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Combined Solar Power and Desalination Plants: Techno-Economic Potential in Mediterranean Partner Countries

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WP1: Technology Review and Selection of CSP and Desalination Configurations adapted for Application in the Southern and Eastern Mediterranean Region

Final Report

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TABLE OF CONTENTS

1 INTRODUCTION

The first work package of the MED-CSD project gives an update on knowledge obtained from recent studies and on CSP and desalination technology as by status of March 2009. The report was delayed for some months with respect to its initial schedule in order to include as much as possible of the dynamic development of CSP industry during the year 2008.

Many new technology providers, project developers and other stakeholders from industry, policy and finance have appeared, and the economic framework conditions are quickly changing due to the global financial crisis.

On one side, investors are more careful and try to introduce the concept of sustainability also to the investment sector, and the prices for steel and other materials required for the installations have strongly decreased, on the other hand fuel prices have also dramatically decreased compared to their climax in summer 2008.

Chapter 2 gives an overview of recent studies on CSP desalination AQUA-CSP (DLR) and Aqaba Solar Water (kernenergien).

Chapter 3 shows CSP principles and gives an overview on concentrating solar power technologies for steam turbines and for gas turbines including recent project developments in Europe and other parts of the world. Finally it gives an update on CSP industry and other stakeholders as scheduled for Task 1.

Chapter 4 gives a review on seawater desalination technology and industry and summarizes recent achievements in this sector as scheduled for Task 2.

Chapter 5 shows several possibilities of integrating CSP and desalination technologies and gives first preliminary recommendations for the MED-CSD process as scheduled for Task 3.

2 STATUS OF KNOWLEDGE - RESULTS FROM RECENT STUDIES

2.1 AQUA-CSP Study

The AQUA-CSP study has analysed the potential of concentrating solar thermal power technology for large scale seawater desalination for the urban centres in the Middle East and North Africa (MENA). It provides a comprehensive data base on technology options, water demand, reserves and deficits and derives the short-, medium- and long-term markets for solar powered desalination of twenty countries in the region. The study gives a first information base for a political framework that is required for the initiation and realisation of such a scheme. It quantifies the available solar energy resources and the expected cost of solar energy and desalted water, a long-term scenario of integration into the water sector, and quantifies the environmental and socio-economic impacts of a broad dissemination of this concept. There are several good reasons for the implementation of large-scale concentrating solar powered desalination systems that have been identified within the AQUA-CSP study at hand:

- Due to energy storage and hybrid operation with (bio)fuel, concentrating solar power plants can provide around-the-clock firm capacity that is suitable for large scale desalination either by thermal or membrane processes,
- CSP desalination plants can be realised in very large units up to several 100,000 m³/day,
- huge solar energy potentials of MENA can easily produce the energy necessary to avoid the threatening freshwater deficit that would otherwise grow from today 50 billion cubic metres per year to about 150 billion cubic metres per year by 2050.
- within two decades, energy from solar thermal power plants will become the least cost option for electricity (below 4 ct/kWh) and desalted water (below 0.4 €/m³),
- management and efficient use of water, enhanced distribution and irrigation systems, re-use of wastewater and better accountability are important measures for sustainability, but will only be able to avoid about 50 % of the long-term deficit of the MENA region,
- combining efficient use of water and large-scale solar desalination, over-exploitation of groundwater in the MENA region can – and must – be ended around 2030,

- advanced solar powered desalination with horizontal drain seabed-intake and nano-filtration will avoid most environmental impacts from desalination occurring today,
- with support from Europe the MENA countries should immediately start to establish favourable political and legal frame conditions for the market introduction of concentrating solar power technology for electricity and seawater desalination.

The AQUA-CSP study shows a sustainable solution to the threatening water crisis in the MENA region, and describes a way to achieve a balanced, affordable and secure water supply structure for the next generation, which has been overlooked by most contemporary strategic analysis.

Chapter 1 (Technology Review) gives a review of the present state of the art of desalination and of concentrating solar power technologies, and shows the main options for a combination of both technologies for large scale solar powered seawater desalination.

Three different technical mainstreams were addressed (Figure 2-1): small-scale decentralised desalination plants directly powered by concentrating solar thermal collectors, concentrating solar power stations providing electricity for reverse osmosis membrane desalination (CSP/RO), and combined generation of electricity and heat for thermal multi-effect desalination systems (CSP/MED). Multi-Stage Flash (MSF) desalination, although at present providing the core of desalted water in the MENA region, has not been considered as viable future option for solar powered desalination, due to the high energy consumption of the MSF process.

Reference systems for CSP/RO and for CSP/MED were defined with 24,000 cubic metres per day of desalting capacity and 21 MW net electricity to consumers. An annual hourly time-step simulation for both plant types was made for seven different sites in the MENA region from the Atlantic Ocean to the Gulf Region in order to compare their technical and economic performance under different environmental conditions.

Both systems have the medium-term potential to achieve base-load operation with less than 5 % of fuel consumption of conventional plants, at a cost of water well below 0.3 €/m³. Today, such integrated plants have been found to be already competitive in some niche markets, like e.g. on-site generation of power and water for very large consumers like hotel resorts or industry.

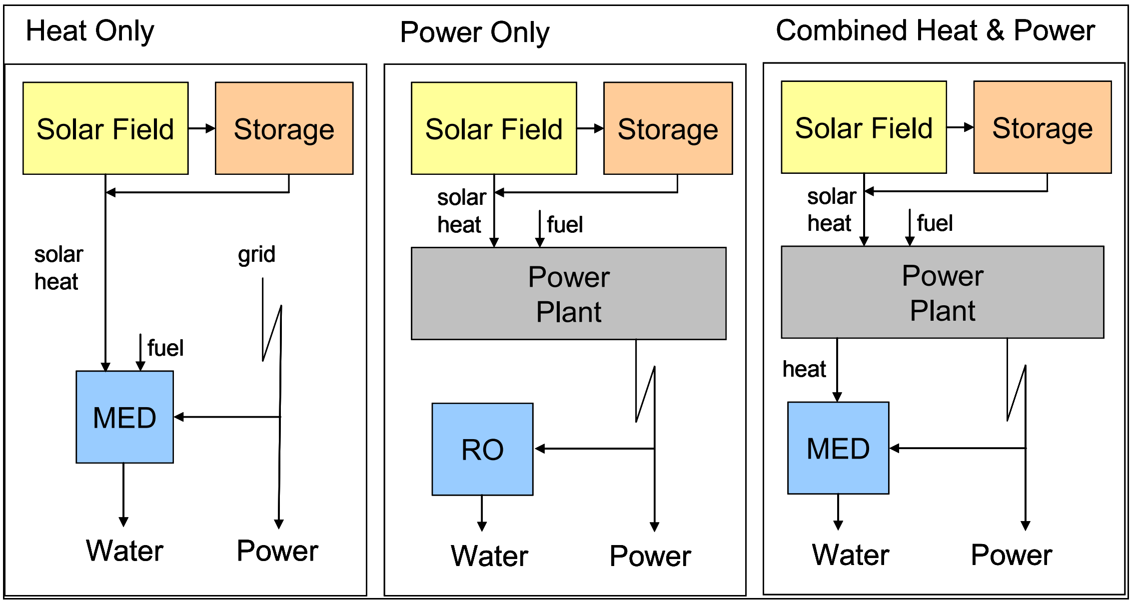


Figure 2-1: Different configurations for desalination by concentrated solar power. Left: Concentrating solar collector field with thermal energy storage directly producing heat for thermal multi-effect desalination. Center: Power generation for reverse osmosis (CSP/RO). Right: Combined generation of electricity and heat for multi-effect desalination (CSP/MED).

Chapter 2 (Natural Water Resources) quantifies the natural renewable and exploitable resources of freshwater in the twenty analysed countries of the MENA region. To date only four countries have renewable freshwater resources that are well above the threshold of 1000 cubic metres per capita and per year that is commonly considered as demarcation line of water poverty (Figure 2-2). With a population expected to be doubling until 2050, the MENA region would be facing a serious water crisis, if it would remain relying only on the available natural renewable freshwater resources.

Internal renewable freshwater resources are generated by endogenous precipitation that feeds surface flow of rivers and recharge of groundwater. External sources from rivers and groundwater from outside a country can also have major shares as e.g. the Nile flowing into Egypt. The exploitable share of those water resources may be limited by very difficult access or by environmental constraints that enforce their protection.

Non-renewable sources like the large fossil groundwater reservoirs beneath the Sahara desert can also be partially exploited, if a reasonable time-span to serve several generations (e.g. 500 years) is assured. However, their excessive use has already triggered significant environmental impacts, like the reduction of the groundwater level and several oases falling dry. Additional measures like re-use of waste water, advanced irrigation, better management and accountability, improved distribution systems and new, unconventional sources of water like the desalination of seawater will therefore be imperative to avoid a foreseeable collapse of water supply in the MENA region.

