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Optimizing the Design of PV Solar Reverse Osmosis Unit (RO/PV) by using Genetic Algorithms for Abu Dhabi Climate

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Abstract: The economic progress in the United Arab Emirates (UAE) induces to a significant increase in the demand for agricultural development. In Emirates the majority of the farms are irrigated by underground water, characterized by a high level of salinity. Liwa, Al Ain and Al Khatem areas are suffering from high water well salinity that exceeds 20,000 ppm. This work focuses on this problem and suggests a suitable solution allowing the use of renewable energy (Solar Photovoltaic) to drive RO desalination units. An optimal design of RO/PV unit adapted to a typical farm in Abu Dhabi was suggested using a model developed by using the software ROSA and HOMER. One of the main important results given by ROSA, besides the characteristics of the RO plant, is the required power to drive the plant. This data is the main input in the second part of the present work which is the design of the PV solar system. Finally, an economic and environmental study was carried to estimate the total cost of the project.

Keywords: Desalination, reverse osmosis, photovoltaic, optimization.

1 Introduction

The development in the United Arab Emirates shows a massive growth in economy, industry, infrastructure, population and agriculture. This rapid growth increases the demand for agricultural development which is directly connected to the individuals and livestock farming. Since the United Arab Emirates is an arid country, the water consumption is critical and it is a valuable resource that should be used wisely.

Most of the agricultural farms depending on watering from underground wells are facing a serious problem due to the high salinity of underground water, and this situation is becoming critical, affecting the farm's crop productivity (Figure 1).

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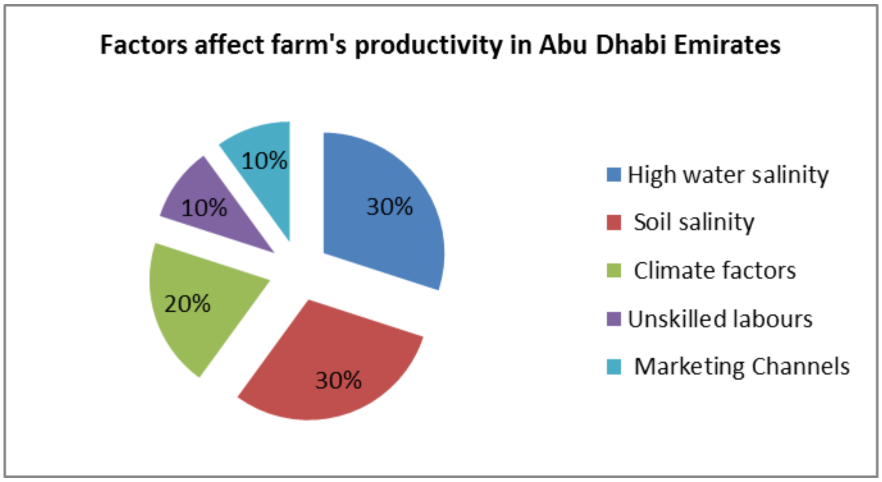

Figure 1: Factors affecting productivity of farms in Abu Dhabi Emirates

On the other hand, some farmers are using water desalination for irrigation. In fact, water desalination is a process used commonly worldwide. More than 15,000 desalination plants exist worldwide providing freshwater from sea and brackish water. This number is increasing due to the improvement of desalination plants in terms of cost effectiveness and energy efficiency [Dana and Porter (2013), Dana and Porter (2012)].

However, the use of desalination for farm irrigations faces some technical constraints. First, it is necessary to find the most suitable feasible desalination technology (MSF, RO, MED) to fit the requirements, assess the current water sources and collect needed water quality and quantity requirements. A survey has been done on several number of farms in Abu Dhabi to estimate the water salinity used in irrigation, the water demand and the problems faced. In our case, it was shown that the most suitable desalination technology is RO due to the flexibility of its capacity and the lower cost [Kalogirou (2005)].

Second, the desalination unit should be designed in optimal way (high efficiency, cost effectiveness, etc.). One of the main results is the calculation of power requirement of the installation. This power can be provided by conventional or renewable energy source, such as solar energy abundant in Abu Dhabi area.

Recently, Reverse Osmosis Technology has been successfully used to desalinate and purify irrigation water for greenhouse and hydroponic use by a farmer in the State of Florida, USA. The RO product water tends to be lower in bacteria and nematodes, which also helps to control plant diseases. Moreover, using RO desalination units allows improving the productivity of the farm, in fact it was shown that production of European cucumbers in one greenhouse increased from about 4000 dozen cucumbers/day to 7000 dozen when the farmer changed the irrigation water supply from a contaminated surface water canal source to an RO-desalinated brackish groundwater source [Brook et al. (2006)].

