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Theoretical analysis of a reverse osmosis desalination system driven by solar-powered organic Rankine cycle and wind energy

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ABSTRACT

The utilization of renewable energy for desalination can solve the problems of energy crisis and fresh water shortage. In this study, a reverse osmosis (RO) desalination system driven by solar-powered organic Rankine cycle (ORC) and wind energy is proposed, which is different from the current desalination system driven by single energy source. In order to ensure the continuous production, energy storage units are employed. A mathematical model is established to simulate the overall system which mainly consists of a solar collector subsystem, an ORC subsystem, a wind power subsystem and a RO desalination subsystem. The sensitive analysis of some key parameters, namely turbine inlet pressure, condenser temperature of ORC, feed water pressure and the water salinity, is conducted to determine the relationship between parameters and fresh water output. The result shows daily fresh water output increases with the increase in the turbine inlet pressure under the given conditions. The condenser temperature has a significant effect on daily fresh water output. With the increase in feed water pressure, the fresh water output and the required membrane area both decreases. The fresh water output is also sensitive to the water salinity, while the required membrane area is less sensitive to it.

Keywords: Solar energy; Wind energy; Organic Rankine cycle; Reverse osmosis desalination

1. Introduction

Water scarcity has become a serious problem faced by many Mideast countries as well as developing countries. One important reason is that fresh water is the essential material in many industrial, agricultural and municipal use fields. However, the amount of fresh water on the planet is limited. Approximate 2.5% of total water on the planet is fresh. What's more, about 70% of the fresh water such as ice in polar areas is difficult to be utilized.

One way to break this shortage is the usage of desalination to produce fresh water. Desalination of saline water is a water processing technique to overcome shortage of fresh water utilized in considerable

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numbers of countries. Nowadays, the desalination techniques include the thermal desalination processes and the membrane desalination processes [1]. The thermal desalination processes take advantage of the evaporation of water heated by sun or other heat resources. The thermal desalination processes mainly contain multi-stage flash (MSF), multi-effect distillation and vapour compression. The membrane desalination processes are based on the selective permeability of membrane to separate the fresh water from sea water, mainly including RO and reverse electro-dialysis. Nafey and Sharaf [2] pointed out that RO and MSF were the most widely used techniques among these techniques nowadays.

Carbon discharge and pollution is another crisis for the world. Renewable energy has been paid more attention and used in many fields to reduce the pollution. Solar energy has the characteristics of continuation and richness especially in areas such as Mideast. The technique of RO desalination driven by solar energy gradually attracts more attention and has a rapid development.

Much research and work has been performed on RO desalination driven by solar energy. Solar energy can be directly transformed into electricity by photovoltaic cell and can also be transformed into mechanical energy by thermodynamic cycle. The latter has been studied coupled with RO desalination. Delgado et al. [3] and Ghermandi et al. [4] carried out some explorations and proposed conceptions about the RO desalination driven by solar energy. For the further exploration, Delgado-Torres et al. and Delgado–Torres and Garcia-Rodriguez [5,6] gave some detailed analyses of coupling the solar ORC with parabolic trough collectors with a sea water reverse osmosis unit. Kosmadakis et al. [7] examined the feasibility of constructing a system for reverse osmosis based on two stages ORC. They [8,9] also presented simulation and economic analysis of a two stages ORC for RO desalination driven by solar energy to estimate the increase in the efficiency and the energy available. Kosmadakis et al. and Manolakos et al. [10,11] also established low or normal temperature system based on ORC, aiming to identify the performance of ORC–RO system and search for the thermodynamic properties of organic working fluids. Bruno et al. [12] made some analyses for RO desalination driven by a low-temperature solar ORC system without thermal energy storage and thermal energy backup which showed partial load operation of pumps for a time of a year. Nafey and Sharaf [13] explored the effects of different energy recovery components from thermal-economic view. Peñate [14] focused on the developments of RO technology in current and future.

Beyond the theoretical investigation, some researchers had conducted some experiments to examine the feasibility of RO desalination system driven by solar energy. Manolakos et al. [15] conducted the experiment study of RO desalination system driven by solar energy under real solar conditions. Detail analyses and certain data of the real weather influence were given in their papers. They [16,17] also did some experiments of the ORC and the small RO unit under laboratory conditions.

As mentioned above, much research has been devoted to RO desalination system driven by solar energy. It is noted that many places which have rich solar resources also have abundant wind resources, such as some shores. The amount of wind energy on the planet is very large. Unlike solar energy, wind can provide the energy in the night. What's more, it may be worth noting that the power densities per area offered by kinetic wind energy and solar radiation are in the same order of magnitude. However, few studies have been done on the desalination system driven by combined solar and wind energy.

