arwadex 2017
تحت رعاية معالي رئيس مجلس الوزراء المصري المهندس شريف إسماعيل
مؤتمر تحلية المياه الحادي عشر في البلدان العربية
UNDER THE PATRONAGE OF THE EGYPTIAN PRIME MINISTER ENGINEER SHERIF ISMAIL
11TH WATER DISALINATION CONFERENCE IN THE ARAB COUNTRIES
18-19 APRIL 2017 • INTERCONTINENTAL CITY STARS - CAIRO - EGYPT

Solar-powered Membrane Distillation System: Review and Application to Performance Enhancement

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وزارة الاسكان والمرافق والمجتمعات العمرانية
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2. Literature Review
3. Conclusion

Introduction

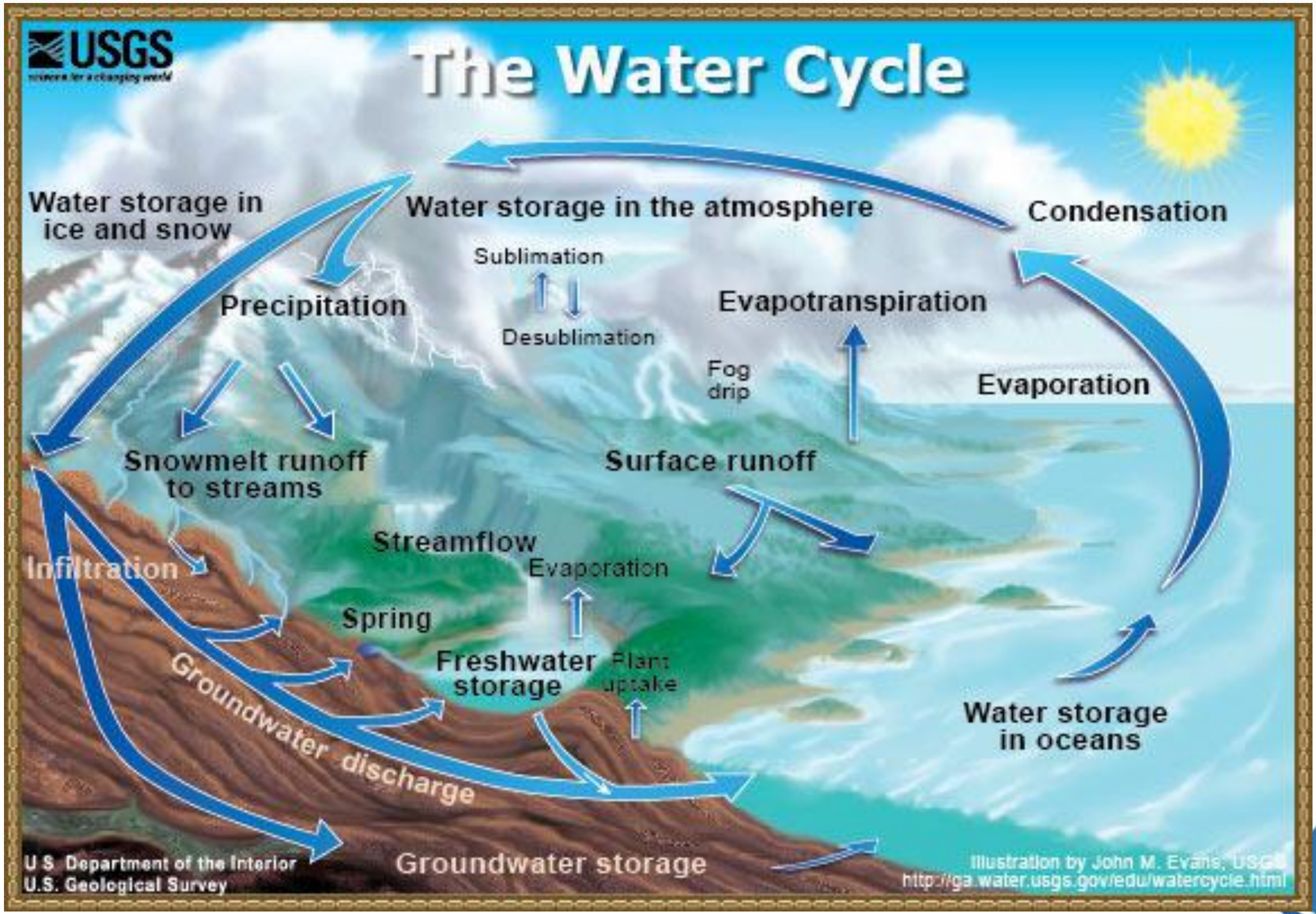
Why Desalination?

- 75% of the Earth's surface is covered by water.
- 97.5% of that water is saline water in oceans, 2.5% of fresh water (Shiklomanov & Rodda, 2003).
- 75% of the fresh water in ice form.
- 25 % of the fresh water is available for drinking.
- The fresh water available for drinking represent 1% from total water covered the Earth's surface.
- It is expected that by the year 2040 the world demand for freshwater will be greater than the amount available, G. Micale et al., [2009].

Natural Desalination: Water Cycle!

Major Stages

1. Evaporation
2. Condensation
3. Precipitation
4. Collection



Highlights

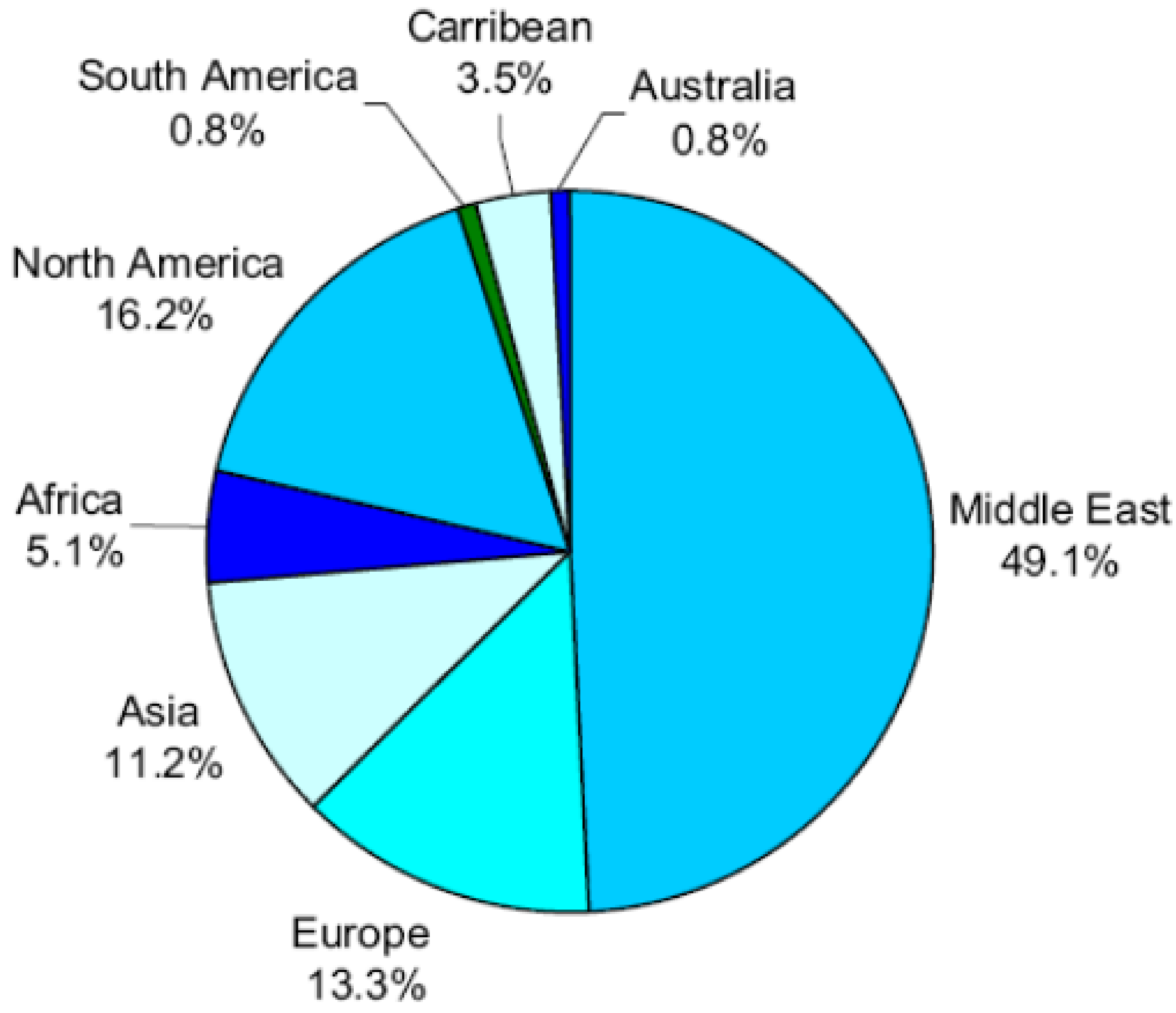
Global water withdrawals amount to around 4,000 billion m3 per year and in some regions – especially the Middle East and Northern Africa (MENA) – desalination has become the most important source of water for drinking and agriculture.

Today's global desalinated water production amounts to about 65.2 million m3per day (24 billion m3 per year), equivalent to 0.6% of global water supply.

The MENA region accounts for about 38% of the global desalination capacity, with Saudi Arabia being the largest desalinating country.

Major desalination technology options are based on thermal processes using both heat and electricity, and membrane technologies using electricity only.

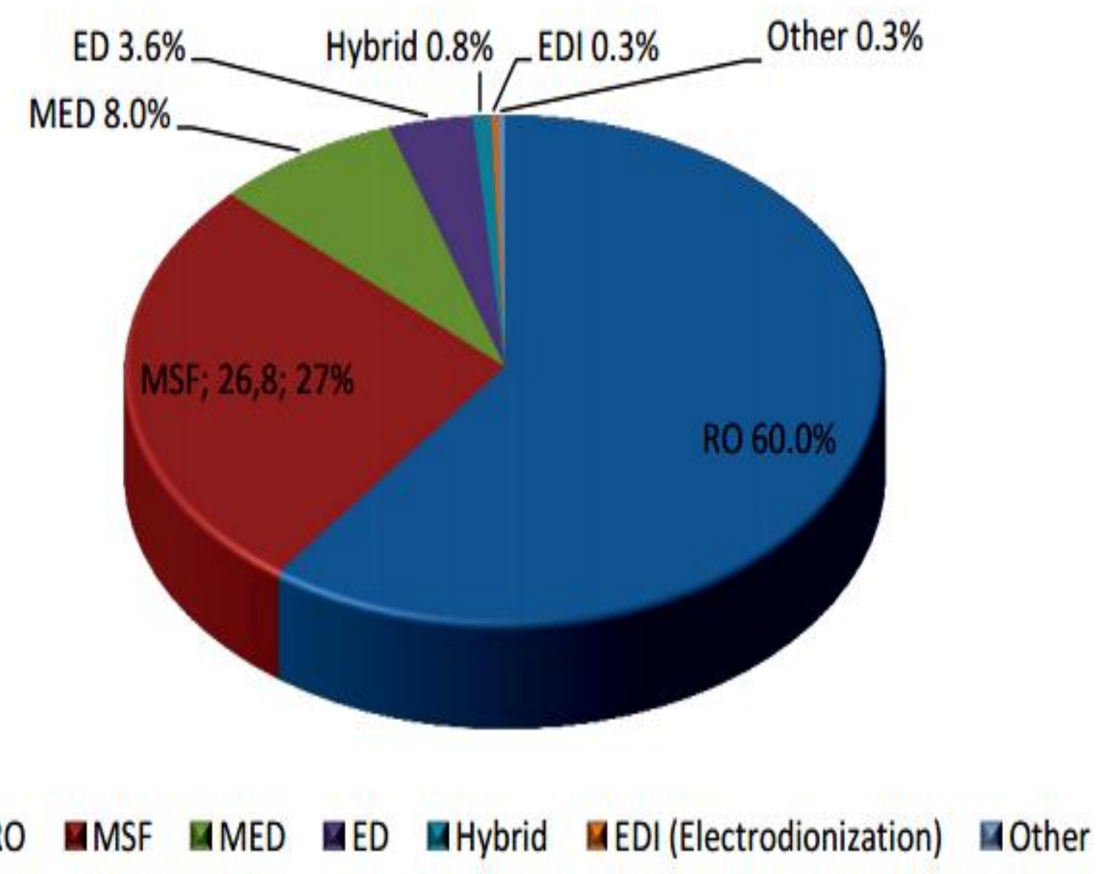
Chart showing fraction of the worldwide capacity of desalination plants by region

