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Solar and wind energy complementary seawater desalination and water-supplying system utilization in an offshore island of eastern China

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ABSTRACT

The integration of renewable energy in desalination is becoming increasingly attractive. A solar-wind powered seawater desalination system with a design capacity of 5 m^3/d demonstration project was developed and tested in Weihai, China. A 26 kW photovoltaic array was used as the main driving source, and a 2.5 kW wind generators as the supplementary source. The desalination unit used was a two-stage reverse osmosis (RO) unit. The system was operated in an automatic mode, showing good suitability to unsteady solar and wind energy, during which the RO unit ran for 5 h/d averagely, showing reliable performance in the automatic off-and-on operation mode. The daily average water production was 5 m^3/d. The comprehensive analysis shows that the power consumption of the seawater desalination equipment is 10 kWh/m^3, and the water production cost of the integrated unit is 2.29 dollars/m^3, with the ways to lower them discussed.

Keywords: Renewable energy; Solar-wind powered; Reverse osmosis; Seawater desalination; Water-supplying system

1. Introduction

Water is one of the most abundant resources on earth, covering three-fourths of the planet's surface [1]. About 97% of the earth's water is salt water in the oceans and 3% is fresh water contained in the poles (in the form of ice), ground water, lakes and rivers, which supply most of human and animal needs [2,3]. However, rapid industrial growth and the worldwide population explosion have resulted in a large escalation of demand for fresh water. Presently, over one-third of the world's population lives in water-stressed countries and by 2025, this figure is predicted to rise to nearly two-thirds [4,5]. In total, water demand doubles every 20 years, so the water emergency situation is certainly very alarming [6].

The only nearly inexhaustible sources of water are the oceans. Desalination has been an increasing part of the water supply mix for urban and industrial use globally [7]. The overarching goal for the future is to increase the fresh water supply via desalination of seawater. Therefore, it would be attractive to tackle the water-shortage problem with desalination of this water. At present, more than 100 scientific research institutions in more than 10 countries are conducting research on seawater desalination, and hundreds of seawater desalination facilities with different structures and capacities are working [4,8–11]. A large modern desalination plant can produce thousands, tens of thousands or even nearly one million tons of fresh water every day. As the cost of desalinated water continues to fall, some countries have reduced it to the price of tap water, and in some areas the amount of desalinated water reaches the size of national and urban water supplies [12]. According to the latest survey of the International desalination Association (IDA) in June 2015 and the Global Water Inelegance (GWI), there are 300 million people in the world relay partially or totally on desalinated water for their daily needs. There are about 18,426 desalination plants operating in

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over 150 countries worldwide producing daily fresh water of about 86.8 million m^3/d [13]. In particular, in the Middle East, seawater desalination is a vital and dependable fresh water resource in countries such as Saudi Arabia, United Arab Emirates, Israel and Kuwait [6]. Seawater desalination systems have been used for more than five decades in Middle Eastern & Northern Africa (MENA), and they currently have over 50% of the world's desalination capacity [14]. The five world leading countries by desalination capacity are Saudi Arabia, USA, the United Arab Emirates, Spain, and Kuwait. In China, the accumulated seawater desalination capacity of existing and upcoming desalination projects is about 600,000 ton/d. From the perspective of policy planning, the market capacity of the seawater desalination industry will grow more than 5 times in the next 10 y, showing a relatively optimistic prospect [15–17].

Desalinize in general means to remove salt from seawater or generally saline water [18]. The common desalination methods are seawater freezing, electrodialysis, distillation, reverse osmosis (RO), and ammonium carbonate ion exchange. At present, the RO method with RO membrane occupies the market rapidly with its advantages of simple equipment, easy maintenance and modularization of equipment, gradually replacing distillation as the most widely used method [19,20]. The RO desalination is the dominate technology with a share of 60% of the worldwide installed desalination plants, while this percentage reaches 82% in China, which is considered one of the fastest developed markets for desalination. RO technology also accounts for 52% of the installed renewable energy powered desalination units [21].

Desalination processes require significant quantities of energy to achieve separation of salts from seawater. The dependence on energy supply restricts the application of the technology in energy-deficient coastal areas and remote islands. To develop new energy desalination technology and reduce its dependence on traditional energy is an important measure to improve the application scope of seawater desalination and reduce the cost of desalination in energy-deficient areas [11]. Compared with traditional fossil energy, renewable energy systems produce energy from sources that are freely available in nature. To achieve a sustainable development in the aforementioned sectors, renewable energies are of utmost importance, which wind and solar energy technologies have considerably developed and shown promising results [22–24]. Their main characteristic is that they are friendly to the environment. The combined effects of the depletion of fossil fuels and the gradually emerging consciousness about environmental degradation have given the first priority to the use of renewable alternative energy resources in the 21st century [25]. The use of solar and wind power for seawater desalination has been intensively studied [26,27]. Production of fresh water using desalination technologies driven by renewable energy such as wind and solar is thought to be a viable solution to the water scarcity at remote areas [28]. In addition, remote island areas are abundant in solar and wind energy, which provides a natural convenience for the implementation of the technology [1].

The total length of China's coastline is 32,000 km, and 40% of the population is concentrated in the coastal areas [17]. Seawater desalination to make up for the shortage of water is an essential strategic measure to ensure the water security and sustainable economic growth of China's coastal and offshore areas [29]. There are tens of thousands of coastal islands in China. With the rapid development of China's marine industry, both the development and construction of islands and the daily life of island residents need sufficient fresh water resources and reliable energy as the guarantee [30]. Although the area of most of the coastal islands is small, they are of great importance in both coastal defense and economy. They are not only the bases of ocean fishing, offshore aquaculture and the development of marine resources, but also the important coastal defense areas of the country.

