Resource-Efficient Technologies 2 (2019) 1–16

TOMSK POLYTECHNIC UNIVERSITY

Resource-Efficient Technologies

journal homepage: http://ojs.tpu.ru/index.php/res-eff

Research Paper

PERFORMANCE ANALYSIS OF HYBRID SOLAR-WIND RO-MSF DESALINATION SYSTEM

B. Heidary[1], T. Tavakoli Hashjin[1*], B. Ghobadian[1], R. Roshandel[2]

[1] Tarbiat Modares University, Tehran, Iran
[2] Sharif University of Technology, Tehran, Iran

Abstract

Introduction: Water, energy, and the environment are three important elements of sustainable development. Production of potable water using desalination technologies powered by renewable energy systems could help solve water scarcity in remote areas with shortages of water or conventional energy sources, or in large cities with air pollution. Hybridization of solar and wind could increase the sustainability and availability of renewable energy sources and reduce energy costs. Additionally, hybridization of reverse osmosis (RO) and MSF could increase efficiency and desalinated water quality and decrease desalinated water cost.
Materials and Methods: The research method in this paper is based on modeling, computer simulation, and optimization with MATLAB software, and manufacturing and evaluating the plant at the Tarbiat Modares University Renewable Energy Laboratory.
Results: The process of manufacturing the MSF system, solar panel structure, and wind turbine was explained and modeling and optimization results were presented. Testing results of the plant were mentioned, as were the produced power of wind turbine simulated and plant performance evaluated under the environmental conditions of the Tehran region. The rate of fresh water production under changing feed water salinity was evaluated and the real costs of fresh water produced ($\$/m^3$) were estimated. At the end of this section, model results and test results were compared.
Conclusion: Hybridization of RO and MSF systems with wind and solar energy resources led to increased system reliability and flexibility and higher produced drinking water quality. The desalinated water cost was 1.35 $\$/m^3$ in theory and 1.5 $\$/m^3$ for actual conditions. Hybridization of wind, solar, RO, and MSF showed proved the best choices to minimize water cost compared to fossil fuel RO or MSF, wind RO, wind MSF, solar RO, solar MSF, or fossil fuel RO-MSF. Hybridization of RO and MSF would result in better economics and operation characteristics than those corresponding to MSF. Water cost can be reduced by 23 to 26 % of that of a sole MSF process and the amount of desalinated water produced by the hybrid RO-MSF system is much greater than that of MSF. A comparison of theory outputs and experimental test results showed very good agreement between measured and model data. The test results of the manufactured hybrid solar-wind RO-MSF justified theory results.

Key words: Hybrid solar-wind RO-MSF, desalinated water, cost of energy, efficiency, comparison of test and theory results.

1. Introduction

Water, energy, and the environment are three issues inextricably linked and are important sustainable development elements [1]. Around the world, many countries are facing water and energy shortages and environmental problems, and Iran is one of that the nations facing water shortages. One solution for freshwater shortages is seawater desalination, which is appropriate in Iran as it has access to sea water to the north and south. Desalination of sea water has now been accepted as a potential freshwater supply; however, existing desalination technologies have energy demands that continue to pose challenges in their applications [2]. Researchers have estimated that producing 1000 m^3 of freshwater per day requires 10,000 m^3 of oil per year [3]. Oil and

* Corresponding author: Tarbiat Modares University, Tehran, Iran. E-mail address: ttavakol@modares.ac.ir

☆ Peer review under responsibility of Tomsk Polytechnic University.
https://doi.org/10.18799/24056537/2019/2/184

other fossil fuel sources are not sustainable energy sources and cause environmental pollution. Use of renewable energy sources such as solar, wind, biofuels, and geothermal energy can provide a sustainable alternative, but the high costs of renewable energy technologies have prevented successful implementation of these resources [4]. Additionally, renewable energy sources have low reliability as there are possible situations such as no sun or wind being present. These problems can be solved by hybridization of renewable energies, which can increase reliability and decrease power loss probability while decreasing energy costs [5]. Production of potable water using desalination technologies driven by renewable energy could solve water scarcity in remote areas characterized by shortages of freshwater or conventional energy sources or for large cities with polluted air.

Hybridizing solar and wind energy can reduce dependence on fossil-based fuels, increasing system reliability and operational efficiency, and allow for distributed generation in places with no traditional large power generation and small-scale power generation such as individual photovoltaic (PV) panels and micro wind turbines [5–7].

Multi-stage flash desalination (MSF) and reverse osmosis (RO) are two main methods used for seawater desalination. In a multi stage flash desalination plant, salty water is heated until it evaporates and begins to flash to steam at low pressure and distilled in multiple stages. MSF facilities consist of three sections, namely the brine heater, heat rejection, and heat recovery sections. Creating efficient MSF facilities and processes requires design, simulation, and optimization studies. Several researchers have conducted these design, simulation, and optimization studies to obtain insights on MSF facility and process performance. Many of these literature reviews concern MSF facility formulas, stage-to-stage calculations, cost calculations, and MSF process modeling, and MSF process performance evaluation [8–15].

Reverse osmosis (RO) is a process in which salty water is pressurized by a pump and diffused across a membrane to separate desalinated water from salty water [16]. RO technology consumes less energy than MSF technology and is flexible in size (small-scale to large-scale). Additionally, RO has a high recovery ratio (more than 40%), but desalinated water is of lower quality than that produced with MSF and operational costs (membrane replacement costs) are greater than MSF when the water being treated is as salty as sea water [8].

Hybridizing RO with MSF improved MSF performance, reduced MSF scale, reduced RO membrane replacement cost, and reduced desalinated water costs. Additionally, distillated water product from the MSF section and can be blended with RO permeate to obtain suitable water quality and decrease the water product temperature, and a single-stage RO process can be used and RO membrane life can be increased. Full integration of RO and MSF provides better control of feed water temperature to the RO plant by using warm reject coolant water from the MSF heat rejection section, and low-pressure steam from the MSF brane can be used to blend and warm the feed to the RO plant at a low cost and increase RO efficiency [8].

Iran has desirable conditions for solar and wind energy [17] and has faced freshwater shortages and environmental problems such as air pollution in big cities. A hybrid solar-wind RO-MSF desalination system that works with two clean and renewable energy resources— solar and wind—could be a sustainable method for producing water. Hybridization of two renewable and clean energy sources could increase the sustainability and availability of using renewable energy and reduce energy costs.

In previous studies, researchers have focused on reducing the water costs of RO, MSF, or RO-MSF plants through hybrid processes, and not by modeling, optimization, manufacturing, and testing a hybrid solar-wind RO-MSF desalination plant. The mathematical models of a hybrid solar-wind RO-MSF plant presented in this paper consider more flexible design parameters than previous research, and for the first time, a hybrid solar-wind RO-MSF plant has been manufactured and tested to compare test results with model results and optimize sizing of a hybrid solar-wind RO-MSF system and desalinated water properties.

This paper's main contributions are:

1. Representing solar-wind RO-MSF desalination system design and modeling results and introducing different parts of the system.
2. Explaining the process of hybrid solar-wind RO-MSF desalination system manufacturing.
3. Designing and manufacturing a hybrid solar-wind RO-MSF desalination system as a package and that can be easily moved and installed in appropriate places.
4. Testing the manufactured hybrid solar-wind RO-MSF plant and analyzing test results under Tehran weather conditions for 48 hours of continuous operation.

5. Evaluating the performance of a hybrid solar-wind RO-MSF desalination plant and parameters of salty and desalinated water such as total dissolved solids (TDS), pH, and electrical conductivity (EC).

6. Comparing the test results with theoretical results.

2. Materials and Methods

Many published articles have explained heat transfer, recovery relations, and performance relations of MSF [1–7, 10–15, 18, 19–23] and RO [1–7, 18, 19] and specified the technical and economic benefits of full integration and hybridization of MSF and RO systems [8–9]. Additionally, many of these articles have explained the advantages of using renewable energies for desalination or the hybridization of different renewable energy sources [1–7, 16, 17, 21–23]. Modeling and parameter optimization of hybrid solar-wind RO-MSF desalination has been done [18], and through comparison with tests results, this system was designed, modeled, optimized [18], and manufactured.