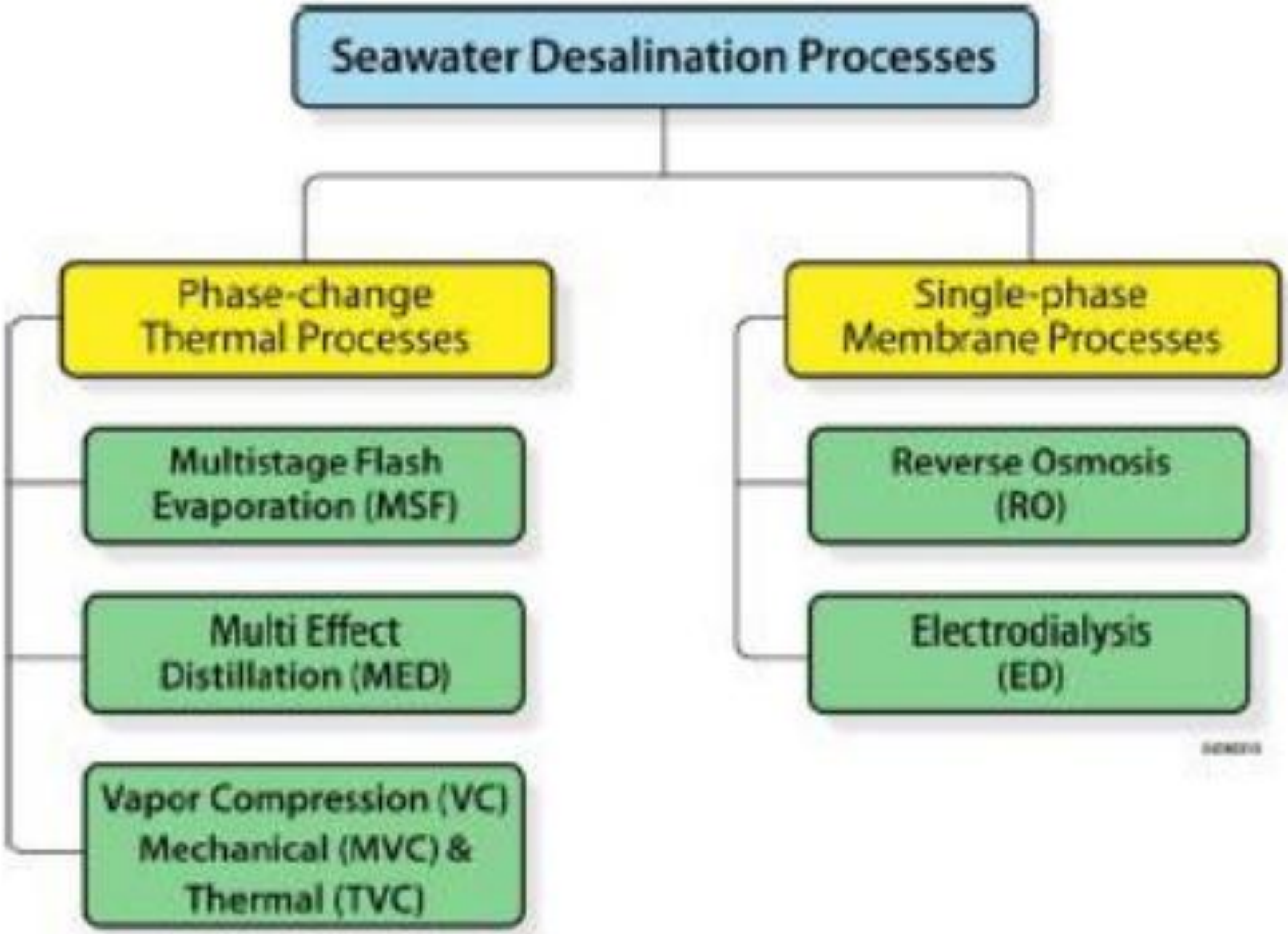


Literature Review

Thermal Technologies
Multi Stage Flash, MSF Multi Effect Distillation, MED Vapor Compression, VC
Membrane Technologies
Reverse Osmosis, RO Electro dialysis, ED

Desalination Technologies

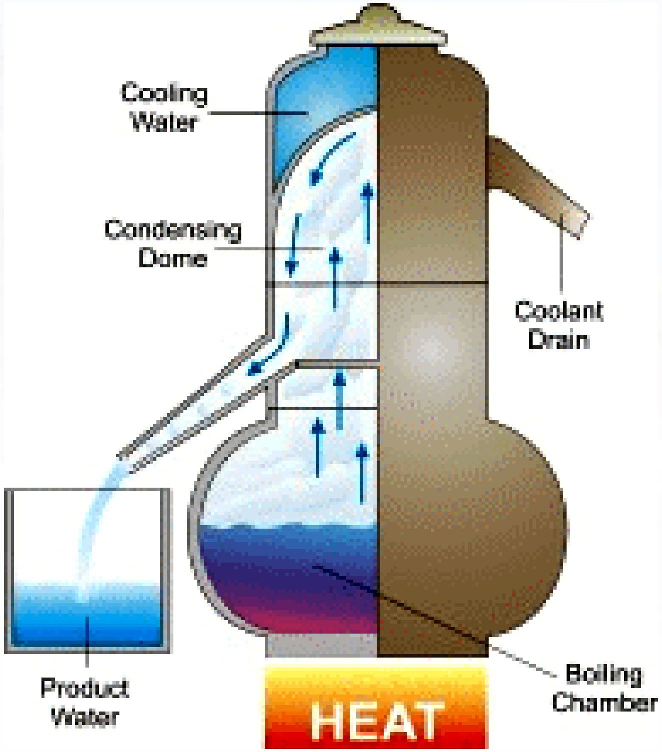



Seawater Desalination Processes
Phase-change Thermal Processes
Single-phase Membrane Processes
Multistage Flash Evaporation (MSF)
Multi Effect Distillation (MED)
Vapor Compression (VC) Mechanical (MVC) & Thermal (TVC)
Reverse Osmosis (RO)
Electrodialysis (ED)

Desalination Technologies

1. **Thermal Desalination Processes**

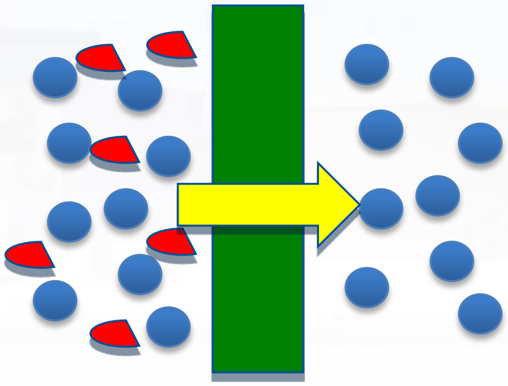
   - Similar to the Earth's natural water cycle
   - Water is heated, evaporated and collected
   - Produces clean water and brine



Desalination Technologies

2. Membrane Desalination Processes

- Saltwater is forced through membrane sheets at high pressures
- Membrane sheets are designed to catch salt ions
- Process produces clean water and brine
- Example: Reverse Osmosis



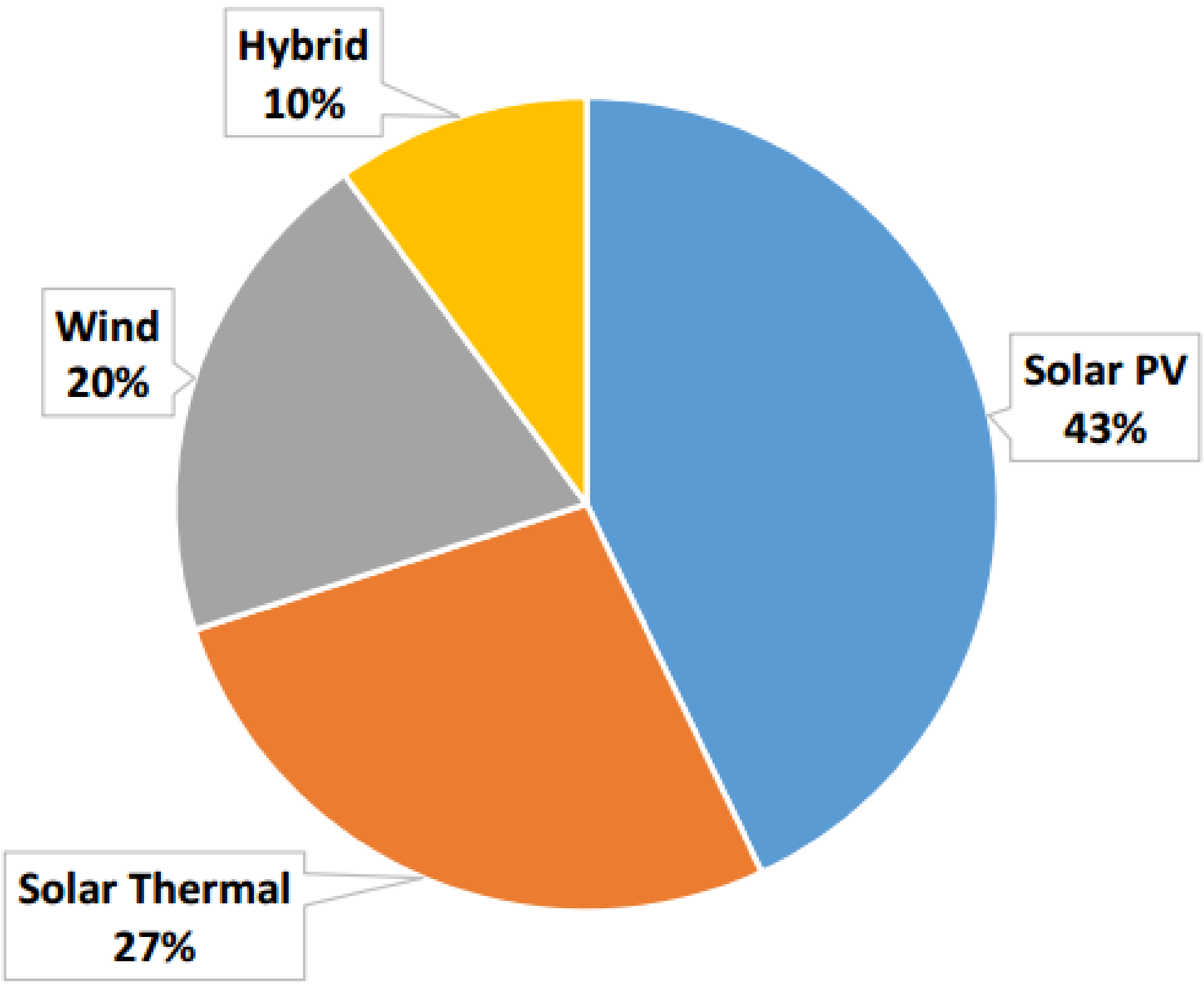
ENERGY REQUIREMENTS

	MSF	MED	MVC	TVC	SWRO	BWRO	ED
Electrical Energy consumption (kWh/m^3)	2.5 - 5	2 – 2.5	7 – 12	1.8 – 1.6	3 - 6	1.5 – 2.5	0.8 – 5.5
Thermal Energy consumption (MJ/m^3)	190 - 282	145-230	-	227	-	-	-
Equivalent electrical to thermal energy (kWh/m^3)	15.83 - 23.5	12.2 - 19.1	-	14.5	-	-	-
Total energy consumption (kWh/m^3)	19.58-27.25	14.45-21.35	7-12	16.26	3 - 6	1.5 – 2.5	0.8 – 5.5

