THE DESIGN OF A DESALINATION PLANT POWERED BY RENEWABLE ENERGIES

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Abstract

A system approach is presented for designing desalination plants. The central objective of the present methodology is the design of a combined user-defined renewable energy source and desalination technology, which will meet the regional water-demand. The selection of the appropriate solution is based on an assessment of costs and revenues from water and energy sales. The basic principles, methodology and algorithms are outlined.

1. Introduction

In many regions around the world, demographic pressure together with economic development resulted into a rapid increase of water and energy demand. Renewable supplies are being threatened and natural resources are rapidly depleted. Electricity and water are vital components in the socio-economic development and the improvement of the living standards.

New water supply schemes have to be developed and if the construction of large scale networks for water transportation from rich in water deposits regions is excluded, the remaining solutions in managing water problems in coastal and insular areas are water transportation by ships, construction of water reservoirs and sea water desalination.

A rational management of water resources admits a number of decisions related to the available energy and water resources, water needs, actions to be used as well as their capabilities and limitations. The selection of the actions that match to each case depends mainly on the type and size of the problem, the cost and the environmental impacts.

Water desalination, though a promising technological candidate, is an energy intensive process. Classical solutions based on conventional energy sources (fossil fuels, electricity) are costly and environmentally risky as they contribute to the already considerable pollution of the air, sea and fresh water resources. The problem becomes more acute in arid areas, with non-existent infrastructure and where electricity production costs are high. This is particularly true for the areas around the Mediterranean Basin where most of the population has limited access to electricity and faces severe potable water shortages. Renewable Energy Sources (RES), and in particular wind and solar energy can constitute a cheap and "clean" supplier of energy for desalination.

In the last decade, a lot of research has been done in the field of applicability and reliability of desalination methods using renewable energy sources [1 – 11]. Furthermore, the results of relative research programmes, [12 – 13], show that the implementation of such desalination schemes can contribute successfully to the water shortage problems. Many reports referring to the assessment of the RES potential have also been presented [14 – 19]. Twidell [20] and Stone [21] provide information on the RES technologies.

The technology arrangements proposed in the literature [9, 22] for desalination plants powered by RES are listed in Figure 1. When several alternative RES-desalination schemes are applicable in a specific case, the final decision concerning the most prominent combination should be based on criteria such as:

- Commercial maturity of technology
- Availability of local support
- Simplicity of operation and maintenance of the system

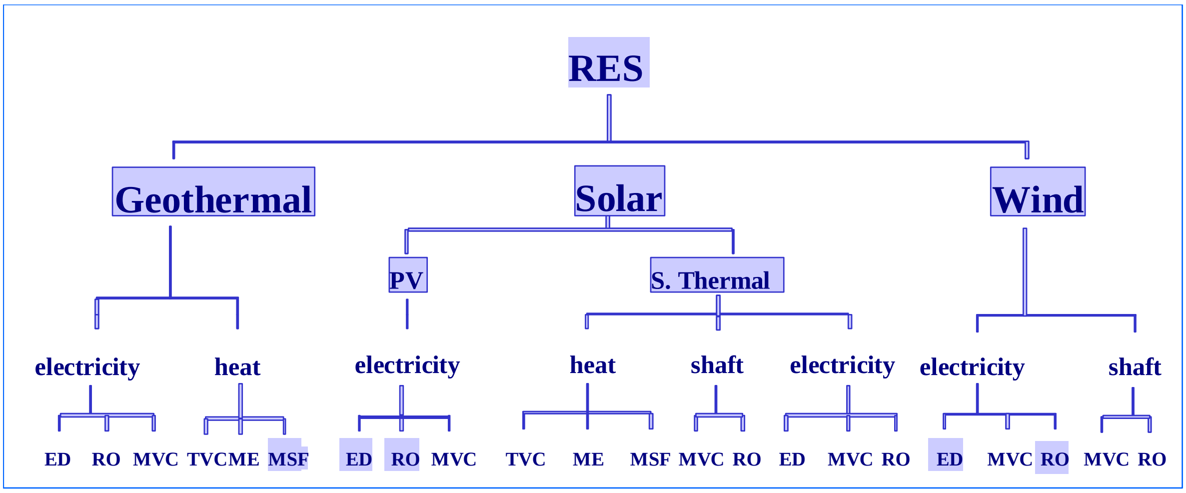

Figure 1. Renewable energy schemes for desalination.

The above factors, in conjunction with available technical information (feed water quality, output water requirements as well as type of RES available) provide a starting point for the engineer or the decision maker. Table 1 depicts the most applicable RES-Desalination combinations according to the plant size, the type of the feed and product water.

Table 1. Recommendations for RES-desalination arrangements

Water Output	Water Input	System Size	Small (1-50 m^3/d)	Medium (50-250 m^3/d)	Large (>250 m^3/d)
Potable	Brackish Water	Conventional Energy + RO, ED	*	*	*
Distillate		Solar Distillation	*		
Potable		PV – RO	*		
		PV – ED	*		
		Wind – RO	*	*	
		Wind – ED	*	*	
Potable / Distillate	Sea Water	Conventional Energy + RO, ED, MSF, VC, MED	*	*	*
Distillate		Solar Distillation	*		
Potable		PV – RO	*		
		PV – ED	*		
		Wind – RO	*	*	
		Wind – ED	*	*	
		Wind – VC		*	*
Distillate		Solar Thermal – MED		*	*
		Solar Thermal – MSF			*
		Geothermal – MED		*	*
		Geothermal – MSF			*

It must be clear that there is no straightforward way to select the appropriate RES-desalination technology. Rather an iterative approach is most probable to be followed, involving careful assessment of the above criteria and technical parameters. Furthermore, each candidate option should be further screened through constraints such as site characteristics and financial requirements.