In this paper, the hybrid solar-wind RO-MSF plant designed, modeled, optimized [18], and manufactured this system to evaluate the performance of system and evaluate its performance.

We provided the plant electricity for 48 hours continually without solar radiation or wind. This desalination plant could be used for small-scale and large-scale off-grid application in remote areas. The optimal parameters for continuous water production costs and maximum desalted water production were presented and compared with test results.

The hybrid solar-wind RO-MSF desalination system package consists of an MSF desalination plant (MSF base, vacuum pump, pressure pump, pipes and taps), and RO desalination plant (RO membrane, pressure pumps, pipes), solar panels and solar panels structure, a wind turbine and wind turbine base, a solar collector, and a table.

Figure 1 shows a diagram of a hybrid system with a desalination plant as a load. We connected a brackish water RO desalination plant to the hybrid power system. This plant produces drinking water when enough power (both generated and stored) is available to operate the plant. If more power was produce, the plant produced an increased amount of water up to its rated capacity Hence the load can handle power generation variations from renewable sources. The RO plant indirectly stores power produced in the form of product water, which eliminates the need to have higher capacities of expensive batteries.

To evaluate water desalination performance by a hybrid RO-MSF desalination plant, we designed and optimized a hybrid system. We considered and technically and economically analyzed different models of solar wind RO-MSF. Finally, a model that can be used in small scale desalination sites is presented in Fig. 1 [18].

2.1. Modeling of hybrid RO-MSF

In the RO-MSF model, heat rejection MSF condenser liquid is used to feed the RO system, and this warm sea water increases RO efficiency. Also a portion of heat rejection MSF condenser liquid is mixed with RO brine and MSF brine and is used as condenser liquid for the MSF heat recovery portion, which causes the recovery of consumed water and heat and increases the system's efficiency (Fig. 2).

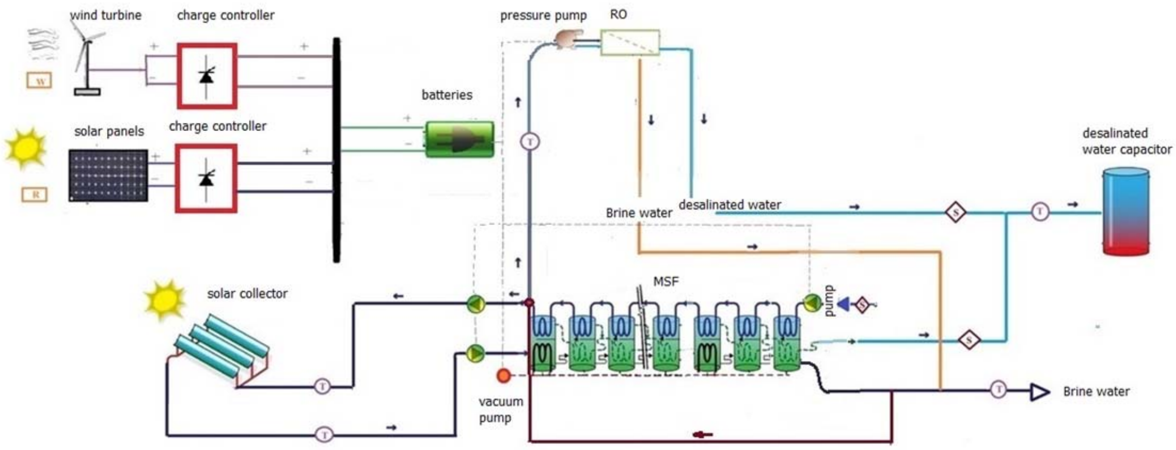


Fig. 1. Schematic of hybrid solar wind reverse osmosis-multi-stage flash desalination system [18]

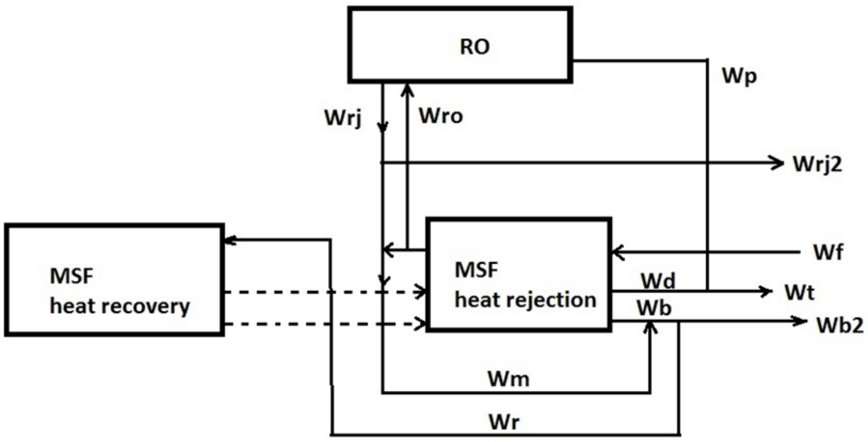


Fig. 2. Integrated reverse osmosis-multi-stage flash desalination heat recovery

We calculated mass and energy balance equations based on Eqs. (1)–(4) in Table 1 [1–7,10–15,18–23].

Table 1. Mass and energy balance of integrated reverse osmosis-multi-stage flash desalination HR3

Term	Equation	
Mass balance	$W_f = W_{rj2} + W_{b2} + W_t$ $W_{rj} = W_{ro} - W_p$ $W_m = W_f - W_{ro} - W_p - W_{rj2}$ $W_{b2} = W_b + W_m - W_r$	(1)
Desalinated water mass balance	$W_t = W_d + W_p$	(2)
Desalinated water salinity balance	$X_t W_t = X_p W_p$	(3)
System salinity balance	$X_{sea} X_f = X_t W_t + X_{b2} W_{b2} + X_{rj2} W_{rj2}$	(4)

2.2. Modeling of hybrid solar-wind energy system

We designed and optimized the hybrid solar-wind desalination system for a small-scale community in the Tehran region. We obtained solar radiation, wind speed, and other climate parameters in the form of average monthly data from the NASA website.

The proposed energy system consists of a wind turbine, a solar panel, and a solar collector. These subsystems are connected to a charge controller and the electricity they produce is saved in batteries. The pumps are operated by electricity produced from solar panels and wind turbines (Fig. 3). The energy system design is intended for the Tehran region.

The solar-wind model is optimized for the performance and economic models. The solar-wind RO-MSF desalination system has an energy demand of 72 kWh/month for full hour RO and MSF working conditions. On rainy or cloudy days, the desalination system could operate using only RO desalination with a less than 30 kWh/month energy demand.

The solar-wind model, as presented in Fig. 3, should ensure the desalination system's energy demand (72 or 30 kWh/month). We summarized the mathematical model process in three steps: data input, t model processing, and result output. Weather conditions, the design parameters of each RO-MSF model, and desalination system energy demand are the inputs. The model is run according to Eqs. (1)–(4), and Eqs. (5)–(7) represent power generated from the wind turbine and solar panel [18]. These equations represent objective functions to minimize energy cost (solar and wind cost).

