Feasibility of Small scale Solar Powered RO Desalination

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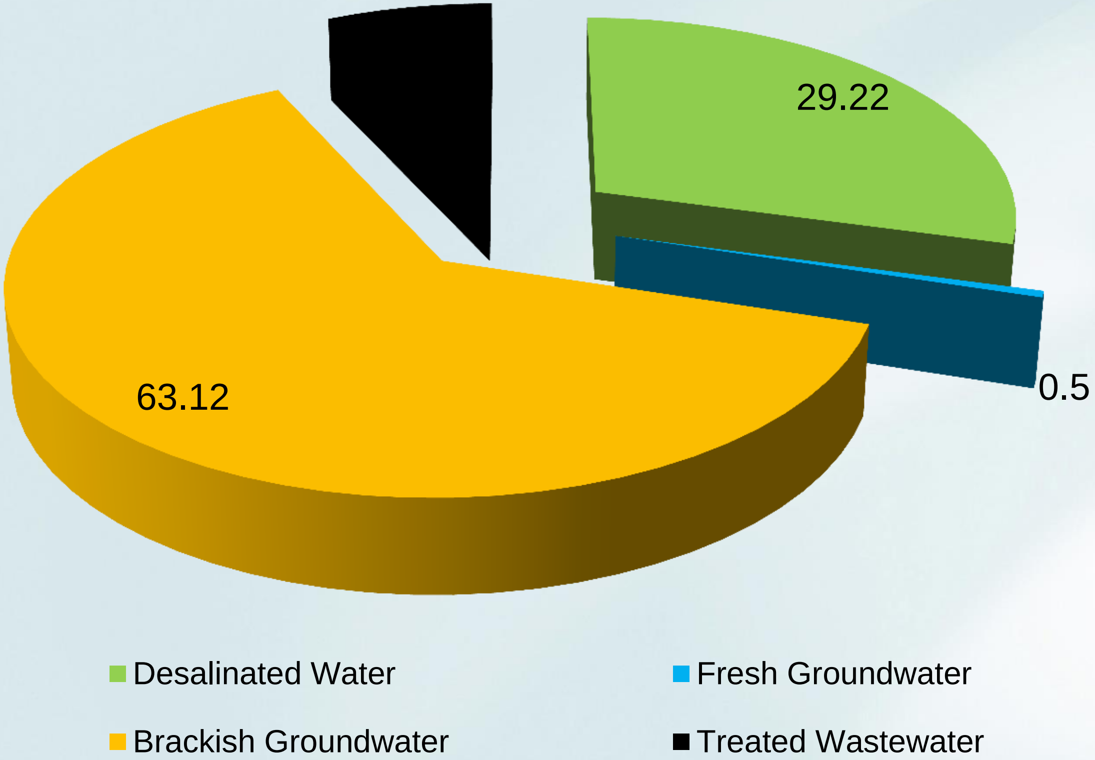
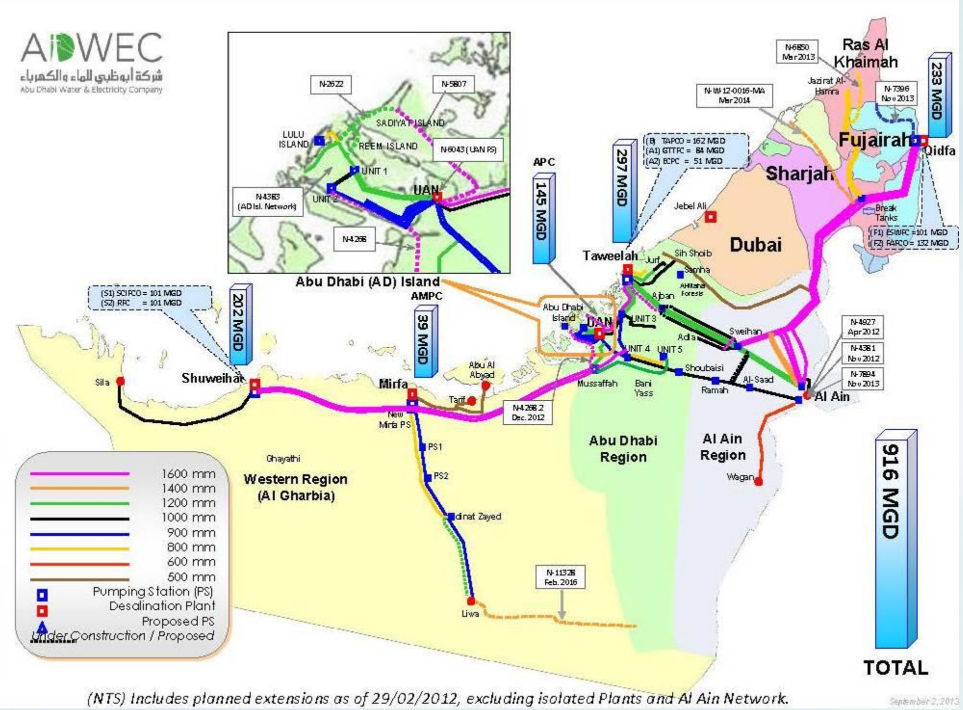
Water Resources in Abu Dhabi

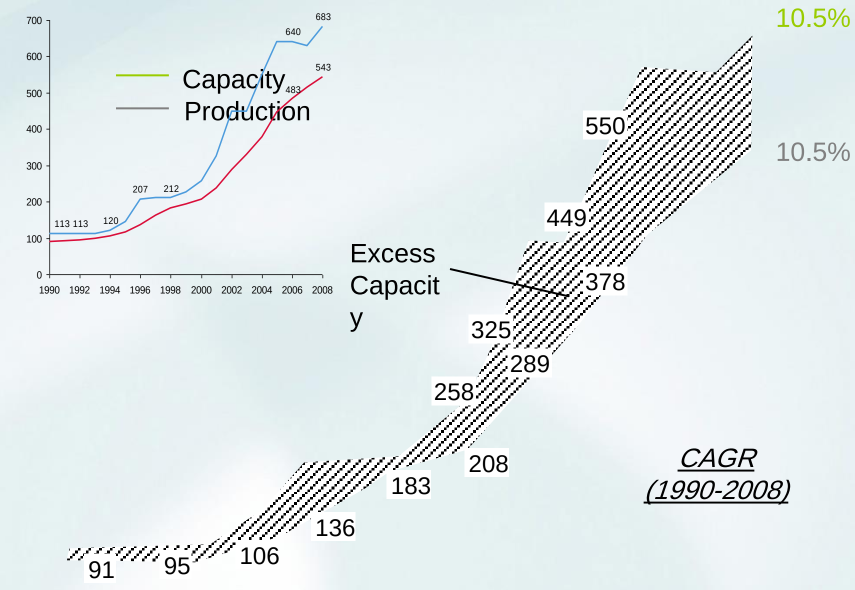


Desalination Plants Capacity and Production in Abu Dhabi



(NTS) Includes planned extensions as of 29/02/2012, excluding isolated Plants and Al Ain Network.

