Multi-Criteria Decision Making on the Energy Supply Configuration of Autonomous Desalination Units

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Abstract

The important energy requirements for the desalination process impose especially in remote plants supply by Renewable Energy Sources (RES). In this paper five alternative energy generation topologies of Reverse Osmosis desalination process are evaluated. Proposed topologies assessed in terms of economic, environmental, technological and societal indices are compared using multi-criteria analysis, namely the Analytic Hierarchy Process (AHP) and PROMETHEE. Ranking of topologies resulted in the selection of direct connection and hybrid configuration. In case of economic priorities prevail diesel generation should also be considered.

Keywords: desalination, reverse osmosis, topologies, multi-criteria analysis, renewable energy sources.

1. Introduction

Fresh water is essential for life for all species. There are many regions that do not have adequate sources of potable water. Increased requirements of modern lifestyle and the crucial role of water in the economic development renders the desalination process a necessity for such regions. The energy consumption that a desalination plant presupposes is so high that makes it not viable especially in the case of remote installations. For this reason, scientific research is focused on the use of Renewable Energy Sources to provide necessary energy in a reliable way at the same time keeping cost as low as possible. Various sources of energy have been tested either individually or in synergy resulting in different configurations to be integrated in desalination plants [1-3].

Alternative configurations have been evaluated against a wide range of issues that have to be taken into account in order to select the best solution. These issues correspond to often conflicting economical, technical, social and environmental criteria.There may be several groups of stakeholders that are involved in the decision making for a project. Except from that, there may be divergent conditions that stand for every region and have to be seriously considered in the evaluation. Given that complexity of the decision making process, multi-criteria (MC) decision methods represent an appropriate approach in a way to implement such an analysis.

There are MCDM methods suitable for decision-making for energy problems featuring non-commensurable and discrete valued indicators that measure their performance on various relevant criteria. Aras, Erdogmus and Koc[4] used the Analytic Hierarchy Method (AHP) to select a wind observation station location. AHP is implemented to evaluate the various renewable energy sources that can be used in desalination in Jordan [5] and to select among alternative technologies [6]. Outranking methods like ELECTRE and PROMETHEE have been proved valuable evaluating energy projects when environmental issues must be considered [7] especially in the case of multi-energy source systems [8]. Doukas et al. [9] applied the Preference Ranking Organization METHod for Enrichment Evaluation (PROMETHEE) to choose between policies aiming at introducing the state of the art technologies of renewable energy in Greece. Begic and Afgan [10] applied PROMETHEE for the renovation of a thermal power plant.

AHP and PROMETHEE methods comprise advantages and disadvantages rendering them complementary in a sense. As a matter of fact some authors proposed combinations of those [11]. The outranking methods avoid trade-offs compensating good scores on some criteria and bad scores on other ones. They also do not force for complete ranking of alternatives providing intuitions for further analysis. On the other hand, AHP is a widespread method that is presumably used in energy planning problems because of its simplicity and consistency test feature [12]. It decomposes complex problems into constituent parts revealing hierarchical structures. In real cases with numerous alternatives and criteriathough, the large number of pairwise comparisons inevitably creates inconsistent responses. The measurement of inconsistency based on eigenvectors and proposed tolerance levels provides clues in order to fine tune initially inconsistent values increasing the validity of the results. Moreover it allows for different levels of criteria that facilitates the weighting process.

This paper studies various desalination topologies related to different combination of energy production and storage aiming at an autonomous operation in the Aegean islands. The aforementioned MC methods classify existing RES systems for desalination. Different preference structures result in somewhat different rankings. In the next section multicriteria algorithms concerning the aforementioned methods are presented. In section 3 the technical description of topologies examined is followed by the case study and the detailed multi-dimensional performance of alternative topologies. Results of both algorithms are presented for different priorities over the criteria. Conclusive comments complete the paper.

2. Methodology

2.1. Analytic Hierarchy Process

AHP method was proposed by Saaty [13] and it has been widely used to construct and solve problems that include multiple and sometimes conflicting criteria. The goal by applying the AHP is to determine the best option and to classify other alternatives taking into account all the criteria that characterize them. The AHP method is performed in four steps:

A. Structuring the problem into a hierarchical structure.

Each problem consists of components, which may depend on each other. At this stage the decision is structured as a model hierarchy. This includes the breakdown of the problem into sub-components according to the common characteristics creating a model hierarchy at different levels revealing the relationship between the objectives, criteria, sub-criteria if necessary, and alternatives. A common configuration of a problem hierarchy is to have three levels: The top one contains the decision making goal, the second contains the criteria and the last holds the various alternatives.

B. Determining the weights of the criteria

A pair wise comparison matrix is filled, which includes numerically the performance of each criterion or alternative against any other based on the decision makers' judgment. Its standard element $P_c(a_i, aj)$ measures the intensity of preference of the element *i* over the element *j* with regard to criterion *c*. Saaty proposed a scale from 1 to 9 to identify the degree of intensity.

Table 1. Evaluation scale for pairwise comparisons

Verbal evaluation	Value
The two factors are of equal importance.	1
i element is slightly more important than j	3
i element is clearly important than j	5
i is much more important than j	7
i is extremely more important comparing withj	9
intermediate values	2, 4, 6, 8

Constructing the comparison matrix we must respect the following rules:

If a_{ij}=a, then a_{ji} =1/a

If criterion i has equal importance to the criterion j, then $a_{ij}=a_{ji}=1$, soa_{ii} =1 for all i.