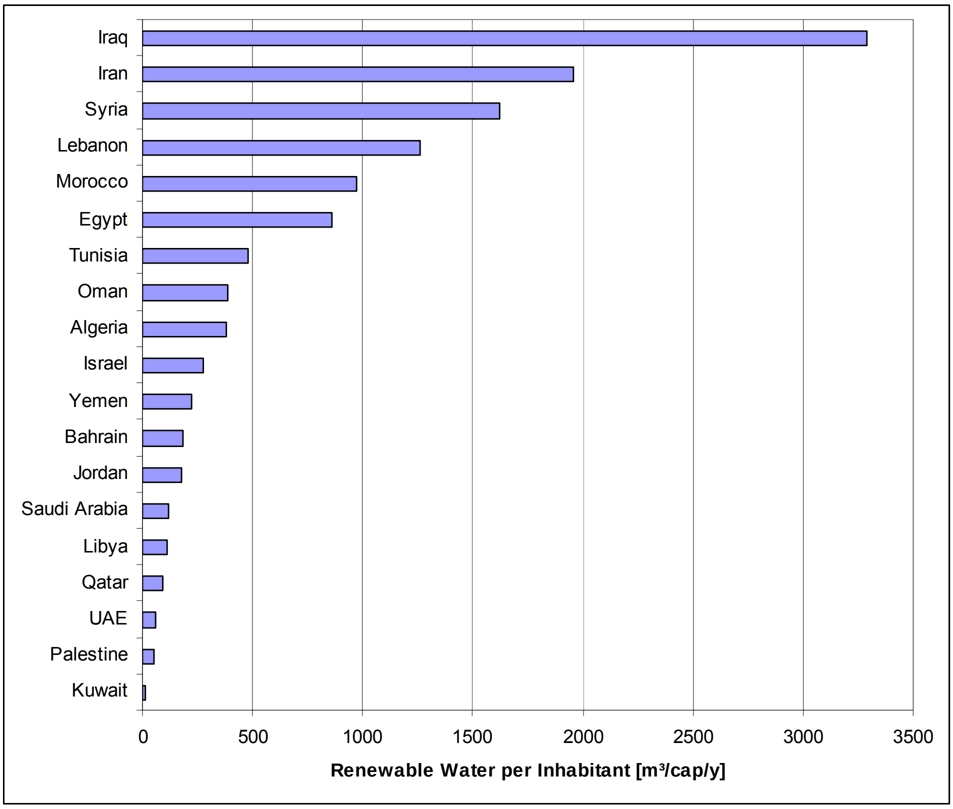


Figure 2-2: Total available natural renewable freshwater sources available per capita in the MENA region of the year 2000. Only four countries are beyond the water poverty threshold of 1000 m³/cap/y.

Chapter 3 (Water Demand and Deficits) provides a long-term scenario of freshwater demand for all MENA countries and quantifies the increasing gap opening between natural renewable reserves and water demand until 2050. Freshwater demand is calculated as function of a growing population and economy starting in the year 2000 and taking into consideration different driving forces for industrial and municipal demand on one site and for agriculture on the other site, that yield a steadily growing freshwater demand in all MENA countries.

Today, agriculture is responsible for 85 % of the freshwater consumption in MENA, a number that is expected to change to 65 % by 2050, because the industrial and municipal sectors will gain increasing importance. In our reference scenario, the total water consumption of the MENA region will grow from 270 billion cubic metres per year in the year 2000 to about 460 billion cubic metres per year in 2050 (Figure 2-3).

Water deficits that are presently covered by over-exploitation of groundwater and – to a lesser extent – by fossil-fuelled desalination, would increase from 50 billion cubic metres per year to 150 billion cubic metres per year, which would equal about twice the physical volume of the Nile River. The AQUA-CSP reference scenario already considers significant enhancement of efficiency of end-use, management and distribution of water, advanced irrigation systems and re-use of waste-water.

In a business-as-usual-scenario following present policies with less emphasis on efficiency consumption would grow much further – theoretically, because this will not be possible in reality – to 570 billion cubic metres per year in 2050, resulting in a deficit of 235 billion cubic metres per year that would put an extraordinary – and unbearable – load on the MENA groundwater resources.

On the other hand, a scenario built on extreme advances in efficiency and re-use of water would lead to a demand of 390 billion cubic metres per year, but would still yield a deficit of 100 billion cubic metres per year, which could only be covered by new, unconventional sources.

The results of our demand side assessment have been compared to several analysis from the literature, that unfortunately do not cover consistently all countries and water supply sectors of the MENA region, and that do not look beyond the year 2030. However, the time span and sectors that could be compared show a fairly good co-incidence of our results with the general state of the art.

Our analysis shows clearly that measures to increase efficiency of water use and distribution are vital for the region, but insufficient to cover the growing demand in a sustainable way. The situation in MENA after 2020 will become unbearable, if adequate counter measures are not initiated in good time. The use of new, unconventional sources of freshwater will be imperative, and seawater desalination powered by concentrated solar energy is the only already visible option that can seriously cope with the magnitude of that challenge.

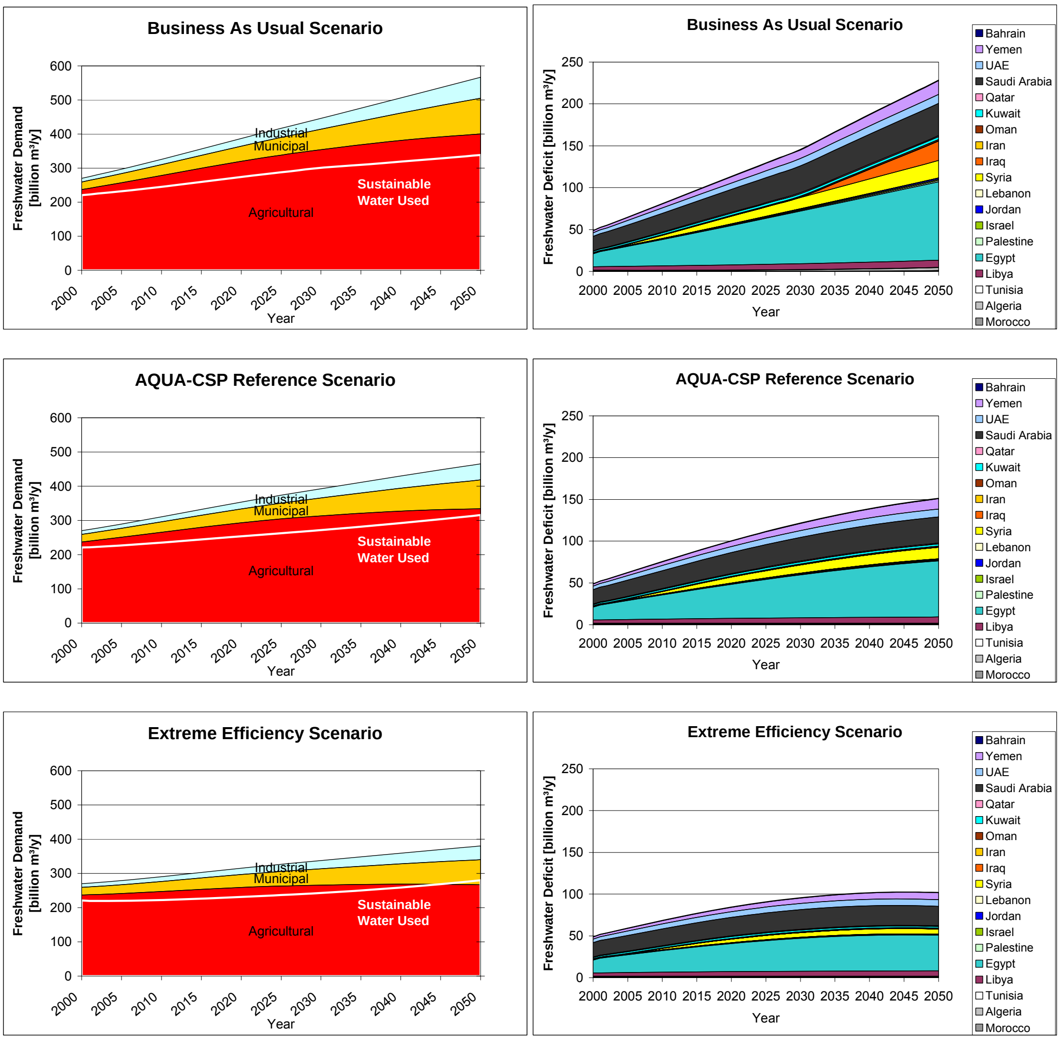


Figure 2-3: Results of the model calculation with minimum (top), reference (centre) and maximum (bottom) measures to increase the efficiency of water use, water distribution and irrigation and the re-use of waste-water for all MENA countries (data for individual countries is given in the annex of the main report)

Chapter 4 (Seawater Desalination Markets) describes the market potential of solar powered seawater desalination between the year 2000 and 2050. The CSP-desalination market has been assessed on a year-by-year basis in a scenario that also considers other sources of water, the natural renewable surface- and groundwater resources, fossil groundwater, conventionally desalted water, re-use of waste water and measures to increase the efficiency of water distribution and end-use. The analysis confirms the economic potential of CSP-desalination to be large enough to solve the threatening MENA water crisis. On the other hand, it shows that the process to substitute the presently unsustainable over-use of groundwater by solar powered desalination will take until 2025 to become visible (Figure 2-4).

