1 Review of CSP and Desalination Technology

The scope of this chapter is to find adequate combinations of technologies for seawater desalination (SD) and concentrating solar power (CSP) used as energy source. Although the desalination of brackish groundwater is also an option, its resources are rather limited when compared to seawater and the use of groundwater is already today related to strong environmental impacts, as will be shown in Chapter 5. Although this option should not be neglected, it is considered here only a minor possible contribution to sustainable water. In the following we will therefore concentrate on seawater desalination. Within this chapter we provide in the first place a brief description of the principle and main characteristics of the most important desalination technologies. In the second place, we describe the state of the art of CSP. Finally, we define and evaluate several combinations of CSP and desalination technologies under different environmental conditions in the Middle East and North Africa.

Separation	**Energy Use**	**Process**	**Desalination Method**
Water from Salts	Thermal	Evaporation	Multi-Stage Flash (MSF)
			Multi-Effect Distillation(MED)
			Thermal Vapour Compression (TVC)
			Solar Distillation (SD)*
		Crystallisation	Freezing (FR)
			Gas Hydrate Processes (GH)
		Filtration/Evaporation	Membrane Distillation (MD)
	Mechanical	Evaporation	Mechanical Vapour Compression (MVC)
		Filtration	Reverse Osmosis (RO)
Salts from water	Electrical	Selective Filtration	Electrodialysis (ED)
	Chemical	Exchange	Ion Exchange (IE)

Table 1-1: Overview of contemporary desalination methods[1].

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[1] due to unknown reasons, the term “solar distillation” is exclusively used for small-scale, decentralised solar powered desalting technologies. The creation of this category is rather misleading. Within this report, we present large scale options for solar distillation which do not fit into the general perception of this category. Therefore, we will use other terms for large scale solar distillation

1.1 Seawater Desalination Technologies

There is a large number of different desalination technologies available and applied world wide. Some of them are fully developed and applied on a large scale, while others are still used in small units for demonstration purposes or for research and development /Miller 2003/. Table 1-1 gives a selection of the most commonly applied technologies /El-Dessouky and Ettouny 2002/.

For the purpose of this study, those desalination technologies were selected for further consideration that have at least reached a semi-commercial state of the art, and that can be realised in sufficiently large units in order to be effectively combined with concentrating solar thermal power stations (CSP). The five technologies highlighted in Table 1-1 come into consideration. These are thermal desalination methods that evaporate seawater by using heat from combustion or from the cold end of a power cycle, and mechanical methods using filtration through membranes. Vapour compression technologies are mainly used in combination with thermal distillation in order to increase volumes and efficiency of those processes.

1.1.1 Multi-Stage Flash Desalination (MSF)

MSF is a thermal distillation process that involves evaporation and condensation of water. The evaporation and condensation steps are coupled to each other in several stages so that the latent heat of evaporation is recovered for reuse by preheating incoming water (Figure 1-2).

In the so called brine heater, the incoming feed water is heated to its maximum temperature (top brine temperature) by condensing saturated steam from the cold end of a steam cycle power plant or from another heat source. The hot seawater then flows into the first evaporation stage where the pressure is set lower. The sudden introduction of hot water into the chamber with lower pressure causes it to boil very quickly, almost exploding or “flashing” into steam. Only a small percentage of the water is converted to vapour, depending on the pressure maintained in this stage, since boiling will continue only until the water cools down to the equilibrium at the boiling point, furnishing the heat of vaporization.

The vapour generated by flashing is condensed on tubes of heat exchangers that run through the upper part of each stage. The tubes are cooled by the incoming feed water going to the brine heater, thus pre-heating that water and recovering part of the thermal energy used for evaporation in the first stage. This process is repeated in up to 40 stages, whereas mostly around 20 stages are employed. To maximize water and energy recovery, each stage of an MSF unit operates at a successively lower pressure. The vacuum can be maintained by a steam ejector driven by high-pressure steam or by a mechanical vacuum pump.

Multi-stage flash (MSF) units are widely used in the Middle East (particularly in Saudi Arabia, the United Arab Emirates, and Kuwait) and they account for 58% of the world’s seawater desalination capacity /IDA 2006/. A key design feature of MSF systems is bulk liquid boiling. This alleviates problems with scale formation on heat transfer tubes.

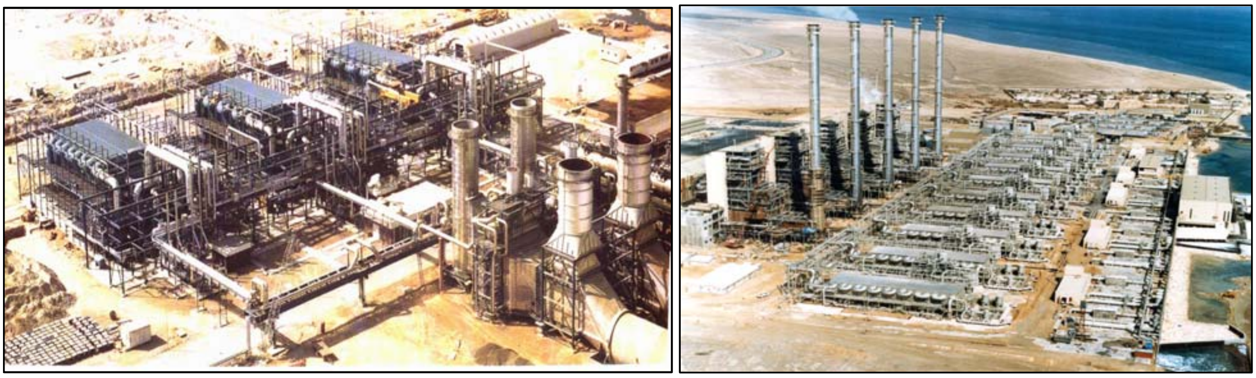

Figure 1-1: Umm Al Nar East MSF Desalination plant, 87260 m3/day (left), Al Khobar Phase II, 267000 m3/day, Saudi Arabia. Source: veolia/entropie

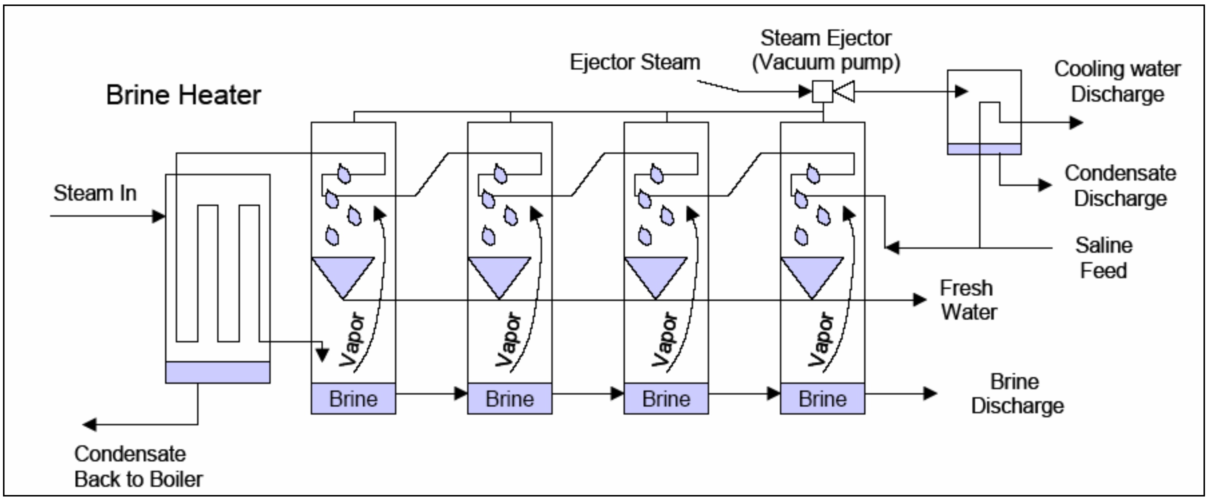

Figure 1-2: Principle of Multi-Stage Flash Desalination (MSF). Source: /Miller 2003/

Large MSF units are often coupled with steam or gas turbine power plants for better utilization of the fuel energy by combined generation. Steam produced at high temperature and pressure by the fuel is first expanded through a turbine to produce electricity. The low to moderate temperature steam exiting the turbine is then used to drive a thermal desalination process. In this case, the capacity of the low pressure stage of the steam turbine to produce electricity is reduced with increasing temperature of the extracted steam.

Multi-Stage Flash plants are usually coupled to the cold end of a steam cycle power plant, extracting steam at 90 - 120 °C from the turbine to feed the brine heater of the MSF unit. If the temperature is above the condensation temperature of water at ambient pressure, special backpressure turbines are required for such a combined process. Moreover, the reduction of power generation with respect to a conventional condensing steam turbine working at 35-40 °C is considerable (Figure 1-3). On the other hand, an advantage of combined generation is that the condenser required for a conventional plant is substituted by the desalination unit. In this case, the feed water must include enough water for desalination and cooling.

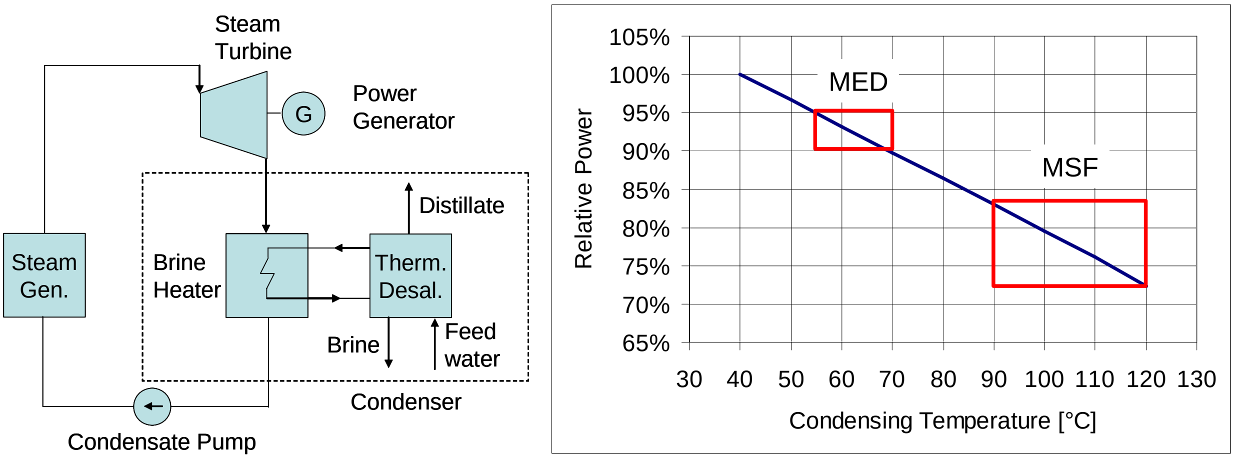

Figure 1-3: Principle of substituting the condenser of a steam cycle power plant by a thermal desalination unit (left) and typical reduction of steam turbine power capacity at increasing condensing temperature (right). The squares show the typical operating range of MED and MSF plants.

The MSF process requires a considerable amount of steam for the evaporation process and also significant amounts of electricity to pump the large liquid streams (Table 1-2). To this adds the power reduction induced within the steam cycle. Two different performance indicators are used, that yield however similar values: the performance ratio (PR) is the ratio of product water and input heat, while the gained output ratio (GOR) is defined as the mass of water product per mass of heating steam. A typical gain output ratio for MSF units is 8. MSF is specially suited for desalination if the quality of the feed water is unfavourable (high salinity, temperature and contamination), as the system is very robust. A MSF plant has a typical heat requirement of 250 - 330 kJ/kg product. The specific electricity consumption is in the order of 3 - 5 kWh/m³. To this adds a loss of electricity from the steam turbine due to the higher cold end temperature equivalent to 6 - 8 kWh/m³.

1.1.2 Multi-Effect Desalination (MED)

Multi-effect desalination (MED) is also a thermal distillation process (Figure 1-4 and Figure 1-5). The feed water is sprayed or otherwise distributed onto the surface of the evaporator surface (usually tubes) of different chambers (effects) in a thin film to promote evaporation after it has been preheated in the upper section of each chamber. The evaporator tubes in the first effect are heated by steam extracted from a power cycle or from a boiler. The steam produced in the first effect is condensed inside the evaporator tubes of the next effect, where again vapour is produced. The surfaces of all the other effects are heated by the steam produced in each preceding effect. Each effect must have a lower pressure than the preceding one. This process is repeated within up to 16 effects. The steam produced in the last effect is condensed in a separate heat exchanger called the final condenser, which is cooled by the incoming sea water, which is then used as preheated feed water for the desalination process.

MED has gained attention due to the better thermal performance compared to MSF. In principle, MED plants can be configured for high temperature or low temperature operation. At present, they operate at top brine temperatures below 70°C to limit scale formation and corrosion. The top brine temperature can be as low as 55 °C which helps to reduce corrosion and scaling, and allows the use of low-grade waste heat. If coupled to a steam cycle, the power losses are much lower than those obtained when coupling a MSF plant (Figure 1-3), and even standard condensing turbines may be used instead of back-pressure turbines.

The MED process can have several different configurations according to the type of heat transfer surface (vertical tube falling film, vertical tube climbing film, horizontal tube falling film, plate heat exchanger) and the direction of the brine flow relative to the vapour flow (forward, backward, or parallel feed). MED systems can be combined with heat input between stages from a variety of sources, e.g. by mechanical (MVC) or thermal vapour compression (TVC). MED-TVC systems may have thermal performance ratios (similar to the gained output ratio, distillate produced to first stage energy input) up to 17, while the combination of MED with a lithium bromide -water absorption heat pump yielded a thermal performance ratio of 21 /Alarcon 2006/.

Figure 1-4: Multi-effect desalination unit with thermal vapour compression (left) and complete plant (right) Source: /entropie 2006/

When coupled to the cold end of a steam cycle power plant, MED plants (without TVC) typically have a heat consumption of 190-390 kJ/kg in the form of process steam at less than 0.35 bar that is withdrawn from the steam turbine, and a specific electricity consumption of 1.5 - 2.5 kWh/m³, mainly for pumping and control, which are fairly independent from raw water salinity, contamination or temperature. MED-TVC plants are driven with motive steam above 2 bar, mostly between 10 and 20 bar.

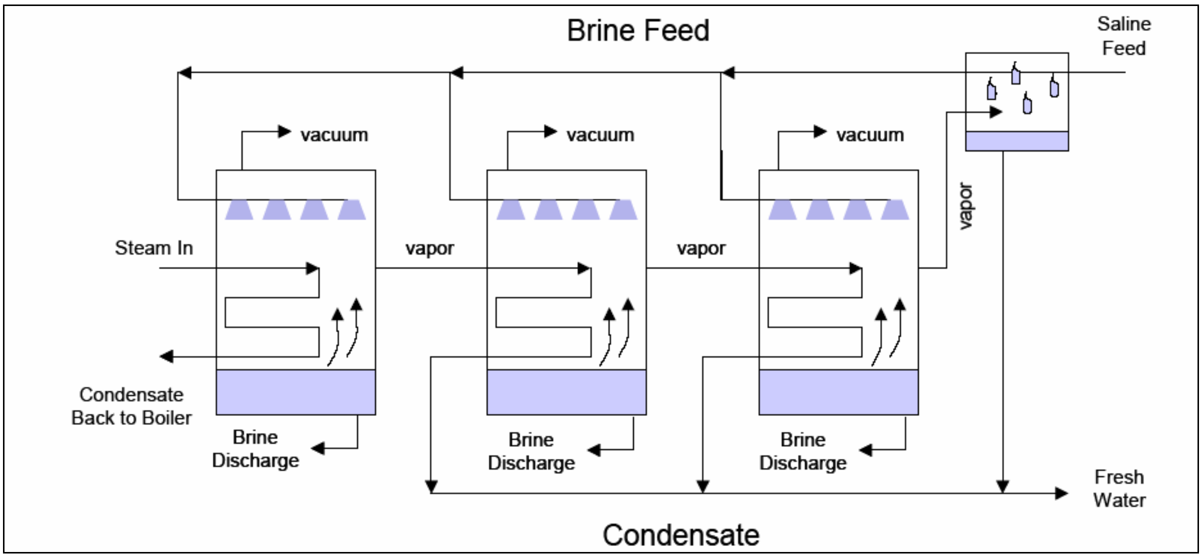

Figure 1-5: Principle of Multi Effect Desalination (MED) /Miller 2003/.