Daily Desalinated Water Capacity and Production



Annual Production (in Mm^3)

151	157	177	225	303	345	480	628	802	903

Capacity Utilisation (%)

80%	84%	88%	66%	86%	81%	64%	69%	76%	79%

ADWEC Desalinated Water Demand and Capacity Forecasts
– In MGD –
(2010F-2030F)

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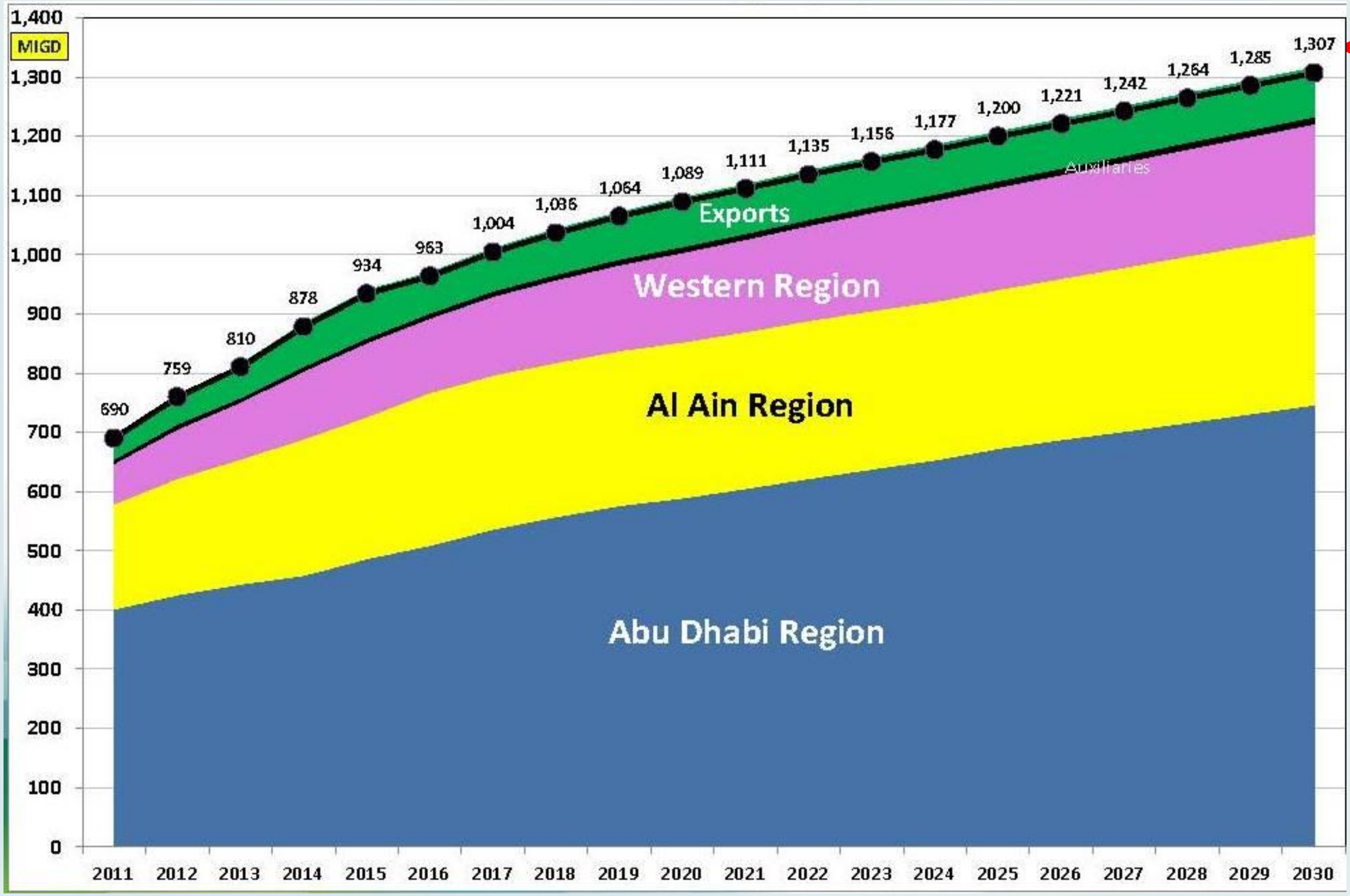
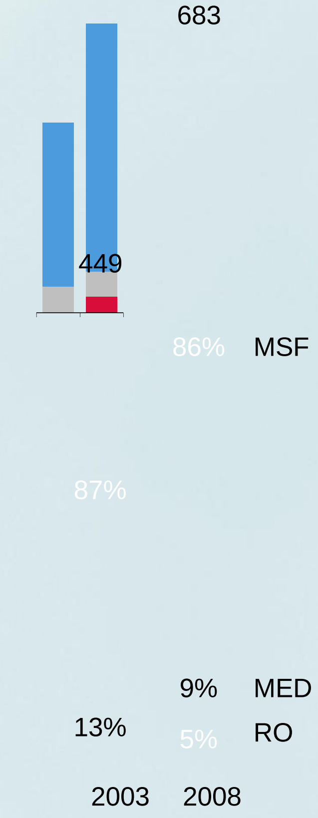


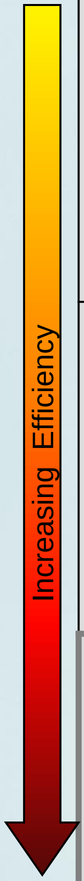
~ 400 MGD Capacity Required by 2030

Assessment of Desalination Technologies

II. Desalinated Water

Abu Dhabi Desalination Capacity by Technology - In MGD - (2003-2008)



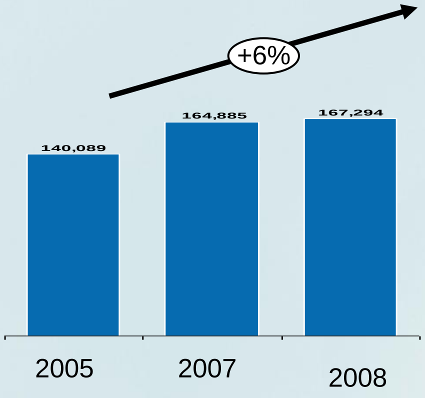


	Description	Total Cost (US$/m^3)	Energy Consumption (kWh/m^3)	Saline Feed Water per m^3 of Fresh Water	Discharged1) Water per m^3 of Fresh Water	Applicability to Abu Dhabi	Country Examples
Multi-stage Flash Distillation (MSF)	▪ Produce fresh water by evaporating heated seawater in a vacuum evaporator and condensing the vapour ▪ Heat efficiency is improved by recovering the latent heat of the condensed vapour and flash-boiling the water at each stage	**1.10-1.25**	**51.5**	**10-11**	**9-10**	▪ Enable co-generation of water and electricity with efficiencies of scale in desalination ▪ Allow generation of large volumes ▪ Exposed to fuel price fluctuations	KSA Qatar Bahrain USA
Multi-effect Distillation (MED)	▪ Utilise steam or waste heat from power production/chemical processes to evaporate seawater in one or more stages at low temperatures (less than 70°C) to produce clean distilled water ▪ Involve low electricity consumption and high production per thermal unit	**0.75-0.85**	**45.1**	**6-7**	**5-6**	▪ May not be suitable to Abu Dhabi due to limited production capacity of MED plants ▪ Exposed to fuel price fluctuations	Bahrain Oman
Reverse Osmosis (RO)	▪ Pass seawater at high pressure through semi-permeable membranes to produce fresh water ▪ Dissolved impurities remain behind and are discharged in a waste stream ▪ Energy-efficient process that does not use steam, unlike distillation	**0.68-0.82**	**6.9**	**3-4**	**2-3**	▪ Difficult to implement in Abu Dhabi due to abundance of algae, high salinity and elevated sea water temperatures ▪ Constrained by production capacity	USA Australia Singapore UK

Environmental Impacts

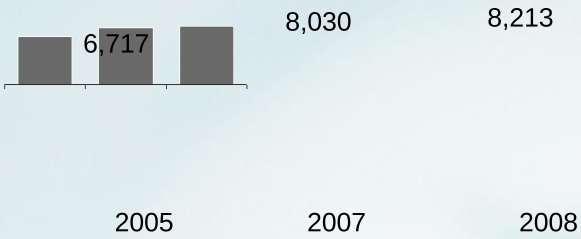
ADWEA Plants Fuel Consumption attributed to Water Production

- In Billion BTU -
(2005-2008)



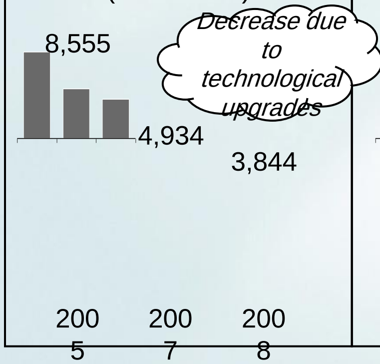
Climate Change

CO$_2$ Emissions from Water Desalination
- In Thousand Metric Tons -
(2005-2008)

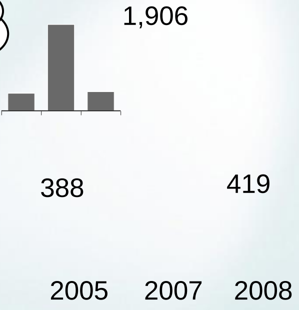


Air Pollution

NOx Emissions from Water Desalination
- In Metric Tons -
(2005-2008)