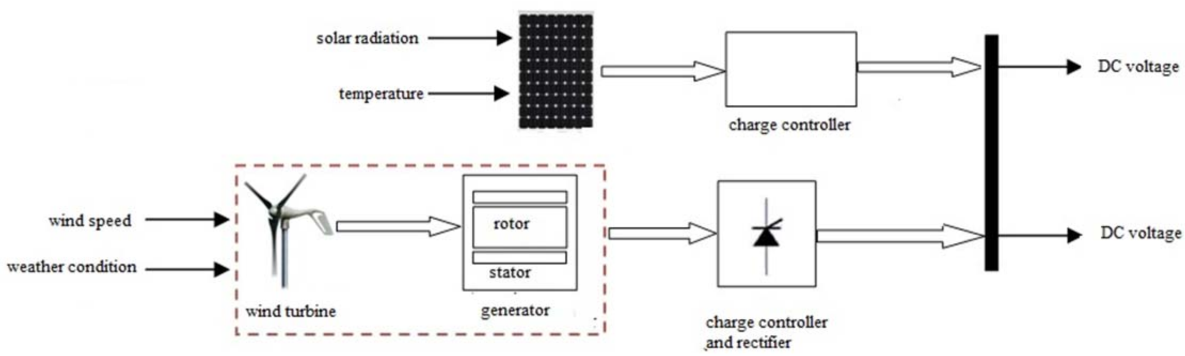


Fig. 3. The configuration of a hybrid photovoltaic-wind turbine power system

$$P(\text{wind}) + P(\text{solar}) \geq P_{\text{demand}} \tag{5}$$

$$p(\text{wind}) = \frac{1}{2} \times \rho \times A \times V^3 = \frac{1}{8} \times \varepsilon \times \rho \times \pi \times d^2 \times V^3 \tag{6}$$

ξ = efficiency of the wind turbine (in general less than 0.4 - or 40%)
ρ = density of air (kg/m^3)
A = wind turbine area perpendicular to the wind (m^2)
v = wind velocity (m/s)
π = 3.14....
d = wind turbine diameter (m)

$$P(\text{solar}) = \frac{\frac{V_{oc}}{q.n.K.T} - \ln\left(\frac{V_{oc}}{q.n.K.T} + 0.72\right)}{\left(1 + \frac{V_{oc}}{q.n.K.T}\right)} \times \left(1 - \frac{Rs}{V_{oc} \times I_{sc}}\right) \times I_{sco} \left(\frac{G}{G_0}\right)^{\alpha} \times \frac{V_{oc}}{1 + \beta.\ln\left(\frac{G_0}{G}\right)} \left(\frac{T_0}{T}\right)^{\gamma} \tag{7}$$

V_{oc}= voltage for open circuit
q = 1.6 × 10^{-19} magnitude of the electron charge
n = number of solar cells
K = 1.38 × 10^{-23} Boltzmann constant
T, T_0 = temperature under standard condition(K)
R_s = series resistance (ohm)
I_{sc} = short circuit current (A)
G, G_o = solar radiation (W/m^2)
α,β,γ = constant parameters for PV module

2.3. Cost model of hybrid solar-wind RO-MSF desalination system

Cost of the system consists of direct capital cost (CDM), indirect capital cost (CIDM), and operational and maintenance cost (COM). Eq. (8) explains the costs of a hybrid solar-wind RO-MSF desalination system [1–7, 10–15, 18, 19–23].

Cost (System) = Cost (Wind) + Cost (Solar) + Cost (Battery) + Cost (RO) + Cost (MSF)

The total annual cost of the hybrid power system for a set of solar PV, wind, and battery capacities is calculated by summing the individual costs. Eq. (9) regards wind turbines, solar panels, and batteries [1].

$$\begin{aligned} Annual\ C_{total}(Energy\ system) = {} & C_{solar\ panel} \times \left[ACC_{solar\ panel} + OMC_{solar\ panel}\right] \\ & + C_{wind\ Turbine} \times \left[ACC_{wind\ turbine} + OMC_{wind\ turbine}\right] \\ & + C_{battery} \times \left[ACC_{battery} + OMC_{battery}\right] \end{aligned} \tag{9}$$

C = capacity factor
OMC = operation and maintenance cost
ACC = annual capital cost

Annual capital cost is shown in Eq. (10).

$$ACC = CC \times CRF \tag{10}$$

CC = capital cost
CRF = capital recovery factor

The desalinated water cost of a hybrid RO-MSF system equals the sum of annual RO and MSF costs and their annual maintenance and repair costs. Eq. (11) explains the annual cost of the desalination system [19, 24].

Annual Cost $_{total}$ = Direct Capital Cost + Indirect Capital Cost + Operation and Maintenance Cost (11)

Eq. (12) is concerned with the MSF desalination system.

$$\text{Annual } C_{total}\ (MSF) = DCC(MSF) + ICC(MSF) + OMC(MSF) \tag{12}$$

Direct capital cost is calculated by Eq. (13).

$$DCC(MSF) = 0.0963 \times \psi \times \left(\frac{A_{total}}{M_d}\right)^{0.27} \tag{13}$$

ψ = 5000-9000

Indirect capital cost is shown in Eq. (14).

$$ICC(MSF) = 0.1\ DCC \tag{14}$$

Operational and maintenance cost is shown in Eq. (15). (8)

$$OMC(MSF) = C_{steam} + C_{che} + C_{power} + C_{spar} + C_{lab} \tag{15}$$

Cost of vaporing the sea water is shown in Eq. (16).

$$C_{steam} = 8000 \times M_s \times [\frac{T_s - 40}{85}] \times (0.00415) \quad (16)$$

Cost of chemical material is shown in Eq. (17).

$$C_{che} = 8000 \times \frac{M_f}{\rho_{rj}} \times 0.024 \quad (17)$$

Power cost is shown in Eq. (18).

$$C_{power} = 8000 \times \frac{M_d}{\rho_d} \times 0.109 \quad (18)$$

ρ_d = density of desalinated water (kg/m^3)

Brine disposal cost is shown in Eq. (19).

$$C_{spar} = 8000 \times \frac{M_d}{\rho_d} \times 0.082 \quad (19)$$

Labor cost is shown in Eq. (20).

$$C_{lab} = 8000 \times \frac{M_d}{\rho_d} \times 0.1 \quad (20)$$

Eq. (21) shows RO plant annual cost.

$$\text{Annual } C_{total}\ (RO) = DCC(RO) + OMC(RO) \quad (21)$$

Direct capital cost is shown in Eq. (22).

$$DCC(RO) = 0.0963 \times \left[C_{mem} + C_{civil} \times R_{at}^{0.9} + C_{pump} \times R_{at}^{0.7}\right] \quad (22)$$

$R_{at} = 24\ F_p/(\rho_{cp} \times Q_{ref})$

RO membranecost is shown in Eq. (23).

$$C_{mem} = cost_{mem} \times \frac{A_{mem}}{A_{module}} \quad (23)$$

Civil cost is shown in Eq. (24).

$$C_{civil} = 2390 \times Q_{ref}^{0.8} \quad (24)$$

Pump cost is shown in Eq. (25).

$$C_{pump} = 0.0141 \times \frac{Q_{ref} \times P \times 101.32}{R_f} \quad (25)$$

2.4. Optimization of the solar-wind RO-MSF hybrid system

We calculated the mathematical and economical models and optimized them for a solar-wind RO-MSF desalination system. The mathematical model's inputs were weather conditions, design parameters for each RO-MSF system (with a fixed saltwater feed of 25 L/h), and desalination system energy demand (72 or 30 kWh/month). The mathematical model was based on Eqs. (1)–(4). The economic model was based on Eqs. (5)–(8), which represented the objective function of minimizing costs of energy (solar and wind) and desalinated water. We calculated the economic model and optimized it for solar panels, wind turbines, batteries, and RO and MSF desalination plants. The mathematical and economical models focused on performance, cost, and water and energy consumption. Additionally, these two models informed the design parameters and adjustments were made to meet energy demands at minimum cost. Finally, we conducted a sensitivity analysis on these two models to achieve minimum water cost for a given energy cost.

For sizing the system, the objective functions were Eqs. (5)–(8) and the saturation terms were Eqs. (26) and (27). In Eq. (26), X is the number of 250-watt solar panels and 200-watt wind turbines, and C represents capacities of solar panels (250 W/h) and wind turbines (200 W/h), and RO and MSF desalinated water production.

$$P\ (wind) + P\ (solar) \geq 2400\ (watt) \quad (26)$$

$$X_{wind} \times C_{wind} \times 24 + X_{solar\ panel} \times C_{solar\ panel} \times 24 \geq 2400$$

$$C\ (RO) + C\ (MSF) \geq 60\ (lit/h) \quad (27)$$

2.5. Manufacturing process of hybrid solar-wind RO-MSF system

2.5.1. MSF manufacturing process

We calculated MSF plant dimensions to manage 25 L of salty water. MSF heat transfer is calculated using Eqs. (28)–(31), which are listed in Table 2. In these equations, ΔT is difference between temperatures of two stages in MSF and was equal to 2.5 Celsius degrees,; ΔT_{loss} represents thermodynamic loss, which is the temperature difference of the brine leaving the stage and the condensation temperature of the vapor, and was 2 Celsius degrees; TTDc is the temperature difference of the condensing vapor and the seawater leaving the condenser and was equal 3 Celsius degrees; C_p is specific heat at a constant pressure for all liquid streams, brine, distillate, and seawater and is 4.18 kJ/kg °C; λ is the latent heat of evaporation, which equals 2256; and A is the heat transfer area. The subscripts j, c, cw, d, h, s, and f refer to heat rejection, condenser, intake seawater, distillate, brine heater, steam, and feed, respectively [19].

