



Research Paper

EXERGY OF A HYBRID SOLAR-WIND REVERSE OSMOSIS-MSF DESALINATION SYSTEMB. Heidary¹, T. Tavakoli Hashjin^{1*}, B. Ghobadian¹, R. Roshandel²¹ Tarbiat Modares University, Tehran, Iran² Sharif University of Technology, Tehran, Iran**Abstract**

Abstract. A novel hybrid solar-wind reverse-osmosis (RO) multistage flash (MSF) distillation desalination system was manufactured and tested in actual conditions in Iran. Solar energy was used to provide both thermal and electrical power and wind energy was used to provide electrical power. Exergy analysis can be used to design more efficient energy systems by reducing inefficiencies, and indicates opportunities for improving performance in existing systems. The exergy involved in the hybrid solar-wind RO-MSF desalination system is analyzed below using data obtained from theoretical and experimental studies. The RO and MSF systems, powered by wind and solar energy, achieved increases in the reliability and flexibility of the system and in the quality of the resulting drinking water. According to the exergy analysis, the irreversible losses from the hybrid solar-wind RO-MSF plant are concentrated in the solar collector and the multistage flash chamber. These exergy losses can be reduced by isolating the collector, coating the pipes and MSF walls, selecting the parameters for the vapor compressor and RO membrane and pumps, and improving the flash process. By optimizing the performance of the hybrid solar-wind RO-MSF system, the amount of water recovery should increase, and the energy consumption should decrease, which should improve the overall efficiency of the system.

Key words: Hybrid Solar-Wind RO-MSF Desalination System, manufacturing, testing, desalinated Water, exergy analysis.

1. Introduction

Iran is facing a shortage of fresh water resources, and must also address environmental problems like air pollution in urban centers. Desalination of ocean water could serve as an alternative for freshwater supplies. The energy demands of existing desalination technologies for water production continue to limit practical applications [1, 2]. Production of potable water via desalination technologies driven by renewable energy systems could address the energy concerns that currently limit the application of desalination technology. Most electricity in Iran comes from non-renewable power plants. Renewable ener-

gy sources (solar, wind, geothermal, biomass, and low-impact hydro) can be used to produce electricity with less environmental impact [3]. Hybridization of solar energy and wind energy can reduce dependence on fossil-based fuels, increase system reliability, and operational efficiency, provide distributed generation in places that lack traditional large power generation plants, and can allow power generation at small scale stations like individual PV panels and micro wind turbines [4–6].

Iran has desirable climate conditions for solar and wind energy [5] and Iran also has access to seawater from the north and south.

Hybrid solar-wind RO-MSF desalination systems that use the two clean and renewable energy resources of solar and wind could be a sustainable source for potable water. The hybridization of solar and wind gen-

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eration could increase the sustainability and availability of a generation plant and improve efficiency.

Hybridization of the desalination processes of RO and MSF can improve upon the performance of MSF, reduce the MSF scale, reduce the cost of RO membrane replacement, and reduce the cost of desalinated water. The distillate water product from the MSF process can be blended with the RO permeate to yield suitable water quality and decrease the output temperature of the desalinated water. A single-stage RO process can be used, and the RO membrane life can be increased. Full integration of the RO and MSF plants allows better control of the feed water temperature to the RO plant by using the warm reject coolant water from the MSF heat rejection section. Low-pressure steam from the MSF membrane can be used to warm up the feed to the RO plant at low cost, which will improve RO efficiency [7].

Desalination is a very energy-intensive process. Exergy analysis can help to isolate and improve upon the equipment and parameters involved in the process. Lower thermodynamic efficiency means higher exergy losses from the system, so the analysis identifies the process components that have high exergy losses [8].

Other researchers have analyzed the exergy of MSF plants and RO plants under different operating conditions and with various design choices. This paper presents the results of modeling, optimization, manufacturing, and testing a hybrid solar-wind RO-MSF desalination plant and gives an exergy analysis of the plant. The exergy variation is verified using actual thermodynamic data about seawater entering the system and desalinated and brine water exiting the system.

The main contributions of the present paper are as follows:

1. Summary of the design and modeling results of a solar-wind RO-MSF desalination system.
2. Detailing the exergy analysis of a hybrid solar-wind RO-MSF desalination plant.
3. Making design recommendations that would reduce exergy losses.

2. Materials and Methods

In this paper, exergy calculations of a hybrid solar-wind RO-MSF desalination plant are performed based on actual test results of a hybrid solar-wind RO-MSF desalination plant.

First, the system was modeled with numerical methods. Then, the parameters were optimized through simulations. Finally, the plant was constructed and tested. The plant's electricity reserves can run the plant for 48 hours continually without solar radiation or wind. This desalination plant can be used for off-grid applications in remote areas at both small and large scale. The optimal parameters for minimize water production costs and maximize desalinated water production are presented and compared against experimental results below.

The hybrid solar-wind RO-MSF desalination system package consist of

1. MSF desalination plant (MSF base, vacuum pump, pressure pump, pipes, and taps),
2. RO desalination plant (RO membrane, pressure pumps, pipes),
3. Solar panels and supports,
4. Wind turbine and wind turbine base,
5. Solar collector,
6. Batteries.