At this paper, a procedure is developed which defines the optimum solution through the comparison of various desalination processes and the available energy sources. The selection of the appropriate solution is based on an assessment of costs and revenues from water and energy sales. The maturity of the relevant RES technologies has indicated the solar-photovoltaic and wind options in the present work.

The estimation of the energy requirements of a desalination plant powered by RES is based on the approach, first proposed by Hanafi [1]. However, many new elements have been added and the whole method has been improved and modified for the present work.

In Section 2, the basic methodology and structure of the tool are analysed. In Appendix 1 and 2, information on the modelling of desalination processes and RES potential exploitation is given.

2. The Design Approach

The most important parameters, which determine the feasibility of a RES-Desalination project, are the capacity and total cost of the entire plant. The basic data-input for the design problem refer to:

- Regional water demand
- Area needed by the RES park and
- RES-potential of the selected region.

Results are provided for the:

- Annual energy flows,
- Water production cost, and
- Investment cost for the entire unit.

The System Design approach evaluates different technology arrangements, which can satisfy the water-demand. The user defines the type of RES and type of desalination process that will be used as well as the grid connection or use of energy-storage devices.

The following algorithm conducts the evaluation procedure of the selected technology combination:

1. Identification of water-shortage, RES potential and available area for the installation of the RES unit.
2. Calculation of the capacity and the energy needs of the desalination plant, according to the water demand and the selected desalination process.
3. Design of the RES-park that will cover the maximum possible of the energy requirements of the system, taking into account the RES potential of the selected region and the area size restrictions.
4. Estimation of water production and annual energy flows.

5. Cost estimation based on the investment cost for the Desalination and RES units, the diesel generator and storage devices.

The overall design algorithm is presented in Figure 2.

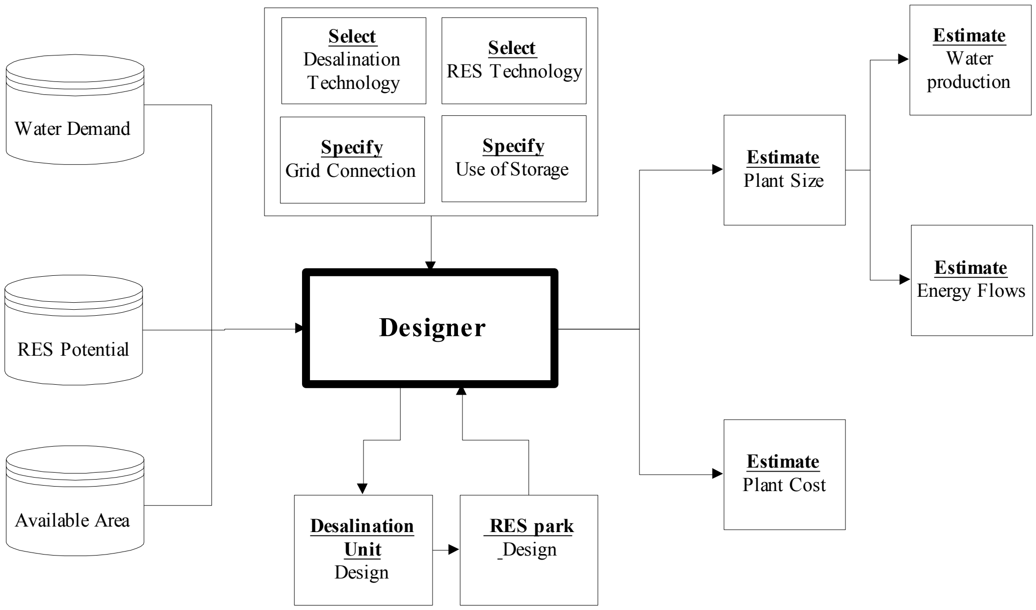

Figure 2. Design algorithm.

The selection of the appropriate desalination technique is based on an overall assessment of the available water sources (brackish and sea-water) in both quantity and quality. If brackish water sources are available, their desalination must be preferred, since, due to low salinity, energy requirements are much lower. Usually brackish water sources are available in inland regions, whereas seawater desalination is mainly employed in coastal sites. The selection of the appropriate desalination technique differs according to the type and potential of the local RES, remoteness, feed water salinity, required product water quality, and the water demand that is to be covered which defines the plant capacity. One must note for example that distillation processes are used for the production of distillate water while membrane processes are used for the production of potable water.

Usually, autonomous systems are selected mainly for remote areas where a grid connection is impossible or very expensive to acquire 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 plants. In these cases a grid connection can provide the plant with the energy needed at periods of low RES energy supply while offering the possibility to sell excess energy to the local grid.

The selection of the appropriate desalination technique depends mostly on feed water and product water quality and secondly on the size of the unit.

Both Electrodialysis and reverse osmosis are used for the production of potable water whereas Vapour Compression leads in the production of distillate water. Electrodialysis can only be applied for brackish water desalination since high-energy requirements for large salinities inhibit the development of the process for seawater desalination. On the opposite Vapour Compression cannot be applied for brackish water sources and is mainly reserved for seawater desalination and for medium or large units. Reverse Osmosis can be applied in all cases.