1.1.3 Reverse Osmosis (RO)

Reverse osmosis (RO) is a membrane separation process that recovers water from a saline solution pressurized to a point greater than the osmotic pressure of the solution (Figure 1-6). In essence, membrane filters hold back the salt ions from the pressurized solution, allowing only the water to pass. RO membranes are sensitive to pH, oxidizers, a wide range of organics, algae, bacteria, depositions of particulates and fouling. Therefore, pre-treatment of the feed water is an important process step and can have a significant impact on the cost and energy consumption of RO, especially since all the feed water, even the amount that will eventually be discharged, must be pre-treated before being passed to the membrane. Recently, micro-, ultra- and nano-filtration has been proposed as an alternative to the chemical pre-treatment of raw water in order to avoid contamination of the seawater by the additives in the surrounding of the plants (Chapter 6). RO post-treatment includes removing dissolved gases (CO_2), and stabilizing the pH via the addition of Ca or Na salts, and the removal of dangerous substances from the brine.

Pressurizing the saline water accounts for most of the energy consumed by RO. Since the osmotic pressure, and hence the pressure required to perform the separation is directly related to the salt concentration, RO is often the method of choice for brackish water, where only low to intermediate pressures are required. The operating pressure for brackish water systems ranges from 10 - 15 bar and for seawater systems from 50 to 80 bar (the osmotic pressure of seawater with a salinity of 35 g/kg is about 25 bar).

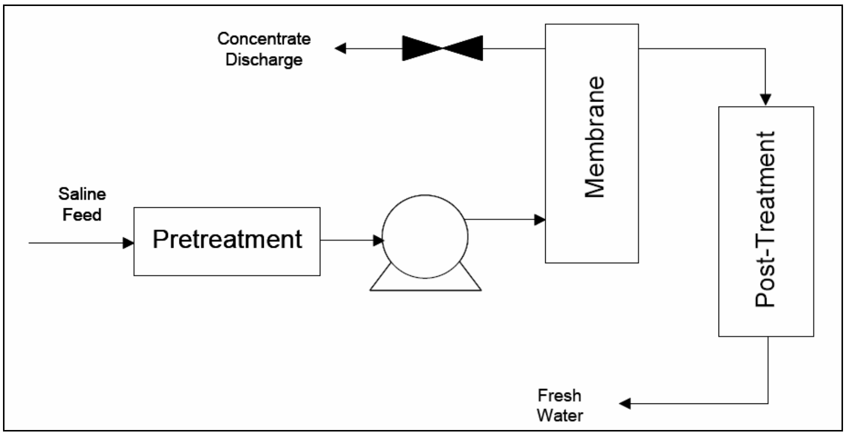

Figure 1-6: Principle of Desalination by Reverse Osmosis (RO) /Miller 2003/.

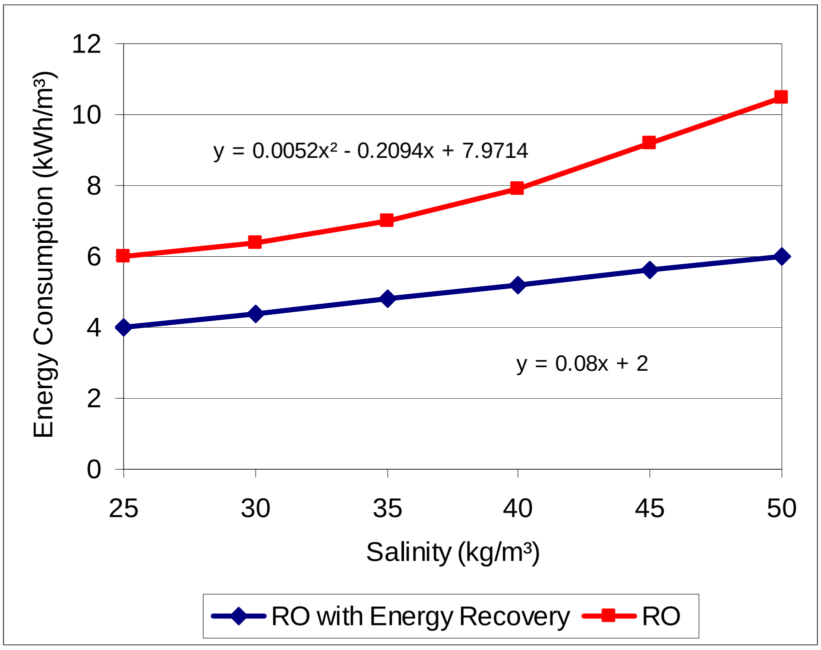

Figure 1-7: Specific electricity consumption of reverse osmosis plants with and without energy recovery system as function of raw water salinity /MEDRC 2005/

Figure 1-8: Left: Pressure cylinders containing the separation membranes of a reverse osmosis plant in Barcelona, Spain, with 30,000 m^3/day desalting capacity; Right: RO-stacks and high pressure pumps of a 30,000 m^3/day desalination plant in Gran Canaria, Canary Islands. Source: Mertes, DME

1.1.4 Thermal Vapour Compression (TVC)

Vapour compression is added to a multi-effect distiller in order to improve its efficiency. Vapour compression processes rely on the reuse of vapour produced in the distiller as heating steam after recompression. The vapour produced in one stage is partially recompressed in a compressor and used to heat the first cell. The vapour is compressed either with a mechanical compressor (mechanical vapour compression, MVC) or with a steam ejector (thermal vapour compression, TVC). For thermal vapour compression, motive steam at higher pressure is withdrawn from another process, e.g. a steam power cycle or industrial process steam.

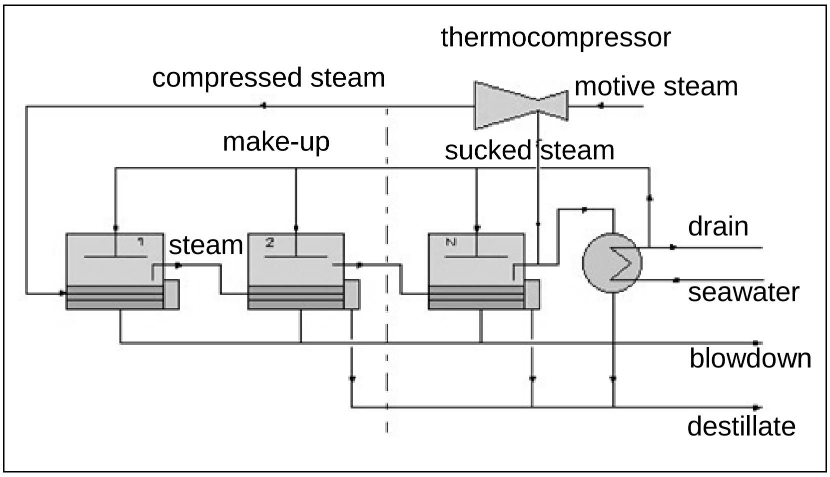

Figure 1-9: Principle of Thermal Vapour Compression (TVC) /Abu-Arabi 2005/

1.1.5 Mechanical Vapour Compression (MVC)

Mechanical vapour compression processes are particularly useful for small to medium plants. MVC units typically range in size up to about 3,000 m³/day while TVC units may range in size to 36,000 m³/day. MVC systems have between one and three stages, most of them only have a single stage, while TVC systems have several stages. This difference arises from the fact that the pressure and temperature increase by the mechanical compressor and its capacity are limited.

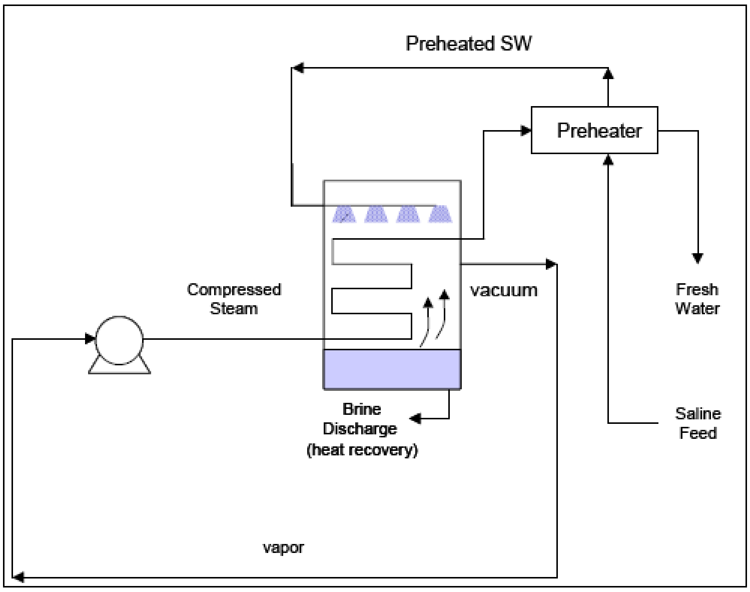

Figure 1-10: Single stage mechanical vapour compression desalination process (MVC) /Miller 2003/.

1.1.6 Pre-Selection of Desalination Technologies

Table 1-2 shows some of the characteristics of the four leading desalination technologies. The purpose of this comparison was to select the most appropriate thermal and mechanical desalination method for the combination with CSP, and to find a plausible combination that could be representative for large scale dissemination.

Comparing MSF and MED, it becomes clear that MED is more efficient in terms of primary energy and electricity consumption and has a lower cost. Moreover, the operating temperature of MED is lower, thus requiring steam at lower pressure if connected in co-generation to a steam cycle power plant. Thus, the combination of CSP with MED will be more effective than a combination of CSP and MSF desalination. Thermal vapour compression is often used to increase the efficiency of an MED process, but it requires steam at higher pressure if connected to a steam power cycle..

Comparing the mechanical driven desalination options, reverse osmosis has a lower electricity consumption and cost per unit product water than the mechanical vapour compression method.

Energy used	thermal		mechanical	
Process	MSF	MED/TVC	MVC	RO
State of the Art	commercial	commercial	commercial	commercial
World Wide Capacity 2004 (Mm^3/d)	13	2	0.6	6
Heat Consumption (kJ/kg)	**250 – 330**	145 - 390	--	--
Electricity Consumption (kWh/m^3)*	**3 - 5**	1.5 - 2.5	**8 - 15**	2.5 - 7
Plant Cost (\$/m^3/d)**	**1500 - 2000**	900 - 1700	**1500 - 2000**	900 -1500
Time to Commissioning (months)	24	18 - 24	12	18
Production Unit Capacity (m^3/d)	< 76000	< 36000	**< 3000**	< 20000
Conversion Freshwater / Seawater	**10 - 25%**	23 - 33%	23 - 41%	20 - 50%
Max. Top Brine Temperature (°C)	**90 - 120**	55 - 70	70	45 (max)
Reliability	very high	very high	high	moderate (for seawater)
Maintenance (cleaning per year)	0.5 - 1	1 - 2	1 - 2	several times
Pre-treatment of water	simple	simple	very simple	demanding
Operation requirements	simple	simple	simple	demanding
Product water quality (ppm)	< 10	< 10	< 10	200 - 500

Table 1-2: Characteristics of the two main thermal desalination technologies and the two main mechanical desalination technology options. The figures refer to seawater as the raw water source. The low performance characteristics of MSF and MVC marked in red have lead to the selection of MED and RO as reference technologies for this study. The range shown for MED/TVC covers simple MED as well as combined MED/TVC plants. (* Power consumption does not include power losses induced by cogeneration due to increasing outlet temperature at the turbine; ** plant cost increases with product water quality and energy efficiency).

The much lower primary energy consumption of RO and the slightly lower cost compared to MED suggests that RO might be the preferred desalination technology anyway. However, if MED is coupled to a power plant, it replaces the cost of the condensation unit of the steam cycle and partially uses waste heat from power generation for the desalination process. In this case, not all the primary energy used must be accounted for the desalination process, but only the portion that is equivalent to a reduction of the amount of electricity generated in the plant when compared to conventional cooling at lower temperature, and of course the direct power consumption of the MED process.

Processes combining thermal and mechanical desalination may lead to more efficient future desalination systems /MEDRC 2001/. However for simplicity, only separated processes have been used for our comparison. For further more detailed analysis of a combination with CSP under different environmental and economic site conditions in Chapter 1.3, only the MED and RO processes will be considered.

1.2 Concentrating Solar Power Technologies

The study focuses on concentrating solar thermal power generation because this is by far the most abundant and most reliable renewable energy resource in the MENA region /MED-CSP 2005/. However, we do not dismiss desalination concepts based on wind power, geothermal energy, biomass or other sources as possible contribution to freshwater supply. On the contrary, they will have important niche markets, mainly in decentralised, small to medium size applications. However, we believe that due to its intrinsic properties that will be described here, CSP will provide the core energy for large scale seawater desalination for the growing urban centres and mega-cities in the MENA region.

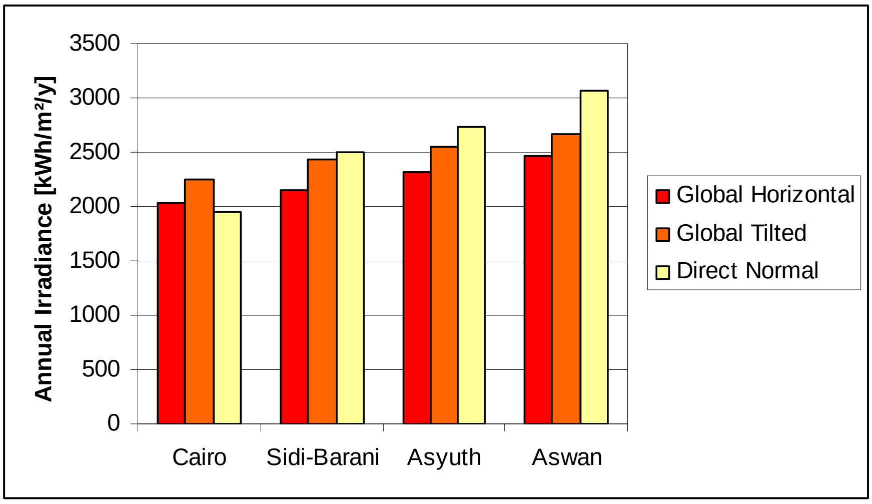

Figure 1-11: Examples of the annual sum of global horizontal irradiance, global irradiance on a surface tilted south and direct normal irradiance for several locations in Egypt (Source: meteonorm database)

Concentrating solar thermal power technologies are based on the concept of concentrating solar radiation to provide high-temperature heat for electricity generation within conventional power cycles using steam turbines, gas turbines or Stirling engines. For concentration, most systems use glass mirrors that continuously track the position of the sun. Contrary to a common belief, the annual sum of direct solar irradiance on a surface tracking the sun (direct normal irradiance) in the desert regions of MENA is usually higher than the global (diffuse and direct) irradiance on a fixed surface, either horizontal or tilted south with latitude angle (Figure 1-11) that would be used e.g. by PV-arrays. In the case of CSP, the sunlight is focused on a receiver that is specially designed to reduce heat losses. A fluid flowing through the receiver takes the heat away towards a thermal power cycle, where e.g. high pressure, high temperature steam is generated to drive a turbine. Air, water, oil and molten salt can be used as heat transfer fluids.

Parabolic troughs, linear Fresnel systems and solar towers can be coupled to steam cycles of 5 to over 200 MW of electric capacity, with thermal cycle efficiencies of 30 – 40 %. Dish-Stirling engines are used for decentralised generation in the 10 kW range. The values for parabolic troughs have been demonstrated in the field. Today, these systems achieve annual solar-to-electricity-efficiencies of about 10-15 %, with the perspective to reach about 18 % in the medium term. A maximum efficiency of 21.5 % for the conversion of solar energy into grid electricity was measured in a 30 MW plant in California. The values for the other systems are based on component and prototype system test data and the assumption of mature development of current technology /Müller-Steinhagen and Trieb 2004/. The overall solar-electric efficiency includes the conversion of solar energy to heat within the collector and the conversion of the heat to electricity in the power block. The conversion efficiency of the power block remains basically the same as in fuel fired power plants, or may be slightly lower if the steam temperature delivered by the solar field is lower.

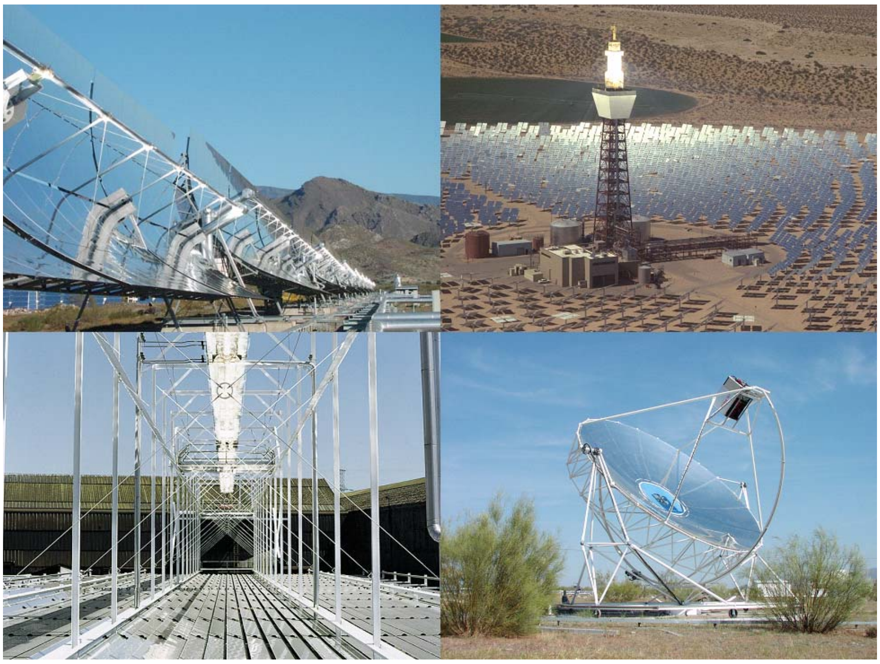

Figure 1-12: The four mainstream CSP-technologies for the production of high-temperature solar heat for power generation and process steam: parabolic trough (upper left), linear Fresnel (bottom left), solar tower (upper right) and dish Stirling (bottom right).