RENEWABLE ENERGY-POWERED DESALINATION

	SOLAR				WIND		GEOTHERMAL		OCEAN POWER		
	THERMAL COLLEC-TORS	CSP		PV							
		THERMAL	ELECTRICAL		MECANICAL	ELECTRICAL	THERMAL	ELECTRICAL	ELECTRICAL	MECANICAL	THERMAL
SD	•										
MD	•	•					•				•
TVC		•					•				•
MSF		•					•				
MED	•	•					•				•
ED			•	•	•			•	•		
MVC			•	•	•	•		•	•	•	
RO			•	•	•	•		•	•	•	

RENEWABLE ENERGY-POWERED DESALINATION

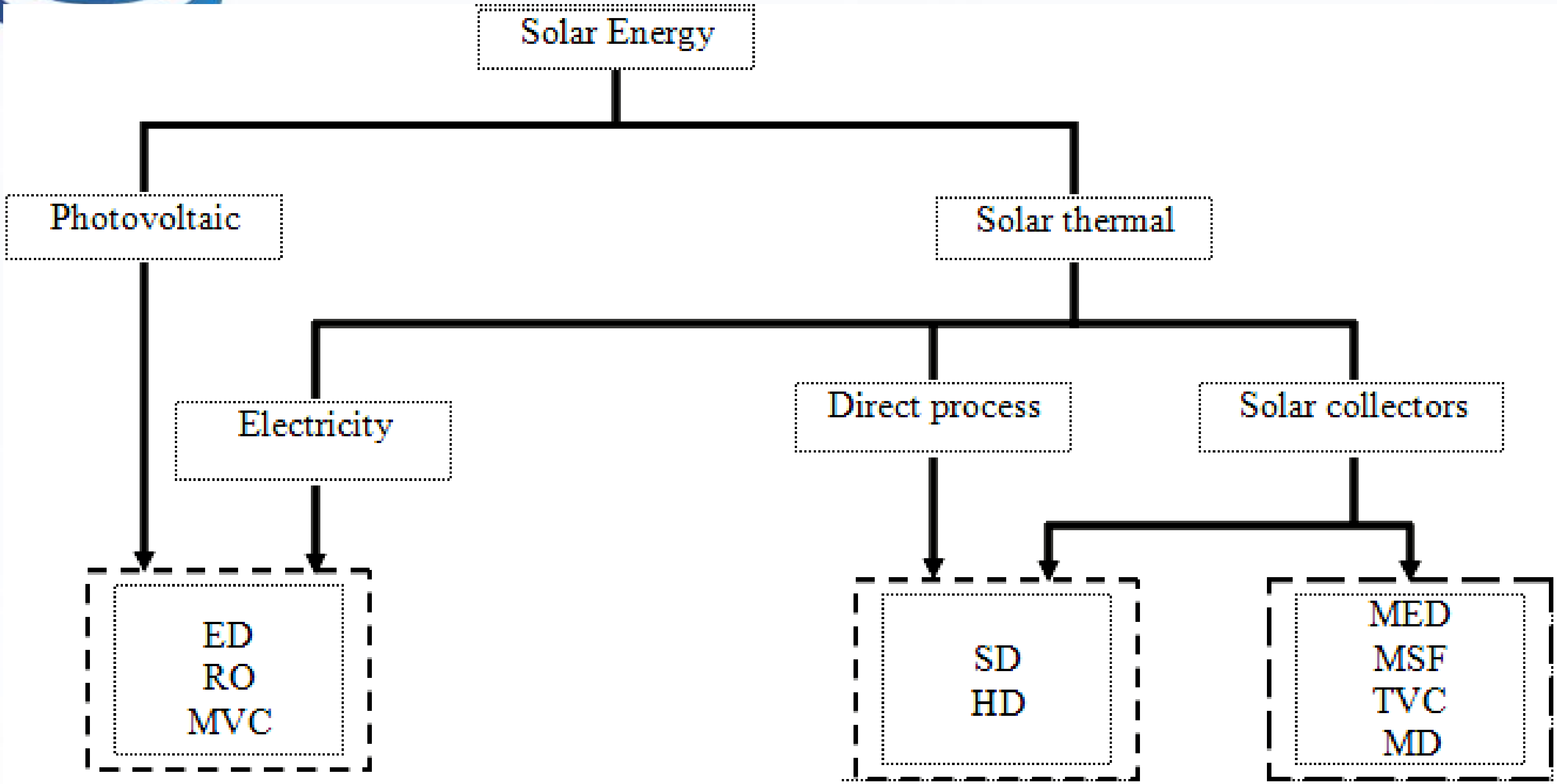


Renewable energy sources currently utilized for Desalination (Quteishat & Abu-Arabi, 2012)

Comparative costs for common renewable desalination

	Technical Capacity	Energy Demand (kWh/m³)	Water Cost (USD/m³)	Development Stage
Solar stills	< 0.1m³/d	Solar passive	1.3–6.5	Application
Solar-Multiple Effect Humidification	1–100 m³/d	thermal: 100 electrical: 1.5	2.6–6.5	R&D Application
Solar- Membrane Distillation	0.15–10 m³/d	thermal: 150–200	10.4–19.5	R&D
Solar/CSP-Multiple Effect Distillation	> 5,000 m³/d	thermal: 60–70 electrical: 1.5–2	2.3–2.9 (possible cost)	R&D
Photovoltaic-Reverse Osmosis	< 100 m³/d	electrical: BW: 0.5–1.5 SW: 4-5	BW: 6.5–9.1 SW: 11.7–15.6	R&D Application
Photovoltaic-Electrodialysis Reversed	< 100 m³/d	electrical: only BW:3–4	BW:10.4–11.7	R&D
Wind- Reverse Osmosis	50–2,000 m³/d	electrical: BW: 0.5–1.5 SW: 4–5	Units under 100 m³/d, BW:3.9–6.5 SW:6.5–9.1 About 1,000 m³/d, 2–5.2	R&D Application
Wind- Mechanical Vapor Compression	< 100 m³/d	electrical: only SW:11–14	5.2–7.8	Basic Research

