from RES-powered desalination plants are:
• direct or indirect price subsidies
• economies of scale for the desalination technology
• economies of scale for the renewable energy technology

The tool has been used to analyze the prospects of these options. The expected water selling price for a grid-connected wind-powered RO plant has been analyzed in relation to the electricity selling price, the desalination unit capacity and the wind energy unit capacity.

Indirect water price subsidies can be achieved through the electricity selling price in grid-connected plants. Fig. 14 presents the dependence of the water selling price on the electricity selling price for different values of the PI. The capacity of the RO desalination plant is $1000 m^3/d$ and the capacity of the wind energy

unit is 920 kW. The increase of the electricity selling price leads to lower water selling prices for all PI values. Higher PI values indicate that both electricity prices and water prices have to be increased. Negative values of the water selling price that are expected for high electricity prices indicate that the examined investment would reach the specified profitability level just by selling the excess electricity to the grid at the selected price. An RES electricity tariff premium can be used to indirectly subsidize the water selling price for grid-connected plants.

Economies of scale for the desalination plant can be evaluated assuming that the desalination plant capacity increases while the wind park capacity is fixed. Fig. 15 presents the effect of the desalination plant capacity on the water selling price for different PI values. The assumed capacity of the wind park is 920 kW. If the PI value is set to zero, the water selling price is equal to the discounted water cost. The water selling price follows the same pattern with the water production cost for all PI values. As the PI increases, the difference of the water selling price with the water cost increases.

The effect of the RE capacity on the overall water cost and consequently on the water price can be analyzed assuming that the desalination unit capacity is fixed and the RES unit capacity is increased. Fig. 16 presents the effect of the RES plant capacity on the water selling price. The RO desalination plant capacity is set to $1000 m^3/d$ and the wind speed at the installation site is 6.4 m/s. In the selected case, as the wind park capacity increases, the plant investment and operational costs increase faster than the increase of electricity selling revenues. Consequently, the water production cost as well as the water selling price increases with the RES plant capacity. The decisive parameter in this analysis is the electricity production cost, which depends on site conditions as well as RE technology costs. Different site conditions (higher wind speed) would decrease the electricity production cost
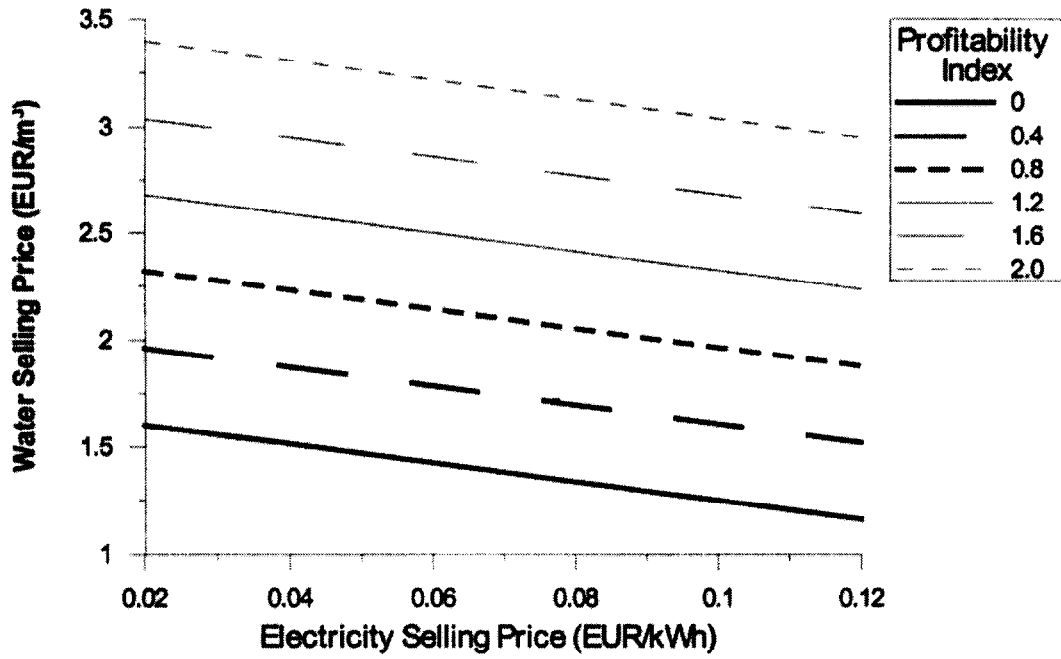
Fig. 14. Effect of the electricity selling price on the water selling price for different values of the profitability index.
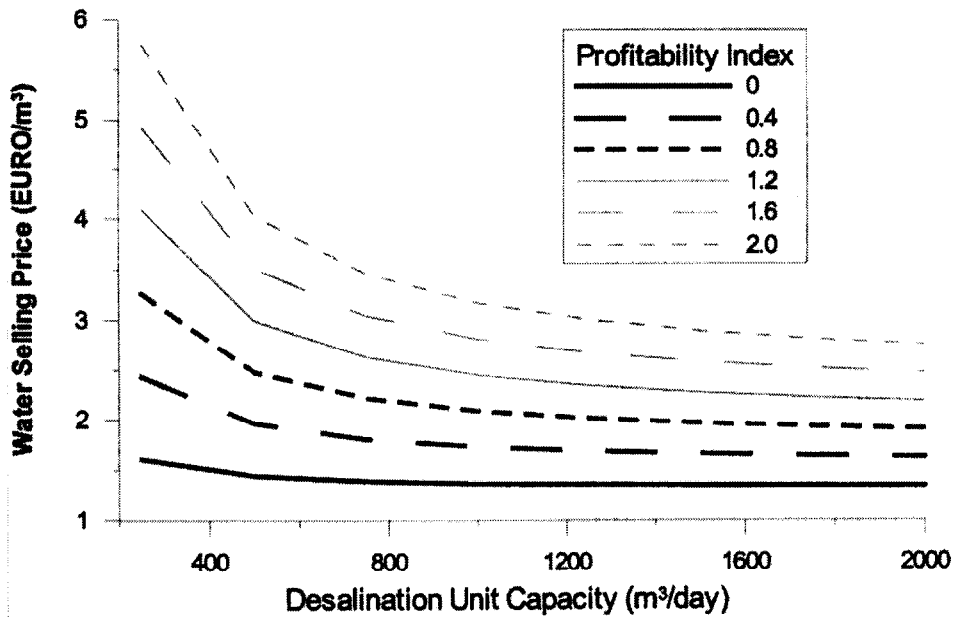