The type of RES to be used with a particulate desalination process depends on the plant capacity and the specific energy consumption of the desalination technique. For small size plants (1-50m^3/day) both wind and photovoltaic cells can be used, keeping in mind the limited experience for ED-PV systems. Storage cells may be applied only for very small capacities (up to 5 m^3/day) and for autonomous systems since high investment costs inhibit their development for larger units.

For medium (50-250 m^3/day) and large (>250m^3/day) plant capacities use of PV is not recommended due to the large foundation costs and low efficiency of PV cells that increase the required solar park area. Only wind energy exploitation can be applied in this case and again there is a limitation: wind-RO and wind-VC autonomous plants are not applicable due to high storage and fuel costs and a grid connection should be established.

2.1 Design of the Desalination Unit

The algorithm estimates the capacity of the desalination unit and the energy consumption needed to meet the water demand of the selected area.

Water demand has been defined but an additional parameter can be specified, that is the percentage of water demand that is to be satisfied, in reality. It can take values from 1% up to 200%, in order to ensure the best possible response in temporary demand increases or the possibility of exploiting extra water supplies not yet known.

The second important parameter of this section is the specific energy consumption [kWh/m^3] of the desalination process. Its value either can be set by the user or estimated by the mass and energy balances of the desalination plant. The design variables for each process are listed in Table 2 and the details of the algorithm are given in *Appendix 1, Sections 1.1 and 1.2.*

Table 2. Design characteristics of the available desalination processes

Desalination process	Input Data
Reverse osmosis	Recovery Ratio Water Density Applied Pressure
Vapour Compression	Recovery Ratio Temperature and Salinity of:
Electrodialysis	Specific energy demand

2.2 Design of the RE Supply Subsystem

Having defined the total energy needs of the unit, the module proceeds in the design of the wind or solar-park that will provide the energy for the operation of the desalination unit. Necessary data for this section are the RES potential and the available area for the installation of the RES unit. The algorithm is differentiated according to the type of RES to be exploited, the possible grid connection or the use of storage devices.

2.2.1 Wind-Park Design

The wind potential, which is defined by the average wind speed and the K-Weibull distribution of the selected region, is exploited using wind turbines. Additional parameters are needed, such as the wind-turbine (WT) type, its power curve (power produced as a function of wind speed), hub-height, diameter etc.

The algorithm used for the wind-park design is outlined in Figure 3 and the mathematical formulation for wind potential exploitation is presented in *Appendix 2, Section 2.1*.