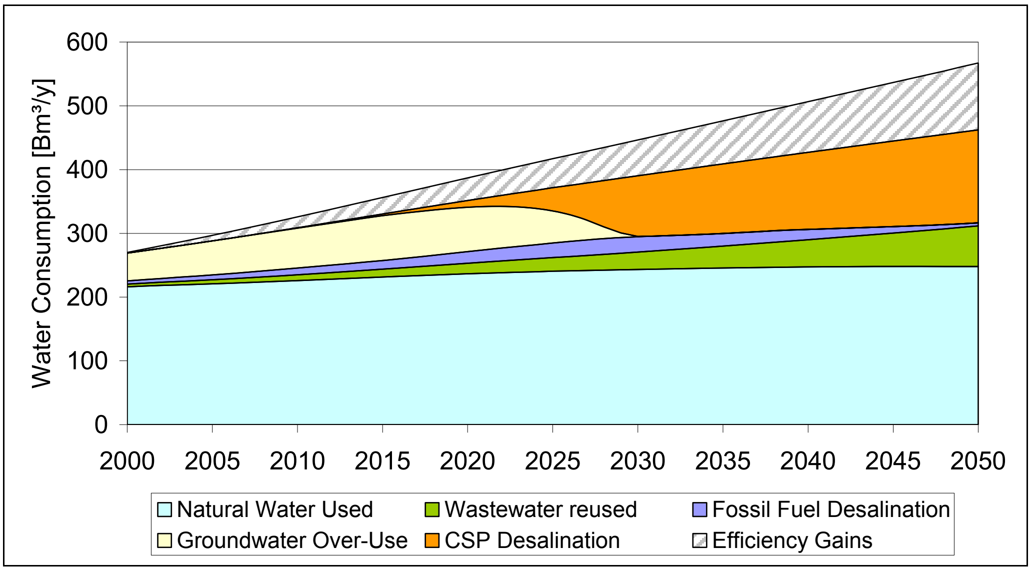


Figure 2-4: Water demand scenario for MENA until 2050 and coverage of demand by sustainable sources, by unsustainable sources and by solar desalination. (shaded: efficiency gains with respect to business as usual)

The total elimination of groundwater over-use will at the best take until 2035 to become accomplished. Over-use will increase from 44 billion cubic metres per year in 2000 to a maximum of 70 billion cubic metres per year in 2020, before it can be subsequently replaced by large amounts of freshwater from solar powered desalination. There is strong evidence that in some regions the available groundwater resources may collapse under the increasing pressure before sustainability is achieved. In those cases, a strong pressure will also remain on fossil fuelled desalination, which will grow to five times the present capacity by 2030.

The industrial capability of expanding the production capacities of concentrating solar power will be the main limiting factor until about 2020, because CSP is today starting as a young, still small industry that will require about 15-20 years of strong growth to become a world market player. MENA governments would therefore be wise to immediately start market introduction of this technology without any delay, as their natural resources may not last long enough until a sustainable supply is achieved.

The largest medium-term market volumes for CSP-desalination until 2020 were found in Egypt (3.6 Bm^3/y), Saudi Arabia (3.4 Bm^3/y), Libya (0.75 Bm^3/y), Syria (0.54 Bm^3/y), and Yemen (0.53 Bm^3/y). All MENA countries together have a total market volume of 10.5 Bm^3/y until 2020, and 145 Bm^3/y until 2050. They will require a decided policy to introduce the technology to their national supply structure and to achieve the necessary market shares in good time.

North Africa		2000	2010	2020	2030	2040	2050
Population	Million	141.9	167.3	192.8	214.5	231.9	244.3
Exploitable Water	Bm³/y	81.8	81.8	81.8	81.8	81.8	81.8
Sustainable Water Used	Bm³/y	72.8	77.5	83.5	90.5	98.7	108.6
Agricultural Demand	Bm³/y	80.4	92.1	103.0	111.4	117.6	120.9
Municipal Demand	Bm³/y	8.6	12.1	16.8	22.6	29.7	38.4
Industrial Demand	Bm³/y	5.4	7.6	10.6	14.3	18.8	24.3
Total Demand North Africa	Bm³/y	94.4	111.9	130.3	148.3	166.1	183.6
per capita Consumption	m³/cap/y	666	669	676	691	716	752
Wastewater Re-used	Bm³/y	3.2	5.6	9.2	14.5	21.7	31.3
CSP Desalination	Bm³/y	0.0	0.2	4.7	49.5	60.9	74.9
Minimum CSP Capacity	GW	0.0	0.1	2.0	21.2	26.1	32.1
Desalination by Fossil Fuel	Bm³/a	0.4	1.3	4.6	9.5	8.1	2.0
Groundwater Over-Use	Bm³/y	21.2	33.2	38.3	0.0	0.0	0.0
Natural Water Used	Bm³/y	69.6	71.6	73.5	74.9	75.5	75.3

Western Asia		2000	2010	2020	2030	2040	2050
Population MP	Mp	126.0	149.9	177.2	200.6	220.8	236.9
Exploitable Water	Bm³/y	238.3	238.3	238.3	238.3	238.3	238.3
Sustainable Water Used	Bm³/y	139.3	148.8	160.6	170.3	180.0	190.2
Agricultural Demand	Bm³/y	127.7	136.7	147.1	153.1	155.9	155.8
Municipal Demand	Bm³/y	8.5	10.9	14.4	18.6	23.9	30.5
Industrial Demand	Bm³/y	4.2	5.7	7.8	10.7	14.8	20.2
Total Demand Western Asia	Bm³/y	140.4	153.4	169.4	182.4	194.6	206.5
per capita Consumption	m³/cap/y	1114	1023	956	909	881	872
Wastewater Re-Used	Bm³/y	0.9	2.5	5.3	9.5	15.9	25.3
CSP Desalination	Bm³/y	0.0	0.0	0.8	9.4	13.6	16.5
Minimum CSP Capacity	GW	0.0	0.0	0.3	4.0	5.8	7.1
Fossil Fuel Desalination	Bm³/a	0.7	1.8	3.0	3.1	1.4	0.4
Groundwater Over-Use	Bm³/y	0.4	2.8	5.2	0.0	0.0	0.0
Natural Water Used	Bm³/y	138.5	146.3	155.2	160.8	164.1	164.8

Arabian Peninsula		2000	2010	2020	2030	2040	2050
Population	Million	48.5	64.8	82.0	99.4	115.8	131.0
Exploitable Water	Bm³/y	7.8	7.8	7.8	7.8	7.8	7.8
Sustainable Water Used	Bm³/y	8.2	8.8	9.8	11.1	12.8	15.0
Agricultural Demand	Bm³/y	29.5	36.7	43.4	49.3	53.9	57.3
Municipal Demand	Bm³/y	4.1	5.7	7.2	8.8	10.5	12.4
Industrial Demand	Bm³/y	0.6	0.9	1.1	1.3	1.6	1.8
Total Demand Arabian Peninsula	Bm³/y	34.3	43.3	51.6	59.4	66.0	71.6
per capita Consumption	m³/cap/y	707	667	630	597	570	547
Wastewater Re-Used	Bm³/y	0.4	1.0	2.0	3.3	5.0	7.1
CSP Desalination	Bm³/y		0.2	5.0	36.6	46.4	54.4
Minimum CSP Capacity	GW	0.0	0.1	2.1	15.7	19.8	23.3
Fossil Fuel Desalination	Bm³/a	4.0	7.7	10.7	11.3	6.8	2.3
Groundwater Over-Use	Bm³/y	22.1	26.5	26.1	0.3	0.0	0.0
Natural Water Used	Bm³/y	7.8	7.8	7.8	7.8	7.8	7.8

Total MENA		2000	2010	2020	2030	2040	2050
Population	Million	316.4	382.0	452.0	514.5	568.5	612.2
Exploitable Water	Bm³/y	327.9	327.9	327.9	327.9	327.9	327.9
Sustainable Water Used	Bm³/y	220.2	235.2	253.9	271.9	291.5	313.8
Agricultural Demand	Bm³/y	237.6	265.6	293.5	313.8	327.4	334.1
Municipal Demand	Bm³/y	21.2	28.7	38.4	50.0	64.1	81.2
Industrial Demand	Bm³/y	10.3	14.2	19.5	26.3	35.2	46.4
Total Demand MENA	Bm³/y	269.1	308.5	351.4	390.1	426.7	461.7
per capita Consumption	m³/cap/y	851	808	777	758	751	754
Wastewater Re-Used	Bm³/y	4.4	9.1	16.5	27.3	42.6	63.8
CSP Desalination	Bm³/y	0.0	0.5	10.4	95.5	120.9	145.8
Minimum CSP Capacity	GW	0.0	0.2	4.5	40.9	51.7	62.4
Fossil Fuel Desalination	Bm³/a	5.2	10.8	18.3	23.9	16.3	4.6
Groundwater Over-Use	Bm³/y	43.7	62.5	69.6	0.3	0.0	0.0
Natural Water Used	Bm³/y	215.9	225.7	236.6	243.5	247.4	248.0

Table 2-1: Aggregated data of all MENA countries of the AQUA-CSP scenario until 2050. North Africa: Morocco, Algeria, Tunisia, Libya, Egypt. Western Asia: Iran, Iraq, Syria, Jordan, Lebanon, Israel, Palestine. Arabian Peninsula: Saudi Arabia, Kuwait, Bahrain, Qatar, United Arab Emirates, Oman, Yemen.

