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

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***In collaboration*:**

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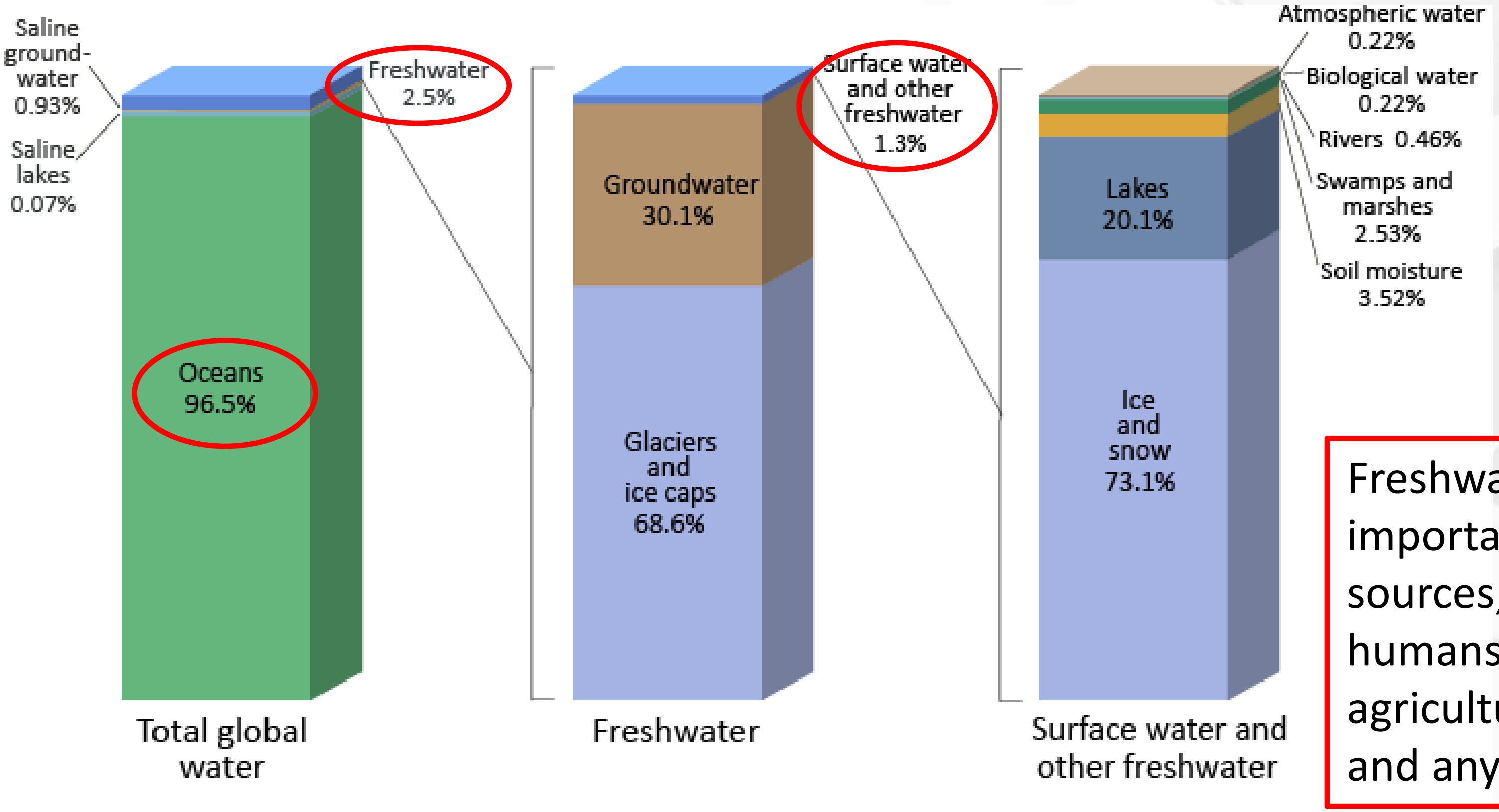
Earth's water distribution



Freshwater is very important renewable sources, required by humans for drinking, agriculture, industry and any other uses.

Source: Igor Shiklomanov's chapter "World fresh water resources" in Peter H. Gleick (editor), 1993, Water in Crisis: A Guide to the World's Fresh Water Resources.

Figure 1. Distribution of Earth's water

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

World population grows

thousands years ago

World population

World population grows and grows …

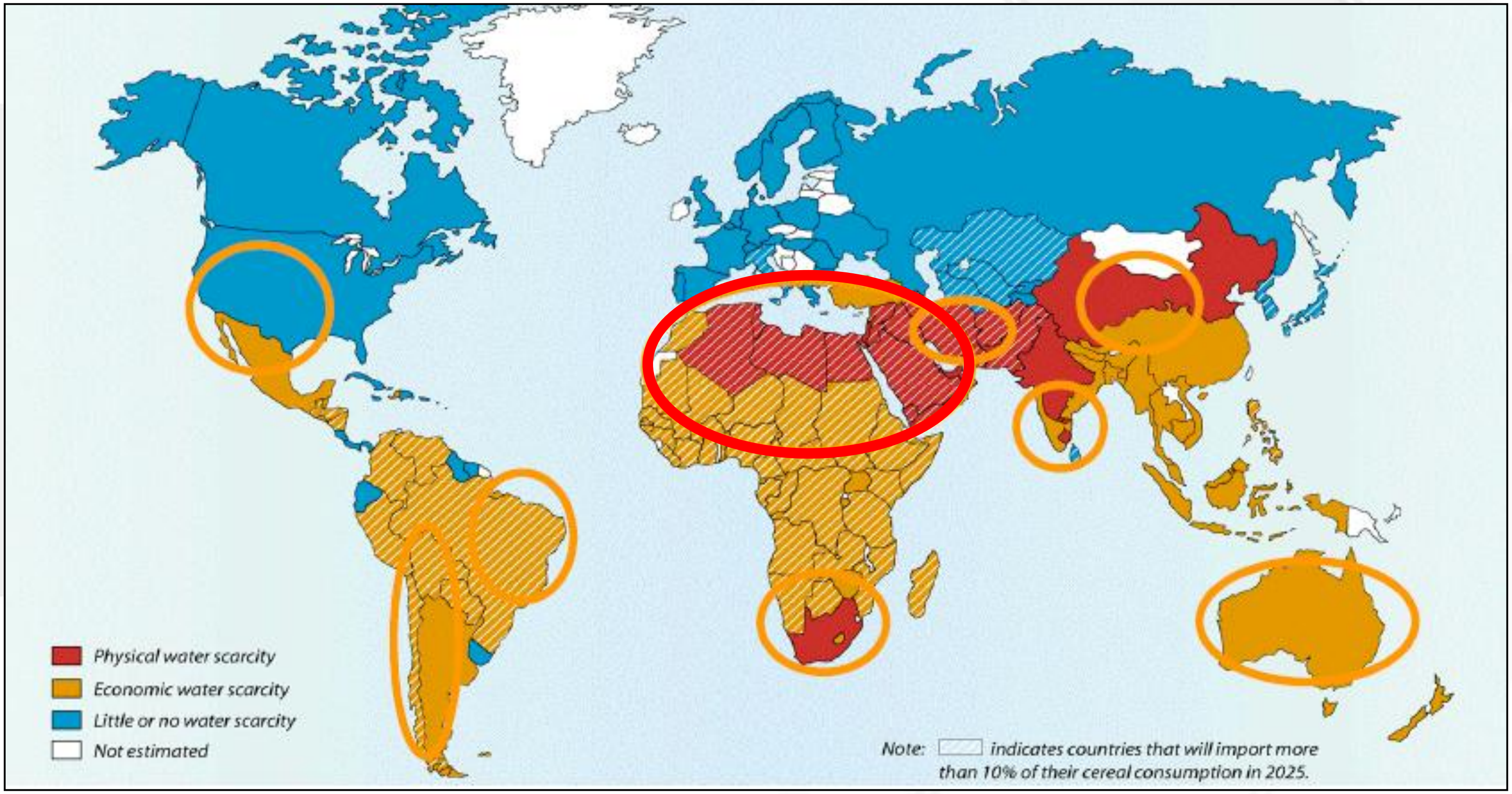
In the year 1850

World population

Today, more people live on this world than ever died on it!

Population growth will decrease fresh water per capita availability

Global water scarcity

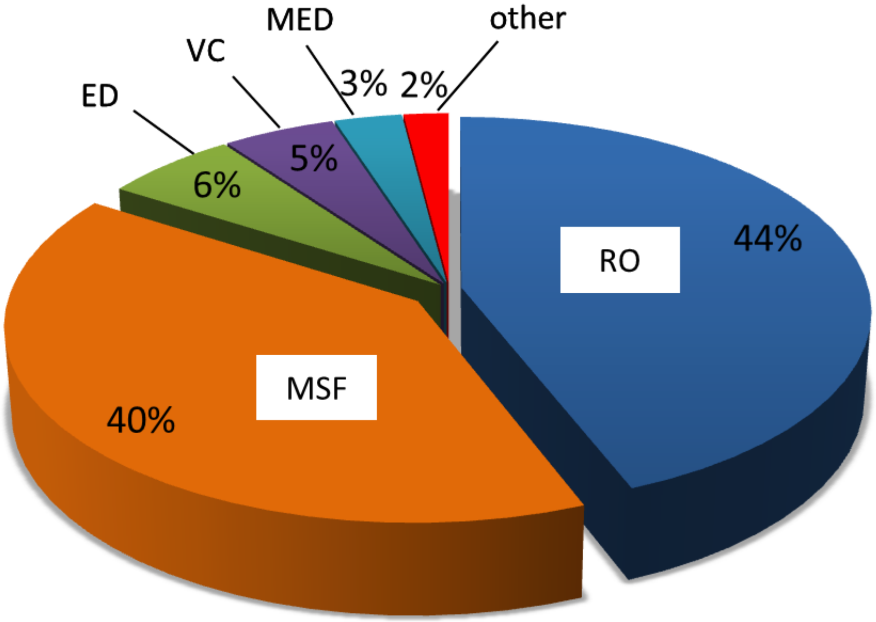


Source: http://images.organicjar.com/wp-content/uploads/2009/07/water_scarcity.jpg

Figure 2. Global water scarcity across the world

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.

Desalination



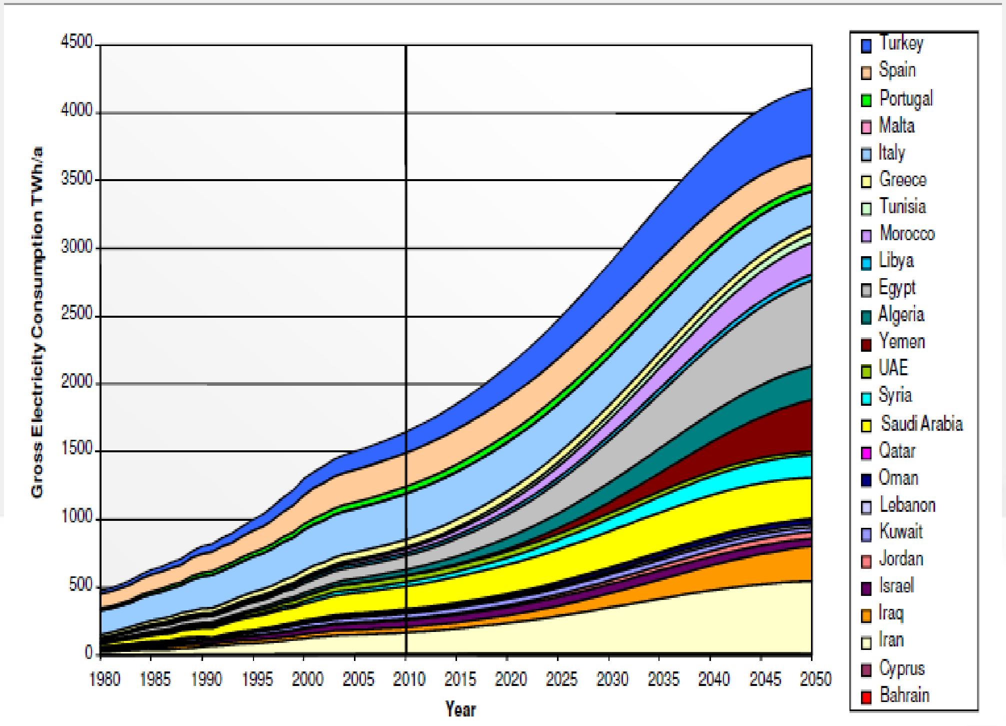
Source: M.K. Wittholz, B.K. O'Neill, C.B. Colby, D. Lewis, Estimating the cost of desalination plant using a cost database, Desalination 229 (2008) 10-20