Although studies on renewable energy such as solar or wind power to drive seawater desalination and various approaches used for optimization of renewable energy system have been reported in the literature [2,10,11,23], the intelligent control of power generation system for RO seawater desalination is rarely involved, and informative models of autonomous solar-wind-RO desalination systems and efficient optimization tools for optimal sizing of this problem to meet both electric load and water desalination needs are seldom found. In addition, there is no recommended multi-source water supply assurance model and solution when the system does not work properly.

The main purpose of this study is to answer a fundamental question about technical viability of using photovoltaic systems and wind turbines for desalinating seawater in a typical small island in Northern China. This study is based on solar-wind RO technology to realize the energy-saving and efficient combination of wind and solar photovoltaic coupling, and to form a multi-source water supply system through desalination water, rainwater and groundwater. Moreover, this study provides the application of a whole-life cycle solar-wind complementary seawater desalination system from the aspects of overall engineering design, equipment selection, system operation and economy, it can provide technical reference for large-scale application in remote islands in the future.

2. System design principle and methods

2.1. Demonstration site

The demonstration site is a small island about 12 km away from the land, located in the northern end of the Yellow Sea of China. The island lies between 122°14′52.8″E to 122°15′50.4″E latitude and 36°44′52.8″N to 36°45′25.2″N longitude, and has an area of 0.472 km^2. The surrounding waters are 6~28 m deep and the coastline is 6.3 km long. The island is characterized by steep terrain, high in the middle and low around. The coastal marine erosion geomorphology is developed and the beach width is very small, the south coast seabed is mostly rocky, the north coast seabed sandstone interphase. The thickness of Quaternary strata on the island is very small, and the vegetation is mainly pine, covering more than 90%. The annual average temperature is 10.1°C, and the average temperature from June to September is 20°C. The island has a resident population of about 30 people, and the island is short of fresh water resources. Several rainwater reservoirs are built in the caves on the island, with a total storage capacity of only about 625 m^3. Based on 90 L of water per person per day, the island's residents need about 985 m^3 of fresh water per year. However, the sea climate is changeable, the wind and waves are high, often not navigable, the island is often short of fresh water supply, drinking water problem is particularly prominent, and the water cost is relatively high, which cannot fully meet the demand of domestic water on the island.

Therefore, seawater desalination is an important way to alleviate the shortage of water resources in the island, as well as an important supplement and strategic reserve of water resources. In addition, the island is rich in solar and wind energy resources, which can provide sufficient energy for solar-wind complementary seawater desalination system. From the perspective of energy conservation and environmental protection, as well as from the perspective of cost, solar-wind complementary seawater desalination technology is very suitable for the island to be applied to ensure the water needs of the island residents.

2.2. System design and equipment selection

The solar-wind integrated desalination device is mainly based on solar-wind complementary power generation, supplemented by municipal power. It integrates a variety of energy generation technologies and intelligent control technologies, and combines with RO seawater desalination technology. The design of the device system is based on the natural resource condition and water demand of an island in Weihai City, Shandong Province, forming a small-scale seawater desalination system with a water production capacity of about 5 m^3/d. The whole device adopts the form of the integration of fixed installation, power generation control cabinet and seawater desalination equipment are installed inside the workshop, solar panels and wind turbines are installed beside the workshop. The internal dimensions of the workshop are 12 m long, 7.5 m wide and 3 m high.

2.2.1. Power generation system equipment

The power system is solar-wind complementary power generation as the main power supply, connected to the municipal power as an emergency backup power supply, to achieve automatic switching. A solar-wind complementary power generation system with a total installed capacity of 28.5 kW is constructed, including a set of photovoltaic power generating with a peak power of 26 kW, wind power generating set with a peak power of 2.5 kW, three-stage lightning protection device, ground line facilities and remote control protection device, to meet the power supply demand of the seawater desalination system.

2.2.1.1. Solar panel module

Solar cell is a device that converts light energy into electrical energy by using the photovoltaic effect. When the sunlight shines on the semiconductor P-N (PASS/NO PASS) junction, voltage will be generated on both sides of the P-N junction, making the P-N junction short circuit and thus generating current. This current increases with the increase of light intensity, and when a certain amount of light intensity is received, the solar cell can be viewed as a constant current source. In the photovoltaic system, the matching characteristics of the load determine the operating characteristics of the system and the effective utilization of solar cells. In order to obtain the maximum power in the solar cell power supply system, it is necessary to track the sunshine intensity and ambient temperature conditions, and constantly change the load impedance, so as to achieve the best match between the array and the load. When temperature and sunlight intensity are determined, the solar cell has a single maximum power output point. With the increase of sunshine intensity, the output current and the maximum power of the solar cell increase, but the maximum power output point voltage does not change much. According to this characteristic, the constant voltage method can be used to track the maximum power point of the solar cell. This process is to constantly adjust the voltage and current automatically, to find the maximum power output point, so that the system in the best working state. This method is called as MPPT (Maximum Power Point Tracking) (Fig. 1).

For the equipment selection of solar cell array, the serial and parallel number of solar cell modules is determined according to the power consumption and technical requirements of the load. The series number is determined by the operating voltage of the solar cell array, and the average floating charging voltage of the battery and the line loss voltage drop should also be considered. The capacity of the battery determines its maximum charging current, which, combined with the load current, determines the number of parallel connections in the solar cell. In addition, the efficiency, quality, attenuation rate and temperature change of solar cell module should be fully considered, so the scientific calculation, reasonable configuration and selection of solar cell module is of great importance (Table 1).

2.2.1.2. Wind turbine generator system

The whole wind power system can be sub divided into following components:

- Model of the wind,
- Turbine model,
- Shaft and gearbox model,
- Generator model and
- Control system model

The first three form the mechanical part of the wind objectives. The generator forms the electro-mechanical link between the turbine and the power system and the control system controls the output of the generator [31].