If the comparisons demonstrate perfect consistency, then $a_{ik} = a_{ij} \times a_{jk} \forall$ i, j, k

Once the pairwise comparison matrix constructed, we have to check its consistency. Small inconsistencies are common and do not cause serious problems. The consistency check is done by following these steps:

1. We calculate $A*W^T$, where W denotes the calculation relating to the criteria weights.

2. We calculate the largest eigenvector (λ_{max}):

$$\frac{1}{n}\sum_{i=1}^{n}\frac{ith\ entry\ in\ AW}{ith\ entry\ in\ W} \quad (1)$$

3. We calculate the consistency index (CI):

$$\text{CI} = \frac{(\lambda \max)-n}{n-1} \quad (2)$$

The smaller the consistency index (towards zero), the greater the consistency is. If the consistency index is sufficiently small, the comparisons are clearly consistent enough to give valid results for the weight of each criterion separately.

4. We compare the consistency index with an arbitrary frequency table provided by Saaty's simulations [13], based on data that are randomly generated.

n denotes the dimension of thepairwise comparisons table and RI the random index which is the average of CI for a large random sample comparison tables.

If the consistency ratio (CR = CI/RI) is lower than 0.10 then the consistency is satisfactory, but if CR > 0.10, then there are inconsistencies which must be corrected, otherwise the method AHP will not provide reliable results.

In case of acceptable consistency we move a step further and calculate the weights of the criteria, W= (w_1, w_2, w_3,...,w_n), from the pairwise comparison matrix, with the following steps:

1. We divide each element of the column i with the sum of the column. So, we create a new table, the normalized table, where the sum of each column is equal to 1.

2. We calculate the average of values entered in column i of the normalized table.

C. Performance of thealternative for each criterion for each table generated.Pair wise comparison using scale 1 to 9 is also applied along with a consistency test as described above.

D. Final performance of each alternative. We synthesize the options' weights with the performance values of each alternative at each criterion to derive the final performance vector in order to rank the alternatives [14].

2.2. PROMETHEE

Among the several methods of multiple criteria decision-aid, outranking methods have presented a rapid development during the last decade because of their adaptability to the poor structure thatmost real decision situations present. The PROMETHEE method is among the most known and widely applied outranking methods, includes the construction of an outranking relation through the pair wise comparison of the examined alternatives in each separate criterion [15]. It is implemented in five stages:

A. Preference relations determination

Given the preference of the researcher for an action a in relation to an action b for a set of actions K, the preference relation, which is a difference relation between two alternatives of a criterion, is defined separately for each criterion and its value ranges between 0 and 1 . The smaller the value, the greater the indifference between the two criteria. \when the value approaches 1, the higher is the preference of one over the other. Strict preference means that the preference value equals 1. The relative preference P (a, b) of a in relation to b is defined as:

$$\mathrm{P(a,b)} = \begin{cases} 0 & for\ f(a) \leq f(b) \\ p[f(a), f(b)] & for\ f(a) > f(b) \end{cases} \quad (3)$$

This method uses the binary comparison of the options one or more of the six criteria:

1) Normal criterion (usual form) - does not include thresholds and assumes a sharp transition from indifference state to preference state.

2) Criterion with indifference threshold (U - form) - formula with indifference threshold q (indifference threshold). Used for qualitative criteria.

3) Criterion with preference threshold (V - form) - formula with preference threshold p (strict preference threshold). Used for quantitative criteria

4) Scalar criterion (level form) - involves indifference threshold q and preference threshold p. Itdefines only an intermediate level between indifference and clear preference. Used for qualitative criteria.

5) Linear criterion (linear form) - involves indifference threshold q and linear transition to a clear preference state defined by the preference threshold p. Used for quantitative criteria.

6) Gauss Criterion (normal distribution bell-shaped) - assumes a gradual transition from the indifference to the clear preference state following the function of a Gauss distribution and is determined by the standard deviation of the distribution σ .

Based on the above criteria types the corresponding non-decreasing functions of the observed deviation between $f_j(a)$ and $f_j(b)$ have been specified by Brans, Vincke and Marechal[15].

B. Calculation of the index of preference

Suppose that for each criterion the preference relation Ph (a, b) be set for each h = 1,2, ..., k. For each pair of actions a, b , we define a preference table for a over b considering all criteria. Let:

$$\pi(a,b) = \frac{1}{k}\sum_{h=1}^{K} P_h(a,b) \qquad (4)$$

a preference indicator gives a standard of the preference of a over b for all criteria.

C. Construction of graph classification

The values calculated in the second stage set the chart rankings of which are the actions of K, so that for all a, b K, the arc (a, b) has a value of p (a, b). We define, for each node in the chart ranking the input stream is:

$$\varphi^{+}(a) = \sum_{x \epsilon K} \pi(a,x) \quad (5)$$

and the output stream:

$$\varphi^{-}(a) = \sum_{x \epsilon K} \pi(x,a) \quad (6)$$

The larger the $\varphi^{+}(a)$, the more dominant it is over the other actions of K . The opposite is true for the $\varphi^{-}(a)$.