Solar energy sources for desalination



ED: Electro Dialysis

RO: Reverse Osmosis

MSF: Multi stage flash

MED: Multi Effect Distillation

MD: Membrane Distillation

TVC: Thermal Vapor Compression

MVC: Mechanical Vapor Compression

SD: Solar Still Desalination

HD: Humidification – Dehumidification

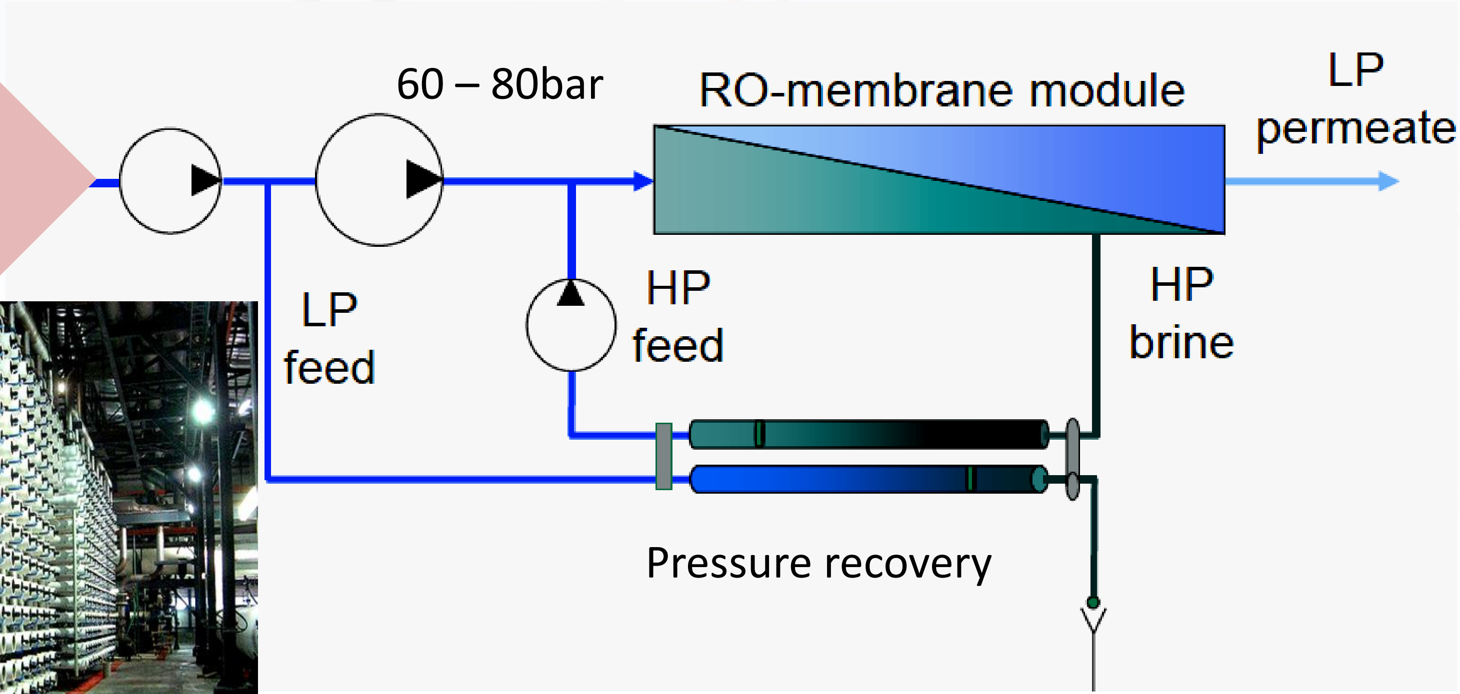
Reverse Osmosis (RO) system

Desalination technologies

Basic set up of a Reverse Osmosis (RO) system

Electrical power

3.5-6 kWh/m3



REVERSE OSMOSIS MEMBRANE AND MODULES

According to Geometric Shape, membranes can be classified in

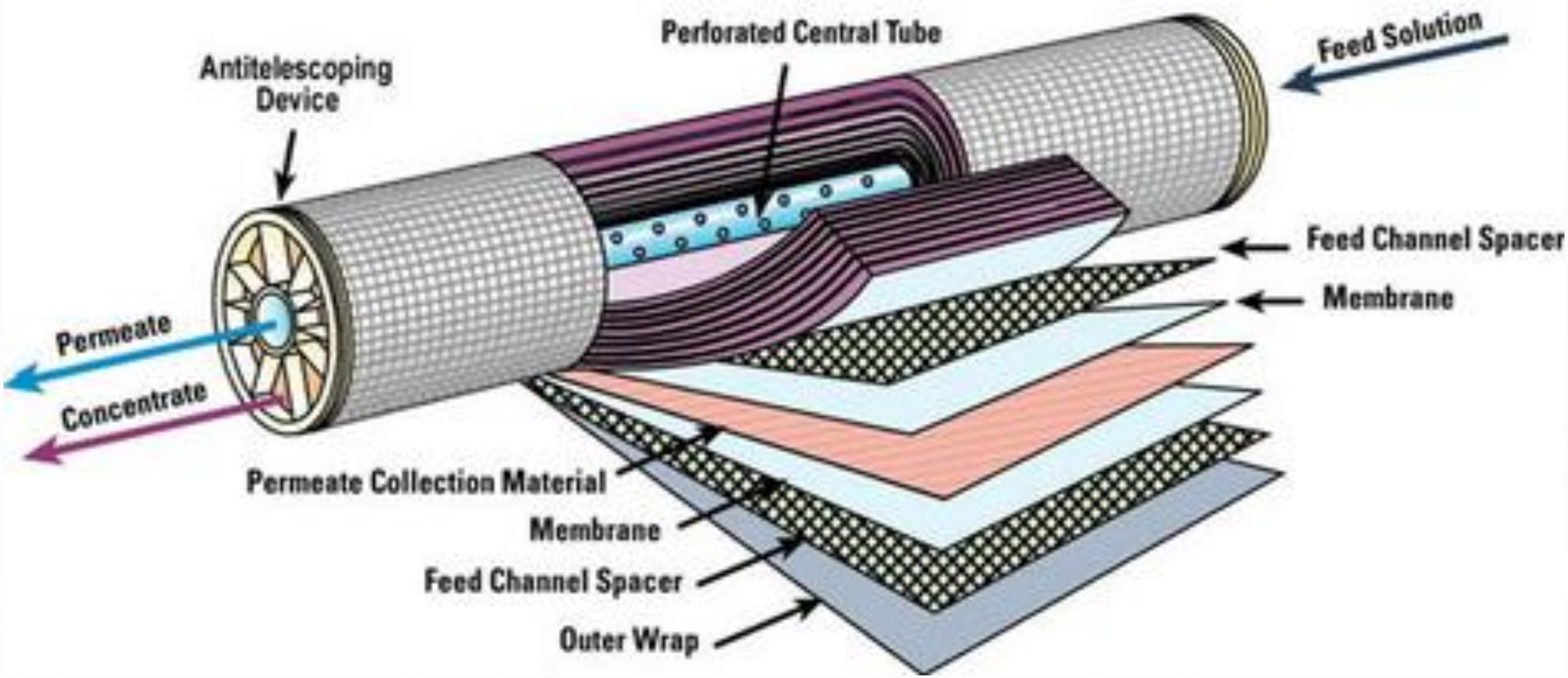
- HOLLOW FIBER → Hollow Fiber module

- FLAT SHEET → Spiral wound module

- FLAT SHEET → Plate and Frame module

- TUBULAR → Tubular module

Spiral-Wound Module



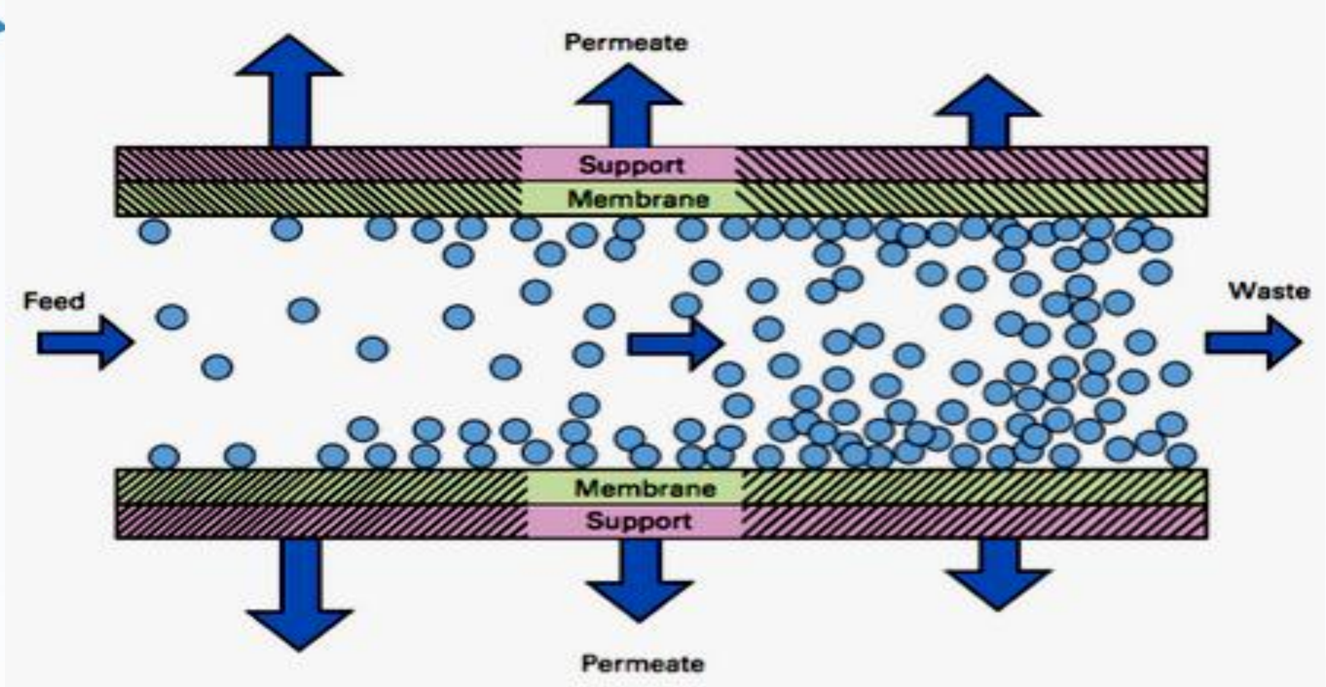
ADVANTAGES

- **Low manufacturing cost**
- **Relatively easy to clean by both chemical and hydraulic methods.**
- **Has a very broad range of applications**
- **High packing density**

DISADVANTAGES

- **It can not be used on highly turbid feed waters without extensive pretreatment.**
- **Susceptible to plugging by particulates**

Tubular Module



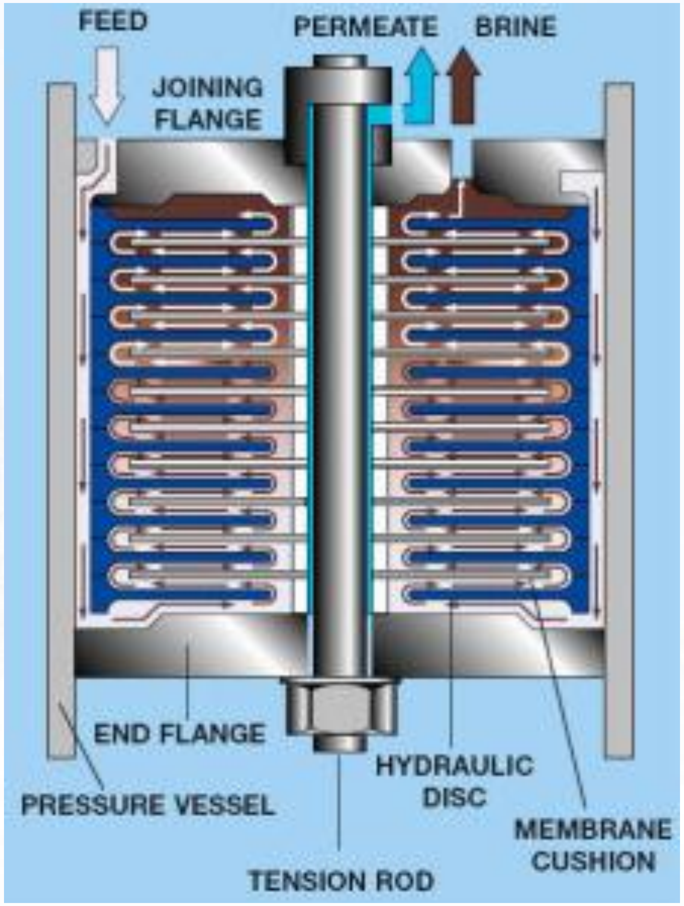
ADVANTAGES

- **Can be operated on extremely turbid feed waters.**
- **Relatively easy to clean either mechanically or hydraulically.**
- **Can process high suspended solid feed with minimal pretreatment.**

DISADVANTAGES

- **High capital cost.**
- **Relative high volume required per unit membrane area.**

Plate and Frame Module



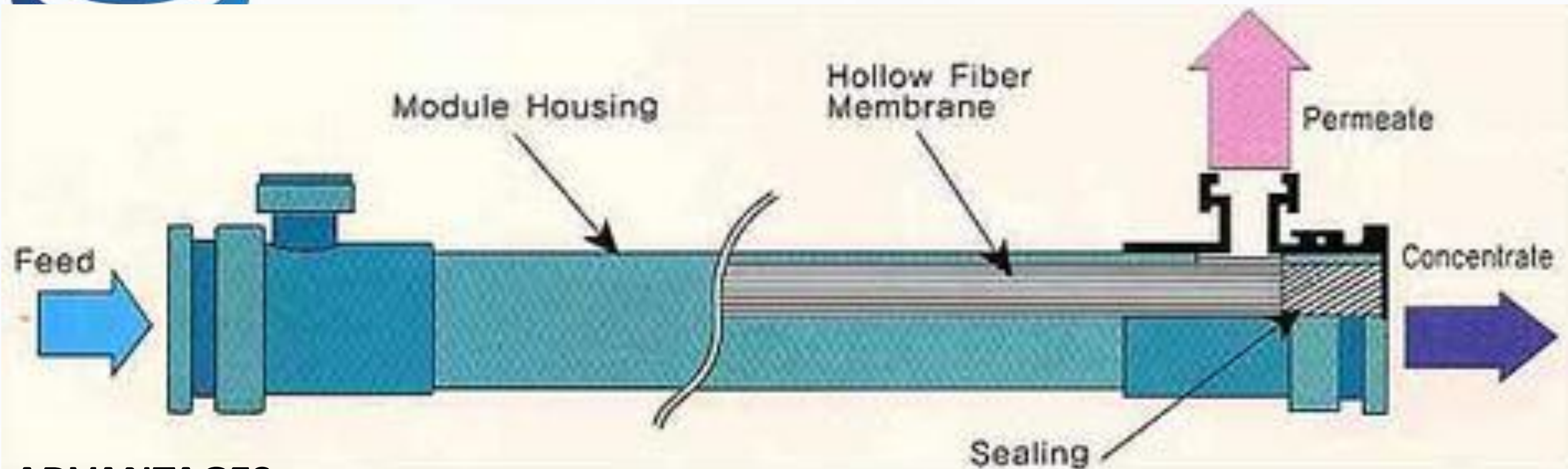
ADVANTAGES

- Moderate membrane surface.
- Well-developed equipment.

DISADVANTAGES

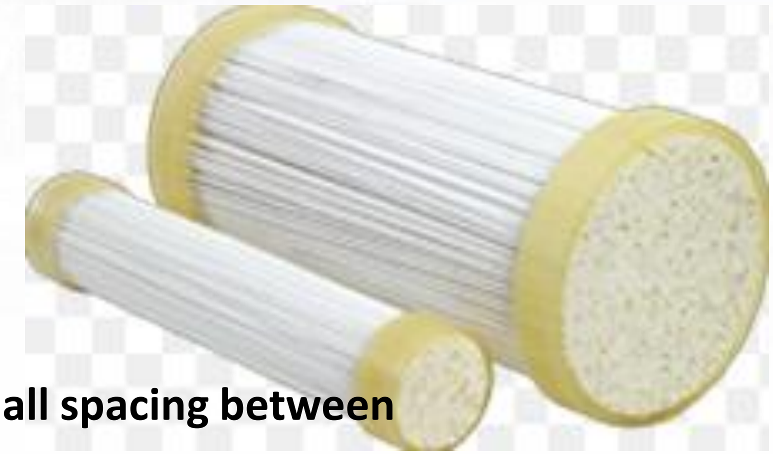
- Expensive to operate for large scale.
- Susceptible to plugging by particulates at flow stagnation points.
- Potentially difficult to clean.