Table 2. MSF heat transfer equations

Term	Equation	No.
Vapor mass flow	$M_s = M_f C_p (\Delta T + \Delta T_{loss} + TTD_c)/\lambda_s$	(28)
Condenser heat transfer	$M_s \lambda_s = UA_h (LMTD)_h$	(29)
Condenser heat recovery heat transfer	$M_r C_p \Delta T_{st} = UA_c (LMTD)_c$	(30)
Condenser heat rejection heat transfer	$(M_f + M_{cw}) C_p \Delta T_j = UA_j (LMTD)_j$	(31)

From Eqs. 1–4, we calculated the MSF plant heating transfer area as:

$M_s = 8 \times 4.18\ (2.5+2+3)/2256 = 0.11$ kg/h = 0.0000305 kg/s

$A_h = 0.0000305 \times 2256/2 \times 13.26 = 0.0026$ m^2

$A_c = 0.0022 \times 4.18 \times 2.5/2 \times 3.315 = 0.00368$ m^2

$A_j = (0.0033 + 0.0022) \times 4.18 \times 3.33/2 \times 4.46 = 0.008669$ m^2

$A = A_h + 7A_c + 3A_j = 0.05$

A person requires between 2 and 3 L of drinking water per day, and in hot weather that can increase to up to 16 L of water per day [25]. Thus, a family of 4 or 5 would require 60 L per day. If a desalination system desalted only 10 percent of salty water, to achieve 60 L of fresh water per day (2.5 L per hour), the desalination system needs a feed of 25 L per hour. From this, we determined that the MSF system dimensions should be 50×40×100 cm. We calculated condenser pipe diameter and desalted water tray dimensions of 30 cm and 110 cm, respectively. Table 3 shows the recommended combinations of properties depending on a saltwater input of 25 L/h.

Table 3. Solar-wind RO-MSF desalination system parameters

Plant properties	Quantities
Entrance sea water	25 lit/h
Rejection of MSF condenser area	86.69 cm^2
Heat recovery of MSF condenser	36.86 cm^2
Heat transfer area of MSF heat recovery	26.22 cm^2

We drew AutoCAD maps to manufacture the MSF plant (Fig. 4). From this, we determined the required materials (4-mm galvanized iron and 8.3-inch copper tube). After performing all calculations, we constructed the framework, installed the fresh water tray and condenser, installed tubes and valves.

2.5.2. Solar panel structure manufacturing process

PV panels and small wind turbines are considered proper solutions for small applications in sunny and windy areas like Tehran. This is often the case for small rural areas or greenhouses in coastal regions. We calculated an energy demand for the plant of 679 W; therefore, we obtained three 250-watt solar panels with dimensions of 197×99 cm (Table 4).

Based on the dimensions of the panels, we determined the device's structure dimensions to be 500×100 cm. We then determined a 30 cm height for the PV structure to create a maximum angle of 45° and minimum angle of 0°. We then designed a diagram of the structure in AutoCAD (Fig. 5).

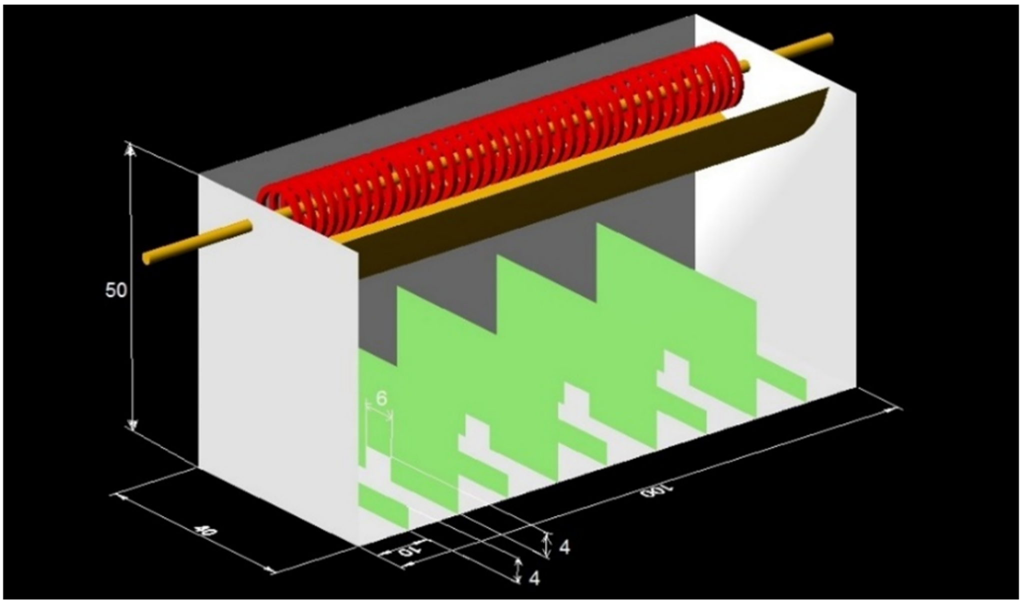


Fig. 4. MSF AutoCAD diagram

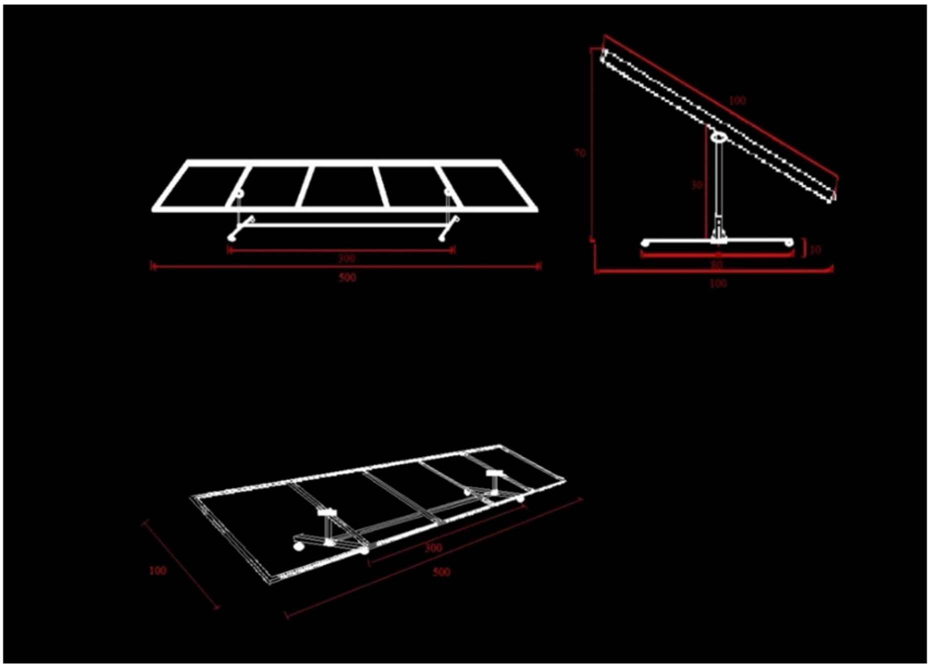


Fig. 5. Solar panel structure diagram

Table 4. Solar wind RO-MSF desalination system energy supply properties

Energy supply properties of solar-wind RO-MSF desalination system	Quantity
Power demand of system	679 W
Solar collector capacity	8 lit/h
Battery capacity	2 No., each 100Ah
Charge controller	30Ah
Solar panel capacity	3 No., each 250W
Wind turbine capacity	1 No., 200W

We then determined the structure's material components (corners, cans 40, cans 30, wheels, and bearings), and evaluated its strength and lifetime in ANSYS software. Table 5 shows the angle profile, maximum wind speed, panel weights, and ANSYS analysis results. From these calculations, we considered a 40 x 40 mm angle profile and assumed that this would be made of an isotropic and homogeneous material. Figures 6 and 7 show structural deformation and stress analysis in ANSYS software.