Solar towers can achieve very high operating temperatures of over 1000 °C, enabling them to produce hot air for gas turbine operation. Gas turbines can be used in combined cycles, yielding very high conversion efficiencies of the thermal cycle of more than 50 %.

Thermodynamic power cycles can be operated with fossil fuel as well as with solar energy. This hybrid operation has the potential to increase the value of CSP technology by increasing its power availability and decreasing its cost by making more effective use of the power block. Solar heat collected during the daytime can be stored in concrete, molten salt, ceramics or phase-change media. At night, it can be extracted from the storage to run the power block. Fossil fuels like oil, gas, coal and renewable fuels like biomass can be used for co-firing the plant, thus providing power capacity whenever required. This is a very important feature for the coupling with desalination processes, as they usually prefer steady-state operation and are not very easily operated with fluctuating energy input. There is also the possibility to by-pass steam directly from the solar field to the desalination plant, thus achieving a certain decoupling of power demand and water production.

	Capacity Unit MW	Concen-tration	Peak Solar Efficiency	Annual Solar Efficiency	Thermal Cycle Efficiency	Capacity Factor (solar)	Land Use m²/MWh/y
Trough	10 – 200	70 - 80	21% (d)	10 – 15% (d)	30 – 40 % ST	24% (d)	6 - 8
				17 – 18% (p)		25 – 90% (p)	
Fresnel	10 - 200	25 - 100	20% (p)	9 - 11% (p)	30 - 40 % ST	25 - 90% (p)	4 - 6
Power Tower	10 – 150	300 – 1000	20% (d)	8 – 10 % (d)	30 – 40 % ST	25 – 90% (p)	8 - 12
			35 % (p)	15 – 25% (p)	45 – 55 % CC		
Dish-Stirling	0.01 – 0.4	1000 – 3000	29% (d)	16 – 18 % (d)	30 – 40 % Stirl.	25% (p)	8 - 12
				18 – 23% (p)	20 – 30 % GT		

Table 1-3: Performance data of various concentrating solar power (CSP) technologies

(d) = demonstrated, (p) = projected, ST steam turbine, GT Gas Turbine,
CC Combined Cycle. Solar efficiency = net power generation / incident beam radiation
Capacity factor = solar operating hours per year / 8760 hours per year

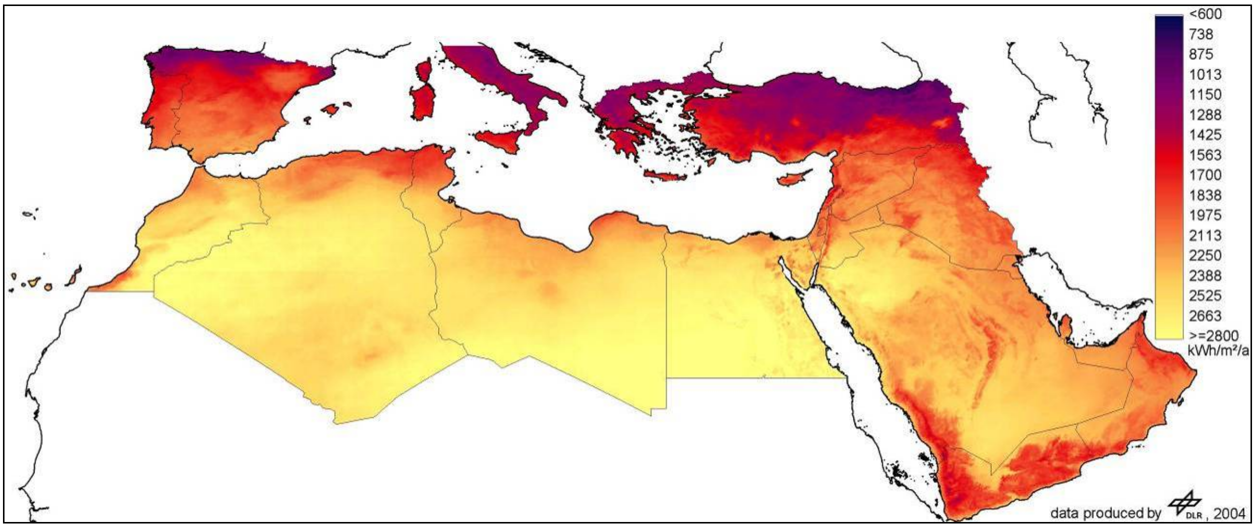

Figure 1-13: Solar energy atlas for Southern Europe, the Middle East and North Africa, showing the annual sum of direct normal irradiance in kWh/m²/y. Normal irradiance is defined as the irradiance perpendicular to a surface that continuously tracks the sun. Direct irradiance excludes the diffuse share of solar irradiance.

Moreover, high-temperature concentrated solar energy can be used for co-generation of electricity and process heat. In this case, the primary energy input is used with efficiencies of up to 85 %. Possible applications cover the combined production of industrial heat, district cooling and sea water desalination. All CSP concepts, except one[1] have the perspective to expand their time of solar operation to base load using thermal energy storage and larger collector fields. To generate one Megawatt-hour of solar electricity per year, a land area of only 4 to 12 m² is required. This means, that one km^2 of arid land can continuously and indefinitely generate as much electricity as any conventional 50 MW coal - or gas fired power station.

From each km² of desert land, about 250 GWh of electricity[2] can be harvested each year using concentrating solar thermal power technology. This is over 200 times more than what can be produced per square kilometre by biomass or 5 times more than what can be generated by the best available wind and hydropower sites. Each year, each square kilometre of land in MENA receives an amount of solar energy that is equivalent to 1.5 million barrels of crude oil[3]. A concentrating solar thermal power plant of the size of Lake Nasser in Egypt (Aswan) would harvest energy equivalent to the present Middle East oil production[4]. A CSP plant covering one square kilometre of desert land will deliver enough energy to desalinate over the whole year an average of 165,000 m³/day, which is equivalent to a major contemporary desalination unit[5].

The main characteristics that make concentrating solar power a key technology in a future renewable energy mix and also a key energy resource for seawater desalination in MENA are:

- it can deliver firm power capacity as requested by demand,
- its natural resource is easily accessible and practically unlimited,
- it can be used for combined generation of heat and power for cooling and desalination,
- its cost is already today lower than world market prices of fuel oil and rapidly decreasing with further market expansion.

Their thermal storage capability and hybrid operation with fuels allows CSP plants to provide power on demand. Their availability and capacity credit is considered to be well over 90 %, availability in the Californian SEGS has been reported to be better than 99 %. CSP plants can be built from several kW to several 100 MW capacity.

The first CSP plants were installed in California in the mid 1980ies, when fuel costs were high and tax credits allowed for a commercial erection and operation of a total of nine plants with 14 – 80 MW unit capacity, each. CSP electricity costs came down dramatically from 27 (1986) to 12 $-cents per kWh in 1991 (today equivalent to a decrease from 40 to 20 €-ct/kWh). In 1991, a

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[1] Integrated Solar Combined Cycle System (ISCCS) has a limited solar share of less than 20 % (ref. Annex 3).

[2] Solar irradiance 2400 kWh/m²/y * 11 % Annual Solar-Electric Net Efficiency * 95 % Land Use (Linear Fresnel)

[3] Solar irradiance 2400 kWh/m²/y x 1 million m²/km² : 1600 kWh/bbl heating value = 1.5 million bbl/km²/y

[4] Lake Nasser has 6000 km² x 1.5 million bbl/km²/y = 9 billion bbl/y = Middle East oil production

[5] Solar irradiance 2400 kWh/m²/y x 11 % CSP efficiency * 95 % Land Use : 4.2 kWh/m³ RO power consumption : 365 days/y = 0.165 m³/m²/day x 1 million m²/km² = 165,000 m³/km²/day

total of 354 MW was installed. However, fuel prices fell to a quarter of their initial cost in the mid eighties and tax credits for solar power were debated in the Californian parliament, and thus, no further CSP plant was installed for 15 years.

Only the implementation of the renewable electricity feed-in law in Spain, the renewable electricity portfolio standards in the U.S. and also the sharp increase of fossil fuel prices since the year 2000 finally lead to a revival of this technology, and several new plants are being commissioned in 2007.

The cost of CSP today is not significantly lower than that of the latest Californian plants, but the cost learning curve is again moving downwards (Figure 1-14). With 5000 MW of capacity scheduled to be installed world-wide by 2015, CSP technology is likely to become competitive by that time with world market prices of most fossil fuels, especially fuel oil, natural gas and liquid natural gas. Heat from a CSP solar field has a cost today that is equivalent to that of fuel oil at 50 $/barrel. Around 2010, a solar heat cost of around 2 €-ct/kWh (7.2 €/GJ) is envisaged, which would be competitive with current market prices of natural gas /oilnergy 2007/. Carbon trading and the introduction of carbon capture and storage (CCS) for fossil fuel-fired power plants will accelerate competitiveness of CSP, as it will add considerable costs to fossil fuel-fired electricity generation /IEA 2004/, /IPCC 2005/.

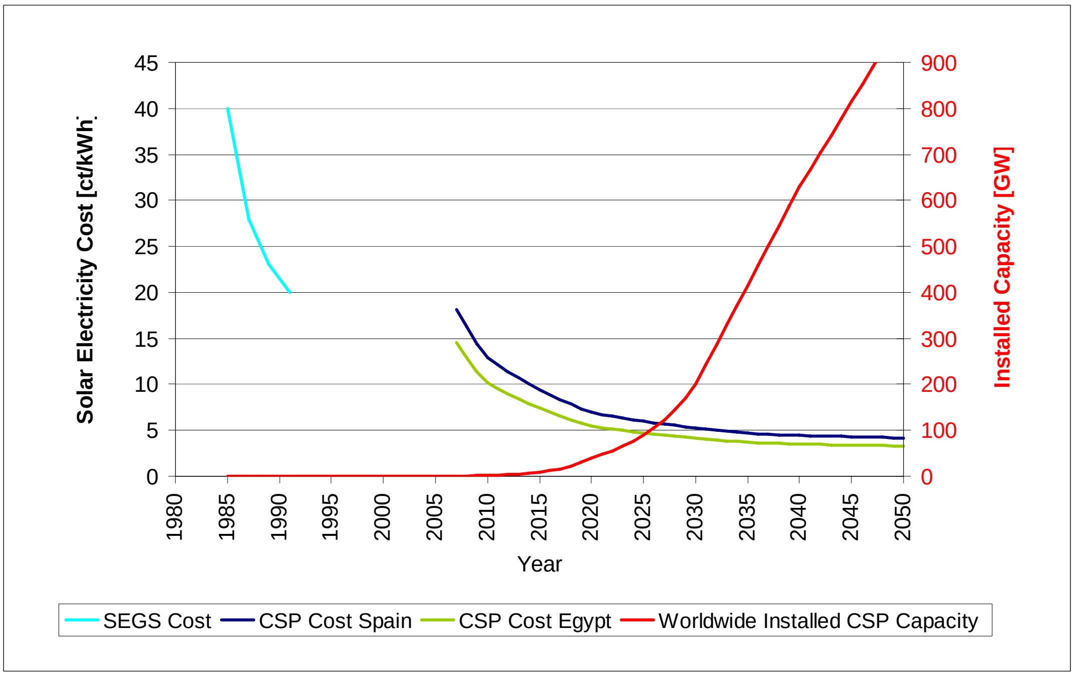

Figure 1-14: Solar electricity cost of concentrating solar power plants as function of time and world wide installed capacity; historical cost of the Californian 350 MW Solar Electricity Generating Systems (SEGS) installed between 1985 and 1991 has been converted to €2005; assumptions for new plants after 2007: solar only operation, thermal energy storage increases from 6 to 18 full load hours in 2020, discount rate 6%, economic life 25 years, cost in real €2005. Long-term relation of €/$=1. Source: /NEEDS 2007/

Cost reduction of CSP will mainly be driven by market expansion within the electricity sector of countries with high solar irradiance. However, other markets are also appearing, ranging from co-generation of heat and power for cooling, seawater desalination and industrial process heat to the long-distance transport of solar electricity from remote arid regions to major centres of demand. With the currently emerging pressure on renewable energies, motivated by the evidence of climate change, exploding fossil fuel costs and increasing risks of nuclear proliferation, it is very likely that the market expansion of CSP shown in Figure 1-14 will take place as a key component of a future renewable energy mix, simply because there are no tangible alternatives /MED-CSP 2005/, /TRANS-CSP 2006/.

1.2.1 Concentrating Solar Power for Steam Turbines

As shown in Figure 1-15, line focusing systems use trough-like mirrors and specially coated steel absorber tubes to convert sunlight into useful heat. The troughs are normally designed to track the sun along one axis, predominantly north-south (Figure 1-16). To generate electricity, a fluid flowing through the absorber tube – usually synthetic oil or water/steam – transfers the heat to a conventional steam turbine power cycle. Recently, molten salt has also been discussed as heat transfer fluid. Concentrating the sunlight by about 70 - 100 times, typical operating temperatures are in the range of 350 to 550 °C. Plants of 200 MW rated power and more can be built by this technology. Hybrid operation with all kinds of fossil or renewable fuels is possible /Müller-Steinhagen and Trieb 2004/. In order to increase the number of solar operating hours beyond the times when the sun shines, the collector field can be designed to provide, under standard conditions, more energy than the turbine can accept. This surplus energy is used to charge a heat storage, which can provide the required energy input to the turbine system during periods of insufficient solar radiation /Tamme et al. 2005/.

Heat storage may consist of two large tanks, each containing a molten nitrate salt mixture as storage medium with the necessary heat capacity for several hours of full load operation of the turbine. Heat is transferred from or to the heat transfer fluid of the collector via a heat exchanger. The liquid molten salt is pumped through this heat exchanger from the cold tank to the hot tank during charging and vice versa during discharging periods (Figure 1-17).

A first plant of this type with 50 MW rated power using synthetic oil as heat transfer fluid and a molten salt storage with 7.5 full load hours capacity is presently built in the Spanish Sierra Nevada /Müller-Steinhagen and Pitz-Paal 2006/. On July 20th 2006, construction started near Almería/Spain for the 50 MW_{el} parabolic trough plant ANDASOL 1, which will be followed by identical plants ANDASOL 2 & 3 in the next couple of years. Its collector area of over 510,000 square meters makes Andasol 1 the world’s largest solar power plant. It will generate approximately 179 GWh of electricity per year to supply some 200,000 people with environmentally friendly solar electricity after a construction time of barely two years. Another

64 MW parabolic trough plant was commissioned in Nevada in summer 2007. All in all, there is a world-wide capacity of about 1000 MW to be commissioned within the coming 5 years period.