Fig. 15. Effect of the desalination plant capacity on the water selling price.
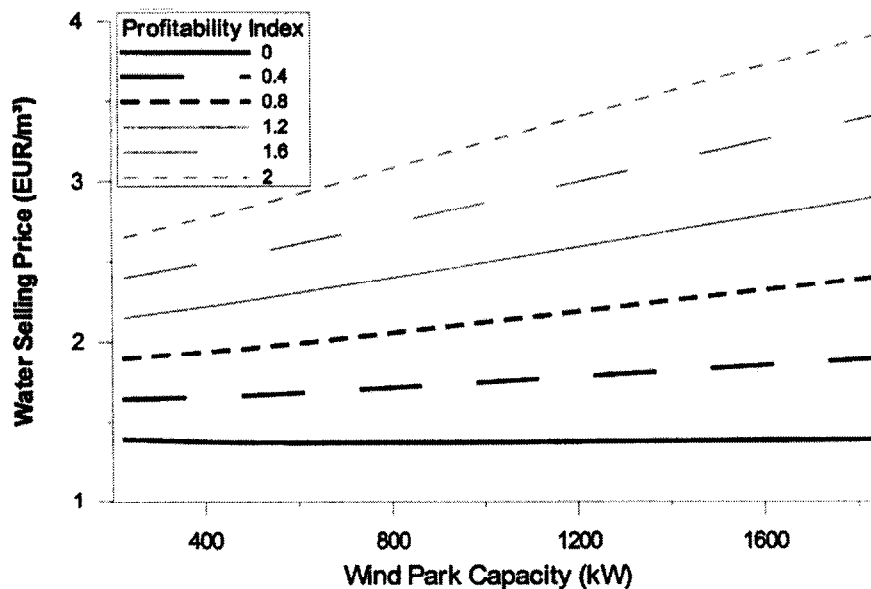
Fig. 16. Effect of the RES unit capacity on the water selling price.

and may alter the shape of the line in the graph leading to water price reduction with the increase of wind plant capacity.

