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Optimal design of a hybrid solar-wind power to drive a small-size reverse osmosis desalination plant

Karim Mousa, Ali Diabat*, Hassan Fath

Masdar Institute of Science and Technology, Abu Dhabi, UAE
Email: adiabat@masdar.ac.ae

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ABSTRACT

Providing clean water to small communities using renewable energy (RE) has long posed as a humanitarian challenge. Reverse osmosis (RO) desalination has been proven as a mature technology for supplying fresh water for different domestic, industrial, and agricultural usages. On the other hand, RE is the targeted future alternative that can drive RO desalination process in many parts of the world. A lot of work has been done on operating desalination processes using either wind or solar energy individually or both energy sources alongside one another. In this paper, a numerical model which would allow finding the optimal design of a hybrid solar-wind power that would drive a small-sized RO desalination plant is presented. The optimized design variables are the number of solar Photovoltaics modules, the number of wind turbines, height of the wind tower, radius of the rotor blade, and the desalination plant capacity. The objective is to obtain a design which would allow us to produce a given amount of fresh water, at minimal cost. As the RO specific energy consumption varies with feed water properties (mainly salinity and turbidity), three values are considered for the present study: 2.5, 5.0, and 7.5 kW/m^3. The study shows that the hybrid power plant exploits the complementary nature of the energy sources to achieve water demand. The optimal design values of the hybrid RE system varies with the water demand and for the study's values of specific energy consumption, the specific water cost is found to be 0.498, 0.851, and 1.211 $\$/m^3$ respectively.

Keywords: Desalination; Renewable energy; Hybrid; Solar; Wind; Reverse osmosis; Off-grid; Optimization; Mathematical programming

1. Introduction

A prominent problem facing communities worldwide is the supply of fresh water, especially to rural areas, ones that are geographically isolated from fresh water sources such as rivers and lakes. Communities living within the range of saline water use desalination plants to provide fresh water, and conventional thermal desalination plants usually require huge amounts of energy to provide adequate water to a large population. In fact, in most areas, such as the Gulf region and UAE, desalination of water sometime accounts for a large percent of energy consumption, resulting in a large carbon footprint. On the other hand, the realization that fossil fuels are being consumed at a rapid rate worldwide, while CO_2 emissions continue to contribute to global warming, has

*Corresponding author.

made it necessary to search for alternative energy sources. In addition, a large percentage of the world's population lives in geographically isolated areas which may not be connected to the electrical grid or to a fresh water network. These communities need to be developed and settled, or migration to larger cities and across borders will take place with its negative impacts of urban over population, overload on utilities, unemployment, and increase in crimes. Thus, efforts are being made to find new and creative ways to provide such geographically remote areas with the necessary supply of water and electricity necessary for development. These efforts have often led to the effective use of Renewable Energy (RE) for desalination, due to the availability of such sources in remote areas without the need for a grid or pipe connection.

Solar and wind energy are two RE sources that are relatively clean, inexhaustible, and environmentally friendly. These characteristics have attracted the energy sector over the years to utilize their sustainable power. In recent years, the world is witnessing large-scale use of wind and solar energy depending, however, on their location as both sources depend on the unpredictable nature of the earth. Fortunately, both sources possess a strong complementary nature (one is abundant in summer, while the other in winter; similarly for day and night), which can be utilized to their advantage [1,2]. This complementary nature brings forward the advantage of the hybrid solar-wind power plant concept. The concept of utilizing hybrid systems (two or more sources of energy) has gained popularity over the recent years, due to the growing interest in RE sources worldwide. Using hybrid RE systems for power applications reduces the dependence on fossil fuels to generate power and thus, reduces the rate of fossil fuel depletion, while contributing to a cleaner environment.

The desalination of saline water is today a well-developed means of fresh water production and can be achieved by a number of techniques, including thermal processes (e.g. multi-stage flash [MSF] and multi-effect distillation [MED]) and membrane (e.g. reverse osmosis [RO]) [3]. RO is a pressure-driven membrane separation process in which the water from a pressurized saline solution is separated from its solutes by diffusion across a membrane. The majority of the energy requirement comes from pressurizing the feed water. The performance of an RO unit is usually characterized by the feed water composition, feed pressure, temperature, and recovery rate [4]. In many parts of the world, RO desalination is gaining a much larger acceptance, due to the lower specific energy consumption of RO relative to other techniques [5]. Within the late 1970s, RO seawater desalination plants consumed 20 kWh/m^3 of energy [6]. Towards the end of the 1990s, this specific energy consumption was reduced to 5.0–7.0 kWh/m^3 for seawater and can be around 2–4 kWh/m^3 for brackish water based on feed water salinity and turbidity. This decrease of specific energy consumption over the years shows a considerable advancement in RO technology, and makes it a relatively attractive desalination technology in terms of energy consumption. In addition, RO has other advantages over the other desalination processes (such as distillation and electro-dialysis), as simple design, lower maintenance costs, easier de-bottlenecking, removal of organic and inorganic impurities, low discharge in the purge steam, and energy savings [7].