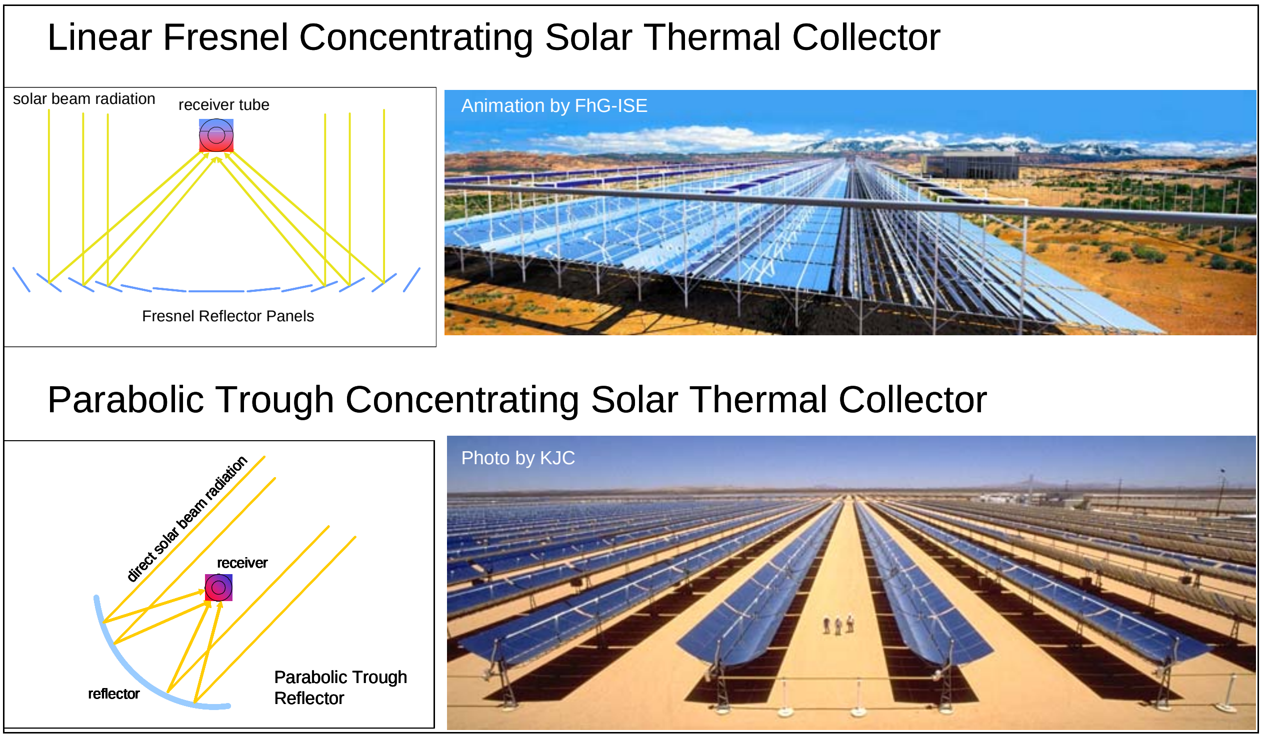

Figure 1-15: Principle of line focusing concentrating solar collector systems. Top: Animation of a Linear Fresnel type concentrating solar thermal collector field for direct steam generation as presently developed by MAN/SPG. Bottom: Parabolic trough solar field of the 5 x 30 MW solar electricity generating system (SEGS) in Kramer Junction, California.

Figure 1-16: Parabolic trough collectors and foundations for the molten salt tanks of ANDASOL 1.

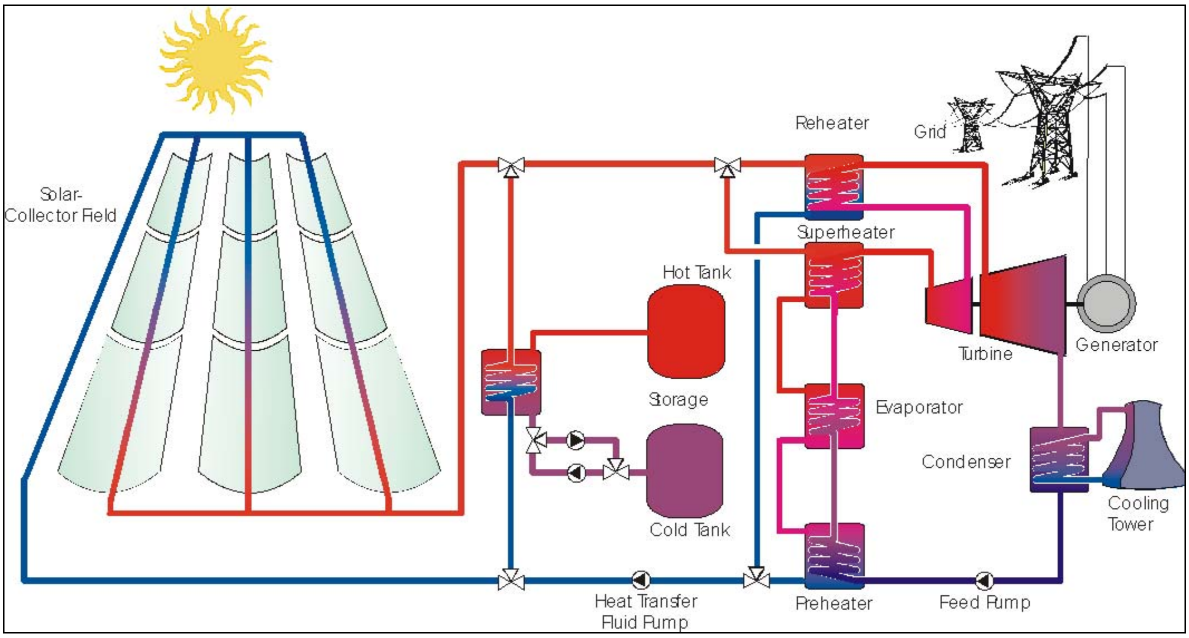

Figure 1-17: Line focusing concentrating collector coupled to a steam cycle power station

The present parabolic trough plant design uses a synthetic oil to transfer energy to the steam generator of the power plant cycle. Direct solar steam generation in the absorber tubes of parabolic trough collectors is a promising option for improving the economy of solar thermal power plants /Eck and Steinmann 2005/, since all oil-related components become obsolete and steam temperature (and hence efficiency) can be increased. Steam temperatures up to 400 °C at 100 bar pressure have been reached within the framework of a European project undertaken over 6000 operating hours at the Plataforma Solar de Almería, Spain. The test loop with 700 m length and an aperture of 5.70 m has been custom designed and constructed for the purpose of demonstrating safe operation and controllability under constant and transient operating conditions.

Linear Fresnel systems have recently been developed by several companies with the goal to achieve a more simple design and lower cost than the parabolic trough. The first prototypes realised up to now are promising, and first power plants are presently in the design phase. It is expected that this technology will be commercially available around the year 2010. In a Fresnel system, the parabolic shape of the trough is split into several smaller, relatively flat segments. These are put on a horizontal rag and connected at different angles to a rod-bar that moves them simultaneously to track the sun during the day (Figure 1-18). Due to this arrangement, the absorber tube can be fixed above the mirrors in the centre of the solar field, and does not have to be moved together with the mirror during sun-tracking.

While parabolic troughs are fixed on central pylons that must be very sturdy and heavy in order to cope with the resulting central forces, the Fresnel structure allows for a very light design, with the forces absorbed by the four corners of the total structure. Large screws instead of pylons are literarily screwed into the ground and hold the lateral bars of the Fresnel structure.

Figure 1-18: Novatec-Biosol linear Fresnel collector prototype at Lorca, Spain

Compared to the existing parabolic trough, the linear Fresnel collector system designed by Novatec-Biosol shows a weight reduction per square metre of 80%. This structure reflects not only a lower cost, but also leads to lower life cycle emissions (Chapter 6). On the other hand, the simple optical design of the Fresnel system leads to a lower optical efficiency of the collector field, requiring about 33% more mirror aperture area for the same solar energy yield compared to the parabolic trough.

In terms of integration of the solar field to its environment, the Fresnel system has considerable advantages over parabolic troughs. Land use is much better, as the distances between mirrors are much smaller (Figure 1-18). The collector aperture area covers between 80 % and 95 % of the required land, while for the parabolic trough, only 30 % of the land is covered by mirrors, because the distances between the single parabolic-trough-rows required to avoid mutual shading are considerable (Figure 1-16). Land use efficiency of a linear Fresnel is thus about 3 times higher than that of a parabolic trough. Considering the lower optical efficiency of the Fresnel (2/3 of that of a parabolic trough), this leads to a roughly two times better solar energy yield per square meter of land of the Fresnel system when compared to a parabolic trough (Figure 1-19).

This fact may not be of much importance in remote desert areas were flat, otherwise unused land is not scarce, but it may be of importance when integrating CSP to industrial or tourist facilities, or placing CSP near the coast and close to urban centres of demand.

The flat structure of the Fresnel segments can be easily integrated to industrial or agricultural uses. In the hot desert, the shade provided by the Fresnel segments may be a valuable extra service provided by the plant. It could cover all types of buildings, stores or parking lots, protect certain crops from excessive sunshine and reduce water consumption for irrigation.

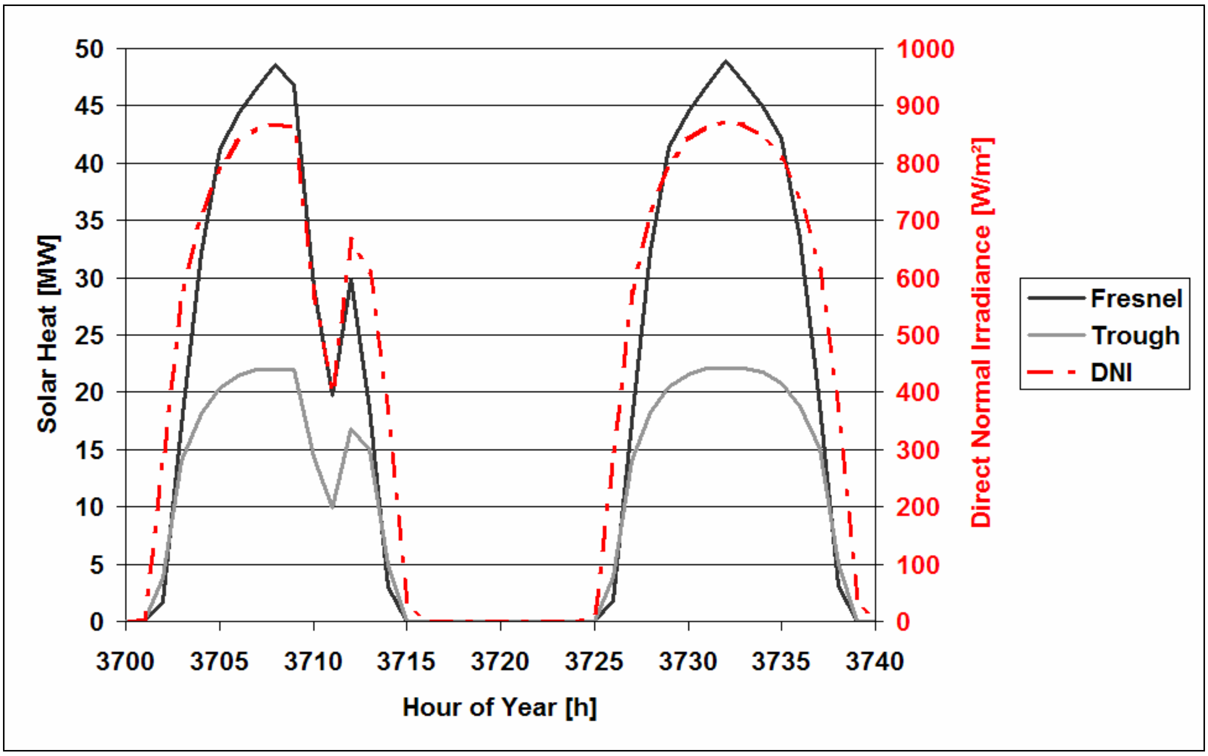

Figure 1-19: Example of the solar heat delivered from a linear Fresnel and from a parabolic trough collector field covering a land area of 110,000 m² as function of time and direct normal irradiance /SolWater 2006/

A parabolic trough solar field must be free of vegetation, because concentrated sunlight could ignite dry grass and lead to grass fires. Specially in those plants that use synthetic oil as heat transfer fluid, this would constitute a significant danger (Figure 1-16). There is no such danger using Fresnel systems, and thus, the land below can be used for pasture or agriculture of low growing crops.

1.2.2 Concentrating Solar Power for Gas Turbines

Solar towers use a large field of two-axis tracking mirrors (heliostats) that reflect the sunlight to a central receiver on top of a tower, where the concentrated solar energy is converted to high temperature heat (Figure 1-20). The typical optical concentration factor ranges from 200 to 1000, and plant sizes of 5 to 150 MW are feasible. The high solar fluxes impinging on the receiver (average values between 300 and 1000 kW/m²) allow working at high temperatures over 1000 ºC and to integrate thermal energy into steam cycles as well as into gas turbines and combined cycles. Solar towers with central receiver systems can be integrated in fossil plants for hybrid operation in a wide variety of options and have the potential to generate electricity with high annual capacity factors by using thermal storage.

Solar towers can be used for steam generation, with a 10 MW plant being recently realised in Spain (Planta Solar 10 near Sevilla) and another one being scheduled for commissioning in 2008

(Solar Tres). At the moment, there is still no reliable performance data available for these systems. In the steam cycle market segment, those systems will have to compete with the established trough technology, and hence, their technical and economic performance characteristics will have to be equal or superior to those of the trough system /EC 2007/.

High efficiencies may be reached with solar-heated gas turbines, which may be increased further in combined cycle processes (Figure 1-21). These systems have the additional advantages that they can also be operated with natural gas during start-up and with a high fossil-to-electric efficiency when solar radiation is insufficient. Hence, no backup capacities of fossil fuel plants are required and high capacity factors are provided all year round. In addition, the consumption of cooling water is reduced significantly compared to steam cycle systems.

The high temperatures for gas turbine operation and the heat transfer using air requires a different receiver concept than the absorber tubes used in linear concentrating systems. Volumetric receivers do not absorb the concentrated solar radiation on an outer tube surface, but within the volume of a porous body. Air can be used as heat transfer medium which is flowing through that porous material, taking away the heat directly from the surface where it has been absorbed. Due to the excellent heat-transfer characteristics, only a small temperature gradient between the absorber material and the air exists, and thermal losses are reduced. Also, the heat flux density can be much higher than in gas cooled tube receivers /Buck et al. 2002/

The porous material can be a wire mesh for temperatures up to 800 °C or ceramic material for even higher temperatures /Fend et al. 2004/. There are two principal designs of volumetric receivers: the open or atmospheric volumetric receiver uses ambient air sucked into the receiver from outside the tower. The heated air flows through the steam generator of a Rankine cycle. The second concept is the closed or pressurised volumetric receiver that uses pressurised air in a receiver closed by a quartz window (Figure 1-22).

This system can heat pressurised air coming from the compressor of a gas turbine power cycle. A first pilot system has been installed and tested on the Plataforma Solar de Almería in Spain, with the following targets being reached:

- receiver outlet temperature 1050 °C with pressures up to 15 bar,
- 90 % secondary concentrator efficiency,
- external cooling of window to maintain glass temperatures below 800 °C, with negligible thermal losses,
- demonstration of controlled system operation, 230 kW electric power output achieved.