We analyzed panel structure for the weight loads and maximum wind speed shown in Table 5. The maximum stress on the structure shown in Fig. 6 was 102.5 Mpa, and the structure's maximum deformation was 2.43 mm, shown in red in Fig. 7. Maximum deformation of the structure, which was 2 mm in the middle of the structure and 4 mm on the side, occurred at a 30° angle.

Table 5. Angular characteristics, maximum wind speed specifications, panel weight, and results from analysis in ANSYS software

Analysis results	PV structure properties	Wind properties	40*40 cm angle iron properties
The maximum deformation was happened at 30 degrees of the panel structure The maximum wind force caused a 2 mm deformation in the middle of the panel and a 4 mm in deformation the side of the panel. The tension in the frame is much less than 350 MPa	Dynamic coefficient $\beta_E = 5$ Weight of modules: $W = 450$ N Area of Module $A = 5$ m^2	Wind Load = 20 m/s Wind load qs = (75/3.6)2×0.613Pa = 0.5 Kpa Pressure = 0.0005 Mpa	Minimum yield strength $F_y = 350$ Mpa Ultimate tension strength $F_u = 400$ Mpa Shear strength = 0.6 py Youngs modulus $E_{st} = 2e11$ Mpa Density = 7850 kg/m^3. Coefficient of thermal expansion α = 1.2e-5

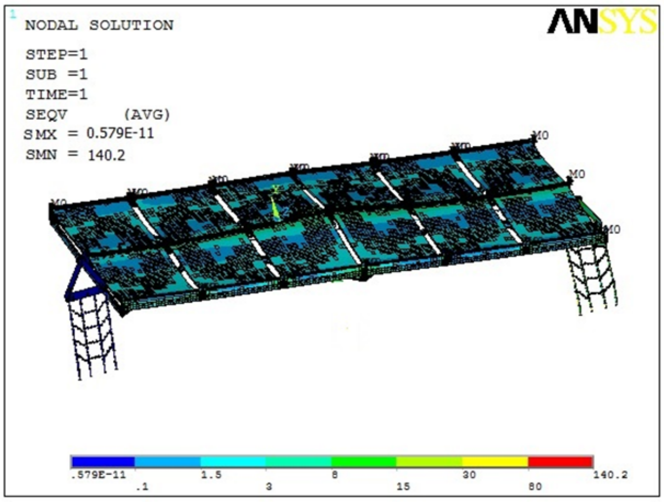


Fig. 6. Structural stress test results from ANSYS software

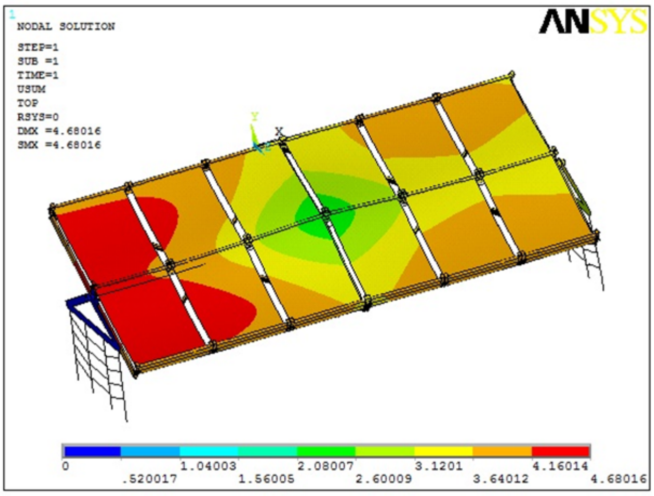


Fig. 7. Structural deformation test results from ANSYS software

We built the structure's main frame and reinforced it in the middle section. After that, we constructed the base of the frame and made two shafts for the turning structure with two bearings mounted on the shaft. Thus, the base was connected to the structure's main frame. To make the structure easy to carry, we attached four wheels to the base. The solar panel structure could adjust to different angles between 0° and 180° to accommodate different hours of the day and seasons of the year. Installing wheels makes the structure easy to carry and move. After manufacturing the structure, we installed the solar panels, connected them in parallel, and connected them to the charge controller and battery to meet the system's electrical.

2.5.3. Wind turbine manufacturing process

We expressed a three-blade wind turbine's diameter component as the diameter of a hypothetical circle traveling through the turbine blades. The blades create an aerodynamic wind force to generate torque. Wind turbine design consists mostly of designing the blades in terms of shape and dimensions. In this research, we used a 200-watt wind turbine generator, with blade length was calculated based on power needs. The turbine diameter was 126 cm and its height was 200 cm. The wind turbine's dimensions are shown in Table 6. Figure 8 shows a diagram of the wind turbine we prepared. We then determined the wind turbine (generator, aluminum sheet for the blades, base can, circular bearing for connecting the turbine to the base). First, we cut and planed the blades to predetermined dimensions, then we connected the blades to the generator using a rivet and mounted the generator on a crank of a specific length and dimensions to allow for ease of movement of the upper part of the turbine on the base. A bearing was used to connect the blade and generator to the base, giving the upper part of the turbine a the ability to rotate 360° with the slightest force being adjusted to rotate the blades in the direction the wind is blowing. Finally, we mounted the bearing at the equilibrium point. The base of the wind turbine made in this study is to be connected to the table to make the whole set a portable package. The last stage of wiring was to connect the generator's power, which was accompanied by installing a voltmeter display on the turbine base.

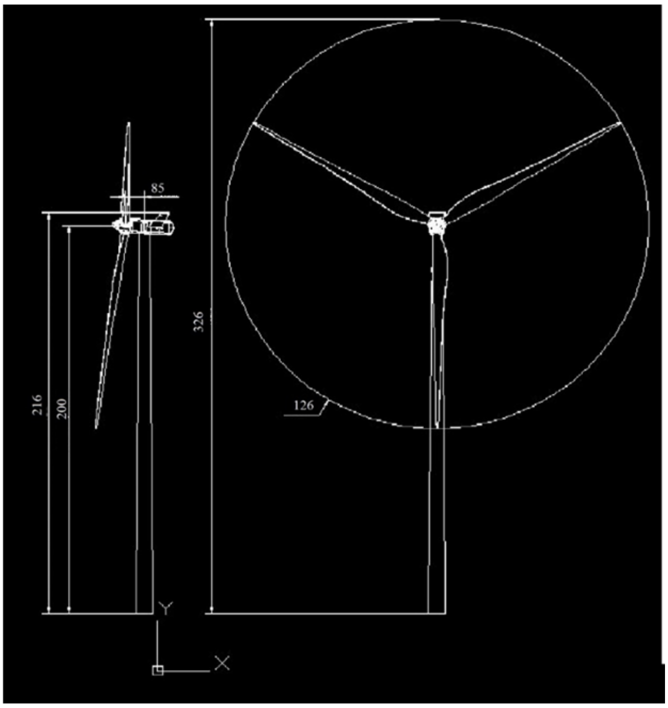


Fig. 8. Front and side view of the wind turbine

Based on Eq. (32) the wind turbine blade for a nominal wind speed was 63 cm and the power generated could be calculated for different wind speeds as below.

$$P\ (wind) = 1/8\ \xi\ \rho\ \pi\ d^2\ V^3 \qquad (32)$$

Table 6. Dimensional characteristics of designed wind turbine

Characteristics	Quantity
Rotor diameter	30 cm
Blades length	63 cm
Nominal power	200 watt
Nominal wind speed	8.6 m/s
Vane length	85 cm

3. Results and discussion

3.1. Solar-wind RO-MSF hybrid system modeling results

We modeled and optimized the parameters [18], which are shown in Table 7. Figure 9 shows the completed hybrid solar-wind RO-MSF desalination system, with a solar concentrator used as a seawater collector. Seawater temperature can increase to 100°C and enter the MSF. We manufactured one RO system and a 10-stage MSF system (dimension 86.69×36.86×26.22 cm). We used two 100 Ah solar batteries, three 250 W solar panels, one 200 W wind turbine, and a 30 Ah charge controller to supply the hybrid system's energy demand.