The wind power generation equipment is composed of a SL-WP2500220s horizontal axis wind power generator set. The wind power generator set is a new generation model of the latest technology of horizontal axis wind power generation, which has the advantages of low starting wind speed and automatic wind direction. The wind power system extracts the wind energy and converts it

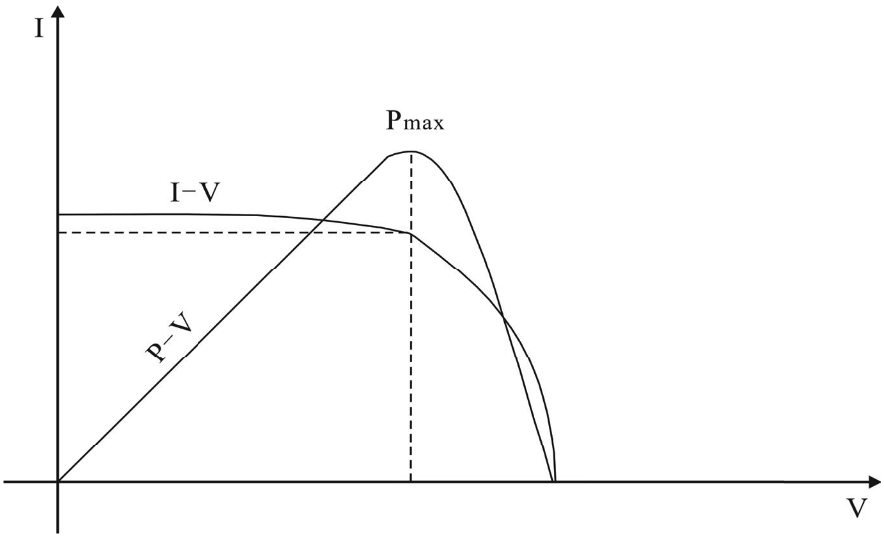

Fig. 1. Solar cell output characteristics I-V and P-V curve (I: current; V: voltage; P: power).

Table 1
Main technical indexes of the monocrystalline silicon solar module

Parameter	Value
Maximum power (Wp)	260
Maximum power voltage (V)	30
Maximum power current (A)	8.66
Open circuit voltage (V)	40.0
Short circuit current (A)	9.08
Number of cells (Pcs)	72/144
Size of module (mm)	1,957 × 990 × 45
Maximum system voltage (V)	700
Short circuit current temperature coefficients of Isc (%)	0.06/°C
Temperature coefficients of Voc (%)	–0.35/°C
Maximum power temperature coefficients of Pm (%)	–0.45/°C
Operating temperature range	–40°C~+85°C
Tolerance wattage	±3%
Surface maximum load capacity	60 m/s (200 kg/sq m)
Allowable hail load	227 g
Cell efficiency (%)	>17.0%
Output tolerance (%)	±3%
Standard test conditions	AM 1.5/100 mW/cm^2/25°C

to the electrical energy. The output power of wind power system varies depend on the wind speed. It is composed of wind blades, hub, generator, engine room, tail fin, charging controller and unloading device. The diameter of the wind wheel is 4.2 m, the starting wind speed is less than 3 m/s, the rated wind speed is 7 m/s, the safety wind speed is greater than 25 m/s, the output rated AC voltage is 220 V, and the rated power is 2.5 kW (Table 2).

Table 2
Main technical indexes of the wind generating set

Parameter	Value
Wind wheel diameter (m)	4.2
Wind turbine blades number	3
Rated wind speed (m/s)	8
Rated power (W)	2,500
Maximum power (W)	3,000
Generator model	SL-WP2500/300r/Ac220V
Generator starting torque (n m)	<1.5
Generator rated speed (rpm)	300

2.2.1.3. *Off-grid photovoltaic inverter*

SLSNB series off-grid photovoltaic inverter is a special power supply designed for wind and solar power generation to provide energy for seawater desalination system. It is the core equipment of the whole power generation system. It adopts double microcontroller unit (MCU) control intelligent operation mode, advanced sine wave pulse width modulation (SPWM) technology, with full bridge pure sine wave inverter design, low harmonic distortion, high efficiency and high reliability. It has the function of 0–50 Hz frequency conversion soft start and works effectively on the motor load. The input voltage range is wide and has the function of automatic voltage stabilization. When the input direct current (DC) voltage is lower than 80 V_{DC} or higher than 160 V_{DC}, the inverter power supply will issue an alarm. Alternating current (AC) priority power supply, when the AC power supply system is abnormal, the power supply is directly switched to the DC power supply system, and has overload, overvoltage, undervoltage, overheating and other protection functions, the operation is more reliable (Table 3).

Table 3
Main technical indexes of the off-grid photovoltaic inverter

Parameter		Value		
		SL-SNB5KVA	SL-SNB8KVA	SL-SNB15KVA
DC input	Rated capacity (kVA)	5	8	15
	Input rated voltage (V_{DC})	120	240	240
	Input rated current (A)	50	35	55
	Input Dc voltage allowable range (V_{DC})	90–150	180–300	180–300
AC bypass input	Ac voltage allowable range (V_{AC})	220% ± 15%	380% ± 10%	380% ± 10%
	Input rated current (A)	22.5	13	22
AC output	Output rated capacity (kVA)	5	8	15
	Output rated power (kW)	3	6.4	12
	Output rated voltage (V_{AC})	220% ± 3%	380% ± 3%	380% ± 3%
	Output frequency (Hz)	50 ± 0.05	50 ± 0.05	50 ± 0.05
	Output rated current (A)	22.5	13	22
	Waveform distortion ratio	≤3%		
	Dynamic response	5%		
	Power factor	0.8		
	Overload capacity	150%, 10 s		
	Crest factor	3:1		
	Inversion efficiency	90%		
	Conversion time (ms)	≤4		

2.2.2. Seawater desalination system equipment

Seawater desalination system, which includes seawater intake, primary pretreatment, deep pretreatment, RO treatment and other devices, and the desalination scale is 1 m^3/h.