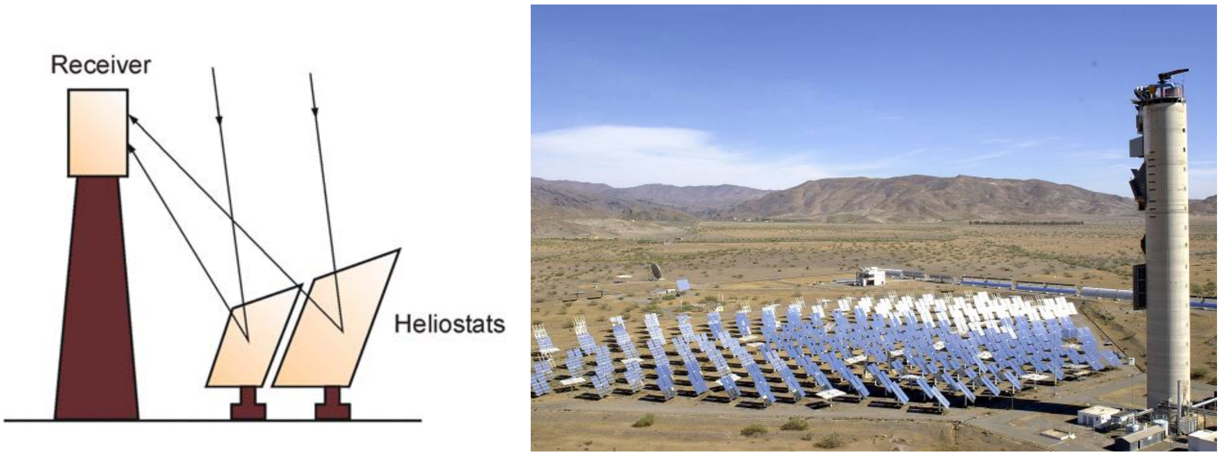

Figure 1-20: Principle of a point focusing solar tower system (Plataforma Solar de Almeria, Spain)

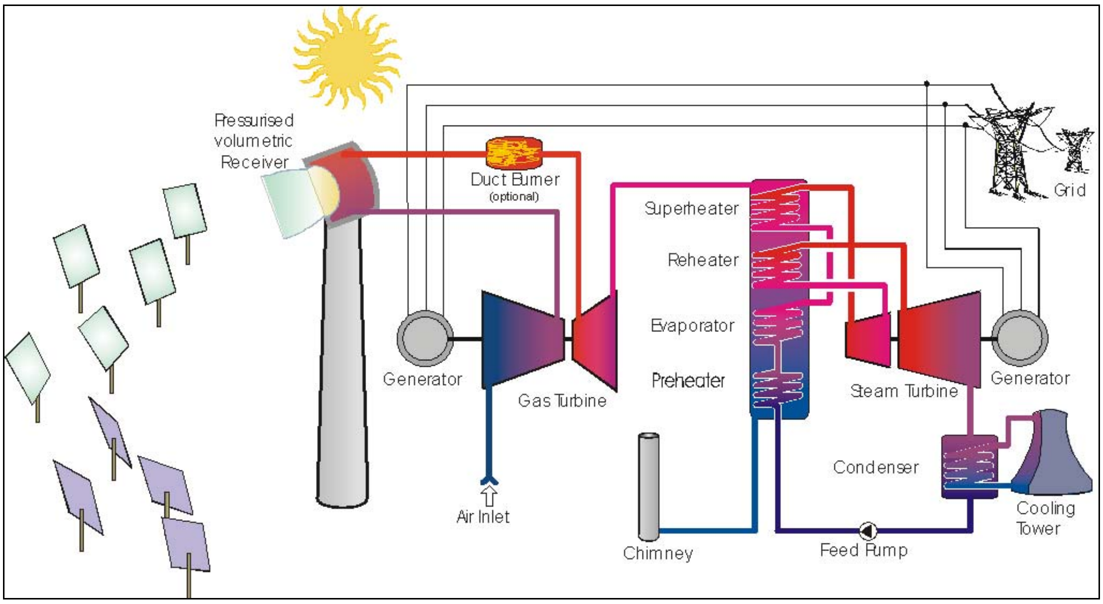

Figure 1-21: Solar tower used for gas turbine operation in a combined cycle power plant

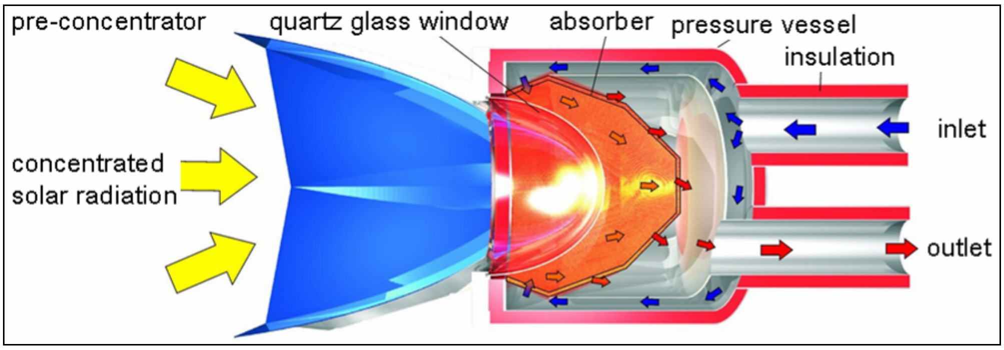

Figure 1-22: Pressurised air heated by solar energy using a volumetric receiver

1.2.3 Concentrating Solar Power for Combined Electricity and Heat

By the end of 2006, a feasibility study was finished by a Jordanian/German consortium to assess the technical and economical feasibility of an integrated production of 10 MW of power, 10,000 tons/day of desalted water and 40 MW cooling capacity for the Ayla Oasis Hotel Resort in Aqaba, Jordan. The system allows for a very efficient use of fossil fuel and uses concentrated solar energy as fuel saver.

A parking lot of 110,000 m² was designated for the integration of the solar field. A linear Fresnel concentrating collector field was selected as solar component /SolWater 2006/. The flat Fresnel structure fitted better than parabolic trough to this particular requirement of integration, and the solar energy yield of the Fresnel field on the limited space is roughly twice of that of an equivalent parabolic trough field (Figure 1-19).

A standard solution for the hotel resort would have been purchasing electricity and water from the public grid and cooling by conventional rooftop compression chillers. As electricity and water are already limited in Aqaba, additional power plant capacity for power and desalination would have been required. As shown in Figure 1-23, the conventional supply of the required commodities would require a natural gas consumption of 85 MW.

The insecurity of future prices for fossil fuels has lead to the investigation of the feasibility of an alternative power plant concept for on-site production based on the combined generation of electricity and heat for absorption cooling and multi-effect desalination. The absorption chillers are used for base load operation during the holiday season, while the compression chillers are only used for peaking and intermittant demand. A cold water district cooling grid will be used to distribute the cooling power from the central plant to the different users in several hotels, residential areas and commercial centres and for the technical operation of the resort. The result of the analysis shows that the integrated process will require 35 % less fuel input, due to the better efficiency of combined generation and the solar fuel saver (Figure 1-24).

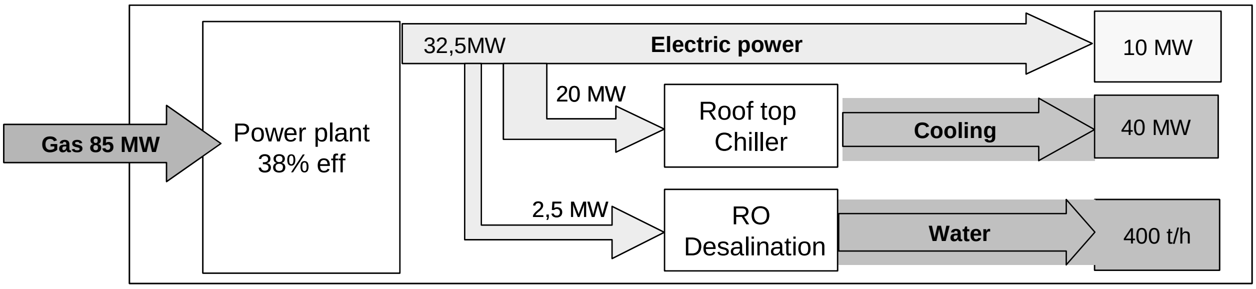

Figure 1-23: Conventional solution for power, cooling and water for a hotel resort in Aqaba /Kern et al. 2006/

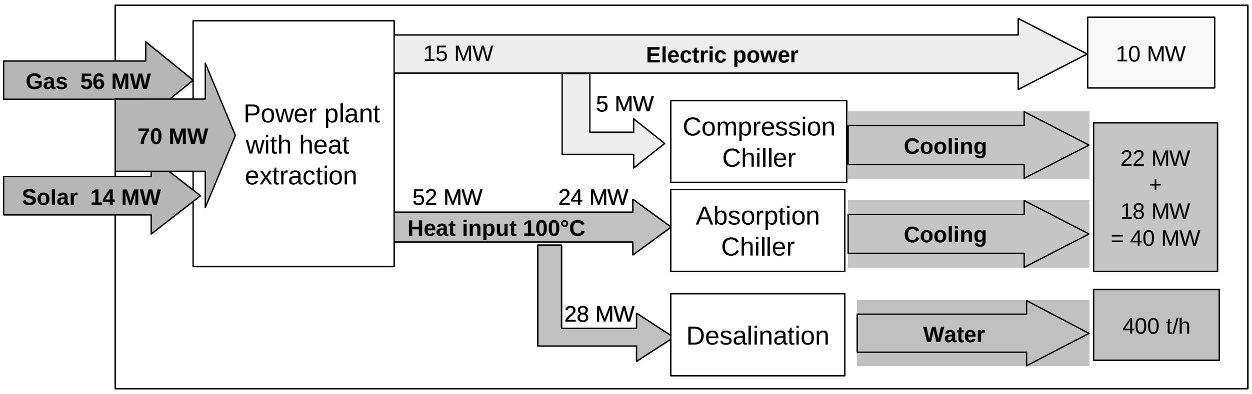

Figure 1-24: Integrated solution for power, cooling and water supported by CSP /Kern et al. 2006/

An advantage of onsite production of commodities like power, water and cooling is that the production cost competes with purchase prices (that include distribution and public infrastructure) rather than with the production cost of large conventional power plants. With revenues of 0.10 $/kWh for electricity, 0.04 $/kWh for cooling and 1.50 $/m³ for water, the project can be realised with a good internal rate of return without depending on subsidies.

In general, there is a good coincidence of solar energy and cooling demand (50 % of the electricity load in the MENA-Region is caused by air-conditioning due to intensive solar radiation), which allows for a very efficient use of the solar energy and for fuel saving specifically during peak load times.

The only requisite for such a relatively large on-site system is a rather large on-site consumption. This innovative concept opens considerable market opportunities for the unsubsidised use of solar energy. The engineering for the power plant is expected to be initiated in early 2008, and commissioning is planned for early 2010.

1.2.4 Pre-Selection of CSP Technologies

In principle, all CSP technologies can be used for the generation of electricity as well as for the desalination of seawater (Table 1-4 and Figure 1-25). The scope of pre-selection within this study is to find a CSP-technology that can be used as reference with respect to performance, cost and integration with seawater desalination in order to develop a long-term market scenario for CSP/desalination in general based on that technology.

The maturity of point concentrating systems is not as high as that of line concentrating systems. In spite of first demonstration projects of central receivers in Europe in the 1970ies, the only commercial CSP plants today are line concentrating parabolic trough systems. It is still uncertain whether central receivers will be able to compete with line concentrating systems in the lower temperature range up to 550 °C for steam generation. Up to now, line concentrating systems have had clear advantages due to lower cost, less material demand, simpler construction and higher efficiency, and there is still no evidence of a future change of that paradigm.

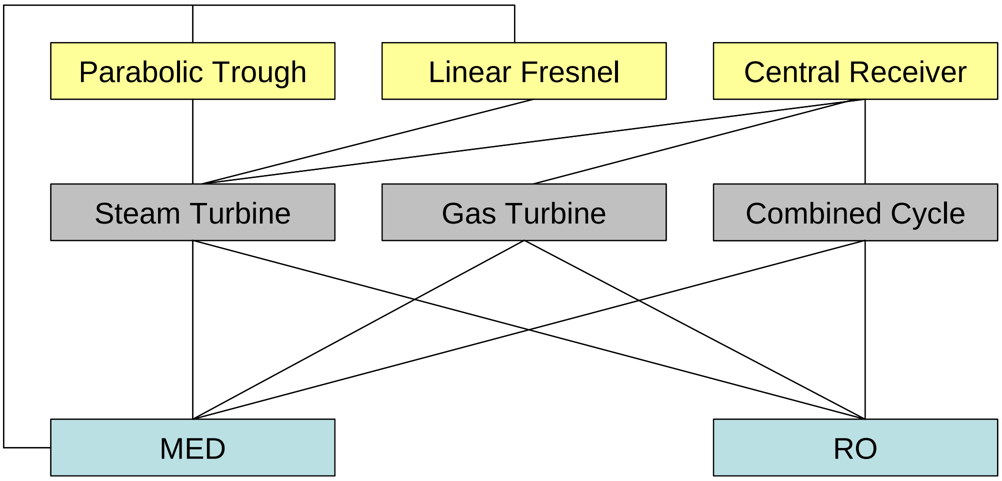

Figure 1-25: Options of combining concentrating solar power with desalination technologies

On the other hand, neither parabolic troughs nor linear Fresnel systems can be used to power gas turbines. In the high-temperature range up to 1000 °C and more, central receivers are the only available option to provide solar heat for gas turbines and combined cycle systems. However, it is still uncertain whether the technical challenge involved with such systems will be solved satisfactorily, and if large scale units will be commercially available in the medium term future. The early stage of development of those systems – although their feasibility has been successfully demonstrated – still leaves open questions with respect to cost, reliability and scalability for mass production at large scale. Therefore, central receiver systems have been discarded from being used as reference CSP technology for this study, although this does not exclude the possibility that they may have an important role in a future competitive market of CSP systems for electricity and desalination.

As the main scope of the study was to assess the potential of large scale desalination units with CSP for the major centres of demand in MENA, parabolic dish systems can be excluded as well, as they only operate in the kilowatt range. However, they could be applied for decentralised, remote desalination as will be described in Chapter 1.4.

The exclusion of point concentrating systems leaves parabolic trough and linear Fresnel concentrators as major candidates for a CSP reference technology. Looking at Table 1-4, Fresnel beats the parabolic trough in most items except for two: current experience with parabolic trough technology is by far more extended than that with linear Fresnel systems and, as a consequence, a comparison of reliability with the highly reliable parabolic trough cannot yet be made.

Concentration Method	line concentrating system		point concentrating system	
Solar Field Type	**Parabolic Trough**	**Linear Fresnel**	**Central Receiver**	**Parabolic Dish**
State of the Art	commercial	pre-commercial	demonstrated	demonstrated
Cost of Solar Field (€/m²)	200 - 250	150 - 200	250 - 300	> 350
Typical Unit Size (MW)	5 - 200	1 - 200	10 - 100	0.010
Construction Requirements	demanding	simple	demanding	moderate
Operating Temperature	390 - 550	270 - 550	550 - 1000	800 - 900
Heat Transfer Fluid	synthetic oil, water/steam	synthetic oil, water/steam	air, molten salt, water/steam	air
Thermodynamic Power Cycle	Rankine	Rankine	Brayton, Rankine	Stirling, Brayton
Power Unit	steam turbine	steam turbine	gas turbine, steam turbine	Stirling engine
Experience	high	low	moderate	moderate
Reliability	high	unknown	moderate	high
Thermal Storage Media	molten salt, concrete, PCM	molten salt, concrete, PCM	molten salt, ceramics, PCM	molten salt, ceramics, PCM
Combination with Desalination	simple	simple	simple	Simple
Integration to the Environment	difficult	simple	moderate	Moderate
Operation requirements	demanding	simple	demanding	Simple
Land Requirement	high	low	high	Moderate

Table 1-4: Characteristics of current concentrating solar power technologies (PCM: Phase Change Materials)

However, looking at the long-term perspective of CSP, it must be noted that the linear Fresnel has many advantages, ranging from lower cost and lower material requirements to a much simpler construction and a much better integration to the environment /NEEDS 2007/. In fact, linear Fresnel systems can be considered as next generation parabolic troughs, if they proof to be technically reliable. Linear Fresnel systems differ from parabolic troughs only in terms of optical performance and mechanical operation of the sun-tracking mirrors. All other components – from the heat transfer circuit to the steam power cycle – are in principle the same as in equivalent parabolic trough plants. This allows to transfer part of the existing experience – which is related to those components – from parabolic trough to linear Fresnel systems.

Taking into consideration the specific advantages of Fresnel systems in relation to seawater desalination, and also the experience with the Aqaba Solar Water project described in Chapter 1.2.3, we have opted for choosing linear Fresnel technology as reference for CSP technology for more in-depth analysis of a combination with seawater desalination and for our long-term scenario evaluations within this study.

This does not exclude any other CSP technology from being considered, assessed or used in combination with seawater desalination, either directly by solar heat or through the generation of electricity. In fact, strong competition of all CSP technologies will be a major driving force to achieve the cost learning curve and the market expansion of CSP shown in Figure 1-14.

1.3 Concentrating Solar Power for Large Scale Seawater Desalination

As shown before, concentrating solar power plants can generate electricity which can be used for membrane desalination via reverse osmosis. Being thermal power stations, CSP plants can also be used for combined heat and power. Thus, also thermal desalination methods like multi-effect or multi-stage-flash can be coupled to and powered by CSP, either directly or in co-generation with electricity.

A major advantage of CSP for desalination can be appreciated in Figure 1-26, Figure 1-27 and Figure 1-28 for a time-series modeling of one week of operation of equivalent wind, PV and CSP systems with 10 MW installed power capacity each at Hurghada, Egypt: while wind and photovoltaic power systems deliver fluctuating power and either allow only for intermitting solar operation of a desalination plant or require considerable conventional backup power, a concentrating solar power plant can deliver absolutely stable and constant power capacity, due to its thermal energy storage capability and to the possibility of hybrid operation with fuel.

In order to operate at constant power, desalination plants using wind or PV electricity would additionally need to be coupled to the electricity grid for external backup. In both cases a 10 MW conventional backup capacity would have to be installed and operated almost all the time, providing a relatively small portion of electricity during daytime and wind periods and full capacity during night and wind calms. On the other hand, if intermittent operation was allowed, much higher power capacities of PV and wind power would have to be installed to produce the same amount of electricity and water.

In this example the renewable share provided by CSP is 91 %, that of PV is 25 % and that of wind power is 37 %. Depending on the conditions at different locations in MENA, these numbers can be also considered as typical for the average annual performance of such systems.

As a consequence, CSP plants save both fuel and installed capacity when compared to other renewable energy sources like PV and wind for desalination. Instead of conventional backup power, electricity generated by all three systems could be stored in batteries, hydro-pump or hydrogen energy storage in order to provide continuous power capacity to desalination. In that case, the additional electrical storage capacities needed by CSP would be rather small, while significant storage would be required for PV and wind power, prohibitively increasing the overall system cost.