Table 7. Optimized parameters of the hybrid solar-wind RO-MSF model [18]

Parameters	Hybrid solar-wind RO-MSF
Feed (salty) water (L/h)	25
Brine water (L/h)	22.3
Brine water Temperature (°C)	55
Brine water Salinity(ppm)	45037
Desalinated water (L/h)	2.7
Desalted water cost	1.35

Helal and colleagues determined a desalinated water cost of 0.751.10$/m^3 for fossil fuel hybrid RO-MSF models [8, 9]. Karaghouli and colleagues estimated a solar MSF cost of 2.84 $/m^3 and a solar RO cost of 12.05 $/m^3 [7].

In this study, we measured voltage and current using a multimeter. Figure 10 shows wind turbine power production and production power regression at different wind speeds. Equation (33) shows the regression of wind turbine power produced by approximation ($R^2 = 0.99$), with V representing wind speed.

$$y = 0.361V^3 - 0.4123V^2 + 0.8926V \qquad (33)$$

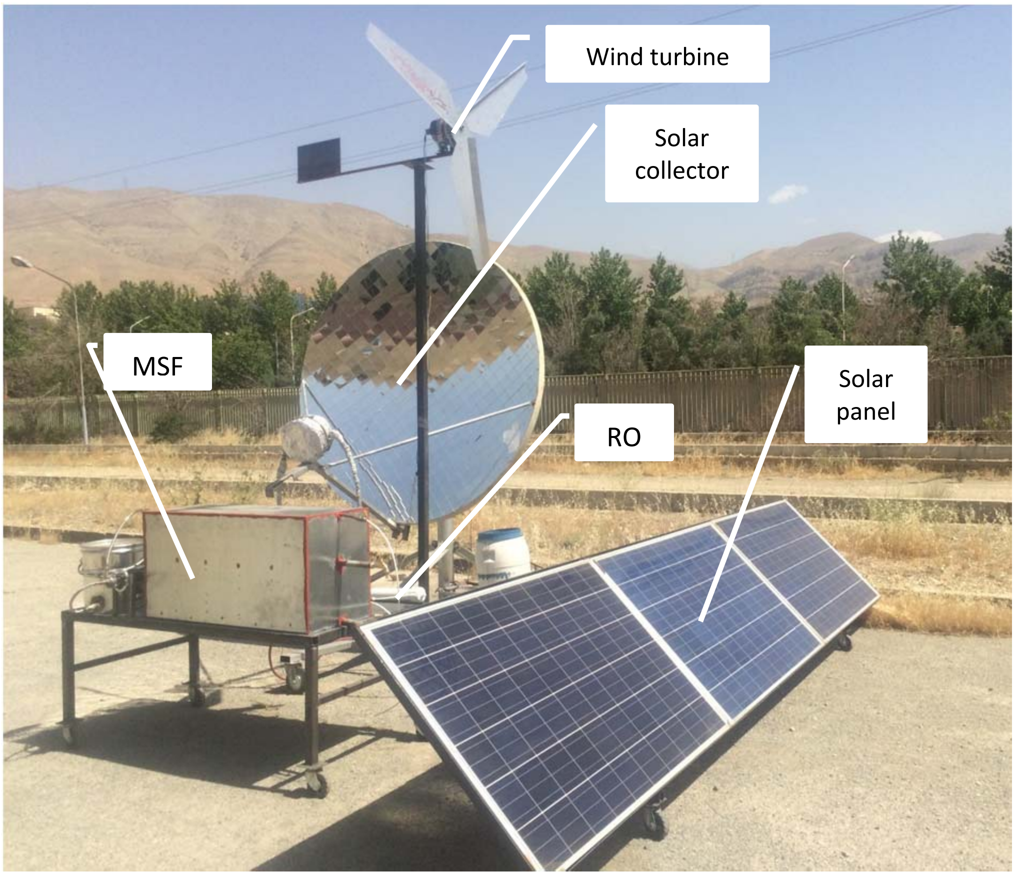
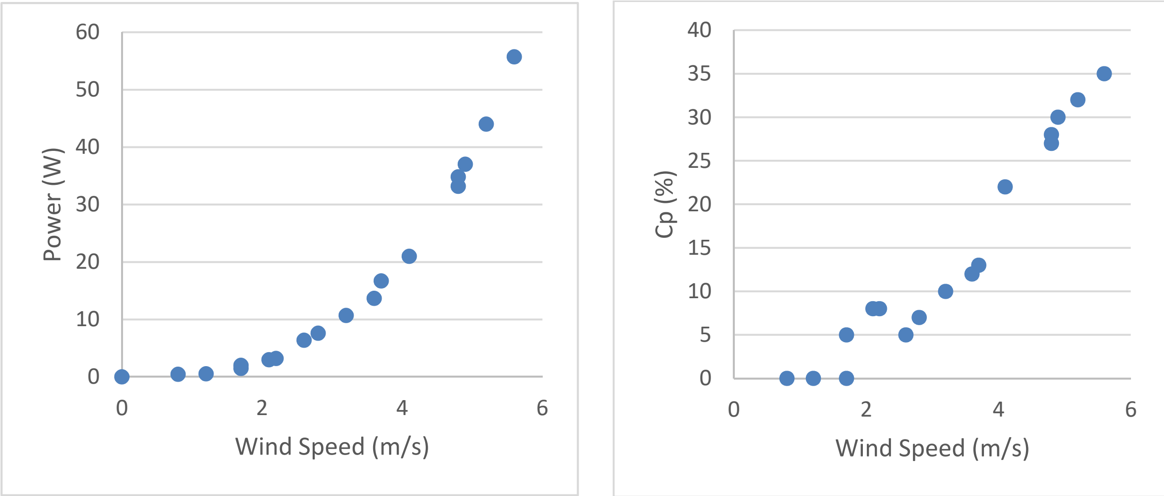


Fig. 9. Completed hybrid solar-wind RO-MSF desalination system [18]



(a) (b)

Fig. 10. Wind turbine power (a) and yield (b) for different wind speeds

3.2. Evaluating hybrid solar-wind RO-MSF desalination system performance

Energy efficiency and clean energy use has increasingly become a new area of discussion in the energy field [25]. To evaluate the developed model's performance, we conducted procedural and experimental analyses. We measured water quality and temperature using a TDS meter (Lutron Company Model WA2017 SD). This instrument can measure TDS, pH, EC, dissolved oxygen (Do), and temperature.

Water with five different salinity levels was input into the hybrid solar-wind RO-MSF desalination system, and we measured the quantity (L), temperature, TDS (ppm), EC (ɲs/cm), and pH of desalted water produced by the hybrid solar-wind RO-MSF desalination system. Table 11 shows the water properties of both feed water and desalted water. A water salinity level of 5 was equal to the salinity of sea water.

As shown in Table 8, as TDS and salinity in water increased, the quantity and qualities of RO desalted water decreased (both desalted and brine water contain more salt). These results demonstrate that with higher water salinity, RO feed water should be decreased and MSF feed should be increased. This is because MSF efficiency and desalted water quality are not sensitive to feed water salt unlike RO efficiency. The replacement cost of RO membranes also increases with an increase in feed water salinity.

Table 9 shows differences between outputs and experimental measured values (Level 5). As shown, there is very good agreement between measured values and model data.