Chapter 5 (Socio-Economic Impacts) assesses the perspectives of cost reduction of CSP-desalination under the condition that market expansion would take place as described before. The cost of heat from concentrating solar collector fields is at present equivalent to heat from fuel oil at 50 US$/barrel, heading for 35 US$/barrel around 2010 and 20 US$/barrel by 2020. In the long-term a cost of 15 US$/barrel will be achievable for solar “fuel” while fossil fuel is not expected to ever return to such low levels equivalent to those in the mid 1990ies. This means that heat from concentrating solar collector fields will become one of the least cost options for energy in MENA, if not the cheapest at all.

Figure 2-5 and Figure 2-6 show that CSP plants providing power and desalted water can be operated economically with attractive interest rates if reasonable, unsubsidised prices are paid either for electricity or water. This must be seen in the context of present power and water utilities in MENA, that often show a zero or negative rate of return of investment, thus highly subsidising power and water.

While it is clear that the threatening MENA water crisis cannot be solved by conventional desalination, it can indeed be solved by solar powered desalination combined with efficient use of water reserves and re-use of wastewater. Building water supply on limited, fossil energy resources with unknown cost perspectives would be very risky, while building a reasonable share of water supply on renewable resources that become cheaper with time would be rather reasonable. CSP-desalination can also help to reduce the subsidiary load of most MENA governments from the power and water sectors and thus liberate public funds that are badly needed for innovation and development.

After comparing the expected cost of solar powered seawater desalination, the cost of measures to increase the efficiency of water use and economic losses induced by the over-use of groundwater, we found that the unsustainable use of groundwater is not only a threat to the environment, but also to the national economies that suffer under such schemes, with losses of national income by a reduced gross domestic product amounting to billions every year.

The concept of sustainable supply of water for the MENA region found within the AQUA-CSP study that is based on efficiency and renewable energy is not only more secure and more compatible with society and the environment, but in the medium-term also cheaper than a business-as-usual approach, that would finally end in a devastating situation for the whole region.

Sound investments and favourable economic frame conditions are now required to start market introduction and massive expansion of CSP for power and desalination in the MENA region. A population doubling until 2050 will not only require more energy and water, but also more space for living. CSP opens the long-term option to gain arable land from the MENA deserts for rural and urban development for the generations to come. Instead of increasingly fighting for limited resources, MENA has the opportunity to change to a cooperative exploitation of renewable ones.

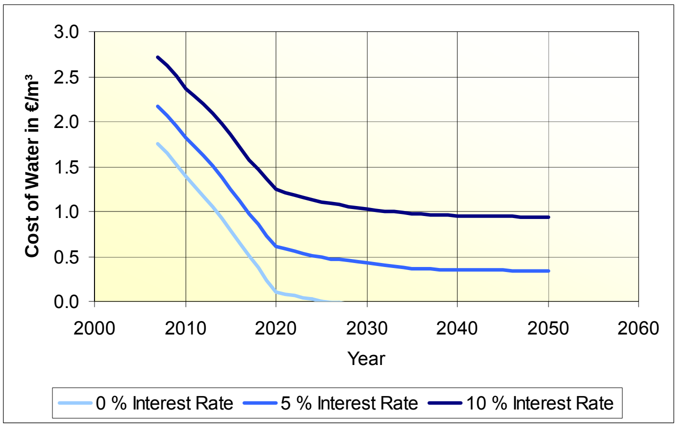


Figure 2-5: Cost of water from CSP/MED plants for different interest rates assuming that electricity produced by the plants will achieve a fixed revenue of 0.05 €/kWh. In the long-term, a cost of water of 0.34 €/m³ and 0.05 €/kWh for electricity can be achieved in the AQUA-CSP reference case with 5 % interest rate (annual real project rate of return). Increasing electricity price will reduce the cost of water and vice versa. Assumed long-term exchange rate US$/€ = 1.

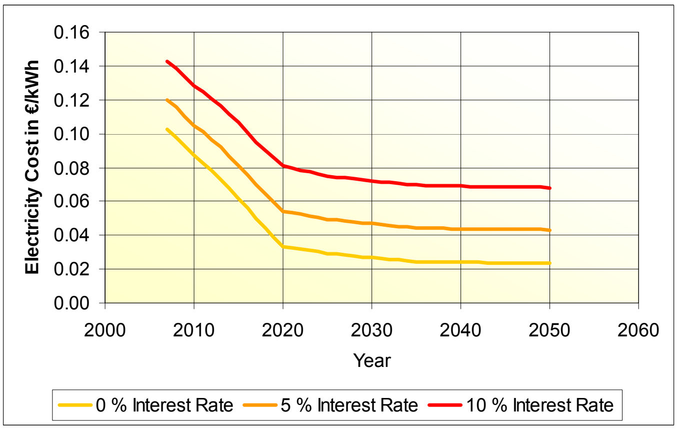


Figure 2-6: Cost of electricity from CSP/MED plants for different interest rates assuming that water produced by the plants will achieve a fixed revenue of 0.5 €/m³. In the long-term, a cost of electricity of 0.04 €/kWh and 0.5 €/m³ of water can be achieved in the AQUA-CSP reference case with 5 % interest rate (annual real project rate of return). Increasing electricity price will reduce the cost of water and vice versa. Assumed long-term exchange rate US$/€ = 1.

Chapter 6 (Environmental Impacts) analyses the environmental impacts caused by solar powered seawater desalination. The main impacts from seawater desalination are the following:

- Seawater intake for desalination and for the cooling system may cause impingement and entrainment of organisms,
- airborne emissions of pollutants and carbon dioxide are caused by the generation of electricity and heat required to power the desalination plants,
- chemical additives and biocides used to avoid fouling, foaming, corrosion and scaling of the desalination plants may finally appear in the brine,
- discharge of hot brine with high salt concentration to the sea may affect local species.

The emissions from power generation have been assessed on a life-cycle basis, including the construction, operation and de-commissioning of the reference CSP/RO and CSP/MED plants, and their impacts have been compared to conventional desalination schemes. The analysis shows that impacts from operation of conventional desalination plants can be reduced by almost 99 % using solar energy as they are primarily caused by fuel consumption. The remaining impacts caused by the construction of plants that are dominating in the case of solar desalination are reduced effectively in the course of time due to the long-term change of the MENA electricity mix to a higher share of renewable energy, as shown in the MED-CSP study.

Due to the direct impacts of desalination plants to their coastal environment a thorough impact analysis must be performed in every case prior to the erection of large scale desalination plants, as sensitive species may be heavily affected. Only sites should be chosen that allow for an effective and quick dilution of brine in order to avoid local overheating and high concentration of salt. Horizontal drain tubes beneath the seabed were recently proposed for intake and discharge, allowing on one hand for a pre-filtering of feed-water and on the other hand for an effective pre-cooling and distribution of the brine. Pre-filtering can be enhanced further by applying nano-filtration, which will require more (solar) energy but will avoid chemical additives like anti-fouling, anti-foaming and anti-scaling agents as well as biocides. Substituting chemicals by solar energy can thus mitigate both chemical additives and emissions from energy supply.

Advanced future CSP/RO and CSP/MED desalination plants have the potential to operate with extremely low environmental impacts compared to today's conventional desalination systems, at an about 20 % higher investment cost, but using a fuel that will be considerably less expensive than today's fossil fuel sources. Clean desalination is possible, but considering the large amounts of water to be desalted in MENA according to our scenario, clean desalination is also absolutely necessary in order to remain compatible with the environment. The environmental impacts from conventional desalination will increase considerably until 2025, as advanced systems will still be a minority until then. After 2025 the share of advanced solar powered desalination will quickly increase, and overall emissions can then be brought back to a compatible level (Figure 2-7).