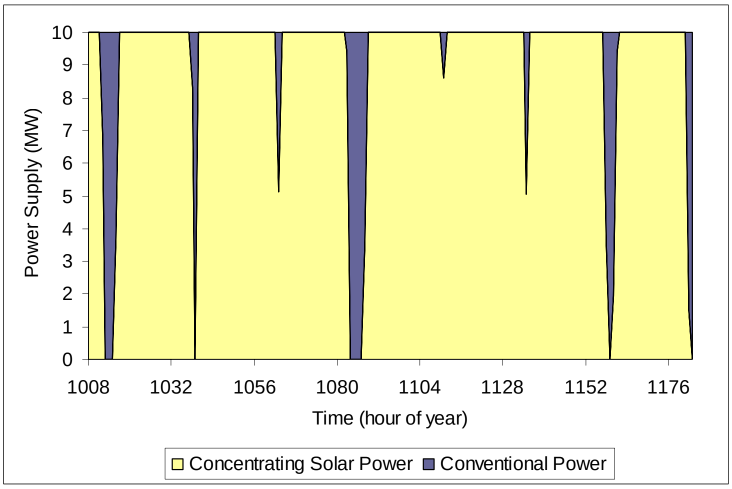

Figure 1-26: Solar power provided by a modelled CSP-plant with 16 hour thermal storage in a week in spring, and fuel consumed in hybrid mode from the same plant for constant 10 MW capacity.

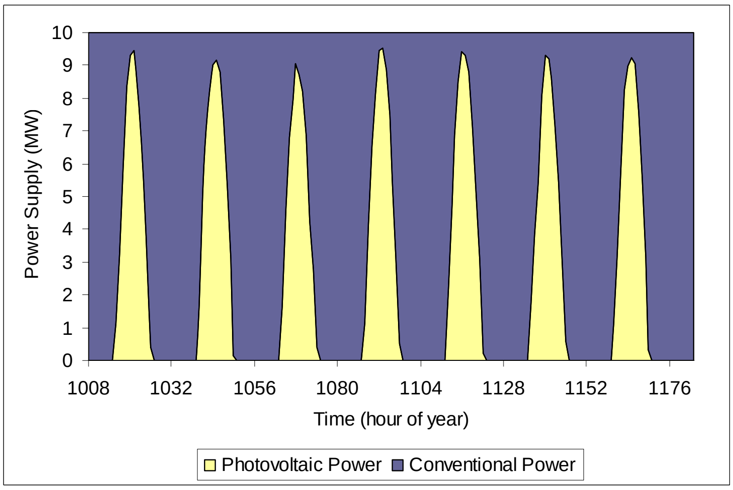

Figure 1-27: Power supplied by modelled 10 MW PV capacity and conventional backup power from the grid needed to provide constant 10 MW power supply for desalination for a week in spring.

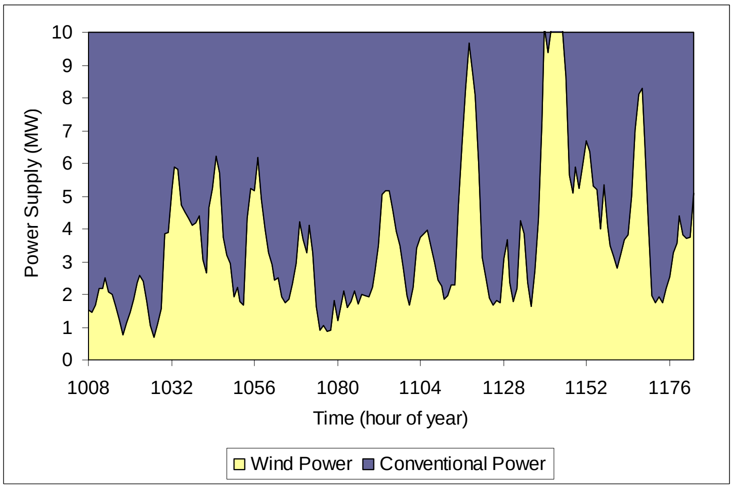

Figure 1-28: Power supplied by 10 MW installed wind capacity and conventional backup power from the grid needed to provide constant 10 MW power supply for desalination for a week in spring.

Intermittent operation of desalination plants is possible and has already been realized in smaller systems /Enercon 2006/, /Al-Sahali and Ettouney 2007/. However, for large-scale seawater desalination plants, intermittent operation would lead to a rather low economic performance as the investment of the desalination plant would not be amortized properly, and the plant's lifetime would be reduced by increased scaling, fouling and corrosion. Overall energy consumption would increase, as temperature- and pressure would continuously change which would lead to efficiency losses within all components of the plants.

In the following we will therefore concentrate on concentrating solar power as energy source for thermal and membrane desalination, and describe the technical and economic performance of large scale systems of this type for the combined generation of power and desalted seawater.

1.3.1 Comparison of Technical Performance

Within this chapter, we have compared a linear Fresnel concentrating solar power system combined with reverse osmosis membrane desalination and with thermal multi-effect distillation using in both cases a simple Rankine power cycle according to Figure 1-29, center and right.

Seven locations in the Middle East and North Africa have been chosen as reference sites for comparing both technical options under equal frame conditions: the Northern Red Sea at Aqaba (Jordan), the Atlantic Coast at Agadir (Morocco), the Arabian Gulf at Abu Dhabi (United Arab Emirates), the Mediterranean Sea near Valetta (Malta), the Southern Red Sea at Al Khawkah (Yemen), the Mediterranean Sea at the Sinai near Gaza (Palestine) and the Western Red Sea at Hurghada (Egypt) as sample locations with a wide spectrum of seawater salinity, temperature, solar irradiance and other environmental parameters (Table 1-6).

In order to compare RO and MED in combination with CSP for different sites, both systems were designed for identical demand of electricity and water of 20-25 MW and 24,000 m³/day (1,000 m³/hour), respectively. Calculating the required input of thermal energy and the necessary size of the solar collector field we obtain an evaluation of the differences in system performance.

The most important design parameters differ for each site, due to different nominal performance of the solar field, which varies mainly with the nominal solar incidence angle that is defined by latitude, and due to different salinity of the desalted seawater, which strongly influences the performance of RO. Other parameters like ambient temperature and relative humidity also influence plant performance, as they have a certain effect on efficiency and the internal electricity requirements (parasitic power) for plant operation. However, their influence on system performance is much smaller than that of seawater salinity and nominal solar irradiance.

Both systems are supposed to deliver product water with a quality satisfying WHO standard that allows a maximum salinity of 200 ppm. This requires a multi-pass reverse osmosis plant, as the final salinity of a single-stage RO process is usually higher. On the other hand, a typical MED plant delivers water at about 10 ppm which is not potable and therefore requires adequate dosing of the necessary minerals and salts for human consumption. Electricity is considered a by-product. All plants are designed thus that net power and water output are identical, while the size of the collector field and fuel consumption varies according to the requirements.

There is a lot of literature comparing RO with thermal desalination, which generally comes to the conclusion that the RO process is more energy efficient than thermal desalination processes. However, our analysis comes to an opposite conclusion for the combination with a full-scale CSP-plant: in all the seven cases considered in the MENA region, the combined CSP/MED process requires between 4 % and 11 % less input energy than the combined CSP/RO process.

The main reason for this supposed contradiction is a fundamental difference of the design targets of conventional and solar power systems: relying on finite, expensive and polluting fossil energy sources, conventional systems are usually designed to yield an optimal efficiency of energy conversion from fuel into useful energy, e.g. maximising the electricity output of a plant with a given fuel input /El-Nashar 2002/. On the other hand, solar power systems are designed to maximise the solar share of a given energy service. Conversion efficiency is of secondary importance only, as far as economic performance and competitiveness to other equivalent systems is concerned. This is obvious if one considers that a considerable reduction of global fuel consumption – a main target of sustainability – can only be achieved to a limited extent by increasing conversion efficiency, but can be fully achieved by increasing the share of renewable energy sources to 100 %. Nevertheless, the overall efficiency of combined generation – producing two valuable products like power and water – is in fact rather high.

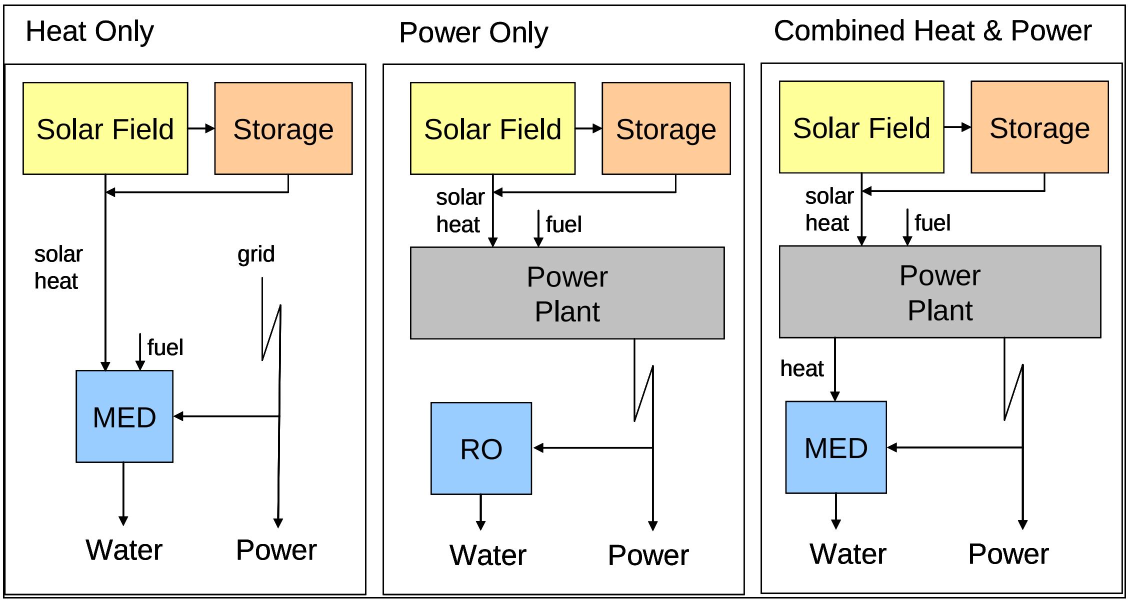

Figure 1-29: Different configurations for desalination powered by CSP. Left: Solar field directly producing heat for thermal multi-effect desalination. Center: Power generation for reverse osmosis (RO). Right: Combined generation of electricity and heat for multi-effect desalination (MED).

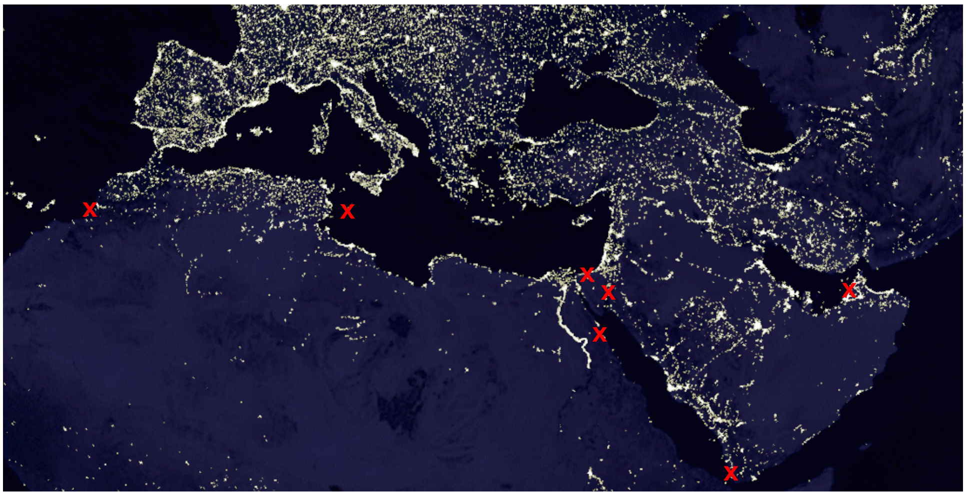

Figure 1-30: Human activities indicated by night-time light emissions in the MENA region and sites chosen for case analysis of CSP combined with seawater desalination (background map by NASA). From left to right: Agadir (Morocco), Valetta (Malta), Gaza (Palestine), Aqaba (Jordan), Hurghada (Egypt), Al Khawkha (Yemen), Abu Dhabi (UAE).

The resulting difference of performance of CSP/MED and CSP/RO is clear, though not very large. It can be noted from Table 1-6, that the specific electricity consumption of MED desalination of 2.2-2.4 kWh/m³ is considerably lower than that of reverse osmosis, which ranges between 4.9-5.9 kWh/m³ depending mainly on the salinity of the input seawater.

It can also be seen from the table, that in case of coupling MED to a CSP plant, the gross electricity yield is considerably lower, as the cold end temperature of around 70 °C of the back-pressure steam turbine is higher. As a consequence 10 % less mechanical work can be delivered to the power generator than in case of power generation with a condensing steam turbine with a lower cold-end temperature of 35-45 °C, that would be used for RO desalination (Figure 1-3). This means, that the thermal energy extracted from the power cycle for MED distillation is equivalent to a specific electricity loss of about 2.3-2.8 MW with respect to a system producing solely electricity that would be used for an RO process.

Finally, the internal electricity consumption of the power block, the so called parasitic losses, differ considerably for both processes, being around 0.2 MW for CSP/MED and about 1.8-2.1 MW for CSP/RO. This is due to the fact that the MED plant fully replaces the cooling system of the conventional power station and all the power consumption related to water intake, pumping and cooling fans. Another effect is related to the fact that part of the cooling energy leaves the plant in form of warm brine and distilled water, thus saving electricity that would otherwise be required for pumping of cooling water and for the cooling fans of the evaporation tower.

Altogether, these effects lead to a slightly better technical performance of CSP/MED compared to CSP/RO. A similar result was obtained by /Wilde 2005/. The advantage of CSP/MED is more pronounced at sites with high seawater salinity like the Arabian Gulf and the coasts of the Red

Sea, and, due to a lower salinity, less pronounced at the Mediterranean Sea and the Atlantic Ocean[1]. This specific result is valid for a combination of MED and RO seawater desalination with a concentrating solar power plant designed for full solar operation using a simple Rankine power cycle, and may look slightly different for plants that are optimised for fossil fuel consumption, e.g. using a more sophisticated (but also more expensive) power cycle with pre-heating of feed water and re-heating of steam.

Our result does not necessarily imply a general preference for CSP/MED plants, because CSP/RO plants also have a number of characteristics that may be advantageous for solar powered seawater desalination, as shown in Table 1-5.

As an example, CSP and RO plants can be completely separated from each other, the CSP plant being installed on an optimal site for power generation, while only the RO plant must be on the coast, both being interconnected by the public grid. In fact this is already the case today, one could say that such plants already exist in California, with a lot of RO plants operating on the seashore, and the famous solar electricity generating systems (SEGS) in the Mojave desert. The de-coupling of CSP and RO can be advantageous if the seashore is highly populated, if land costs are very high at the coast, if the coastal topography does not allow for the installation of large solar collector fields or if the coast should be protected due to environmental constraints. On the Western South-American coast and the Western South African coast, there is the phenomenon of dense fog banks from the ocean covering several kilometres inland for several months per year. In case the solar irradiance is considerably lower at the coast than further inland, it may be preferable to install the CSP plant out of the range of such weather phenomena.

Desalination plants are preferably operated at constant load. Part load can cause additional problems of scale formation and fouling, and of course it reduces the economic attractiveness of the respective project. Solar energy is only available during daytime and is considerably reduced on cloudy days. Therefore, the direct coupling of CSP with a MED plant requires thermal energy storage of solar input energy and/or hybrid operation with fossil or bio fuels in order to allow for continuous operation. An RO plant connected to the grid can compensate fluctuations of the solar energy input by taking electricity from other sources from the grid.

On the other hand, electricity transfer from a remote CSP plant to a RO plant at the shore will produce electricity losses. Placing the CSP plant in a hot desert may require dry cooling, which could lead to a cold end temperature of the steam cycle of 70 °C and more, which would be equivalent to that of a combined CSP/MED process. However, in this case the heat would be rejected to the desert instead of being used for desalination. Thus, rather than loosing process efficiency by ineffective cooling, it may be favourable to place the CSP plant near the shore in spite of lower solar irradiance. All these details have to be decided upon project-wise.

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[1] Recently, several references have appeared claiming for an opposite result in favour of CSP/RO. However, they contain methodical errors and are thus not quoted here. Annex 2 will explain this context.