Hollow Fiber Module



ADVANTAGES

- Relatively low manufacturing cost.
- Compact
- High packing density
- Modes energy requirement

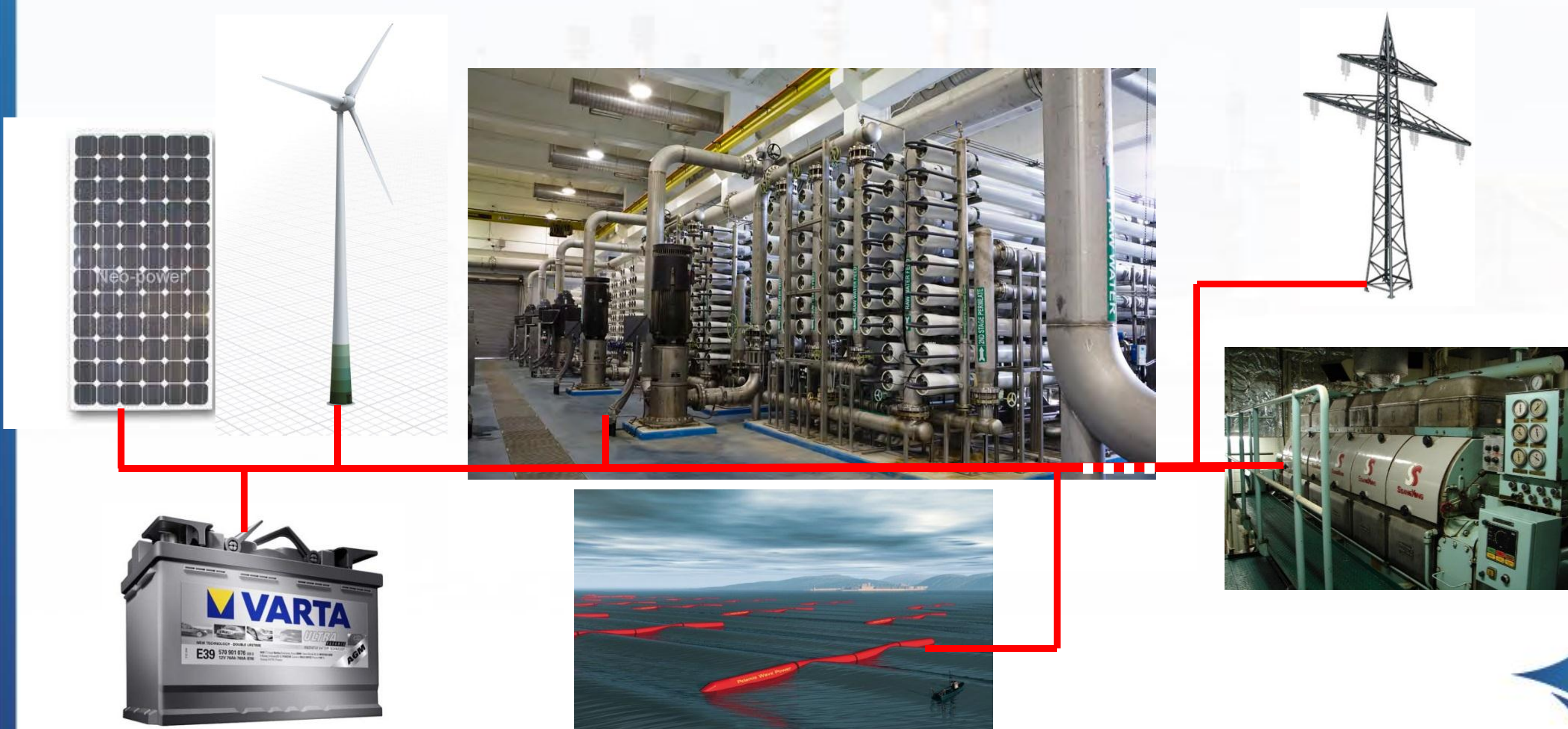


DISADVANTAGES

- Extremely susceptible to fouling due to very small spacing between fibers.
- Difficult to clean.
- Requires extensive pretreatment.
- Limited range of applications.

Energy supply Reverse Osmosis (RO) system

PV-RO - stand alone system configuration with and without back up for small and medium scale application



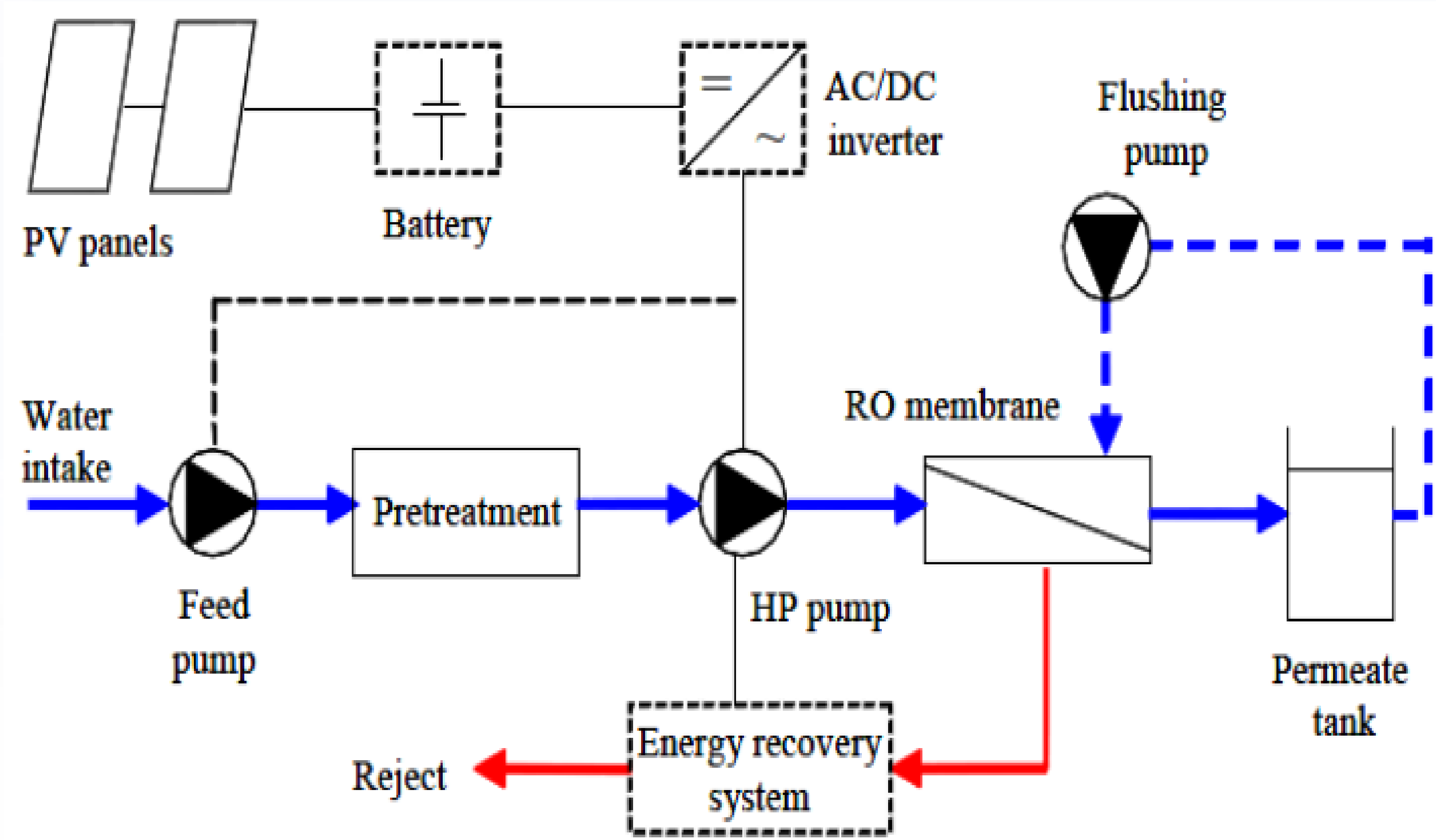
Photovoltaic-driven reverse osmosis (PV-RO)

The PV-RO system consists of a photovoltaic field that supplies electricity to the desalination unit through a DC/AC converter and a RO membrane for the desalination.

Specific cost of drinking water in the range of 3.5 –7 €/m³ for brackish and 9 –12 €/m³ for seawater RO units depend on the capacity of RO units.

COMBINATION	COST (€/m³)	ASSUMPTIONS
Seawater PV-OR	11.81	• Nominal capacity: 100 m³/d • Number of annual operation hours: 3,000 • Specific energy consumption: 6 kWh/m³
Brakish water PV-RO	8.29	• Nominal capacity: 100 m³/d • Number of annual operation hours: 3,000 • Specific energy consumption: 1.6 kWh/m³

PV-RO - stand alone system



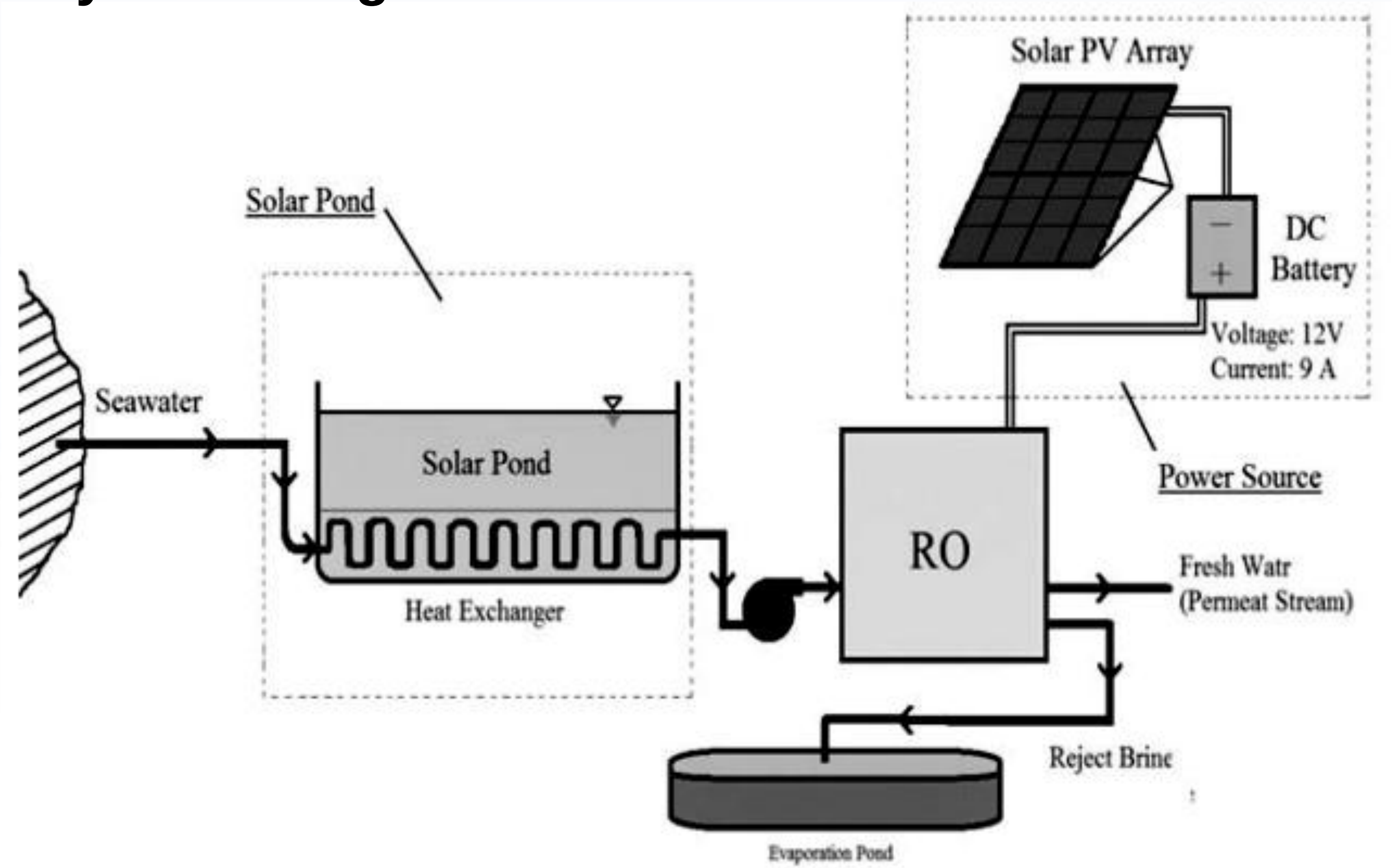
PV-RO - stand alone system

Technology: PV-RO
Water source: bracKish water
Year of installation: 2006
Location: tunisia