2.2.2.1. Multi-media filter

This system sets two-stage multi-media filter, the diameter of the filter is 60 cm, treatment capacity is 6~8 m^3/h, working pressure is 0.6 MPa, working temperature 5°C~50°C, the material is fiber reinforced plastic. The multi-media filter uses quartz sand of various sizes to remove suspended solids in raw water. When the raw water flow through the filter, suspended material is trapped on the surface of the filter material. When the surface of the filter material intercepts a certain amount of suspended solids, the water production of the filter will gradually decline. At this time, the filter starts to automatically backwash, so that the interception on the surface of the quartz sand in the filter is peeled off and taken away by the water flow to restore the filtration function.

2.2.2.2. Activated carbon filter

Activated carbon filter mainly removes organic matter in seawater. Excessive organic matter is very easy to breed bacteria. Activated carbon can absorb organic matter and protect RO membrane from organic matter pollution. The diameter of the filter is 60 cm, treatment capacity is 6~8 m^3/h, working pressure is 0.6 MPa, working temperature 5°C–50°C, the material is fiber reinforced plastic.

2.2.2.3. Precision filter

The precision filter can prevent large particles in the water from entering the RO membrane and ensure the normal operation of RO. Precision filter is vertical columnar equipment, equipped with PP injection filter element. This system sets two-stage precision filter, the filtration precision of the first and second-stage precision filters are 20 and 5 um respectively.

2.2.2.4. RO system

After pretreatment, qualified raw water enters the membrane module placed in the pressure vessel, and water molecules and a very small amount of small molecular organic matter pass through the membrane layer. After being concentrated by the collection pipeline, it leads to the production pipe and then to the follow-up system. On the contrary, the impassable material is collected through another set of collection pipes and then leads to the concentrated water discharge pipe, which is discharged out of the tank or discharge system. A series of control valves, monitoring instruments and programmed operating systems are installed in the system's intake, production and concentrated pipes. The RO system is equipped with an automatic flushing system, a flushing water tank and a flushing water pump. The RO system is flushing with the RO produced water to ensure the equipment is not corroded and runs steadily for a long time. This system sets two-stage RO device. The number of membranes in the first-stage RO device is 12, and the water yield is 1 m^3/h. The number of membranes in the second-stage RO device is 4, and the water yield is 0.85 m^3/h.

2.2.3. Remote monitoring system

The remote monitoring system can realize the monitoring and control of the power generation status, the working status of the inverter, as well as the real-time monitoring of supply voltage and frequency, battery voltage and charge and discharge flow, wind speed, solar radiation intensity and other parameters. The system can realize the monitoring and control of the working state of the seawater desalination system, the working state of each pump, raw water flow rate, producing water flow rate, water production index, desalination efficiency and water level of the high position reservoir, and realize the 24-h uninterrupted monitoring of the working area.

In addition, the demonstration project integrated a multi-source water supply security system. When the solar-wind complementary seawater desalination system fails, or during regular maintenance to the system, the system does not produce fresh water, then the island residents can switch to the original rain water or a small amount of groundwater supply, which really forms the "desalination water – rainwater – groundwater" multi-source water supply guarantee mode.

3. Results and analysis

3.1. Solar-wind complementary power generation

3.1.1. Solar power generation

According to the meteorological data of the study area for many years (Table 4), the average number of hours of sunlight per year over many years is 2,578.5 h, which is converted to 1432.6 peak hours, and the annual average solar radiation is 123.5 kcal/cm^2 (5,162.3 MJ/m^2). In order to obtain maximum solar radiation, the solar panels are installed with a fixed angle of 37°. To calculate the total annual radiation from the inclined surface of solar panels the following equation is used:

$$H = \frac{Q}{1,000} \tag{1}$$

Table 4
Average solar radiation in the study area

Months	Hours	Insolation (%)	Radiation (kcal/cm^2)
1	190.7	65	6.3
2	190.8	63	7.9
3	236.2	66	11.5
4	234	62	13
5	264.7	63	15.2
6	234.2	56	13.8
7	186.7	44	11.3
8	219.1	53	11.8
9	232.8	63	11.4
10	228.5	67	9.3
11	184.2	62	6.3
12	177.9	61	5.7
Total	2,578.5	60	123.5

where H and Q stand for peak sunshine hours and total annual radiation of the inclined plane [32].

The annual generating capacity (L) is calculated as the following equation:

$$L = W \times H \times \eta \tag{2}$$

where L is the annual generating capacity of the solar panel module. W and η stand for total installed capacity and efficiency of photovoltaic power station system.

Therefore, according to the average peak sunshine hours, the calculated annual generating capacity of the solar panel module is 29,798 kWh.

3.1.2. Wind power generation

According to the meteorological data of the study area from 1971 to 2010 (Table 5), the average annual wind speed is 3.1 m/s [33]. The electric energy generated by the wind turbine generator can be calculated as the following equations:

$$P = E \cdot A \cdot C_p \tag{3}$$

$$E = \frac{1}{2} \cdot \rho \cdot V^3 \tag{4}$$

where P is the electric energy generated by the wind turbine generator. E, A and C_p stand for wind energy, cross sectional area and power coefficient, respectively. ρ and V denote the air density and wind speed. This is known as the wind energy density formula [34].