4. Partial ordering of actions (PROMETHEE I)

If the decision maker wants to classify the actions of K from the best to the weaker, he must decide whether to make full or partial ordering. Let us define two overall classifications (P +, I +) and (P-, I-) so that:

$$\begin{cases} a\,P^{+}b\ if\ \varphi^{+}(a) > \varphi^{+}(b) \\ a\,P^{-}b\ if\ \varphi^{-}(a) < \varphi^{-}(b) \\ \qquad and \\ a\,I^{+}b\ if\ \varphi^{+}(a) = \varphi^{+}(b) \\ a\,I^{-}b\ if\ \varphi^{-}(a) = \varphi^{-}(b) \end{cases} \qquad (7)$$

Consequently we derive the following partial ordering (P (1), I (1), R), taking into account:

$$\begin{cases} a\ dominates\ over\ b\ if \begin{cases} aP^{+}b\ and\ aP^{-}b\ or \\ aP^{+}b\ and\ aI^{-}b\ or \\ aI^{+}b\ and\ aP^{-}b \end{cases} \\ a\ is\ \ indifferent\ over\ b\ if aI^{+}b\ and\ aI^{-}b \\ a\ and\ b\ are\ not\ compared,\ \ otherwise \end{cases} \qquad (8)$$

In the case of incomplete ranking (when no comparison is the case between one or more pairs of alternatives) PROMETHEE I suggests that the decision maker should engage in additional evaluation efforts.

E. Classification of operations with completeranking (PROMETHEE II)

We consider for each criterion a K the net flux:

$$\varphi(a) = \varphi^{+}(a) - \varphi^{-}(a) \qquad (9)$$

which is used for classification of actions:

$$\begin{cases} a\ dominates\ over\ b\ if \varphi(a) > \varphi(b) \\ a\ is\ indifferent\ over\ b\ if \varphi(a) = \varphi(b) \end{cases} \qquad [(10)$$

3. Case study

3.1 Technology: Description of the alternative topologies

There are many seawater desalination methods that use thermal energy for water distillation like the Multiple Effect Distillation (MED), the multi Stage Flash Distillation (MSF) and Vapour compression(VC). However, these methods are designed mainly for large-scale desalination units and have intense energy requirements. Other desalination methods such as Membrane Distillation are very promising, but they are still under development with few installed units. Sea Water Reverse Osmosis (SWRO) method (or simply called Reverse Osmosis- RO) has been applied in many areas in the world due to its low energy consumption, relatively simple operation and low water production cost.A small scale SWRO has been experimentally tested in the laboratory with different energy sources [16-19] and the results are used in the current Multi-Criteria Analysis.

The Sea Water Reverse Osmosis (SWRO) unit in a remote area could be directly connected to either a conventional source of energy, such as diesel generator or to a renewable energy system. The particular way the SWRO unit is connected to the electric energy source is called a topology. Five topologies of the energy source of the SWRO unit are analyzed in the current work. The main goals of testing several topologies of energy production for SWRO units is the minimization of power production and transmission losses, the minimization of the environmental impact of the system and the maximization of the socioeconomic benefits of the system. The five topologies are described and analyzed below.

Topology No. 1 – Photovoltaic system with battery bank (top.1)

In this topology, a charge controller equipped with Maximum Power Point Tracker (MPPT) directs the PV power to the desalination unit. Depending on the Battery State of Charge (SOC) and the amount of the produced power from the PV panels, the charge controller directs this power to the battery bank for charging or directly to the desalination unit, thus reducing the battery charging and discharging cycles and as a result increasing its life span.

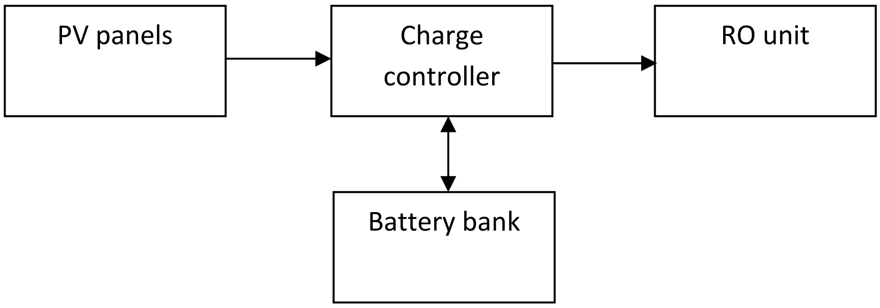


Fig. 1. Photovoltaic system with batteries (top.1)

Topology No. 2 – Hybrid configuration (wind and photovoltaics) (top.2)

A small wind turbine of 1 kW rated power is added to the previous topology in order to utilize the benefits of the energy produced from the wing turbine at night and in the winter in cloudy yet windy days. The wind turbine is connected in parallel with the PV panels charging the same battery bank. In the current topology, the charge controller still controls the power to the desalination unit. The wind turbine is connected to the battery via a rectifier – charger. The rectifier - charger transforms the three phase power of the generator to DC power suitable for battery charging (24V).

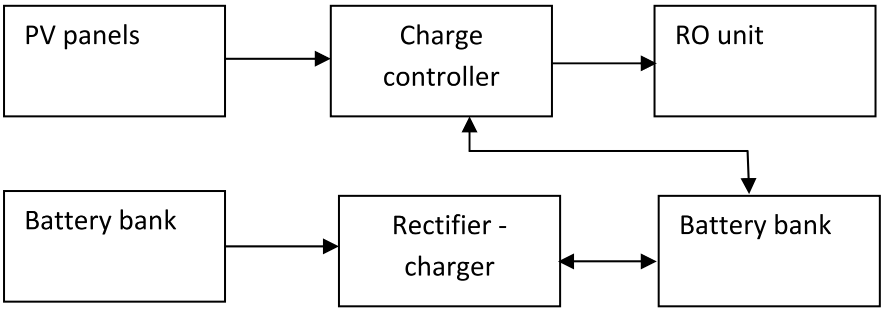


Fig.2. hybrid wind and PV system with batteries (top.2)

Topology No. 3 – Direct connection of photovoltaics with the RO unit (top.3)

In this topology, the desalination unit is directly connected to the PV panels without batteries or charge controller. This was done in order to reduce the initial and operating cost of the system. However, the effect of the intermittent operation of the desalination was taken into consideration by reducing the life span of the membranes from 3 to 2 years.