System	**CSP/MED**	**CSP/RO**
Site Selection	limited to coast	CSP may be anywhere, RO must be at the coast, while the public grid can be used for interconnection
Flexibility	interdependent operation	independent operation possible if plants interconnected through the public grid
Optimal Irradiance	defined by coastal site	CSP can be placed at site with higher irradiance, but certain amount of power is then lost by transmission to RO plant, and dry cooling leads to lower efficiency
Storage Options	molten salt, concrete, low temperature hot water storage possible, PCM	molten salt, concrete, phase change materials (PCM)
Water Quality	independent of raw water quality, very high quality of product water	may be favourable for brackish raw water and if low product water quality is allowed
Other Uses	industrial co-generation of process heat, district cooling, integrated systems for power, cooling, desalination for tourism and rural development	power only

Table 1-5: Selected characteristics of CSP/MED and CSP/RO plants

The direct coupling of CSP with MED has certain advantages: first of all, the primary energy consumption is reduced, and with that, the environmental impact of the plant (Chapter 6). Also, as demonstrated by the Aqaba Solar Water project described in Chapter 1.2.3, this type of integrated plants is very attractive for large consumers like hotel resorts or industrial parks, because on-site operation of such plants can be highly competitive with power and water purchase prices from external sources.

The results shown here were obtained by modelling the combined CSP desalination plants with an adaptation of the SolWater simulation model developed by DLR and partners during the Aqaba Solar Water project /Kern et al. 2006/. The program is based on a thermodynamic model of the solar field and of the power block combined with a semi-empirical model of the desalination system.

Today, MED and RO process design is in a phase of very dynamic development for cost reduction, efficiency gains, material enhancement and environmental impact reduction /Abu-Arabi and Reddy 2004/, /Alarcon et al. 2007/. A combination of these desalination technologies with CSP is in a very early stage of feasibility analysis, with no plants of this type operating up to now. A general forejudge for one or the other technology or combination at the present state of the art would therefore be rather premature.

For those reasons, we believe that there is no general preference for one or the other plant type or combination, and that there will be considerable markets for both CSP/MED and CSP/RO plants.

The individual economic competitiveness of each project and the local economic and environmental frame conditions will define the preference for one or the other plant type in each single case. In some cases, there may even be a combination of both systems to form a combined CSP/MED/RO plant, as this integration may allow for further synergies and efficiency gains, as suggested by /MEDRC 2001/. Most of the literature, and also the existing capacity shares on the global desalination market confirms that the technical and economic difference between RO and MED are relatively small and depend on the specific conditions at each site /Al-Sahali and Ettouny 2006/, /Younos and Tulou 2005/, /IDA 2006/. Both systems have advantages and drawbacks and will continue competing on the market.

Advanced future CSP/MED and CSP/RO plants will have additional features to reduce the environmental impacts of seawater intake, chemical additives and brine discharge, which will elevate the investment cost of the desalination units (Chapter 6.6). E.g. nano-filtration for the pre-treatment of feed water, which could avoid considerable part of the chemical additives for the protection of the desalination plants used today, would add about 200-250 €/m³/day to their investment /MEDRC 2001/. Other options for reducing impacts of intake and brine discharge discussed are horizontal drains using the seabed itself as filter (Chapter 6.5.2).

On the other hand, all desalination technologies show considerable technical learning effects, with considerable reductions of investment cost in the past years that are expected to continue, and also the solar collectors will become significantly cheaper with time, more than compensating the higher cost of additional measures for pollution control that will be indispensable for a large scale implementation in the MENA region.

As will be shown in the following chapters, the large demand for desalination plants in MENA will require the development of advanced, solar powered desalination systems with almost zero emissions to the air or to the water body. The technologies required for such systems are ready for the market. The development, design and demonstration of such plants should therefore start immediately, as will be described in Chapter 6.6.

Case		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Site		**Aqaba**	**Aqaba**	**Agadir**	**Agadir**	**Abu Dhabi**	**Abu Dhabi**	**Malta**	**Malta**	**Al Khawkha**	**Al Khawkh**	**Gaza**	**Gaza**	**Hurghada**	**Hurghada**
Seawater Temperature	°C	28	28	22	22	35	35	24	24	33	33	25	25	31	31
Ambient Temperature	°C	35	35	28	28	36	36	28	28	36	36	28	28	35	35
Relative Humidity		0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.8	0.8	0.6	0.6	0.5	0.5
Seawater Salinity	ppm	42000	42000	36500	36500	45000	45000	38000	38000	43000	43000	38000	38000	43000	43000
Atmospheric Pressure	bar	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Design Point DNI (June 21, 12:00)	W/m²	900	900	900	900	900	900	900	900	900	900	900	900	900	900
Latitude	°	29.8	29.8	30.5	30.5	24.4	24.4	35.8	35.8	13.8	13.8	31.2	31.2	27.2	27.2
Longitude	°	34	34	-9.5	-9.5	54.4	54.5	14.5	14.5	43.2	43.2	34.1	34.1	33.8	33.8
Desalination		**MED**	**RO**	**MED**	**RO**	**MED**	**RO**	**MED**	**RO**	**MED**	**RO**	**MED**	**RO**	**MED**	**RO**
Top Brine Temperature	°C	65	--	65	--	65	--	65	--	65	--	65	--	65	--
Number of Stages		12	--	12	--	10	--	12	--	10	--	12	--	12	--
GOR		10.4	--	10.4	--	8.6	--	10.4	--	8.6	--	10.4	--	10.4	--
Desalination Capacity	m³/day	24336	24336	24240	24240	24000	24000	24024	24024	24024	24024	23976	23976	24096	24096
Specific Heat Consumption	kWh/m³	61.4	--	61.3	--	74.3	--	61.3	--	74.2	--	61.4	--	61.4	--
Specific Electricity Consumption	kWh/m³	2.20	5.36	2.21	4.92	2.49	5.60	2.25	5.04	2.77	5.44	2.17	5.04	2.10	5.44
Feed Pump	MW	0.45	--	0.46	--	0.45	--	0.49	--	0.53	--	0.40	--	0.43	--
Cooling Pump	MW	0.73	--	0.72	--	0.84	--	0.72	--	0.86	--	0.71	--	0.72	--
Brine Pump	MW	0.12	--	0.11	--	0.11	--	0.12	--	0.14	--	0.09	--	0.10	--
Destillate Pump	MW	0.09	--	0.09	--	0.09	--	0.09	--	0.09	--	0.09	--	0.09	--
Intake	MW	0.14	--	0.13	--	0.13	--	0.13	--	0.15	--	0.11	--	0.12	--
Cooling Fans	MW	0.70	--	0.72	--	0.87	--	0.70	--	1.00	--	0.77	--	0.65	--
Total Electricity for Desalination	***MW***	***2.23***	***5.44***	***2.23***	***4.97***	***2.49***	***5.60***	***2.25***	***5.05***	***2.77***	***5.45***	***2.17***	***5.03***	***2.11***	***5.46***
Power Plant		**ST**	**ST**	**ST**	**ST**	**ST**	**ST**	**ST**	**ST**	**ST**	**ST**	**ST**	**ST**	**ST**	**ST**
Gross Electricity Generation	**MW**	**23.7**	**28.7**	**23.6**	**28.0**	**28.3**	**33.6**	**23.4**	**27.9**	**28.3**	**33.4**	**23.4**	**28.0**	**23.5**	**28.6**
Total Heat Consumption	**MW**	**87.2**	**94.2**	**86.9**	**89.7**	**104.0**	**111.0**	**86.0**	**89.9**	**104.0**	**111.8**	**85.9**	**89.2**	**86.3**	**93.3**
Cold End Temperature	°C	70	41.4	70	35.4	70	41.4	70	35.4	70	45.9	70	35.4	70	39.4
PB-Feed Pump Parasitics	MW	0.15	0.16	0.15	0.15	0.18	0.19	0.15	0.15	0.18	0.19	0.15	0.15	0.15	0.16
Combustion Parasitics	MW	0.07	0.07	0.07	0.06	0.08	0.09	0.07	0.07	0.09	0.09	0.07	0.07	0.07	0.07
Cooling Pump Parasitics	MW	--	0.73	--	0.68	--	0.85	--	0.69	--	0.87	--	0.69	--	0.72
Intake Pump Parasitics	MW	--	0.01	--	0.01	--	0.01	--	0.01	--	0.01	--	0.01	--	0.01
Cooling Fans Parasitics	MW	--	1.06	--	1.04	--	1.25	--	1.05	--	1.52	--	1.05	--	0.96
PB Total Parasitics	***MW***	***0.22***	***2.03***	***0.22***	***1.94***	***0.26***	***2.39***	***0.22***	***1.97***	***0.27***	***2.68***	***0.22***	***1.97***	***0.22***	***1.92***
Solar Field		**Fresnel**	**Fresnel**	**Fresnel**	**Fresnel**	**Fresnel**	**Fresnel**	**Fresnel**	**Fresnel**	**Fresnel**	**Fresnel**	**Fresnel**	**Fresnel**	**Fresnel**	**Fresnel**
SF Aperture Area	**m²**	**120000**	**131000**	**120000**	**125000**	**141000**	**152000**	**121000**	**128000**	**122500**	**144000**	**119000**	**125000**	**118000**	**129000**
Direct Irradiance on Aperture	W/m²	883	883	881	881	895	895	866	866	878	878	879	879	888	888
SF Thermal Energy	MW	67.5	73.7	67.2	70.3	80.5	86.8	66.6	70.5	80.5	87.3	66.5	69.9	66.8	73
Fossil Superheater	MW	19.7	20.5	19.7	19.4	23.5	24.2	19.4	19.4	23.5	24.5	19.4	19.3	19.5	20.3
SF Electric Parasitics	***MW***	***0.31***	***0.34***	***0.31***	***0.33***	***0.37***	***0.4***	***0.31***	***0.33***	***0.37***	***0.41***	***0.31***	***0.33***	***0.31***	***0.34***
SF Water Consumption	***m³/day***	***0.82***	***0.90***	***0.82***	***0.85***	***0.97***	***1.04***	***0.83***	***0.88***	***0.99***	***1.06***	***0.83***	***0.86***	***0.81***	***0.88***
Electricity to Grid	**MW**	**20.9**	**20.9**	**20.8**	**20.8**	**25.2**	**25.2**	**20.6**	**20.6**	**24.9**	**24.9**	**20.7**	**20.7**	**20.9**	**20.9**
Water to Grid	**m³/day**	**24335**	**24335**	**24239**	**24239**	**23999**	**23999**	**24023**	**24023**	**24023**	**24023**	**23975**	**23975**	**24095**	**24095**

Table 1-6: Technical performance of combined CSP, MED and RO plants for different sites in the MENA Region

1.3.2 Comparison of Economic Performance

Due to its better technical performance, CSP/MED requires a 10 % smaller collector field than CSP/RO. The substitution of the cooling system by the MED plant leads to a 10 % lower investment for the power block than in the case of CSP/RO. On the other hand, the investment needed for the MED plant is about 50 % higher than that of an equivalent RO plant. All in all, the total investment of CSP/MED is about 10 % higher than that of CSP/RO (Table 1-7).

Investment of CSP/RO Plants		**Investment of CSP/MED Plants**	
Solar Collector Field	**27.9 M€**	**Solar Collector Field**	**25.7 M€**
Land and Civil Works	1.3 M€	Land and Civil Works	1.2 M€
Mechanical Structures	4.1 M€	Mechanical Structures	3.8 M€
Reflector Boxes	6.3 M€	Reflector Boxes	5.8 M€
Absorber and Piping	6.5 M€	Absorber and Piping	6.0 M€
Electricity Supply	1.4 M€	Electricity Supply	1.3 M€
Instrumentation & Control	0.9 M€	Instrumentation & Control	0.9 M€
Solar Field Superheater (Gas)	0.6 M€	Solar Field Superheater (Gas)	0.5 M€
Materials & Work	3.7 M€	Materials & Work	3.4 M€
Freight & Transport	0.8 M€	Freight & Transport	0.8 M€
Contingencies	2.2 M€	Contingencies	2.1 M€
Power Block	**23.6 M€**	**Power Block**	**21.5** M€
Turbine & Generator	8.5 M€	Turbine & Generator	8.5 M€
Electric System	1.2 M€	Electric System	1.2 M€
Cooling System	1.5 M€	Cooling System	M€
Water Treatment	0.1 M€	Water Treatment	M€
Steam Boiler (Gas)	1.8 M€	Steam Boiler (Gas)	1.8 M€
Fuel System (Gas)	0.4 M€	Fuel System (Gas)	0.4 M€
Flue Gas Treatment	1.1 M€	Flue Gas Treatment	1.1 M€
Instrumentation & Control	0.8 M€	Instrumentation & Control	0.8 M€
Connection to Grid	1.1 M€	Connection to Grid	1.1 M€
Materials & Work	4.5 M€	Materials & Work	4.3 M€
Freight & Transport	0.7 M€	Freight & Transport	0.6 M€
Contingencies	1.9 M€	Contingencies	1.7 M€
RO Plant (multi-pass)	**24.9 M€**	**Multi-Effect Desalination Plant**	**37.7 M€**
Intake (beachwell)	2.2 M€	Intake (beachwell)	2.2 M€
Pre-Treatment	5.4 M€	Pre-Treatment	1.5 M€
Pumps & Engines	2.1 M€	Heat Exchangers	8.1 M€
Pressure Tubes	2.3 M€	Shells	7.9 M€
RO Membranes	2.5 M€	Pumping	1.8 M€
Post-Treatment	1.1 M€	Instrumentation & Control	1.1 M€
Instrumentation & Control	1.1 M€	Post-Treatment	0.5 M€
Energy Recovery Unit	2.0 M€	Cooling System	1.1 M€
Brine and Backwash Treatment	0.0 M€	Materials & Work	9.5 M€
Materials & Work	3.6 M€	Freight & Transport	1.1 M€
Freight & Transport	0.7 M€	Brine Treatment	0 M€
Contingencies	1.9 M€	Contingencies	2.9 M€
CSP/RO Total Investment	**76.4 M€**	**CSP/MED Total Investment**	**84.9 M€**

Table 1-7: Investment of the system components of CSP/RO and CSP/MED, Status 2007 using linear Fresnel technology, solar field 120,000 m² (MED), 130,000 m² (RO), gross power 25 MW, desalination 24,000 m³/d

The long-term economic performance of both reference plants has been modelled for a site with a solar irradiance of 2400 kWh/y and a seawater salinity of 40,000 ppm. Under these conditions, both reference plants achieve an annual solar share of about 19 % using a solar field that is designed to provide nominal power capacity without thermal energy storage. The solar field size has been varied in four steps equivalent to one unit design solar field and storage has been added in steps of 6 full load operating hours until reaching a solar share of 75 % (Table 1-8).

The annual capital cost is calculated from a real discount rate of 5 % and an economic plant life of 25 years, which defines an annual fixed charge rate (annuity) of 7.1 %.

Further annual cost items are given by the operation and maintenance cost which is assumed in the order of 2 % of the investment and the annual insurance cost equivalent to 1 % of the investment per year for both plant types.

The plants are operated in hybrid solar/fossil mode with additional fuel input of natural gas. The average life-cycle fuel cost has been assumed to be 25 €/MWh. Fuel consumption and the related annual cost depends on the annual solar share that varies with the size and investment of the solar field and thermal energy storage, with present costs used for the calculation.

Finally, replacement of membranes for reverse osmosis is assumed to take place every five years, adding 20 % of the initial membrane investment to the annual operation cost of the CSP/RO system.

The economic performance of the combined generation of electricity and desalted water was compared by fixing the sales price for electricity at 0.07 €/kWh which would be the production cost of a gas-fired combined cycle power station and subtracting the resulting annual electricity revenue from the total annual expenditure. The remaining annual cost was charged to the annual desalted water production, yielding the average cost per cubic meter of desalted water, which resulted to be in the range of 1.55 – 1.85 €/m^3.

In all cases the CSP/MED configuration shows a slightly lower cost of water than CSP/RO. Due to the better technical performance of the CSP/MED system, fuel consumption is about 10 % lower than that of CSP/RO. To this adds the necessary replacement of RO membranes every five years. These cost items make up for a slightly better economic performance of the CSP/MED system, in spite of its higher initial investment cost.

Again, this result is contrary to the commonly presumed statement that RO is cheaper than MED. Although this may be true in terms of investment, in the case of a combined CSP/desalination plant, the overall result is opposite, although the difference in cost among both systems is not very large. Therefore, we believe that only in-depth, project-wise analysis of technical and economical performance can lead to a well-founded decision for the one or the other technical configuration of the most appropriate CSP-desalination system, and competition will define the shares of the different existing options in the future desalination market.