Desalination systems powered by RE sources have been, therefore, extensively presented as innovative approaches to desalinate water in an economic and environmental-friendly manner, especially in remote regions where the use of conventional energy may be unavailable or too expensive. Literature studies on desalination plants powered by various energy systems (including hybrid) usually involve mathematical modeling as well as design and performance assessment. An overview of what other authors have looked at from this perspective will help aid the direction of this study. This paper, therefore, tackles the two life-crucial problems: fresh water supply as well as clean-energy supply. A hybrid solar-wind power plant that would take advantage of the two energy sources' complementary characteristics to power an RO desalination plant would provide fresh water at relatively low specific energy consumption and, therefore, a low water production cost.

2. Literature review

Vince et al. [8] developed an optimization and evaluation method for RO system configurations evaluated by economical (investment and operating costs), technical (energy requirement, recovery rate), and environmental performanceal indicators (life cycle assessment). A simultaneous optimization of the RO process layout and operating conditions required a mixed-integer nonlinear programming formulation, which was solved using a multi-objective optimization (MOO) approach. This model allowed the authors to identify the best technological alternatives for a given set of objectives, and to compare optimal solutions while viewing the trade-off between opposing objectives such as economical costs and environmental impacts. The model was applied on a case study which considered a brackish water RO project.

Marcovecchio et al. [9] presented an optimization model of hybrid desalination processes of MSF and

RO systems. The objective of the study was to determine and to evaluate the optimal operating conditions and process design for a given water production. For the MSF evaporator, the decision variables within the model were the geometric design of each stage, the number of tubes in the pre-heaters, brine velocity, and total heat transfer coefficients. For the RO unit, the optimization variables included the number of permeators of each stage, the operating pressure, internal and outlet rate flows, and the internal and outlet salt concentrations. The resulting formulation contained nonlinear and nonconvex constraints, and was used to provide the basic design of a hybrid MSF–RO desalination plant given a set of parameters.

A multi-objective optimization for the desalination of brackish and sea water using RO spiral wound or tubular modules was carried out by Guria et al. [7]. The model was used to analyze optimal designs of two existing plants, and for the design of new plants. Three possible objective functions were considered: maximize the permeate throughput, minimize the permeate concentration, and minimize the cost of desalination. The decision variable for the existing unit case is the operating pressure difference. For the design of a new plant, the decision variables are the operating pressure, the active area of the membrane, the type of membrane used, and the type of module to be used. The designs of different RO desalination units were obtained successfully in the form of nondominated Pareto solutions.

Khayet et al. [10] presented an optimization of solar-powered RO desalination pilot plant using response surface methodology (RSM). The plant has been constructed and optimized for brackish water desalination. The RSM was used to develop models to be used in the simulation and prediction of different design aspects such as the salt rejection coefficient, the specific permeate flux, and the RO specific index which takes into consideration the two previous variables in addition to energy consumption and the conversion factor. The input variables were the feed water temperature, flow-rate, and pressure. The designed optimal RO plant guarantees $20\,m^3$/day water production with specific energy consumption below $1.3\,kWh/m^3$.

Spyrou and Anagnostopoulos [11] investigated the optimal operation strategy and design of an off-grid desalination unit, used to provide fresh water to meet the demands of remote areas. The set up consisted of an RO desalination unit powered by solar and wind energy systems. An algorithm was developed to capture in detail the entire simulation of the operation of the plant as well as a detailed economic evaluation. Various objective functions were used, such as the minimization of water production cost and the maximization of meeting the water demand. Sensitivity analysis was conducted to test for crucial parameters, such as population, water pricing, water demand satisfaction, and Photovoltaics (PV) costs. The results showed the performance of each subsystem and the plant as a whole. The authors found that the optimally designed scheme was economically viable, although it had high energy rejections, and there is a clear need for the better usage of energy surplus.