SO$_2$ Emissions from Water Desalination
- In Metric Tons -
(2005-2008)

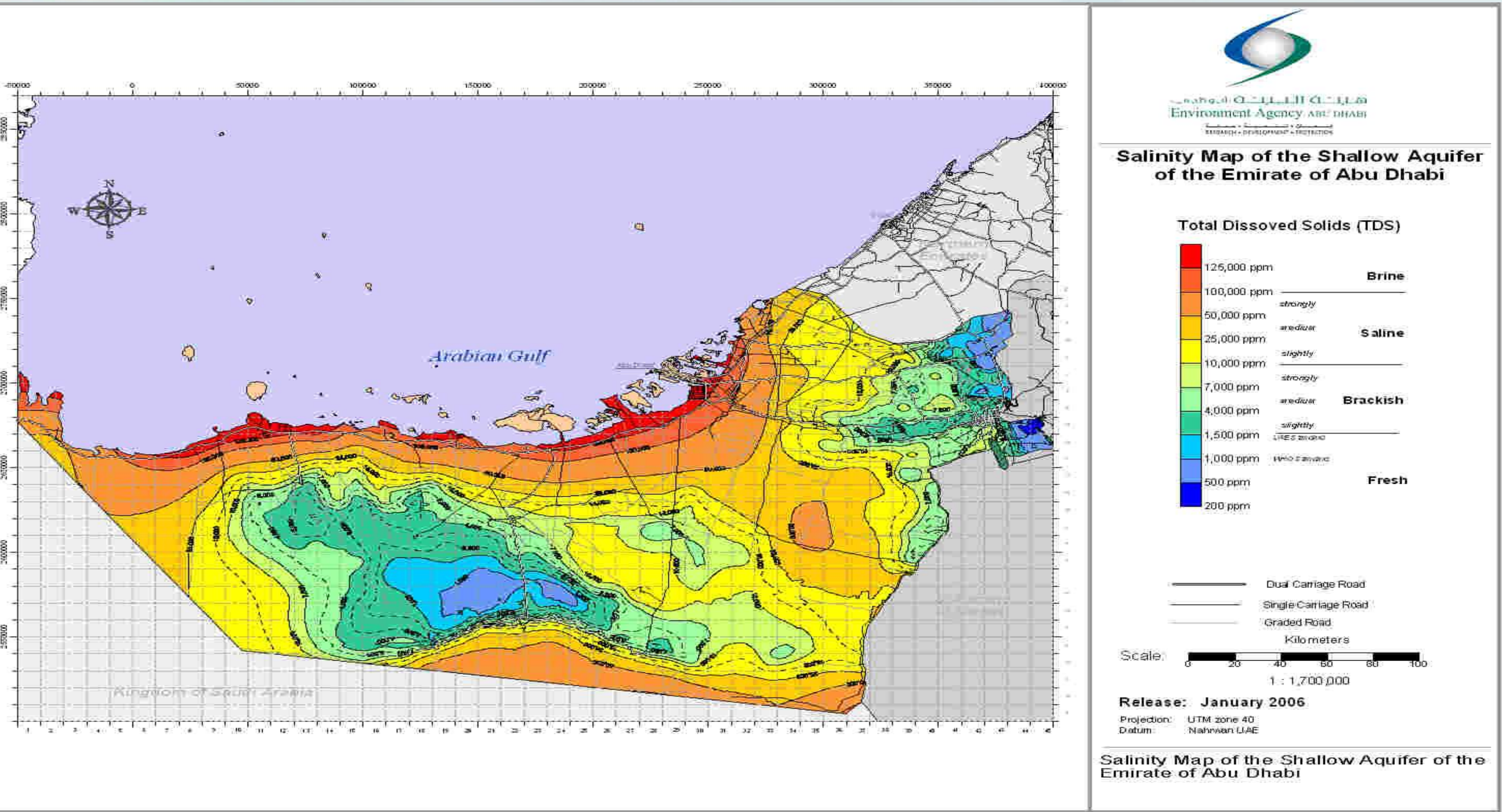


Environmental Impacts of Increased Fuel Consumption

- Water desalination in Abu Dhabi is an energy-intensive activity with non-renewable fossil fuel consumption reaching 167,294 Billion BTU in 2008, as a result of increasing production
- Due to high energy consumption, the desalination industry is exacerbating air pollution through NOx and SO$_2$ emissions; however, the following should be noted:
  - NOx emissions are decreasing due to technological upgrades
  - SO2 emissions fluctuate depending if oil is used instead of natural gas
- In addition, the water production sector is the second largest emitter of CO$_2$ and contributor to climate change after the oil sector in Abu Dhabi
- Fuel consumption is expected to continue to increase as new desalination capacity becomes operational

Protected Areas

Groundwater Deterioration



Salinity Map of the Shallow Aquifer of the Emirate of Abu Dhabi

Site Photos

Layout

Brine Water Evaporation Pond

PVC-RO Design Technical Details

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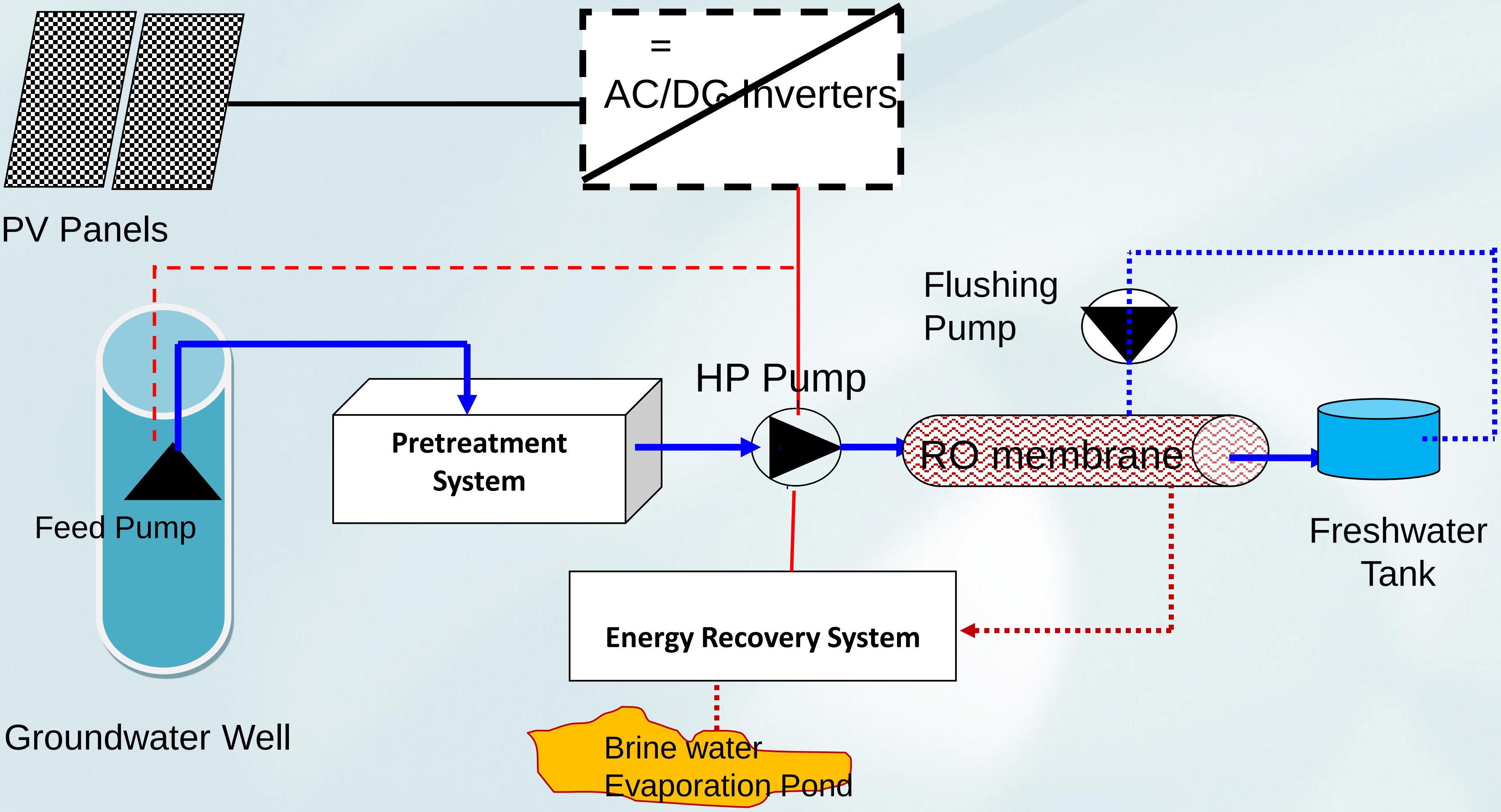