In this paper, we propose a RO desalination system driven by solar-powered ORC system and wind energy. This system couples the solar and wind energy to provide power to the RO desalination system. Solar-powered ORC system produces mechanical energy to drive one high-pressure pump in the RO desalination system, and wind energy is transformed to electricity to drive another high-pressure pump. The system consists of a solar collector subsystem, an ORC subsystem, a wind power subsystem and a RO desalination subsystem. The energy storage units are considered to enable the whole system operating continuously and stably. A mathematical model based on several assumptions is established to simulate the whole system and the sensitive analyses of some key parameters, namely turbine inlet pressure, condenser temperature of ORC, feed water pressure and the salinity of fresh water, are also conducted to determine the relationship between parameters and fresh water output.

2. System description

The proposed RO desalination system driven by solar-powered ORC system and wind energy consists of a solar collector subsystem, an ORC subsystem, a wind power subsystem and a RO desalination subsystem. Figs. 1 and 2 illustrate the concept and schematic diagram of a reverse osmosis desalination system driven by solar-powered organic Rankine cycle (ORC) and wind energy, respectively.

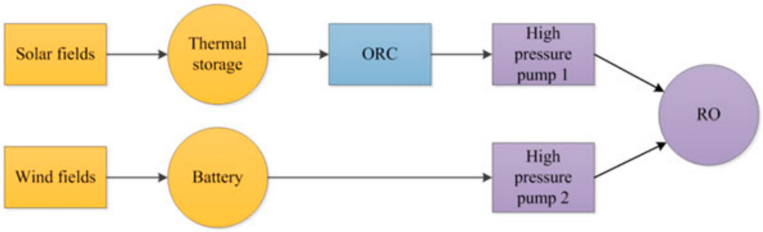

Fig. 1. Concept of a reverse osmosis desalination system driven by solar-powered organic Rankine cycle and wind energy.

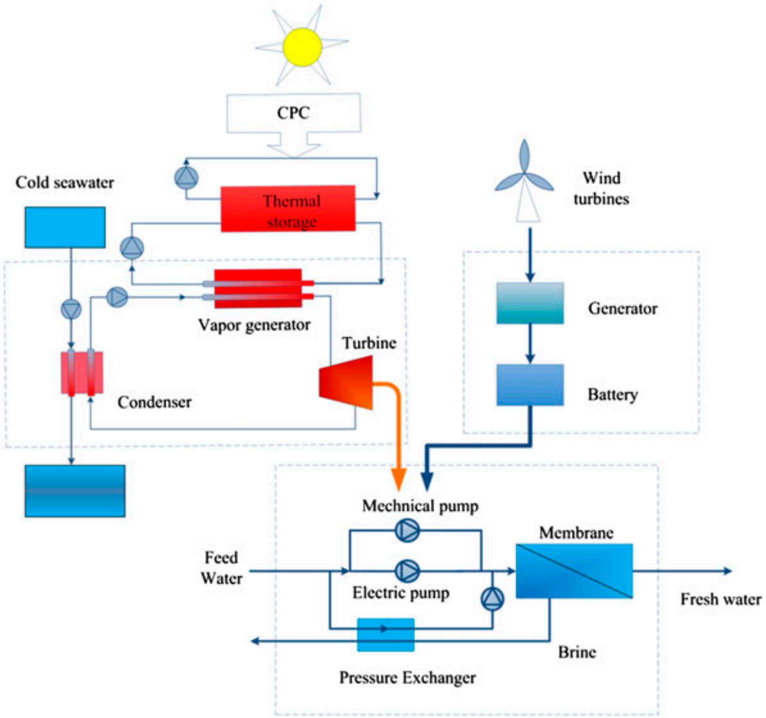

Fig. 2. Schematic diagram of the reverse osmosis desalination system driven by solar-powered organic Rankine cycle and wind energy.

The solar collector subsystem consists of two main components, namely, solar collectors and thermal storage unit. Compound parabolic collector (CPC) is chosen to be the solar collector considering its good performance in collection and controllability. Thermal storage unit is employed to ensure the stability and sustainability of the whole system by coping with the mismatch between the availability of solar energy and energy discharged to ORC. In this subsystem, thermal oil is heated to high temperature in the solar collector first, and then flows through the thermal storage unit to store the solar energy. After that, thermal oil heats the working fluid of ORC in vapour generator.

The ORC subsystem is a thermodynamic power cycle that uses organic working fluid and provides mechanical work. Organic working fluid is heated to vapour state with high temperature and pressure in the vapour generator. It then expands through the turbine to produce mechanical work to drive the high-pressure RO pump. After the expansion, the turbine exhaust is condensed into the liquid state by cold sea water in the condenser.

In the wind power subsystem, the impellers of wind turbine get energy from wind to drive the generator producing electricity and the electricity is stored in battery which can also improve the stability and sustainability. The stored electricity is used to drive a high-pressure electrical pump for RO to increase the fresh water output. The surplus electricity is stored for some unpredictable situations.