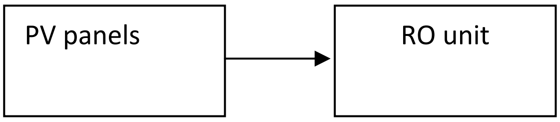


Fig. 3. direct coupled system with PV (top.3)

Topology No. 4 – Wind only powered RO (top.4)

In this topology, the desalination unit is powered by the wind turbine and the battery bank that is charged and discharged by the rectifier – charger.

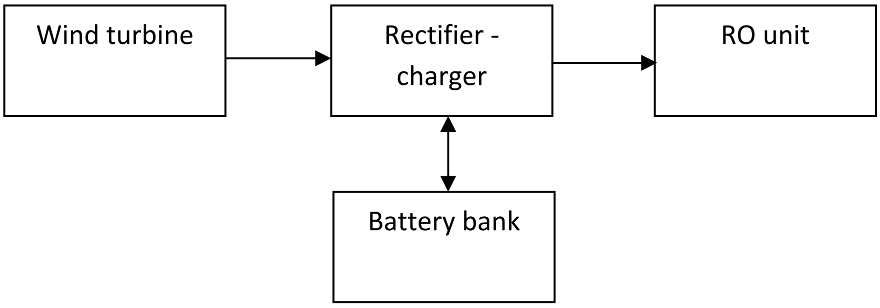


Fig. 4. wind driven system with batteries (top.4)

Topology No. 5 – Diesel generator coupled with the RO unit (top.5)

This topology represents the alternative solution to the renewable powered desalination. The desalination unit is powered directly with a DC diesel generator of 1 HP.

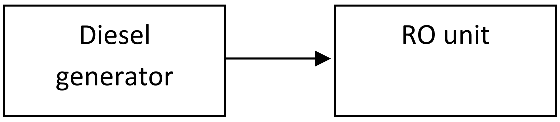


Fig. 5. desalination unit powered by diesel generator (top.5)

3.2 Elements of economic analysis

Discounting cost analysis was performed in order to calculate the fresh water production cost for each topology. A 20 year system life span and a discount rate of 8% for the entire period is assumed. The initial investment cost consists of the purchase, transportation and installation cost. The Operating and Maintenance (O&M) cost was also calculated for each subsystem. Then the annual equivalent cost was calculated using life times for the several parts of the systems, such as the batteries and membrane useful life spans. Water sales price is currently 8.5€/m^3 and diesel fuel price amounts at 1300 €/m^3.

The current prices of photovoltaic panels (0.2 – 0.6 €/Wp) lead to drastic reduction in the cost of renewable energy production subsystem. Further reduction in the cost of other parts, such as the solar batteries, could further enhance the economic viability of renewable energy powered desalination units. The price of mature renewable energy technologies, such as wind turbines, are not likely expected to be lower in the future due to the technical maturity and the high installed power. However, small scale wind turbines still under research development and could play a dominant role in the future in small scale application such as wind driven sea water desalination units.

Location in the Aegean

The topologies considered can be installed in various islands in the Aegean covering either the entire demand in individual houses or in clusters of remote dwellings. Capacities vary between 257 to 567 cubic meters of water per year. Typical cases that correspond to different capacities can be Hydra and Donousa island. Hydra is an island in the Saronic gulf with a population estimated at 2719 habitants according to 2001census. It has water shortage problems and the annual water needs are about of 200.000m^3. In Hydra the environmental protection and tradition conservation is of great concern. It is remarkable that there are no vehicles on the island. Donousa is a small island in the eastern part of Cyclades with population of 163 inhabitants on a surface of 13,652 km^2. Annual water use amounts at about 12000m^3 [17]. In this case economic sustainability and technical robustness seems to be of higher priority than environmental considerations. When designing policies of supporting households to install renewable energy systems it is common to examine decision scenarios on the basis of alternative strategies oriented towards either social, economic, environmental or technological priorities [20].

The meteorological data used are the typical year (TMY) of Meteonorm for latitude 36:21:21 , obtained with conjunction of the transient system simulation program (TRNSYS) software[21]. A summary of the solar radiation and wind speed appears in figure 6.

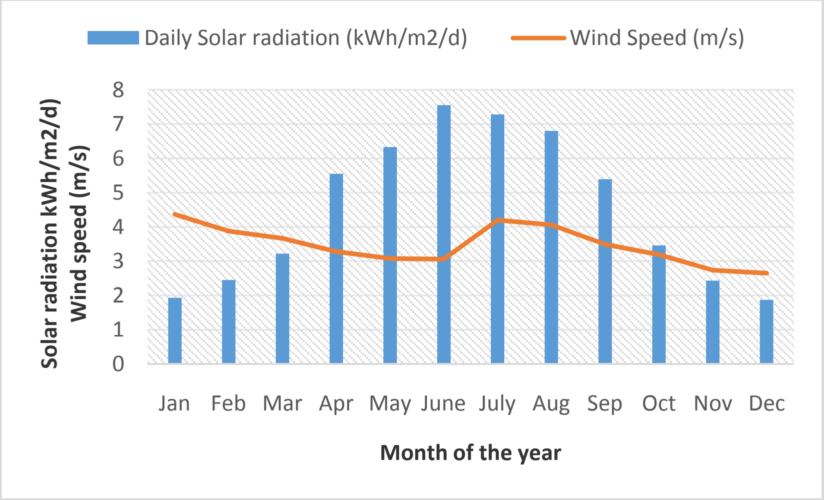


Fig 6. Daily solar radiation and wind speed average values annual distribution

3.3 Criteria description and hierarchical structure

Different criteria categories are presented next with detailed description for each individual sub-criterion along with performance matrices by category of the alternative topologies under scrutiny.