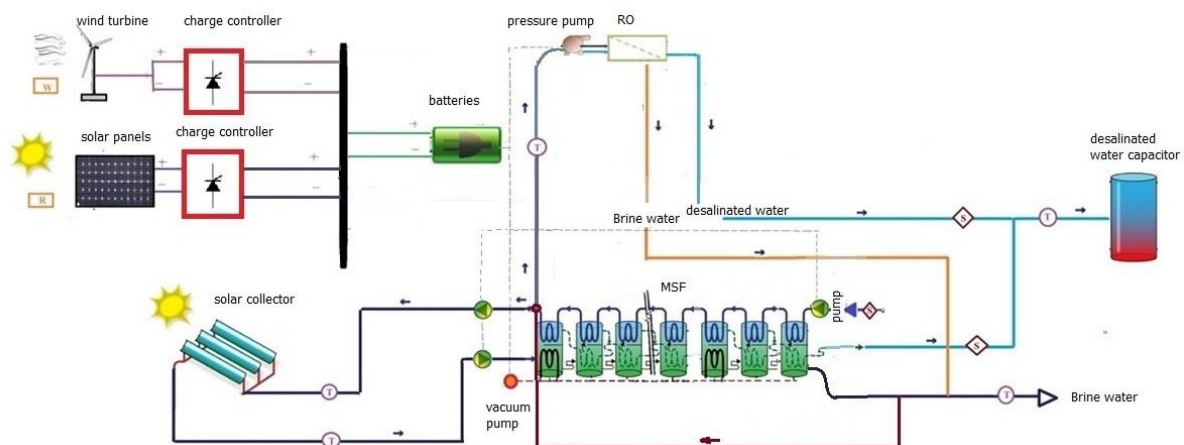


Fig. 1. Configuration of the hybrid solar-wind RO-MSF desalination system

Fig. 1 shows a schematic of the hybrid system with the desalination plant as the load. A brackish-water RO desalination plant is connected as the load to the hybrid power system. This plant produces drinking water when enough power is available to run the plant. The amount of water produced will increase up to the plant’s rated capacity if more power is available. Hence, the load can handle variations in power generation from the renewable sources with changes in the weather. The RO plant stores power indirectly in the form of desalinated water, thereby eliminating the need for expensive large-capacity batteries to make the installation of renewable generators economical. In this system, the seawater stream passes from the collector through the MSF module and the resulting brine is discarded after mixing with the RO brine. Then the condenser stream enters the RO, which increases the RO efficiency.

2.1. Modeling of hybrid RO-MSF

In the RO-MSF model, the heat-rejection MSF condenser liquid is used to feed the RO and this warm sea water increases the RO efficiency. A portion of the heat-rejection MSF condenser liquid is mixed with the RO and MSF brine and is then used as condenser liquid for the heat recovery part of the MSF, encouraging the recovery of consumed water and heat, which increases the overall system efficiency (Fig. 2).

The mass and energy balance equations are calculated with equations (1) to (4) in Table 1 [1–5, 9–21].

The hybrid solar-wind desalination system is designed to serve a small scale community in the Tehran region. The solar radiation, wind speed, and other climate parameters are recorded in the form of average monthly data from NASA’s website.

The proposed energy system consists of a wind turbine, solar panel, and solar collector. These sub-systems are connected to a charge controller and the

produced electricity is stored in batteries. The desalination pumps are driven with the electricity produced from solar panels and wind turbines (Fig. 3).

Table 1. Mass and energy balance of Integrated RO-MSF

| 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) |

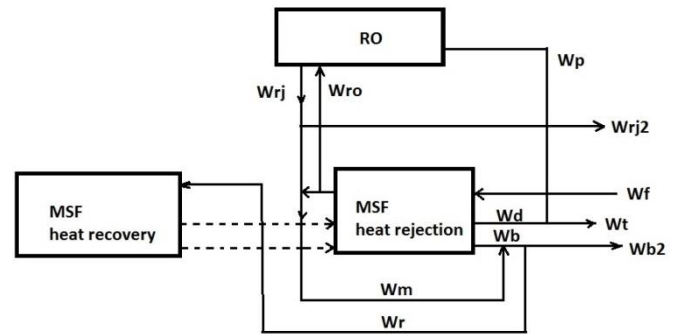


Fig. 2. Integrated RO-MSF Heat Recovery

2.2. Modeling of hybrid solar-wind energy system

The model solar and wind generators are optimized for performance and economy. The energy demand of the RO-MSF desalination system is 72 kWh/month for 24-hour operation. On a rainy or cloudy day, the desalination system could use only RO desalination, which needs less than 30 kWh/month.