The RO subsystem consists of three components: high-pressure pumps, pressure exchanger and reserve osmosis membranes. The high-pressure pumps are driven by both the mechanical power from the ORC turbine and the electricity generated by wind energy. Sea water containing lots of salt is compressed up to high pressure by these pumps. It then flows through the membranes and splits into two streams: fresh water flow and brine flow. The pressure exchanger is applied to the RO desalination subsystem to recover the surplus pressure energy of brine flow.

3. Modelling of the proposed system

3.1. Solar collector subsystem

The solar collector subsystem is used to collect the solar radiation by CPC which can accept both beam and diffuse radiation because of its large acceptance angle.

The main parameters of the collector are given in Table 1. The beam radiation flux falling on the aperture plane is $I_{\mathrm{be}}R_{\mathrm{be}}$, while the diffuse radiation flux within the acceptance angle is given by (I_{di}/C). The total effective flux absorbed at the collector surface is [18]

$$S = \left[I_{\mathrm{be}}R_{\mathrm{be}} + \frac{I_{\mathrm{di}}}{C}\right]\tau\rho\alpha \tag{1}$$

The useful heat gain rate is

$$Q_u = F_R WL\left[S - \frac{U_{\mathrm{lo}}}{C}(T_{\mathrm{fi}} - T_a)\right] \tag{2}$$

where

$$F_R = \frac{\dot{m}_{\mathrm{solar}}c_{\mathrm{poil}}}{bU_{\mathrm{lo}}L}\left\{1 - \exp\left[\frac{F'bU_{\mathrm{lo}}L}{\dot{m}_{\mathrm{solar}}c_{\mathrm{poil}}}\right]\right\} \tag{3}$$

where

$$\frac{1}{F'} = U_{\mathrm{lo}}\left[\frac{1}{U_{\mathrm{lo}}} + \frac{b}{N\pi D_i k}\right] \tag{4}$$

The solar radiation intensity varies greatly with the time, reaching the peak in midday and dropping sharply towards zero when the sun sets. So the thermal storage is necessary in the ORC system. In order to make the system operating at night, part of the total solar radiation in the daytime is stored in the thermal storage [18]. The thermal storage is an insulated oil storage tank acting as a buffer between the solar collector and the ORC subsystem. It is assumed that the material in storage is in a well-mixed state. Consequently, the storage tank temperature T_{sto} varies only with time. The energy balance in the tank can be expressed by following equation:

$$\left[(\rho Vc_p)_w + (\rho Vc_p)_t\right]\frac{dT_{\mathrm{sto}}}{dt} = Q_u - Q_{\mathrm{load}} - (UA)_t(T_{\mathrm{sto}} - T_a) \tag{5}$$

where $(UA)_t$ stands for the product of overall heat transfer coefficient and the surface area of storage tank, T_a is the environment temperature around storage tank, $(\rho Vc_p)_w$ denotes the heat capacity of the oil in the storage tank and $(\rho Vc_p)_t$ denotes the heat capacity of tank material. In order to simplify Eq. (5), it is assumed that Q_u, Q_{load} and T_{sto} are constant within a reasonably small time such as an hour or less. Eq. (5) can be simplified to the following form based on the assumptions:

$$\frac{Q_u - Q_{\mathrm{load}} - (UA)_t(T_{\mathrm{sto}} - T_a)}{Q_u - Q_{\mathrm{load}} - (UA)_t(T_{\mathrm{si}} - T_a)} = \exp\left[-\frac{(UA)_t t}{(\rho Vc_p)_e}\right] \tag{6}$$

where $(\rho Vc_p)_e$ is the sum of two heat capacities and T_{si} is the storage temperature when $t = 0$. Q_u represents the useful energy gain from solar collector which can be expressed as Eq. (7) and Q_{load} is the energy discharged to the ORC subsystem which can be expressed as Eq. (8):

$$Q_u = \dot{m}_{\mathrm{solar}}c_{\mathrm{poil}}(T_{fo} - T_{\mathrm{sto}}) \tag{7}$$

$$Q_{\mathrm{load}} = \dot{m}_{\mathrm{oil}}c_{\mathrm{poil}}(T_{\mathrm{sto}} - T_{\mathrm{oil1}}) \tag{8}$$

The thermal storage has two functions. The first is trying to make the turbine inlet temperature to vary in a small range and the second is storing the surplus energy of the solar radiation.

3.2. ORC subsystem

The following assumptions are made to simplify the analysis of the ORC subsystem.