Energy source: solar PhotoVoltaic
Hourly capacity (nominal): 2.100 liter
Type of installation: commercial

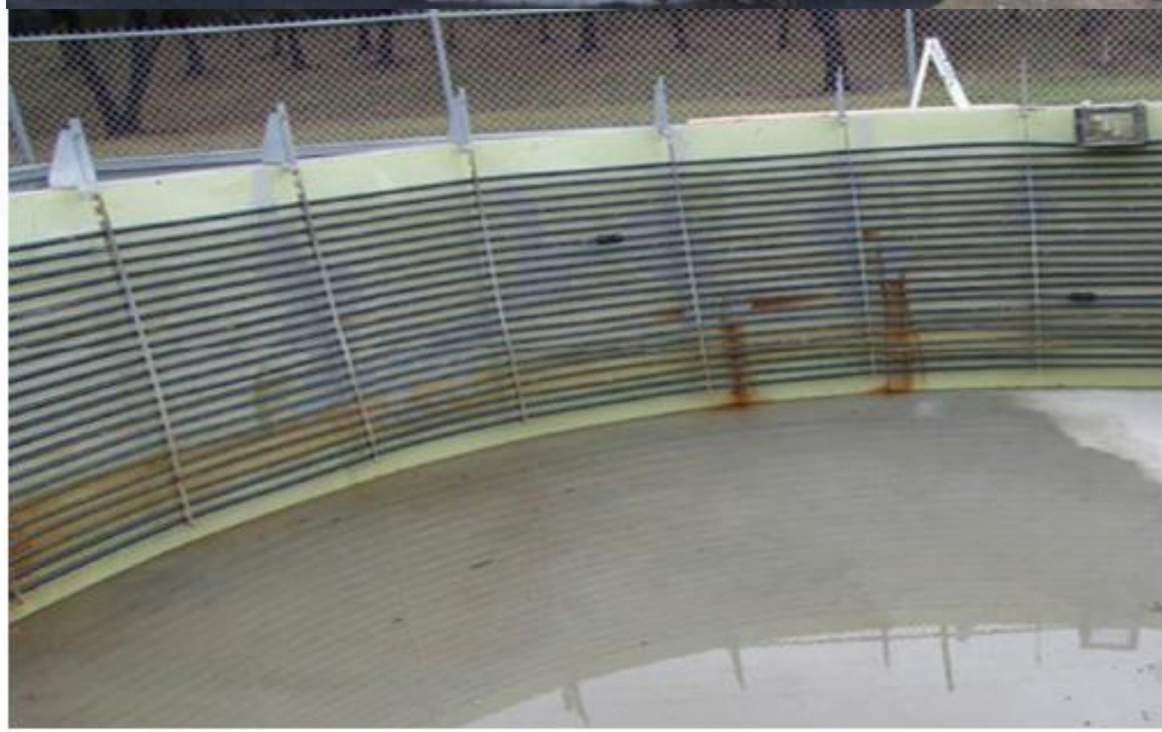
Solar thermal energy -assisted PV-RO desalination plant

RO system integrated direct with Solar Pond



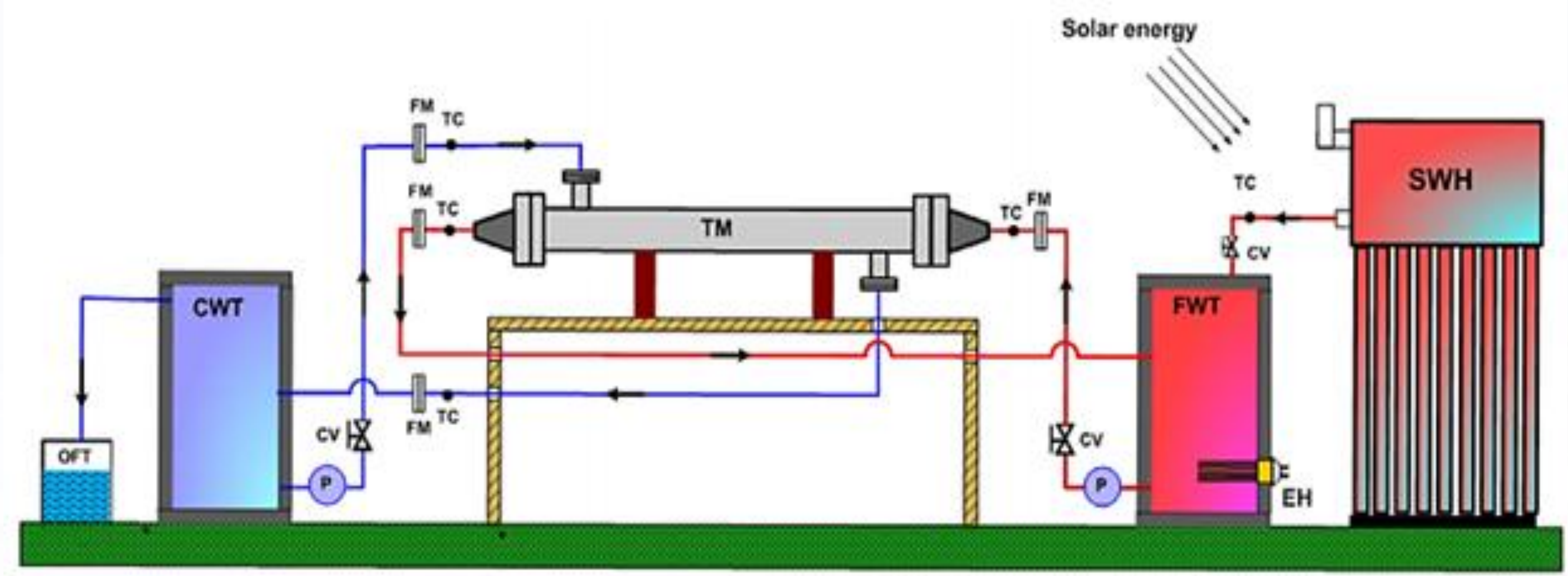
Solar Pond

All solar collectors, solar pond was chosen to provide the heat for pre-heating the feed water for RO desalination process, due to its high efficiency to serve as a solar heat storage system.



Internal heat exchanger in the solar pond

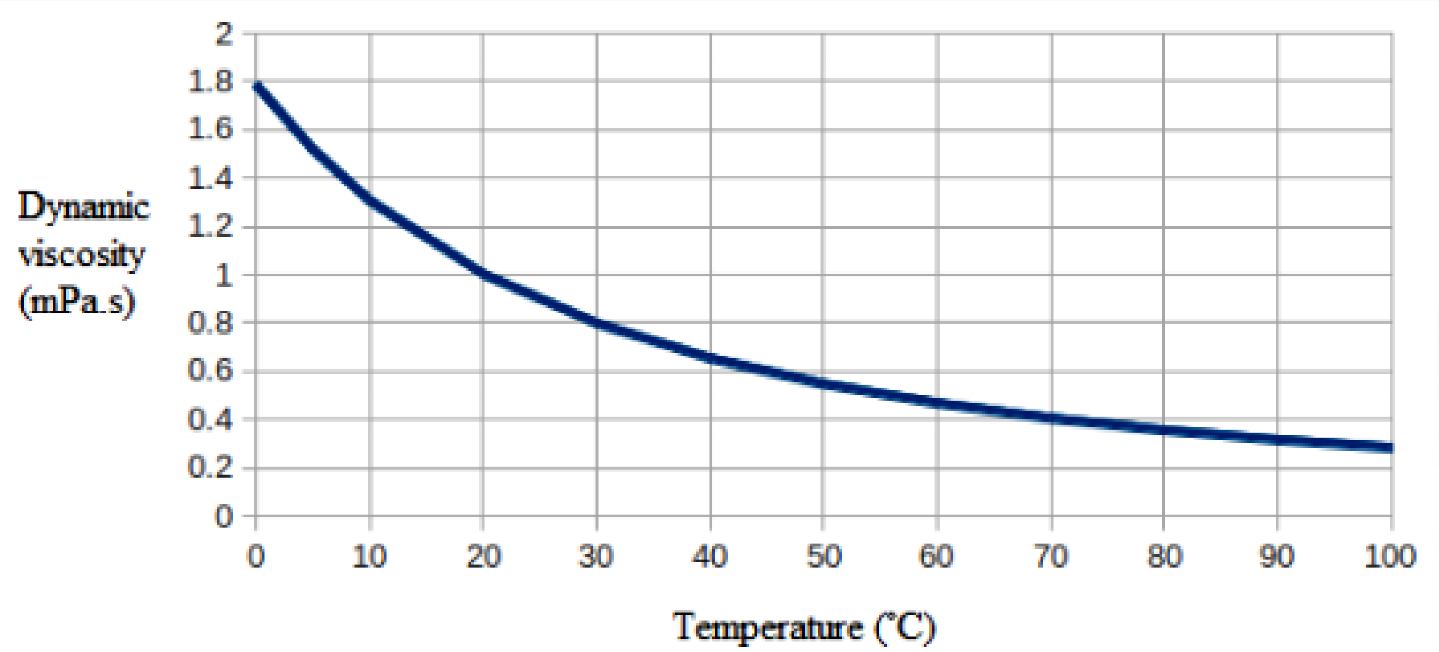
RO system integrated direct with solar water collector



CV	Control Valve	OFT	Overflow Tank	FM	Orifice Flow Meter
CWT	Cooling Water Tank	P	Pump	FWT	Feed Water Tank
EH	Electric Heater	SWH	Solar Water Heater	TC	Thermo Couple
				TM	Tubular Membrane Module