Hence, one of the possible solutions for water well high salinity in Abu Dhabi is to use RO water desalination unit working by renewable energy; this kind of solution is economically interesting and friendly for the environment. The main objectives of this investigation are the following:

- Find solar-powered desalination system which is more economic and eco-friendly.
- Design of RO desalination unit working by solar photovoltaic (PV) for farm's irrigation in Abu-Dhabi.
- Perform optimization to achieve the best system configuration based on farm's different seasonal solar characteristic, water chemical composition, and water demand.

2 Abu dhabi agriculture development

Since 1970, Abu Dhabi government has promoted agricultural expansion. During 2011 the number of farms in Abu-Dhabi was 24,394 showing the importance of agriculture activity in the emirate. The great part of the farms are irrigated by using municipal water sources, underground, others (water tank).

Abu Dhabi Emirate is divided into 3 major regions: Abu Dhabi, Al Ain, and Western region. Abu Dhabi has 3,837 farms (representing 13% of the total farms in the Emirates), Western region with 8,572 farms (28%), and Al Ain with 11,985 farms (59%) [ADFCA (2011)]. The complete data related to farms in Abu Dhabi are summarized in Table 1.

Table 1: Farms in Abu Dhabi and water sources

	Farms				Water sources for farms' irrigation		
Region	Number Of Farms	Farm % by region	Area Of Farms (Donum)	% Of Farms	Underground	Using Desalination unit	Others (water tank,)
Abu Dhabi	3,837	13%	95,483	16	Yes	Yes	Yes
Western Region	8,572	28%	210,458	35	Yes	Yes	Yes
Al Ain	11,985	59%	446,898	49	Yes	Yes	Yes

The distribution of water resources in Abu Dhabi is presented in Fig. 2. From this Figure we can see that the main source is Groundwater (79%) used mainly for irrigation. The second one is desalination (17%). On the other hand, the main activity consumer of water in Abu Dhabi is agriculture with 57%. Hence, an effort should be done to provide new solutions for water use in irrigation.

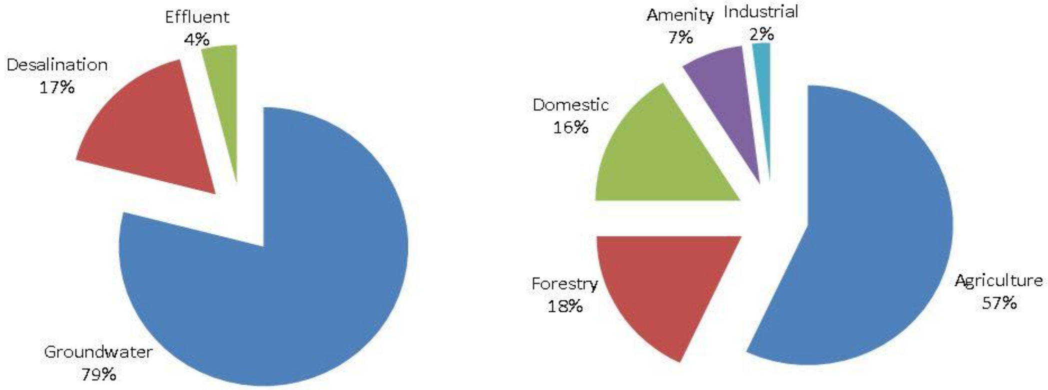

Figure 2: Water resources and water consumption in Abu Dhabi

During 2008, the Environmental Agency of Abu Dhabi has published studies, showing that Total Dissolved Salinity (TDS) of the underground water in Abu Dhabi Emirate measured by ppm (particles per million) is classified into eight major groups (Table 2).

Table 2: Underground Water salinity in Abu Dhabi

Group 1: TDS less than (1,000) ppm,
Group 2: TDS between (1,000 - 1,500) ppm
Group 3: TDS between (1,500 -4,000) ppm
Group 4: TDS between (4,000 -7,000) ppm
Group 5: TDS between (7,000 -10,000) ppm
Group 6: TDS between (10,000 -25,000) ppm
Group 7: TDS between (25,000 -50,000) ppm
Group 8: TDS more than (50,000) ppm

The classification of farms based on their underground water salinity is presented in Table 3. These information was elaborated during agricultural season 2010/2011, based on classes of salinity where: Class A: having TDS < 4,000 pp, and Class B: having TDS > 4,000 ppm. Based on the Table 3 we can see that 2/3 of the farms have high salinity [Kazmerski (2013)]. On the other hand, for farm's irrigation purpose the water's TDS should be less than 3,000 ppm, otherwise the crops productivity will be low or impossible. To overcome this problem some farmers are using stand-alone desalination unit especially in remote areas.