Table 1
Condition of the system simulation

City	Qingdao, China
Time	June 1st, 2012
Ambient temperature (K)	293
Ambient pressure (MPa)	0.101325
Sea water temperature (K)	288
Number of wind turbine	5
Diameter of wind turbine (m)	10
Density of air (kg/m^3)	1.2
Power coefficient of wind turbine	0.45
Efficiency of generator	0.95
Area of CPC (m^2)	48
Number of CPC	210
Specific heat capacity of oil (J/kg K)	2,350
Concentration ratio of collector	6.5
Reflectivity of concentrator	0.87
Transmissivity of glass cover	0.89
Absorptivity of absorber surface	0.94
Overall loss coefficient of CPC ($W/m^2 K$)	7.5
Heat transfer coefficient on side of absorber tube ($W/m^2 K$)	230
Mass flow rate of oil in CPC (kg/s)	0.6
Turbine isentropic efficiency (%)	75
Turbine mechanical efficiency (%)	90
Pump efficiency (%)	70
Feed salinity (kg/m^3)	35
Brine salinity (kg/m^3)	69
Permeate salinity (kg/m^3)	0.145
Feed pressure (kPa)	8,000
Brine pressure (kPa)	7,800
Permeate pressure (kPa)	101

- The system reaches a steady state.
- The pressure drop through the vapour generator and condenser can be negligible.
- Heat transfer with the environment in ORC is neglected.
- The turbine and pump, respectively, have a given isentropic efficiency and mechanical conversion efficiency.
- The stream at the condenser outlet is the saturated liquid.

In the vapour generator, the high-pressure working fluid is heated by high-temperature thermal transfer oil. The vaporizing process is shown in Fig. 3.

The heat transferred in the vapour generator can be described by the following equations:

$$T_{\text{oil2}} = T_{\text{sto}} \tag{9}$$

$$Q_{\text{in}} = \dot{m}_{\text{oil}} c_{\text{poil}} (T_{\text{oil2}} - T_{\text{oil1}}) = \dot{m}_{\text{orc}} (h_1 - h_5) \tag{10}$$

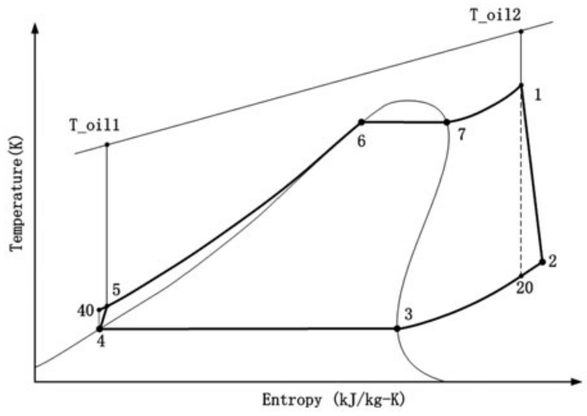

Fig. 3. T–s diagram of ORC subsystem.

where Q_{in} is the heat gain from the thermal storage.

The mechanical power produced by turbine is expressed as:

$$W_{\text{turb}} = \dot{m}_{\text{orc}}(h_1 - h_2)\eta_{m\_\text{turb}} \tag{11}$$

where η_{m_turb} is the mechanical conversion efficiency of turbine and η_{turb} is the isentropic efficiency of the turbine which can be described as:

$$\eta_{\text{turb}} = \frac{h_1 - h_2}{h_1 - h_{20}} \tag{12}$$

In the pump, the isentropic efficiency of pump is

$$\eta_{\text{pump}} = \frac{h_{40} - h_4}{h_5 - h_4} \tag{13}$$

The pump power consumption is given by:

$$W_{\text{pump}} = \frac{\dot{m}_{\text{orc}}(h_5 - h_4)}{\eta_{m\_\text{pump}}} \tag{14}$$

where η_{m_pump} is the mechanical conversion efficiency of pump.

Thus, the mechanical power produced in the ORC system can be calculated by:

$$W_{\text{net}} = W_{\text{turb}} - W_{\text{pump}} \tag{15}$$

The heat transferred in the condenser is expressed as:

$$Q_{\text{out}} = \dot{m}_{\text{orc}}(h_2 - h_4) \tag{16}$$

The thermal efficiency of ORC subsystem is calculated by:

$$\eta_{\text{orc}} = \frac{W_{\text{net}}}{Q_{\text{in}}} \tag{17}$$

3.3. Wind power subsystem

The wind power subsystem consists of wind turbines, wind generator and storage battery. The wind turbine with horizontal shaft, upwind arrangement and preferably three rotor blades can receive the kinetic energy of wind which can be described as [19]:

$$W_w = \frac{\rho}{2} A_w v^3 \tag{18}$$

where ρ is the density of air which depends on air pressure, height and moisture. A_w is the circular swept area wind passing and v is the wind velocity.

The useful mechanical power W_{uw} obtained from wind turbine is expressed by means of the power coefficient c_p:

$$W_{uw} = c_p \frac{\rho}{2} A_w v^3 \tag{19}$$

Betz [20] used a simply extreme calculation of power coefficient c_p whose value was 0.59. In reality, because of the losses such as profile loss, tip loss and loss due to wake rotation the maximum value $c_{p,\max}$ is in the range of 0.4–0.5.