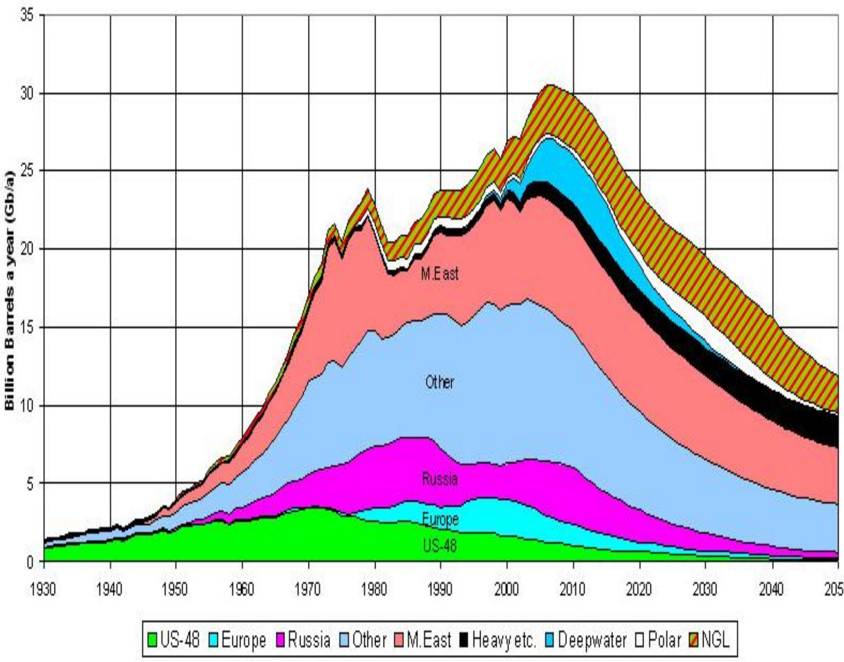
Figure 3. World's installed desalination plant by processes

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 …





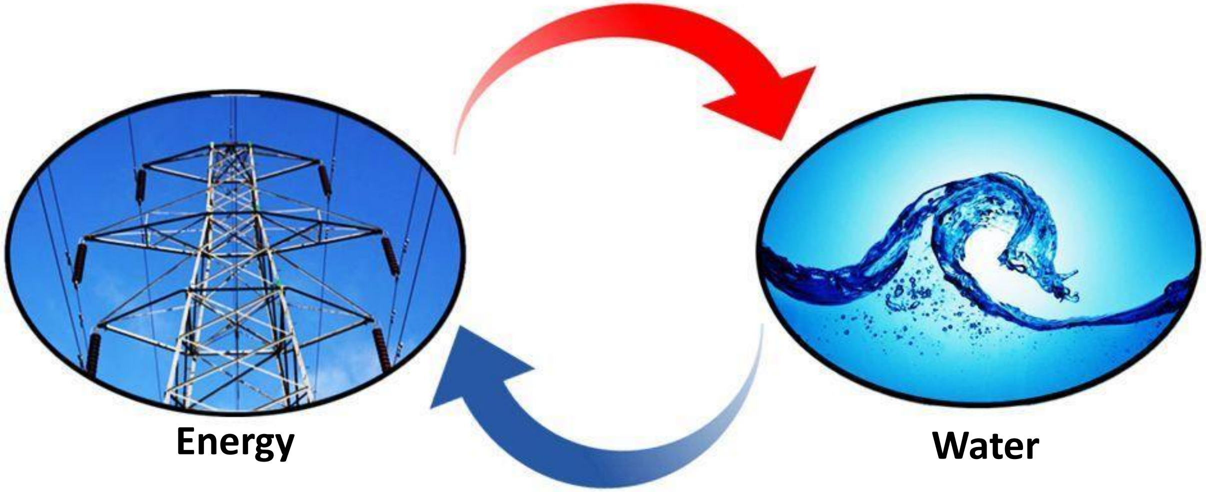
http://www.oilcrisis.com/campbell/images/2004Scenario.jpg

Figure 4. Expected energy demand in EU - MENA

Figure 5. Oil and Gas Liquids – 2004 scenario

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

Nexus of Water and Energy



Water desalination, waste water treatment, transmission, etc.

Energy

Water

Cooling, steam generation, fuel production, etc.

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 CO_2 emission from fossil fuels → climate change which will affect water supply and availability

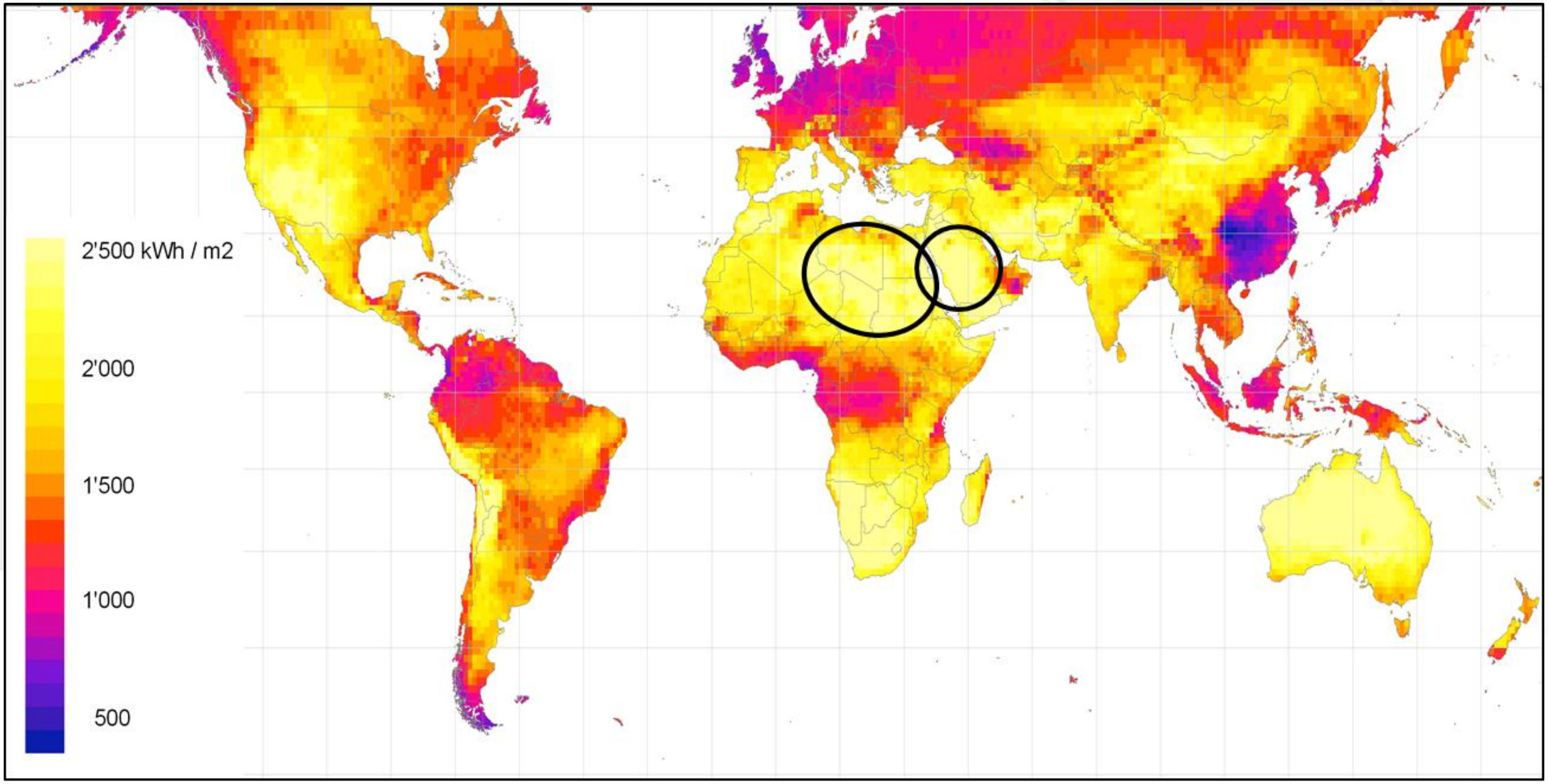
An alternative method ....

Table 1. Yearly estimated potential of different renewable energies

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

Source: J. Blanco, et al. Review of feasible solar energy applications to water processes, Renewable and Sustainable Energy Reviews 13 (2009) 1437-1445

Solar energy potential



Source: Meteonorm 6.0 (www.meteonorm.com); uncertainty 15%
Period: 1981 - 2000; grid cell size: 1°

June 2008

source http://meteonorm.com/fileadmin/user_upload/maps/world_beam_8100.png

Figure 6. Yearly sum of direct normal irradiance across the world

Portable solar-driven desalination system

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)

Portable solar-driven desalination system

The container

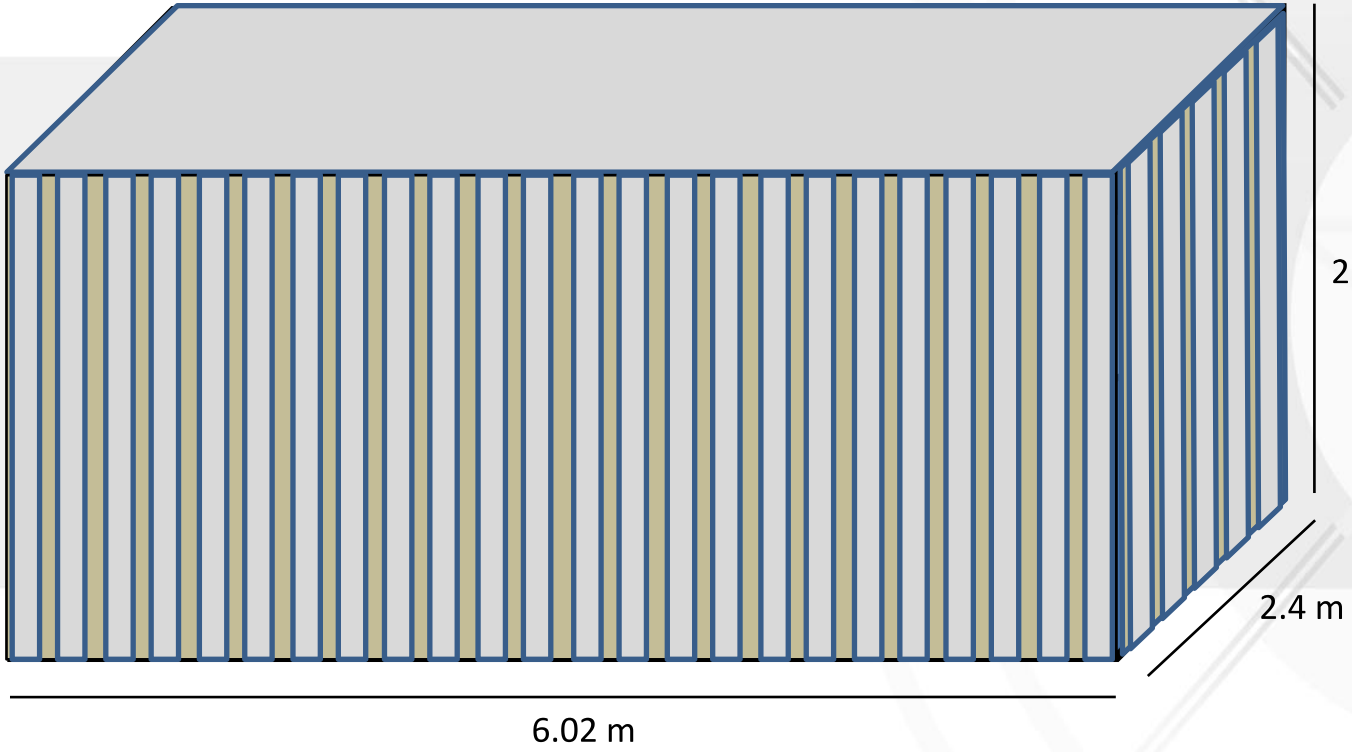
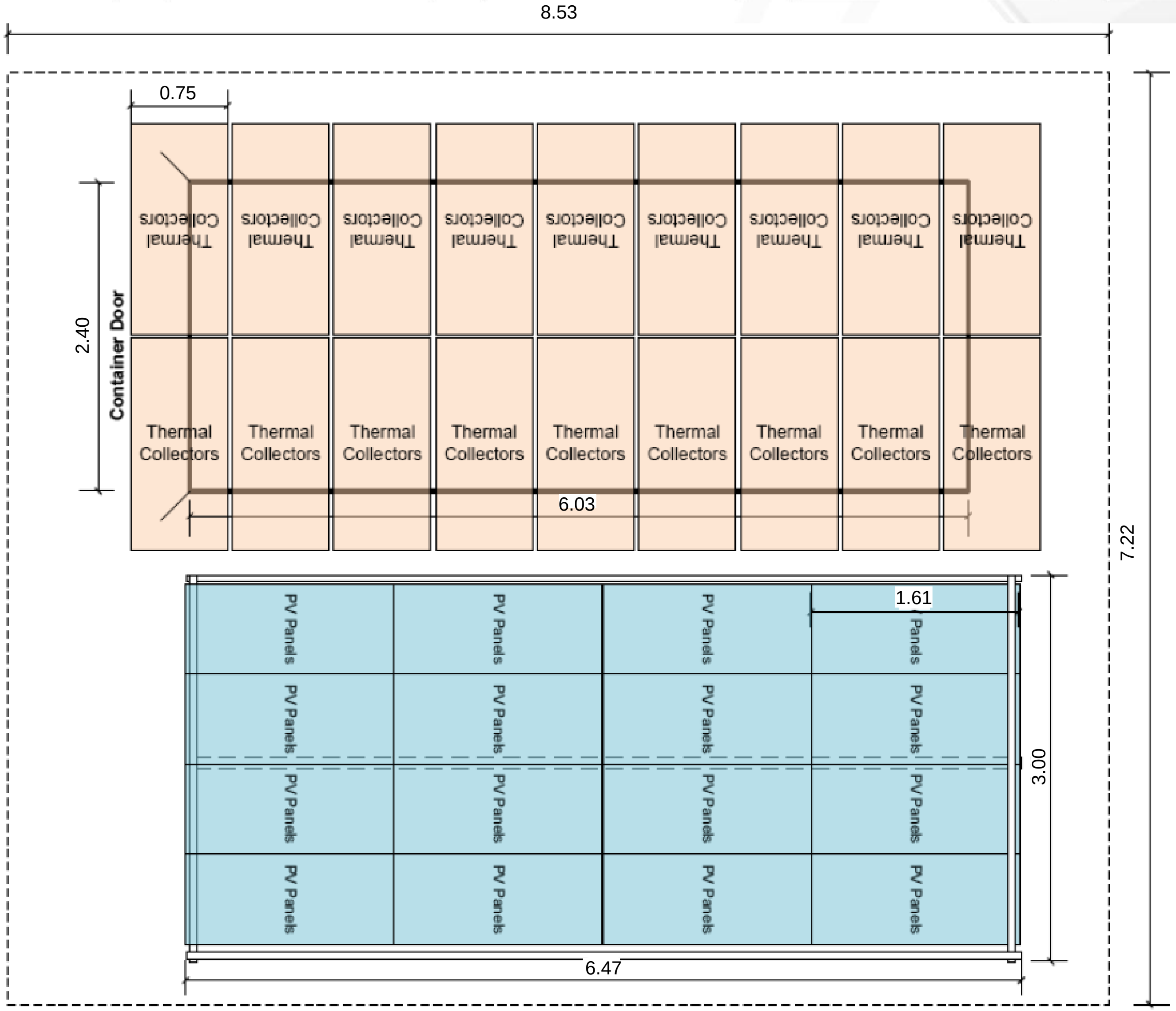


Figure 8. The layout of the container

Ultrafiltration cartridge (pre-filter) Hollow fibre, hydrophilic modified PAN

The system is designed to be able to operate in remote areas or areas affected by natural disaster. 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.