Table 2 Economic criteria*

		NPV (€)	Capital investment indicator (€)	Water production cost (€/m^3)
1	System with battery*	-1.457 €	11.587	9,08
2	Hybrid configuration*	20.896 €	14.567	4,75
3	Direct connection*	6.946 €	10.135	6,36
4	Wind powered***	-50,30 €	13.327	8,52
5	Fossil fuel generator**	3.424 €	9.895	7,54

* Values are based on raw data on costs and prices presented in the Appendix.

The Net Present Value is the main economic criterion for the comparisons between the topologies (max). However, due to liquidity considerations and the importance of the water production cost in the final fresh water selling price, capital investment amount (min) and the fresh water production cost (min) are also calculated. Water production cost is a composite index providing information of fixed and variable costs as well as capacity of equipment.

Table 3. Technical criteria

		Complexity	Maturity	Amount of produced water (m^3/d)	Quality of produced water (μS/cm)	Specific energy consumption (kWh/m^3)	Technological Risk
1	System with battery	Medium	Medium	257	400	4.7	Medium
2	Hybrid configuration	High	Medium	567	400	4.7	Medium
3	Direct connection	Low	Low	330	500	4.1	High
4	Wind powered	Medium	Medium	310	400	5	Medium
5	Fossil fuel generator	Medium	High	282	350	5	Low

Complexity: This indicator describes how complex is the construction and operation of a specific technology. Therefore, a hybrid renewable energy system with PV, wind, charge controllers and batteries, is more complex than directly connected PV system to the RO unit.

Maturity (max): Technical maturity of a system is an important factor that shows that a specific technology it has successfully passed all research stages and has been commercialized for a number of years without severe problems in the operation[18].

Quality and quantity of produced water: the quantity and the quality of water produced from a RO unit depends on the operation conditions. When the RO unit is powered by constant power system, such as solar batteries or diesel generator, the quality of water is better (represented by the electrical conductivity of the produced water in μS/cm). The quantity of the produced water is higher in the case of the hybrid system due to the higher availability of energy.

Specific Energy Consumption (kWh/m^3)(max): it is an indicator that quantifies the efficiency of transforming energy to fresh potable water. It is an important technical indicator for the decision maker and allows for direct comparison between different systems. The lower the specific energy consumption, the more efficient is the system.

Technological risk: it is an indicator for a new technology that has just come out from the laboratory and has not been tested in real world at least for one year continuous operation. This is applicable to the direct connection of the PV to the RO system.

Table 4. Environmental criteria performance matrix

		CO_2 (kg/yr)	NO_x (kg/yr)	SO_x (kg/yr)	Waste
1	System with battery	0	0	0	High
2	Hybrid configuration	0	0	0	High
3	Direct connection	0	0	0	Low
4	Wind powered	0	0	0	High
5	Fossil fuel generator	1417	31.2	2.84	Medium

NOx emission (min): Emission of nitrogen oxides can cause environmental pollution and climate change. Nitrogen oxides can also react with ammonia, with volatile organic constituents, usual chemical components and generate toxic substances harmful to human health. It can be generated during combustion of fossil fuels and biomass, especially by combustion at high temperatures.

CO_2 emission (min): Carbon dioxide is transparent, odorless and tasteless gas. It contributes 9-26% to the greenhouse effect. It is released primarily from burning coal, lignite, oil and natural gas to energy systems.

SO_2 emission (min): Sulfur dioxide is another harmful substance. Further oxidation creates sulfuric acid, which is responsible for acid rain, which is a great concern for the environmental impacts of the use of fuel cells as a power source. It causes respiratory problems and premature death.

Waste: this indicator represents several wastes produced by the system during the operation on top of the emissions. It includes the battery disposal to the environment after its life span and oil and fuel leaks to the environment from the diesel generator operation.

Table 5. Social criteria performance matrix

		New Jobs	Standard of living	Community approval	Capital paid abroad
1	System with battery	Medium	High	High	Medium
2	Hybrid configuration	High	High	High	High
3	Direct connection	Low	High	High	Low
4	Wind powered	Medium	High	High	Medium
5	Fossil fuel generator	Medium	Medium	Medium	Medium

Community approval and social acceptance (max): Estimation of adjacent community concerns about the project in question taking into consideration attitudes and opinions expressed in similar cases if not available for the case study either officially or informally. Community benefits both tangible ones and perceived by the stakeholders. As can be seen in Table 5, the renewable energy options brings more benefits (environmental and standards of living) rather than the fossil fuel option.

Job creation (max): The energy supply systems create jobs during their life cycle. From construction and operation until the end of their operation. Local communities where energy systems were settled supported growth and prosperity for many decades. The evaluation of this criterion is crucial for the decision process when it is taken by the local government. It is counted by the number of new jobs to be opened corresponding to the respective option. The hybrid system creates more jobs due to its complexity.

*Standards of living (max):*This dimension refers to global social benefits triggered by the installation of the energy system (individual or municipal income and improvement of quality of life in general) [22].

capital flow abroad: the imports indicator represents the currency paid abroad due to imports of the components of the system. The direct connected system has low impact due to the minimum components of the system compared to the hybrid system.