The main part of these RO units is designed in empirical way, and their electrical consumption presents an important part of the operational cost.

3 Design of the PV/RO unit

The main advantage of PV/RO systems is their ability to develop small size desalination plants. The electricity from PV systems can be used to drive high pressure pumps in RO plants. The energy production unit consists of a number of photovoltaic modules, which convert solar radiation into direct electric current (DC). Energy storage (batteries) is required for PV output power smoothing or for sustaining system operation when insufficient solar energy is available.

The main design parameters in the combination PV/RO are: solar radiation on the site, efficiency of PV modules and the installed capacity for the RO unit. This kind of combination permits operation in a stand-alone manner, without any auxiliary supply. PV/RO systems are available on the market and their prices continue to decline.

Several authors were interested on this type of configuration by carrying experimental studies [Koroneos et al. (2007), Kalogirou et al. (2005)]. These investigations showed that a power consumption of 0.89 kWh/m^3 can be achieved. Thomson (2003) has attempted to model this type of coupling without using batteries. Abdallah et al. (2005) studied one RO unit coupled to a photovoltaic system using the “Tracking” principle allowing East/West rotation of the PV field. With the introduction of such systems, the performance of the unit was increased by 15%.

3.1 Modeling of the RO unit

Table 3 summarizes the model equations for RO process simulation. The equations of flow and salt distribution, used in the model, are similar to those provided by the software for the design of RO membrane “FILMTEC-ROSA“ [Lorenzo (1994)] and those used by Crossley [Michalewicz (1994)].

RO membranes are selected after checking the feed water characteristics. Hence, the number of membranes N_{mb} which is a function of unit capacity, the stream flow and the membrane surface is calculated from Eq. (1). The number N_{tp} of pressure vessels in the system is calculated from Eq. (2). Eq. (3) is used to calculate the water flow rate produced by RO membranes.

The osmotic pressure in the different elements of RO unit is given by Eq. (4). The average pressure drop ΔP between the first and the last element is given by Eq. (5). ΔP_{fs} represents the pressure drop between feed and discharge of a single element, Eq. (6).

The efficiency (Y_k) of the membrane is a function of the overall performance of the RO system Y and N_{mb} in the system, Eq. (7). The product concentration C_P is function of recovery rate and salt rejection, Eq. (8). The brine concentration C_c of RO element is calculated from Eq. (9).

Table 3: Equations for the RO model

Meaning	**Equations**	**No**
Number of the membranes in the RO unit	$N_{mb} = \dfrac{Q_p}{f \times S_{mb}}$	(1)
Number of the pressure tube vessels in the RO unit	$N_{tp} = \dfrac{N_{mb}}{N_t}$	(2)
Water product flow rate	$Q_p = A \times S_{mb} \times TCF \times FF \times (\Delta P - \Delta\Pi)$	(3)
Osmotic pressure	$\Pi = 0.002654 \times (T + 273) \times C \times \dfrac{1}{1000 - \dfrac{C}{1000}}$	(4)
Pressure drop between the feed and the brine	$\Delta P = (P_f - \frac{1}{2} \Delta P_{fs})$	(5)
Pressure drop in a membrane	$\Delta P_{fs} = 0.01.\overline{Q}_{fc}^{1.7}$	(6)
Efficiency of the membrane k	$Y_k = 1 - (1 - Y)^{1/N_{mb}}$	(7)
Salt product concentration	$C_p = (1 - R_{mb}) \times C_{fc} \times p_f \times TCF \times \dfrac{S_{mb}}{Q_p}$	(8)
Charge conservation through the membrane	$Q_f.C_f = Q_p.C_p + Q_c.C_c$	(9)
Total Volume of produced water	$Q_T = \sum_{k=1}^{N_{mb}} Q_k$	(10)
Concentration of the produced water	$C_T = \dfrac{\sum_{k=1}^{N_{mb}} C_k.Q_k}{Q_T}$	(11)

By applying Eqs. (6), (7) and (8) the flow rates and concentrations of permeate and concentrated brine in the first element are determined respectively. Thus, product water is collected in the central tube and the brine becomes feed to the second element. This process is repeated for all elements in series. To determine the feed pressure of the system, the model starts from last element for which the applied pressure Pa is calculated from Eq. (3).

