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An energy-efficient vertical-shaft seawater desalination plant

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ABSTRACT

We propose a design of a seawater desalination plant (SDP) consisting of two vertical shafts underground. One shaft is designed for producing freshwater, in which the reverse osmosis modules (ROMs) are installed several hundred meters deep. The other shaft is used to reserve the brine rejected from the ROMs. The pressure required to force the seawater to penetrate through the ROMs is provided by the hydrostatic pressure of seawater of 550 m deep or more. Consequently, the main energy consumption of the SDP is the power required to pump the freshwater up to the ground. Therefore, if coupled with other sporadic energy consumptions, the energy consumption per cubic meter of freshwater produced is approximately 2 kWh/m^3, which can be generated by, for instance, wind turbines or photovoltaic panels on the ground. In the case where the generated brine can be fully recovered, the entire SDP is a non-polluted freshwater production facility, which is quite in line with today's energy and environmental requirements.

Keywords: Seawater desalination plant; Reverse osmosis modules; Vertical shaft; Energy efficiency; Cost reduction

1. Introduction

Due to the rapid growth of the population and the high development of the economy, the demand for freshwater has increased rapidly worldwide. Especially in the case where most of the growing population is concentrated in the metropolitan area, the requirement of freshwater in the highly populated area is even more imminent. Given that most of the developed metropolitan areas are close to the sea, the development of freshwater resources has gradually shifted from building reservoirs in the mountainous areas to setting up seawater desalination plants (SDP) on the seashore. There are two reasons for this shift: one is the aforementioned geographical relationship between water sources and people, the other is that the ocean is full of huge amounts of seawater available for converting into freshwater. Driven by these two factors, many countries with water shortages such as Singapore, Israel, Saudi Arabia, etc., are doing their best to build SDPs in coastal areas such that the water supply and resource distribution can be effectively improved [1].

Although seawater can be accessed virtually unlimitedly, the energy supply is unfortunately expensive and harsh. Most traditional SDPs require significant electricity to execute operations, resulting in a high production cost of freshwater. An energy-efficient desalination scheme has accordingly become a basic requirement for the SDP design. Under the framework of this basic requirement, engineers have developed a wide variety of SDP designs, such as the multi-stage flash distillation SDP [2], the use of renewable energy [3], the electrodialysis desalination [4] and the use of reverse osmosis modules (ROMs) [5]. Among them, the use of ROMs has proved the most energy-efficient scheme consuming 3–10 kWh [6] or 3–7 kWh [7] for producing a cubic meter of freshwater.

In the SDPs designed using ROMs, the most energy-consuming part is the use of a high-pressure pump to force

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the saltwater to penetrate through the ROMs. The pressure difference required for penetration depends on the type of saltwater used. For example, when using brackish water for desalination, the pressure required is approximately 218–435 psi (15–30 bar) [8]. When using seawater for desalination, the required pressure is between 800–1,000 psi (55–70 bar) [9]. Because the cost of energy consumption by the pump accounts for about 40% of the production cost of the SDP [6], a feasible technology to replace the high-pressure pump has become the most urgent need. After many attempts in years, technologies that using hydrostatic pressure to replace a high-pressure pump have proved to be highly energy-efficient and environmentally friendly [9], refer please also to the information shown in Fig. 1.

Nevertheless, the SDP using hydrostatic pressure has constrained under two criteria. Firstly, the SDP shall be located close to the sea; secondly, the ROMs must be placed several hundred meters below the sea surface although there are designs that may exempt from this requirement, for example [5]. Under these two criteria, many different designs have emerged. For example, in considering the reduction of construction maintenance and operating cost, the ROMs and related equipment can be installed on land, on the seabed or in the ground. These options have been used interchangeably by many SDPs during the past two decades, which will be discussed in a chronical order in the following.

The first was the design proposed by Reali et al. [10]. They installed the ROMs in the ground so that the hydrostatic pressure is used to produce the fresh water, and the energy used to pump the fresh water to the ground accounts for 92.2% of the total energy consumption. Because the ROMs are installed in the ground, a large-scale well-drilling project is required for the plant construction, leading to an increase in the construction cost. To reduce the construction cost, Colombo et al. [11] proposed another design by placing the ROMs on the seabed, which is about 500 m below the sea surface. However, to extract the freshwater produced on the seabed to land, a long pipe is used resulting in higher energy consumption. To reduce the maintenance cost under the sea, Pacenti et al. [12] proposed another submarine desalination system. They placed the entire equipment including the ROMs, high-pressure pumps, pipes, and water tanks in a cylindrical steel vessel. In the vessel, a set of multi-function sensing equipment was used to detect operation data so that the staff on land can effectively monitor the operation of equipment in the deep sea. Due to the solid structure of the entire equipment and the immediate monitoring of the entire plant operation, this design can reduce the maintenance and production costs to a satisfactory level.