Design Technical Details

- *Small Community*
- *No connection to power or water grid*
- *High demand for water*

Capacity	60 m^3/day
Feed Water Source	Brackish Groundwater
Feed Water Salinity (ppm)	Less than 35,000 ppm
Product Recovery (%)	65 - 70%
Pressure (kPa)	$1.1 \times 10^3 – 1.2 \times 10^3$
Power Requirement (kw)	2.5 – 4.0
Product Salinity (ppm)	200 – 250 ppm
Brine water	Evaporation bond

Site Photos

Design Technical Details

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Groundwater Well

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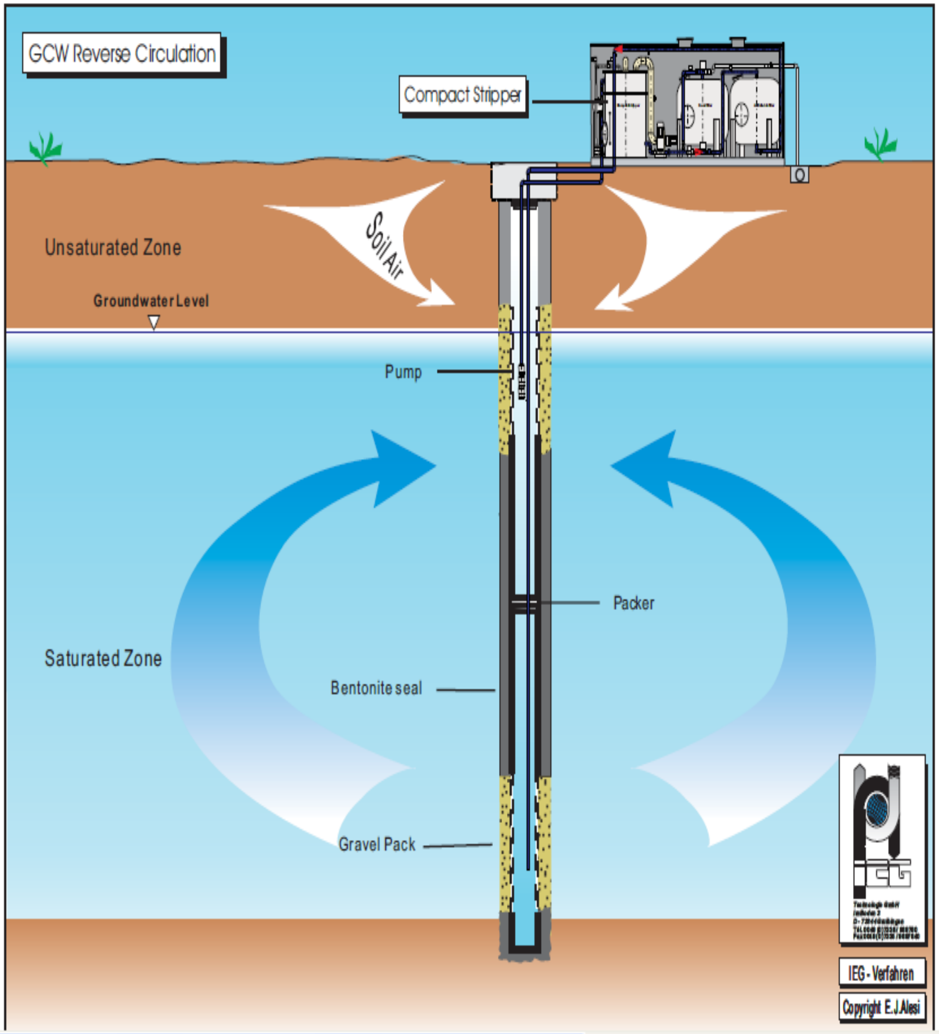
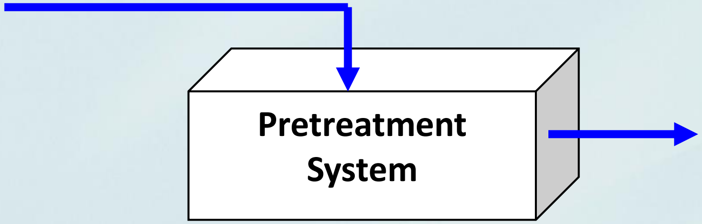


Groundwater well(s) and feed pump(s):
It is electrical submersible pump with a capacity of 15 m^3/hr and 50 m head that convey the feed water from the groundwater well to the pretreatment system. It is powered by the arrays of the PV modules. The groundwater wells depths ranges from 50 m to more than 100 m and the depth to groundwater ranges between 5 m to 20 m from the ground surface.

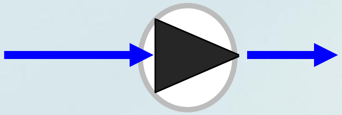
Recovery Ratio = 1- (Ci/Co) %

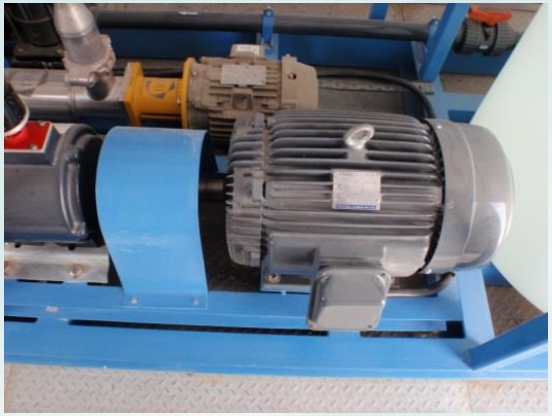
Pretreatment unit



Conventional RO pretreatment is generally implemented. The main filter barrier typically has a pore size of 5 μm and is preceded by a coarser filter with pore sizes of 20-25 μm or larger. Active carbon filtration follows for the removal of free chlorine, which can damage the RO membranes. Where bacterial counts in the feed water are high, disinfection by ozonation or chlorination are used to protect the membranes from biofouling. The experience with ultrafiltration (UF) as a pretreatment step was limited to several experimental tests performed in Australia with different kinds of brackish groundwater. UF pretreatment involves higher investment costs than conventional pretreatment, but because it removes significant numbers of microorganisms and generally delivers higher quality RO feed, which eliminates the need for membrane disinfection, UF pretreatment may reduce RO membrane cleaning and replacement costs. Chemical pretreatment with antiscalants is frequently implemented to reduce the risk of membrane surface scaling. Alternatively, the plant may be operated at low recovery rates to prolong membrane viability.

High-pressure pump



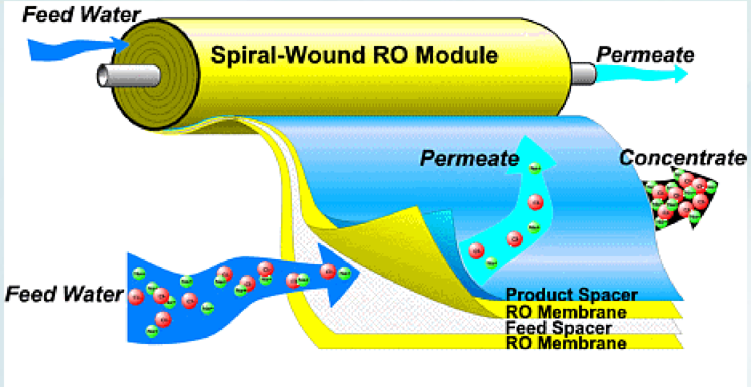


As a rule, positive displacement pumps are used because of their higher energy efficiencies -with respect to centrifugal pumps- at low flows. Both rotary positive displacement pumps and reciprocating pumps were used. The Clark pump, a reciprocating pump that was specifically developed for energy recovery in small desalination systems and that was used in several PV–RO applications in combination with reciprocating plunger pumps and rotary vane pumps for seawater desalination, was shown to significantly reduce energy consumption. For the desalination of brackish water, systems using rotary pumps have the lowest energy consumption. Specific energy consumptions (SEC) as low as 1.4 kWh/m^3 were reported both for rotary vane pumps and for progressive cavity pumps.