The total water quantity, Q_T, produced by RO system is given by Eq. (10) Where Q_k is the amount of water produced by the cell k. The desalinated water salinity concentration is deduced from Eq. (11).

3.2 Modeling of the PV unit

With the flow and feed pressure calculated, the energy consumption of the desalination unit is determined. These energy requirements are used to model the primary source of renewable energy (photovoltaic PV) in the mode “without batteries”. In this configuration, the desalination unit and the photovoltaic system are coupled directly to ensure water needs. In the second configuration, the PV system is connected to a battery unit to drive the RO desalination unit. Both energy model configurations (non-coupled and connected to batteries) allow, firstly, to estimate the hourly photovoltaic power delivered by the solar module based on the climate data of the region (radiation and temperature variation). Secondly, they are used for sizing both the photovoltaic array and volume of the water tank in the mode “without batteries”, or photovoltaic and battery characteristics (number and autonomy) in the mode “coupled with batteries”. Table 4 summarizes the equations used for PV array modeling.

In this model PV is coupled to batteries whose state of charge and discharge control the operation of the desalting system. The number N_B of batteries is determined using Eq. (17). In the case, where the produced energy by the PV array is more than the consumption of the RO unit, the battery is charging, Eq. (18).

In the opposite case, when the energy provided by the batteries is less than that required by the RO unit, the batteries are in discharging state, Eq. (19).

Table 4: Equations for PV model

Meaning	**Equations**	**N°**
photovoltaic power	$P_i = \eta_{PV}(T_{a,i}) \times N_{PV} \times S_{PV} \times G_i$	(12)
Efficiency of the PV system	$\eta_{PV}(T_{a,i}) = \eta_{PV} \times [1 - \beta \times (T_{PV,i} - T)]$	(13)
Daily state of the storage tank	$E_c(j+1) = E_c(j) + Pr(j) - B(j)$	(14)
Average number of the PV modules.	$N_{PV,m} = \dfrac{\overline{P}_{RO}}{\overline{P}_{PV}}$	(15)
Maximal volume of the tank	$V_c = \max_{j=1..365}\left(\Pr(j) - B(j)\right)$	(16)
Average number of batteries	$N_B = \dfrac{E(RO) \times A_t}{U_B \times \eta_B \times DOD}$	(17)
Charging equation of the system	$E_B(i) = \eta_B.(E_{CH.B}.(1 - \alpha)) + (P(i) - B(i))$	(18)
Discharging equation of the system	$E_B(i) = (E_{CH.B}.(1 - \alpha)) - (P(i) - B(i))$	(19)

3.3 Modeling of the system

The PV panels must be sized such that the produced energy during the year allows to completely satisfy the desalination system energy requirements. Hence, the remaining battery bank capacity at the end of the simulation period must be higher than its initial value:

$$C^{365}(24) \geq C^{1}(0) \qquad (20)$$

When the necessary power for the RO operation is available, then the desalination process is performed and desalinated water is produced. Otherwise, the operation of the

RO units is suspended. In this case, cleaning of each RO unit membranes should be performed, using flushing techniques. The total power produced by the PV at hour t of day i is calculated as follows:

$$P_{RE}^{i}(t) = N_{ch}^{PV}.n_{S}.P_{M}^{i}(t,\beta) \tag{21}$$

At the hour t of the day i the total DC power input to the DC/AC inverters, $P_T^i(t)$ (W), is related with the total AC power supplying the desalination units, $P_{RO}^i(t)$ (W), according to the following equation:

$$P_T^i(t) = \frac{P_{RO}^i(t)}{n_i} \tag{22}$$

where n_i (%) is the power conversion efficiency of the DC/AC inverters. The minimum permissible amount of water stored in the tank, V_{min} (m^3), should be fixed (generally set equal to 25% to 30% of the tank total volume, V_{TANK} (m^3)).

The volume of the available water stored in the tank at hour t of day i, V_i (t) (m^3), is modified during the desalination system operation, such that:

$$V_{\min} \leq V^{i}(t) \leq V_{TANK} \tag{23}$$

The developed desalination system model should be used to simulate the system operation on a yearly basis to check the feasibility of the proposed solution. The optimization of the whole system is achieved by using the Genetic Algorithms methods by considering potential solutions.

