Development of an integrated solar-driven desalination system for remote areas in Saudi Arabia

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\textit{In collaboration:}

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The world’s fresh water source represents **2.5%** of the world’s total water supply. Over 68% is locked in glaciers and polar ice caps. Another 30% is groundwater. The rest is surface water (rivers and lakes) which is only **0.005%** of the total water in the world.
World population grows

thousands years ago
In the year 1850
Today, more people live on this world than ever died on it!

Population growth will decrease fresh water per capita availability
The World Water Council predicted that about two-thirds of world’s population may face freshwater shortage problem by 2025. Saudi Arabia and other Middle East and North Africa (MENA) countries are facing physical water scarcity.
Figure 3. World’s installed desalination plant by processes

Saudi Arabia → large-scale desalination plants account for about 24% of total world capacity and most of them are driven by fossil fuels.

Energy crisis

The problem is …

Figure 4. Expected energy demand in EU - MENA

Energy demand is multiplying, while fossil resources are depleted → Energy crisis

Figure 5. Oil and Gas Liquids – 2004 scenario

Water and energy are critical and mutually dependent resources. The production of energy requires large volumes of water and water infrastructure requires large amounts of energy.

Energy crisis due to the decline of oil resources in the world → water scarcities are predicted to get worse. Water scarcity certainly will lead to energy problems and will become more complicated.

Not to mention the global warming caused by increase of CO₂ emission from fossil fuels → climate change which will affect water supply and availability.
### Table 1. Yearly estimated potential of different renewable energies

<table>
<thead>
<tr>
<th>Energy Type</th>
<th>Gross theoretical useful potential</th>
<th>Technically feasible potential</th>
<th>Current economic potential</th>
<th>Total installed capacity (2003)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biomass</td>
<td>8-14 TW</td>
<td>6-8 TW</td>
<td>No data</td>
<td>1.6 TW</td>
</tr>
<tr>
<td>Hydraulic</td>
<td>4.6 TW</td>
<td>1.6 TW</td>
<td>0.8 TW</td>
<td>0.65 TW</td>
</tr>
<tr>
<td>Geothermal</td>
<td>66 TW</td>
<td>11.6 TW</td>
<td>0.6 TW</td>
<td>0.054 TW</td>
</tr>
<tr>
<td>Wind</td>
<td>20 TW</td>
<td>2 TW</td>
<td>0.6 TW</td>
<td>0.006 TW</td>
</tr>
<tr>
<td>Solar</td>
<td>600 TW</td>
<td>60 TW</td>
<td>0.15-7.3 TW</td>
<td>0.005 TW</td>
</tr>
<tr>
<td>Ocean</td>
<td>234 TW</td>
<td>No data</td>
<td>No data</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>1030 TW (approx.)</td>
<td>85 (approx.)</td>
<td>7 TW (approx.)</td>
<td>2.3 (approx.)</td>
</tr>
</tbody>
</table>

Figure 6. Yearly sum of direct normal irradiance across the world
A portable solar-driven desalination system has been developed in collaboration between KSU and NTU.

The system covers the two keys sources of water and energy. The system is a self-contained (stand-alone) system which does not need external energy sources. It utilizes the renewable energy from the sun (by PV-thermal collector) for its operation to produce high quality of water for human use.

Figure 7. Picture of the portable solar-driven desalination system (at King Saud University)
The system is designed to be able to operate in remote areas or areas affected by natural disasters. The system should be compact so that numerous systems can be deployed in case of emergency such as natural disasters. For the portability purpose, a 20 ft container (cargo) is used. All the equipment are mounted on the container except for the PV array.
Figure 9. The layout of the portable solar-driven desalination system (top view)
Figure 10. Flow diagram of the portable solar-driven desalination system (simplified)
Portable solar-driven desalination system

Figure 11. Schematic design of the portable solar-driven desalination system
Portable solar-driven desalination system

Figure 12. Hybrid Energy System architecture
# Solar-thermal system

![Figure 13. HMI screen display of solar thermal collector loop](image)