In 2006, Al-Kharabsheh [5] proposed another SDP located on land. He placed a seawater tank on a raised platform about 50 m above the ground, and then placed the ROMs on the ground. The required hydrostatic pressure is provided by a water tank placed at a height of 500 m. Pipes and valves are installed between these two tanks. By controlling the valves in a designed sequence, a functional cycle of pressurizing and de-pressurizing is executed. During the execution cycle, the seawater is forced through the ROMs to dilute. Its characteristic is that, through the valve control sequence, the energy needed is to pump the seawater to a storage tank at 50 m high. Later, Charcosset et al. [8] improved the designs of [5,10,11] while increased the energy consumption of the desalination plant. Hastings [13] put the entire SDP into the deep sea again while installing a water turbine at the seawater inlet to generate electricity to supply a portion of the power required by the equipment.

In 2012, Dashtpour and Al-Zubaidy [6] also placed the entire equipment on the seabed but installed a set of ballast tanks on the equipment. When the ballast tanks are filled with seawater, the entire equipment sinks into the sea; when maintenance is to execute, the seawater in the ballast tanks is discharged and the entire equipment floats up to the surface. The hydrostatic pressure is used to press seawater through the ROMs, a wave energy conversion device is used to supply the power needed to pump fresh water to the surface. Later, Guizani [14] proposed design is an improved version of Al-Kharabsheh [5]. The improvement was to replace the

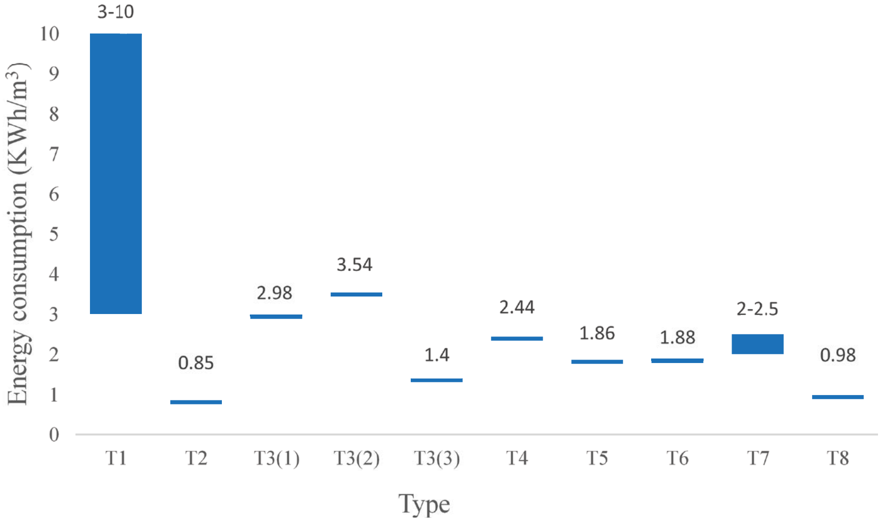

Fig. 1. Comparison of energy consumption of SDPs designed with different pressurizing schemes. T1 stands for traditional SDP; T2 is the SDP proposed in [5], T3 (1–3) in [8], T4 in [6], T5 in [10], T6 in [11], T7 in [12], and T8 in [14].

sink, which was placed at a height of 500 m, with a heavy object.

We compile the energy consumption of the SDPs mentioned in Fig. 1. The leftmost T1 accounts for the traditional SDPs pressurizing the seawater with a high-pressure pump and its energy consumption is between 3–10 kWh/m^3. The other SDPs in the figure, from T2 to T8, are the SDPs using hydrostatic pressure to pressurize the seawater, and its energy consumption is between 0.85–3.54 kWh/m^3. The data of Fig. 1 reveal a fact that the SDP using hydrostatic pressure is generally of higher energy efficiency than the traditional SDP.