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Its obvious that the modeling of RO/PV system is a complex problem due to the non linearity of the different components of the system and the stochastic nature of solar energy. The design of such complex systems requires the development of tools permitting to take into account a large number of parameters and considering different possible solutions (configurations of the system). In this context, Genetic Algorithms are considered as one of the most adequate methods to this kind of optimization problems, [Koutroulis et al. (2006)].

4 Genetic algorithm

Genetic algorithms (GA) belong to the family of evolutionary algorithms. They are stochastic techniques of global research and bio-inspired from optimization of natural evolutionary processes of species proposed by Darwin (1859), which is generally robust in the search for optimal global solutions in the multi-modal process optimization.

By analogy with biology, we find terms such as "selection", "crossing", "mutation" or even population.

With a GA, each potential solution of the problem is called an individual. Like a potential solution that is characterized by a combination of optimization parameters, the individual is characterized by a combination of genes. By analogy, genes are the parameters to be optimized in all of these individuals form the population. The objective function is used to assess the adaptation of an individual to his environment (that is to say, a potential solution to the problem). Therefore, the genetic algorithm evaluates different individuals from a certain population (called its fitness). Then, individuals showing a good adaptation to the problem will be selected to create a part of a new population (Figure 3).

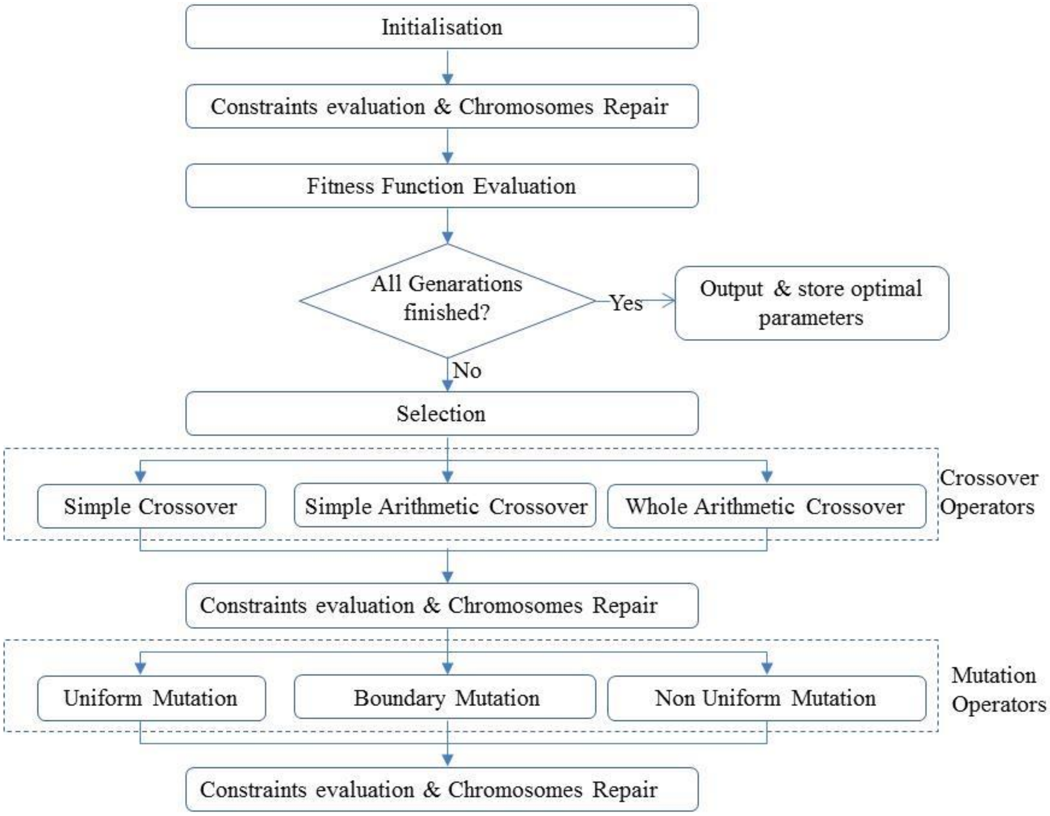

Figure 3: The GA Optimization Process [Koutroulis et al. (2006)].

The objective is to obtain an approximate solution to an optimization problem, when there is no exact method to solve it in a reasonable time. GA use the concept of natural selection and apply it to a population of potential solutions to the given problem.