Portable solar-driven desalination system



All dimension in meter

Estimated area required = 56 -72 m2

Figure 9. The layout of the portable solar-driven desalination system (top view)

Portable solar-driven desalination system

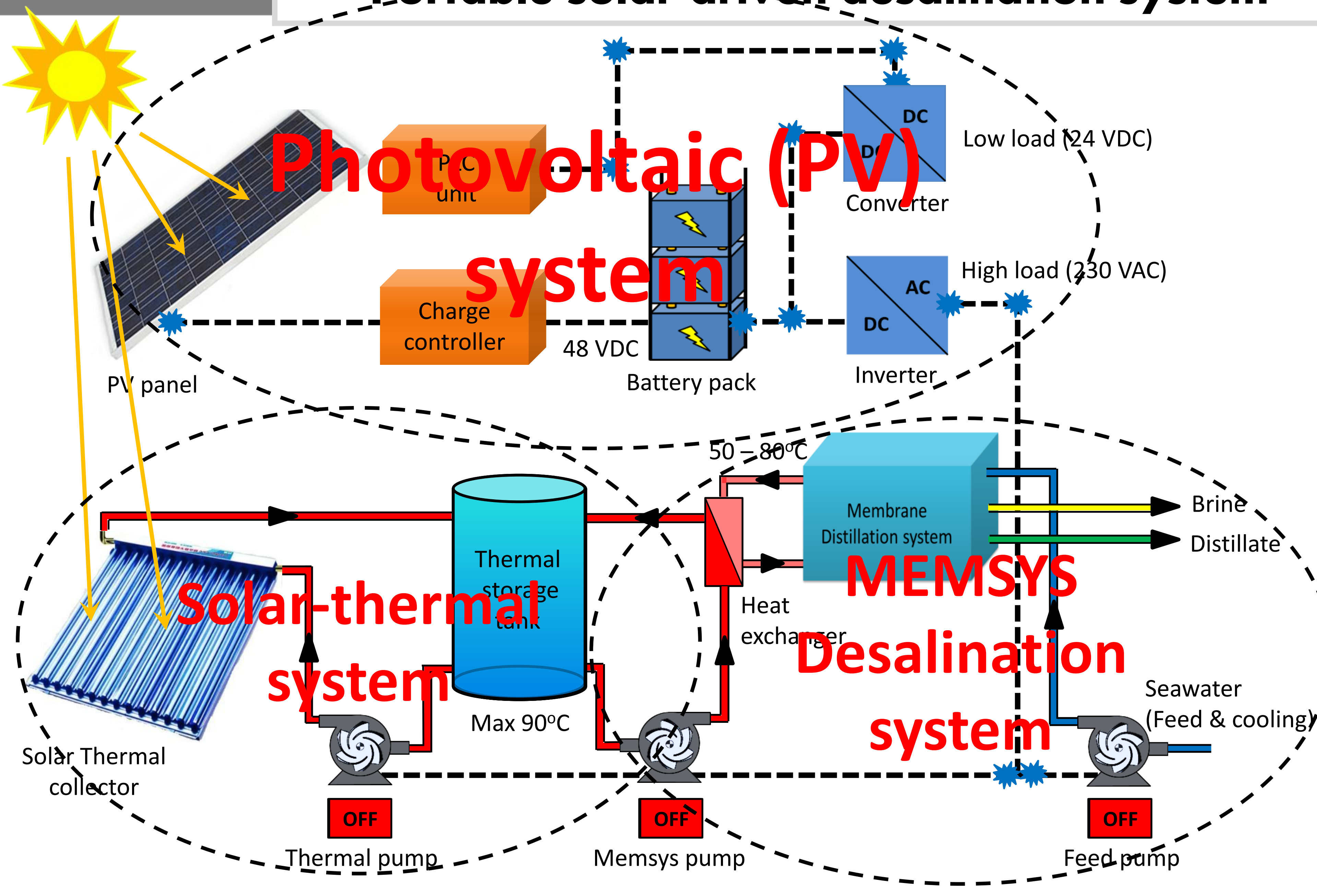


Figure 10. Flow diagram of the portable solar-driven desalination system (simplified)

Portable solar-driven desalination system

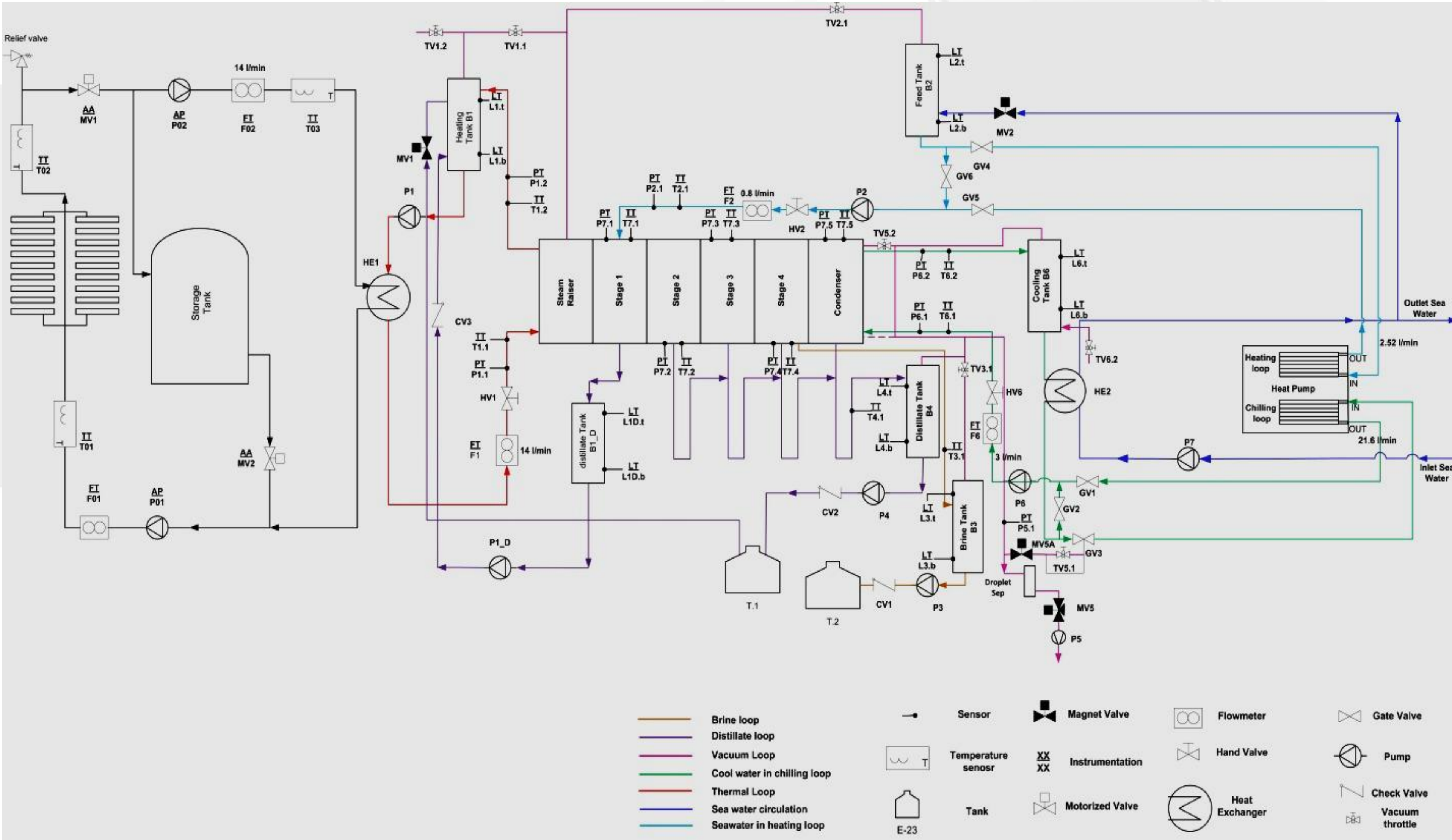


Figure 11. Schematic design of the portable solar-driven desalination system

Portable solar-driven desalination system

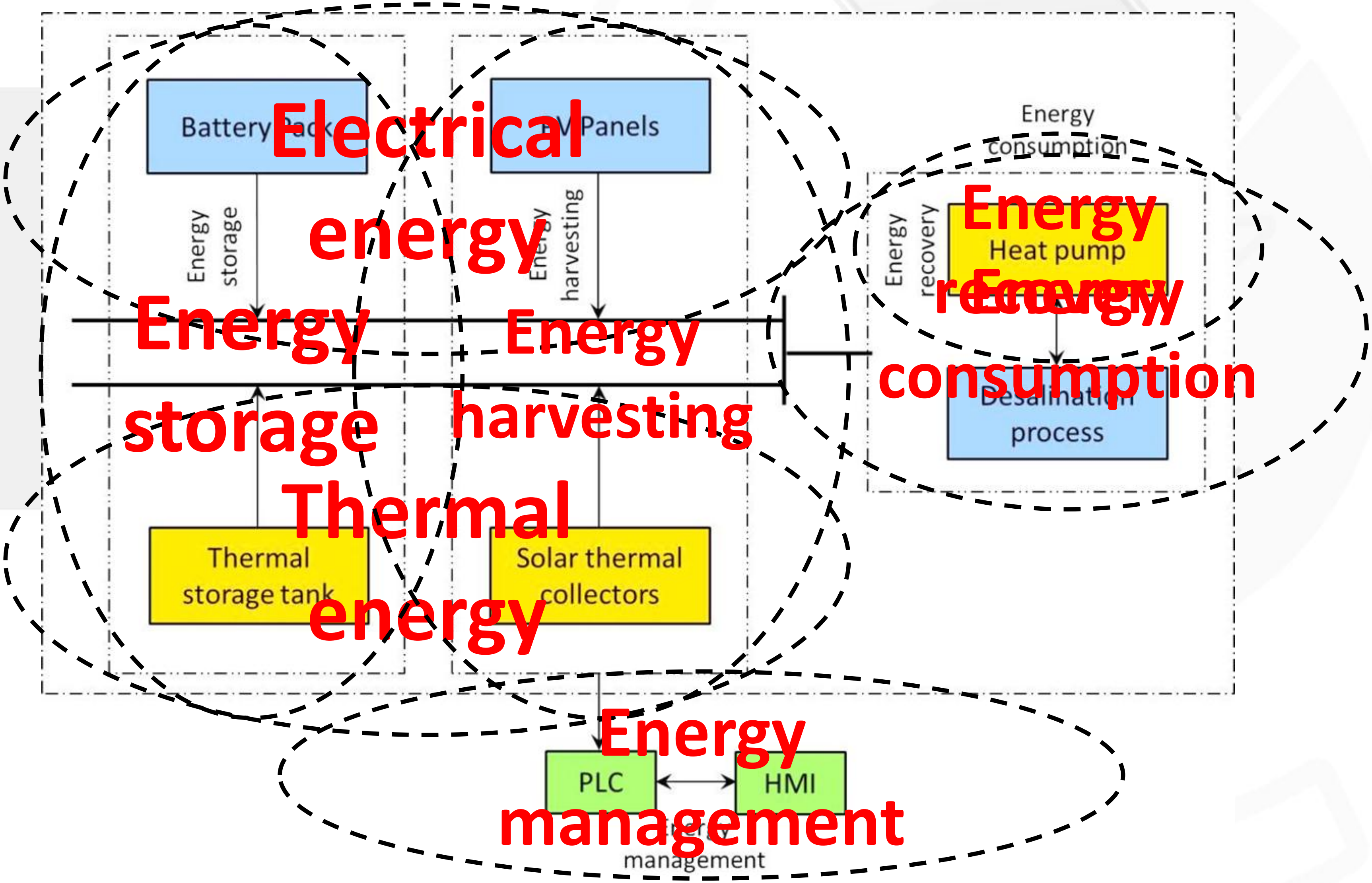
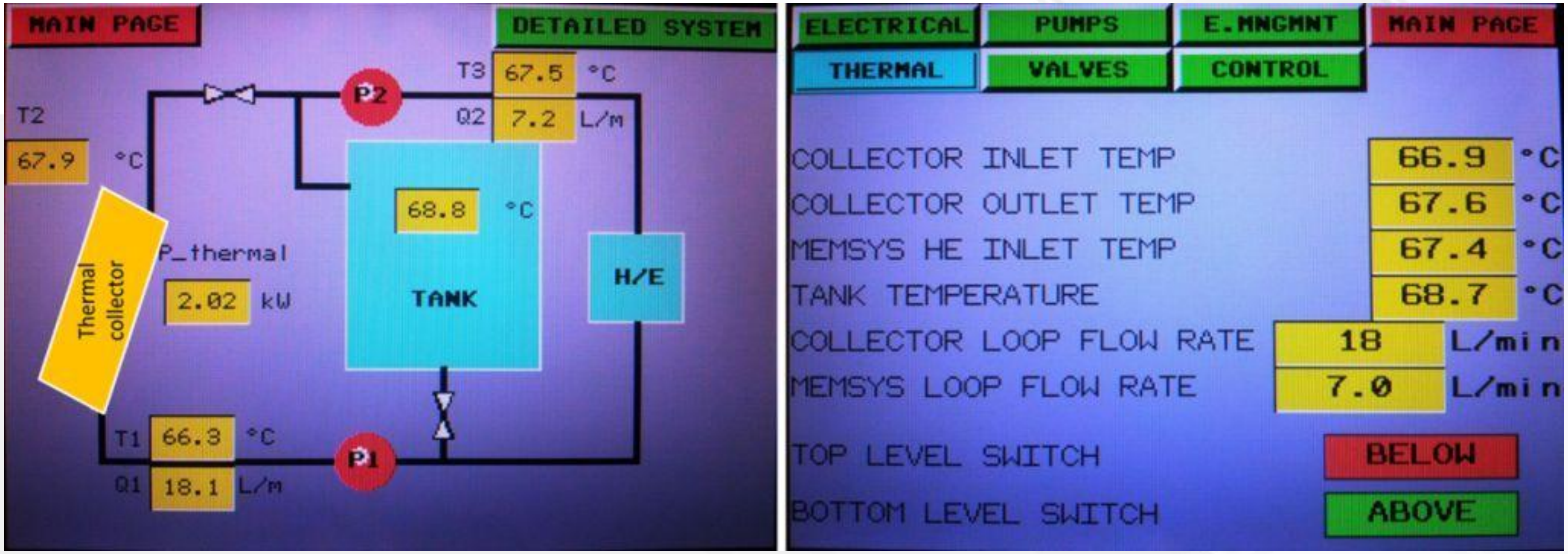