In this paper, we propose an energy-efficient SDP featured with utilizing the hydrostatic pressure and the main structure consisting of two vertical shafts. One shaft is designed for producing freshwater, in which a set of ROMs is installed at a depth of 550 m and a horizontal pipeline is used to introduce seawater to the bottom of the shaft. The hydrostatic pressure serves to press the seawater through the ROMs and the fresh water is pumped to the storage tank on the ground. The other shaft is used to reserve the brines rejected by the ROMs. Assuming that the friction loss in the shaft is small, the brine's level will be lifted to near the sea level. Consequently, the major energy consumption of the present SDP is the power to pump the fresh water up to the ground, leading to a result that the energy needed to produce a cubic meter of fresh water is less than 2 kWh/m^3, which is rather competitive in terms of energy efficiency.

In the following, we will introduce the design and operation principle of this vertical shaft desalination plant (VSDP afterward) in Section 2. In Section 3, the energy consumption for producing a cubic meter of freshwater under different design specifications will be discussed. In Section 4, a comparison of the present VSDP with the existing SDPs utilizing hydrostatic pressure will be given. Concluding remarks are summarized in Section 5, in which the design characteristics of VSDP are emphasized and sustainable development of VSDP in the future is also discussed.

2. Design and operation

Fig. 2 shows a schematic illustration of the VSDP, which consists mainly of a freshwater shaft, a brine shaft, and a horizontal channel *A* connecting the two shafts to introduce seawater into the plant. Since the inlet *B* of the horizontal channel is located at a depth *H* which shall be larger than 600 m, there will be enough hydrostatic pressure to overcome the pressure loss through *A* and to provide the pressure needed to penetrate the seawater through the ROMs. Since the inner diameter of channel *A* may exceed 1 m and the flow rate is low, the friction loss of *A* can be negligible. Therefore, only the pressure required to penetrate the ROMs will be considered in this paper.

When the seawater encounters the ROMs, some of them will be pressed through and become freshwater, which will accumulate in the freshwater shaft up to a depth of 50 m. The freshwater will be pumped to the ground by Pump *C* via a vertical pipeline. The remaining seawater rejected by the ROMs will accumulate in the brine shaft to reach a level about the sea surface because the friction loss of the brine shaft is negligible. We assume that the depth of the liquid surface below the ground is $d_2 = 10$ m

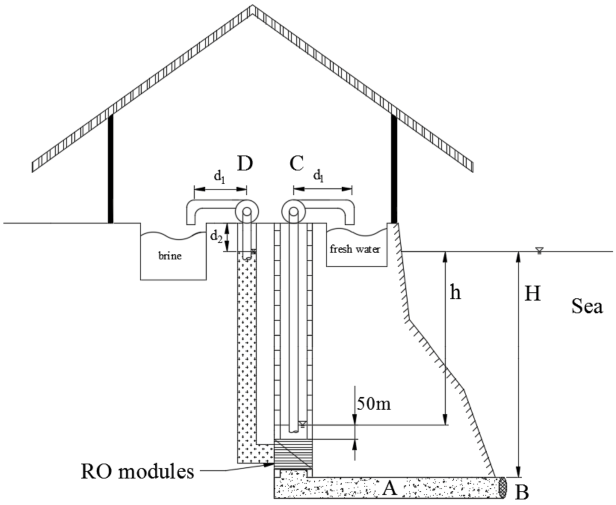

Fig. 2. Schematic illustration for the vertical shaft desalination plant (or VSDP). In the figure, *A* is the horizontal channel to introduce seawater into the vertical shaft, *B* is the seawater inlet filter, *C* is the freshwater pump, *D* is the brine pump. Moreover, the depth of the freshwater is $h = 550$ m, the seawater inlet depth is *H* which shall be 600 m plus the height of ROMs, the brine level is $d_2 = 10$ m underground, the pipe length on the ground is $d_1 = 10$ m.

Consequently, the energy needed to operate VSDP can be divided into three parts. Firstly, the power for Pump *C* to pump the fresh water at a depth of $h + d_2$ to the ground. Secondly, the power for Pump *D* to pump the brine at a depth of d_2 to the ground. And thirdly, the power for Pumps *C* and *D* to send freshwater and brine to their storage tanks on the ground. There are some smaller pressure losses, such as the pressure loss when the brine encounters with the ROMs, the friction loss of the two shafts and the horizontal channel *A*, the friction loss due to the pressure fluctuation at the *B* inlet due to sea waves, and so on. All of them may require extra power to overcome the associated pressure losses, which are nevertheless often negligibly small and will be ignored in this paper accordingly.