The terminology used in GA is borrowed from genetics: chromosomes are the elements from which solutions (individuals) are developed. These chromosomes are grouped in population and the combination of chromosomes is the reproduction stage. This is done using a cross operator and/or a mutation operator. Other notions are specific to the field of GA such as the "fitness" quality index, also called performance index, which is a measure for classifying chromosomes. The same method is applied for the evaluation function or cost function, which represents the theoretical formula for calculating the quality index of a chromosome.

The basic algorithm of genetic algorithms starts from an initial population (family) of individuals (parents). The content of this initial population (n individuals) is generated randomly. Each solution is assigned a value that corresponds to its adaptation to the problem (Fitness). Then, a selection is made for k individuals in this population who will migrate directly to the next family or child family (Figure 3).

In the second step, the crossover operator is applied to two randomly selected parents to create new individual, this operation will then be applied until the generation of new population.

In the last step, the algorithm selects a small portion of the parent to apply the mutation operator. So, this whole process will create a new family that will be the parent family for the next generations.

The process of the genetic algorithm is repeated many times in order to imitate the principle of evolution, which only takes its meaning over a large number of generations. The process can be stopped after an arbitrary number of generations or when a solution has a sufficiently satisfactory value.

To develop a GA and effectively solve the problem, it is necessary to identify how to represent the solutions (chromosome coding), to define the evaluation function (fitness function), to elaborate the different operators and to determine the parameters, such as the choice of the stopping criterion and the probability of application of the operators.

5 System total cost minimization by using genetic algorithms

The genetic algorithms (GAs) are used for designing and sizing, through the calculation of optimum solutions in the overall state space. The role of the GA is to derive the optimal desalination system configuration by selecting chromosomes from the total state space of potential solutions, which minimize the problem's objective function and simultaneously lead to a successful system operation during the whole year. GAs is an optimum search technique based on the concepts of natural selection and survival of the fittest individuals. It works with a fixed-size population of possible solutions of a problem, which are evolving in time. A genetic algorithm utilizes three principal genetic operators; selection, crossover and mutation.

Compared to conventional optimization methods, such as dynamic programming and gradient techniques, genetic algorithms are able to: (i) handle complex problems with linear or non-linear cost functions, both accurately and efficiently and (ii) attain the global optimum solution with relative computational simplicity, without being restricted by local optima [Michalewicz (1994)].

The GA chromosomes are in the form of $X = [N_{mb}, N_{PV}, N_{WG}, N_{BAT}, h, \beta, W_{TANK}]$. The objective function to be minimized by the GA is equal to the sum of the capital and maintenance costs evolving during the desalination system lifetime period.

5.1 Objective function

The objective function corresponds to the total cost of produced water CO_{TOT}. It includes all the costs throughout the useful lifetime of the system, which are translated into the initial moment of the investment using the effective interest rate according to standard economical procedures.

These costs include:

- Acquisition of the RO and PV components,
- Pretreatment in the RO installation,
- Replacement of membranes,
- Replacement of battery charger,
- Maintenance of membranes, PV panels, and wind turbines,
- Replacement of batteries, inverter and charge regulator,

Hence, CO_{TOT} can be given by the following equation:

$$CO_{TOT} = \sum_i CO_{ACQ,i} + \sum_i CO_{REP,i} + \sum_i CO_{O\&M,i} \tag{24}$$

Where:

$CO_{ACQ,i}$: the cost of acquisition of different components (RO, PV panels, batteries, etc.)

$CO_{REP,i}$: the cost of replacing several components during the life time of the installation (RO membranes, battery charger, etc.)

$CO_{O\&M-i}$: the costs of operation and maintenance of different subsystems during the life time of the installation (RO, PV, etc.)

We assume that the system life corresponds to that of the PV panels which have the higher lifetime in the system (20 years).

5.2 Different steps of the methodology

The flowchart of the applied algorithm is shown in Figure 4.