Koutroulis and Kolokotsa [12] developed a model used for the optimal sizing of desalination systems to be powered by a hybrid combination of wind generators and PV modules. The objective of the simulation was to derive the optimal number of each power subsystem (wind turbines and PV panels) needed to meet a certain water demand while minimizing cost. Only commercially available devices were considered. The cost function minimization is implemented by genetic algorithms, and the simulation would be used to determine the design of desalination systems which would cover the demand of both a small community and a residential household, in order to test the model's capability of coping with different desalination system size scales. The paper showed that the cost of the whole system is strongly affected by the ability of the devices within the system to exploit the available solar and wind energy.

Zejli et al. [13] presented a model to study a solar-wind hybrid system that would produce domestic water. The system studied consists of a photovoltaic module, a wind turbine, a mechanical vapor compression desalination plan,t and a storage unit. The mathematical model developed aims to optimize the design by controlling the energy flows exchanged within the system components in order to meet a specified water demand. The model was used to solve for three different case studies in Morocco. Two cases tracked attempts to satisfy the hourly and monthly water demand of 20 households in Rabat and one case aimed to satisfy the water demand of 40 households in Essaouira. The motivation behind selecting two geographically different locations was to evaluate the efficiency and feasibility of the desalination system in areas with different characteristics of RE sources. The study shows that the domestic water demands can be met at each time interval with the optimal system design, and can be done at reasonable cost relative to the cost of water in Morocco which is about $0.7\,€/m^3$.

A study which elaborated on the design of a hybrid solar-wind energy plant coupled with RO desalination unit in Southern Tunisia has been carried out by Cherif and Belhadj [4]. The desalination unit was used for potable water production. The input parameters to measure power production were metrological data (solar irradiance, wind speed, etc.), and the calculations were made using steady-state models. Double-stage configuration in the desalination process using spiral modules is used. The results show that the hybrid system is able to cope with water demand across the year, despite changing energy patterns across the seasons. The brackish water supplied to the RO unit was supplied from the Djebra region, and it was found that the RO unit powered by a hybrid solar-wind system would be a suitable solution to southern Tunisia.

In the above previous and other recent literature, most authors focused on reducing the energy cost of water by optimizing the RO process itself through hybrid processes, and not by optimizing the energy source providing the power to the RO unit. The current study presents, however, a novel model to optimize the design of a hybrid solar-wind power plant, which can provide power to off-grid applications such as an RO unit. In addition, recent literature has focused on using ready-made wind turbines provided by manufacturers, and because these come at set heights and radiuses, these turbines may restrict the solution, with the result that the model would not find the true optimum design parameters in a given geographical location. The formulation presented in this paper allows for more flexibility within the design parameters than demonstrated in previous literature (e.g. turbine height, rotor diameter), resulting in a more sensitive and cost-efficient design. The formulation also allows the design to take better advantage of the complementary nature between solar and wind energy sources. The present study uses a newly constructed model aiming to optimize the design of a hybrid solar-wind power plant coupled with an RO desalination unit that would supply the required water demand to a small community in the Emirate of Abu Dhabi, UAE. The model should provide the optimal design parameters for minimal water production costs. It will be tested under different specific power consumption values.

3. The model

3.1. Notation: parameters and values

Table 1 displays the notations used in the present model. Values for input parameters are shown, and variables with an "X" as a value are the decision variables in the model.

In addition, the definition and justification of some of the parameters used within the model are as follows:

Coefficient of performance, C_p: Albert Betz, a German physicist, performed a study in 1919 theorizing that no wind turbine can convert more than 59% of the kinetic energy of the wind into mechanical energy to turn the rotor. This is known, to this day, as the Betz Limit, and the theoretical maximum power efficiency of any design of wind turbines is 0.59. This value is stated as the coefficient of performance, $C_p = 0.59$.

Ideality factor, n: Also known as the quality factor, this notation has a value between 1 and 2 depending on the quality, semiconductor material, and fabrication process of the diode. The ideality factor measures how closely the diode follows the ideal diode equation.

Hellman exponent, a: This exponent is used to measure the variance in wind speed with height and turbulence. It depends upon the coastal location and the shape of the terrain. The value we will consider in this study is the average value of the exponent for onshore locations, and that is equal to 0.142. A lower value may be used for offshore locations, and a higher value can be used for urban or forest locations.