3. Analysis of energy consumption

According to the operation of VSDP described in the previous section, we can use the following formulas to calculate the physical parameters relevant to the design of VSDP. First of all, we need to use:

$$\Delta h = \frac{8 \times f \times L \times Q^2}{\pi^2 \times g \times D_i^5} \tag{1}$$

to calculate the head loss of the pipeline [10]. In Eq. (1), *f* is the dimensionless friction factor of the pipeline, *L* is the length of pipeline having a unit m, *Q* is the volume flow rate of the liquid having a unit m^3/s, *g* is the gravitational constant having a unit m/s^2 and D_i is the inner diameter of pipeline having a unit m. Also used is the formula to calculate the power of the pump [10], which is:

$$w = \frac{Q \times \rho \times g \times h_i}{\eta} \tag{2}$$

in which w is the power of pump having a unit watt, ρ is the density of liquid having a unit kg/m^3, h_i is the head loss having a unit m, η is the dimensionless pump efficiency. Then the energy needed to produce a 1 m^3 of freshwater is calculated with [6]:

$$P_o = \frac{1000 \times w}{Q_f \times 3600} \tag{3}$$

in which P_o is the energy needed to produce a cubic meter of freshwater having a unit kWh/m^3, and Q_f is the volume flow rate of freshwater having a unit m^3/s. Also, the formula to define the recovery coefficient r of freshwater from seawater is:

$$r(\%) = \frac{\text{Permeate Flow Rate}}{\text{Feed Flow Rate}} \times 100\% \tag{4}$$

We first calculate the energy needed by Pump C to pump the fresh water from a depth h to the storage tank on the ground. The length of the vertical pipe is $h + d_2$ and the length of the horizontal pipe is d_1. We then calculate the energy needed by Pump D to pump the brine to the ground storage tank, where the length of the vertical pipe is d_2 and the horizontal pipe is d_1. After obtained the results calculated above, the energy needed for VSDP is the summation of the above calculations. In performing the aforementioned calculations, we use the following parameters. The freshwater yield is 12,540 m^3/d, $r = 0.3$, the density of freshwater is $\rho_w = 1{,}000$ kg/m^3, the density of brine is $\rho_b = 1{,}035$ kg/m^3, the efficiency of Pumps C and D are invariably 80%, or $\eta = 0.8$, the friction factor is $f = 0.012$, $g = 9.8$ m/s^2, $d_2 = 10$ m and $d_1 = 10$ m. As for the selection of the ROMs, we assume that the inner diameter of the freshwater shaft is 5 m, so that we can install up to 132 pieces of TOYOBO RO [15] modules whose diameter is 38 cm, and its model is HOLLOSEP-HL10255SI1 (or HHL) [15]. Due to the yield of an HHL is 95 m^3/d, the freshwater produced is 12,540 m^3/d, and the converted freshwater production rate is $Q = 0.145$ m^3/s. By considering $r = 0.3$, the brine production rate is 0.334 m^3/s, which is about 2.3 times the freshwater production rate.

According to the above algorithm, under the assumption that the diameters of all the pipes of VSDP are the same, the energy needed to produce a cubic meter of freshwater can be calculated for different pipe diameters and the results are shown in Table 1. Results show that when the pipe diameter is very small, such as $D_i = 0.1$ m, the friction loss is large so that the energy consumption reaches a high value of 5.960 kWh/m^3. When the pipe diameter increases to $D_i = 0.2$ m, the friction loss immediately decreases significantly and the energy consumption drops to 2.034 kWh/m^3. When the pipe diameter increases to $D_i = 0.3$ m, the friction loss continues to decrease and the energy consumption is reduced slightly to 1907 kWh/m^3, which remains virtually the same when the pipe diameter increases further. Please note that all the calculations are done with Eqs. (1) and (2), which, after applying relevant data above, can be written into the following two formulas respectively,

$$\Delta h = \frac{8 \times 0.012 \times 570 \times 0.1451^2}{\pi^2 \times 9.81 \times D_i^{\,5}} \tag{5}$$

$$w = \frac{0.1451 \times 1000 \times 9.81 \times \left(\Delta h + 550 + 10\right)}{0.8} \tag{6}$$

in which $Q = 0.1451$ m^3/s, $h + d_1 + d_2 = 570$ m, $d_1 = 10$ m and $d_2 = 10$ m are considered.