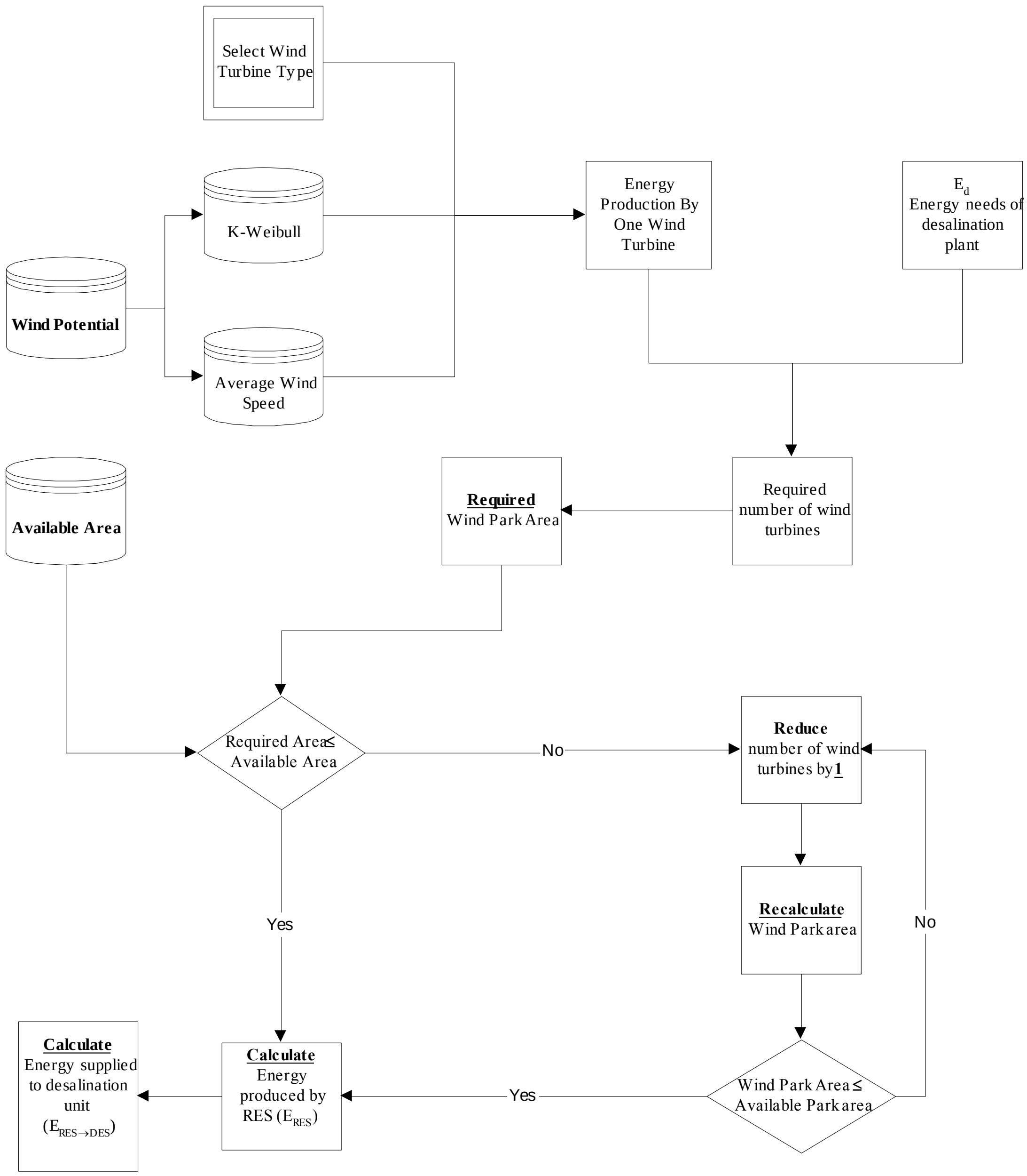

Figure 3. Wind-Park Design

The estimation of the wind turbines needed and, consequently, the required wind-park area is conducted through the yearly energy production of a *single* wind turbine. Then, the minimum number of WT is defined, taking into account the energy needs of the desalination plant and the available area for the wind-park. The latter is performed through the following checks:

- If the required area is equal to or smaller than the one available, the algorithm proceeds in the estimation of the annual energy production, the exploitable energy by the desalination unit and the energy needed from auxiliary energy sources.

- If the required area is larger than the one available then the number of wind turbines is gradually reduced until the calculated wind-park area is found equal or smaller than the one available. Afterwards, the algorithm proceeds in the estimation of the annual energy flows as it is described above.

One must note the following:

1. The wind-park area, in all cases, is the minimum area that can be covered by the specified number of wind turbines, taking into account the number and diameter. However, due to wake development, the power produced by the wind park can be smaller than the one estimated (maximum reduction of 20% per WT).
2. The energy available for the desalination unit depends on wind speed fluctuations. This fact makes the use of an auxiliary energy source (grid or diesel generator) obligatory even if the total energy balance is positive.

2.2.2 Solar-Park Design

Solar radiation is converted to electricity by photovoltaic cells and therefore the solar-park design is differentiated accordingly, by selections concerning grid connection and use of storage batteries. The design algorithm used in the case of a grid-connected and stand-alone (without storage-batteries) park is presented in Figure 4.

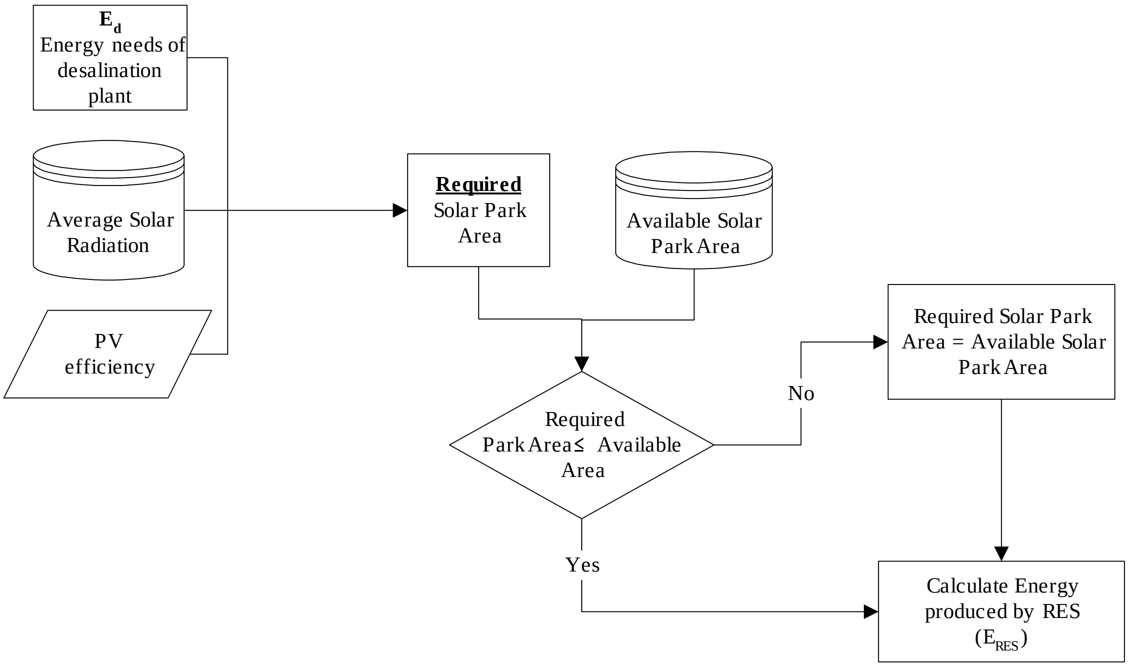

Figure 4. Design of grid-connected and autonomous (without storage cells) solar park

The energy needs of the desalination unit, combined with the average yearly solar radiation and the efficiency of the photovoltaic cells, define the required solar-park area. The final solar-park area and the energy produced by photovoltaic cells are determined through the comparison of the required and the available solar-park area. Then, as before, the tool proceeds in the estimation of the annual energy flows.

The use of storage batteries increases the energy demand of the unit due to energy losses during charging and discharging. The design of storage devices is based on the number of days for a continuous and stand-alone operation. This is defined by the user, and indicates the time that storage can fully provide the desalination unit with the energy needed. Other parameters concerning the storage batteries are their voltage, which, by default, for this type of application is set at 48V, efficiency (85%) and depth of discharge (65%). The additional energy demand, due to storage losses, is used in the definition of the required solar park area and at the calculation of the annual energy flows. The mathematics for the solar energy transformation are presented in *Appendix 2, Section 2.2*.