Figure 12. Hybrid Energy System architecture

Solar-thermal system



T3 67.5 °C
Q2 7.2 L/m
T2 67.9 °C
68.8 °C
P_thermal 2.02 kW
T1 66.3 °C
Q1 18.1 L/m

COLLECTOR INLET TEMP 66.9 °C
COLLECTOR OUTLET TEMP 67.6 °C
MEMSYS HE INLET TEMP 67.4 °C
TANK TEMPERATURE 68.7 °C
COLLECTOR LOOP FLOW RATE 18 L/min
MEMSYS LOOP FLOW RATE 7.0 L/min
TOP LEVEL SWITCH BELOW
BOTTOM LEVEL SWITCH ABOVE

Figure 13. HMI screen display of solar thermal collector loop

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

No.	Item	Quantity	Specification
1	Solar thermal collectors	18	Evacuated tube collector CPC 1506 (6 tubes each)
2	Thermal storage tank	1	600 L capacity, with 50 mm polyurethane foam insulation and backup heater 3kW.
3	Circulation pump	2	Rated power 0.37kW/0.5 HP
4	Temperature sensor	3	Pt 100
5	Flow meter	2	Measuring range 0.010 - 6 m^3/h
6	Motorized valve	2	Power 14 W, rotation angle (0^o-90^o)
7	Floating switch	1	3 floating sensor located at 5, 60 and 115 cm

Solar-thermal system

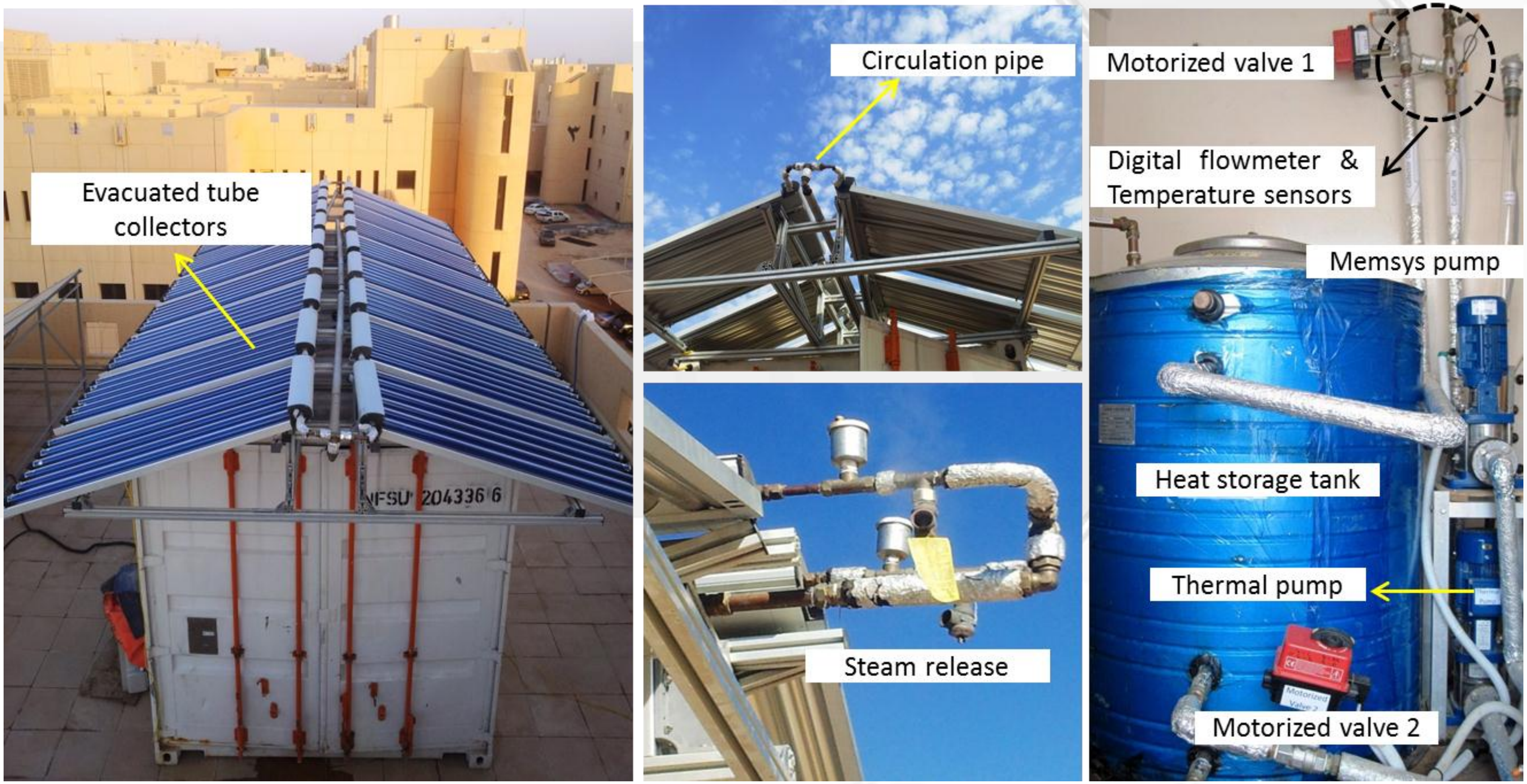
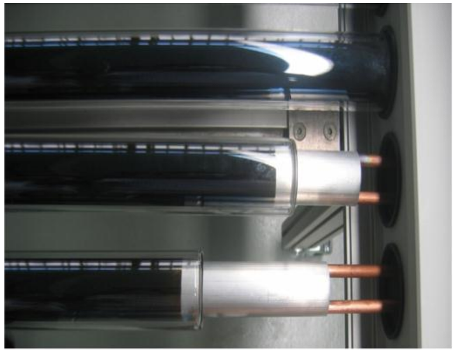


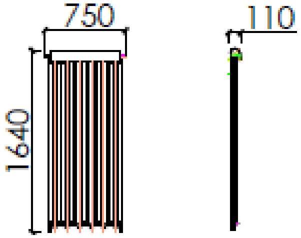
Figure 14. Photograph of the solar-thermal system

Solar-thermal system

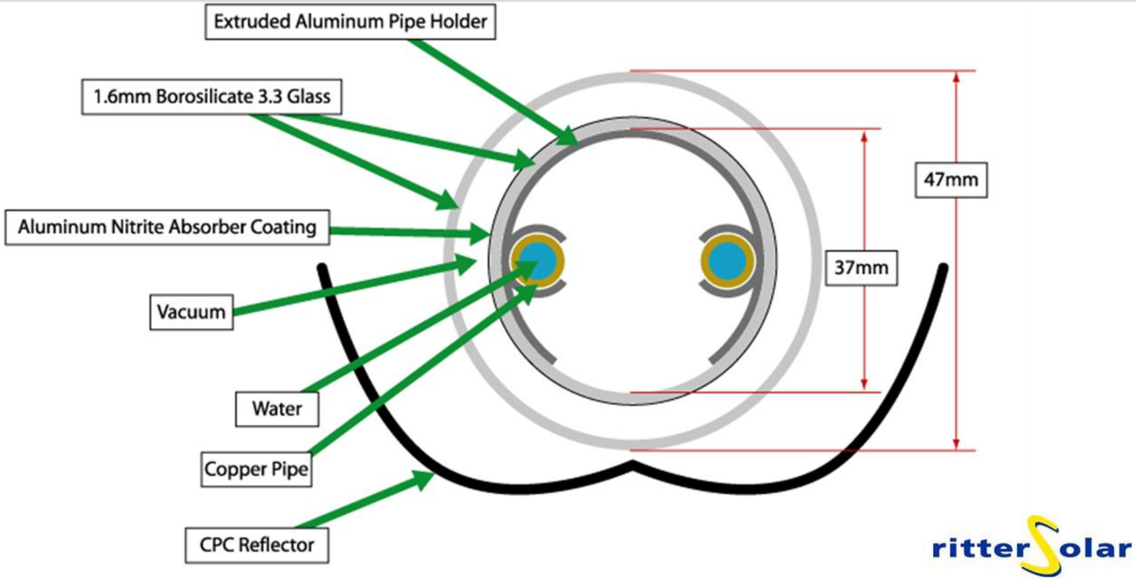
Close up of CPC (Compound Parabolic Concentrator) reflector



Exploded top view of tubes near manifold



Dimension



Cross section of tube and CPC reflector

Table 3. Technical characteristics of the solar thermal collector

Series	CPC 1506
Number of evacuated tubes	6
ηo (%, Aperture area), DIN 4757	66.1
C_1 with wind, in relation to aperture area (W/m^2 K)	0.82
Gross surface area / aperture area (m^2)	1.15 / 1.0
Collector contents (l)	0.8
Weight (kg)	19
Max. working overpressure (bar)	10
Max. stagnation temp. (^{o}C)	295
Tube material	copper
Glass tube material	Borosilicate glass 3.3
Selective absorber coating material	Aluminium nitrite
Glass tube (ø ext./ ø int./wall thickness/tube len.) (mm)	47/37/1.6/1500