We then use the algorithm for Table 1 to calculate the energy required to pump the brine to the storage tank on the ground. Since the brine does not pass through the ROMs, the hydrostatic pressure introduced via the horizontal pipeline located in the deep sea does not disappear. Therefore, we can use this hydrostatic pressure to send the brine to a level close to the ground. Assuming the brine shaft is large enough and the flow is slow enough, the friction loss in the shaft will

Table 1
Energy consumption and relevant data of the VSDP required to pump a cubic meter of freshwater to the ground storage tank under different pipe diameters

D_i (m)	P_o (KWh/m^3)	Δh (m)	L (m)	Q (m^3/s)	W (KW)
0.1	5.96062	1,189.91	570	0.1451	3,113.589
0.2	2.03416	37.1846	570	0.1451	1,062.564
0.3	1.92418	4.89674	570	0.1451	1,005.114
0.4	1.91146	1.16202	570	0.1451	998.4693
0.5	1.90880	0.38077	570	0.1451	997.0792
0.6	1.90802	0.15302	570	0.1451	996.6741
0.7	1.90774	0.07080	570	0.1451	996.5277
0.8	1.90762	0.03631	570	0.1451	996.4663
0.9	1.90757	0.02015	570	0.1451	996.4376
1	1.90754	0.01190	570	0.1451	996.4229

be negligible. Therefore, the pressure loss needed to extract the brine consists of the head loss due to the height $d_2 = 10$ m and the pipe friction loss of a total length $d_1 + d_2 = 20$ m. Like Table 1, we still use Eqs. (1) and (2) and relevant data and obtain Eqs. (7) and (8), respectively to calculate the energy consumption required for different pipe diameters D_i.

$$\Delta h = \frac{8\times 0.012\times 20\times 0.3385^2}{\pi^2\times 9.81\times D_i^5} \tag{7}$$

$$w = \frac{0.3385\times 1035\times 9.81\times\left(\Delta h+10\right)}{0.8} \tag{8}$$

The results are listed in Table 2, which shows that when the pipe diameter is as small as 0.1m, the friction loss is very large and the energy consumption is 1.95 kWh/m^3. When the pipe diameter becomes as large as 0.3 m or more, the friction loss decreases rapidly and the energy consumption reduces dramatically to 0.09 kWh/m^3 or less.

We sum up the energy consumptions of Tables 1 and 2 and obtain the total energy consumption needed to produce one cubic meter of freshwater, and the results are shown in Fig. 3. When the pipe diameter is less than 0.3 m, the required energy consumption rises rapidly with reducing pipe diameter. When the pipe diameter is greater than 0.3 m, the required energy consumption remains approximately 1.99 kWh/m^3 being virtually independent of the pipe diameter. Note please that the motor efficiency is not considered in the calculations of Tables 1 and 2, which is because the most advanced motor of the scale used in the VSDP is usually as high as 95%, implying that the consideration of motor efficiency will not alter the results shown in these two tables.

Since the energy consumed by the pumps is the major power consumption of present VSDP, which is used to overcome the friction loss of the pipelines, the value of friction factor f of Eq. (1) becomes crucial to the correctness of the design. In present calculations, we consider $f = 0.012$, which is a mean value of a pipe diameter lying between 0.1 m to 1 m considered by the present study. To confirm the mean value of f is representative to the cases considered, we carry out a comprehensive calculation for all the cases by using six different values of fs, which is $f = 0.010(0.001)0.015$. It ends up that the results of six calculations are of insignificant differences from the result using the mean value of f, implying that $f = 0.012$ is indeed able to represent all the cases considered.

4. Comparisons with other SDPs

From the energy consumption data shown in Fig. 3, we can say the energy efficiency of the present VSDP is satisfactorily good. However, if compared with the other types of SDP shown in Fig. 1, the energy efficiency of the VSDP is not so outstanding. In the following, we will make a comprehensive comparison of the VSDP with the other four SDPs using the hydrostatic pressure to penetrate seawater through the ROMs. We note that the daily freshwater yields of these four designs are all 20,000 m^3/d, which is different from the present yield 12,540 m^3/d Moreover, since their pipelines in terms of diameters and lengths are different from the present VSDP, we shall accordingly re-calculate the performance of the present VSDP based on relevant specifications of each respective design to make the comparison justified.