**Table 2.** List of solar-thermal system equipment in portable desalination system

<table>
<thead>
<tr>
<th>No.</th>
<th>Item</th>
<th>Quantity</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Solar thermal collectors</td>
<td>18</td>
<td>Evacuated tube collector CPC 1506 (6 tubes each)</td>
</tr>
<tr>
<td>2</td>
<td>Thermal storage tank</td>
<td>1</td>
<td>600 L capacity, with 50 mm polyurethane foam insulation and backup heater 3kW.</td>
</tr>
<tr>
<td>3</td>
<td>Circulation pump</td>
<td>2</td>
<td>Rated power 0.37kW/0.5 HP</td>
</tr>
<tr>
<td>4</td>
<td>Temperature sensor</td>
<td>3</td>
<td>Pt 100</td>
</tr>
<tr>
<td>5</td>
<td>Flow meter</td>
<td>2</td>
<td>Measuring range 0.010 - 6 m³/h</td>
</tr>
<tr>
<td>6</td>
<td>Motorized valve</td>
<td>2</td>
<td>Power 14 W, rotation angle (0°-90°)</td>
</tr>
<tr>
<td>7</td>
<td>Floating switch</td>
<td>1</td>
<td>3 floating sensor located at 5, 60 and 115 cm</td>
</tr>
</tbody>
</table>
Figure 14. Photograph of the solar-thermal system
**Table 3. Technical characteristics of the solar thermal collector**

<table>
<thead>
<tr>
<th>Series</th>
<th>CPC 1506</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of evacuated tubes</td>
<td>6</td>
</tr>
<tr>
<td>$\eta_0$ (%, Aperture area), DIN 4757</td>
<td>66.1</td>
</tr>
<tr>
<td>$C_1$ with wind, in relation to aperture area (W/m$^2$ K)</td>
<td>0.82</td>
</tr>
<tr>
<td>Gross surface area / aperture area (m$^2$)</td>
<td>1.15 / 1.0</td>
</tr>
<tr>
<td>Collector contents (l)</td>
<td>0.8</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>19</td>
</tr>
<tr>
<td>Max. working overpressure (bar)</td>
<td>10</td>
</tr>
<tr>
<td>Max. stagnation temp. (°C)</td>
<td>295</td>
</tr>
<tr>
<td>Tube material</td>
<td>copper</td>
</tr>
<tr>
<td>Glass tube material</td>
<td>Borosilicate glass 3.3</td>
</tr>
<tr>
<td>Selective absorber coating material</td>
<td>Aluminium nitrite</td>
</tr>
<tr>
<td>Glass tube (Ø ext./Ø int./wall thickness/tube len.) (mm)</td>
<td>47/37/1.6/1500</td>
</tr>
</tbody>
</table>
**Table 4. Equipment list of PV system on portable desalination system**

<table>
<thead>
<tr>
<th>No.</th>
<th>Item</th>
<th>Quantity</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PV module</td>
<td>16</td>
<td>Max. power ($P_{\text{max}}$) 3.36 kW (SANYO HIT)</td>
</tr>
<tr>
<td>2</td>
<td>Solar battery charger with Maximum Power Point Tracker (MPPT)</td>
<td>2</td>
<td>Max 60 amps continuous battery current; max. solar input 12,24,36,48 VDC</td>
</tr>
<tr>
<td>3</td>
<td>Battery pack</td>
<td>8</td>
<td>12 V 170 Ah lead acid battery</td>
</tr>
<tr>
<td>4</td>
<td>AC/DC Inverter</td>
<td>1</td>
<td>Output: Rated power (typ) 3000 W, sinewave, 50-60 Hz, 200-240 VAC; Input: 48 V, 75 A.</td>
</tr>
<tr>
<td>5</td>
<td>DC/DC Converter</td>
<td>1</td>
<td>Rated power (typ) 504 W, 24 VDC, 0-12 A; Input: 19-72 VDC,</td>
</tr>
<tr>
<td>6</td>
<td>DC shunts</td>
<td>3</td>
<td>Sensing element: manganin</td>
</tr>
</tbody>
</table>
**Solar-photovoltaic (PV) system**

![Photograph of the PV array beside the container](image_url)

**Figure 16.** Photograph of the PV array beside the container
The core of the portable desalination system is MEMSYS Vacuum Multi Effect Membrane Distillation (V-MEMD) system.

MEMSYS process is a new desalination technology which combines the advantages of multi-effect distillation process and membrane separation process into a small modular configuration under vacuum and multiple recycling of thermal energy.