The wind power coefficient can also be called the wind energy utilization coefficient. For fixed-pitch wind turbines, the wind power coefficient is only related to the tip speed ratio, and there is a single optimal tip speed ratio value to maximize the wind power coefficient. For variable

Table 5
Average pressure and wind speed in the study area (10 m above the ground)

Months	Atmospheric pressure (Pa)	Wind speed (m/s)	Maximum wind speed (m/s)
1	1,021.4	3.4	13.3
2	1,019.9	3.5	14
3	1,016.6	3.6	17.7
4	1,011.4	4.0	19
5	1,006.7	3.5	16
6	1,002.8	3.0	15
7	1,000.6	2.7	12
8	1,003.0	2.4	15
9	1,009.8	2.1	10.7
10	1,015.6	2.5	14
11	1,019.4	3.0	13
12	1,021.2	3.4	11.3
Total	1,012.4	3.1	19

pitch wind turbine, the wind energy utilization coefficient is related to tip speed ratio and pitch angle. When the pitch angle increases gradually, the wind energy utilization coefficient of the wind turbine will decrease gradually, which is determined by the characteristics of the blades. According to Betz's Law, the maximum value of the wind power coefficient is Cp_{max} = 0.593, which applies to all models. However, in fact, the wind power coefficient of modern commercial wind turbines is about 0.45, which is less than the theoretical limit. The Cp value in the wind energy calculation formula of this demonstration project is calculated by 0.45. Therefore, the calculated annual generating capacity of the wind turbine generator is 1,291 kWh.

In summary, the theoretical annual generating capacity of the solar-wind energy complementary generator set is 31,089 kWh.

3.2. Operation of seawater desalination system

3.2.1. Technological process

Solar-wind complementary desalination system is mainly composed of wind turbine, solar photovoltaic panel, intelligent controller, battery, desalination device and so on. The electricity generated by wind turbines and photovoltaic panels is charged through an intelligent controller to the battery. The intelligent controller can charge and discharge the battery according to the voltage change of the battery, and the battery plays the role of storage and regulation of electric energy. When the power generation is insufficient, the system automatically switches to the municipal power supply to maintain the stability of the power supply voltage.

Both DC and AC can be used as the power supply of solar-wind complementary RO device. If the working voltage of the DC power supply is consistent with the battery voltage, it can be directly used from the output end of the controller, and if the working voltage does not match, the DC-DC conversion function should be added. For the use of alternating current seawater desalination device, it is necessary to use the inverter to convert the direct current into 50 Hz alternating current before use.

In addition, the RO desalination method is easy to be coupled with solar-wind complementary power supply technology. RO seawater desalination device has low energy consumption, simple system, and can be started and stopped at any time according to sunshine conditions. Besides, it is convenient to couple the unstable solar-wind power supply device by adjusting the water production, while maintaining the stable water quality generated by the RO system (Fig. 2).

The RO seawater desalination treatment system includes multi-stage treatment equipment. After the seawater is extracted by the pump, it is entered into the two-stage RO device after the two-stage multi-medium filter, activated carbon filter and two-stage precision filter. Two dosing systems are set, one is raw water influent flocculant dosing system, the other is RO scale inhibitor dosing system. Multiple measuring instruments are set in the whole system for real-time monitoring of inlet flow, water production flow, RO inlet conductivity, RO water production conductivity, inlet pressure and water production pressure of each treatment device. The total power consumption of the seawater desalination system in normal operation is about 10 kWh/m^3, and the solar-wind can generate enough electricity to power the entire facility.

The RO system adopts programmable logic controller (PLC), the working state of each pump is transmitted to the upper computer through the 485 signal channel, and the system is started and shut down according to the instructions of the upper computer, so as to achieve the purpose of adjusting the working state of the pump and water

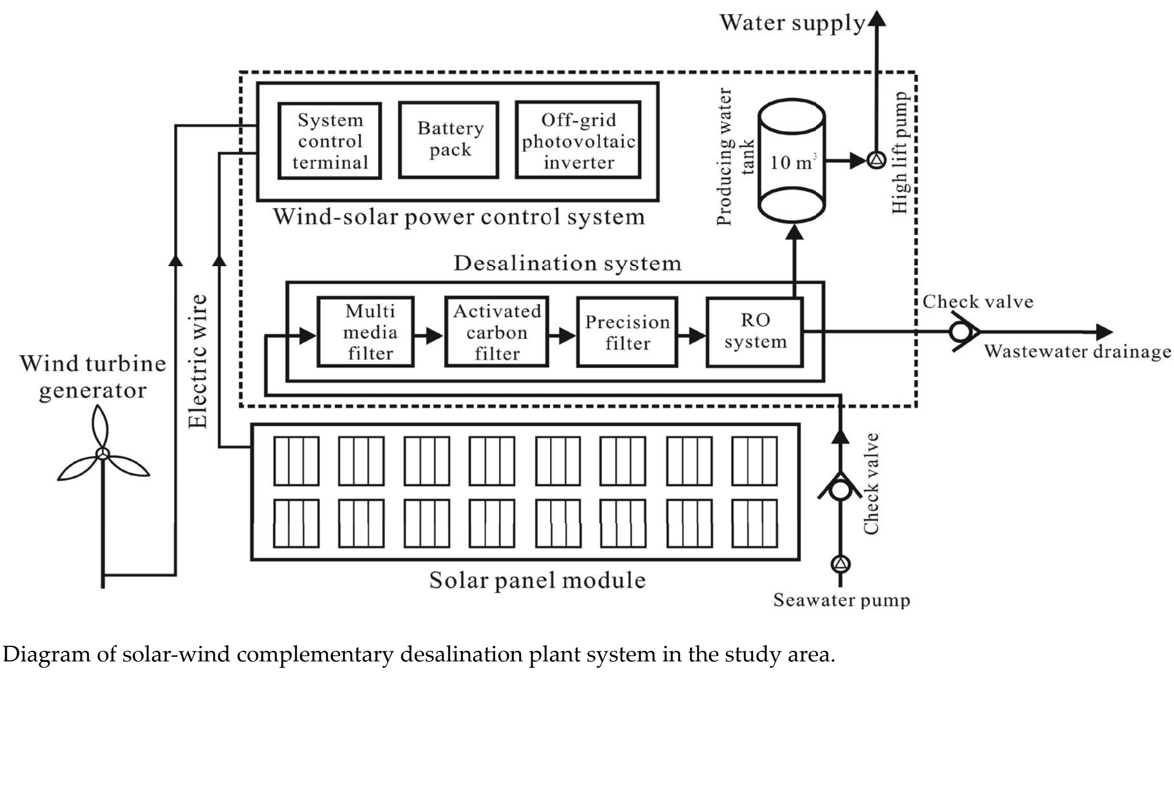

Fig. 2. Diagram of solar-wind complementary desalination plant system in the study area.

production according to the solar-wind power generation output, so that the solar-wind energy and water production form a closed-loop control.