Solar-photovoltaic (PV) system

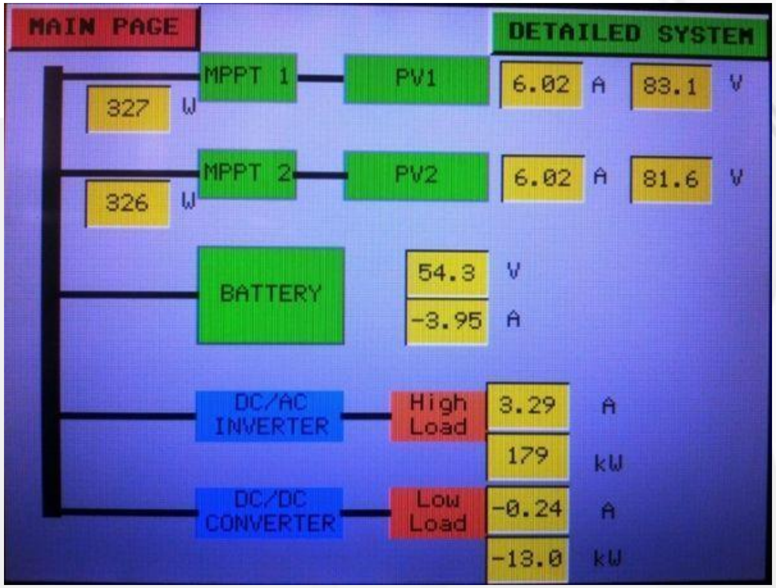


Figure 15. HMI screen display of solar photovoltaic (PV) system

Table 4. Equipment list of PV system on portable desalination system

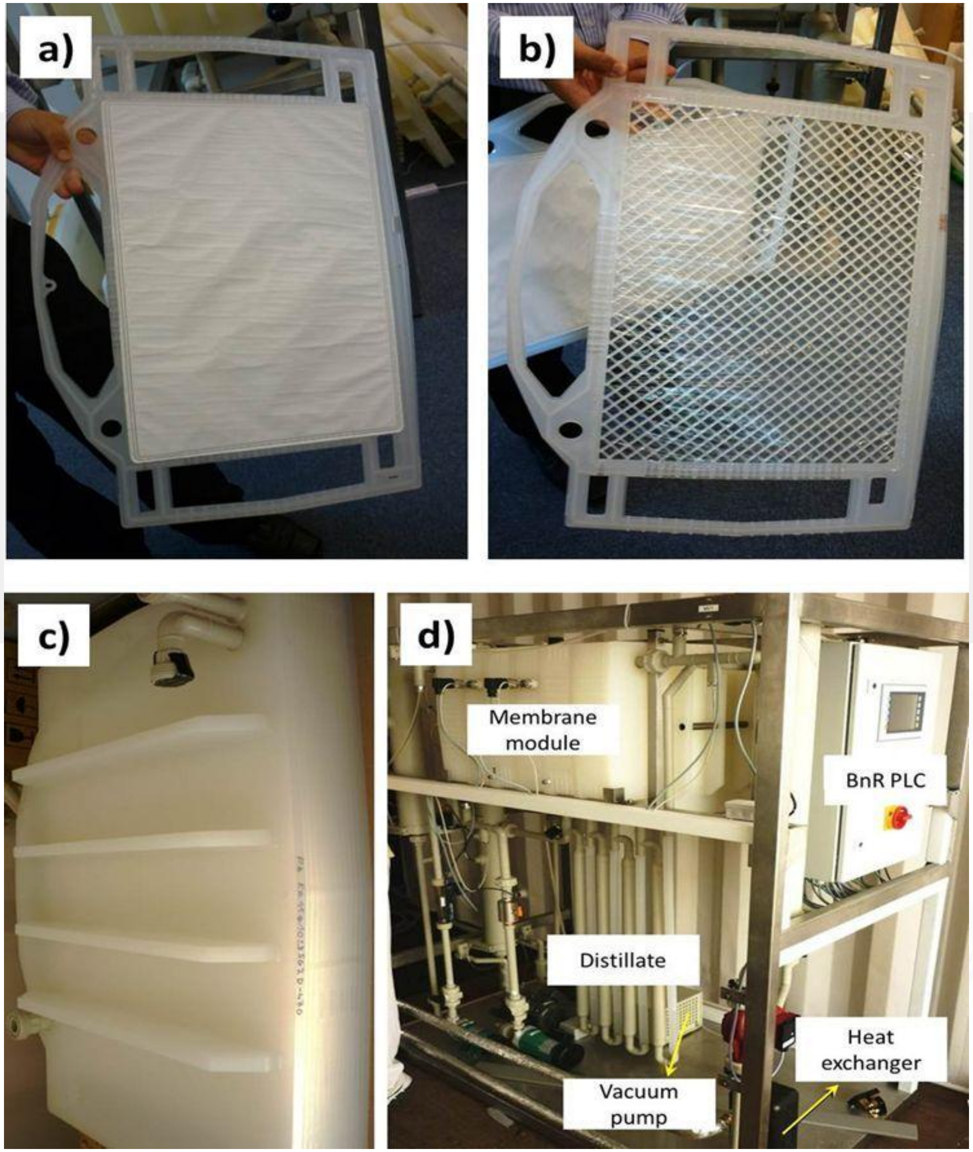
No.	Item	Quantity	Specification
1	PV module	16	Max. power (P_{max}) 3.36 kW (SANYO HIT)
2	Solar battery charger with Maximum Power Point Tracker (MPPT)	2	Max 60 amps continuous battery current; max. solar input 12,24,36,48 VDC
3	Battery pack	8	12 V 170 Ah lead acid battery
4	AC/DC Inverter	1	Output: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

Solar-photovoltaic (PV) system

SANYO

Figure 16. Photograph of the PV array beside the container

MEMSYS V-MEMD system



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

memsys®
thermal separation processes

Figure 17. Photographs of a) PTFE hydrophobic membrane; b) PP foil; c) single stage; and d) complete MEMSYS system

MEMSYS V-MEMD system

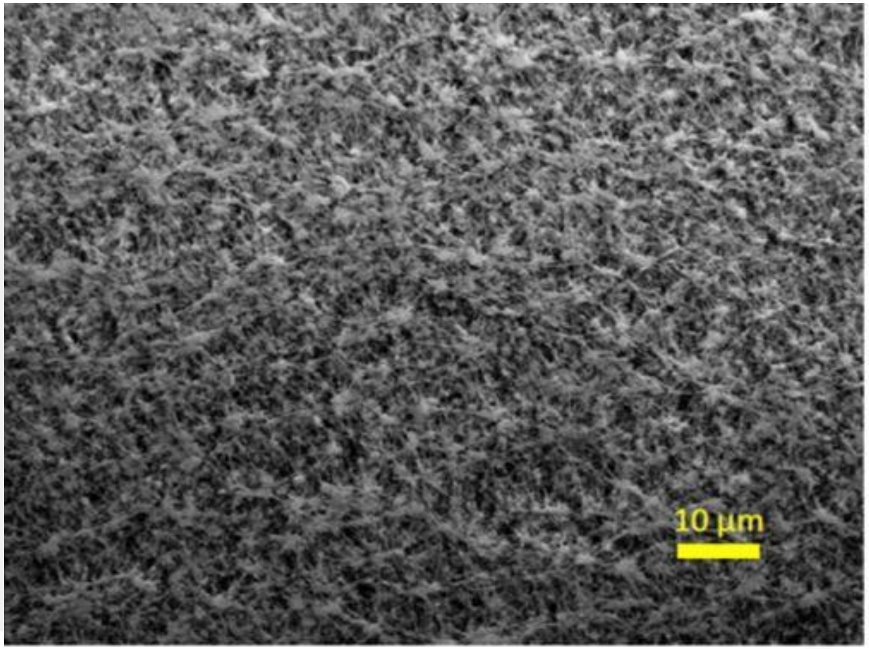


Figure 18.a. SEM image of top surface of PTFE hydrophobic membrane

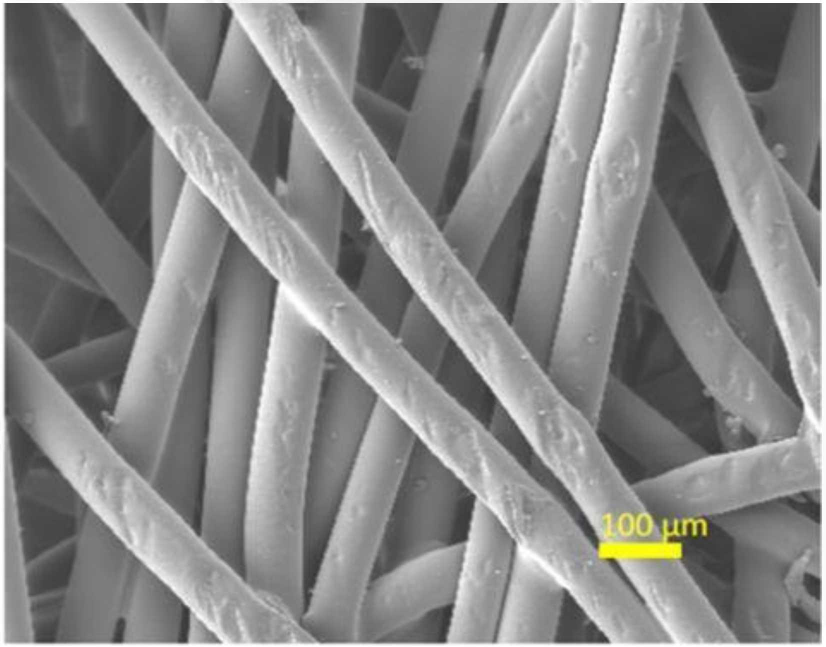


Figure 18.b. SEM image of substrate of PTFE hydrophobic membrane

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.

Membrane Distillation (MD) process

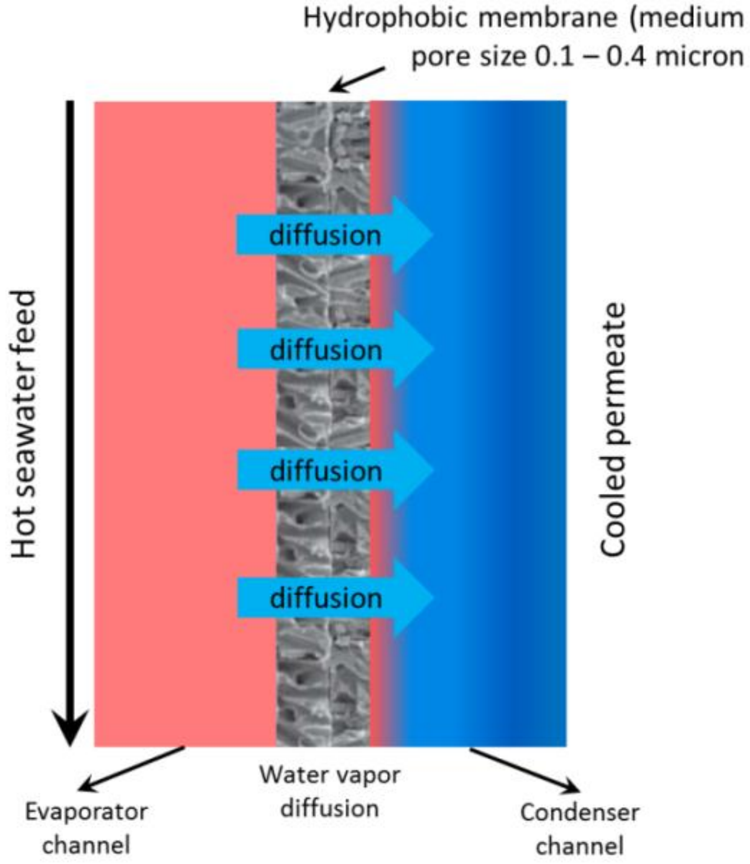
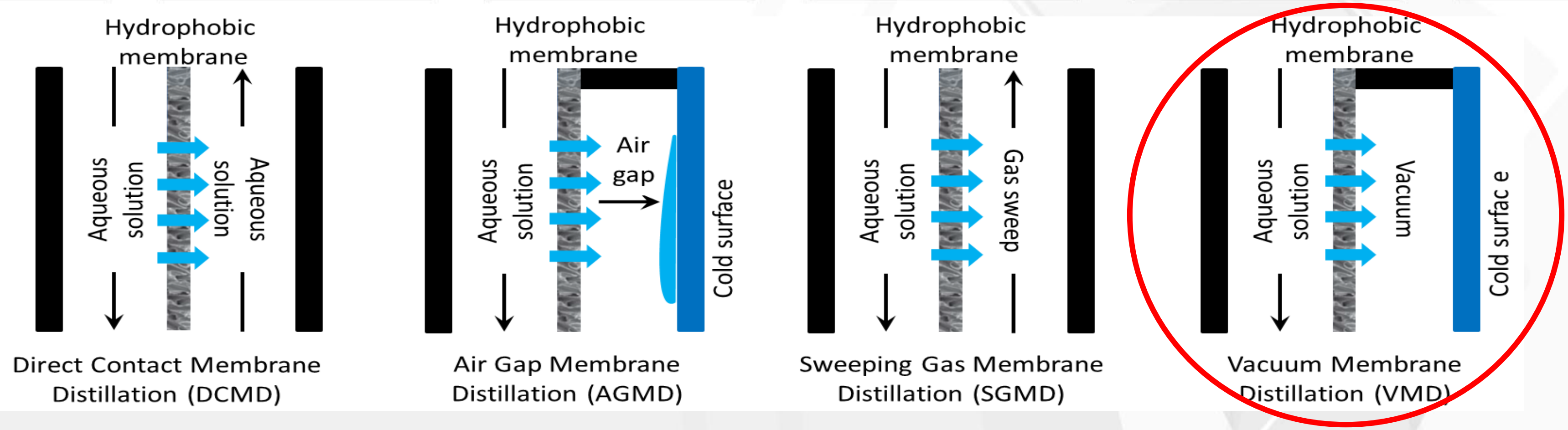


Figure 19. Schematic operating principle of membrane distillation (MD) process - DCMD

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



Direct Contact Membrane Distillation (DCMD)

Air Gap Membrane Distillation (AGMD)

Sweeping Gas Membrane Distillation (SGMD)

Vacuum Membrane Distillation (VMD)

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^{o}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