The first comparison is made for the SDP proposed by Colombo et al. [11]. The features of this design are that the ROMs, pipelines, and pumps are placed on a seabed about 500 m below the sea surface, the hydrostatic pressure is used to force the seawater penetrating through the ROMs, the fresh

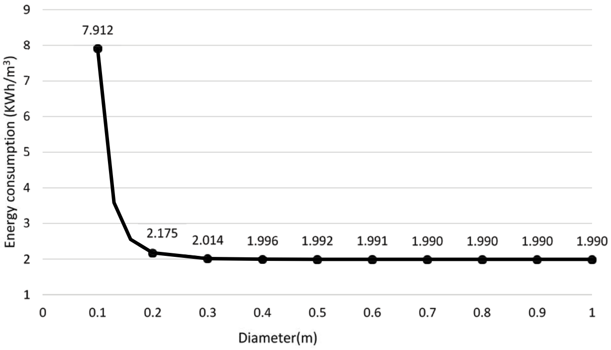

Fig. 3. Energy consumption for producing one cubic meter of freshwater under different pipe diameters.

Table 2
Energy consumption and relevant data for pumping a cubic meter of brine to the ground storage tank under different pipe diameters

D_i (m)	P_o (kWh/m^3)	Δh (m)	L (m)	Q (m^3/s)	W (kW)
0.1	1.951027	227.2221	20	0.3385	1,019.138
0.2	0.140644	7.10069	20	0.3385	73.4669
0.3	0.089935	0.93507	20	0.3385	46.97855
0.4	0.08407	0.221897	20	0.3385	43.91466
0.5	0.082843	0.072711	20	0.3385	43.27374
0.6	0.082485	0.029221	20	0.3385	43.0869
0.7	0.082356	0.013519	20	0.3385	43.01944
0.8	0.082302	0.006934	20	0.3385	42.99115
0.9	0.082276	0.003848	20	0.3385	42.97789
1	0.082263	0.002272	20	0.3385	42.97112

water is pumped to a ground storage tank, and the rejected brine is directly discharged into the deep sea. Particularly, the lengths of freshwater pipe and brine pipe used are 2,000 and 100 m respectively, and the pipe diameters are 0.2 and 0.4 m respectively. In their design, only four ROM units were used while the calculation was made based on a single ROM unit. For each ROM unit, the freshwater flow rate was 0.0579 m^3/s, the brine flow rate was 0.174 m^3/s, and consequently, the seawater flow rate was 0.232 m^3/s being a summation of the flow rates of freshwater and brine. Because hydrostatic pressure was used to replace high-pressure pumps, the energy consumption is lower than most of the conventional SDPs.

We use the inner diameter of their pipes to calculate the energy consumption and the results are shown in Table 3, which shows that the energy consumption for producing freshwater is larger for the VSDP. The main reason can be attributed to that Colombo et al. [11] calculated the P_o of a single ROM unit. Compared with the present calculation involved with 132 ROM units, the calculation of [11] is to some extent deviated from the actual situation, leading to that the P_o of a single ROM unit is lower.

Dashtpour and Al-Zubaidy [6] improved the design of Colombo et al. [11] although the specifications were approximately similar. The improvement is done by using a cylindrical ballast tank to contain all the equipment. The advantage is that, as equipment maintenance is required, the high-pressure air is driven into the ballast tank so that the equipment can float up to sea surface for maintenance. After the maintenance is completed, the pressurized air is released and the seawater is driven into the ballast tank so that the equipment sinks to the seabed again. In this design, although the diameter of the freshwater pipeline is as small as 0.25 m, its total length, however, is higher than 3,000 m. This long pipeline causes a significant friction loss, resulting in high energy consumption of 2.41 kWh/m^3, which is much higher than the energy consumption of the present VSDP. Please see the comparison shown in Table 4.

Reali et al. [10] proposed another design by placing the ROMs, pipes, and pumps directly on a seabed about 500 m below the sea surface. Because of the height of 500 m, it could generate enough hydrostatic pressure for the seawater to penetrate through the ROMs. The freshwater produced was pumped to the ground storage tank but the brine was discharged directly into the sea. The overall design is quite similar to the present VSDP although its energy consumption is relatively small. The reason is that the ROMs used by the two designs have a different recovery rate. The ROMs of [10] have a recovery rate of 0.25 and the required depth is 500 m. The recovery rate of the present study is 0.3 and the required depth is 550 m. A deeper position of the ROMs means a longer pipe is needed for the freshwater pipe, leading to an increase of 11% of energy consumption, please see the comparison shown in Table 5.