3.2. Governing equations

3.2.1. Objective function

Eq. (1) represents the objective function, with the aim to minimize the total costs of wind and solar components as well as the cost of the RO unit, including both operation and maintenance costs, while considering the interest rate over the project lifetime. The cost functions are elaborated on in Section 3.2.4.

$$\mathrm{Cost(Wind)} + \mathrm{Cost(Solor)} + \mathrm{Cost(RO)} \tag{1}$$

3.2.2. Power demand constraint

Eq. (2) ensures that the model meets the power demand load, using the power generated from the hybrid system—from both wind turbines and solar arrays. The generated power by both sources is considered over a 12-month period with different weather conditions (e.g. higher solar radiation in summer).

$$P_o(\mathrm{Wind}) + P_o(\mathrm{Solar}) \geq P_{demand} \tag{2}$$

3.2.3. Wind turbine constraints

Eq. (3) limits the height of the wind turbine to 100 m, while Eq. (4) limits the rotor radius to 30% of the tower height.

$$H \leq 100 \tag{3}$$

$$R \leq 0.3 * h \tag{4}$$

Table 1
Notations

Parameter	Value	Description
N_w	X	Number of wind turbines
C_{wm}		Annual maintenance cost for wind turbine
H	X	Wind tower height (m)
R	X	Radius of wind turbine (m)
C_{wf}		Installation + Fabrication cost of wind turbine (steel cost not included)
I	5%	Real interest rate
ffY_{proj}	20 year	Project lifetime
N_s	X	Number of solar cells
C_{sm}		Annual maintenance + cleaning cost for solar panel
C_{sc}		Solar panel capital cost + installation cost
ρ	1.225 kg/m^3	Air density
c_p	0.59	Coefficient of performance
V_w		Wind speed (m/s)
N_g	50%	Generator efficiency
N_b	95%	Gearbox bearing efficiency
V_{oc}, V_{oco}		Voltage for open circuit
η	$1 < \eta < 2$	Ideality factor
K	1.38×10^{-23} J/K	Boltzmann constant
q	1.6×10^{-19}	Magnitude of the electron charge
R_s		Series resistance (ohm)
I_{sc}, I_{sco}		Short circuit current (A)
G, G_o		Solar radiation, W/m^2
T_o, T		Temperature under standard conditions (K)
α, β, γ		Constant parameters for PV module

3.2.4. Overall costs

Eq. (5) presents the cost incurred from operating and maintaining the wind turbines. The equation incorporates the costs of increasing the height of the wind turbine and the rotor diameter. These costs are a multiple of the number of wind turbines installed, N_w [14].

$$\mathrm{Cost(Wind)} = N_w C_{wm} + N_w(250h + 2.449r^{2.7} + C_{wf})\left(\frac{i * (1+i)^{Y_{proj}}}{(i=1)^{Y_{proj}} - 1}\right) \tag{5}$$

Eq. (6) calculates the cost incurred when finding the optimal design and placement of the solar arrays. The costs considered are the capital and maintenance costs. This cost is a multiple of the optimal number of solar arrays N_s.

$$\mathrm{Cost(Solar)} = N_s C_{sm} + N_s C_{sc}\left(\frac{i * (1+i)^{Y_{proj}}}{(i=1)^{Y_{proj}} - 1}\right) \tag{6}$$

The equation used to calculate the cost of the RO unit is shown below, and consists of the capital and operational costs. These costs are discussed later in the paper and are given in terms of water production in meters cubed per day.

$$\mathrm{Cost(RO)} = \mathrm{CAPEX} + \mathrm{OPEX} \tag{7}$$

3.2.5. System generated power output

Eq. (8) shows the expected total output power generated by the total number of wind turbines in the design. The equation incorporates the effect of the turbine height and diameter, [14].

$$P(\mathrm{Wind}) = 0.5 \times \rho \times Ac_p * \left(v_{10} * \left(\frac{h^a}{10}\right)\right)^3 N_g N_b \tag{8}$$

The overall power output generated by the solar arrays is presented in Eq. (9). It is based on a similar model used in the analysis of a hybrid solar-wind power generation system by Yang et al. [15].

$$P_o(\text{Solar})N_s = \left(\begin{array}{c} \dfrac{\frac{V_{oc}}{\frac{nKT}{q}} - \ln\left(\frac{V_{oc}}{\frac{nKT}{q}} + 0.72\right)}{1 + \frac{V_{oc}}{\frac{nKT}{q}}} * \\ \left(1 - \frac{\frac{R_s}{V_{oc}}}{I_{sc}}\right) * I_{sco}\left(\frac{G}{G_o}\right)^{\alpha} * \frac{V_{oco}}{1+\beta\ln\frac{G_o}{G}}\left(\frac{T_o}{T}\right)^{\gamma} \end{array} \right) \tag{9}$$

4. Hybrid PV-wind-RO system: case study

4.1. System layout

The proposed hybrid power system would consist of 150 W mono-crystalline solar modules as well as wind turbines ranging from 1 to 10 kW. These subsystems are interconnected using DC converters and a DC bus, coupled with a RO unit through a DC–AC inverter. The photovoltaic power output is controlled by a DC/DC converter, similar to the wind turbine power. The common DC bus collects the total power from the hybrid system, before channeling it to the DC/AC inverter to the pump of the RO unit. The system configuration schematic is presented in Fig. 1.