Reverse osmosis membranes

Spiral-wound, thin film composite RO membranes are the standard choice for PV-RO desalination systems. The most common RO configuration is single pass, in which the membranes are organized in series within one or more pressure vessels. Concentrate recirculation was used in some brackish water desalination installations to increase the overall water recovery rate and reduce brine disposal issues. PV-RO desalination systems are often designed with generous membrane areas since, for a fixed recovery rate, they can operate at lower pressures and thus at higher energy efficiencies. Large membrane areas, however, introduce a trade-off with permeate quality, which decreases as operating pressure increases.

Reverse osmosis membranes (Spiral-wound)



The advantages of using Spiral-wound, thin film composite RO membranes can be summarized as follows:

- The specific energy requirement is significantly low 3–9.4 kW h/m3 product.
- The process is electrically driven. As a result, it is readily adaptable to powering by solar panels.
- The RO plant is normally operated at ambient temperature, which reduces the headache of scale formation and corrosion problems, especially when the pretreatment system is properly designed and kept under control. Again this will reduce maintenance cost.
- The modular structure of the RO process increases flexibility in building desalination plants within a wide range of capacities.

Photo Voltaic Cells

Both mono-crystalline and multi-crystalline silicon modules were used in the experimental units in Abu Dhabi. Whether module orientation was fixed or adjustable was recognized as an important factor in determining the electrical power output and thus the overall performance of the desalination plant.

Modern commercial solar cells are typically 18% peak efficient; 100 W of solar radiation hitting a solar panel will be converted to 18 W, at most. As a result of manufacturing subsides, recent photovoltaic trends favor low cost high volume PV cells rather than high conversion efficiency. Given prevailing trends, low cost flat plat PV collectors were chosen for the model as opposed to high efficiency panels or concentration. PV cells benefit from concentration as well, but system performance is not linked to cell temperature as with solar thermal power systems. Concentration increases photon intensity per unit area, increasing the number of photons available to free electrons. Compared to thermal systems, concentration is not as necessary for economical work extraction.

Photo Voltaic Cells

The advantages of using photovoltaic cells as a source of power can be summarized as follows:

- **Modularity: this feature avails system enlargement whenever needed.**
- **Low maintenance, especially in the case of battery-less systems means reduced operation and maintenance cost.**
- **Low noise level: as a power generating system, solar panels have no rotating parts. The only noise would be from the pump. Without batteries, the system would only run in daytime and would not disturb people at night.**
- **Long life: currently, solar panels are guaranteed to stay in service up to 20 years, and withstand harsh environments.**
- **Well-matched to load as solar panels produce more energy in areas of higher solar irradiation where the people are likely to consume more drinking water.**
- **Environmentally friendly: CO2 emissions normally accompanying burning of fossil fuels in conventional power plants do not exist. Nevertheless, we have to remember that considerable amounts of CO2 are produced by the current silicon-based technologies applied for the production of photovoltaic cells. Such technologies are energy intensive and require large amounts of conventional fuels to be burnt.**
- **Possible use of single- or dual-axis trackers: this makes the array point directly at the sun throughout the day, which increases the amount of water produced by up to 30%.**

AC/DC inverter

Desalination plants that use AC induction motors for the high pressure pumps require inverters to transform the DC current generated in the PV modules or stored in the batteries. The use of DC motors eliminates the need for inverters but generally involves a higher initial investment. Since DC motors do not experience the energetic losses inherent in inverters, PV–RO desalination plants with DC motors are expected to function at higher energy efficiencies

Electrical Storage

Batteries can be included in the system either to balance the electrical output of the PV modules during day-time operation or to provide extended operation during night-time and overcast days. Although electrical storage enables steady plant operation and may increase overall productivity, it entails a series of drawbacks: (i) Installation and replacement add significantly to the investment cost of the plant. (ii) Batteries imply additional losses of electricity and reduce system efficiency. (iii) When all auxiliary components such as charge controller and wiring are considered, the inclusion of batteries in the system results in a more complex system. (iv) The absence of careful maintenance typical in remotely located systems may dramatically reduce battery life, particularly for large storage batteries. **Battery--less PV–RO systems are based on the idea that water storage is often more efficient and cost-effective than energy storage.**

Brine Water Discharge

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One of the main challenges facing the inland brackish/saline groundwater desalination is the efficient discharge methods for brine water. Some options for inland brine disposal include deep-well injection and storage in evaporation ponds. However, using the injection in deep groundwater wells has been rejected because these wells are difficult to permit, costly, and impossible to use or limited in capacity to accept fluids. Since reject brine is corrosive, many safeguards must be added to the well.

The costs associated with implementing these safety measures can make the deep well disposal option prohibitively expensive. An evaporation pond is merely an excavated depression in the ground which serves as a reservoir for desalination wastewater. Often, evaporation ponds are the final destination of concentrate. In these situations, once the water evaporates, the residual solids may be landfilled in situ or collected and disposed of elsewhere. To design the evaporation pond, the evaporation in each location was calculated and the brine disposal from the same site. This option is also cheaper than deep wells.

Overview of PV-powered RO membrane Desalination

Location and country	**Year**	**Feed TDS, mg/L (*)**	**PV capacity, kW_p**	**Battery storage**	**Pump drive**	**Production, m^3/day**	**Cost, US\$/m^3**
Abu Dhabi, UAE	2008	45,000	11.25	no	AC	20.0e	7.3
Athens, GRC	2006	30,000	0.85	no	DC	0.35e	9.8
Aqaba, JOR	2005	4,000	16.8	yes	AC	58.0	9.8
Doha, QAT	1984	35,000	11.2	no	AC	5.7e	3.0
El Hamrawein, EGY	1986	4,400	19.84	yes	AC	53.0	11.6
Heelat Ar Rakah, OMN	1999	1,010	3.25	yes	AC	5.0e	6.5
Denver, ITN, USA	2003	1,600	0.54	no	DC	1.5	6.5
Jeddah, SAU	1981	42,800	8	yes	DC	3.22	6.5
Ksar Ghilène, TUN	2005	3,500	10.5	yes	AC	7.0	6.5
Kulhudhuffushi, MDV	2005	2,500	0.3	no	DC	1.0e	6.5
Kuwait, KWT	2005	8,000	0.3	yes	DC	1.0	6.5
NRC, Cairo, EGY	2002	2,000	1.1	yes	AC	1.0e	3.7
Pine Hill, AUS	2008	5,300	0.6	no	DC	1.1	3.7
Pozo Izquierdo, ESP	2000	35,500	4.8	yes	AC	1.24	9.6
SERIWA, Perth, AUS	1982	5,700h	1.2	yes	DC	0.55	9.6
Univ. of Amman, JOR	1988	400	0.07	no	DC	0.1	2.5
Univ. of Bahrain, BHR	1994	35,000	0.11	yes	DC	0.2	2.8
Various locations, JOR	2007	7,000	1.1	yes	AC	3.6e	9.0
VARI-RO, USA	1999	7,000f	1.1	no	AC	3.6	9.0

Financial Model

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To ass the feasibility of the solar powered desalination system a financial model covers a wide range of finance options and too detailed was developed for the purposes of this study. The developed model was generally disregarded and replaced with a custom, spreadsheet based model. In place of the financial model, a simplified initial capital and amortization approached was used to calculate total cost and payback for each configuration, treating desalting and solar capital separately.