5. Conclusions

The proposed method focuses on the selection of the most applicable RES and desalination technology combination for a specific region. The tool provides an insight to the design of the RES desalination system and power matching of the intermittent RES supply and the steady energy demand by the desalination process. The plant design algorithm focuses on the energy balance between the desalination plant, the energy production unit and the auxiliary energy sources.

The use of the PI provides the tool for comparing the expected water selling price to the current water consumption rates. This comparison represents one of the possible criteria in order to select the best option to cover the water needs of a specific region.

The estimation of investment and operational costs for both the desalination and the renewable energy plants allows for the evaluation of the expected economic outcome of the investment. The tool provides the option to test different scenarios and identify the optimum combination of RES and desalination based on a detailed financial analysis. The relative costs of desalination and RES technologies as well as the RES potential represent parameters that can be analyzed with the tool in order to identify the best option to match RES supply and desalination energy demand.

6. Symbols

A	—	Area covered by PV cells
A_m	—	Membrane area
a	—	Polarization factor
b	—	Proportionality factor
C	—	Scale coefficient
C_B	—	Salt concentration in the brine stream

C_F	—	Salt concentration in the feed stream
C_{INV}	—	Initial investment cost
$C_{O\&M}$	—	Annual operation and maintenance cost
c_{P_i}	—	Specific heat capacity of streams i as a function of salinity
C_{PW}	—	Salt concentration in the product stream
CR	—	Capital recovery factor
DA	—	Days of continuous stand-alone operation
dP_A	—	Applied pressure differential
dP_o	—	Osmotic pressure differential
DC_W	—	Discounted water cost
E	—	Annual energy production
E_S	—	Energy production from storage cells
E_{WT}	—	Annual energy production of the wind turbine
E_{WT-DES}	—	Wind energy absorbed by the desalination plant
h_i	—	Enthalpy of streams i
k	—	Shape coefficient of the k-Weibull distribution
NPV	—	Net present value of the investment
N_{WT}	—	Number of wind turbines
$p(U)$	—	Probability of occurrence of wind speed U
$P(U)$	—	Power output at wind speed U
P_{in}	—	Input solar power
P_{out}	—	Output electric power
P_W	—	Power requirements of the reverse osmosis unit
Q_B	—	Brine flow rate
Q_E	—	Excess power sold to the grid
Q_F	—	Feed flow rate
Q_{PW}	—	Product water flow rate (plant capacity)
Q_W	—	Desalination plant capacity
R	—	Plant recovery ratio
r	—	Index depending on the roughness of the terrain (for flat regions, 0.17)
S	—	Solar radiation

SP_E	—	Electricity selling price
SP_W	—	Water selling price
T_i	—	Temperature of streams i
T_{ref}	—	Reference temperature, K
U	—	Wind speed, m/s
U_{Cutout}	—	Maximum operating wind speed
$\bar{U}$	—	Mean annual wind speed
U_H	—	Wind speed at height H
U_{Pdes}	—	Wind speed which corresponds to power equal to at the power curve of the wind turbine
U_{ref}	—	Wind speed at reference height (in most cases 10 m)

Greek

β_1	—	Membrane coefficient
Γ	—	Γ function
η_S	—	Storage cell efficiency
ρ_W	—	Seawater density as a function of salinity

Acknowledgements

References

[1] Joule-Thermie Programme, Desalination guide using renewable energies, European Commission, 1998.
[2] A. Hanafi, Desalination, 97 (1994) 339.
[3] M. Rodriguez-Girones, J. Perez and J. Veza, A systematic approach to desalination powered by solar, wind and geothermal energy sources, Mediterranean Conference on Renewable Energy Sources for Water Desalination, Santorini, Greece, 1996.
[4] J. Rheinlander, F. Lippke, M. Schmitz-Goeb and G.F. Tusel, Renewable Energy, 14(1–4) (1998) 23.
[5] G. Caruso and A. Naviglio, Desalination, 122 (1999) 225.

[6] E. Zarza and M. Blanco, Proc., Mediterranean Conference on Renewable Energy Sources for Water Production, Santorini, Greece, 1996, pp. 45–53.

[7] M. El-Nashar and M. Samad, Proc., Mediterranean Conference on Renewable Energy Sources for Water Production, Santorini, Greece, 1996, pp. 62–72.

[8] L. Sardi, Proc., Mediterranean Conference on Renewable Energy Sources for Water Production, Santorini, Greece, 1996, pp. 36–44.