2.3 Estimation of Water Production and Annual Energy Flows

Water production is estimated by the capacity of the desalination plant. An energy balance of the total energy produced by RES, the energy requirements of the desalination unit, and the energy available for its operation is formed. The algorithm for the analysis of the energy flows for the entire unit and the determination of auxiliary energy supply needs is outlined in Figure 5. The algorithm makes the following checks:

- 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 (such as electricity grid).
- Possible energy shortage should be met by the electricity grid or in the case of stand-alone units, by a diesel generator.
- Energy surplus can be sold to the grid (obviously, only for grid-connected systems).

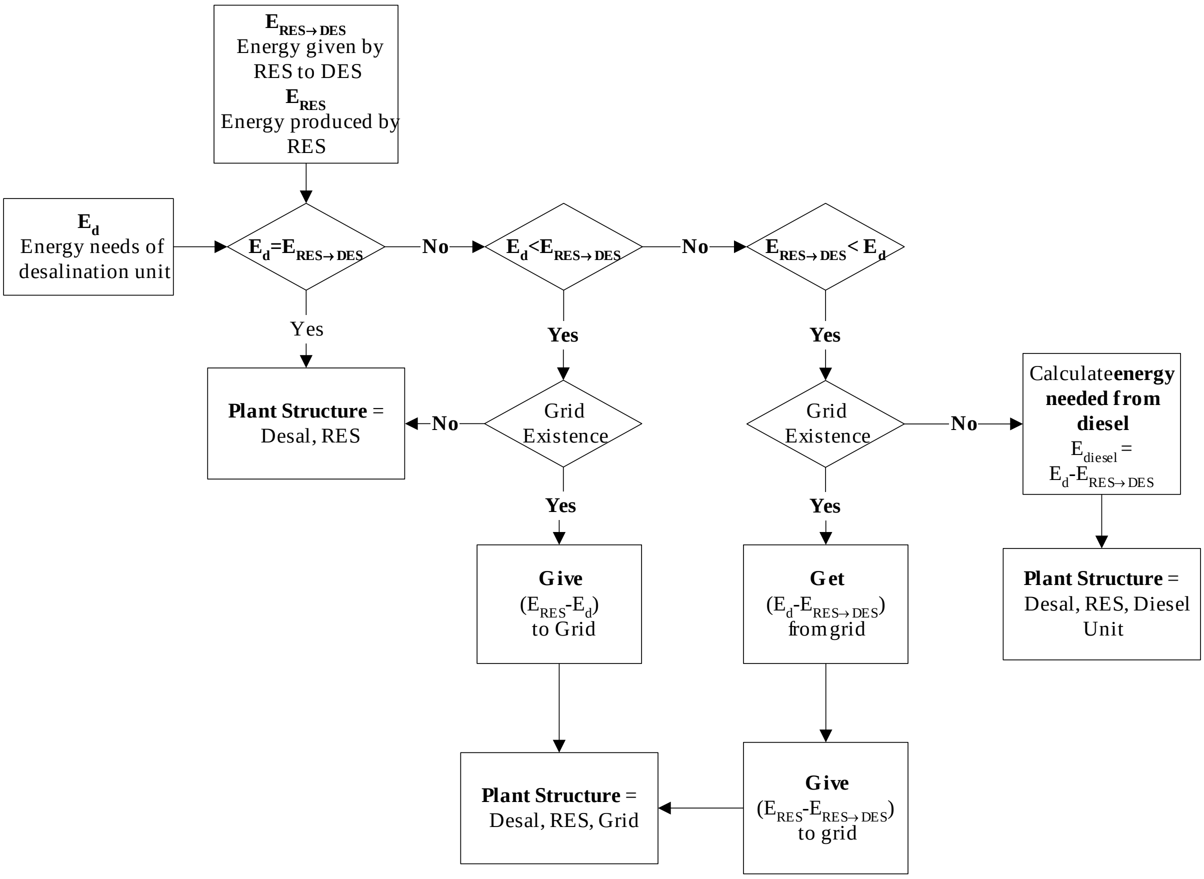

Figure 5. Algorithm for the estimation of the annual energy flows and plant structure

2.4 Financial Evaluation

The evaluation of the financial profitability of the combined RES-desalination system is based on the Profitability Index Method proposed by Chabot [23]. This method has been used for the assessment of the premiums required to secure the profitability of wind energy investments. In the present work the Profitability Index Method is used to specify the water-selling price based on the overall discounted cost of the RES–Desalination system. The algorithm for the financial evaluation of the proposed investment is based on the following steps:

- Analytical estimation of the investment, operational and maintenance costs over
- Definition of the financing parameters of the investment (discount rate, life time, construction period, available grants or loans)
- Estimation of the overall discounted cost of water
- Definition of the required Profitability Index which determines the minimum NPV per unit of initial investment
- Estimation of the water-selling price based on the profitability index and the overall discounted cost.

The estimated water price can be compared to the consumer water prices in order to specify whether the proposed investment is competitive towards conventional methods used to cover the water demand. Figure 6 presents the algorithm for the evaluation of the water selling price.