3.2.2. Desalinated water quality

The desalinated water after seawater desalination by RO membrane method has obvious advantages in quality compared with surface water, groundwater and other water sources, but the desalinated water is characterized by high purity, low hardness, low salt content, extremely poor chemical stability, low alkalinity, weak acidity, and basically does not contain minerals. The demonstration project adopts multi-stage pretreatment and two-stage RO treatment. The water temperature (T), pH, electrical conductivity (Ec), dissolved oxygen (DO) were tested by Multi 340i portable water quality multi-parameter analyzer produced by the WTW company in Germany at the scene. The ion content was analyzed by ion chromatography (Dionex ICS3000) by The Institute of Seawater Desalination and Multipurpose Utilization, MNR (Tianjin). Except for boron (B), the quality of produced water completely meets the limit of domestic and drinking water standards [35].

According to the water quality analysis results in May (Table 6), the content of B in the sea water of the study area is 4.17 mg/L, and after treatment, it is 0.67 mg/L. Because B does not exist in ionic state in water under normal pH conditions, RO membrane has a low rejection rate to it [36]. Nevertheless, the B treatment of this equipment system is still close to drinking water standard.

3.3. Multi-source water supply

According to the actual situation of the demonstration site, a set of water supply scheme based on multiple water sources and water quality is designed (Fig. 3). The desalinated water is transported to the office and living area through the high-pressure pump, and is divided into two pipelines through the triple valve, one is transported to the high position reservoir and the other to the dining room. Desalinated water can be directly used for washing and sanitation in office and living area. The mixing water of desalinated water and filtered rainwater can be used for dining water. When the solar-wind complementary seawater desalination system fails or is repaired, the water source of domestic water and dining hall water can be switched to filtered rainwater. In exceptional dry years, when there is not enough rain and the desalination system cannot work properly, the water source can be switched to using groundwater as an emergency backup water source. Because the amount of underground fresh water in the island is small

Table 6
The raw water and two-stage RO water chemical composition

	pH	EC	TDS	Cl	B
		μs/cm	mg/L	mg/L	mg/L
RO water	6.91	24	6.51	7.77	0.67
Raw water	7.77	/	32,440	18,200	4.17

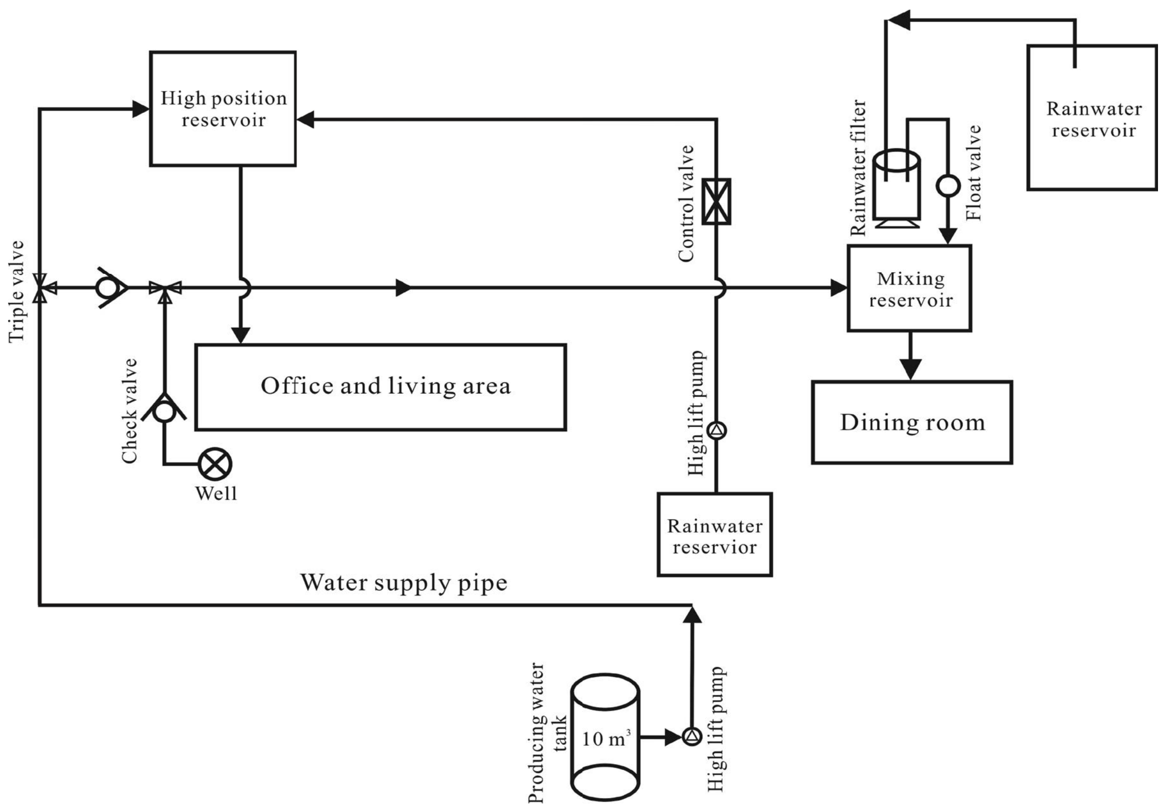

Fig. 3. Diagram of multi-source water supply system in the study area.

and unstable, small flow frequency conversion pump can be used for water intake and use after purification.