[9] M. McCourt, R. Hunter and J. Mugnai, Proc., Mediterranean Conference on Renewable Energy Sources for Water Production, Santorini, Greece, 1996, pp. 118–123.

[10] REDES, Decision support system for the integration of renewable energies into water desalination systems, Final Report, EEC, DG XII, APAS RENA CT94-0058, 1996.

[11] PRODESAL, Towards the large scale development of decentralized water desalination, Final Report, EEC, DG XII, APAS RENA CT94-0005, 1996.

[12] MEDCODESAL, Mediterranean cooperation for water desalination policies in the perspective of sustainable development, Task 2, Interim Report, EEC, DG XII, INCO, 1999.

[13] D. Voivontas, K. Yannopoulos, K. Rados, A. Zervos and D. Assimacopoulos, Desalination, 121 (1999) 159.

[14] F. Ben Jemaa, I. Houcine and M.H. Chahbani, Renewable Energy, 18 (1999) 331.

[15] R. Vujcic and M. Krneta, Renewable Energy, 19 (2000) 173.

[16] B. Chabot, From costs to prices: How to determine tariffs to secure a private development of wind power, European Wind Energy Conference, Wind Energy for the Next Millennium, Nice, 1999.

[17] B. Chabot, Progress in Photovoltaics: Research and Applications, 6 (1998) 55.

Appendix 1
Modelling of desalination processes

A1.1. Reverse osmosis

The pre-treated feed water is forced by a high-pressure pump to flow across the membrane modules. The product (or permeate water) passes through the membrane while the majority of the dissolved solids is rejected from the membrane modules as high-pressure brine. Fig. 17 presents the RO plant structure as well as the main variables used for the evaluation of energy requirements.

The overall mass balance for a RO plant is given by Eq. (A1-1) and the salt balance is given by Eq. (A1-2).

$$Q_F = Q_B + Q_{PW} \qquad \text{(A1-1)}$$

$$Q_F C_F = Q_B C_B + Q_{PW} C_{PW} \qquad \text{(A1-2)}$$

Assuming that the salt concentration in the product stream is very low compared to the salt concentration in brine and feed streams, the brine concentration is given by Eq. (A1-3).

$$C_B = \frac{C_F}{1-R} \qquad \text{(A1-3)}$$

The plant recovery ratio is defined by Eq. (A1-4).

$$R = \frac{Q_{PW}}{Q_F} \qquad \text{(A1-4)}$$

The feed flux is given by Eq. (A1-5).

$$Q_F = \frac{\beta_1 A_m \left(dP_A - dP_O\right)}{R} \qquad \text{(A1-5)}$$
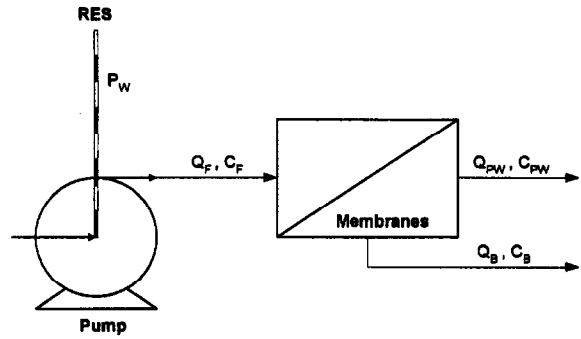

Fig. 17. Reverse osmosis unit.

The osmotic pressure differential is defined as

$$dP_O = b \cdot C_B \cdot \alpha \qquad \text{(A1-6)}$$

The polarization factor is defined as

$$\alpha = \frac{C_{FB} + C_B}{C_B} \qquad \text{(A1-7)}$$

The feed-brine salt concentration, C_{FB}, is calculated by Eq. (A1-8).

$$C_{FB} = \frac{Q_F C_F + Q_B C_B}{Q_F + Q_B} = \frac{2}{2-R} C_F \qquad \text{(A1-8)}$$

For a specified recovery ratio, the feed flow rate is calculated using Eq. (A1-5) and the product flux is calculated by Eq. (A1-4). The power needed to produce capacity equal to the product flow rate is calculated using Eq. (A1-9).

$$P_W = \frac{Q_P \cdot dP_A}{R \cdot \rho_W} \qquad \text{(A1-9)}$$

A1.2. Vapour compression

The main equipment for the VC desalination process is the evaporator, the heat exchanger and the compressor. The feed water is preheated in a heat exchanger or a series of heat exchangers by the hot discharge of the brine and the distillate. The distilled water produced by the condensation leaves the plant through the pre-heaters as product water. Plant layout and necessary input parameters are presented in Fig. 18.