Total cost was calculated using annuity present value:

$$TC = n.IC.i\left[1-\frac{1}{(1+i)^n}\right]^{-1}$$

Where,
TC = total cost [$]
n = term [years]
IC = initial capital (cost) [$]
i = annual interest rate [-]

Assumption

- Levelized Cost of Energy (LCOE) was calculated using a 3% interest rate over 25 years.
- The simulations assume water produced can be supplied when it is produced.
- Solar insolation levels are seasonal and therefore solar power plants produce more energy in summer than winter.
- A solar powered desalination plant would potentially produce more fresh water during periods of high insolation—perhaps in disproportion to demand.
- The model does not consider demand-supply mismatch.
- The system is self sufficient (not connected to grid and there is no conveyance system). For dispersed brackish groundwater desalination, conveyance would likely be of little importance. However, for major seawater desalination operations intent on delivering water inland, conveyance cost may be high or even prohibitive.

Cost analysis input data

Plant capacity	**40**	**m3/d**
RO plant configuration	**1stage**	
Feed concentration	**35,000**	**ppm**
Fouling correction factor	**0.7**	
Atmospheric pressure	**100,000**	**Pa**
Feed temperature	**25**	**°C**
Salt molecular weight	**58.5**	**kg/kg mol**
Friction parameter (permeate)	**1.10E+09**	**m−2**
Solution viscosity	**0.00089**	**kg/m s**
Solution density	**1100**	**kg/m3**
Diffusivity	**1.6E-09**	**m2/s**
Mass transport characteristics of membranes		
Stage 1		
Water permeability coefficient	**3.31E−12**	**m S−1 Pa−1**
Salt permeability coefficient	**3.34E−07**	**m/s**
Mass transfer coefficient	**3.76E−05**	**m/s**

Solar Desalination Cost

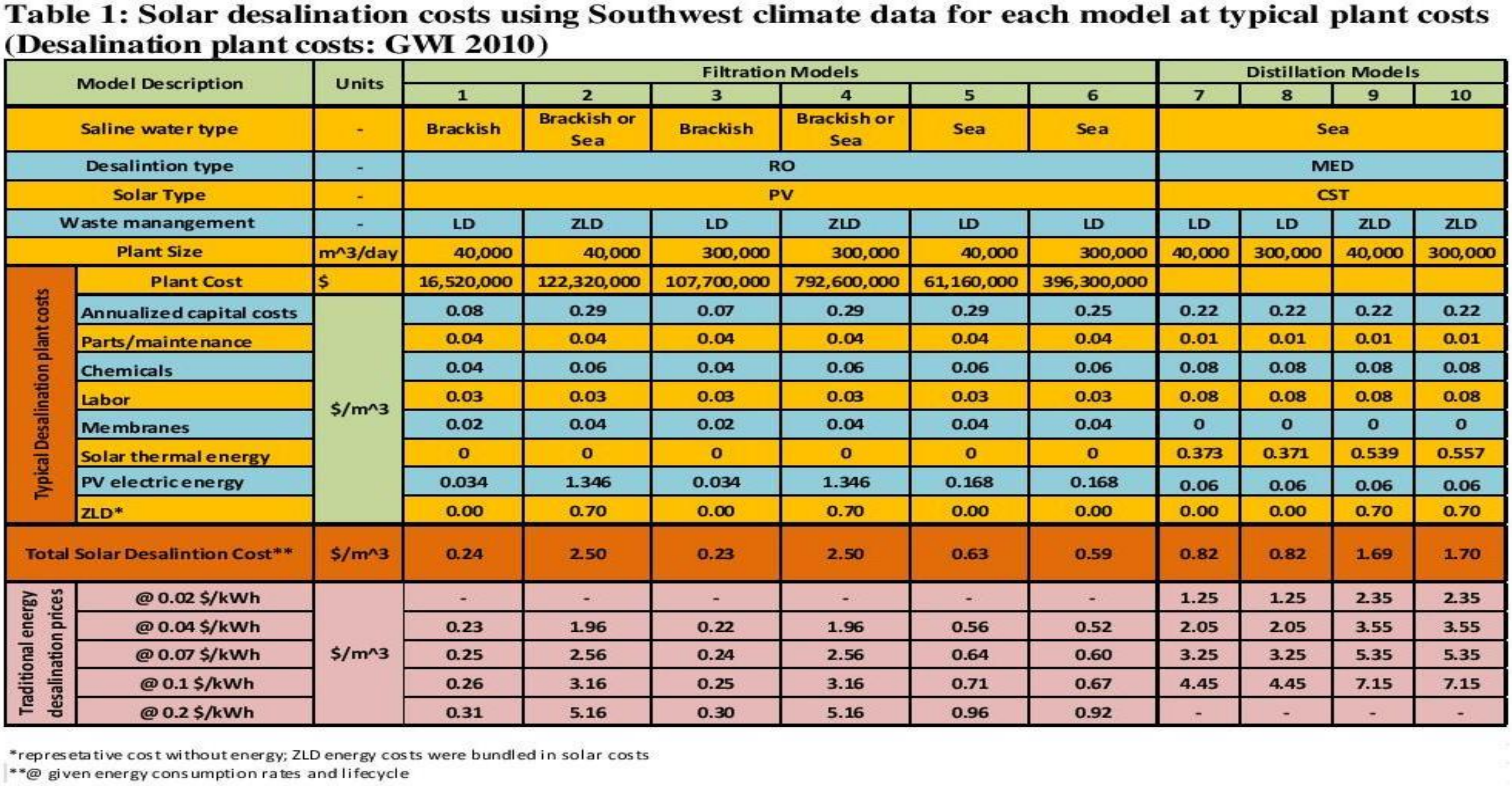


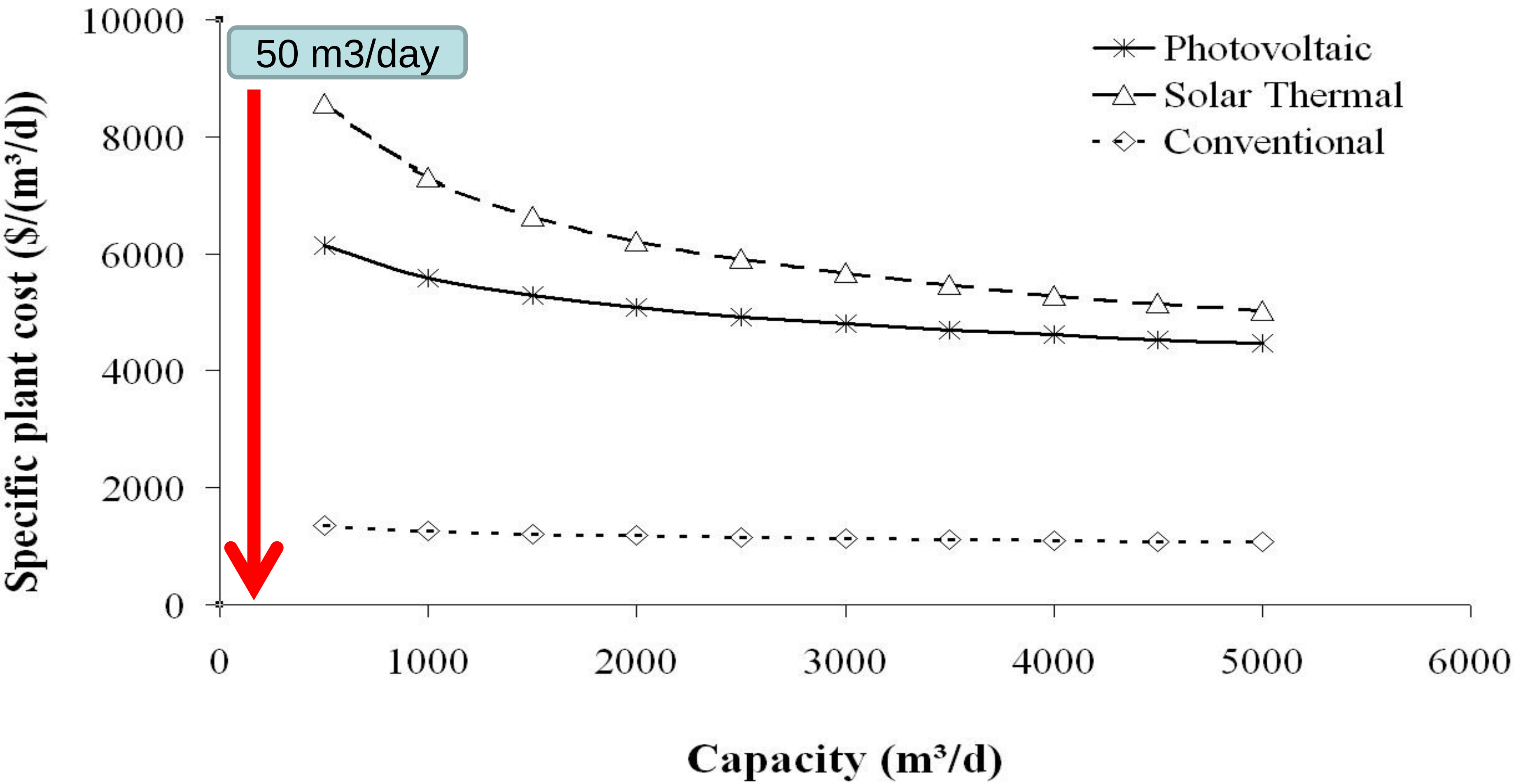
Table 1: Solar desalination costs using Southwest climate data for each model at typical plant costs (Desalination plant costs: GWI 2010)