3.4 Implementation and results

Calculation of the criteria weights

Both multicriteria methods presented previously have been implemented in the case study. Weights allocated to criteria are estimated based on the AHP rationale. Pairwise comparison matrix is filled using a 1-9 scale in order to cast values denoting preference for every row criterion against every column criterion. Then the vector of weight values is approximated by the geometric mean calculation completed by the consistency test. This process has been repeated to represent three preference structures. Firstly the environmental concern is more important, then the economic and finally an equal weight scenario is considered.

As an example, pairwise comparison matrix presented in table 6 shows detailed values when the environmental concern prevails. In fact the environmental criteria are clearly preferred against the social and technical criteria and at a lower rate when compared with the economic criteria. Evaluation in the 1-9 scale shown in Table 6 is transformed into the vector of weights (first column in Table 7).

Table 6. Pairwise comparison matrix when emphasis in the environment

Matrix	**economic**	**technical**	**environm.**	**social**
economic	1	2	0,166667	2
technical	0,5	1	0,125	1
environm.	6	8	1	8
social	0,5	1	0,125	1

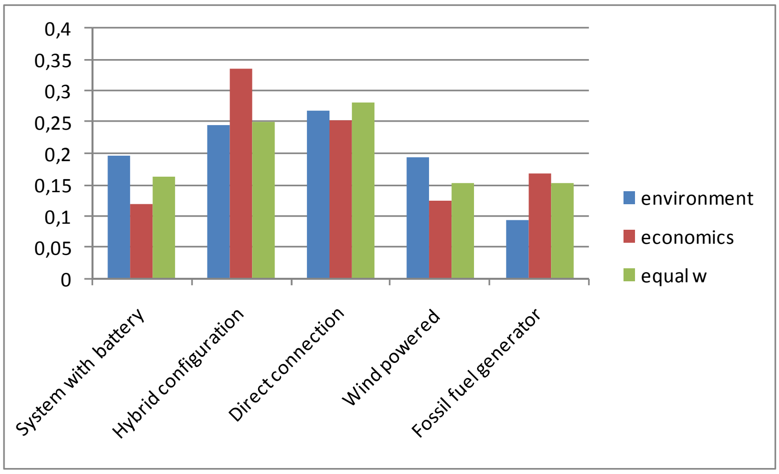
Table 7. Preference structure in terms of weights

sets	environment	economics	equal w
Economic	14,4%	64,7%	25,0%
Technical	7,9%	7,8%	25,0%
Environmental	69,7%	19,6%	25,0%
social	7,9%	7,8%	25,0%

Results of AHP

Rankings generated by different weight sets are presented separately for both methodologies implemented and compared. The five topologies are compared in regards to each sub criterion within the context of the four broad objectives. Thus three pair wise comparison matrices are populated to compose the economic dimension for NPV, initial investment and water unitary cost. Partial rankings are weighted by the relative importance of the three sub-criteria above in order to produce the composite raking vector. Similarly we proceed for the three other criteria (technical, environmental and social objectives) evaluating in total 17 matrices. The final ranking is shown in table 8, also illustrated in the graph (figure 8). We can observe that topology 2 is preferable in case of emphasis in economics whereas topology 3 ranks first in case of environmental preference as well as in the case of equal weights in all criteria.

Figure 8. Final AHP ranking of topologies



Results of PROMETHEE

In PROMETHEE method higher level priorities are multiplied to the second level criteria weights so that a vector with a number of elements equal to the sum of criteria at the second level is generated (17 sub-criteria, relationship (11)). Detailed weighting is presented in the last 3 columns in table 9 for different overall priorities. Type and direction of the criteria as well as preference and indifference threshold where applicable are also presented in detail in Table 9.

$$\begin{vmatrix} env & 0 & 0 & 0 \\ 0 & eco & 0 & 0 \\ 0 & 0 & tech & 0 \\ 0 & 0 & 0 & soc \end{vmatrix} \cdot |crit\ X\ 1| = |criteria\ X\ 1| \qquad (11) \text{ with } crit = \begin{vmatrix} env \\ eco \\ tech \\ soc \end{vmatrix}$$

$$\text{where } env = \begin{vmatrix} CO2 \\ NOx \\ SOx \\ waste \end{vmatrix} \quad eco = \begin{vmatrix} NPV \\ inv \\ cost \end{vmatrix} \quad tech = \begin{vmatrix} complexity \\ maturity \\ size \\ quality \\ security \\ risk \end{vmatrix} \quad soc = \begin{vmatrix} \#\,jobs \\ living \\ commun. \\ imports \end{vmatrix}$$

Table 9. Different types of preference functions, thresholds and weights for each sub criterion.

	direction	type	q	p	emphasis in : the environment	Economic criteria prevail	Equal priorities
NPV	max	5	2000	4000	0,99%	4,44%	1,72%
invC	min	4	1000	2000	1,87%	8,42%	3,25%
cost	min	2	1	0	8,36%	37,58%	14,51%
risk	min	1	0	0	3,18%	14,30%	5,52%
complex.	min	1	0	0	1,76%	1,74%	5,56%
maturity	max	1	0	0	0,87%	0,86%	2,75%
quantity	max	2	25	0	0,45%	0,44%	1,42%
quality	max	5	40	99	0,29%	0,28%	0,90%
SEC	min	3	0	0,5	4,56%	4,50%	14,38%
CO2	min	1	0	0	6,78%	1,91%	2,43%
NO x	min	1	0	0	21,02%	5,91%	7,54%
SO x	min	1	0	0	35,55%	10,00%	12,74%
waste	min	1	0	0	6,38%	1,79%	2,29%
jobs	max	1	0	0	2,29%	2,25%	7,20%
std.living	max	1	0	0	1,01%	0,99%	3,18%
Community approval	max	1	0	0	1,10%	1,08%	3,45%
imports	min	1	0	0	3,54%	3,49%	11,17%

When performance is measured in Likert scale, normal criterion is used (type 1 function) observed in Table 9. Risk, complexity, maturity from technical criteria group, waste (environmental criteria) and all social dimensions (job creation, standard of living, social acceptance and import substitution) belong to this category. Type 1 is also used for criteria related to direct emissions such as CO2, NOx, SOx where RES based units are considered zero pollutants. U-form criterion (only indifference threshold) is applied in the case of investment expenses, unitary cost and plant capacity. V-form (only preference threshold) is applied in the case of SEC criterion. Finally "linear form" with both preference and indifference thresholds is selected for NPV and quality of water (table 9).