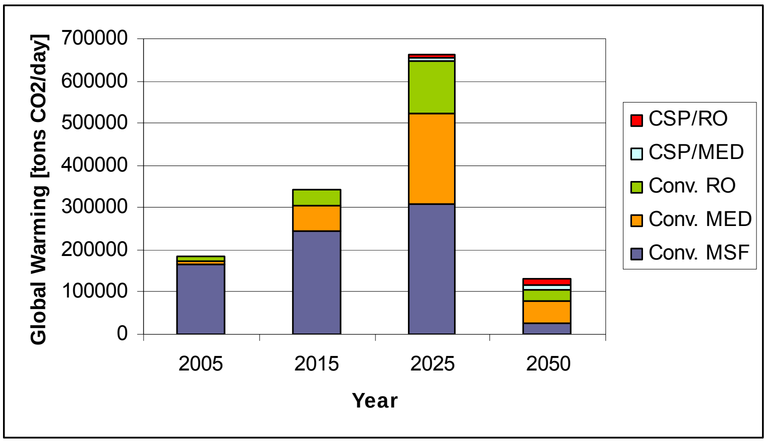


Figure 2-7: Greenhouse gas emissions from desalination in the AQUA-CSP scenario taking as basis for life-cycle assessment the electricity mix of the MENA countries with increasing renewable shares according to the MED-CSP study. A similar pattern results for all pollutants, showing that the introduction and large scale implementation of advanced CSP/MED and CSP/RO plants is imperative for sustainable supply.

Contrary to the conclusions of most contemporary strategic analysis of the MENA water sector, seawater desalination can in fact have a major share on freshwater supply that will be affordable for all countries, will be based on a domestic energy source and will not cause major environmental impacts, if concentrating solar power (CSP) is used for energy supply.

Absolutely clean desalination plants will be imperative for a massive implementation to solve the MENA water crisis. This can only be achieved if chemical additives can be substituted by enhanced intake and filtering of seawater that will require more energy than usual. Concentrating solar power is the key to this solution, as it is the only source that is at the same time emission-free, domestic to the MENA region, large enough to cope with the huge demand, based on available technology and expandable to the necessary large volumes within a time-frame of only 15 to 25 years.

Together with appropriate measures to increase the efficiency of water distribution and end-use, market introduction of CSP for power and seawater desalination must start immediately, and adequate political and economic frameworks must be established in the MENA countries to foster implementation of first pilot plants and to assure a quick expansion of this technology in the whole region. Any delay will increase the danger of a catastrophic depletion of groundwater resources that would have major detrimental effects on economic development and social peace.

2.2 AQABA SOLAR WATER Project

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 (Kern et al., 2009). 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.

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 2-8, 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 led 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 intermittent 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 2-9 from Kern et al., 2009).

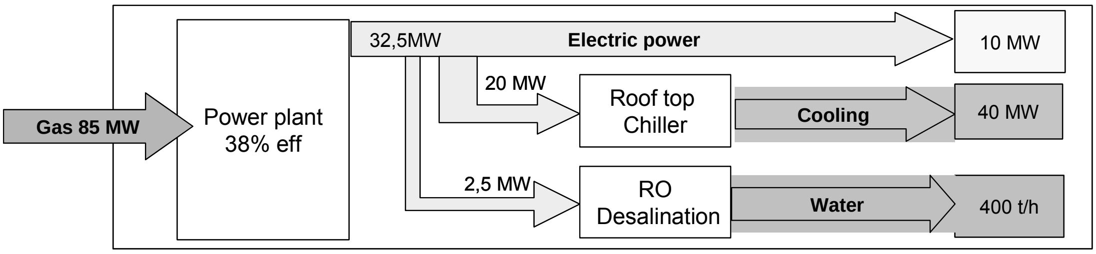


Figure 2-8: Conventional solution for power, cooling and water for a hotel resort in Aqaba

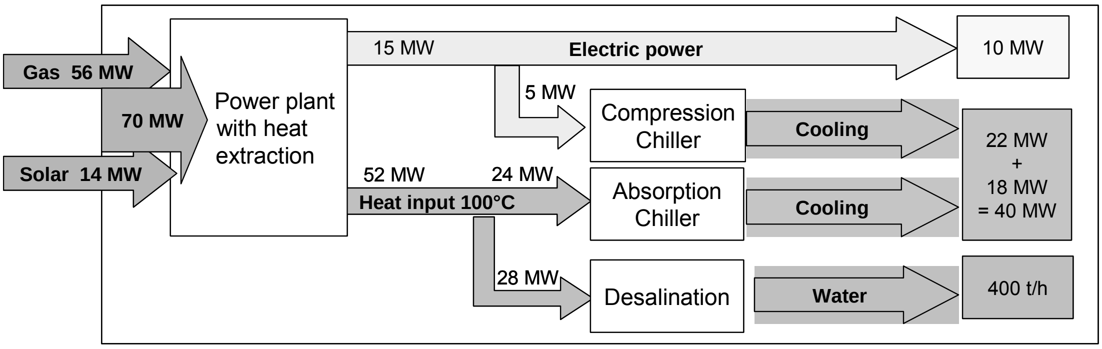


Figure 2-9: Integrated solution for power, cooling and water supported by CSP

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 savings specifically during peak load times.

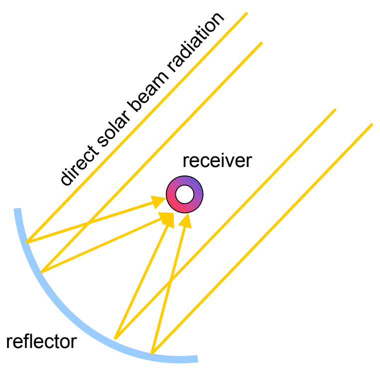
The only requisite for such a relatively large on-site system is a rather large on-site consumption. This innovative concept opens considerable market opportunities for the unsubsidised use of solar energy. The engineering for the power plant is expected to be initiated in early 2009, and commissioning is planned for early 2011.

3 TASK 1: CONCENTRATING SOLAR POWER TECHNOLOGY REVIEW

3.1 PRINCIPLES OF CONCENTRATING SOLAR POWER

Concentrating solar thermal power plants have the capability for thermal energy storage and alternative hybrid operation with fossil or bio-fuels, allowing them to provide firm power capacity on demand. The core element is a field of large mirrors reflecting the captured sun rays to a small receiver element, thus concentrating the solar radiation intensity by 80 to several 100 times and producing high temperature heat at several 100 to over 1000 °C. This heat can be either used directly in a thermal power cycle based on steam turbines, gas turbines or Stirling engines, or stored in molten salt, concrete or phase-change material to be delivered later to the power cycle for night-time operation.

The principle of operation of a concentrating solar collector and of a CSP plant is drafted in Figure 3-1, showing the option for combined generation of heat and power. The use of a simple power cycle for electricity generation only is of course also possible. From the point of view of a grid operator, CSP behaves just like any conventional fuel fired power station, but with less or no fuel consumption, thus being an important factor for grid stability and control in a future electricity supply system based mainly on renewable energy sources. CSP plants can be designed from 5 MW to several 100 MW of capacity.



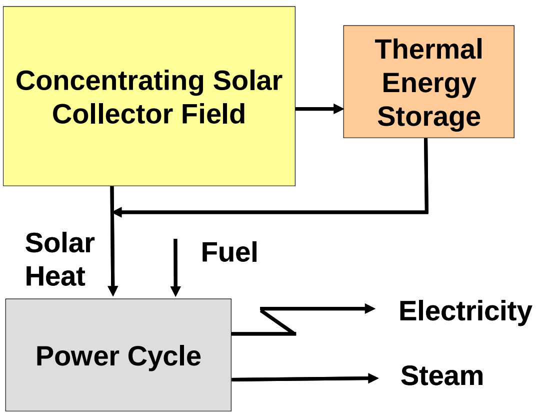


Figure 3-1: Principle of a concentrating solar collector (left) and of a concentrating solar thermal power station for co-generation of electricity and process steam (right).

Another major advantage of CSP power stations is the fact that the steam turbines used for power generation provide an excellent spinning reserve, which is very important for short time compensation of any failures or outages within the electricity grid. Spinning reserve can only be provided by rotating machines like steam or gas turbines. Moreover, the flexible design of CSP plants allows them to operate in all load segments from base load and intermediate load to peaking load services, just as required by grid operators.

The advantage of CSP for providing constant base load capacity for seawater desalination can be appreciated in Figure 3-2, Figure 3-3 and Figure 3-4 for a time-series modelling 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 or require considerable conventional backup, a concentrating solar power plant can deliver stable and constant power capacity, due to its thermal energy storage capability and to the possibility of hybrid operation with fuel.

To cover a constant load or to follow a changing load by wind or PV electricity would additionally require the electricity grid and conventional plants for external backup. In both cases an additional backup capacity would have to be installed and operated for most of the time, generating a relatively small portion of electricity during daytime and wind periods, but full capacity during night and wind calms.

In our example the renewable share provided by CSP is about 90%, that of PV is 25% and that of wind power is about 35-40%. Depending on varying conditions at different locations, these numbers can be also considered as typical for the average annual renewable share of such systems.

As a consequence, CSP plants can save more fossil fuel and replace more conventional power capacity compared to other renewable energy sources like PV and wind power. Theoretically, instead of conventional backup power or fuel, electricity generated by all three systems could be stored in batteries, hydro-pump or hydrogen energy storage in order to provide continuous power capacity. 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 and energy losses.