A three blade rotor wind turbine is used to collect the wind energy because it has a good characteristic in most situations. The torque produced by wind turbine is converted to electricity by electrical generator. The electricity produced by the generator is stored in the battery. The electricity generated by wind can be expressed considering the efficiency of electrical generator c_T.

$$W_{\text{elec}} = c_T W_{\text{uw}} \tag{20}$$

Then considering the inlet and outlet electricity loss of the battery, the output electricity of the battery can be calculated by:

$$W_{\text{eout}} = \eta_{\text{bin}} \eta_{\text{bout}} W_{\text{elec}} \tag{21}$$

where η_{bin} is the charging electricity transfer coefficient and η_{bout} is the drawing electricity transfer coefficient.

3.4. Reverse osmosis desalination subsystem

Reverse osmosis is a modern process technology to produce fresh water. It is widely used in semiconductors, food processing, biotechnology, pharmaceuticals, power generation, sea water desalting and municipal drinking water [2]. It is based on the principle of selective permeability and it is driven by high pressure. So the salinity of sea water and salt rejection percentage determine the amount of energy required for RO directly.

The mathematical model for the RO unit is developed by Dessouky [21].

The feed mass and salt balances are given by:

$$\dot{m}_f = \dot{m}_p + \dot{m}_b \tag{22}$$

$$X_f \dot{m}_f = X_p \dot{m}_p + X_b \dot{m}_b \tag{23}$$

The feed water mass flow rate $\dot{m}_f$ based on recovery ratio RR and fresh water mass flow rate $\dot{m}_p$ is:

$$\dot{m}_f = \frac{\dot{m}_p}{RR} \tag{24}$$

The following relation defines the rate of water passage through a semipermeable membrane:

$$\dot{m}_p = (\Delta p - \Delta \pi) K_w A_m \tag{25}$$

where K_w is the water permeability and A_m is the area of reserve osmosis membrane. Permeate hydraulic and osmotic pressure can be expressed by:

$$\Delta p = \bar{p} - p_p \tag{26}$$

$$\Delta \pi = \bar{\pi} - \pi_p \tag{27}$$

where $\bar{p}$ and $\bar{\pi}$ are the average feed water pressure and osmotic pressures on the feed side and brine side are given by:

$$\bar{p} = 0.5(p_f + p_b) \tag{28}$$

$$\bar{\pi} = 0.5(\pi_f + \pi_b) \tag{29}$$

Osmotic pressures can be expressed by:

$$\pi_f = 75.84 X_f \tag{30}$$

$$\pi_b = 75.84 X_b \tag{31}$$

$$\pi_p = 75.84 X_p \tag{32}$$

The required power W_r input to the RO driving pump is estimated as:

$$W_r = \frac{\Delta P \dot{m}_f}{\rho_f \eta_p} \tag{33}$$

where ρ_f is the feed flow rate density, η_p is the driving pump mechanical efficiency and ΔP is the net pressure difference across the high-pressure pump.

4. Result and discussion

The RO desalination system driven by solar-powered ORC system and wind energy can be successfully applied for fresh water production from both sea and brackish water. The simulation of the system driven by solar-wind energy was carried out using a simulation programme with Matlab. The thermodynamic properties of the working fluid were calculated by REFPROP 9.0 [22] developed by the National Institute of Standards and Technology of the United States. Table 1 lists the condition of the system simulation. Every five CPCs are installed in series called CPC series and the 42 CPC series are installed in parallel to collect the solar radiation.

In ORC, the selection of working fluid is important. The working fluid must have proper thermal physical properties and adequate chemical stability at the desired working condition. The selection of working fluids mainly depends on working performance while the stability and environmental properties also have been considered. In this paper, R245fa is used as the working fluid in the ORC subsystem. Its critical temperature and critical pressure make it appropriate for the low-temperature ORC system. In addition, R245fa has less harm to the environment considering its zero value of ODP and high-safety group of ASHRAE 34. The properties of R245fa are listed in Table 2.

Fig. 4 shows the solar radiation and wind velocity on June 1st in Qingdao. It can be seen that the solar radiation increases from zero to maximum at midday, then reduces to zero in the afternoon and there is no solar radiation at night. In addition, the wind velocity is random and unpredictable. It is influenced by geographical location and time, which undergoes season and short-time variations. The change of mechanical power of ORC in one day is displayed in Fig. 5. It can be seen that the mechanical power of ORC varies in a small range within a day, reaching its highest value at 16:00 and lowest value at 08:00. The random velocity of wind influences the total input power to RO desalination subsystem. As a result the amount of produced fresh water has the similar trend as the power produced by wind as shown in Fig. 5.