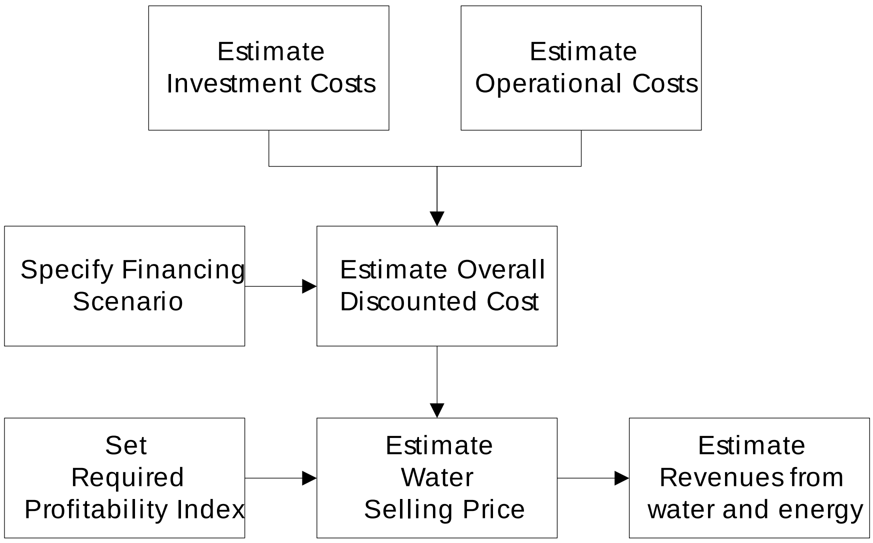

Figure 6. Algorithm for the estimation of the water-selling price

3. Conclusions

A system approach was presented for designing desalination plants powered by renewable energies. The selection of the appropriate system arrangement was based on an assessment of costs and revenues from water and energy sales. The basic principles, methodology and algorithms were outlined.

4. Acknowledgement

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Appendix 1: Modelling Desalination Processes

I. Vapour Compression

The fundamental concept of this process is that after vapour has been produced, it is compressed in order to increase its pressure and therefore its saturation temperature. Then, the vapour is returned to the evaporator where it is used as the heating vapour for the evaporation of more liquid. The main equipment for the VC desalination process is the evaporator, the heat exchanger and the compressor (Figure 7). 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 hot feed water enters the evaporator, where it is heated up to its boiling point and some of it is evaporated. The vapour formed in the evaporator enters then the compressor where its pressure and consequently its saturation temperature are raised. Afterwards the compressed vapour is fed back to the evaporator to be condensed, providing the thermal energy to evaporate the applied seawater on the other side of the tubes. The distilled water produced by the condensation leaves the plant through the pre`-heaters as the product water.

The efficiency of the entire process depends on the pressure of the compressed vapour. Therefore, the compressor is the large energy consumer of this process and the power produced by RES is mainly used for its operation.

Input data needed for the estimation of the energy consumption of the process are the desalination plant capacity, the recovery ratio of the process, as well as the temperature and the specific heat capacity (defined by water salinity and temperature) for flux 3 (product), flux 5 (feed) and flux 7 (brine). The simplified model and the mathematical formulation of the vapour compression process are described in the following paragraphs.

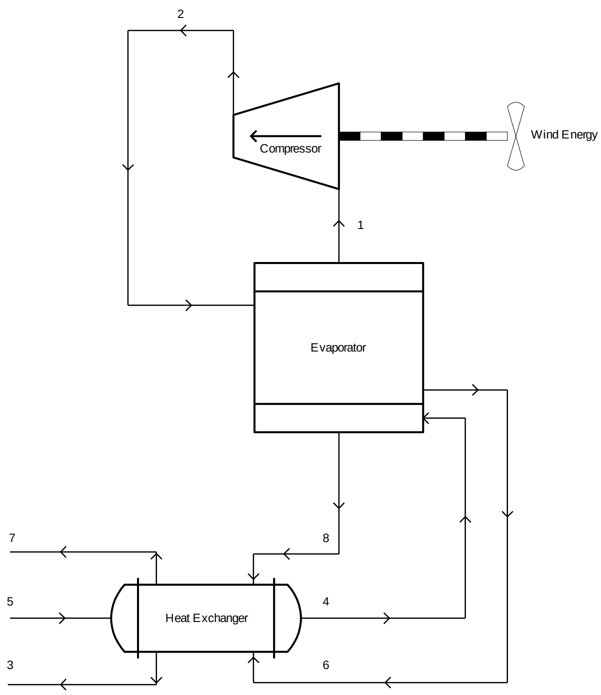

Figure 7. Vapour compression unit

The energy balance for the compressor is written:

$$P_W = m_d \left(h_2 - h_1\right) \quad \textbf{(1)}$$

where P_W is the wind power output [*W*], m_d is the distillate stream [*kg/s*] and h_i is the enthalpy of stream *i* [*J/kg*].

The energy balance for the evaporator is written as:

$$m_d h_2 + m_{sw} h_4 = m_d h_1 + m_d h_6 + m_b h_8 \quad (2)$$

where m_{sw} is the seawater stream [*kg/s*] and m_b is the brine stream [*kg/s*].

The energy balance for the heat exchanger is written as:

$$m_{sw}\left(h_5 - h_4\right) = m_d\left(h_3 - h_6\right) + m_b\left(h_7 - h_8\right) \quad (3)$$

The enthalpy of each stream is calculated by:

$$h_i = c_{P_i}\left(T_i - T_{ref}\right) \quad (4)$$

where c_{P_i} is the specific heat capacity of stream *i* [*J/kg K*], T_i is the temperature of stream *i* [*K*], and T_{ref} is the reference temperature [*K*].