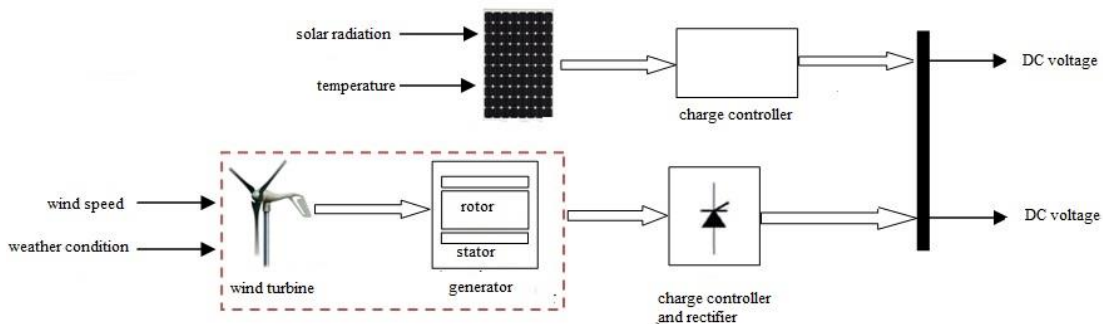


Fig. 3. The configuration of hybrid PV-Wind turbine power

The solar-wind model, as presented in Fig. 3, should always be able to meet the energy demand of the desalination system (72 or 30 kWh/month). The weather conditions, designed parameters of the RO and MSF modules and the energy demand of the desalination system are the inputs. The model is calculated according to equations (1) to (4). The three equations from (5) to (7) describe the power generated from wind turbine and solar panels [17], and serve as the objective function for minimizing the energy costs.

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

$$P(\text{wind}) = \frac{1}{2} AV^3 = \frac{1}{8} \varepsilon \rho \pi d^2 V^3 \quad (6)$$

ξ = efficiency of the windmill (in general less than 0.4 – or 40 %)

ρ = density of air (kg/m³)

A = wind mill area perpendicular to the wind (m²)

v = wind velocity (m/s)

d = wind mill diameter (m)

$$P(\text{solar}) = \frac{\frac{V_{oc}}{q.n.K.T} - \ln\left(\frac{V_{oc}}{q.n.K.T} + 0.72\right)}{\left(1 + \frac{V_{oc}}{q.n.K.T}\right)} \times \quad (7)$$

$$\times \left(1 - \frac{R_s}{V_{oc} \times I_{sc}}\right) I_{sco} \left(\frac{G}{G_0}\right)^\alpha \frac{V_{oc}}{1 + \beta \cdot \ln\left(\frac{G_0}{G}\right)}$$

V_{oc} = voltage for open circuit

$q = 1.6 \times 10^{-19}$ magnitude of the electron charge

n = number of solar cell

$K = 1.38 \times 10^{-23}$ Boltzmann constant

T, T_0 = temperature under standard condition (K)

R_s = series resistance (ohm)

I_{sc} = short circuit current (A)

G, G_0 = solar radiation (W/m²)

α, β, γ = constant parameters for PV module

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

The costs include direct capital cost (CDM), indirect capital cost (CIDM), and operational and maintenance cost (COM). Equation (8) describes the costs of a hybrid solar-wind RO-MSF desalination system [1–5, 9–21].

$$\text{Cost (System)} = \text{Cost (Wind)} + \text{Cost (Solar)} + \text{Cost (Battery)} + \text{Cost (RO)} + \text{Cost (MSF)} \quad (8)$$

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

$$\begin{aligned} \text{Annual } C_{\text{total}} (\text{Energy system}) &= \\ &= C_{\text{solar panel}} \times [\text{ACC}_{\text{solar panel}} + \text{OMC}_{\text{solar panel}}] + \\ &+ C_{\text{wind Turbine}} \times [\text{ACC}_{\text{wind turbine}} + \text{OMC}_{\text{wind turbine}}] + \\ &+ C_{\text{battery}} \times [\text{ACC}_{\text{battery}} + \text{OMC}_{\text{battery}}] \end{aligned} \quad (9)$$

C = capacity factor

OMC = operation and maintenance cost

ACC = annual capital cost

The annual capital cost is shown in equation (10).

$$\text{ACC} = \text{CC} \times \text{CRF} \quad (10)$$

CC = capital cost

CRF = capital recovery factor.

The desalinated water cost of the hybrid RO-MSF system is equal to the sum of the annual RO cost and MSF cost and their annual maintenance and repair costs. Equation (11) describes the annual cost of the desalination system [18].

$$\begin{aligned} \text{Annual Cost}_{\text{total}} &= \text{Direct Capital Cost} + \\ &+ \text{Indirect Capital Cost} + \text{Operation and} \\ &+ \text{Maintenance Cost} \end{aligned} \quad (11)$$

Equation (12) describes the individual costs of the desalination systems in the MSF module.

$$\begin{aligned} \text{Annual } C_{\text{total}} (\text{MSF}) &= \text{DCC}(\text{MSF}) + \\ &+ \text{ICC}(\text{MSF}) + \text{OMC}(\text{MSF}) \end{aligned} \quad (12)$$

Direct capital costs are calculated by equation (13).

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

The 0.0963 is the constant value in formula (13)

$\psi = 5000\text{--}9000$.

Indirect capital costs are given in equation (14).

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

Operational and maintenance costs are shown in equation (15).

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

The cost of evaporating the sea water is calculated by equation (16).

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

The cost of chemical materials is calculated by equation (17).

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

Power costs are given equation (18).

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

ρ_d = density of desalinated water (kg/m³)

Brine disposal costs are described by equation (19).

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

Labor costs are given in equation (20).

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

Equation (21) focuses on the RO module. Equation (21) describes the annual cost of the RO plant.

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

Direct capital costs are given in equation (22).

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

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

The cost of the RO membrane is given in equation (23).

$$C_{mem} = \text{cost}_{mem} \times \frac{A_{mem}}{A_{module}} \quad (23)$$

Civil costs are shown in equation (24).

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

Pump costs are shown in equation (25).