Fig. 6 shows the daily variations of CPC outlet temperature and thermal storage temperature in the simulation. The CPC outlet temperature increases when the solar radiation is strong in the daytime, then decreases when the solar radiation is weak in the afternoon. It would decrease and has the same varia-

Table 2
Properties of R245fa

Critical temperature (K)	427.16
Critical pressure (MPa)	3.65
Normal boiling point temperature (K)	288.29
Molecular weight (kg/k mol)	134.05
ODP (ozone depletion potential)	0.0
GWP (global warming potential) (100 years)	820
ASHRAE 34 (safety group)	A1

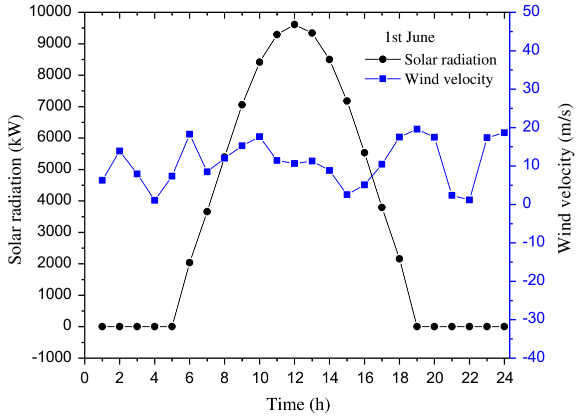

Fig. 4. Solar radiation and wind velocity on June 1st in 2012.

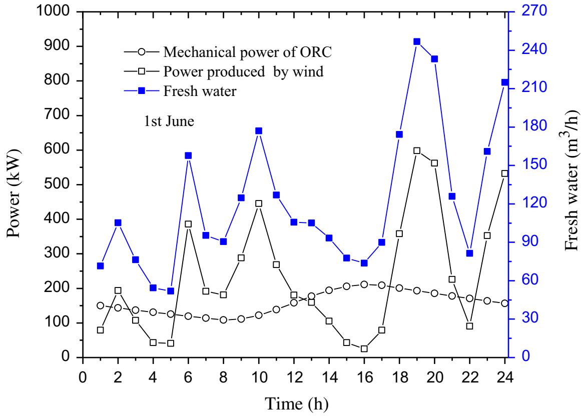

Fig. 5. Output of mechanical power of ORC and fresh water on June 1st in 2012.

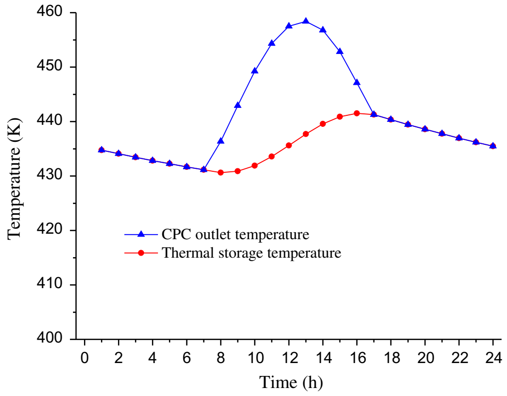

Fig. 6. Daily variation of CPC outlet temperature and thermal storage temperature on June 1st in 2012.

tion with the thermal storage temperature at night since there is no radiation. The oil temperature at CPC outlet varies from 430 K to 450 K. The thermal storage temperature has small variation within a day considering its high-heat capacity.

The daily results of the simulation on June 1st are given in Table 3, showing the energy input and the fresh water output. It is found that the fresh water is 2512.12 m^3 with energy consumption of 8056.70 kWh on June 1st in 2012.

As discussed above, the mechanical power of ORC is the main parameter to evaluate the system performance and it is mainly influenced by the turbine inlet temperature, the turbine inlet pressure and condenser temperature.

Fig. 7 shows the variation of turbine inlet temperature within a day at different turbine inlet pressures. It can be seen that at a certain pressure, the temperature varies in a small range, increasing in the daytime and reaching its peak value at 16:00, then decreasing at night. When the turbine inlet pressure rises, the turbine inlet temperature increases at the same time. The change of the temperature meets the variation of solar radiation. Strong solar radiation boosts the temperature of thermal storage in the daytime while discharged energy to ORC subsystem lowers the thermal storage temperature at night.