The membrane is polytetrafluoroethylene (PTFE) with a pore size ~ 0.2 mm. The dimension of single sheet of membrane is 335 mm x 475 mm.

**Figure 17.** Photographs of a) PTFE hydrophobic membrane; b) PP foil; c) single stage; and d) complete MEMSYS system
The membrane is polytetrafluoroethylene (PTFE) with a pore size $\sim 0.2$ mm.
The dimension of single sheet of membrane is 335 mm x 475 mm.
Membrane Distillation (MD) process

Figure 19. Schematic operating principle of membrane distillation (MD) process - DCMD

The temperature difference across the membrane generates a vapor pressure difference between the two sides. This is the driving force that makes the water vapor pass through the membrane and then condenses on the lower temperature side, and distillate is formed. The hot aqueous seawater solution cannot penetrate through the pores, of the hydrophobic membranes.
Membrane Distillation (MD) process

In general, MD process offers some advantages, which are:

- High-quality distillate because it has a high rejection factor.
- Operated at around atmospheric pressure, with different levels of salinity due to the absence of osmotic pressure-driven limitation of a reverse osmosis (RO) process.
- Moderate operating temperature (in the range of 60-80°C).
- Less demanding of membrane characteristics, and less-expensive material can be involved such as plastic, thus diminish corrosion problems.
- The membrane pore size is relatively larger than other processes, such as RO; therefore resistant to scaling and fouling.
- No chemical pre-treatment of the feed seawater.
- With abundant solar energy available, MD process offers advantages for the construction of a solar powered, stand-alone desalination system.
Figure 20. Basic principle of MEMSYS Vacuum-Multi-Effect-Membrane-Distillation (V-MEMD) process.
Figure 21. MEMSYS Human Machine Interface (HMI)

Table 5. Equipment list of MEMSYS V-MEMD system

<table>
<thead>
<tr>
<th>No.</th>
<th>Item</th>
<th>Quantity</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Internal heat loop pump</td>
<td>1</td>
<td>220 V, 50 W</td>
</tr>
<tr>
<td>2</td>
<td>Feed pump</td>
<td>1</td>
<td>220 V, 45 W</td>
</tr>
<tr>
<td>3</td>
<td>Cooling pump</td>
<td>1</td>
<td>220 V, 95 W</td>
</tr>
<tr>
<td>4</td>
<td>Brine discharge pump</td>
<td>1</td>
<td>220 V, 180 W</td>
</tr>
<tr>
<td>5</td>
<td>Distillate discharge pump</td>
<td>1</td>
<td>220 V, 180 W</td>
</tr>
<tr>
<td>6</td>
<td>Seawater circulation pump</td>
<td>1</td>
<td>220 V, 95 W</td>
</tr>
<tr>
<td>7</td>
<td>Vacuum pump</td>
<td>1</td>
<td>230 V</td>
</tr>
<tr>
<td>8</td>
<td>Membrane module</td>
<td>1</td>
<td>PTFE hydrophobic membrane, PP foil &amp; frame</td>
</tr>
<tr>
<td>9</td>
<td>BnR PLC</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Heat exchanger</td>
<td>1</td>
<td>Flat plate heat exchanger</td>
</tr>
</tbody>
</table>
Advantages of the MEMSYS process are:

- Energy efficient through multiple recycling of energy
- Robust, because its thermal self adjusting properties and small tendency for fouling and scaling, because not water that passes through the membrane but only the clean vapour.
- Low investment cost, through the use of plastic materials
- Low operating cost, because of the efficient use of low waste energy and very little need of pretreatment.
- Sustainable, since materials are recyclable, the need for chemical and pretreatment is low and waste of solar energy is efficiently put to use.
- Wide variety of application due to its modularity and ability to also deal with very highly concentrated salt solution (different solutions).
Figure 22. Picture of the heat pump and all its parts
Figure 23. Schematic of refrigeration system of the heat pump

Cooling capacity 3.0 kW (1.6-3.2 kW) min temp. 10°C; Heating output 4.0 kW (2.2-4.2 kW) max temp. 55-60°C, input 220-240 V/420-1200 W
Programmable Logic Controller - PLC

Figure 24. Photograph of Schneider PLC (left) and BnR PLC (right)
Figure 25. Logic flowchart for the automation control.
SCADA system stands for **Supervisory Control and Data Acquisition** system. This system refers to the centralized system that allows an operator to monitor, control and coordinate processes online that are installed in various remote sites. It will acquire all the required data from the process and giving commands to the process.
Figure 26. Illustration of SCADA implementation to control and monitoring the portable system in remote areas of Saudi Arabia
Successful development of a portable solar-powered desalination system will be very useful for Kingdom of Saudi Arabia.