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

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

The mathematical and economical models were calculated and optimized for the solar-wind RO-MSF desalination system. Mathematical models were considered and the inputs were weather conditions, design parameters of each RO-MSF model

(with fixed feed rate of 25 L/h of salty water) and the energy demand of desalination system (72 or 30 kWh/month). The models were simulated according to equation (1) to (4). The equations from (5) to (8) represent the objective function to minimize the energy cost (solar and wind cost) and desalinated water cost. The economic models were then calculated and optimized for each of the five components of solar panels, wind turbine, batteries, RO, and MSF desalination plants. The mathematical and economical models address performance, cost, and consumption of water and energy. These two models were optimized to meet the energy demands with minimum cost. Finally, sensitivity analysis was used to minimize water costs by minimizing energy costs.

To size the system, the objective functions were equations 5 to 8 and the saturation terms were equation 26 to 27. In these equations, X is the number of 250-watt solar panels and 200-watt wind turbines, and C is the capacity of solar panel (250 W/h), wind turbine (200 W/h), RO and MSF desalinated water production.

$$P(\text{wind}) + P(\text{solar}) \geq 2400(\text{watt})$$

$$X_{wind} \times C_{wind} \times 24 + X_{solar\ panel} \times C_{solar\ panel} \times 24 \geq 2400 \quad (26)$$

$$C(\text{RO}) + C(\text{MSF}) \geq 60(\text{L/h}) \quad (27)$$

2.5. Sizing of Solar-wind RO-MSF desalination system based on modeling and optimization

The MSF plant dimensions were calculated for 25-liter input of salty water. The dimensions of MSF were determined as 50 × 40 × 100 cm². The condenser-pipe diameter and desalinated water tray dimensions were determined to be 30 cm and 110 cm, respectively. 10 MSF stages were deemed appropriate. Table 2 give the properties of recommended combinations that process the 25 L/h salty water input by the sizing code [17].

The best hybrid solar-wind RO-MSF system parameters (in terms of water quantity and temperature and salinity and produced water) are listed in Table 3. The desalinated water production cost was calculated for each proposed hybrid solar-wind RO-MSF desalination system. The economic parameters (capital cost and operation and maintenance cost) were calculated and the resulting desalinated water cost was \$1.35/m³.

Helal et al. found that the price of desalinated water powered by fossil fuels was \$0.75–\$1.10/m³ for fossil-fuel hybrid RO-MSF models [10, 22]. Karaghoulis et al. found that the price of solar MSF was about \$2.84/m³ and solar RO was about \$12.05/m³ [11].

Table 2. Optimized parameters of Solar-wind RO-MSF desalination system [17]

| Plant properties | Quantities |
|---|-----------------------|
| Input rate for sea water | 25 L/h |
| Brine water from system | 19.27 L/h |
| Brine water temperature | 44.8°C |
| Desalinated water output | 2.5 L/h |
| Desalinated water temperature | 48.2°C |
| Saline water input to MSF | 16.6 L/h |
| Saline Water input to RO | 8.3 L/h |
| Number of RO stages | 1 |
| Number of MSF stages | 10 |
| Heat rejection area of MSF condenser | 86.69 cm ² |
| Heat recovery area of MSF condenser | 36.86 cm ² |
| Heat transfer area of MSF heat recovery | 26.22 cm ² |
| Maximum pipe temperature | 100°C |

2.6. Test results of hybrid solar-wind RO-MSF desalination system

To evaluating the performance of the developed model, experimental analysis was conducted. The water quality and temperature were measured with a TDS meter from the Lutron Company (model WA2017 SD). This measurement instrument can measure TDS, pH, EC, Do, and temperature. Fig. 4 shows the manufactured hybrid solar-wind RO-MSF desalination system. A solar concentrator was used

as the seawater collector. The seawater temperature can reach 100 °C before entering the MSF. One RO stage and 10 stages of MSF (dimension 86.69×36.86×26.22 cm²) were manufactured. Two batteries with 100Ah capacity, three 250-W solar panel, one 200-W wind turbine, and a 30-Ah charge controller were used to supply the energy demand of hybrid system.

Table 3. Optimized parameters of solar-wind RO-MSF models [17]

| models | Hybrid solar wind RO-MSF |
|---|--------------------------|
| Feed (salty) water (L/h) | 25 |
| Brine water (L/h) | 22.2 |
| Brine water temperature (°c) | 55 |
| Brine water salinity(ppm) | 43665 |
| desalinated water (L/h) | 2.8 |
| Desalinated Water Cost (\$/m ³) | 1.35 |

Salty water with five different levels of salinity was input to the hybrid solar-wind RO-MSF desalination system and the quantity (*L*), temperature, TDS (ppm), EC (µs/cm) and PH of the output desalinated water were measured. Table 4 shows the water properties of the input water and the desalinated water. The level-5 water salinity was equal to sea-water salinity.