Fig. 8 shows that with the increase in turbine inlet pressure the daily net work of ORC and fresh water output obviously increase. It is obvious that the enthalpy difference of turbine and the mass flow rate of working fluid are main factors to the daily net work of ORC. The increase in turbine inlet pressure results in the raise of enthalpy difference of turbine but decreases the mass flow rate of working fluid. So there would be an optimal turbine inlet pressure to achieve

Table 3
Simulation result of system performance

Solar radiation, kWh/d	81,971.58
Wind energy, kWh/d	9,918.74
Energy gain by CPCs, kWh/d	23,661.66
Mass flow rate of thermal oil, kg/s	10.00
Mass flow rate of ORC working fluid, kg/s	2.36–4.27
Turbine inlet temperature, K	425.63–436.51
Turbine inlet pressure, kPa	3,000
Turbine outlet temperature, K	336.80–352.54
Net work of ORC, kWh/d	3,805.92
Thermal efficiency of ORC, %	16.08
Work produced by wind turbine, kWh/d	4,250.78
Fresh water by solar, m^3/d	1,186.70
Fresh water by wind, m^3/d	1,325.42
Work for desalination, kWh/d	8,056.70
Total fresh water, m^3/d	2,512.12

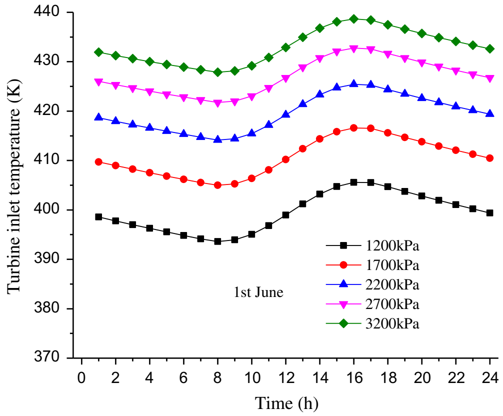

Fig. 7. Variation of turbine inlet temperature under different turbine inlet pressure within a day.

the highest daily net work of ORC if the turbine inlet temperature has an enough variation range. What's more, the fresh water has the same changing trend with the net work of ORC for the linear relationship between them. Thus, the daily fresh water also increases with the increase in the turbine inlet pressure.

In this system, we use cold sea water as the heat sink of ORC. Sea water temperature varies with seasons and days. The effects of condenser temperature on daily net work of ORC and fresh water output are shown in Fig. 9. As it can be seen, the daily net work of ORC and fresh water output decrease with the increase of condenser temperature. The fall of condenser temperature increases the temperature difference between heat source and heat sink, resulting in the increase in the net work of ORC and fresh water output. So, the colder water in winter can improve the efficiency of ORC.

RO desalination subsystem operates based on the energy supply by ORC system and electricity generated by wind. Mechanical and electrical power compresses sea water to high pressure in order to separate fresh water from sea water based on the selective permeability of semipermeable membrane. So, the amount of fresh water is related to the feed flow pressure directly. Fig. 10 presents the variation of the permeate water output and membrane area required, with the change of feed flow pressure. It indicates that under the condition of a certain power input and salinity of fresh water, with the increase in feed flow pressure, the fresh water output decreases smoothly and the membrane area decreases sharply at first and then decreases slowly when the pressure is high. High pressure can supply more energy across the membrane but under a certain input power, it could reduce the mass flow rate of feed water, resulting in the decrease of fresh water output and membrane area.

The salinity of sea water and fresh water determine the amount of fresh water output of RO directly. More fresh water will be produced with the same energy provided when the salinity of fresh water is higher. Fig. 11 illustrates the relationship among the fresh water output, the required membrane area and the salinity of fresh water. It indicates that the membrane area decreases but the output of fresh water increases with the increase in fresh water salinity. Under the given input power and feed water pressure, increasing fresh water salinity implies reducing osmotic pressure difference across the membrane, which means less resistance in the desalination progress and more fresh water production.

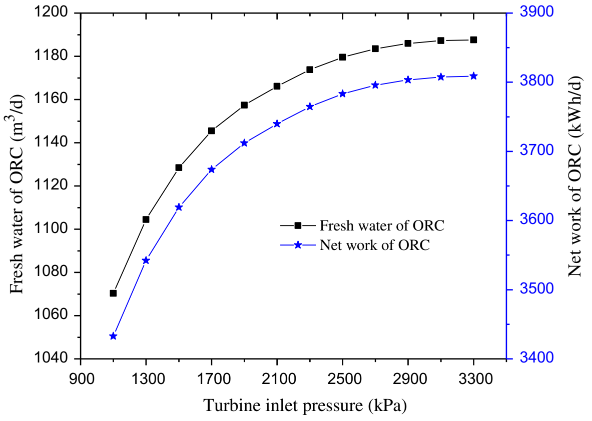

Fig. 8. Effects of turbine inlet pressure on net work and fresh water output.