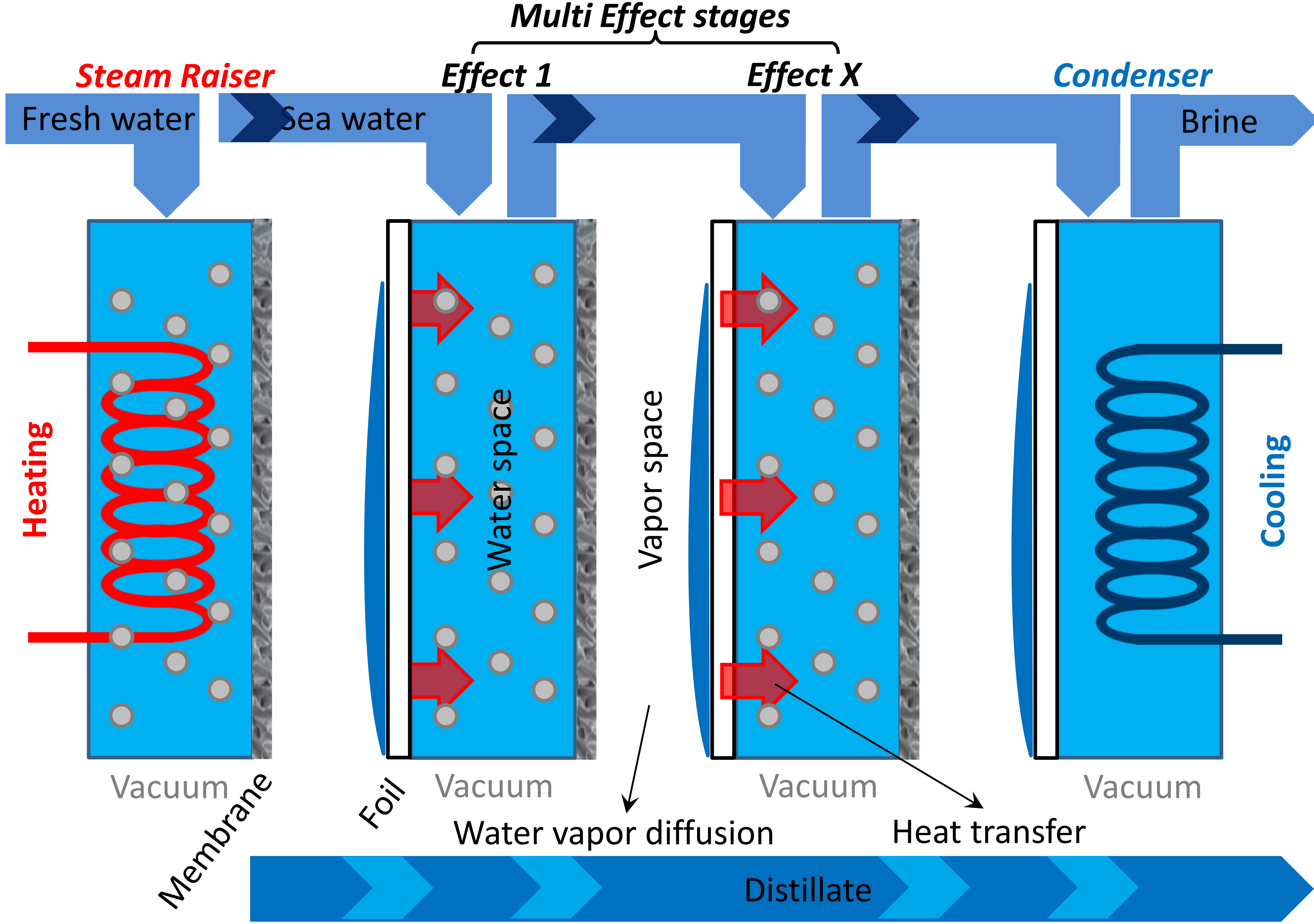


Figure 20. Basic principle of MEMSYS Vacuum-Multi-Effect-Membrane-Distillation (V-MEMD) process.

MEMSYS V-MEMD system

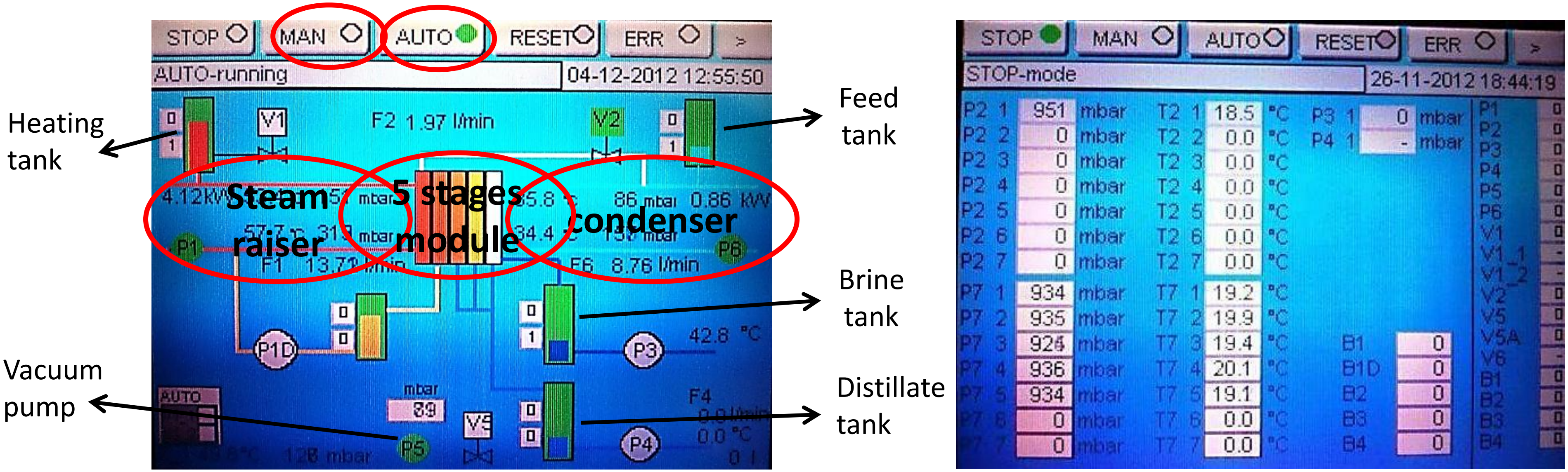


Figure 21. MEMSYS Human Machine Interface (HMI)

Table 5. Equipment list of MEMSYS V-MEMD system

No.	Item	Quantity	Specification
1	Internal heat loop pump	1	220 V, 50 W
2	Feed pump	1	220 V, 45 W
3	Cooling pump	1	220 V, 95 W
4	Brine discharge pump	1	220 V, 180 W
5	Distillate discharge pump	1	220 V, 180 W
6	Seawater circulation pump	1	220 V, 95 W
7	Vacuum pump	1	230 V
8	Membrane module	1	PTFE hydrophobic membrane, PP foil & frame
9	BnR PLC	1	
10	Heat exchanger	1	Flat plate heat exchanger

MEMSYS V-MEMD system

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).

Heat pump

FIG 4

End view of
unit showing
water connections

FIG 1

Electrical
panel with cover
removed.

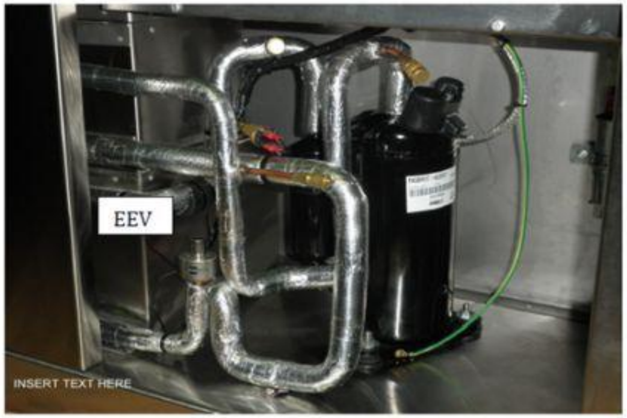


FIG 3
COMPRESSOR
SECTION.