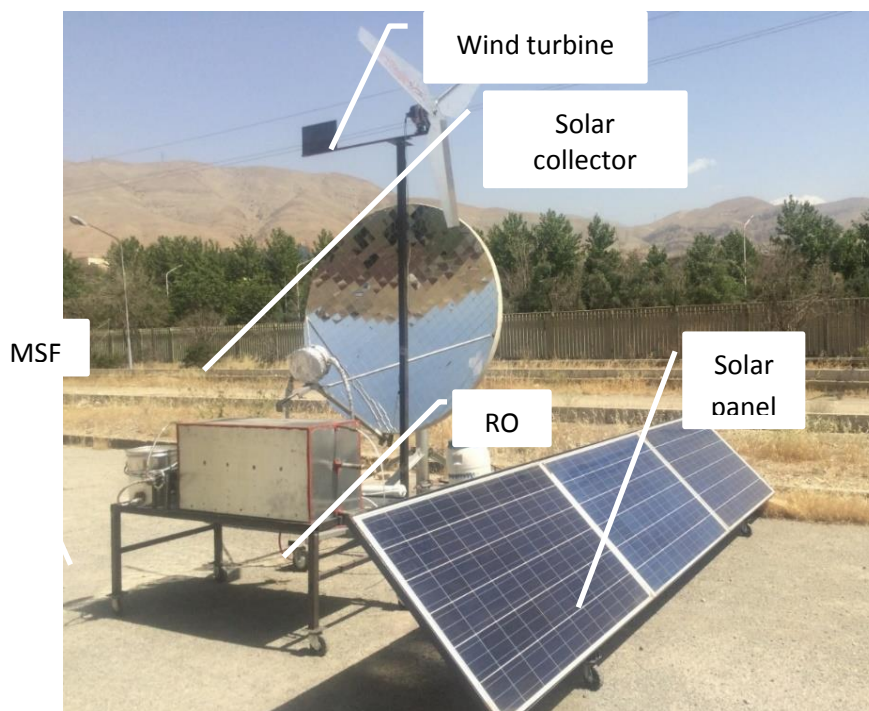
**Fig. 4.** Prototype hybrid solar-wind RO-MSF desalination system [17]

Table 4. Test results of the hybrid solar-wind RO-MSF desalination system

| Level 1 (525 ppm salinity) | | | | | |
|-------------------------------|--------------|-----------------|-----------|------------|-------|
| parameters | quantity (L) | temperature(°C) | TDS (ppm) | EC (µs/cm) | pH |
| input salty water | 25 | 75.5 | 525 | 820.3125 | 7.07 |
| brine water | 16.6 | 54.5 | 544 | 850 | 7.025 |
| desalinated water | 8.3 | 47.6 | 487 | 760.9375 | 7 |
| Level 2 (3500 ppm salinity) | | | | | |
| input salty water | 25 | 74 | 3500 | 5468.75 | 7.85 |
| brine water | 18.85 | 53 | 4287 | 6698.4375 | 7.95 |
| desalinated water | 6.15 | 43 | 1030 | 1609.375 | 7.45 |
| Level 3 (11000) ppm salinity) | | | | | |
| input salty water | 25 | 74 | 11000 | 17187.5 | 7.95 |
| brine water | 20.4 | 52 | 12971 | 20267.1875 | 8.2 |
| desalinated water | 4.6 | 43.2 | 2019 | 3154.6875 | 7.55 |
| Level 4 (25000 ppm salinity) | | | | | |
| input salty water | 25 | 73.8 | 25000 | 39062.5 | 8.48 |
| brine water | 21.72 | 51 | 28124 | 43943.75 | 8.4 |
| desalinated water | 3.28 | 42.8 | 3549 | 5545.3125 | 7.55 |
| Level 5 (40000 ppm salinity) | | | | | |
| input salty water | 25 | 73.6 | 40000 | 62500 | 8.18 |
| brine water | 22.25 | 51.3 | 43306 | 67665.625 | 8.3 |
| desalinated water | 2.5 | 42.3 | 4143.832 | 6474.7375 | 7.5 |

Table 5. Evaluating the performance of a hybrid solar-wind RO-MSF

| Parameters | Modeling outputs | Measured values | Difference values | Different percentage |
|-----------------------------|------------------|-----------------|-------------------|----------------------|
| Feed (salty) water (L/h) | 25 | 25 | 0 | 0% |
| Brine water (L/h) | 22.2 | 22.25 | 0.05 | 0.02% |
| Brine water temperature(°C) | 55 | 51.3 | 3.7 | 6.7% |
| Brine water salinity(ppm) | 43665 | 43306 | 359 | 0.8% |
| desalinated water (L/h) | 2.8 | 2.5 | 0.3 | 10% |

As it can be seen in Table 5, with an increase in TDS and salinity, the quantity and quality of RO desalinated water decrease; i.e., the desalinated and brine water is more saline. These results show that with higher-salinity input water to the system, less

water should be directed to the RO module and more should be directed to the MSF module, since the MSF process is not sensitive to salinity but salinity both reduces the efficiency of the RO process and leads to more-frequent replacement of the RO membrane.

Table 4 shows the difference between the outputs and experimental measured values (level 5 of experiments). As one can see, the measured and modeled data agree very well.