Model Description		Units	Filtration Models						Distillation Models			
			1	2	3	4	5	6	7	8	9	10
Saline water type		-	Brackish	Brackish or Sea	Brackish	Brackish or Sea	Sea	Sea	Sea			
Desalintion type		-	RO						MED			
Solar Type		-	PV						CST			
Waste manangement		-	LD	ZLD	LD	ZLD	LD	LD	LD	LD	ZLD	ZLD
Plant Size		m^3/day	40,000	40,000	300,000	300,000	40,000	300,000	40,000	300,000	40,000	300,000
Typical Desalination plant costs	Plant Cost	$	16,520,000	122,320,000	107,700,000	792,600,000	61,160,000	396,300,000				
	Annualized capital costs	$/m^3	0.08	0.29	0.07	0.29	0.29	0.25	0.22	0.22	0.22	0.22
	Parts/maintenance		0.04	0.04	0.04	0.04	0.04	0.04	0.01	0.01	0.01	0.01
	Chemicals		0.04	0.06	0.04	0.06	0.06	0.06	0.08	0.08	0.08	0.08
	Labor		0.03	0.03	0.03	0.03	0.03	0.03	0.08	0.08	0.08	0.08
	Membranes		0.02	0.04	0.02	0.04	0.04	0.04	0	0	0	0
	Solar thermal energy		0	0	0	0	0	0	0.373	0.371	0.539	0.557
	PV electric energy		0.034	1.346	0.034	1.346	0.168	0.168	0.06	0.06	0.06	0.06
	ZLD*		0.00	0.70	0.00	0.70	0.00	0.00	0.00	0.00	0.70	0.70
Total Solar Desalintion Cost**		$/m^3	0.24	2.50	0.23	2.50	0.63	0.59	0.82	0.82	1.69	1.70
Traditional energy desalination prices	@ 0.02 $/kWh	$/m^3	-	-	-	-	-	-	1.25	1.25	2.35	2.35
	@ 0.04 $/kWh		0.23	1.96	0.22	1.96	0.56	0.52	2.05	2.05	3.55	3.55
	@ 0.07 $/kWh		0.25	2.56	0.24	2.56	0.64	0.60	3.25	3.25	5.35	5.35
	@ 0.1 $/kWh		0.26	3.16	0.25	3.16	0.71	0.67	4.45	4.45	7.15	7.15
	@ 0.2 $/kWh		0.31	5.16	0.30	5.16	0.96	0.92	-	-	-	-

*represetative cost without energy; ZLD energy costs were bundled in solar costs

**@ given energy consumption rates and lifecycle

Desalination Capix Cost



Desalination Opex Cost

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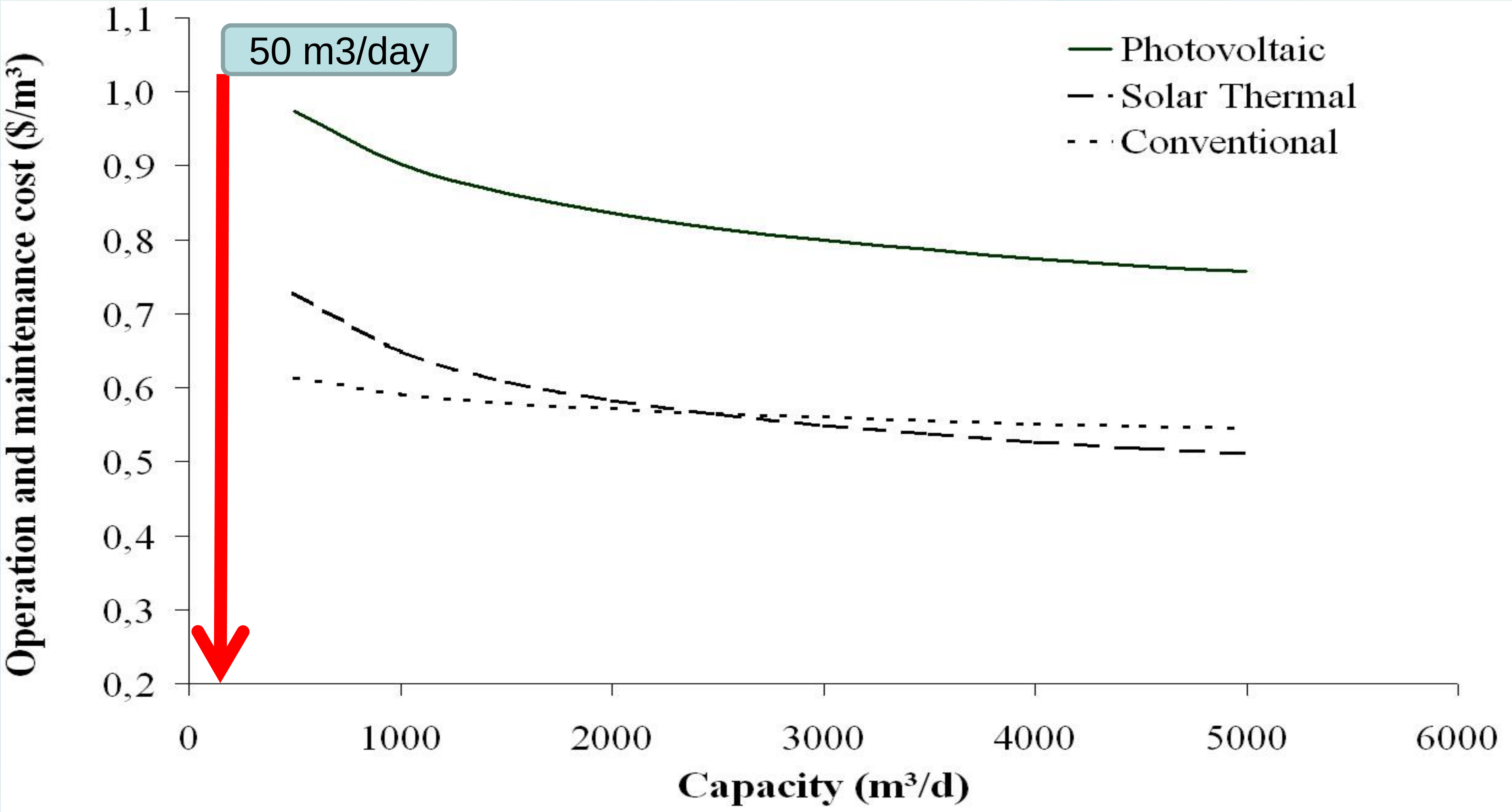
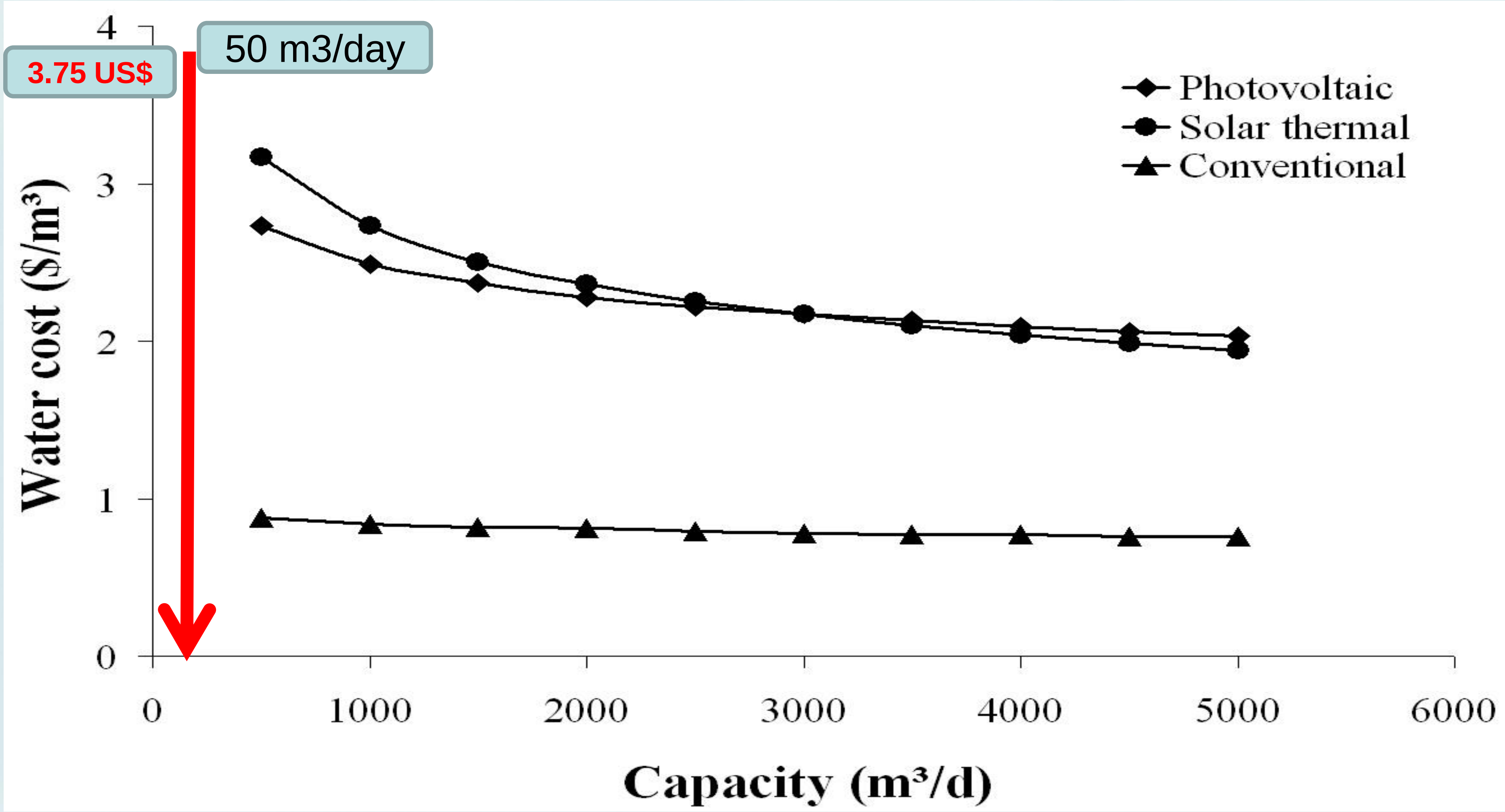