The specific heat capacity in the current module is calculated as a function of water-salinity using the approximation of Millero et. al. (1973) and Fofonoff (1985).

The recovery ratio of the process is given by:

$$R = \frac{m_d}{m_{sw}} \tag{5}$$

From Eq. (5) and Eq. (2) the energy balance for the evaporator can be written as:

$$Rh_2 + h_4 = Rh_1 + Rh_6 + (1-R)h_8 \tag{6}$$

From Eq. (6) and Eq. (3) the energy balance for the evaporator can be written as:

$$h_5 - h_4 = R(h_3 - h_6) + (1-R)(h_7 - h_8) \tag{7}$$

From Eq. (6) and Eq. (3), Eq. (8) derives:

$$h_2 - h_1 = \frac{Rh_6 - h_5 + R(h_3 - h_6) + (1-R)h_7}{R} \tag{8}$$

Substituting Eq. (8) in Eq. (1) the power needed for vapour compression is calculated by:

$$P_W = m_d \frac{Rh_3 - h_5 + (1-R)h_7}{R} \tag{9}$$

II. Reverse Osmosis

Reverse Osmosis, due to its low operating and maintenance cost, is one of the most widely used methods for seawater desalination. It involves the forced passage of water through membranes against the natural osmotic pressure to accomplish separation of water and ions.

The permeator flow through a reverse osmosis membrane is presented in Figure 8, where q is the flow rate and C is the salt concentration. The input data are the desalination plant capacity, the recovery ratio of the process, the applied pressure and the water density. The simplified model and the mathematical formulation of the reverse osmosis process are given in the following paragraphs.

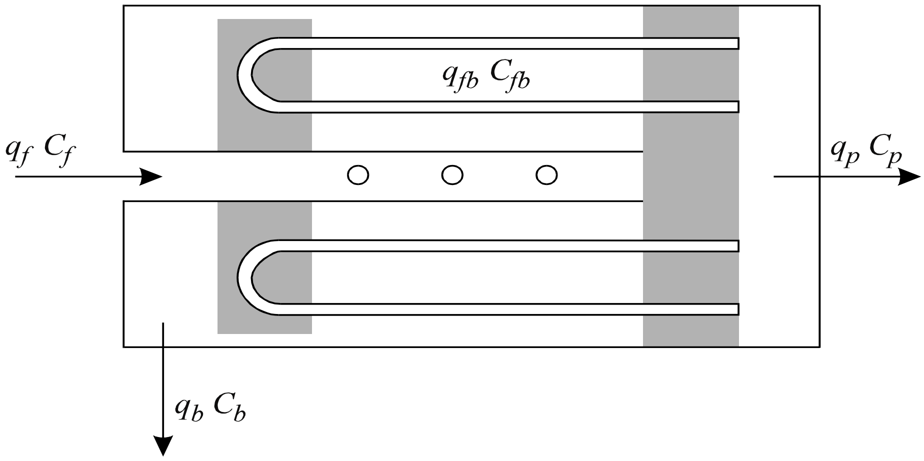

Figure 8. Permeator flow

From the flow balance:

$$q_f = q_b + q_p \qquad (10)$$

From the salt balance:

$$q_f C_f = q_b C_b + q_p C_p \qquad (11)$$

Given that salt concentration in product is too small comparing it with the salt concentration in feed and brine fluxes, Eq. (11) is written:

$$q_f C_f = q_b C_b \qquad (12)$$

Defining the recovery ratio as:

$$R = \frac{q_p}{q_f} \qquad (13)$$

the salt concentration in brine is calculated from Eq. (12):

$$C_b = \frac{C_f}{1-R} \qquad (14)$$

The feed flux is given by:

$$q_f = \beta_1 A_m \left(dP_a - dP_o\right)/R \qquad (15)$$

where β_1 is the membrane coefficient [*kg/m² s Pa*], A_m is the membrane area [*m²*], dP_a is the applied pressure differential [*Pa*] and dP_o is the osmotic pressure differential [*Pa*].

The osmotic pressure differential is calculated:

$$dP_o = b \cdot C_b \cdot \alpha \qquad (16)$$

where b is the proportionality factor [$Pa\ m^3/kg$] and α is the polarisation factor. The polarisation factor is calculated by the following relationship:

$$\alpha = \frac{C_{fb} + C_b}{C_b} \tag{17}$$

where C_{fb} is the feed-brine concentration. The salt concentration in feed-brine is calculated by:

$$C_{fb} = \frac{q_f C_f + q_b C_b}{q_f + q_b} = \frac{2}{2-R} C_f \tag{18}$$

From Eq. (15) the feed flux for maximum recovery ratio is calculated (R = 0.8). Given the feed flux for a specified value of recovery ratio, the product flux is calculated using Eq. (13).

The power needed to produce capacity equal to the product flux derived from Eq. (13) is calculated using Eq. (18):

$$P_W = \frac{q_p dP_a}{R\rho_w} \tag{19}$$

where ρ_w is the sea-water density.