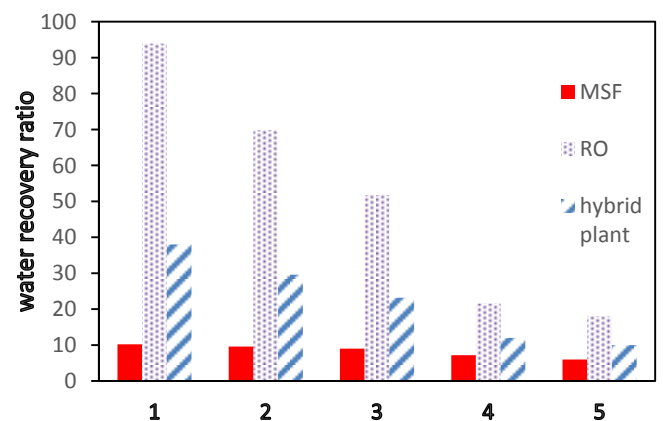
**Fig. 5.** Comparison of water recovery ratio at five levels of input salinity [17]

Table 6. Comparison of daily production rates, recovery factor, energy consumption, and desalinated water prices collected from the literature

| Type | Desalinated water price (\$/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 | [9, 11–14] |
| MSF | 0.77–1.85 | 8300–14600 | 3.5–4.5 | 50–200000 | [1] |
| Solar RO | 12.05 | 1500–6000 | 10–51 | Less than 100 | [9] |
| RO | 0.55–2.37 | 5000 | 35–50 | 100–300000 | [12] |
| RO-MSF | 0.84–1.1 | - | 9.6 | 8.78 | [1, 10,15,22] |

To determine the efficiency and productivity of the system, water-recovery factors were measured. The water-recovery factor for 25 L/hour of input sea water were calculated for the RO, MSF, and RO-MSF systems of the hybrid solar wind RO-MSF. Fig. 5 shows the RO, MSF, and RO-MSF water-recovery factors.

To compare the performance of hybrid desalination plant with results in the literature, the production rate, recovery factor, energy consumption, and price of desalinated water is shown in Table 6.

2.7. Exergy

Exergy is defined as the maximum amount useful work that can be extracted when a system is moved to equilibrium from the initial state to the environmental (dead) state. Determining exergy is the main goal of thermodynamics [23]. Exergy is conserved only when all processes of the system and the environment are reversible. Exergy is destroyed whenever an irreversible process occurs. Exergy analysis can reveal whether and the extent to which an energy system can be made more efficient by modifying existing components [24]. Exergy destruction represents the exergy destroyed due to irreversibility within a system. Irreversible processes include chemical reactions, heat transfer through a finite temperature difference, mixing of matter, unrestrained expansion, and friction.

The exergy equilibrium involves thermal, mechanical, and chemical components. These equilibriums can be achieved when the temperature (T), pres-

sure (p) and concentration (W) of the system matches the ambient values (T_0, P_0, W_0). The thermomechanical exergy is the maximum work obtained when the temperature and pressure of the system changes to the environment temperature and pressure and the concentration remains constant. The chemical exergy is the maximum work obtained when the concentration of substances in the system changes to the concentrations in the environment at the environment's pressure and temperature [25].

Exergy of a control mass (closed system) is expressed as [25]:

$$e = (u - u^*) + p_0(v - v^*) - T_0(s - s^*) + \sum_{i=1}^n x_i(\mu_i^* - \mu_i^0) \tag{28}$$

Where $u, v, s, x,$ and μ are the specific internal energy, specific volume, specific entropy, mass fraction, and chemical potential, respectively. In equation 1, * indicates a parameter at the same concentration as the initial state and at the temperature and pressure of the environment.

Flow exergy of a control volume (open system) is expressed as [25]:

$$ef = e + v(p - p_0) \tag{29}$$

Since $h = u + pv$, and substituting this into equation 1, the flow exergy can be rewritten as [25]:

$$e = (h - h^*) - T_0(s - s^*) + \sum_{i=1}^n (\mu_i^* - \mu_i^0) \tag{30}$$

The actual energy consumption of a desalination system is much greater compared to the theoretical energy consumption because of irreversible losses. The first step in the improvement process is diagnostics, and exergy analysis is a powerful diagnostic tool. Such an analysis is used when designing desalination processes to determine the sites of the highest irreversible losses (or exergy destruction) [25]. The exergy balance is

$$\text{Exergy Destruction} = \sum \text{Inlet Exergy} - \sum \text{Outlet Exergy} \quad (31)$$

The overall plant exergy efficiency is defined as the ratio of the minimum required separation work to the total input exergy [25, 26]. The total input exergy is the sum of the flow exergy for driving the MSF pump, pressurizing RO pump, and heating the stream by the collector.

$$\eta = \frac{W_{\min}}{E_{\text{input}}} \quad (32)$$

The fraction of exergy destruction in each process is determined by dividing the exergy destruction of each component by the total exergy destruction in the plant [20, 21].

3. Results and discussion

3.1. Exergy analysis

Exergy analysis was applied to the hybrid solar-wind RO-MSF described above. Fig.6 diagrams the hybrid solar-wind RO-MSF. The capacity of this system is 25 L/h or 600 L/day, and the power production is 950 Wh in typical conditions. The plant was tested in Tehran, Iran, at Tarbiat Modares University. The MSF plant includes of 10 units with capacity of 16.6 L/h and the RO plant consists of 1 unit with capacity of 8.3 L/h. The salt concentration of input seawater was 40000 ppm at 25 °C and at atmospheric pressure (101.325 kPa). The collector heats the seawater to the boiling point.