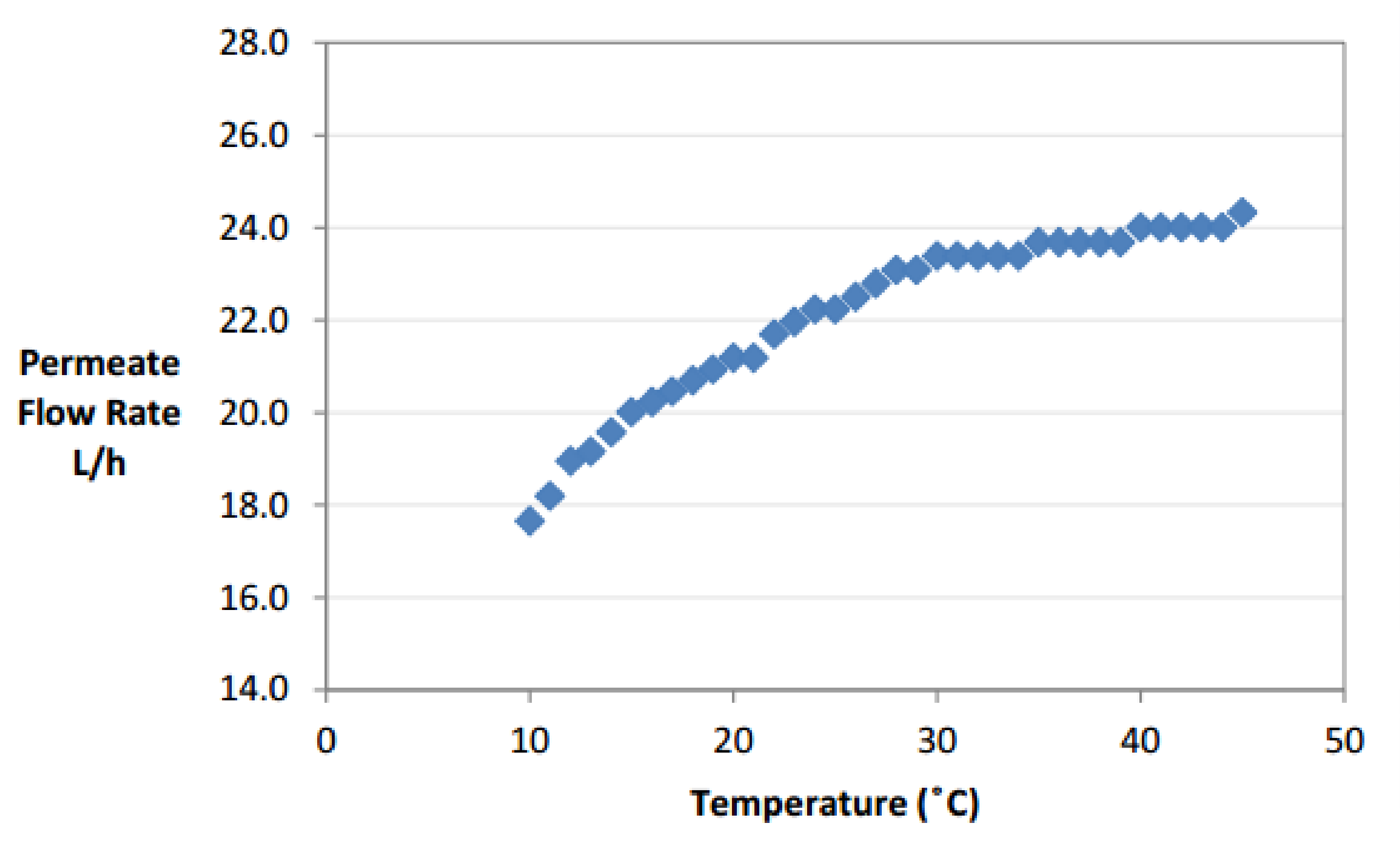
Effect of solar thermal energy on the performance of RO desalination

Effect of Temperature on the dynamic viscosity



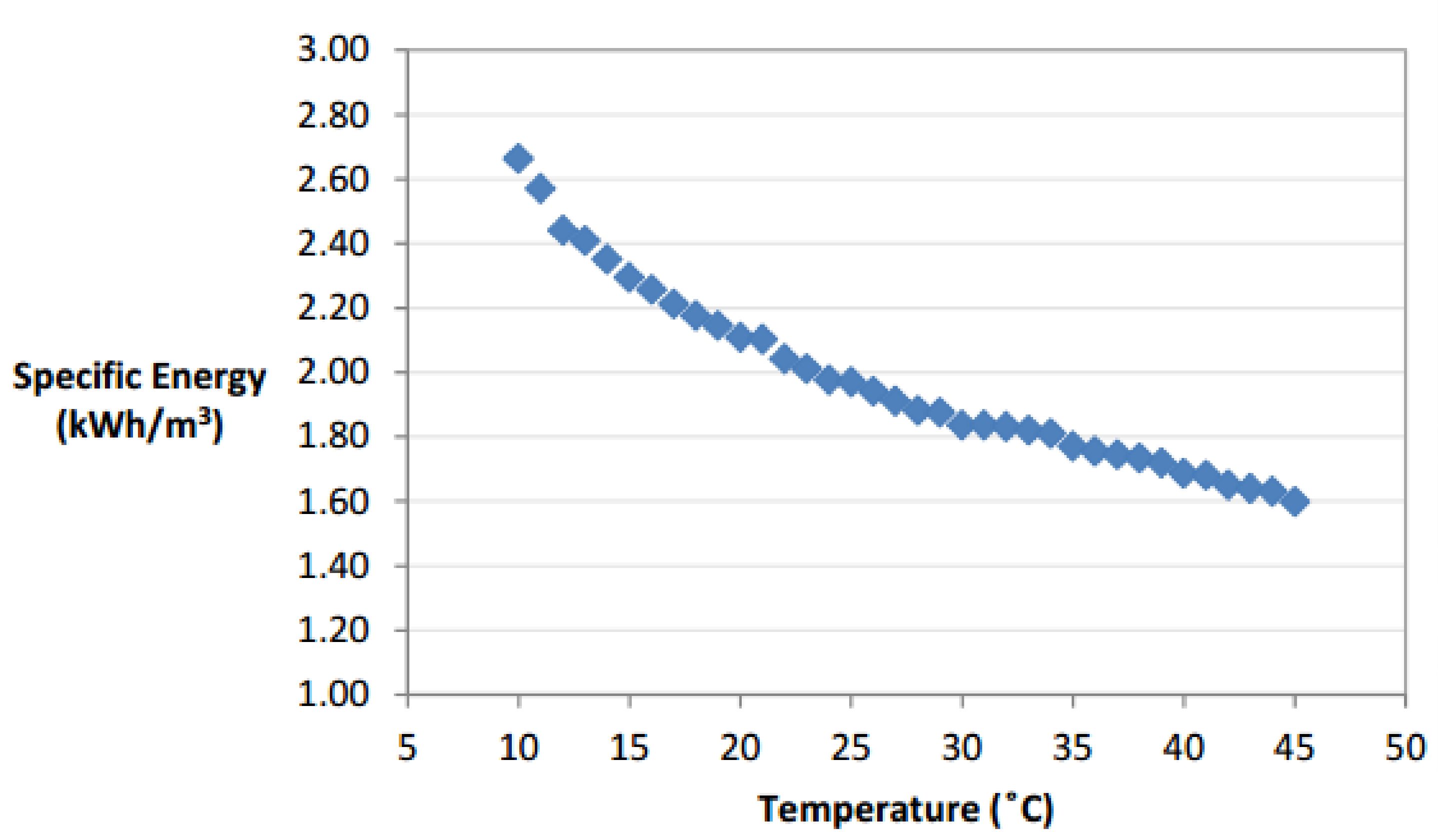
The dynamic viscosity of such water can be found from the figure to be approximately around 1.4 mPa.s. By increasing its temperature to for example 45 degrees, the viscosity drops to 0.6 mPa.s. This is a 60 percent reduction, and has a considerable effect on reduction of the frictional head losses.

Effect of Temperature on the permeate flow rate



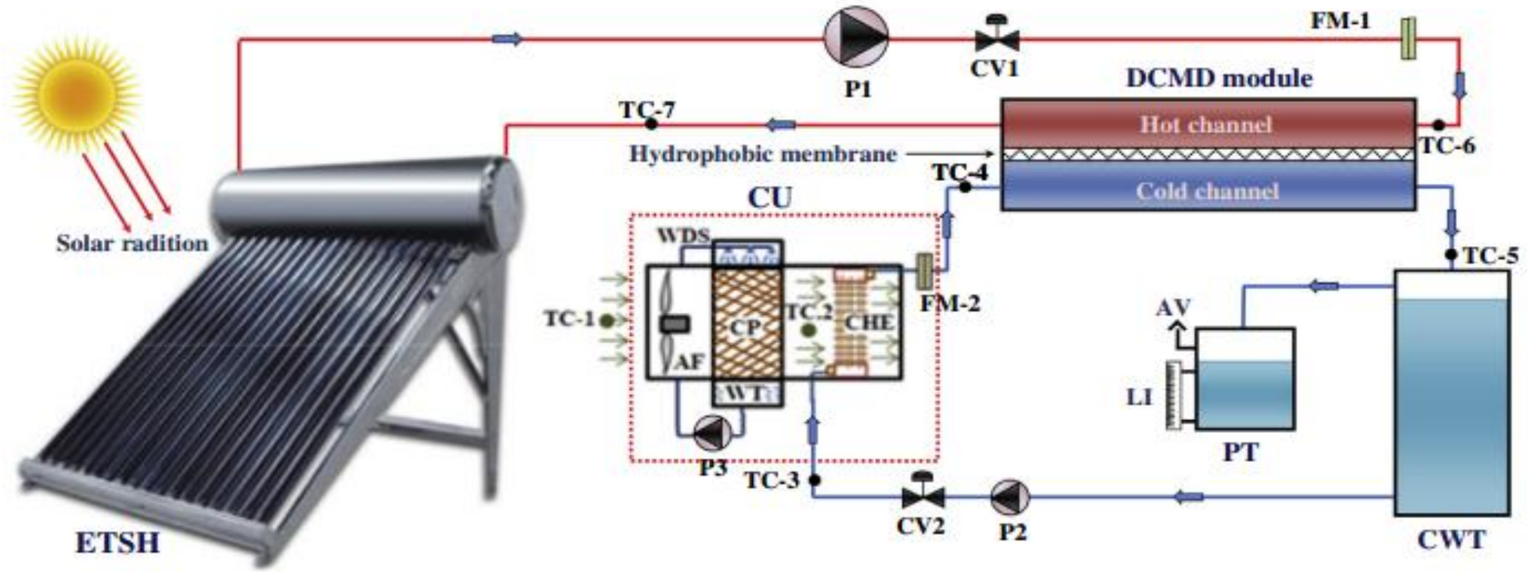
the flow rate has increased from 17.6 liters per hour at 10 C to 24.3 liters per hour at 45 C.

Effect of Temperature on the specific power consumption



The experiment showed that there is a 40% drop in the required Energy per Unit of Permeate Flow, when the temperature was increase from 10 C to 45 C.