Table 8. Test results of hybrid solar-wind RO-MSF desalination

Level 1 (525 ppm salinity)					
Parameters	Quantity (L)	Temperature (˚C)	TDS (ppm)	EC (ɲs/cm)	pH
Feed water	25	75.86	525	820.31	7.07
Brine water	15.4	54.56	544	850	7.025
Desalinated water	9.5	47.6	133.22	208.16	7
Level 2 (3500 ppm salinity)					
Feed water	25	74.33	3500	5468.75	7.85
Brine water	17.5	53.11	4287	6698.43	7.95
Desalinated water	7.4	44.08	199.36	311.50	7.45
Level 3 (11000) ppm salinity)					
Feed water	25	74.33	11000	17187.5	7.95
Brine water	19.1	52.17	12971	20267.18	8.2
Desalinated water	5.8	44.11	276.53	432.08	7.55
Level 4 (25000 ppm salinity)					
Feed water	25	74.16	25000	39062.5	8.48
Brine water	21.9	50.72	28124	43943.75	8.4
Desalinated water	3	44.02	280.47	438.24	7.55
Level 5 (40000 ppm salinity)					
Feed water	25	73.93	40000	62500	8.18
Brine water	22.4	50.99	43306	67665.62	8.3
Desalinated water	2.5	44.24	309.39	483.43	7.5

Five levels of saline water, brine water, and desalinated water salinity are compared in Fig. 11. As shown, with increased feed water salinity, MSF, RO, and MSF-RO fresh water production decreases. Additionally, the proportion of MSF feed water is increased and RO feed water is decreased to produce high quality desalinated water. RO efficiency decreases with increased salinity RO membrane lifetime will increase and repair and maintenance costs will be reduced. The reduction in MSF efficiency is much lower than RO; therefore MSF brine water is reduced and RO brine water is increased. The MSF desalinated water salinity is always constant (zero) and the salinity of the desalinated water produced from the RO is increased, thus the salinity of the desalinated water produced by the system is also increased.

The test results shown in Table 9 and Fig. 11 show that an increase in feed water salinity yields decreased quality and quantity of desalinated water. Iran's drinking water standard calls for a TDS amount of 1500 ppm, thus, desalinated water production from all levels of feed water salinity is considered drinkable. Additionally, brine water and desalinated water of all salinity levels have appropriate pH. Figure 12 shows a comparison of qualitative parameters obtained from test results with those from model results.

Table 9. Evaluating hybrid solar-wind RO-MSF performance

Parameters	Modeling outputs	Measured values	Difference values	Different percentage
Feed (salty) water (L/h)	25	25	0	0%
Brine water (L/h)	22.2	22.4	0.2	0.9%
Brine water temperature(°C)	55	51	4	7%
Brine water salinity(ppm)	43665	43306	359	0.8%
Desalinated water (L/h)	2.8	2.5	0.3	10%

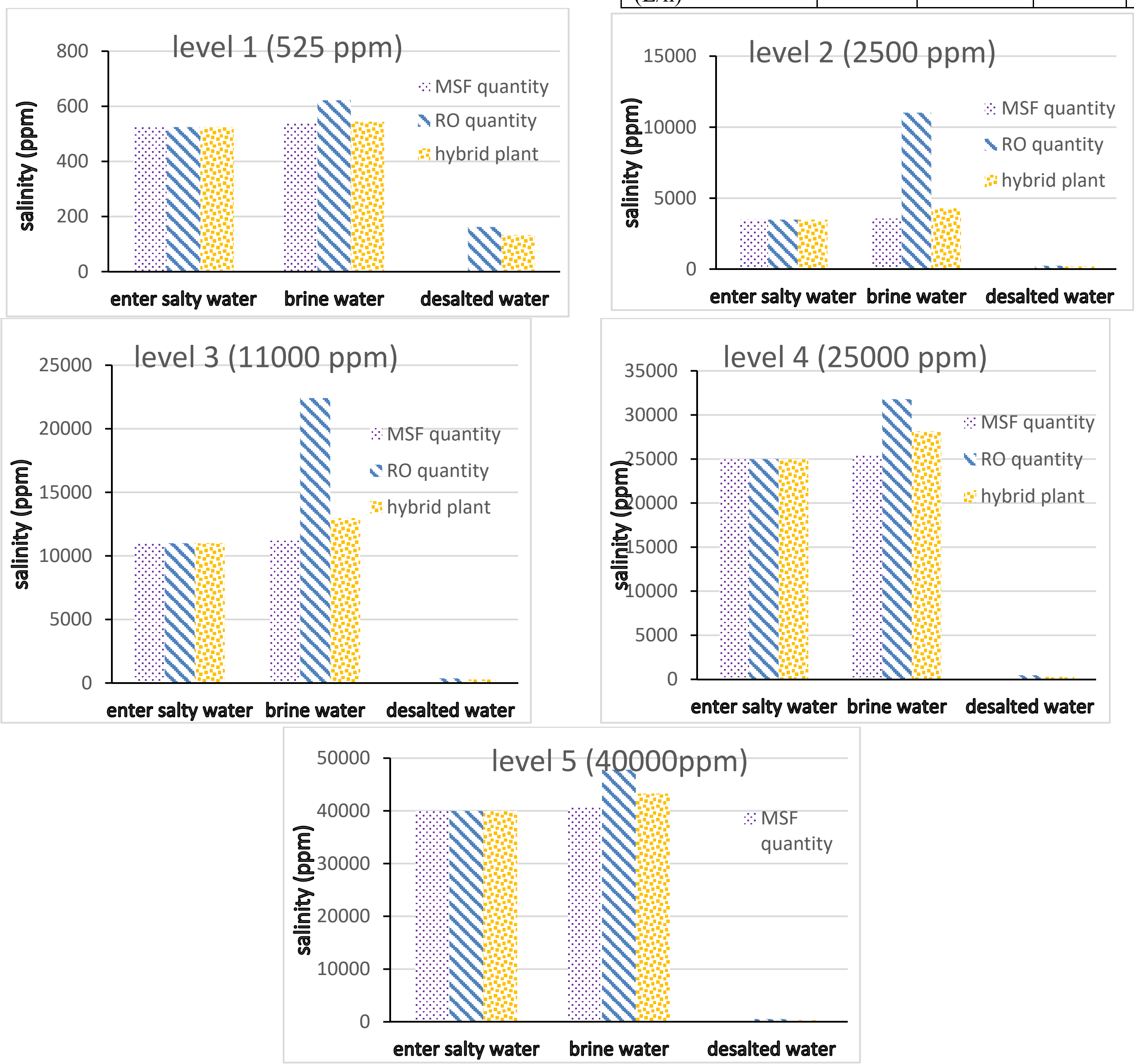


Fig. 11. Salinity of hybrid solar-wind RO-MSF desalination system test results.

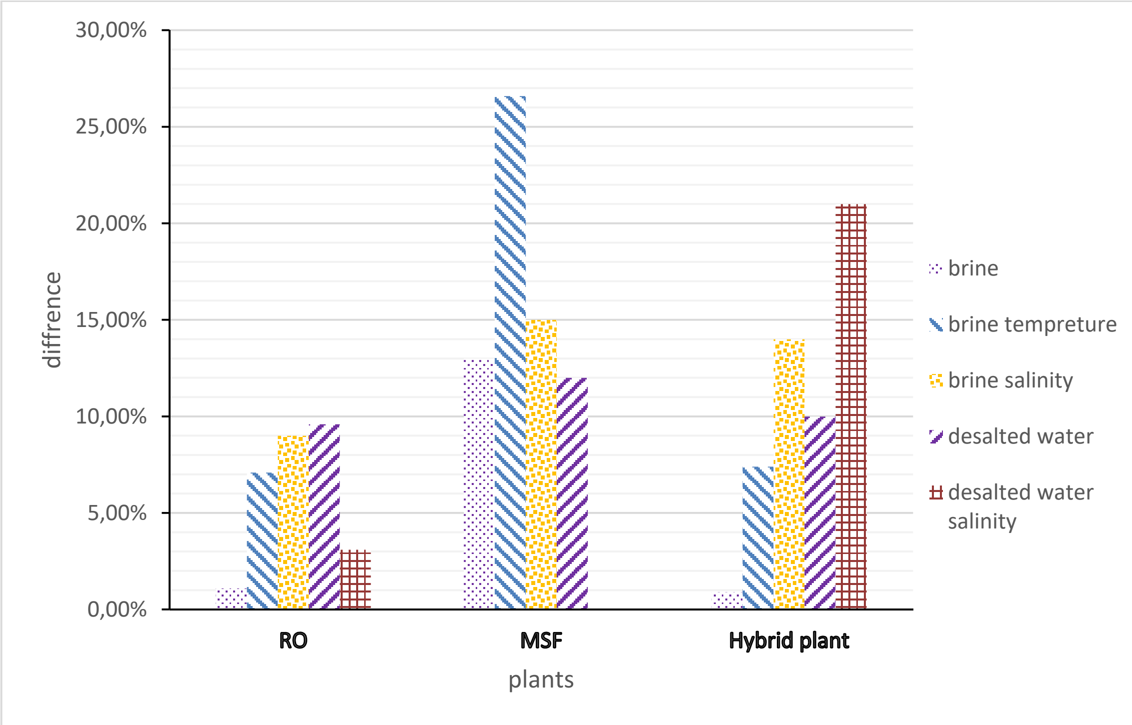


Fig. 12. Comparison of qualitative parameters obtained from test results with those from model results

To determine system efficiency and productivity, we investigated water recovery factors. We calculated the water recovery factor for 25 L per hour of feed water for RO, MSF, and RO-MSF systems of the solar-wind powered Integrated RO-MSF 1. Table 10 and Fig. 13 show RO, MSF, and RO-MSF water recovery factors of hybrid solar-wind RO-MSF test results and compare those values with model results of a solar-wind Integrated RO-MSF.