The exergy analysis results are given in Table 7. The numbered stream properties listed in Table 7 are labeled in Fig. 6. In the exergy analysis in this research, the dead state (equilibrium with environment) is selected at $P_0 = 101.325 \text{ kPa}$, $W_0 = 40000 \text{ ppm}$ and $T_0 = 25 \text{ °C}$, which matches the seawater intake parameters. The most exergy destruction occurs in the collector and in the MSF plant, respectively.

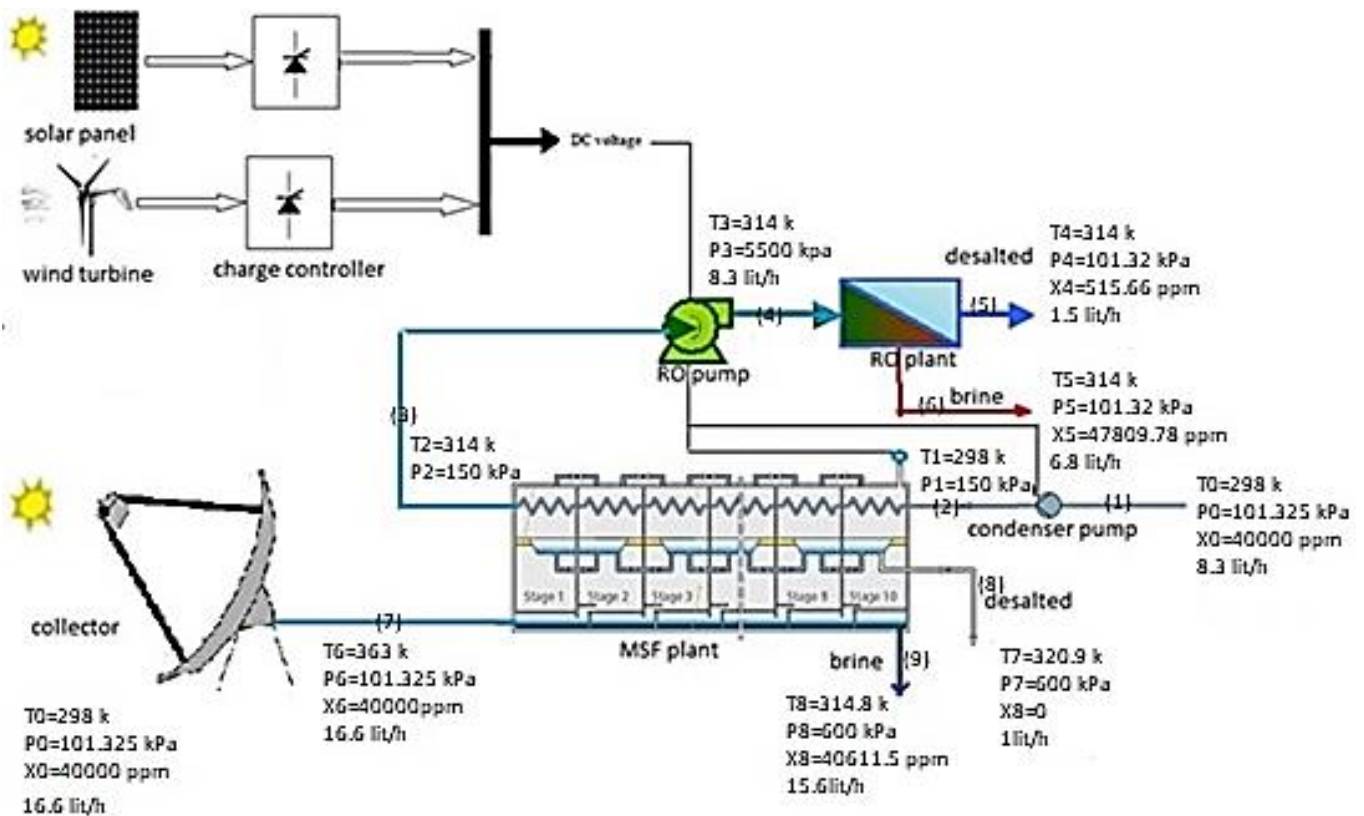


Fig. 6. Configuration of the hybrid solar-wind RO-MSF plant

Table 7. Exergy analysis results of the streams indicated in Fig. 6 for hybrid solar-wind RO-MSF plant

| Stream No | Mass(kg/s) | $T(^{\circ}\text{k})$ | X (ppm) | E_f (kJ/kg) | Total Exergy destruction (W) |
|-----------|------------|-----------------------|-----------|---------------|------------------------------|
| 1–2 | 0.0023 | 298 | 40000 | 0.971 | 2.2333 |
| 2–3 | 0.0023 | 314 | 40000 | 1.668 | 3.8364 |
| 3–4 | 0.0023 | 314 | 40000 | 9.403 | 21.6269 |
| 4–5,6 | 0.0023 | 314 | 515.6 | 21.425 | 49.2775 |
| 0–7 | 0.0046 | 363 | 40000 | 24.674 | 113.5004 |
| 7–8,9 | 0.0046 | 320.9 | 0 | 23.440 | 107.824 |