50 m3/day

Desalinated Water Cost



3.75 US$

50 m3/day

Advantage and Disadvantage of PVC-RO

RO COUPLED WITH PHOTOVOLTAIC	
ADVANTAGES	**DRAWBACKS**
✓ lowest specific land occupation ✓ ideal for stand-alone configuration ✓ any capacity possible with no dramatic rise in cost ✓ best potential towards further cost reduction	✓ sensitive to feed water quality ✓ advanced materials required ✓ complexity of design and management ✓ most costly operation due to membrane and battery replacement

Future Prospective

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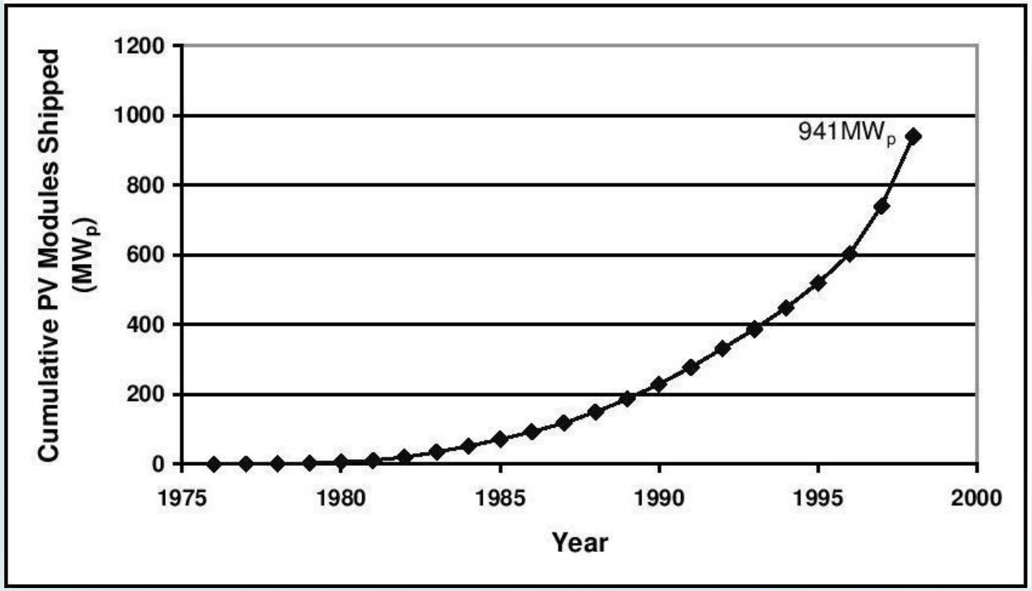
PV technology improvement (1995–2010).

Parmer	1995	2000	2005	2010
PV modules efficiency (%)	7-17	8-18	10-20	12-22
PV modules cost ($/$W_p$)	7-15	5-12	2-8	2-5
System life (years)	10-20	>20	>25	>25



Future Prospective

New Innovative Technologies (FO)

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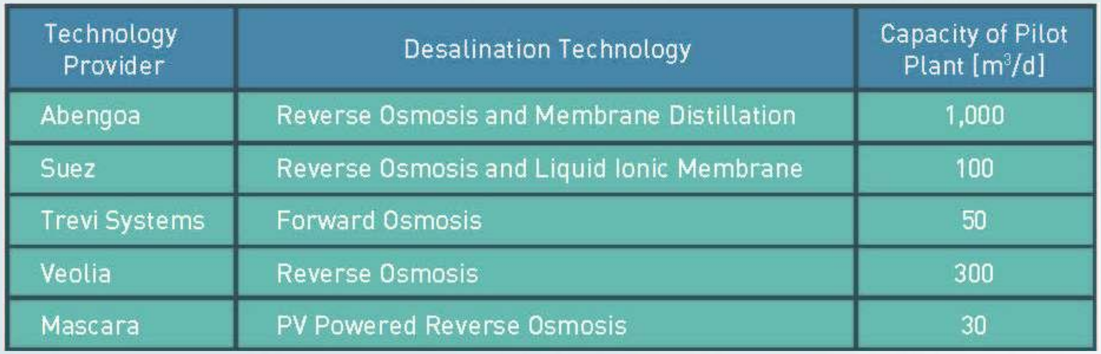

Technology Provider	Desalination Technology	Capacity of Pilot Plant [m^3/d]
Abengoa	Reverse Osmosis and Membrane Distillation	1,000
Suez	Reverse Osmosis and Liquid Ionic Membrane	100
Trevi Systems	Forward Osmosis	50
Veolia	Reverse Osmosis	300
Mascara	PV Powered Reverse Osmosis	30

Le démonstrateur OSMOSUN 40 à Ghantoot

Solar Desalination (Conclusion)

- Compared to conventional processes, water cost using solar desalination for plants of capacity 50 m3/day, is still quite expensive.
- For remote areas with no access to electricity, conventional systems water cost rises up to 2.5 $/m³
- Cost of PV/RO system is about 3.75 $/m³
- Environmental Impacts
- Using new innovative technology in desalination

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