The energy requirements of the compressor are estimated by Eq. (A1-10):

$$P_W = Q_{PW}(h_2 - h_1) \qquad (A1-10)$$

The energy balance for the evaporator is written as

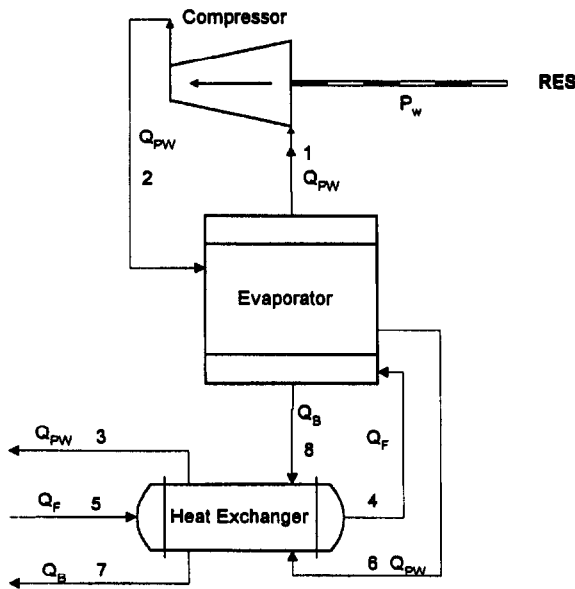$$Q_{PW}h_2 + Q_F h_4 = Q_{PW}h_1 + Q_{PW}h_6 + Q_B h_8 \qquad (A1-11)$$

Fig. 18. Vapour compression unit.

The energy balance for the heat exchanger is written as

$$Q_F(h_5 - h_4) = Q_{PW}(h_3 - h_6) + Q_B(h_7 - h_8) \qquad (A1-12)$$

The enthalpy of each stream is calculated by

$$h_i = c_{P_i}(T_i - T_{ref}) \qquad (A1-13)$$

The recovery ratio of the process is given by

$$R = \frac{Q_{PW}}{Q_F} \qquad (A1-14)$$

From Eqs. (A1-14) and (A1-11), the energy balance for the evaporator can be written as

$$Rh_2 + h_4 = Rh_1 + Rh_6 + (1-R)h_8 \qquad (A1-15)$$

From Eqs. (A1-12) and (A1-14), the energy balance for the evaporator can be written as

$$h_5 - h_4 = R(h_3 - h_6) + (1-R)(h_7 - h_8) \qquad (A1-16)$$

From Eqs. (A1-15) and (A1-16), Eq. (A1-17) is derived:

$$h_2 - h_1 = \frac{Rh_6 - h_5 + R(h_3 - h_6) + (1-R)h_7}{R} \qquad (A1-17)$$

Then Eq. (A1-10) can be written as

$$P_W = Q_{PW} \frac{Rh_3 - h_5 + (1-R)h_7}{R} \qquad (A1-18)$$

Appendix 2
Modelling of RES converters

A2.1. Wind energy

The produced energy from a wind turbine depends on the power curve of the wind turbine and the instant wind velocity. The time variability of wind speed is usually modelled by the K-Weibull distribution. The probability of occurrence of a specific wind speed is estimated using Eq. (A2-1).

$$p(U) = \frac{k}{C}\left(\frac{U}{C}\right)^{k-1} \exp\left[-\left(\frac{U}{C}\right)^{k}\right] \qquad \text{(A2-1)}$$

The scale parameter of the Weibull distribution can be estimated using Eq. (A2-2).

$$C = \frac{\overline{U}}{\Gamma\left(1 + \dfrac{1}{k}\right)} \qquad \text{(A2-2)}$$

Consequently, the only necessary inputs for modelling the wind speed in a specific region are the mean annual wind speed and the parameter shape.