Figure 22. Picture of the heat pump and all its parts

Heat pump

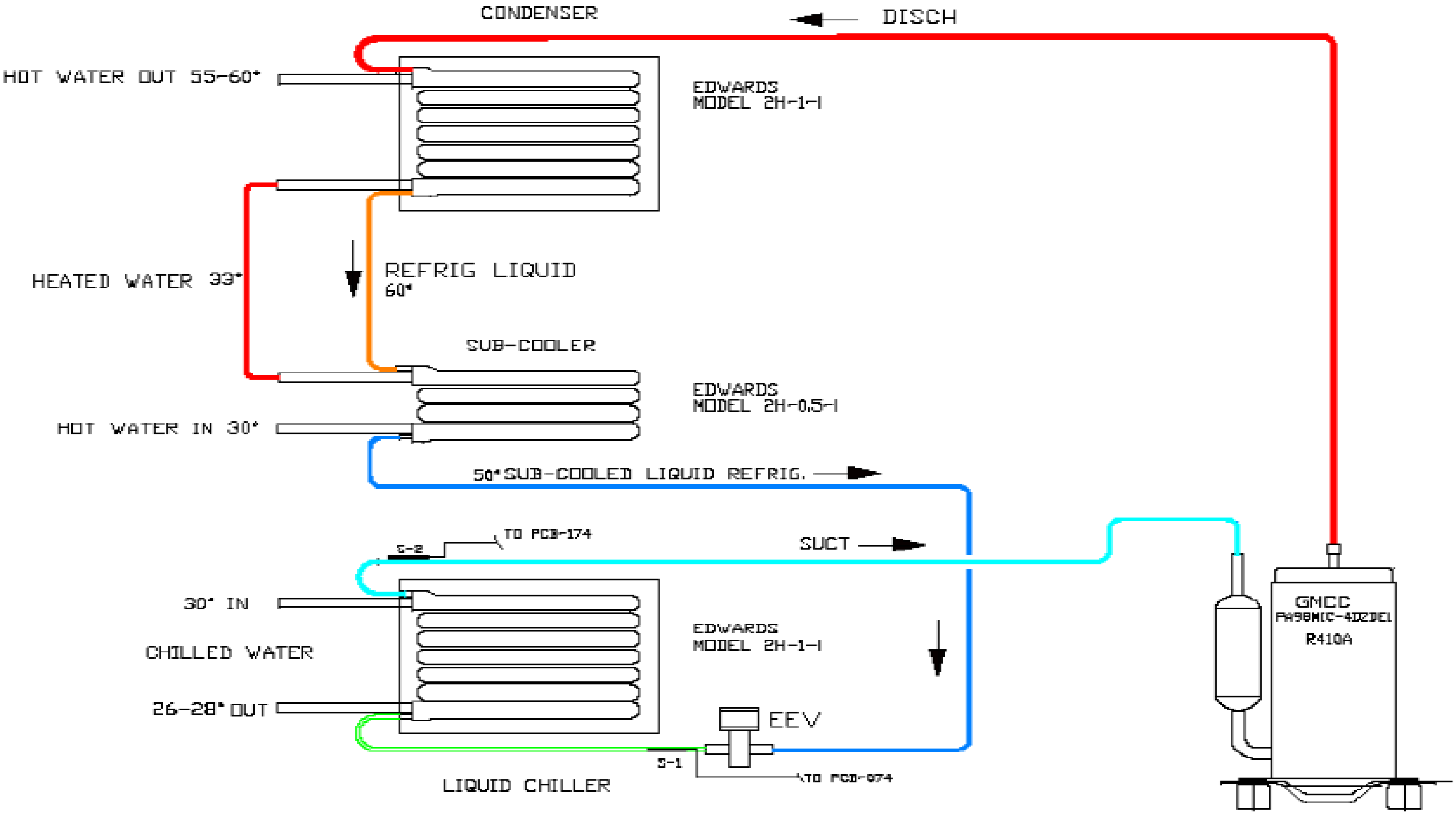


Figure 23. Schematic of refrigeration system of the heat pump

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

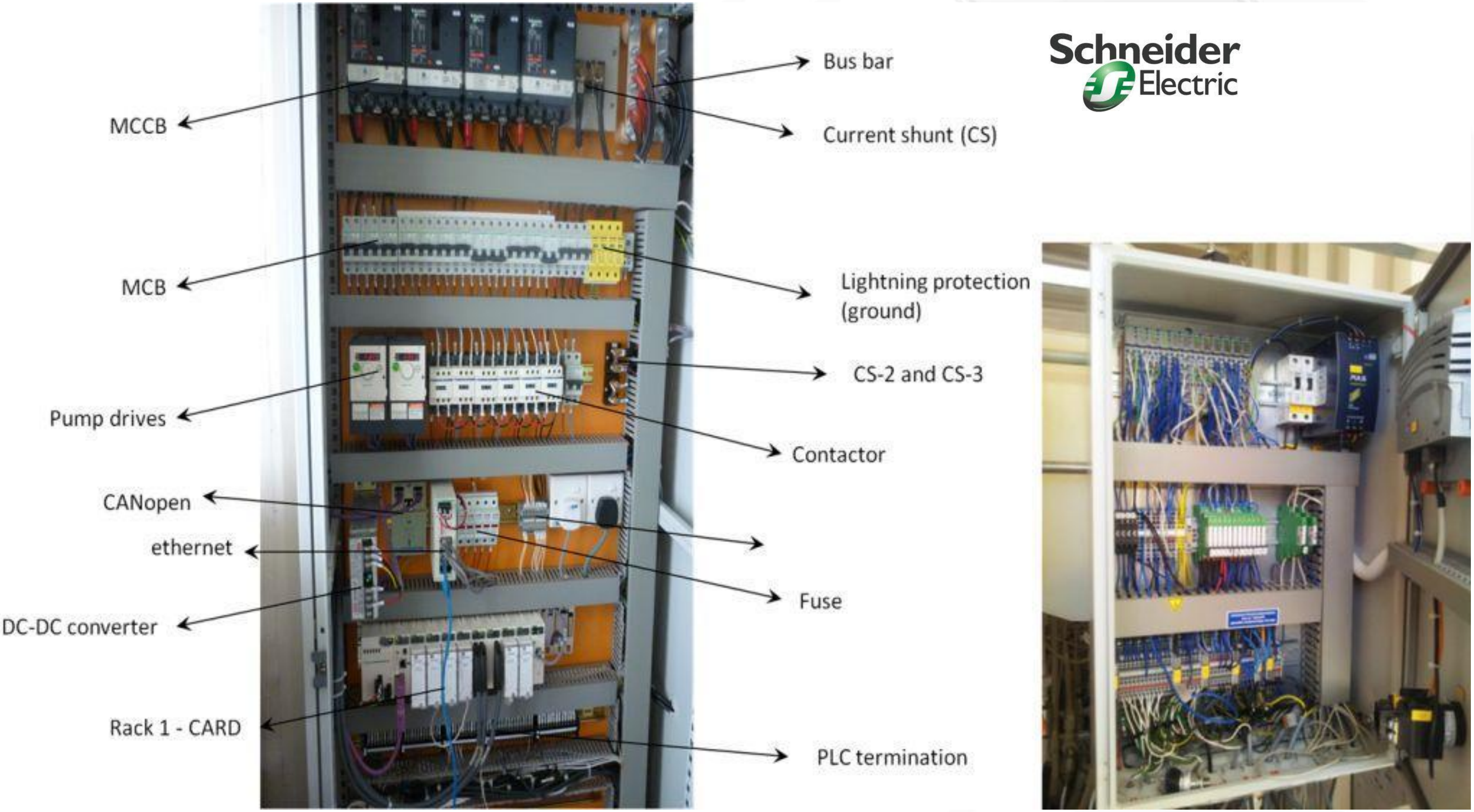
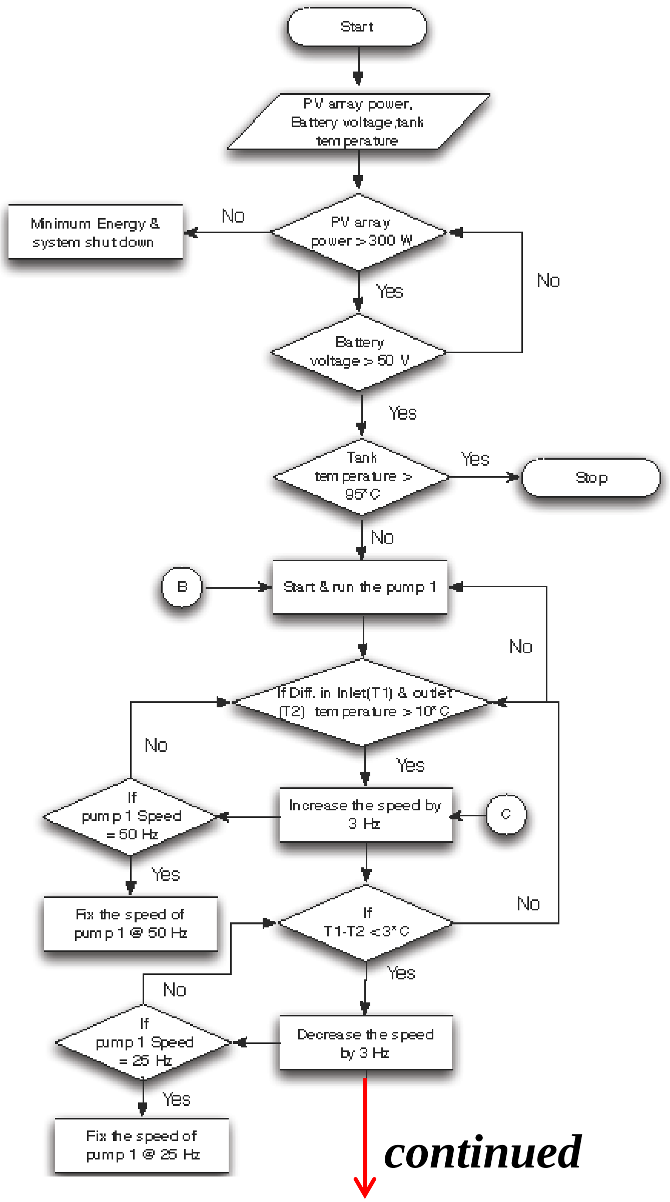


Figure 24. Photograph of Schneider PLC (left) and BnR PLC (right)

Automation control



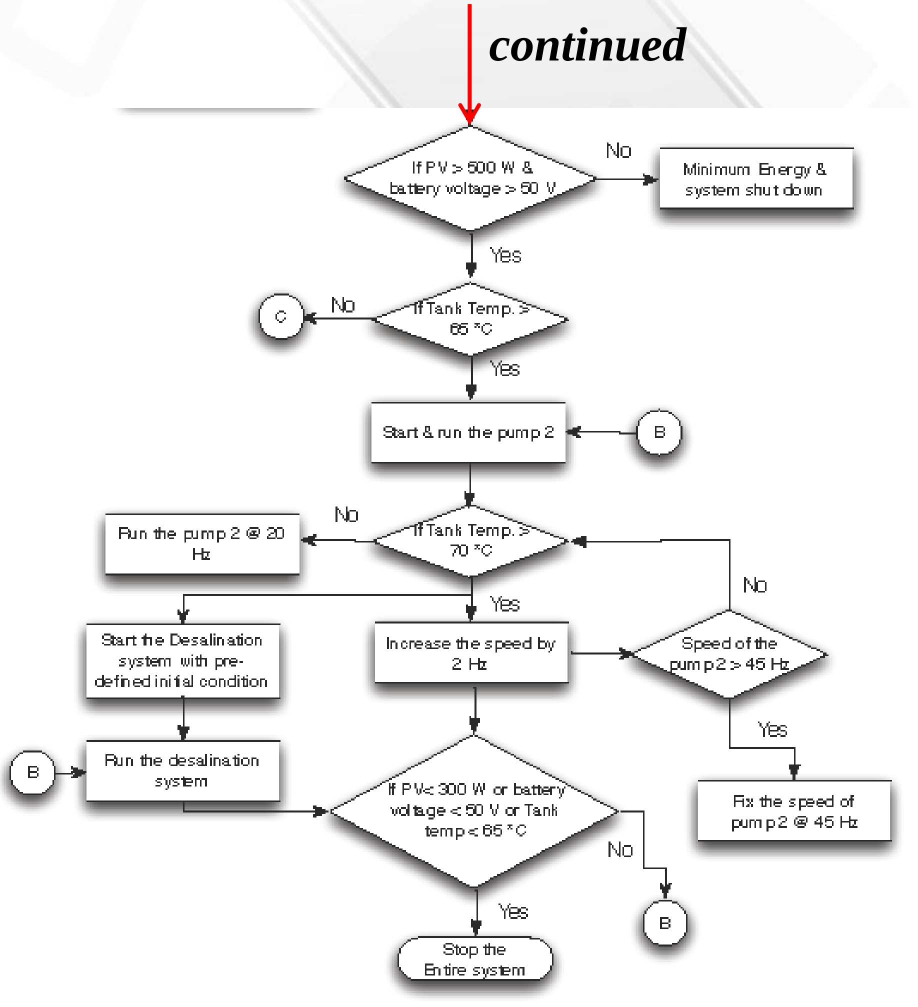
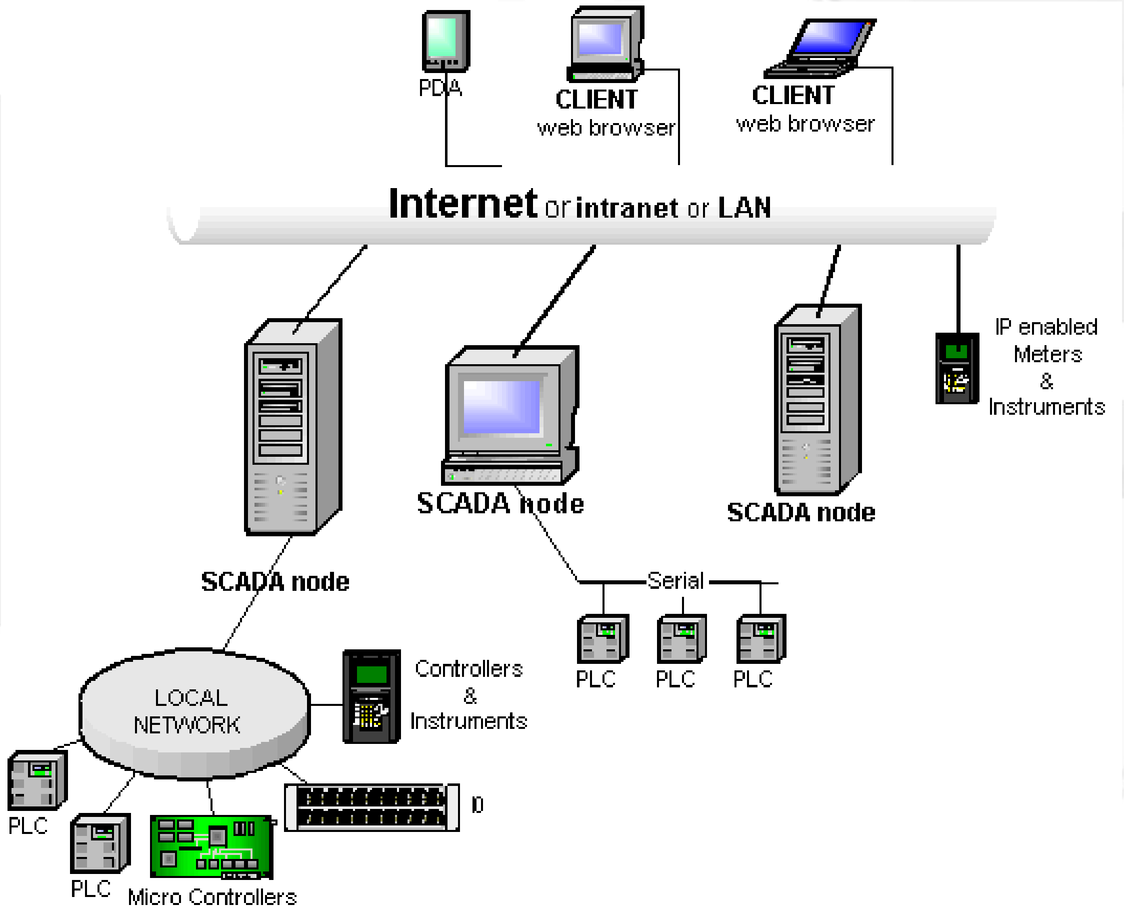


Figure 25. Logic flowchart for the automation control

SCADA implementation



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.

SCADA implementation

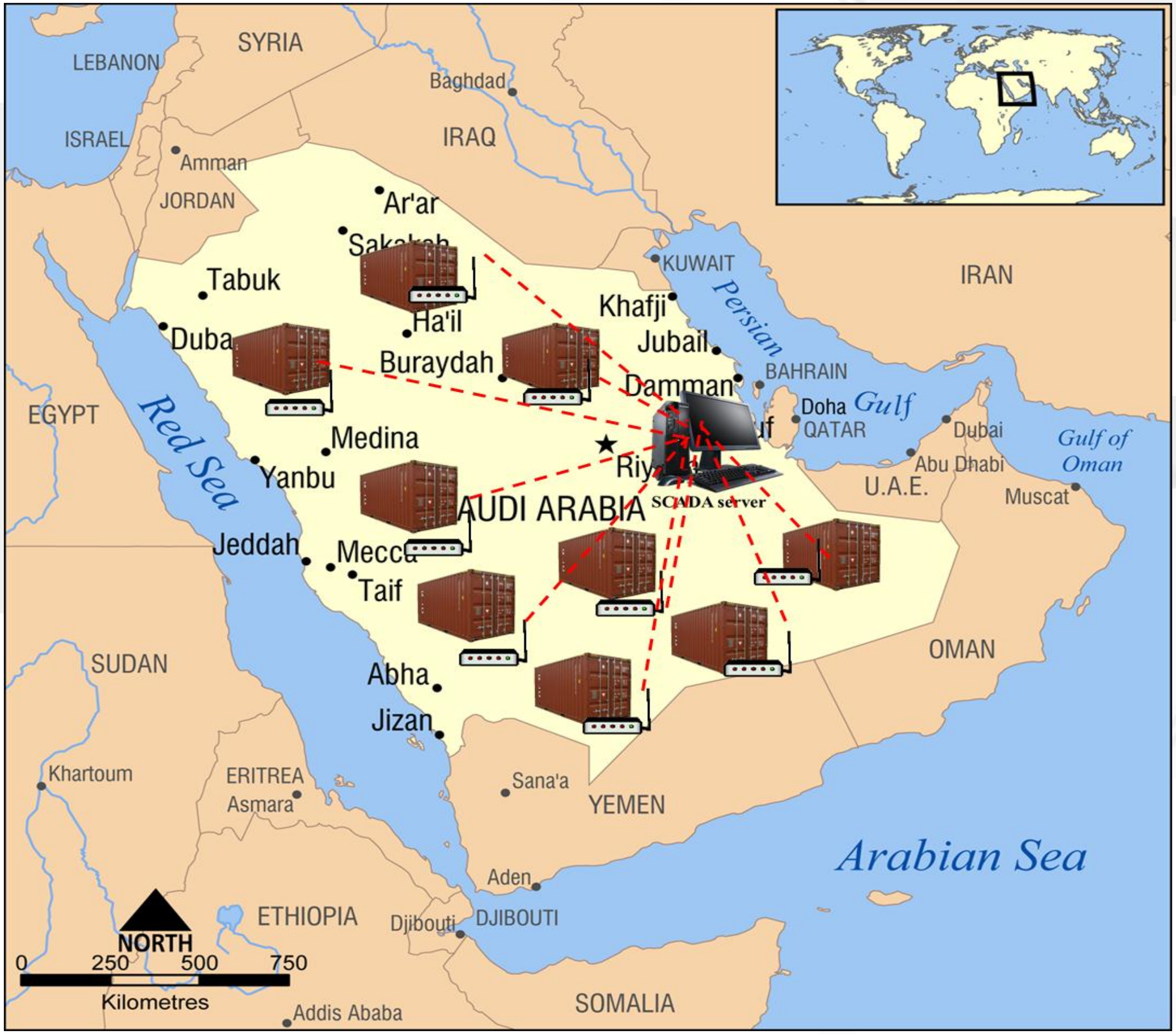


Figure 26. Illustration of SCADA implementation to control and monitoring the portable system in remote areas of Saudi Arabia

Values to the kingdom

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.