Charcosset et al. [8] also proposed an SDP similar to [11]. Namely, all equipment such as the ROMs, pipes, and pumps are placed on the seabed about 500 m below the sea surface, the hydrostatic pressure is used to force the seawater to penetrate through the ROMs, the freshwater produced is pumped to the ground storage tank, and the brine is discharged into the sea. We list in Table 6 the specifications of their design and the energy consumption calculated, which are used to compare with the corresponding data of present VSDP. The results show that the much longer pipe used by [8] results in much higher energy consumption than the present VSDP.

In summary, the differentiation of present VSDP from the previous ones stems from several design criteria. Firstly, the length of the pipeline of the present design is much smaller. Secondly, the use of the seawater pipeline proposed by Colombo et al. [10] is exempted from the present design. Moreover, because hydrostatic pressure is used to replace high-pressure pumps, the energy consumption of the present design is lower than most of the conventional SDPs. Finally, the equipment places in deeper water than other designs do. The major differentiations are that the present design

Table 3
Energy consumption and the pipeline specification of the SDP proposed by Colombo et al. [11], which are compared with the data of present VSDP (numbers in parentheses)

	D_i (m)	L (m)	P_o (KWh/m^3)
Fresh water pipe	0.2	2,000 (570)	1.771 (2.034)
Brine pipe	0.4	100 (20)	0.107 (0.084)
Seawater pipe	0.4	10 (none)	negligible

Table 4
Energy consumption and the pipeline specification of the SDP proposed by Dashtpour and Al-Zubaidy [6], which are compared with the data of present VSDP (numbers in parentheses)

	D_i (m)	L (m)	P_o (kWh/m^3)
Fresh water pipe	0.25	3,050 (570)	2.41 (1.95)
Brine pipe	0.5	50 (20)	0.0084 (0.083)
Sea water pipe	0.5	10 (none)	0.0036 (0)

Table 5
Energy consumption and the pipeline specification of the SDP proposed by Reali et al. [10], which are compared with the data of present VSDP (numbers in parentheses)

	D_i (m)	L (m)	P_o (kWh/m^3)
Fresh water pipe	0.4	600 (570)	1.716 (1.911)
Brine pipe	0.8	700 (20)	0.1164 (0.0823)
Sea water pipe	0.8	700 (none)	0.0276 (0)

Table 6
Energy consumption and the pipeline specification of the SDP proposed by Charcosset et al. [8], which are compared with the data of present VSDP (numbers in parentheses)

	D_i (m)	L (m)	P_o (kWh/m^3)
Fresh water pipe	0.2	2,000 (570)	2.819 (2.034)
Brine pipe	0.4	100 (20)	0.156 (0.084)
Sea water pipe	0.4	10 (none)	0.01 (0)

installs the pipeline in the vertical shaft so that the possible erosions of the pipeline due to the harsh environment in the deep ocean can prevent, the life span of pipelines will extend and the maintenance cost may reduce. Moreover, the present design exempts from the use of the seawater pump, leading to a decrease in energy consumption and a waiver of the maintenance work for pipelines.

5. Concluding remarks

We have proposed a VSDP consisting mainly of two vertical shafts to respectively produce the freshwater and recover the rejected brine. The freshwater was produced by penetrating seawater through ROMs and the plant is powered by hydrostatic pressure. As a result, the overall energy consumption is approximately 2 kWh/m^3, being an energy-efficient SDP when comparing with other designs. To reveal the design characteristics of present VSDP, we refer to the data shown in Dashtpour and Al-Zubaidy [6] to make Table 7, in which relevant specifications of the SDPs constructed by different technologies are shown. As one can see from the data listed in the table, the freshwater output of the present design is 12,540 m^3/d, which is about 1/10 of most SDPs listed in the table, while it is about double compared to the smallest one. Nevertheless, the energy performance is 1.99 kWh/m^3 which is rather outstanding compared with other designs.

In addition to the low energy consumption, the present VSDP has the following advantages. For example, the pressure to press seawater through the ROMs is hydrostatic, which is not like the dynamic pressure generated by rotating a high-pressure pump that may damage the ROMs accidentally [6]. Moreover, the seawater used is from the sea at 500 m deep, which is generally less polluted and may contain some trace elements having added-value to the freshwater produced. Finally, except Pump *C* and Pump *D* which are machines equipped with rotating mechanisms, the other components of present VSDP are pipelines and RO modules. As a result, the maintenance work is relatively simple because cleaning the pipelines and replacing the RO modules stand for most of the maintenance work. Fixing the pumps on the ground is relatively simple and easy, although it may occur only on rare occasions.