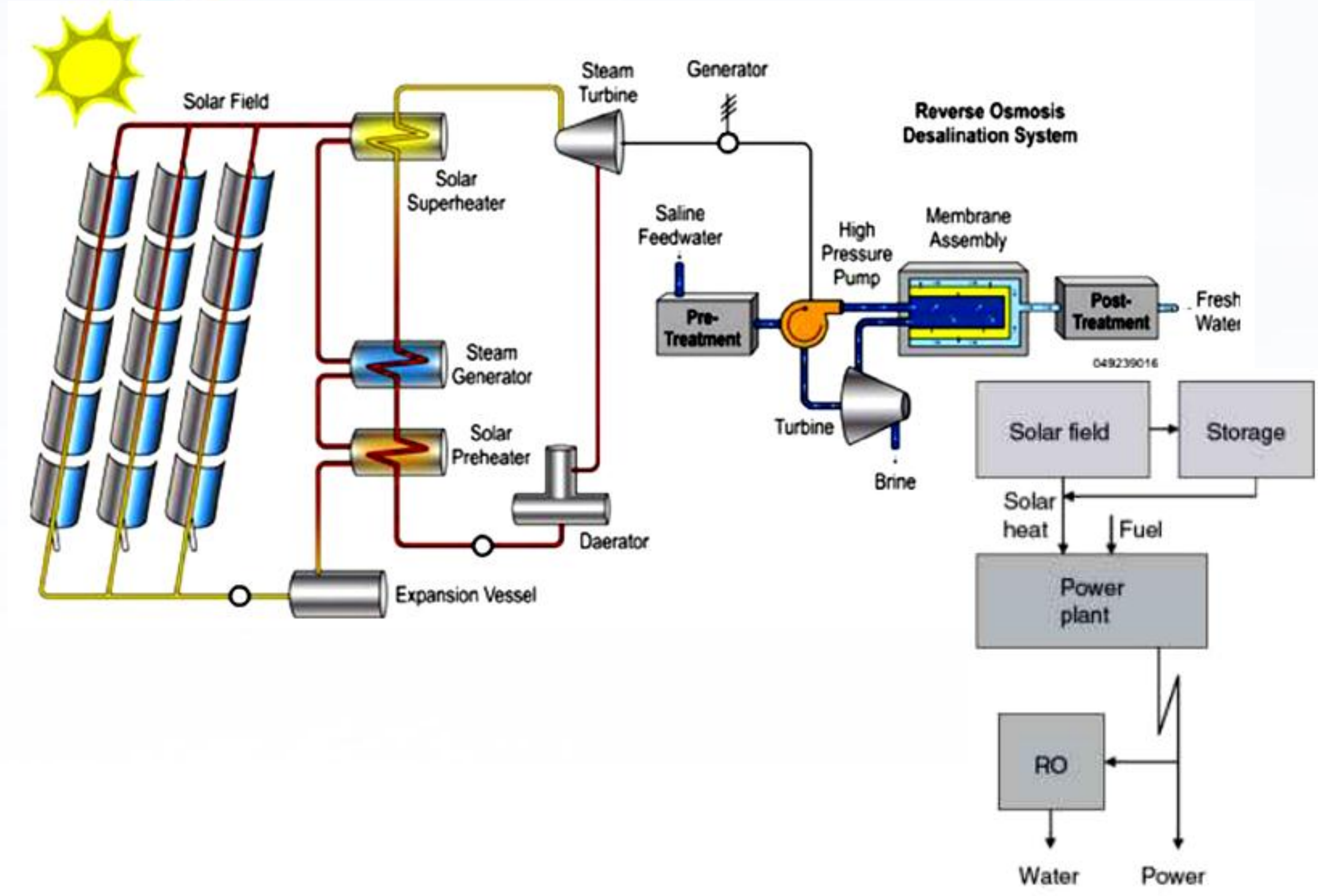
RO system integrated direct with solar water heater and cooling unit



AF	Air Fan	TC	Thermocouple
CHE	Cross- Flow Heat Exchanger	DCMD	Direct contact membrane distiller
CP	Cooling Pad	P	Pump
CU	Cooling Unit	WDS	Water Distribution System
CV	Control Valve	WT	Water Tank
CWT	Cooling Water Tank	PT	Product Tank
FM	Orifice Flow meter	LI	Level indicator
ETSH	Evacuated Tube Solar Heater	AV	Air vent

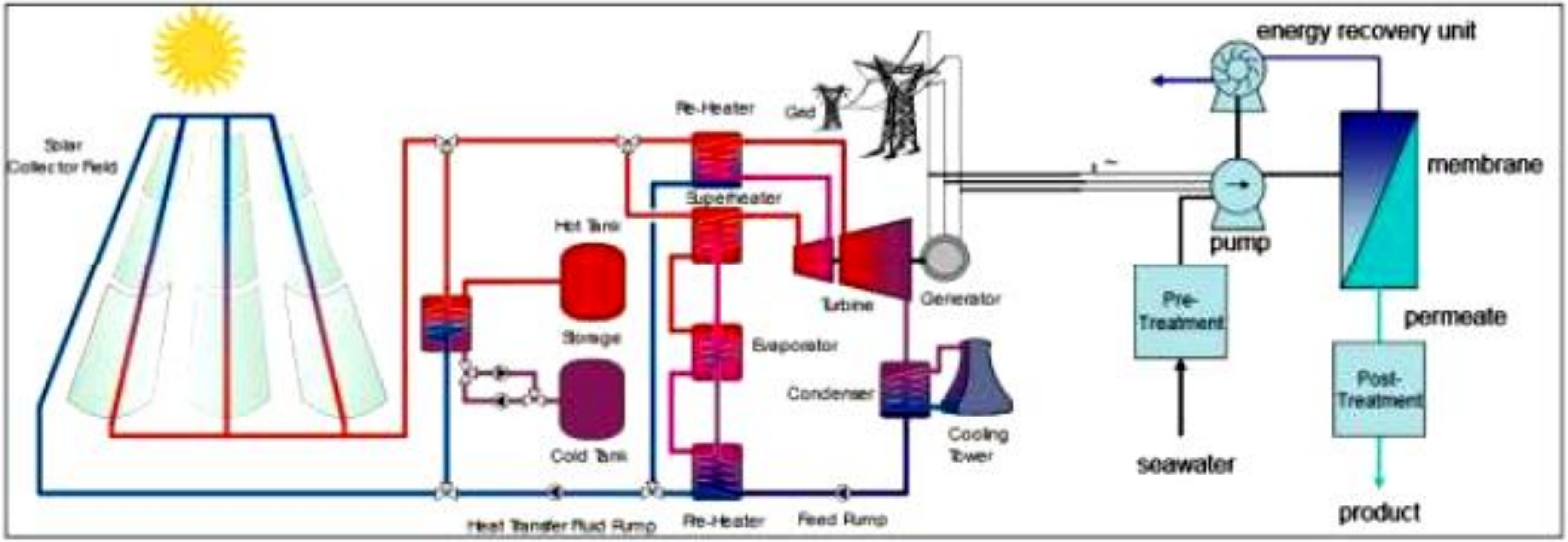
The solar energy to reduce energy required by more than 50%. The use of the cooling unit significantly increased the system productivity, almost 1.25 of that without the cooling unit.

Concentrated solar power plants (CSP) integrated with RO desalination system



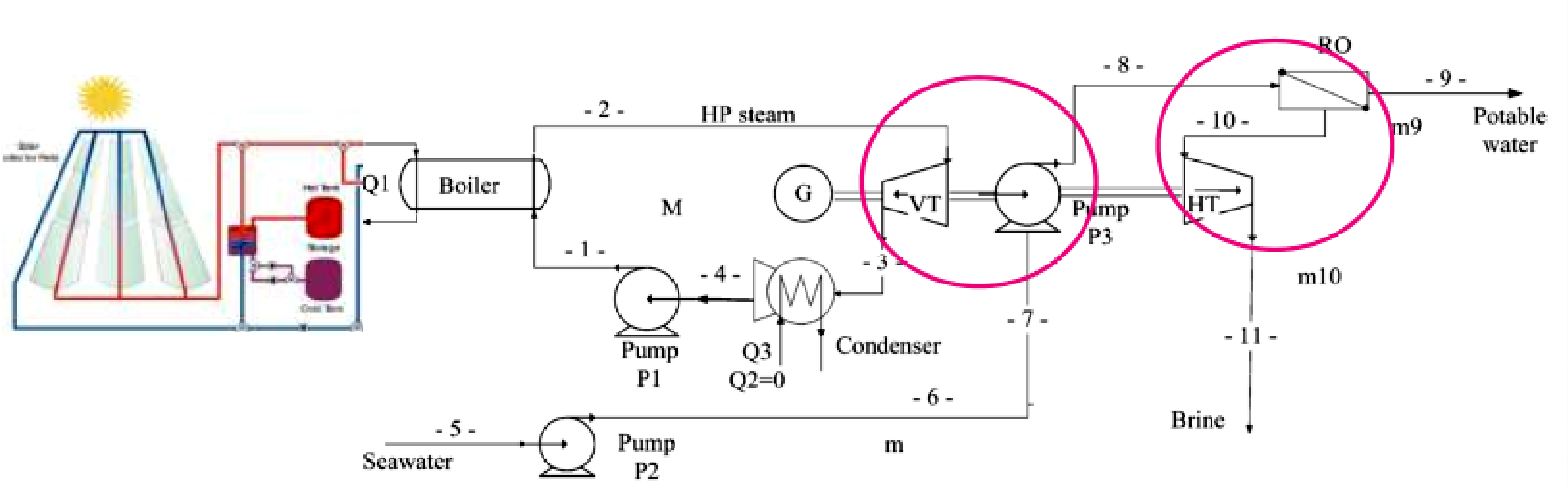
Type of CSP/Power plant-RO Coupling

1- Not really coupled



- The desalination process is driven by the power output from the CSP plant
- Full expansion of the steam in the turbine

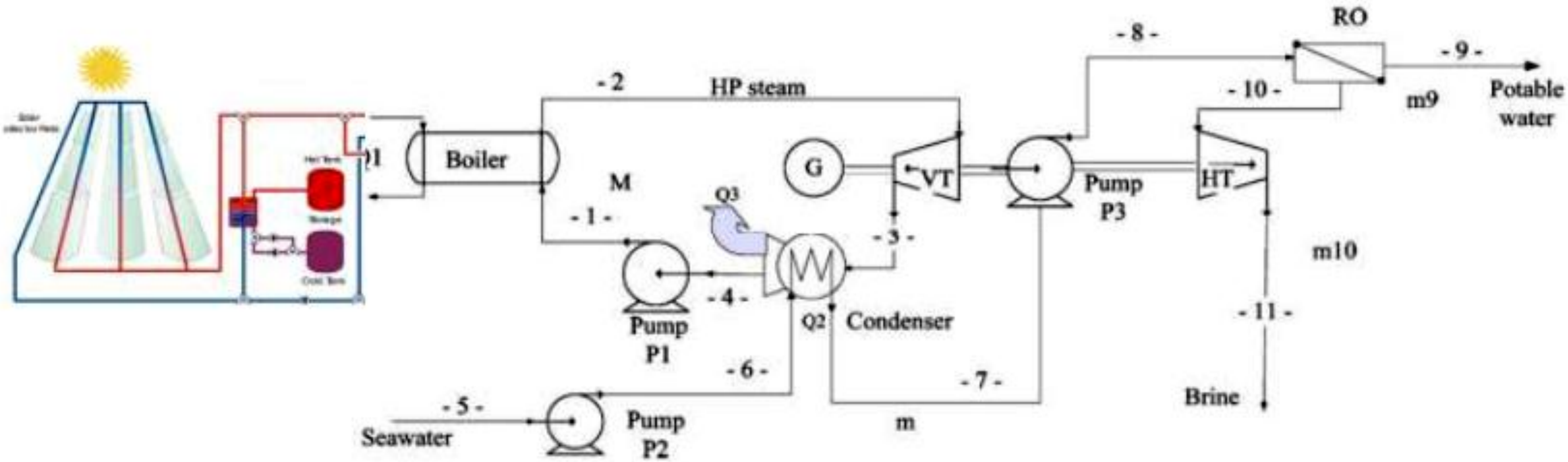
2- Mechanically coupled



• **The steam turbine and the RO subsystem (pumps) are mechanically coupled (the power plant provides mechanical power to the pumps of the RO subsystem)**

• **The RO subsystem incorporates a power recovery unit (Hydraulic turbine**

3- Mechanically and thermally coupled



- The steam turbine and the RO subsystem (pumps) are mechanically coupled
- The RO subsystem incorporates a power recovery unit (Hydraulic turbine/PES)
- Part of the heat rejected by the condenser of the power plant is transferred to the Seawater
- More water produced

Conclusion

For membrane desalination processes, the average power consumption of RO ranges between 3.7 to 8 kWh/m^3 for seawater. For sea water RO unit with energy recovery the power consumption varies between 4 to 6 kWh/m^3 at 24.000 m^3/day capacity. For brackish water RO unit's the power consumption ranges between 1.5 and 2.5 kWh/m^3.

The solar energy to reduce energy required by more than 50%. The use of the cooling unit significantly increased the system productivity, almost 1.25 of that without the cooling unit.

In 2025, Egyptian water demand is expected to reach a level of 130 billion m3/year, with more than 80% used for agriculture, while water supply is currently expected to remain at 73 billion m3/year.

Areas of current and future research on solar thermal desalination focus on the following three aspects: (1) enhancing solar-energy collection, (2) improving the technology of desalination techniques, and (3) better matching the solar field and desalination unit. These areas of investigation directly relate to the economic performance improvement of the system.

The End