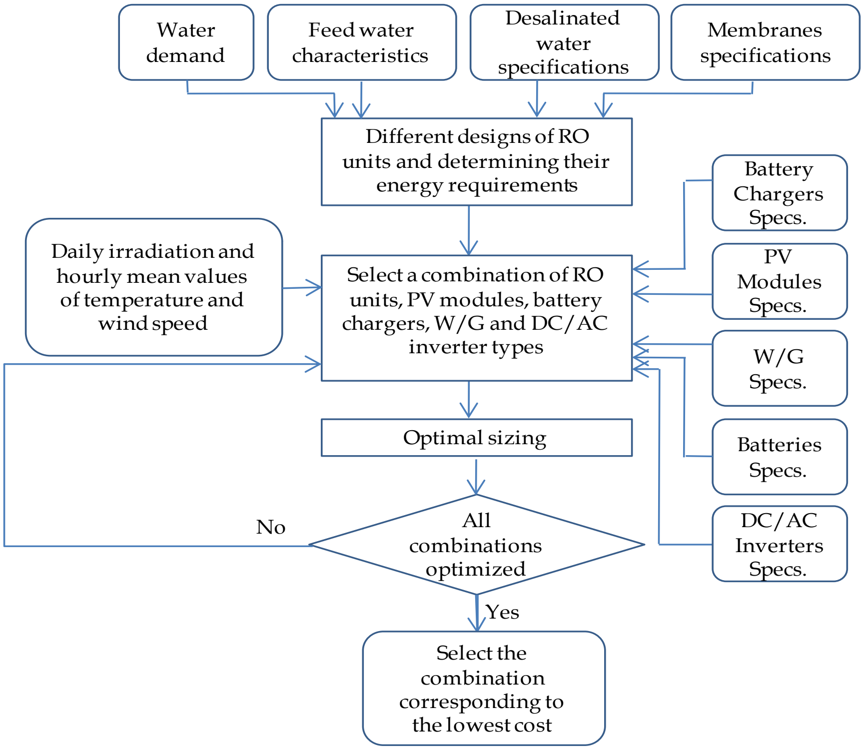

Figure 4: Flowchart for the developed method

Initially, a population of chromosomes is generated randomly and the constraints described by the inequalities (23) are evaluated for each chromosome. If any of the initial population chromosomes violates these constraints then it is replaced by a new, randomly generated chromosome, which fulfills these constraints. The first step of the GA-based optimal sizing algorithm iteration is the fitness function evaluation for each chromosome of the extracted population. If any of the resulting fitness function values is lower than the lowest value obtained at the previous iterations then this value is considered to be the optimal solution of the minimization problem and the corresponding chromosome's values are considered to be the desalination system's optimal sizing and operational parameters.

This optimal solution is replaced by better solutions, if any, produced in subsequent GA generations during the program evolution. The selection of the chromosomes which will be subject to the crossover and mutation operations, thus producing the next generation population, is based on the roulette wheel method [Michalewicz (1994)]. The crossover mechanism uses the Simple Crossover, Simple Arithmetical Crossover and Whole Arithmetical Crossover operators. Next, the selected chromosomes are subject to the mutation mechanism, which is performed using the Uniform Mutation, Boundary Mutation and Non-Uniform Mutation operators. In case that the application of the crossover or mutation operators results in a chromosome which does not satisfy the optimization problem constraints, then a “repair” procedure is performed and that chromosome is replaced by the corresponding parent. In case of the Simple Crossover operation, where each new chromosome is generated by two parents, then the chromosome is replaced by the parent with the best fitness function value. The GA optimization process described above is repeated until a predefined number of population generations have been evaluated.

6 Simulation results and discussion

As part of this work, an optimal design is performed for the case of farm irrigation in Abu Dhabi. In this frame one farm is selected as a reference for our study with a water demand of $50m^3$/day and a salinity of used water of 35,000 ppm. After applying the model to this case and simulating different configurations the following components were selected for the system.

The different components of the RO unit are optimized by using the RO module of the model and their power consumption is determined. In the second step the PV modules were designed and their number determined. Finally, the batteries are fixed and their number is optimized.

To validate the energy unit different simulations are carried along one year to follow the Charge and Discharge state of the batteries. For these simulations, the climate data of the site in Abu Dhabi for the year 1990 are used [EAP (2013)].

Figure 5 shows a simulation result for the Battery Charge and Discharge state (DOD) during all the year for one configuration of the system. This Figure shows that this solution can be considered since the DOD remains in the required interval during all the year.