The water supply scheme takes the actual situation of the island into full consideration. The users can convert the water source according to the weather condition and equipment operation, combined with the amount of water and the way of water use, so as to realize reasonable water use.

3.4. Economic analysis

3.4.1. Construction investment

Construction investment costs mainly include equipment costs, civil construction costs and installation costs. The main equipment of the power generation system includes solar cells, wind turbines, batteries, controllers, inverters, power distribution cabinets, installation brackets, etc. The total civil construction investment is about \$31,300. The main equipment of RO system includes water tank, high pressure pump, multi-medium filter, precision filter, RO membrane module, control cabinet, etc. The total cost (including installation cost) of the RO system is about \$54,500. According to the current industry price standard, the price of an ordinary 3000 W wind turbine is \$3,000 and the price of a solar panel is \$2/W [37,38]. The total cost (including installation cost) of the solar-wind power generation system is about \$84,500.

Therefore, the total construction investment (including installation cost) of the project is about \$169,000, of which the equipment cost is \$58,000.

3.4.2. Operation and maintenance cost

Operating costs mainly include depreciation of fixed assets, replacement of equipment components, inspection and maintenance of equipment. The maintenance cost of equipment components is calculated as 0.2% of the original value of fixed assets, and the cost is about \$116/y. In terms of the replacement of equipment components, the replacement cycle of the battery is 4 years, the replacement cycle of the RO membrane element is 5 years, and the replacement cycle of the filter element is 6 months. The replacement cost of the inverter and controller components is not taken into account. It is calculated that the replacement cost of the equipment components of this set of device is \$1,330/y, in which the replacement cost of the battery is about \$814/y, and the replacement cost of RO membrane element and filter element is about \$516/y. In terms of depreciation of fixed assets, the depreciation life of the whole set of devices is calculated as 20 y, and the residual value rate is 5%, which results in a depreciation cost of \$2,740/y, of which the depreciation expense of the power generation system is about \$860/y, and the depreciation cost of RO system is about \$1,880/y.

3.4.3. Water production cost

According to calculation, the annual peak power generation of solar cells is 29,798 kWh, and the annual peak power generation of wind turbines is 1,291 kWh. Therefore, the annual theoretical peak power generation of the solar-wind complementary power generation system is 31,089 kWh. Considering the solar panel angle, solar panels surface dust, wind turbines installation angle, the local temperature, air density, humidity, atmospheric pressure and the efficiency of the control system, material aging, performance degradation, the influence of factors such as climate change and equipment maintenance, the actual output power of the system is calculated at 85% of the peak power output, therefore the annual capacity of power generation system is about 26,425 kWh, it is concluded that the cost per kWh of the solar-wind complementary power generation system is \$0.185. This value does not take into account the generation capacity of the system under off-peak generation conditions, so the actual cost would be lower.

The power consumption of the above-mentioned seawater desalination equipment is about 10 kWh/m^3, and the electricity cost is \$0.185/kWh, so the electricity cost of the seawater desalination equipment is \$1.85/m^3. Depending on local natural conditions, the system can operate normally for about five hours a day and the annual freshwater production capacity is 1,825 m^3. The comprehensive analysis shows that the water production cost of the integrated unit is about \$2.29/m^3.

4. Discussion

In recent years, seawater desalination is developing towards the goal of high efficiency, low energy and large-scale. Reverse osmosis and multi-stage flash evaporation have become the mainstream technologies for large-scale seawater desalination. Although the distillation technology is mature, but the investment cost is high, the energy consumption is large, has gradually lost the advantage of the original technology. The RO seawater desalination method has the advantages of low investment, low energy consumption, short construction period and easy automatic control, which is suitable for large and medium-sized seawater desalination projects. RO device has the advantages of small volume, simple equipment and operation, direct operation at room temperature, low corrosion and scaling degree of equipment, which has become the most widely used method at present and has a good development prospect. The utilization of seawater resources in China is still in the development stage. In addition, there are differences among regional water resources, the utilization degree is different, and the price advantage compared with fresh water, groundwater and other water sources is not prominent, so there are still difficulties in the development and utilization of seawater.

4.1. Technical solutions

The technical solution is the overall plan of the project, and different technical solutions have different equipment selection and investment costs. Therefore, the technical solution is a major factor determining the applicability and economy of the solar-wind complementary seawater desalination system [39]. For this set of solar-wind RO desalination plant, firstly, the process program was analyzed and selected according to raw water quality, environmental conditions, design requirements, to determine a reasonable and economic desalination process program and accurate equipment process parameters, and to analyze the energy consumption of the desalination system. Then, considering the energy consumption of the desalination system and the local wind and light resources, a reasonable solar-wind complementary power generation capacity is allocated, and the optimal power supply mode and control strategy are determined [37]. In this demonstration project, the total power of RO system equipment is 10 kW, and the total installed capacity of the power generation system is 28.5 kW, which is enough to guarantee the electricity demand of the equipment. In addition to desalination equipment, the surplus power generation can also supply part of domestic electricity. There are many equipment components in the whole device. The selection of the brand, model and material of each equipment component in the device should not only meet the design requirements, but also avoid overqualification, especially some key equipment components, such as solar panels, wind turbines, batteries, water pumps, RO membrane components and so on. It can be seen that in the process of formulating the technical plan of this set of equipment, the analysis and comparison of seawater desalination process plan, the configuration of solar-wind complementary power generation capacity and the selection of equipment components will directly affect the construction investment cost.