4.2. Site weather conditions

The design for the hybrid power-desalination system is intended to be used for a small residential community in the Abu Dhabi region. The geographical data of the region is obtained from Islam et al. [16] in the form of average monthly data, and is displayed in Fig. 2 as a percentage of the maximum energy resource. Maximum wind speed is 6 m/s in January, while maximum (daily average) solar intensity is 290 W/m^2, in May.

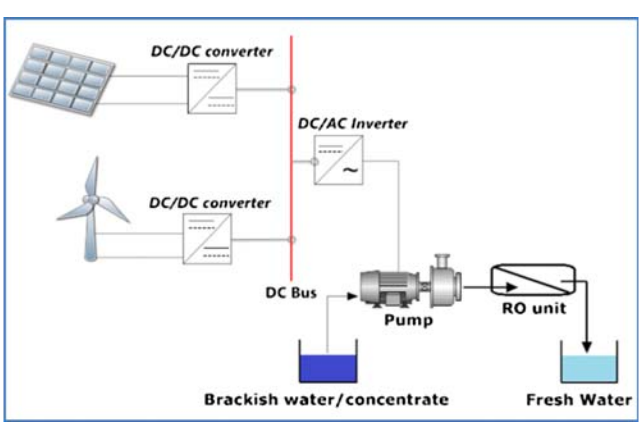


Fig. 1. The configuration of the hybrid PV-wind power plant coupled with a RO desalination unit.

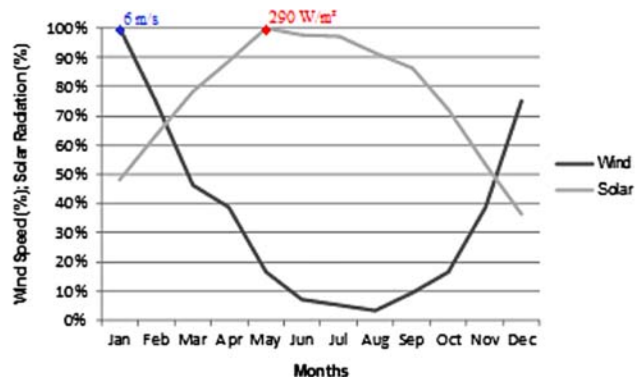


Fig. 2. Abu Dhabi energy sources as a percent of their maximum over the year.

4.3. Community water demand and energy required by RO unit

To estimate the water that would be required by a small community (say 100 people), the large-scale figures of water production in the city are linearly scaled down to a smaller number of the community population. These figures are shown in Table 2. The energy / power requirement by the RO unit to meet the water supply of the small community is calculated for different specific power consumption values of 2.5, 5, and 7.5 kWh/m^3 and displayed in Table 3. The required power demand, for each case, would need to be met by the hybrid solar-wind system.

4.4. System cost parameters

The cost parameters pertaining to the solar and wind components are taken from Islam et al. [16], while the RO cost parameters are taken from a study carried out by the IAEA [17]. These can all be seen in Table 4. These cost parameters used, however, can be changed within the model.

4.5. Model calculation overview

The model, as presented in Section 3.2, can be displayed graphically as in Fig. 3. It is divided into three parts: the performance model, the economic model, and the constraints section. The performance model is in charge of ensuring that all power demands required by the RO unit are met by both solar and wind components. The economic model is working alongside the performance model and continuously measuring the cost, forcing adjustments till the minimum cost is reached while the power demand is being met. The constraints are constantly guiding the performance equations, giving boundaries and

Table 2
Water production for Abu Dhabi region as well as per capita and per 100 persons

Month	Total (Mm^3)	Per capita (m^3)	For 100 ppl (m^3)
Jan	43.17568	44.50	4,449.62
Feb	38.9233	40.11	4,011.38
Mar	44.54766	45.91	4,591.02
Apr	46.78376	48.21	4,821.47
May	49.07671	50.58	5,057.78
Jun	45.5558	46.95	4,694.92
Jul	43.89199	45.23	4,523.45
Aug	43.38034	44.71	4,470.72
Sep	41.38301	42.65	4,264.87
Oct	43.00513	44.32	4,432.05
Nov	39.69646	40.91	4,091.06
Dec	42.87627	44.19	4,418.77

Table 3
Energy and power requirements by the RO unit to desalinate under three different specific power consumption values