Table 10. Final results for environmental priorities

	top 1	top 2	top 3	top 4	top 5	Φ+
System with battery		0,07182	0,063375	0,039165	0,682418	0,856779
Hybrid configuration	0,120831		0,161347	0,150629	9,769492	10,2023
Direct connection	0,272702	0,184099		0,27756	11,76086	12,49522
Wind powered	0,03189	0,089832	0,063375		6	6,185097
Fossil fuel generator	0,207138	0,176128	0,109009	0,130329		0,622603
Φ-	0,632561	0,521879	0,397106	0,597683	28,21277	

After implementing PROMETHEE pair wise comparisons and total inflows and outflows have been calculated (Table 10 illustrates results in the case of "emphasis in the environment"). Then partial preorders have been formed for the three preference structures (PROMETHEE I) that appear in Table 11. For instance in the case of "equal importance", topology 3 is not outranked by any other alternative (and is simultaneously outranking all the others), which means that it is the alternative with the highest power over the other alternatives in terms of all objectives.

Further, topology 2 is outranked only once, topologies 4 and 5 are outranked by other alternatives twice and we observe incomparability between them, thus they are both classified in the third position. Finally the alternative 1 is outranked by all other alternatives, which denotes that it has the weakest power over the alternatives and the lowest potential in meeting the defined policy objectives. Based on those relations, the partial preorder of the RES topologies and in a similar way partial preorders for the other preference structures were established (Table 11). Further, the analysis proceeds to calculate total flows (PROMETHEE II) out of inflow and outflow information (Φ+ - Φ^-) provided in Table 10. The following rankings (in Table 12) represent complete and transitive relations (dominance order) with no incomparability or indifferences between the alternatives.

Table 11. Partial preorders by PROMETHEE I

priorities	environment	economic	equal importance
System with battery	4	5	5
Hybrid configuration	2	2	2
Direct connection	1	1	1
Wind powered	3	3	3
Fossil fuel generator	5	4	3

Table 12. Complete preorders by PROMETHEE II

priorities	environment	economic _	equal importance
System with battery	0,051824	-1,87377	-0,61735
Hybrid configuration	0,754248	1,594592	0,477242
Direct connection	1,421626	1,888096	1,549337
Wind powered	0,181394	-1,23484	-0,4151
Fossil fuel generator	-2,40909	-0,37409	-0,99413

Comparison of the implemented methods for each scenario appears in table 13. We observe that for decision makers with "environmental concerns" and the "equal weights" scenario according to both AHP and PROMETHEE II algorithms first and second most interesting topologies coincide with top.3 and top. 2. Different ranks are attributed to the rest of the topologies. It is not surprising that PROMETHEE I resulted in incomparability in the case of topologies ranked differently in AHP and PROMETHEE II. This suggests that further research should be performed to resolve the issue. This remark is not that important in this case study since divergent views do not concern the first two positions in the rank. In the case of "economic priorities" AHP and PROMETHEE II result in highly correlated peaking orders.

Table 13. Comparative ranking by AHP and PROMETHEE I (PROMETHEE II)

	environm_concerns		economic preference		equal weights	
	AHP	PROMETHEE I and II	AHP	PROMETHEE I and II	AHP	PROMETHEE I and II
Top 1	3	4 (4)	5	5 (5)	3	5 (4)
Top2	2	2 (2)	1	2 (2)	2	2 (2)
Top 3	1	1 (1)	2	1 (1)	1	1(1)
Top 4	4	3 (3)	4	3 (4)	5	3 (3)
Top 5	5	5 (5)	3	4 (3)	4	3 (5)

5. Conclusion

The main goal of this paper was to select the most suitable desalination system for areas taking into account differences in the weights of the criteria that were considered as appropriate to be examined. The results of the selection of an appropriate desalination system show that the "Direct connection of photovoltaics with the RO unit" is the best whatever the preference of the DM. When the economics have greater weight AHP proposes the "Hybrid configuration (wind and photovoltaics)" as the most suitable system. Taking everything into account there are some differences among the classification of other topologies thus not providing clear information.

Regarding the energy supply for the reverse osmosis desalination system, several topologies of the renewable energy systems were examined and compared to the diesel generator option. The drastic decrease of the photovoltaic panels price, along with the continuous increase in the fossil fuel prices during the past five years, favors the installation of renewable energy powered desalination units. The direct coupled system (top 3), despite its shorter membrane life and high risk due to its technical innovation, it represents a robust selection, that was mainly due to its simplicity and low waste (no batteries or hazardous effluents). The economic performance of this system could be enhanced by further research on the improvement of the permeate production and reliability.