A reasonable economic performance of concentrating solar power plants is given at an annual direct solar irradiance of more than 2000 kWh/m²/y. The economic potential of CSP in Europe has been assessed in (Trieb et al. 2005). It is limited to Spain, Portugal, Greece, Turkey and the Mediterranean Islands and amounts to 1580 TWh/y of which 1280 TWh/y are located in southern Spain. Although there is a relatively large CSP potential in Europe, more attractive sites are located south of the Mediterranean Sea with an annual direct solar irradiance of up to 2800 kWh/m²/y.

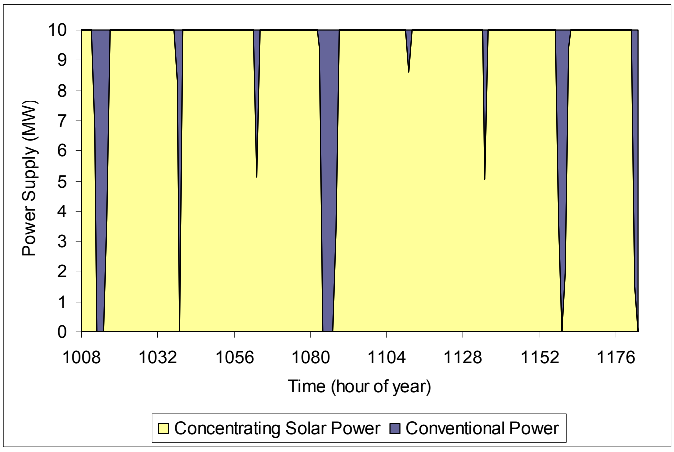


Figure 3-2: Solar power provided by a CSP-plant with 16 hour storage and conventional power from fuel from the same plant for constant 10 MW base load supply.

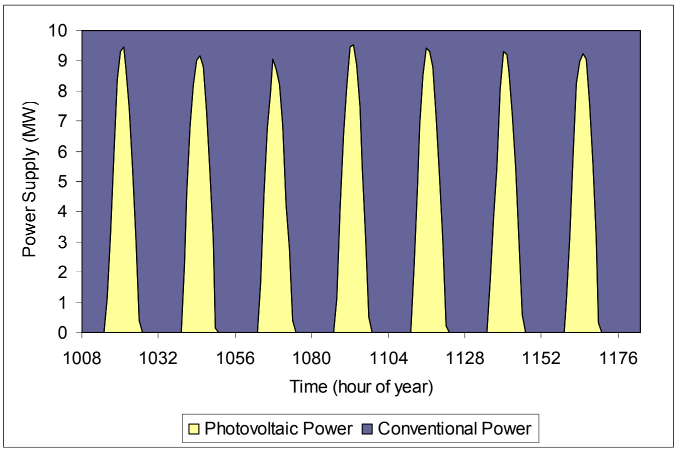


Figure 3-3: Power supplied by 10 MW PV capacity and conventional backup power from the grid needed to provide constant 10 MW base load supply.

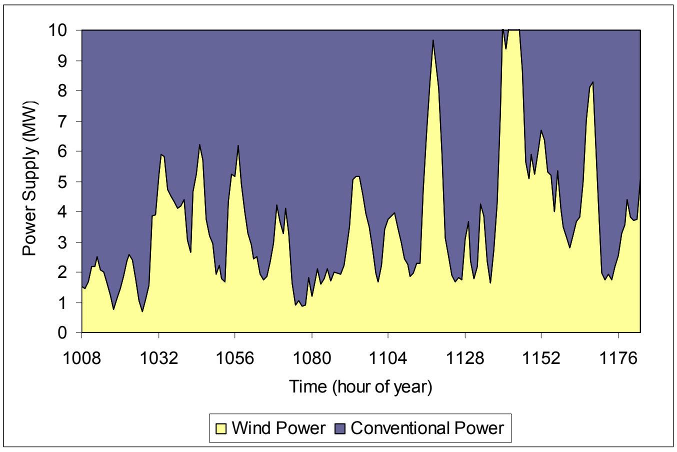


Figure 3-4: Power supplied by 10 MW wind capacity and conventional backup power from the grid needed to provide constant 10 MW base load supply.

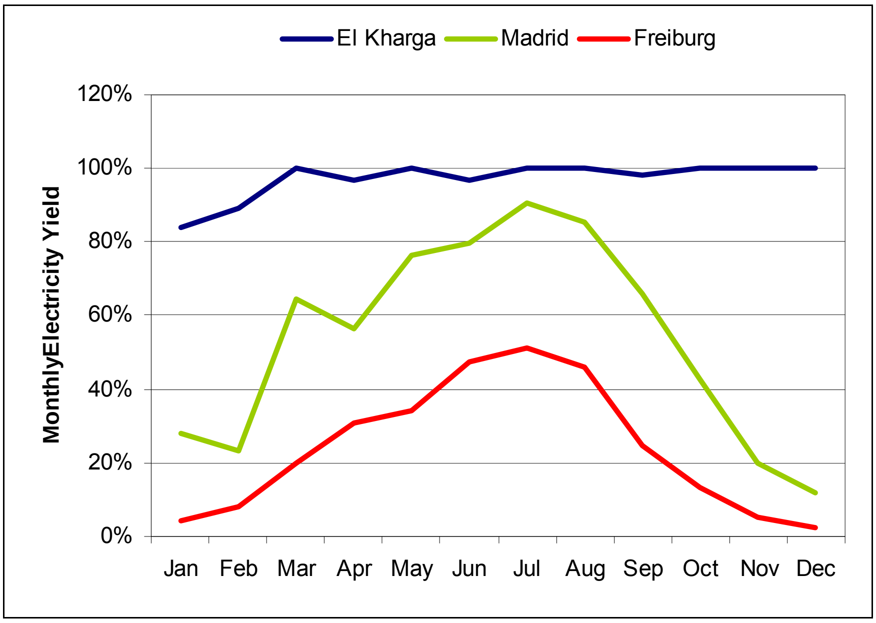


Figure 3-5: Simulation of the relative monthly electricity yield of a solar thermal power plant with 24 hour storage at sites with different annual solar irradiance and latitude assuming solar only operation without fuel input. Total equivalent annual full load hours achieved: Freiburg (Germany) 2260 h/y, Madrid (Spain) 5150 h/y, El Kharga (Egypt) 8500 h/y. Source: (May 2005).

Figure 3-5 shows the monthly electricity yield of a CSP plant with a one-day thermal energy storage capacity at different locations in Europe and North Africa. The site El Kharga in Egypt represents the best case in this comparison. Throughout the whole year the solar electricity yield stays at almost 100 %, just in January and February it declines to about 85 %, a behaviour that correlates very well with local power demand. The more the plant is located to the North the lower is its monthly electricity yield. In Madrid and Freiburg values of less than 20 % are achieved in wintertime, and neither achieves 100 % in summer, compared to the site in Egypt.

In our model, a Solar Multiple of one (SM1) defines a collector field with an aperture area of 6000 m² per installed MW of power capacity. A single storage unit has a capacity of 6 full load operating hours that will be used when applying additional collector fields for night time storage. SM2 would require one 6 h storage unit and 2 times 6000 m² solar field per MW. This model considers as reference current parabolic trough technology with molten salt storage, steam cycle power block and dry cooling tower with an annual net solar electric efficiency of about 12% (Trieb et al. 2009).

Annual full load hours are shown in Table 3-1 for varying solar multiple, latitude and annual solar irradiation. As an example, a CSP plant with a Solar Multiple 4 would have 4 x 6000 = 24000 m²/MW solar field aperture area plus 3 x 6 = 18 hours of storage capacity. Such a plant would achieve about 5900 full load operating hours at 2000 kWh/m²/y of annual solar irradiation in Southern Spain (Latitude 35°) and almost 8000 full load hours at a site in Southern Egypt (Latitude 25°) with 2800 kWh/m²/y annual solar irradiation.

Table 3-1: Annual full load hours (h/y) of CSP plants for different Solar Multiple (SM)*, different annual direct normal irradiation (DNI in kWh/m²/year) and different latitudes (Lat.) from hourly time series modelling (Trieb et al. 2009).