	2.5 kWh/m^3		5 kWh/m^3		7.5 kWh/m^3	
Month	Energy required (kWh)	Power required (kW)	Energy required (kWh)	Power required (kW)	Energy required (kWh)	Power required (kW)
Jan	11,124.06	15.45	22,248.12	30.90	33,372.18	46.35
Feb	10,028.45	13.93	20,056.90	27.86	30,085.35	41.79
Mar	11,477.55	15.94	22,955.09	31.88	34,432.64	47.82
Apr	12,053.67	16.74	24,107.34	33.48	36,161.01	50.22
May	12,644.44	17.56	25,288.88	35.12	37,933.32	52.69
Jun	11,737.29	16.30	23,474.58	32.60	35,211.87	48.91
Jul	11,308.61	15.71	22,617.23	31.41	33,925.84	47.12
Aug	11,176.79	15.52	22,353.58	31.05	33,530.37	46.57
Sep	10,662.18	14.81	21,324.37	29.62	31,986.55	44.43
Oct	11,080.12	15.39	22,160.24	30.78	33,240.35	46.17
Nov	10,227.65	14.21	20,455.30	28.41	30,682.95	42.62
Dec	11,046.92	15.34	22,093.84	30.69	33,140.75	46.03

limiting them to reality as well as ensuring all demand is met.

The model process can also be summarized in three steps: the input data process, the processing of the model, and the output results. The input process is where the weather conditions as well as the demanded load are input. Then, the model is run, and the equations (Section 3.2) process are all given

Table 4
System components' cost parameters

Component	Capital cost	Maintenance cost/year
RO unit	800 US$/$m^3$/day	0.8 US$/$m^3$
PV module	6,500 US$/kW	65 US$/kW
Wind turbine	3,500 US$/kW	95 US$/kW
Tower	350 US$/kW	6.5 US$/kW
Rotor	Exponential	

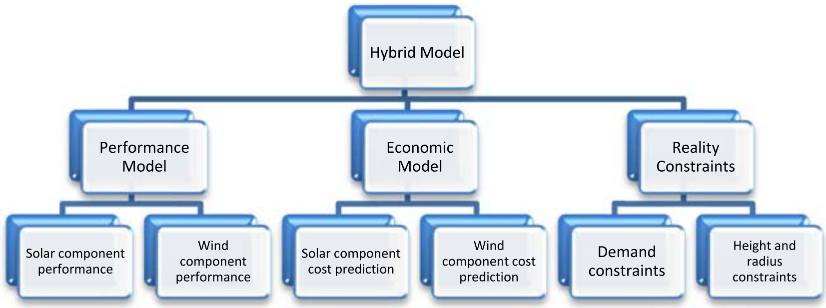


Fig. 3. Model structure.

parameters and constraints to produce an output, showing the design parameters and costs. These steps can be presented graphically as in Fig. 4.

5. Simulation results and discussion

The present simulation consists of designing a hybrid solar-wind power system coupled with a RO desalination unit to provide water to a small community of 100 people in the region of Abu Dhabi, UAE for 20 years. The water and power requirements from all subsystems have been calculated and displayed in Tables 2 and 3. Monthly power demand requirements by the RO unit are also input, for each of the three specific power consumption cases. Running the model for each of the three cases shows the following:

5.1. 2.5 kWh/m^3 case

Fig. 5 displays the power output from the different system components as well as the total power produced by the hybrid system when the specific energy consumption is 2.5 kWh/m^3, and the monthly power demand of the RO unit is also shown. The optimal design parameters for this set up are shown in the figure as well, displaying the number of wind turbines, number of solar modules as well as the height and radius of the wind turbines. Table 5 displays the annualized cost of both the hybrid system and the RO unit. The specific water cost is then calculated in \$/m^3.

5.2. 5 kWh/m^3 case

The system's similar design parameters are changed, and the output can be seen in Fig. 6 and Table 6.

5.3. 7.5 kWh/m^3 case

The system design parameters are changed and the output can be seen in Fig. 7 and Table 7.