To gain these advantages, the vertical shafts need to be easily cleaned and the ROMs need to be easily replaced. Accordingly, several features shall be embedded in the shaft design. Firstly, the diameter of the shaft is preferably greater than 1m, so that the maintenance machine can easily enter the shaft and operate. However, the shaft diameter should not be too large because the cost of shaft construction is proportional to its size. Therefore, a proper shaft size shall be an important parameter to be decided by the designer. Also, the inner wall of the shaft is preferably supported by a circular hollow bushing, which can be made of reinforced concrete to prevent the shaft from collapsing and the surrounding groundwater seeping into the well. Each hollow bushing can have a thickness of 10 cm and a height of 3 m. Rivets and holes can be set on the upper and lower circumferences of the bushing respectively to facilitate the joining of the upper and lower bushings. The inner surface of the bushing should be sprayed with a non-staining coating. After excavating the shaft to a predetermined

Table 7
Specification and energy performance of various SDPs and present study [6]

Plant name	Country	Product flow rate (m^3/d)	Energy consumption (kWh/m^3)
Ashkelon	Israel	330,000	4
Taweelah	UAE	227,000	4
Carlsbad	USA	189,000	3.6
Fujairah	UAE	170,000	3.8
Palmachim	Israel	150,000	2.91
Kwinana-Perth	Australia	140,000	3.7
Ionics Trinidad	Trinidad and Tobago	136,000	3.8
Tuas	Singapore	136,000	4.1
Tugun Queensland	Australia	133,000	3.6
Medina-Yanbu II	KSA	128,000	5.56
Jeddah Phase I & II	KSA	113,000	8.2
Tampa Bay	USA	95,000	2.96
Al-Jubail	KSA	91,000	7.45
Las Palmas III-IV	Spain	80,300	4.4
Marbella	Spain	55,000	4
Larnaca	Cyprus	54,000	4.5
Grand Cayman	Cayman Island	37,000	4.2
Sureste	Spain	33,000	4.4
Ċirkewwa	Malta	18,600	4.5
Porto Santo	Portugal	6,000	4.28

depth, the bushings are buried one by one until the entire shaft is supported by the bushings.

After the construction of the vertical shaft is completed, the ROMs shall then install at a designed position about 550 m below the surface, where a fixed bushing had been placed on the predetermined position. When the ROMs are fixed above the bushing, they shall cover with another bushing to assure that the ROMS will not displace due to the pressure fluctuation generated by the ocean wave. Regarding the horizontal water intake pipe *A*, it is suggested to install a screen filter at the seawater inlet to prevent foreign matter such as submarine organisms or seabed rock from entering the pipeline. Near the RO modules, one may connect a pressure relief pipe to the main shaft to release the pressure fluctuation from the ocean wave at the surface.

On the other hand, the present VSDP can be seen as an environment-friendly design due to the following reasons. By observing Figs. 1 and 3, one can easily reach the conclusion that the energy consumption of present design is lower than most of the previous designs, implying that the present VSDP is more environmentally friendly because the energy consumption is lower. Furthermore, the present VSDP extracts the brine up to the ground instead of dumping directly into the ocean to prevent brine pollution in the deep ocean. Finally, because the wind is generally strong close to the seashore where the VSDP is supposed to construct, we propose to set up a medium-size wind turbine to supply the power needed by VSDP, which is also an environment-friendly design.

Finally, we propose the following schemes to reduce production costs. Firstly, the rejected brine can be recovered and processed to be made into a wide variety of products for sale [16]. Nonetheless, if the brine is not of high economic value, it can be considered to be rejected directly to the sea. As a result, the need to construct the brine shaft is eliminated and the operating cost to extract the brine is saved. As one can see from Tables 2 and 3, the energy consumption can accordingly decrease by 4%, enhancing the competitiveness of this design. To make the VSDP ecologically friendly, the required electricity can be generated by renewable energy such as solar photovoltaic or wind turbine. For the VSDP producing 12,540 tons of fresh water per day, for example, the required electrical energy is $1.99\text{k Wh/m}^3 \times 12{,}540\ \text{m}^3/\text{d} = 24{,}955\ \text{kWh/d}$. To generate the electricity needed, a 5 MW wind turbine running 6 h/d in full capacity may be sufficient. If the solar photovoltaic panel is used to generate electricity, assuming a daily sunlight exposure of 4 h, a PV of about $6 \times 2.496 \times 10^4\ \text{m}^2$ area is required.

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