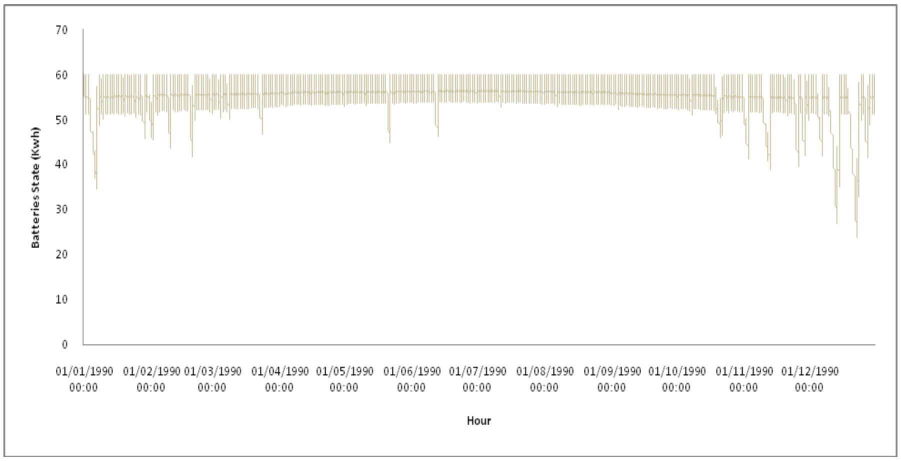

Figure 5: Battery Charge and Discharge state

Figure 6 shows the variation of the objective function (total cost) during the optimization process. To calculate the energy needs of the system, first we calculate the total power requirements for different subsystems, given the maximum operation hours of the RO system.

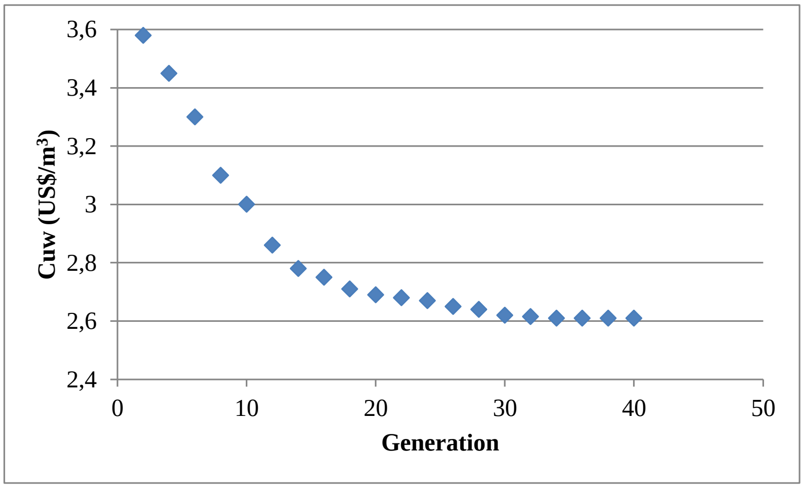

Figure 6: Variation of the objective function during the optimization process

In the present case we found that the total energy demand for the RO plant is 670 Wh. In the first iteration of the optimization methodology 30 individuals were generated. During the optimization process we remark that the working pressure in the RO unit fluctuates between 30 to 35 bars. The optimal solution corresponds to one RO unit using Filmtec membranes (BW30-2540) that can work under a maximum pressure of 41 bars.

This population contains different combinations allowing to provide the water required by the farm and the power to drive the RO plant. From the chromosomes generated in the first step a second generation is provided by using selection (30%), crossover (50%) and mutation (20%). We found that the minimum cost of water in the first generation was 3.58 $\$/m^3$. It decreased to 3.45 $\$/m^3$ in the second generation. The variation of the water cost during the GA-based optimization process evolution is investigated. This analysis shows a significant decrease of the objective function total cost CO_{Tot} for the first 30 generations and stabilizes around 2.61 $\$/m^3$. This means that the optimal solution is reached.

After an economic comparison between different feasible solutions the optimal solution to the site was determined showing a total cost 20% less than the actual applied solutions. By this case study we can see that the contribution of GA can reduce the cost of the produced water in RO/PV in a significant way.

7 Conclusion

There are a number of issues that should be taken into consideration while designing Solar RO systems as: the characteristics of water demand, the cost of water and fuel, the availability of renewable energy resources, the initial cost of the project, including the cost of each component required, the life time of the project, the interest rate subsidies, etc. A technical and economic comparison between different scenarios can be carried out to study the feasibility of the project. In this study, we presented, in a first step, the different possibilities of coupling RO with solar energy (photovoltaic). In a second step, we modeled the RO system, the photovoltaic module and the battery system. This allows us to create a calculation model for sizing both the RO unit, the photovoltaic's array and batteries based on the climate data and the characteristics of the water sites. For this investigation one Farm in Abu Dhabi was chosen. This first part was validated by a comparative study with reference software (ROSA for the RO unit and HOMER for the PV modules).

In a final step, the potential of coupling the RO unit with solar energy sources (photovoltaic) were studied. In this case, the software HOMER was used. Based on the obtained results, the elements of power system are designed in an optimal way. An economic study based on the estimation of the value of kWh/m3 highlights the particular interest of solar desalination technology.

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