The instantaneous power output of a wind turbine is a function of the wind speed at the rotor height and is given by the power curve $P(U)$. Usually the mean annual wind speed is measured at a height of 10 m. The wind speed at rotor height can be estimated from the wind speed at 10 m using Eq. (A2-1). The annual energy production of the wind turbine is estimated using Eq. (A2-3).

$$U_H = U_{ref}\left(\frac{H}{H_{ref}}\right)^{r} \qquad \text{(A2-3)}$$

$$E_{WT} = 8760 \cdot \int_{0}^{U_{cutout}} p(U) \cdot P(U)\, dU \qquad \text{(A2-4)}$$

The annual energy requirements of the desalination process, E_{DES}, are estimated by

$$E_{DES} = 8760 \cdot P_W \qquad \text{(A2-5)}$$

where P_W is the power needed by the desalination process.

Assuming that the wind turbines can provide the desalination plant with power up to P_W, the maximum annual wind energy that the desalination plant can absorb is estimated by

$$E_{WT \to DES} = 8760 \cdot N_{WT}$$
$$\qquad \text{(A2-6)}$$
$$\cdot \left[\int_{0}^{U_{Pdes}} P(U)p(U)\, dU + \int_{U_{Pdes}0}^{U_{cutout}} P_{Pdes}\, p(U)\, dU\right]$$

Fig. 19 presents the interrelation of the power requirements by the desalination process and the power output of the wind turbine. The auxiliary energy sources such as the grid or a diesel generator provide the desalination plant with the required energy in order to cover the energy demand during low wind speed. The annual energy flows from auxiliary energy sources is estimated by Eq. (A2-7).

$$E_{Aux \to DES} = E_{DES} - E_{WT \to DES} \qquad \text{(A2-7)}$$

The excess power that is not used by the desalination unit is sold to the grid in the case of grid-connected plants or dumped in the case of stand-alone plants. The wind energy sold to the grid is given by Eq. (A2-8).
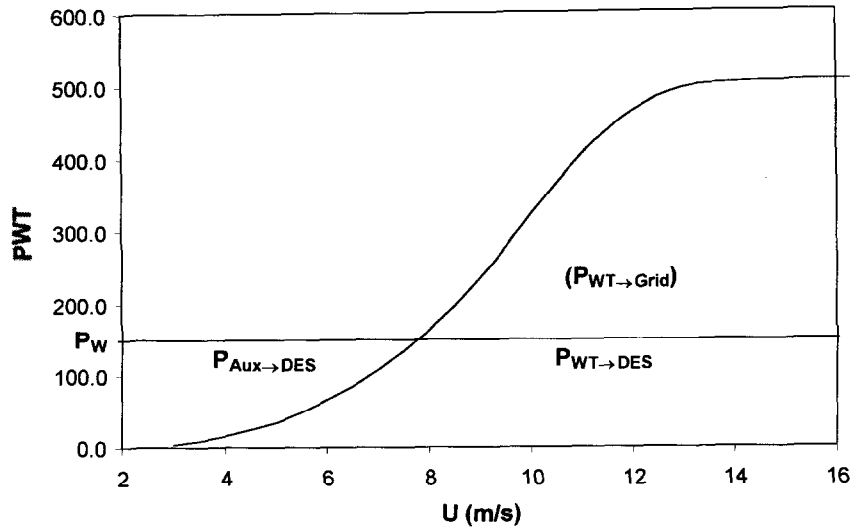
Fig. 19. Power curve and power absorbed by the desalination unit for one Enercon E-40/500 kW wind turbine.

A2.2. PV energy

The energy produced by solar cells depends on the solar radiation of the specified region, the area of the PV cells and their efficiency. The efficiency of PV is defined as

$$\eta = \frac{P_{out}}{P_{in}} \qquad \text{(A2-9)}$$

The annual produced energy is equal to

$$E = \eta \cdot S \cdot A \qquad \text{(A2-10)}$$

In the case of stand-alone PV-powered desalination plant, energy storage cells are used to cover the plant's energy requirements for periods of low solar radiation. The maximum capacity of the storage cells is estimated on the basis of the maximum period that the plant should operate without any input from the PV cells. The energy production of the storage cells is calculated by Eq. (A2-11). Energy losses from charging and discharging the batteries are estimated using Eq. (A2-12).

$$E_S = \frac{E_{DES}}{365} \cdot DA \qquad \text{(A2-11)}$$

$$E_{lost} = \frac{\left(1 - \eta_S\right)}{\eta_S} \cdot E_S \qquad \text{(A2-12)}$$

Therefore, storage cell use increases the total energy demand of the unit, and the new energy demand is estimated using Eq. (A2-13):

$$E_{TOTAL} = E_{DES} + E_{lost} \qquad \text{(A2-13)}$$