SM1	**DNI 1800**	**DNI 2000**	**DNI 2200**	**DNI 2400**	**DNI 2600**	**DNI 2800**
Lat. 0 °	1613	1869	2128	2362	2594	2835
Lat. 10 °	1607	1859	2130	2344	2581	2808
Lat. 20 °	1559	1801	2082	2269	2502	2725
Lat. 30 °	1460	1689	1977	2128	2350	2580
Lat. 40 °	1310	1524	1815	1920	2127	2366
SM2	**DNI 1800**	**DNI 2000**	**DNI 2200**	**DNI 2400**	**DNI 2600**	**DNI 2800**
Lat. 0 °	3425	3855	4221	4645	4931	5285
Lat. 10 °	3401	3817	4187	4612	4909	5222
Lat. 20 °	3310	3719	4098	4495	4810	5096
Lat. 30 °	3147	3539	3943	4283	4605	4887
Lat. 40 °	2911	3285	3719	3984	4301	4604
SM3	**DNI 1800**	**DNI 2000**	**DNI 2200**	**DNI 2400**	**DNI 2600**	**DNI 2800**
Lat. 0 °	4869	5414	5810	6405	6713	7147
Lat. 10 °	4829	5358	5752	6365	6690	7074
Lat. 20 °	4711	5223	5630	6229	6583	6929
Lat. 30 °	4499	4995	5434	5970	6352	6676
Lat. 40 °	4189	4674	5163	5601	5987	6322
SM4	**DNI 1800**	**DNI 2000**	**DNI 2200**	**DNI 2400**	**DNI 2600**	**DNI 2800**
Lat. 0 °	5987	6520	6796	7563	7859	8243
Lat. 10 °	5918	6430	6711	7514	7831	8160
Lat. 20 °	5761	6260	6563	7380	7724	8009
Lat. 30 °	5506	5999	6340	7110	7497	7738
Lat. 40 °	5155	5650	6045	6717	7115	7348

* SM1: 6000 m²/MW, no storage; SM2: 12,000 m²/MW, 6 h storage; SM3: 18,000 m²/MW, 12 h storage; SM4: 24,000 m²/MW, 18 h storage

For concentration of the sunlight, most systems use curved or flat glass mirrors because of their very high reflectivity. Point focusing and line focusing collector systems are used, as shown in Figure 3-6. These systems can only use the direct portion of solar radiation, but not the diffuse part of the sunlight that can not be concentrated by mirrors. Line focusing systems are easier to handle than point concentrating systems, but have a lower concentration factor and hence achieve lower temperatures than point focusing systems. Therefore, line concentrating systems will typically be connected to steam cycle power stations, while point concentrating systems are additionally capable of driving gas turbines or combustion engines.

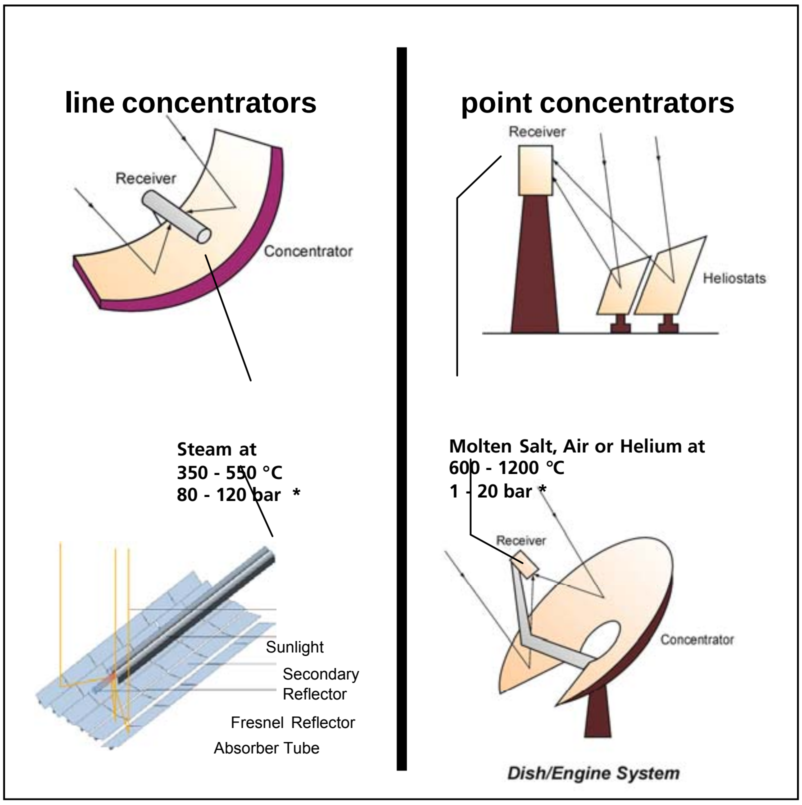


Figure 3-6: Concentrating solar collector technology mainstreams: Parabolic trough (top left), linear Fresnel (bottom left), central receiver solar tower (top right), dish-Stirling engine (bottom right).

Table 3-2 gives a comparison of the main features of solar thermal power technologies. In addition to the concentrating solar power technologies described above, the solar thermal updraft tower has been included for comparison.

Technology	Parabolic Trough System	Linear Fresnel System	Solar Power Tower	Dish Stirling Engine	Solar Updraft Tower
Applications	Superheated steam for grid connected power plants	Saturated and superheated steam for process heat and for grid connected power plants	Saturated and superheated steam for grid connected power plants	Stand-alone, decentralized, small off-grid power systems. Clustering possible.	Large grid connected systems.
Capacity Range (MW)	10-200	5-200	10-100	0.1-1	30-200 MW
Realized max. capacity of single unit (MW)	80 (250 projected)	2 (30 under construction)	10 (20 under construction)	0.025	0.05
Capacity installed (MW)	480 (500 under construction)	2 (30 under construction)	10 (20 under construction)	trials	0
Annual Efficiency (%)	10 to 16 (18 projected)	8 to 12 (15 projected)	10 - 16 (25 projected)	16 to 29	1 to 1.5
Heat Transfer Fluid	Synthetic Oil, Water/Steam demonstrated	Water / Steam	Water / Steam, Air	Air	Air
Temperature (°C)	350-415 (550 projected)	270-400 (550 projected)	250-565	750-900	30-50
Concentration Ratio (mirror aperture / absorber aperture)	50-90	35-170	600-1000	Up to 3000	no concentration
Operation mode	solar or hybrid	solar or hybrid	solar or hybrid	solar or hybrid	solar only
Land Use Factor (aperture area / land area)	0.25-0.40	0.60-0.80	0.20-0.25	0.20-0.25	1
Estimated investment costs (€/kW) for SM1-SM2	3,500-6,500	2,500-4,500	4,000-6,000	6,000-10,000 (SM1 only)	4,000-8,000
Development Status	Commercially proven	Recently commercial	Semi-commercial	Prototype testing	Prototype testing
Storage Options	Molten Salt, Concrete, Phase Change Material	Concrete for pre-heating and superheating, Phase Change Material for Evaporation	Molten Salt, Concrete, Phase Change Material	No storage available	Storage possible
Reliability	Long-Term Proven	Recently Proven	Recently Proven	Demonstrated	Not yet demonstrated
Material Demand of Solar Field (kg/m²)	120-140	30-130	100-250	300-400	90-110
Advantages	Long-term proven reliability and durability	Simple structure and easy field construction	High temperature allows high efficiency of power cycle	High temperature allows high efficiency of power cycle	Easily Available Materials
	Storage options for oil-cooled trough available	Tolerance for slight slopes	Tolerates non-flat sites	Independent from land slope	
		Direct steam generation proven	Possibility of powering gas turbines and combined cycles	High Modularity	
Disadvantages	Limited temperature of heat transfer fluid hampering efficiency and effectiveness	Storage for direct steam generating systems (phase change material) in very early stage	High maintenance and equipment costs	Not commercially proven	Not commercially proven
	Complex structure, high precision required during field construction			High complexity compared to stand-alone PV	Tower height approx. 1000 m
	Requires flat land area				High land requirements
					Very high material demand
					Requires large flat land area

Table 3-2: Comparison of solar thermal power technologies (SM1-SM2 explained in text)

3.2 HEAT STORAGE OPTIONS FOR CONCENTRATING SOLAR POWER

3.2.1 Principles of Heat Storage

Heat storage is one of the most distinguishing features of CSP with respect to other renewable energy technologies like wind power or photovoltaics. It allows production of electricity on demand just like from fuel oil or natural gas, but based on fluctuating solar energy resources (Figure 3-7). This is a very important option to increase the revenues from power sales, as off-peak solar energy from the morning hours can be shifted to the evening on-peak electricity demand, often achieving sales prices by a factor of two or three higher. In the case of seawater desalination, the continuous operation of the desalination plants - either by reverse osmosis or thermal desalination - is crucial in order to avoid scaling and bio-fouling which would occur immediately if plants would be left idle.

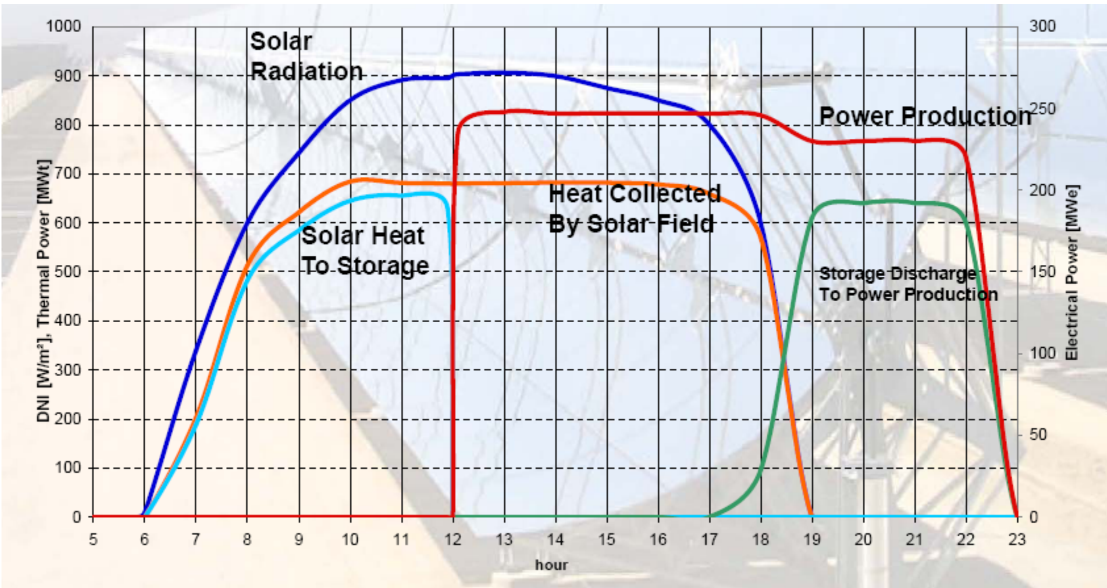


Figure 3-7: The use of thermal energy storage in a CSP plant to shift electricity output from morning off-peak to evening on-peak demand (Dracker and Riffelmann 2008).