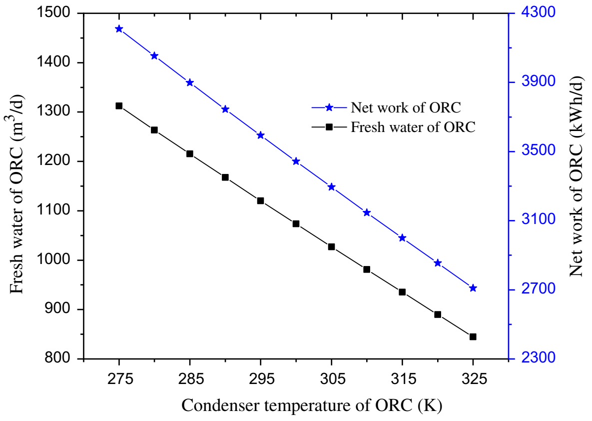

Fig. 9. Effects of condenser temperature on net power of ORC and fresh water output.

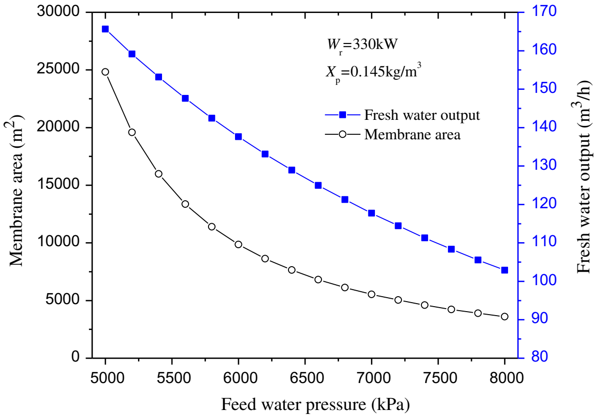

Fig. 10. Effects of feed water pressure on the output of fresh water and membrane area required.

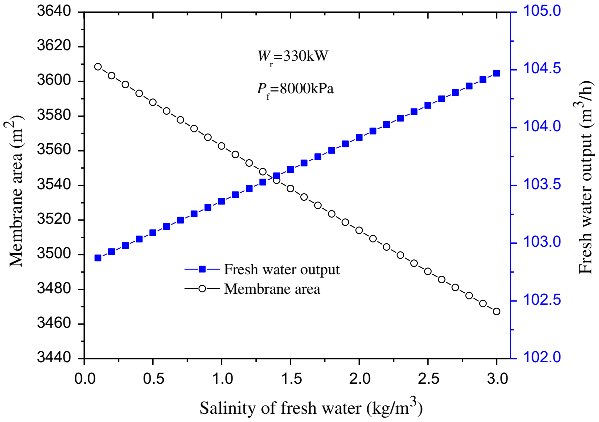

Fig. 11. Effects of the salinity of fresh water on the output of fresh water and membrane area required.

5. Conclusion

In the present study, a reverse osmosis desalination system driven by solar-powered ORC and wind energy is proposed. Thermal storage and battery are added to the system to ensure the stability and sustainability. Based on the simulation, we have obtained a better understanding of the system performance by parameters sensibility analyses and the examining of some key parameters in the whole system. The main conclusions drawn from the study are summarized as follows:

(1) By introducing wind power subsystem and thermal storage unit into ORC system, the output of fresh water has been much increased and the stability sustainability of the proposed system has been improved.

(2) A day's net work of ORC and fresh water output obviously increase with an increase in turbine inlet pressure under the given conditions.

(3) An increase in condenser temperature decreases both net work of ORC and fresh water output.

(4) The feed water mass flow rate decreases with the increase in feed water pressure, resulting in a decrease in fresh water output and required membrane area. The raise of salinity of fresh water decreases the membrane area but increases the fresh water output.

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Symbols

A — area, m^2
b — width of absorber, m
c_p — specific heat, kJ/kg K
C — concentration ratio of CPC
D — diameter, m
E — energy, kJ
F' — collector efficiency factor
FR — heat removal factor
h — enthalpy, kJ/kg
I — hourly radiation, W/m^2
k — heat transferring coefficient, W/m^2 K
K_w — water permeability coefficient, m^3/m^{2}s kPa
L — length, m
$\dot{m}$ — mass flow rate, kg/s
N — number of tubes
p — pressure, kPa
Q — heat rate, kW
R — tilt factor for radiation
RR — recovery ratio
S — incident solar flux, W/m^2
T — temperature, K
U — loss coefficient, W/m^2 K; heat transfer coefficient, W/m^2 K
V — volume, m^3
v — wind velocity, m/s
W — power, kW; width, m
X — salinity, kg/m^3

Greek letters

α — absorptivity of the absorber surface
η — efficiency
π — osmotic pressure, kPa
ρ — reflectivity of the concentrator surface; density, kg/m^3
τ — transmissivity of the cover

Subscripts

b — brine flow
be — beam
di — diffuse
elec — electricity
f — feed water flow
f0 — feed water in thermal storage tank
in — inlet
load — energy discharged in thermal storage tank
lo — loss
m — reserve osmosis membrane
net — net
oil — thermal oil
orc — organic Rankine cycle
p — permeate flow
pump — pump
sto — thermal storage
turb — turbine
u — useful
w — wind

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