In Figs. 5–7, it can be seen that the power demand is continuously met across the year by the hybrid system. This means that the RO unit can produce the target amount of water each month that has been set in the case study to be supplied to the community. It can also be seen that both subsystems in the hybrid set up are working together to meet the total demand in each case. In addition, the model utilized the complemen-

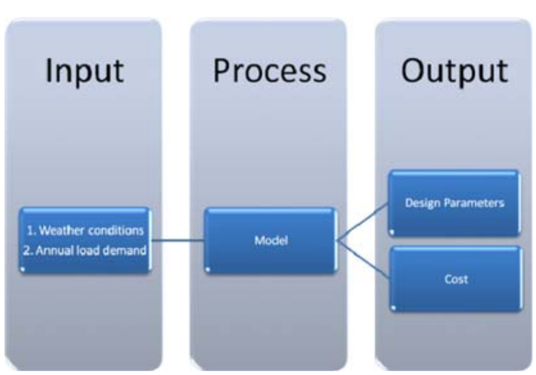
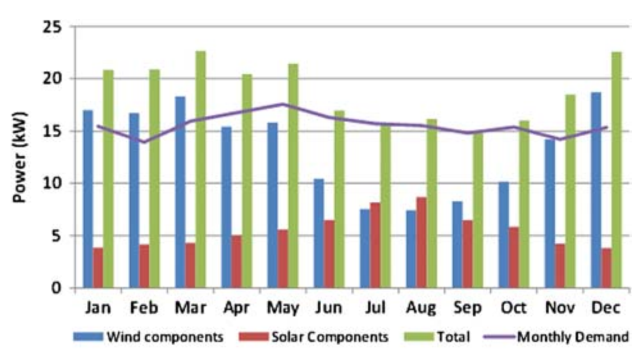


Fig. 4. The three stages of running the model.



N_w	N_s	Height	Radius
2	53	18.1m	5.4m

Fig. 5. Monthly power output from the hybrid system components and optimal design parameters.

Table 5
The annualized costs of 2.5 kWh case

Hybrid system	\$19,920.14
RO CAPEX	\$6,743.70
RO OPEX	\$215.31
Total	\$26,879.15
Water production cost	0.498 $\$/m^3$

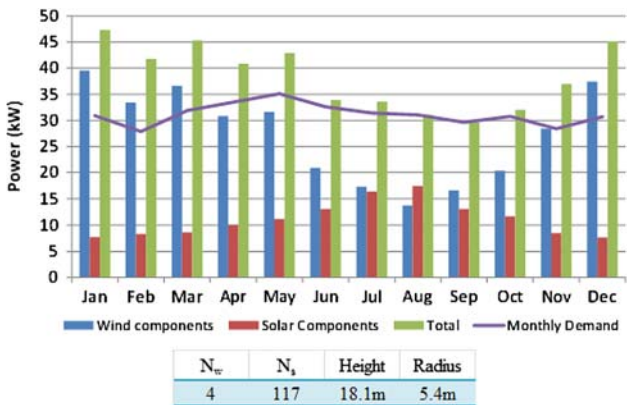


Fig. 6. Output with a specific energy consumption of 5 kWh/m^3 and optimal design parameters.

Table 6
Annualized cost for the 5 kWh case

Hybrid system	\$38,841.10
RO CAPEX	\$6,743.70
RO OPEX	\$215.31
Total	\$45,800.11
Water production cost	0.851 $\$/m^3$

tary nature of solar and wind energy. The power output from the wind turbines is higher during the winter time than in summer, and vice versa for solar panels. It was essential to use this complementary nature to meet the required power at minimal cost. To further minimize the cost, it can be seen that the model chooses to produce excess (above demand) power from the wind turbines during winter, since it would mean that this would decrease the system's dependence on solar energy throughout the year. The fewer solar panels the system needs, the less the cost, since solar panels cost more per kW than wind turbines.

Figs. 5–7 also display the optimal design parameters for this case study given by the model. The

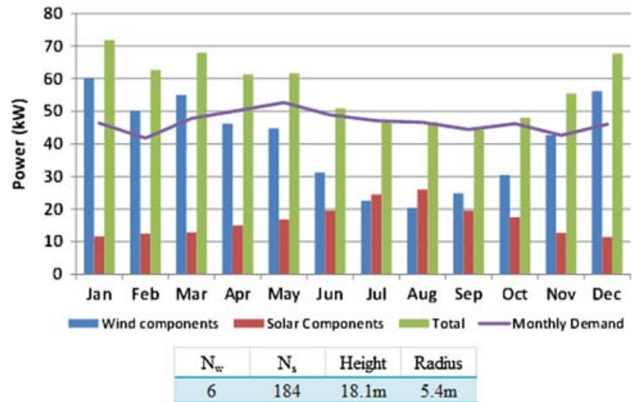


Fig. 7. Output for the 7.5 kWh case.