Short test of the system

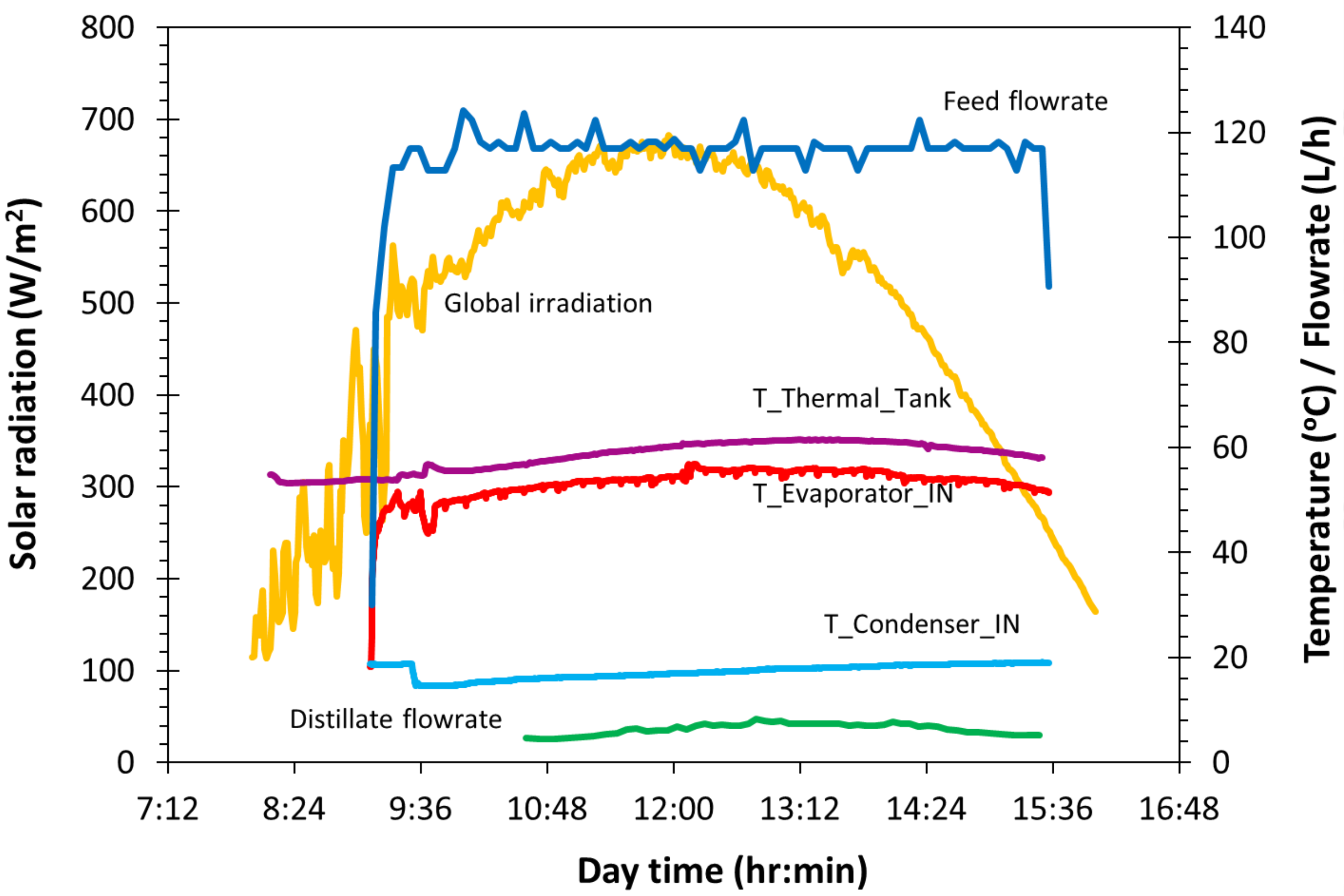


Figure 27. Measured performance of the portable system (with heat pump) during one day operation (24/12/2012) in King Saud University, Riyadh, KSA

Short test of the system

The system started at 8:00 AM, followed the course of global solar radiation with a maximum of 682 W/m^2 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.

Short test of the system

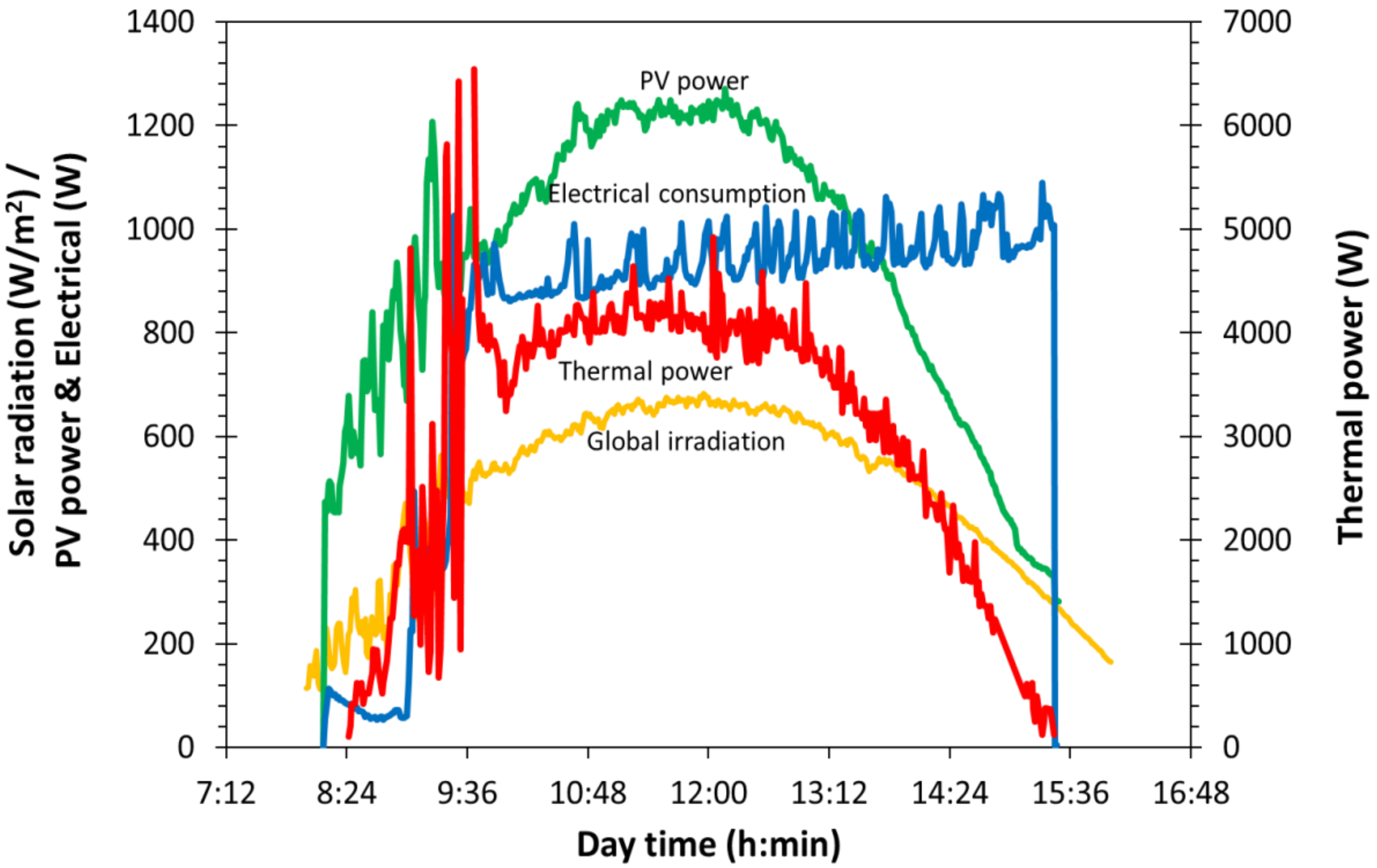


Figure 28. Energy harnessed and converted into thermal and electrical energy during one day operation (24/12/2012) in King Saud University, Riyadh, KSA

Short test of the system

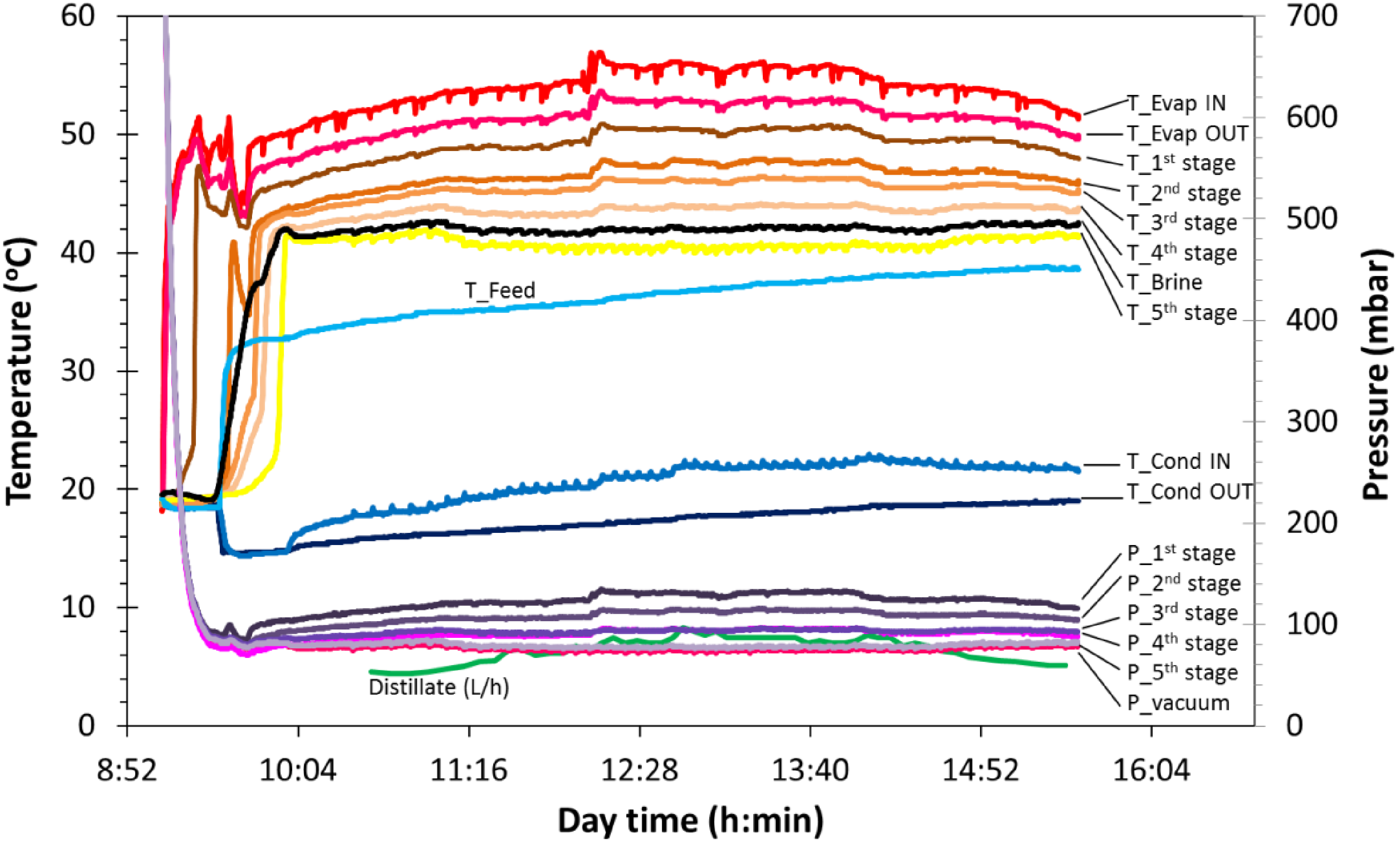


Figure 29. Dynamic behaviour of the MEMSYS V-MEMD system during one day operation (24/12/2012) in King Saud University, Riyadh, KSA

Summary

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/m^2 (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^{o}C
4. Feed flowrate = **117 l/h** (brackish water with average conductivity 1650 µs/cm)
5. Pre-heated feed temperature = 19.2 – **38.6^{o}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.

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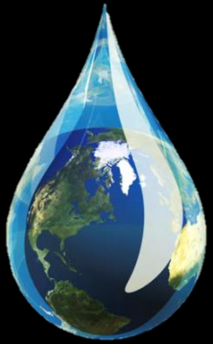
Thank  You