Table 8. Comparison of current exergy analysis results with other researches results

| Term | Present work | Sharqawy et al., [25] | Kahraman and Cengel [23] | Eshoul et al., [27] |
|---|--------------|-----------------------|--------------------------|---------------------|
| Exergy destroyed in flash chambers (%) | 36.14 | 75.54 | 77.80 | - |
| Exergy destroyed in collector (heat exchangers) (%) | 38.04 | 10.53 | 8.30 | - |
| Exergy destroyed in pumps (%) | 7.99 | 5.58 | 5.30 | - |
| Exergy destroyed in cooling processes (%) | 1.28 | 4.46 | 4.80 | - |
| Exergy destroyed in RO (%) | 16.51 | - | - | - |
| Minimum separation work (kW) | 0.043 | 1306 | 710 | 154 |
| Exergy destruction (kW) | 0.133 | - | - | 411 |
| Second-law efficiency (%) | 32.65 | 7.65 | 4.20 | 27.3 |

Table 8 shows a comparison of the above exergy analysis results with results taken from the literature. Our exergy analysis results for each component (Fig. 6) in the hybrid solar-wind RO-MSF plant were calculated using the values of the flow exergy in Table 4 according to equations (28) to (32). As shown in Table 7, different percentages of exergy destruction were calculated by Sharqawy et al. for MSF desalination system [25], by Kahraman and Cengel for seawater desalination systems [23], by Eshoul et al. for RO desalination system [6] and in the present work. This greatest difference is around 39–41% for the exergy destroyed in the flash chamber and 27–29% for the exergy destroyed in the heat exchangers. In addition, the value of the second-law efficiency calculated in the present work is 32.65 %, while that calculated by

Sharqawy et al. is 7.65% [25], by Kahraman and Cengel is 4.2% [23], and by Eshoul et al. is 27.3% [27]. The efficiency in the present work is higher than other researchers' results because of the hybridization of renewable energy supplies and of desalination processes.

According to the exergy analysis, the irreversible losses from the hybrid solar-wind RO-MSF plant is concentrated at the heat exchanger (solar collector)

and the flash chambers in the MSF units. Coating of collector pipes and the MSF walls could decrease this heat loss and exergy destruction, improving efficiency. Also, the vapor compressor and RO membrane and pumps are the most-important parts of the system, and the selection of their parameters and components affects exergy destruction and efficiency.

The above exergy analysis indicates several ways by which performance could be improved. After applying these measures, the performance of VCF seawater desalination would increase, the yield of fresh water would increase, and the unit's energy consumption would decrease.

4. Conclusions

The following conclusions can be drawn from the exergy analysis of the hybrid solar-wind RO-MSF plant.

1. Hybridization of RO and MSF systems with the two renewable energy resources of wind and solar increased the reliability and flexibility of the system and the quality of the resulting drinking water.
2. The price of desalinated water was \$1.35/m³.

3. Hybridization of the wind, solar, RO plant, and MSF plant minimized water cost when compared with combinations of the two technologies with fossil-fuel generation or one renewable source alone.

4. The price of desalinated water from this system can be reduced by 23 to 26% when compared with the MSF process alone, and output volume is much greater.

5. The manufacturing process of the hybrid solar-wind RO-MSF desalination system was tested. The plant achieved successful flow of desalinated water, proving the feasibility of the process. The accuracy of the thermo-physical parameter calculations was also confirmed.

6. The system test results showed that with an increase in TDS and salinity in the input water, the RO desalinated water quantities and qualities decrease, as the desalinated and brine water contains more salt. The tests showed that by increasing the salt in the input water, the system can direct less water to the RO and more to the MSF because MSF has not sensitive to salt but the RO module works less efficiently and needs more-frequent replacement with higher-salinity input water. As these test results show, with an increase in entrance water salinity, the quality, and quantity of the output water decrease. The amount of TDS in Iran's drinking water standard is 1500, and the output desalinated water in the

present tests always met this standard. The pH of the brine water and desalinated water produced from all levels of input salinity were also appropriate. The water-recovery factors for input rate of 25 liters per hour of sea water, were calculated for each desalination system in the hybrid plant.

7. According to the exergy analysis, exergy destruction is concentrated in the collector and MSF plant.

8. The vapor compressor and RO membrane and pumps are the most-important parts of the system, so the selection of their parameters and components has the most effect on exergy destruction and efficiency.

9. The above exergy analysis returns several suggestions for improving performance. Isolating the collector, coating the pipes and MSF walls, and improving the flash process could decrease the exergy loss while heating the seawater and in the flash process. These adjustments could increase the overall efficiency of the system.

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Symbols

T = temperature (°k)

p = pressure (Pa)

X = concentration (ppm)

U = internal energy

V = specific volume

S = specific entropy

μ = chemical potential

“*” = parameter at environment state

W_{ro} = saline water to RO

W_f = saline water to MSF

W_{rj} = brine from RO

W_{b2} = brine from MSF

W_t = desalinated water

W_p = desalinated water from RO

W_d = desalinated water from MSF

W_{b2} = brine from MSF

X_t = desalinated water salinity

X_p = salinity of brine water from RO

X_b = salinity of brine water from system

X_{b2} = salinity of brine water from MSF

X_{rj} = salinity of brine water from RO

X_{sea} = salinity of sea water

X_t = salinity of desalinated water from system

X_{b2} = salinity of brine water from MSF

X_{rj} = salinity of brine water from RO

A_{total} = sum of heat transfer area (m²)

M_d = desalination rate (kg/h)

ρ_{rj} = Density of brine water (kg/m³).

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