Economic Parameters	**Unit**	**CSP/RO**	**CSP/MED**	**CSP/RO**	**CSP/MED**	**CSP/RO**	**CSP/MED**	**CSP/RO**	**CSP/MED**
Design Power Capacity	MW	21	21	21	21	21	21	21	21
Design Desalination Capacity	m³/d	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000
Investment	M€	76.4	84.9	110.6	117.0	151.1	155.3	197.9	200.0
Interest Rate	%	5%	5%	5%	5%	5%	5%	5%	5%
Economic Life	years	25	25	25	25	25	25	25	25
Fixed Charge Rate	%/y	7.1%	7.1%	7.1%	7.1%	7.1%	7.1%	7.1%	7.1%
Specific Storage Cost	€/kWh	50	50	50	50	50	50	50	50
Storage Capacity	h	0	0	6	6	12	12	18	18
Solar Field Size	m²	130,000	120,000	260,000	240,000	390,000	360,000	520,000	480,000
Annual O&M Rate	%/y	2%	2%	2%	2%	2%	2%	2%	2%
Annual Insurance Rate	%/y	1%	1%	1%	1%	1%	1%	1%	1%
Annual Solar Irradiance	kWh/m²/y	2400	2400	2400	2400	2400	2400	2400	2400
Annual Solar Share	%	19.0%	19.0%	38.0%	38.0%	57.0%	57.0%	76.0%	76.0%
Annual Water Production	m³/y	7,446,000	7,446,000	7,446,000	7,446,000	7,446,000	7,446,000	7,446,000	7,446,000
Annual Power Generation	GWh/y	156.4	156.4	156.4	156.4	156.4	156.4	156.4	156.4
Annual Heat Consumption	GWh/y	704.9	651.2	704.9	651.2	704.9	651.2	704.9	651.2
Annual Fuel Consumption	GWh/y	571.0	527.4	437.1	403.7	303.1	280.0	169.2	156.3
Annual Solar Heat	GWh/y	133.9	123.7	267.9	247.4	401.8	371.2	535.8	494.9
Life Cycle Fuel Cost	€/MWh	25	25	25	25	25	25	25	25
Annual Plant Cost	**M€/y**	**22.49**	**21.76**	**22.59**	**21.90**	**23.33**	**22.68**	**24.70**	**24.10**
Annual Capital Cost	M€/y	5.42	6.03	7.85	8.30	10.72	11.02	14.04	14.19
Annual O&M Cost	M€/y	1.53	1.70	2.21	2.34	3.02	3.11	3.96	4.00
Membranes (5 years replacement)	M€/y	0.50		0.50		0.50		0.50	
Annual Insurance Cost	M€/y	0.76	0.85	1.11	1.17	1.51	1.55	1.98	2.00
Annual Fuel Cost	M€/y	14.28	13.19	10.93	10.09	7.58	7.00	4.23	3.91
Electricity Revenue (pre-set)	**€/kWh**	**0.070**	**0.070**	**0.070**	**0.070**	**0.070**	**0.070**	**0.070**	**0.070**
Annual Electricity Revenue	**M€/y**	**10.95**	**10.95**	**10.95**	**10.95**	**10.95**	**10.95**	**10.95**	**10.95**
Cost of Water	**€/m³**	**1.55**	**1.45**	**1.56**	**1.47**	**1.66**	**1.58**	**1.85**	**1.77**

Table 1-8: Annual cost calculation and product cost calculation for electricity and water for the CSP/RO and CSP/MED reference plants, taking into account different solar shares and solar field sizes, Status 2007

Economic Parameters	**Unit**	**CSP/RO**	**CSP/MED**	**CSP/RO**	**CSP/MED**	**CSP/RO**	**CSP/MED**	**CSP/RO**	**CSP/MED**
Design Power Capacity	MW	21	21	21	21	21	21	21	21
Design Desalination Capacity	m³/d	24,000	24,000	24,000	24,000	24,000	24,000	24,000	24,000
Investment	M€	56.2	59.6	72.8	75.1	91.6	92.8	112.7	112.8
Interest Rate	%	5%	5%	5%	5%	5%	5%	5%	5%
Economic Life	years	25	25	25	25	25	25	25	25
Fixed Charge Rate	%/y	7.1%	7.1%	7.1%	7.1%	7.1%	7.1%	7.1%	7.1%
Specific Storage Cost	€/kWh	18	18	18	18	18	18	18	18
Storage Capacity	h	0	0	6	6	12	12	18	18
Solar Field Size	m²	130,000	120,000	260,000	240,000	390,000	360,000	520,000	480,000
Annual O&M Rate	%/y	2%	2%	2%	2%	2%	2%	2%	2%
Annual Insurance Rate	%/y	1%	1%	1%	1%	1%	1%	1%	1%
Annual Solar Irradiance	kWh/m²/y	2400	2400	2400	2400	2400	2400	2400	2400
Annual Solar Share	%	25%	25%	45%	45%	70%	70%	95%	95%
Annual Water Production	m³/y	7,446,000	7,446,000	7,446,000	7,446,000	7,446,000	7,446,000	7,446,000	7,446,000
Annual Power Generation	GWh/y	156.4	156.4	156.4	156.4	156.4	156.4	156.4	156.4
Annual Heat Consumption	GWh/y	704.9	651.2	704.9	651.2	704.9	651.2	704.9	651.2
Annual Fuel Consumption	GWh/y	528.7	488.4	387.7	358.1	211.5	195.3	35.2	32.6
Annual Solar Heat	GWh/y	176.2	162.8	317.2	293.0	493.5	455.8	669.7	618.6
Life Cycle Fuel Cost	€/MWh	29.0	29.0	29.0	29.0	29.0	29.0	29.0	29.0
Annual Plant Cost	**M€/y**	**21.51**	**20.18**	**19.09**	**17.97**	**15.88**	**15.04**	**12.90**	**12.33**
Annual Capital Cost	M€/y	3.99	4.23	5.16	5.33	6.50	6.59	8.00	8.01
Annual O&M Cost	M€/y	1.12	1.19	1.46	1.50	1.83	1.86	2.25	2.26
Membranes (5 years replacement)	M€/y	0.50		0.50		0.50		0.50	
Annual Insurance Cost	M€/y	0.56	0.60	0.73	0.75	0.92	0.93	1.13	1.13
Annual Fuel Cost	M€/y	15.33	14.16	11.24	10.39	6.13	5.67	1.02	0.94
Electricity Revenue (pre-set)	**€/kWh**	**0.070**	**0.070**	**0.070**	**0.070**	**0.070**	**0.070**	**0.070**	**0.070**
Annual Electricity Revenue	**M€/y**	**10.95**	**10.95**	**10.95**	**10.95**	**10.95**	**10.95**	**10.95**	**10.95**
Cost of Water	**€/m³**	**1.42**	**1.24**	**1.09**	**0.94**	**0.66**	**0.55**	**0.26**	**0.19**

Table 1-9: Annual cost calculation and product cost calculation for electricity and water for the CSP/RO and CSP/MED reference plants, taking into account different solar shares and solar field sizes, Status 2020

In our analysis, we have taken into consideration relatively high lifetime cost of fuel of 25 €/MWh and the present cost of solar collector fields of around 215 €/m². Also we have taken into consideration a relatively high investment cost of MED plants of around 1600 €/m³/d due to recently increasing costs of the required raw materials copper and steel on the world market.

The resulting cost of water of around 1.55-1.85 €/m³ is relatively high if compared to cost of desalted water taken from literature, although it is still in the range of reported values. Cost of water from MED and RO is reported to be in the range of 0.40-2.00 €/m³, which represents a large variety of sites, sea- and product water qualities and economic frame conditions /Kaldellis and Kondili 2007/, /Al-Sahali and Ettouny 2007/, /DME 2007/, /Quteishat 2006/, /Abu Arabi 2005/, /Ashur and Ghurbal 2004/, /Miller 2003/, /Andrianne and Alardin 2002/. Most of the quoted references calculate with rather favourable economic assumptions in terms of fuel cost and investment that were a reality in early 2000, but have considerably changed since then. According to /World Bank 2007/, typical desalination cost quotations have changed from 0.4-0.6 €/m³ some years ago to a present level of 0.6-0.8 €/m³. The assessment of future economic frame conditions is a matter of predicting cost of fuels and materials, and how increasing costs can be compensated in the future by additional efficiency and learning. Although in the past there was a clear trend to decreasing cost of seawater desalination due to technological innovation and learning, there may be seen further increasing costs in the future due to rising fuel prices on the world market.

The analysis of costs looks very different when taking into account the learning curve of CSP until 2020 (Table 1-9). At that time, specific collector costs will have come down to about 110 €/m², the power block will be better adapted to the solar field saving around 150 €/kW, RO will cost 900 €/m³/d including enhanced measures for environmental protection, and MED will have a cost around 1150 €/m³/d due to increasing global production capacities of copper and steel. Due to efficiency gains of the solar field the solar share of the reference plant will increase to 25 % without thermal storage and to 95 % using full scale storage capacity. Lifetime fuel cost will have increased to 29 €/MWh. Revenues from electricity sales are again assumed to be constant around 0.07 €/kWh, which may be a rather conservative guess. Under those conditions, the cost of water comes down to 1.24-1.42 €/m³ for CSP desalination without thermal storage. This cost is still rather high, which is due to the high fossil share of 75 % and the high cost of fossil fuel that has increased to 29 €/MWh. However, increasing the solar share to 95 % with full storage capacity, water prices will now be as low as 0.19-0.26 €/m³, becoming competitive even for irrigation (also refer to Chapter 5).

We can conclude that depending on specific site conditions and future development, CSP for desalination can already be – as in the case of niche applications like the Aqaba Solar Water Project – or soon become a cost-competitive solution for sustainable desalination of seawater in the MENA and similar regions world-wide, if investments into this technology are started now.

1.4 Concentrating Solar Power for Small Scale Seawater Desalination

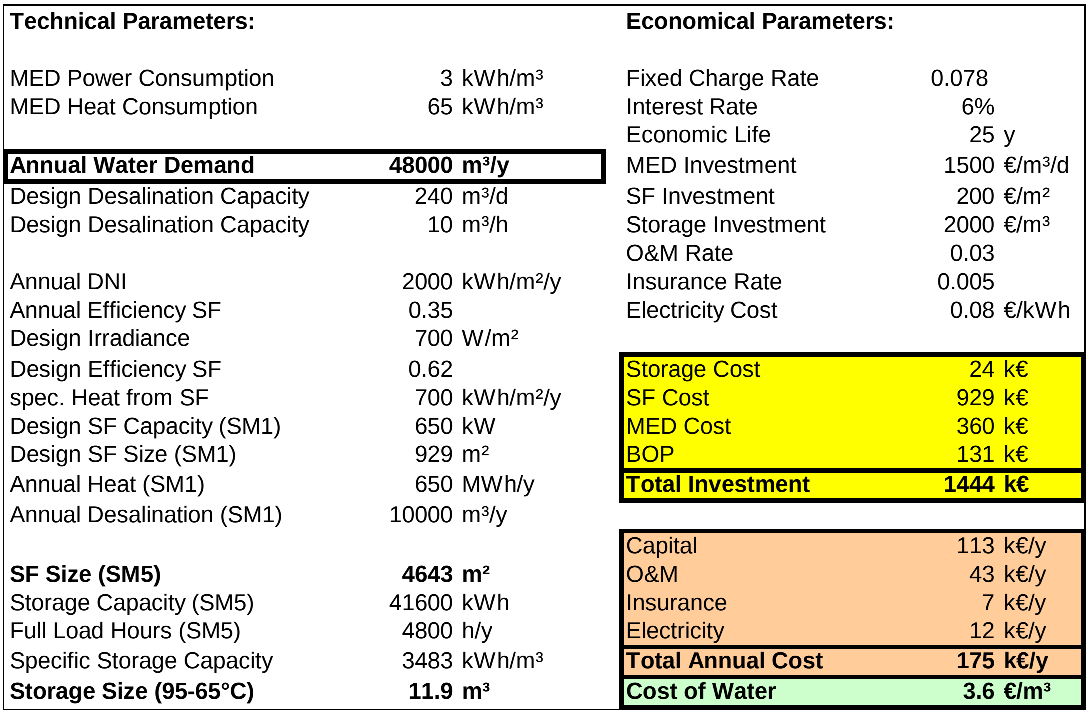
The configurations shown in Figure 1-29 can also be applied to small-scale seawater desalination systems in a capacity range below 1 MW or 1000 m³/day, respectively. There are cases for directly applying heat from parabolic troughs or linear Fresnel collector fields to thermal MED desalination (Figure 1-29, left), or to realise small scale co-generation systems in the 10 kW range using parabolic-dish-Stirling engines (Figure 1-31).

An important issue for small systems is the usual up-scaling of specific system costs when downscaling the size of the collector fields. Conventional parabolic troughs or central receivers will hardly be competitive when they are scaled down to units smaller than 1 MW. In this market segment, CSP will have to compete with PV- and wind-powered RO-systems and with non-concentrating solar thermal collector systems /Zejli et al. 2002/.

However, low-temperature parabolic trough and linear Fresnel systems are likely to be competitive in this market segment, as they offer low cost and a unique possibility of energy storage by hot water at temperatures below 100 °C. Considerable amounts of energy (35 kWh/m³) can be stored in hot water in the temperature range between the maximum storage temperature of e.g. 95 °C and the operating temperature of an MED plant of e.g. 65 °C. It may be feasible to directly heat and store incoming seawater for later processing in hours without sunshine. Thus, fluctuating solar energy input would not affect continuous operation of the desalination plant. Small part of the solar collector field or a different source could be used to provide the relatively small amounts of electricity required by MED.

Figure 1-31: Left: Low-temperature parabolic trough for direct steam generation from SOLITEM, center: linear Fresnel from NOVATEC-Biosol, right: Dish-Stirling engine from Schlaich, Bergermann & Partner

There is a considerable market for small-scale solar systems for seawater and brackish water desalination in remote urban and in agricultural areas (Chapter 3). In order to apply these technologies to rural development, their technical and economic feasibility must be assessed for specific sites and applications, and pilot plants must be build to demonstrate reliability of system operation. An overview of present activities is given in /Rizzuti et al 2007/, /Delyannis and Stefanakos 2003/, /Quteishat and Abu-Arabi 2004/, /EasyMED 2007/.



Technical Parameters:			**Economical Parameters:**		
MED Power Consumption	3	kWh/m^3	Fixed Charge Rate	0.078	
MED Heat Consumption	65	kWh/m^3	Interest Rate	6%	
			Economic Life	25	y
Annual Water Demand	**48000**	**m^3/y**	MED Investment	1500	€/m^3/d
Design Desalination Capacity	240	m^3/d	SF Investment	200	€/m^2
Design Desalination Capacity	10	m^3/h	Storage Investment	2000	€/m^3
			O&M Rate	0.03	
Annual DNI	2000	kWh/m^2/y	Insurance Rate	0.005	
Annual Efficiency SF	0.35		Electricity Cost	0.08	€/kWh
Design Irradiance	700	W/m^2			
Design Efficiency SF	0.62		Storage Cost	24	k€
spec. Heat from SF	700	kWh/m^2/y	SF Cost	929	k€
Design SF Capacity (SM1)	650	kW	MED Cost	360	k€
Design SF Size (SM1)	929	m^2	BOP	131	k€
Annual Heat (SM1)	650	MWh/y	**Total Investment**	**1444**	**k€**
Annual Desalination (SM1)	10000	m^3/y			
			Capital	113	k€/y
SF Size (SM5)	**4643**	**m^2**	O&M	43	k€/y
Storage Capacity (SM5)	41600	kWh	Insurance	7	k€/y
Full Load Hours (SM5)	4800	h/y	Electricity	12	k€/y
Specific Storage Capacity	3483	kWh/m^3	**Total Annual Cost**	**175**	**k€/y**
Storage Size (95-65°C)	**11.9**	**m^3**	**Cost of Water**	**3.6**	**€/m^3**

Table 1-10: Performance and cost calculation of a small-size CSP/MED system for the Aegean Sea

As an example, in the Cyclades and Dodecanese islands in the Aegean Sea, about 1 million m^3 per year of freshwater is supplied by transport from the Greek mainland at a cost of 5-7 €/m^3 /Kaldellis and Kondoli 2007/. A concentrating solar collector field producing heat for a thermal multi-effect desalination plant and taking the electricity required for pumping from the grid (Figure 1-29, left) would be able to generate water at a cost of about 3-4 €/m^3 (Table 1-10), which would lead to a considerable reduction of costs and environmental impacts in this sector. Also, PV and wind power would be available for desalination, as described by /Kaldellis and Kondoli 2007/, however, only CSP/MED would provide a reliable, continuous solar operation during the main tourist-season, where most water is required, making use of the very low cost option of storing hot water for night-time operation of the desalination plant.

The above analysis in Table 1-10 is based on a very rough analysis of the situation and on rather conservative assumptions for plant performance and costing. Future cost reduction will make small scale desalination systems based on all kinds of renewable energy sources a key to freshwater supply on the islands of the Mediterranean, Atlantic, Red Sea and the Arabian Gulf.

The example shows that at least in the Aegean Sea, seawater desalination by renewable energy from concentrating solar power systems seems to be already a competitive and sustainable option for freshwater supply.