4.2. Desalinated water quality assurance

According to the existing water quality testing data and relevant reports, although RO desalinated water can meet the existing sanitary standards of drinking water to a certain extent, its long-term use as drinking water may cause health and safety problems. RO membrane can remove most of the ions in seawater, desalinated water quality is high, basically does not contain minerals. In this way, the alkalinity and hardness of the desalinated water are greatly reduced, and the hardness is generally in the range of 1~99 mg/L (based on $CaCO_3$) [40,41]. In the process of desalination, the removal rate of beneficial mineral elements, especially divalent ions, is very high, such as calcium, magnesium and chloride, the removal rate usually reaches more than 95% [42]. Except for boron, the other indexes of desalinated water meet the standard [43]. However, in view of the limitations and technical bottlenecks of the current desalination process, the RO process has no material selectivity, and the removal or retention degree of some ions in desalination water has not reached the ideal level. In view of the present situation that the content of B in desalinated water exceeds the standard of drinking water, improvements can be made from the following three aspects: in terms of water supply, the B concentration can be reduced to less than 0.5 mg/L by mixing with tap water. In terms of technology, the B concentration can be reduced by developing RO membrane with high B removal rate or post-processing B removal. In terms of policy, standards should be formulated scientifically and in line with international standards, B limits should be relaxed, and obstacles for desalinated water to be used as drinking water sources should be eliminated [44].

In terms of adjusting the pH and mineral content of desalinated water to improve the stability of water quality, there are mainly four methods, such as mixing desalinated water with other raw water, lime method, limestone dissolution method and adding chemical agents [45]. More and more desalinated water is treated by mixing with other water sources [46]. The quality of the source water used for mixing is particularly important for the quality of the mixed water. When mixing with tap water, tap water is directly mixed with desalinated water in a ratio of 1~5:1. The pH of the water after mixing is not significantly changed, and the stability of the water quality is still at a low level with strong solubility [47]. When seawater is used as the source of mixing, the mixing ratio is usually less than 1%. At this time, the calcium content increases by 4~5 mg/L and magnesium by 12~17 mg/L. When desalinated water is mixed with partially treated seawater, the amount of seawater can vary from less than 1% to 10% [46], with corresponding increases in sodium, potassium, chloride, and other salts. When untreated groundwater or surface water is mixed with desalinated water, the ratio of 3~5:1 can better meet the requirements of water quality stability [47,48].

4.3. Economic and feasibility analysis

As for the economic and feasibility of seawater desalination, Karki and Billinton [39] conducted cost analysis of independent small-scale solar-wind complementary power generation system, and proposed that reasonable allocation of the power generation system based on solar-wind powered resource conditions and load is an important way to reduce the cost. Mohamed and Papadakis [13] calculated that the cost of water production for a solar-wind desalination system was $5.87–5.95/m^3. Kershman et al. [49] studied system operating costs for larger water production scales (e.g., 300 m^3/d), which can be as low as $2.74/m^3 when photovoltaics are combined with wind turbines and connected to the grid. Tian et al. [50] conducted a study on a seawater desalination plant using multistage flash evaporation method and found that the cost could be reduced by 15% if the same volume of water was produced using reverse osmosis seawater desalination device. Zhang et al. [51] conducted an economic analysis on the solar-wind complementary seawater desalination system of Yongxing Island in Sansha City, China. The wind turbine power of the system is 100kW, the photovoltaic array power is 400 kW, the seawater desalination device scale is 500 m^3/d, and the cost of water production is about $0.9/m^3. However, if fresh water is transported by ship for Yongxing Island residents, the freight cost alone is as high as $15.6/m^3. Zhang et al. [52] took Dayushan Island in Zhoushan City as an example to design a photovoltaic solar water desalination demonstration project with a capacity of 5 m^3/d and a total installed power of 6 kW. At present, the power supply of the island is mainly provided by diesel generators, which have very low utilization efficiency and high power supply cost of about $0.47/kWh. If seawater desalination is powered by diesel generators, the cost of water production is about $2.58/m^3, while the cost of water production by photovoltaic solar power is about $2/m^3. Liu et al. [37] introduced a 5 m^3/d integrated device system of solar-wind complementary power generation reverse osmosis seawater desalination based on the natural resource conditions of an island in Zhuhai City. The solar photovoltaic system is equipped with 12 monocrystalline silicon photovoltaic cells with a total capacity of 3.6 kW and a vertical axis magnetic levitation wind generator with a rated capacity of 0.6 kW. The battery group consists of four colloidal lead-acid batteries with a rated capacity of 150 Ah and rated voltage of 12 V in series. In the seawater desalination system, five 64 mm RO membrane elements and a high pressure pump with energy recovery device were selected. Comprehensive analysis and calculation show that the water production cost of the integrated device system is about \$2.16/m^3.

Comprehensive analysis shows that the economic cost of the solar-wind complementary seawater desalination system is restricted by a variety of factors such as water yield, equipment selection, and work efficiency. The solar-wind complementary seawater desalination system developed in this study has good economy and applicability. Compared with the same type of system, it not only saves energy, but also reduces the cost.

5. Conclusions

This study sought to assess simultaneously the accessibility to electricity and cost in a small scale solar-wind complementary power generation reverse osmosis seawater desalination system in a typical island in north coast of China. For remote island areas where fresh water resources are in short supply, the use of solar-wind energy complementary desalination device can save the huge cost of laying cable and transporting fresh water resources. The device can not only effectively protect the natural environment of the island, but also provide electric energy and fresh water resources, and promote the development of small wind turbine and solar photovoltaic industry to a certain extent, which has a good demonstration role in promoting the comprehensive utilization of new energy.

The system is based on solar-wind RO technology to realize the energy-saving and efficient combination of wind and solar photovoltaic intelligent coupling, and to form a multi-source water supply system through desalination water, rainwater and groundwater. For setting up the solar-wind RO desalination system, the RO device can provide maximum of 5 m^3/d. Maximum production cost of potable water was estimated at most \$2.29/m^3. Results indicate that using the proposed system of desalination would be technically and economically feasible for the remote island.

Through the optimization and improvement of solar-wind complementary RO desalination system device, at this stage in the battery charging and discharging control, RO desalination process optimization, the high pressure pump and the reasonable selection of energy recovery device for the further study of the key technology, will greatly promote solar-wind energy complementary RO desalination system applicability and economical efficiency.

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