Table 7
Annualized cost for the 7.5 kWh case

Hybrid system	\$58,261.36
RO CAPEX	\$6,743.70
RO OPEX	\$215.31
Total	\$65,220.37
Water production cost	1.211 $\$/m^3$

number of solar panels that should be installed is shown in the output, along with the number of wind turbines with their respective height and rotor radius. All these results are summarized in Table 8. The resulting annualized costs of the system are displayed in Tables 5–7, and the costs displayed are annualized over 20 years. The RO unit costs are divided into capital and operational costs. The hybrid system costs also consider capital and maintenance costs, but are displayed as a total due to the nature of the formulation. Table 8 also shows that the water production cost in $\$/m^3$ increases linearly with the incremental increase of specific power consumption. This is demonstrated in Fig. 8. Also, note that the RO OPEX does not change across the cases, and this is because the amount of desalinated water remains the same, and the increase in specific energy consumption is accounted for in an increase in cost of the hybrid power system (CAPEX + OPEX).

The height and radius of the wind turbines across all cases also remains the same due to the fact that the maximum wind turbine capacity in the model is set to 10 kW, and for each wind turbine to achieve that, they have to be at a certain height and radius depending on the geographical data (wind speed). The dependence of power generated by the wind turbines on height, radius, and wind speed can be seen in Eq. (8). Because the case is set in one city (Abu Dhabi), the

Table 8
Summary of output results for the three cases

Specific energy consumption	N_w	N_s	Height	Radius	Hybrid system	RO CAPEX	RO OPEX	Total	Water production cost
2.5 kWh/m^3	2	53	18.1 m	5.4 m	$19,920.1	$6,743.7	$215.3	$26,879.2	0.498 $/m^3
5 kWh/m^3	4	117	18.1 m	5.4 m	$38,841.1	$6,743.7	$215.3	$45,800.1	0.851 $/m^3
7.5 kWh/m^3	6	184	18.1 m	5.4 m	$58,261.4	$6,743.7	$215.3	$65,220.4	1.211 $/m^3

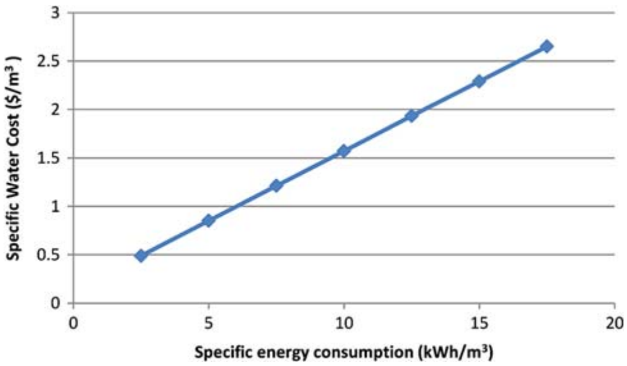


Fig. 8. Linear relationship of the cost of water and specific energy consumption by the RO unit.

geographical data remains the same across all three cases, resulting in the same design parameters for the wind turbines. Only the number of wind turbines and PV panels varies with power requirements.

As it is well known, the product water specific cost in RO technology depends on the feed water quality (mainly salinity for high-pressure pump and turbidity for the level of pretreatment required). These are translated into specific power consumption (kWh/m^3). For typical Gulf water in UAE (high salinity and high turbidity), specific power consumption of 5–7.5 kWh/m^3 is acceptable and the cost of 0.85–1.2 $/m^3 is acceptable for commercial plants. On the other hand, the cost of water is optimistic in this study mainly because of the flexibility of the design allowed within the developed model. To clarify further, wind and solar component distributors usually sell the components in standard sizes (e.g. wind turbines from the brand X come in sizes of 10, 20, 40, 50 m, etc.).This restricts the ability of tailoring an optimized design for a specific application. If the actual height of a wind turbine required to generate 15 kW within a certain climate is 22.6 m, say, one would still have to purchase the 40 m wind turbine from the brand, resulting in extra and unnecessary cost. Thus, the presented model provides optimized heights and radiuses for specific applications, which results in less cost.

6. Conclusion

A model which can be used in the optimal sizing of a hybrid solar-wind plant coupled with an RO desalination unit was presented. The RO unit would have to produce the required monthly water demand needs to a small community (of 100 people) in the region of Abu Dhabi, UAE, across the year. The power required by the RO unit to match the monthly water demand of the small community is then calculated, and used as required monthly energy by the hybrid solar-wind system.

The simulation produced an optimal sizing design for the hybrid power plant which would provide the target power to the RO unit. The number of wind turbines and solar panels as well as the turbine height and radius are displayed for different RO specific power consumption of 2.5, 5, and 7.5 kWh/m^3. In addition, the cost of the subsystems and the system as a whole were calculated, and the results showed that water can be produced at a cost ranging from 0.498, 0.851 to 1.211 $/m^3 for the three specific energy consumptions, respectively, using the design parameters in this case-study.

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