To compare the performance of a hybrid desalination plant with other research results, the production rate, recovery factor, energy consumption, and desalinated water cost are shown in Table 11.

Table 10. Water recovery factors of hybrid solar-wind RO-MSF

Salinity levels of entrance sea water	MSF recovery factor	RO recovery factor	System recovery factor
Level 1 (525 ppm salinity)	0.102	0.939	0.38
Level 2 (2500 ppm salinity)	0.096	0.698	0.296
Level 3 (11000 ppm salinity)	0.09	0.518	0.232
Level 4 (25000 ppm salinity)	0.072	0.216	0.12
Level 5 (40000 ppm salinity)	0.06	0.18	0.1
Model results (40000 ppm salinity)	0.137	0.25	0.112

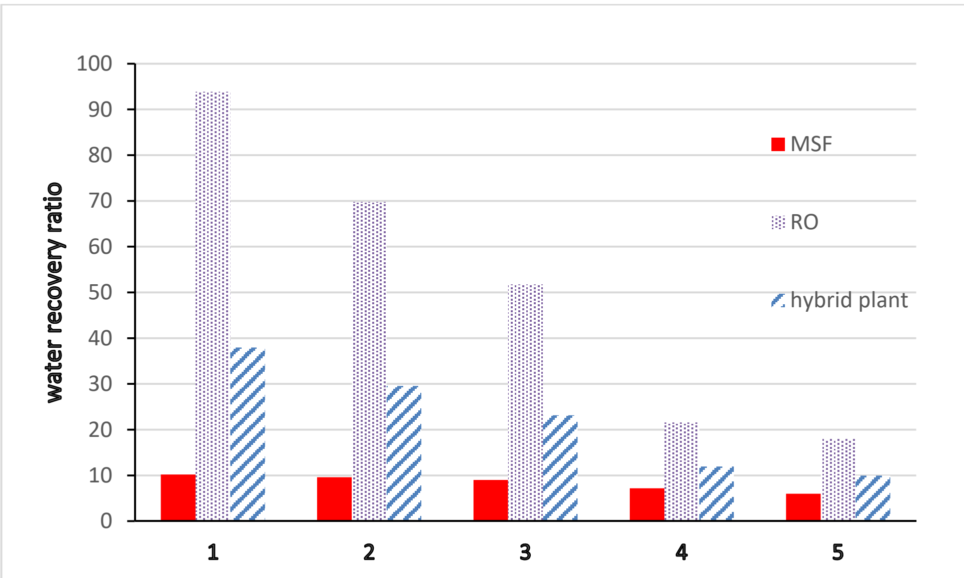


Fig. 13. Comparison of water recovery ratios at five salinity levels

Comparing the results of this study with those of other research shows very close performance and proximity of the RO-MSF hybrid system in this paper to those are designed solely for fossil fuel sources.

This research suggests that the hybridization of both RO and MSF and solar and wind power will increase productivity compared to individual RO, MSF, solar RO, or solar MSF systems, and reduce the cost of fresh water. The cost of desalinated water in this research was similar to that of a conventionally powered hybrid RO-MSF system, even though renewable sources are much more expensive than fossil fuels.

Table 11. Comparison of daily production rates, recovery factors, energy consumption, and desalinated water costs from other studies

Type	Desalinated water cost ($/m^3)	Energy consumption (Wh/m^3)	Recovery factor (%)	Production rate (m^3/day)	References
Solar MSF	2.84	electrical 2500–8000 thermal 50000–194000	0.4–6	0.009–10	[3,7,21,23]
MSF	0.77–1.85	8300–14600	3.5–4.5	50–200000	[22]
Solar RO	12.05	1500–6000	10-51	Less than 100	[7]
RO	0.55–2.37	5000	35–50	100–300000	[7]
RO-MSF	0.84–1.1	–	9.6	8.78	[8,9,22,26]

4. Conclusion

In this study, we modeled, manufactured, and evaluated a hybrid solar-wind RO-MSF desalination plant under weather conditions in Tehran, Iran, and compared the results of models and tests under actual conditions.

System sizing parameters based on an optimized model were presented in Tables 3, 4, 6, and 7. Hybridization of RO and MSF systems with wind and solar energy resources led to increased system reliability and flexibility and produced drinking water quality. Desalinated water cost was 1.35 $/m^3 in theory and 1.5 $/m^3 for actual conditions. Hybridization of wind, solar, RO, and MSF proved a better choice to minimize water cost rather than fossil fuel RO or MSF, wind RO, wind MSF, solar RO, solar MSF, or fossil fuel RO-MSF.

Hybridization of RO and MSF would result in better economics and operation characteristics than those corresponding to MSF. Water costs can be reduced by 23–26% compared to a sole MSF process, and the hybrid RO-MSF system produces much more desalinated water than MSF alone. The hybridization of RO and MSF reduced membrane costs compared to RO alone, and produced desalination water has a lower salinity than that from an RO plant solely. Additionally, hybridization of the solar-wind RO-MSF resulted in no air pollution and reduced costs of fuel, repairs, and operation as well as increasing the capital cost characteristics compared to those corresponding to fossil fuels. However, the water costs of this small-scale hybrid solar wind RO-MSF desalination system was about half that of a solar MSF noted in Al-Karaghouli et al. [7]. We explained the manufacturing process of a hybrid solar-wind RO-MSF desalination system in section 2.1. Tables 8 and 9 displayed test results, showing that increased TDS and salinity in feed water yielded reduced quality and quantity of RO desalinated water (i.e., the desalinated and brine water contained more salt). Test results showed that an increase in RO feed water salinity, the quantity of desalinated water decreased, but MSF desalinated water did not change much and MSF is not sensitive to feed water salinity. RO efficiency is decreased with increased feed water salinity, and membranes also need to be replaced more often. As shown in the test results in Tables 8 and 9, increased feed water salinity yields decreased desalinated water quality and quantity. Desalinated water produced from all five levels of feed water salinity are drinkable. The brine water and desalinated water pH levels are appropriate (7–7.5) for all salinity levels. Water recovery factors were displayed in Table 10. The water recovery factor for 25 L per hour of feed water were calculated for the RO, MSF, and RO-MSF systems of the hybrid solar-wind RO-MSF desalination system. The water recovery of the system in theory was 10% and under actual conditions it was 11%. There was very good agreement between measured results and those from model data. The test results of the manufactured hybrid solar-wind RO-MSF justified theory results.

Acknowledgment

This research was supported by Tarbiat Modares University. This support included the facilities for manufacturing the hybrid solar wind RO-MSF desalination system and relevant measurement instruments.

Symbols

A_{total} = sum of heat transfer area (m^2)
M_d = desalination rate (kg/h)
ρ_{rj} = density of brine water (kg/m^3)
A_{mod} = module surface (m^2)
R_f = water recovery ratio
P = pressure of pump (kpa)
ξ = efficiency of the wind turbine (in general less than 0.4 - or 40%)
ρ = density of air (kg/m^3)
A = wind turbine area perpendicular to the wind (m^2)
v = wind velocity (m/s)
π = 3.14....
d = wind mill diameter (m)
n = number of solar cells
ΔT_{loss} = thermodynamic losses
TTD_c = temperature difference between the condensing vapor and seawater leaving thei condeniser
C_p = specific heat at constant pressure
λ = latent heat of evaporation.

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Received: 30.06.2018