1. As one of the countries in the world which has abundant solar irradiation and limited natural water resource will make the system is highly suited to be implemented in the kingdom.

2. The system utilizes renewable solar energy for its operation instead of fossil fuels. By this way, the oil reserves in Saudi Arabia can be saved.

3. Indirectly, it will also reduce CO$_2$ emissions (global warming) which coming from the use of fossil fuels that are generally used as energy sources in most desalination plant in Saudi Arabia.

4. Furthermore, this system can be served as sustainable desalination technology for the future of Saudi Arabia when there is no oil reserves remain.
Figure 27. Measured performance of the portable system (with heat pump) during one day operation (24/12/2012) in King Saud University, Riyadh, KSA
The system started at 8:00 AM, followed the course of global solar radiation with a maximum of 682 W/m² at noon and stopped at 3:30 PM. The first hour, was used to heat up the water by circulating the water from the tank to the thermal collector. The temperature of the thermal storage tank was 53.2 – 65°C.

The MEMSYS V-MEMD system started at 9:00 AM. The feed used was brackish water with average conductivity of 1650 μs/cm. The conductivity was measured using Multi-Parameter Analyzer DZS-708 from Cheetah. The feed flow was manually adjusted to about 117 l/h. The maximum evaporator inlet temperature only reaches 56.9°C. Around the same time, the maximum of distillate production reached 7.45 l/h. The cumulative volume of distillate gained on that operating day was about 32.4 l with average conductivity of 12 μs/cm. Whereas, the total amount of distillate gained from a short test (12:00 AM – 4:00 pm) during summer 2012 was about 48 l.
Figure 28. Energy harnessed and converted into thermal and electrical energy during one day operation (24/12/2012) in King Saud University, Riyadh, KSA
Figure 29. Dynamic behaviour of the MEMSYS V-MEMD system during one day operation (24/12/2012) in King Saud University, Riyadh, KSA
The system was running smoothly during the short test. The system was operated in manual mode to observe and evaluate some parameters (e.g. feed temperature, feed flowrate, etc.)

- Data during a short term test on winter 24 Dec 2012 (9:00 AM – 3:30 PM, 6.5 hours):
  1. Maximum global solar radiation = 682 W/m² (at noon)
  2. Thermal power harnessed = 4924 W (max at noon); PV power harnessed = 1270 W (max at noon)
  3. Thermal storage tank temperature = 53.2 – 65°C
  4. Feed flowrate = 117 l/h (brackish water with average conductivity 1650 μs/cm)
  5. Pre-heated feed temperature = 19.2 – 38.6°C (during operation)
  6. Max distillate production rate = 7.45 l/h (at noon)
  7. Total distillate volume gained = 32.4 l (average conductivity 12 μs/cm)

- During a short test on summer 16 May 2012 (12:00 PM – 4:00 PM)- Distillate volume gained = 48 l

- During a short test on winter 25 Dec 2012 (9:00 AM – 3:30 PM, 6.5 hours) – without heat pump (without feed pre-heating) and same flowrate (117 l/h) → Distillate volume gained = 7.2 l

- During a short test on winter 26 Dec 2012 (9:00 AM – 3:30 PM, 6.5 hours) – without heat pump and lower flowrate (78 l/h) → Distillate volume gained = 16.2 l

From the short test, it can be concluded the feed rate and temperature will significantly affect the distillate production. Adjustment of these two parameters is needed to get the optimum operating condition. Other important parameter : thermal energy supply, solar radiation (winter vs summer), etc. Automation of the system will be tested in the near future.
References

13. Pangarkar BL, Sane MG, Parjane SB, and Guddad M. Engineering and Technology 2011;51:797-802.
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