References

[1] El-Nashar, M. A. (2000), Why use Renewable Energy for Desalination, *Renewable Energy Systems and Desalination,* vol. 1, pp. 1-4

[2] Eltawil, M. A., Zhengming, Z., Yuan, L. (2009), A review of renewable energy technologies integrated with desalination systems, *Renewable and Sustainable Energy Reviews,* vol. 13, pp. 2245-2258

[3] Garcia-Rodriguez, L. (2002), Seawater desalination driven by renewable energies: a review, *Desalination,* vol. 143, pp. 103-110

[4] Aras, H., Erdogmus, S., Koc, E. (2004), Multi-criteria selection for wind observation station location using analytic hierarchy process, *Renewable Energy*, vol. 29, pp. 1383-1392

[5] Akash, A. B., Al-Jayyousi, R. O., Mohsen, S. M. (1997), Multi-criteria analysis of non-conventional energy technologies for water desalination in Jordan, *Desalination,* vol. 114, pp. 1-12

[6] Hajeeh, M., Al-Othman, A. (2005), Application of the analytical hierarchy process in the selection of desalination plants, *Desalination,* vol. 174, pp. 98-100

[7] Haralambopoulos, D. A., Polatidis, H. (2003), Renewable energy projects: structuring a multi-criteria group decision-making framework, *Renewable Energy,* vol. 28, pp. 961-965

[8] Catalina, T., Virgone, J., Blanco, E. (2011), Multi-source energy systems analysis using a multi-criteria decision aid methodology, *Renewable Energy,* vol. 36, pp. 2245-2247

[9]Doukas, H., Papadopoulou A. G., Nychtis, J., Psarras, N., Van Beeck, N. (2008), Energy Research and Technology Development Data Collection Strategies: The Case of Greece, *Renewable and Sustainable Energy Reviews,* vol. 13, pp. 1-4

[10] Begic, F., Afgan, N. H. (2007), Sustainability assessment tool for the decision making in the selection of energy system- Bosnian case, *Energy,* vol.32, pp. 1979-1985

[11]Macharis, C., Springael, J., De Brucker, K., Verbeke, A. (2004), PROMETHEE and AHP: The design of operational synergies in multicriteria analysis - StrengtheningPROMETHEE with ideas of AHP, *European Journal of Operational Research*, 153 (2), pp. 307-317.

[12] Raju, K.S., Pillai, C.R.S. (1999), Multicriterion decision making in river basin planning and development, *European Journal of Operational Research*, 112 (2), pp. 249-257.

[13] Saaty, T.L., 1988. TheAnalyticHierarchyProcess. McGraw Hill, New York.

[14] San Cristobal Mateo, J. R. (2012), *Multi-Criteria Analysis in the Renewable Energy Industry.* NW: Springer

[15]Brans, J.P., Vincke, Ph., Mareschal, B. (1986), How to select and how to rank projects: The Promethee method, *European Journal of Operational Research*, 24 (2), pp. 228-238.

[16]Essam Sh. Mohamed, G. Papadakis, E. Mathioulakis and V. Belessiotis(2008), A direct coupled photovoltaic seawater reverse osmosis desalination system toward battery based systems — a technical and economical experimental comparative study. *Desalination*, 221 (1-3): 17-22.

[17]Essam Sh. Mohamed, G. Papadakis, E. Mathioulakis and V. Belessiotis (2006), An experimental comparative study of the technical and economic performance of a small reverse osmosis desalination system equipped with hydraulic energy recovery unit. *Desalination*, 194 (1-3): 239-250.

[18]Essam Sh. Mohamed and G. Papadakis (2004),Design, simulation and economic analysis of a stand-alone reverse osmosis desalination unit powered by wind turbines and photovoltaics. *Desalination* 164(1) : 87-97.

[19]Manolakos D., Essam Sh. Mohamed, I. Karagiannis and G. Papadakis (2008), Technical and economic comparison between PV-RO system and RO-Solar Rankine system. Case study: Thirasia Island. *Desalination*221(1-3): 37-46.

[20] Beccali, M., Cellura, M., Mistretta, M. (2003), Decision-making in energy planning. Application of the Electre method at regional level for the diffusion of renewable energy technology, *Renewable Energy,* vol. 28:2064-2069

[21] TRNSYS 17, Transient System Simulation Tool. The University of Wisconsin-Madison College of Engineering Solar Energy Laboratory (SEL).

[22] Wang, J. J., Jing, Y. Y., Zhao, J. H. (2009), Review on multi-criteria decision analysis aid in sustainable energy decision-making, *Renewable and Sustainable Energy Reviews,* vol. 13, pp. 2264-2274

Appendix: Detailed Equipment cost

Photovoltaic system

	Size	**2013 values**
PV panels €/kW$_p$	0.85kW$_p$	600 €/kWp* (510 €)
Charge controller	0.84 Kw	300 €/kW (252 €)
Supporting structure		350 €
Wiring		30
Transport and installation		350
Solar Batteries	12 batteries 305 Ah/2V	1200 €

Total		**2692 €**

*only these changes were considered

Annual O&M cost for the PV vasries according to the topology

Wind turbine

		2013
Wind turbine	1 kW	2980

Annual O&M cost for the wind turbine is 130 €/yr

RO Unit:

No change in prices were considered

High pressure vessels	1.500,00
Feed water Pump	300,00
Direct current Motor DC	1.000,00
high pressure pump (Clark)	3.400,00
Control unit	500,00
Pipes and auxiliary hydraulic material	100,00
Wires and cables	100,00
Feed water tank	150,00
water Product water tank	100,00
RO membrane modules	900,00
Transport and installation	300,00
Sensors and transducers	500,00
Filters	45,00
Total	**8.895,00**

Annual O&M cost for the RO unit varies according to the annual amount of water production from each topology

Diesel generator (600 W):

Capital cost:	1000 €
Fuel price:	1.3 €/l (2013)
O&M	100 €/yr (not including fuel costs)