Appendix 2: Modelling of RES converters

I. Wind Energy

The produced energy from a wind turbine is depended of the power curve of the wind-turbine and the instant wind velocity. To estimate the wind speed as a function of time, the K-Weibull distribution is used, given from Eq. (20):

$$p(U) = \frac{k}{C}\left(\frac{U}{C}\right)^{k-1} \exp\left(-\left(\frac{U}{C}\right)^k\right) \tag{20}$$

where $p(U)$ is the occurrence frequency of speed U, U is the instant wind velocity, k is the shape coefficient, C is the scale coefficient given from Eq. (21)

$$C = \overline{U} / \Gamma\left(1 + \frac{1}{k}\right) \tag{21}$$

where Γ is the Γ-function and $\overline{U}$ is the average wind speed.

The stochastic characteristics of the wind speed are taken into account by means of the Weibull distribution of the wind data. More specifically, assuming that the wind turbines can provide the desalination plant with power up to P_{des}, the calculated maximum annual wind energy that the desalination plant can absorb is:

$$E_{WT\rightarrow des} = 8760 \cdot N_{WT} \cdot \left[\int_0^{U_{Pdes}} P(U)p(U)dU + \int_{U_{Pdes}0}^{U_{cutout}} P_{Pdes} p(U)dU \right] \qquad (22)$$

where the subscript 'des' stands for desalination, N_{WT} denotes the number of the wind turbines, $P(U)$ is the power curve of the wind turbine and U_{Pdes} is the wind velocity which corresponds to power equal to P_{des} / N_{WT} at the power curve of the wind-turbine.

The annual energy production of the wind turbines is calculated by:

$$E_{wt} = 8760 \cdot \int_0^{Ucutout} p(U) \cdot P(U)dU \qquad (23)$$

whereas the annual energy requirements of D_{TOT} fresh product water are $E_{des} = SP_{des} \cdot D_{TOT}$. Thus, the annual energy flows are calculated as follows:

1. If $E_{des} > E_{WT\rightarrow des}$:

$E_{WT\rightarrow des}$ wind generated kWh, which are used by the desalination plant.

$E_{des} - E_{WT\rightarrow des}$ kWh, which are supplied either by a utility grid or by a diesel generator.

$E_{WT} - E_{WT\rightarrow des}$ wind generated kWh, which are sold to grid or used by a dump load.

2. If $E_{des} < E_{WT\rightarrow des}$:

E_{des} wind generated kWh, which are used by the desalination plant.

$E_{WT} - E_{des}$ wind generated kWh, which are sold to grid or used by a dump load.

The algorithm described above is presented in Figure 9 for Enercon E-40/500 kW, wind turbine.

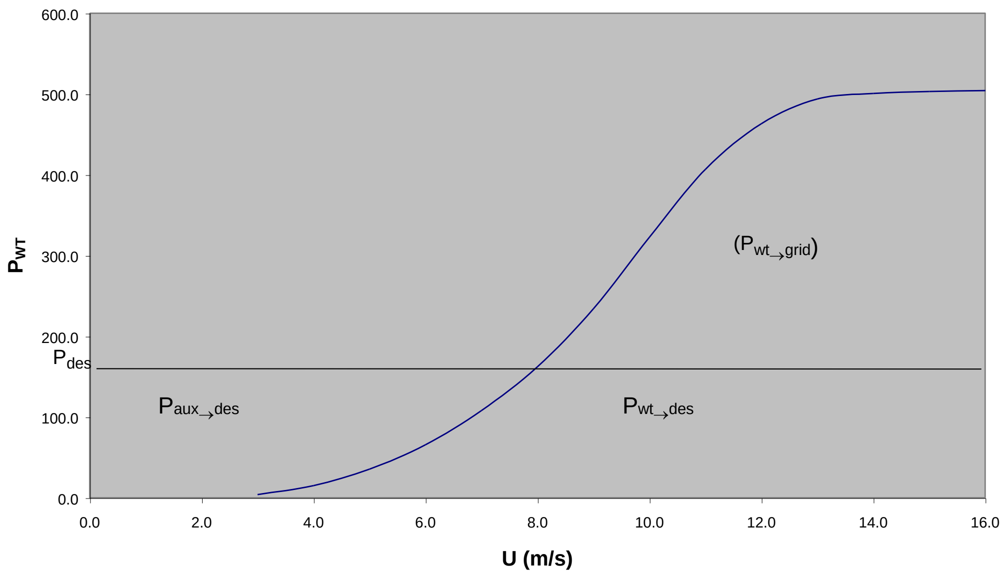

Figure 9. Power curve and power absorbed by the desalination unit for 1 WT Enercon E-40/500 kW.

The wind turbines currently available in the database of the program are listed in [15].

II. Solar 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:

$$\eta = \frac{P_{out}}{P_{in}} \tag{24}$$

where P_{out} is the output electric power and P_{in} is the input solar power.

The annual produced energy is given by Eq. (25):

$$E = \eta \cdot S \cdot A \tag{25}$$

where S is the solar radiation [kWh/m^2/year] and A the surface area to be covered by PV-cells [m^2].

The energy needed by storage cells E_s is calculated by Eq. (26):

$$E_s = \frac{E_{DES}}{365} \cdot DA \qquad (26)$$

where E_{TOT} are the total yearly energy needs of the desalination unit and DA the days of continuous stand alone operation.

Energy losses (E_{lost}) during charging and discharging are derived from the following equation (Eq.27):

$$E_{lost} = \frac{(1-\eta_s)}{\eta_s} \cdot E_s \qquad (27)$$

where η_s is the storage cell efficiency, equal to 0,85. Therefore, storage-cell use increases the total energy demand of the unit and Eq. 28 gives the new energy demand:

$$E_{TOTAl} = E_{DES} + E_{lost} \qquad (28)$$