Therefore, heat storage was always an important issue during CSP development, and in the meantime, significant experience has been accumulated world wide (Figure 3-8). Direct storage of synthetic oil heat transfer fluid and molten salt as storage media have been investigated and used in industry since the 1980ies and thus can be considered commercial. While the use of HTF is considered too expensive as storage medium, molten salt has been developed to maturity and is currently applied in several CSP plants in Spain. New storage concepts based on concrete and phase change material are presently under development.

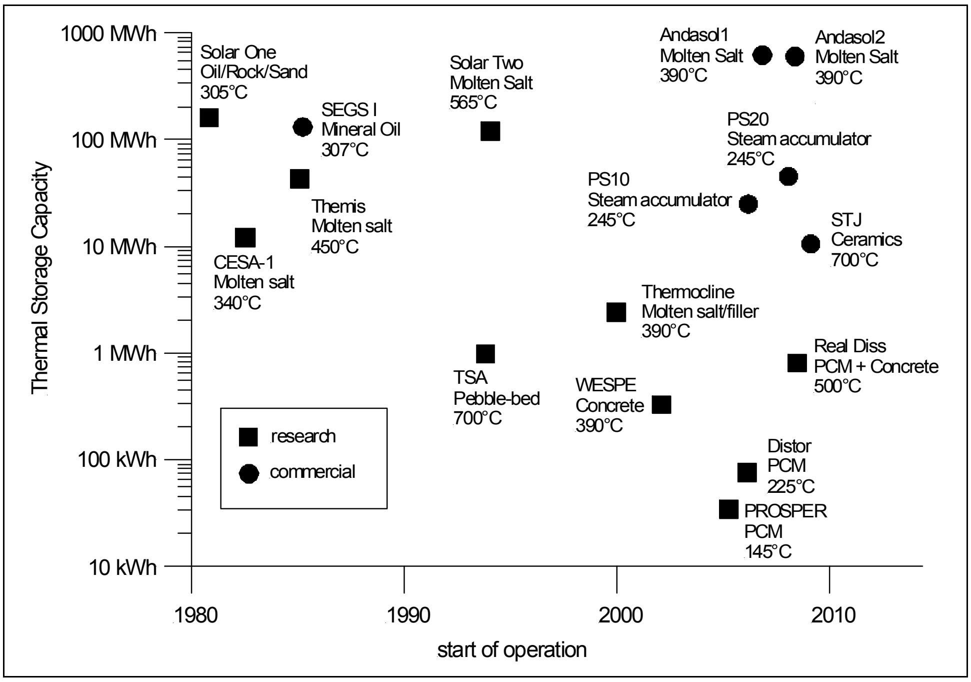


Figure 3-8: Experience using energy storage systems in CSP plants (Zunft 2008)

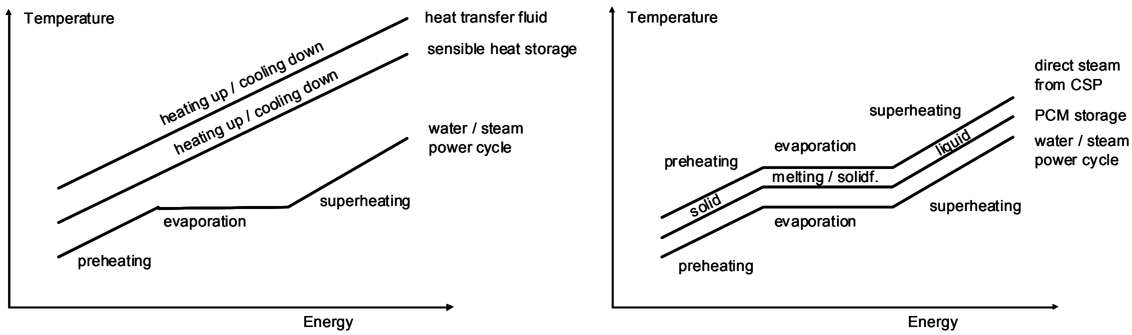


Figure 3-9: Temperature of heat transfer fluid and sensible heat storage vs. steam temperature of a Rankine cycle (left) and temperature of direct steam generating CSP and PCM vs. steam temperature of Rankine cycle (right).

The main reason for developing phase change materials for heat storage is the fact that most of the energy transfer to the water steam cycle of a power plant takes place at constant temperature during the evaporation phase from water to steam (Figure 3-9). Using synthetic oil heat transfer fluid and sensible heat storage is on one side limited by the upper allowable temperature of the HTF which is about 390 °C and on the other side by the required steam conditions of the power plant, which are best if pressure and temperature are high, ideally above 500°C and 120 bar. Using HTF only 370 °C at 100 bar pressure can be achieved, limiting the efficiency of the power cycle to values below state of the art. Moreover, the limited temperature difference between the cold and hot end also limits storage capacity and increases the amount of material required.

Direct steam generating concentrating solar collector systems can easily achieve the temperatures required by steam power cycles, but there is no suitable sensible heat storage technology available for the evaporation phase which allows for a significant heat transfer at constant temperature. Therefore, phase change materials are applied, using the melting heat of the material for energy storage (Laing et al. 2009). As PCM materials are usually rather expensive, it was proposed to use sensible heat storage for the pre-heating and superheating segments of a steam power cycle and PCM only for the evaporation segment. Such systems are presently under development (Laing et al. 2009).

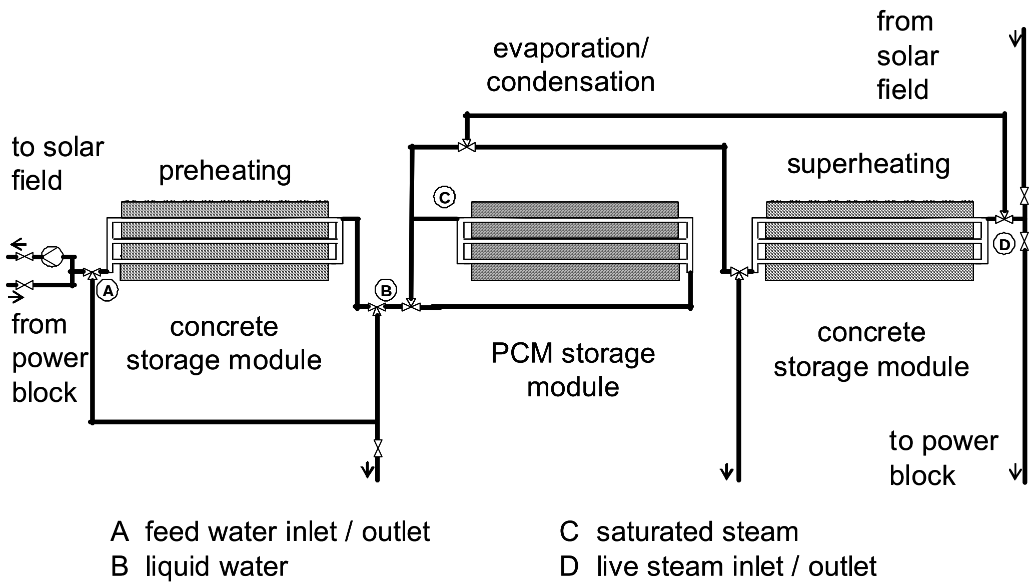


Figure 3-10: Concept of using a combined concrete/phase change material storage systems for direct steam generating solar power plants (Zunft 2008, Laing 2009)

In the following we will explain different heat storage options for CSP and show the experience gained within concrete projects in Europe.

3.2.2 Sensible Heat Two-Tank Molten Salt Storage

Molten salt is a medium often used for industrial thermal energy storage. It is relatively low-cost, non-flammable and non-toxic. The most common molten salt is a binary mixture of 60% sodium nitrate (NaNO3) and 40% potassium nitrate (KNO3). During operation, it is maintained at 290°C in the cold storage tank, and can be heated up to 565°C. Two-tank storage systems are very efficient, with about 1-2%

loss over a one day storage period. Because the molten salt mixture freezes at temperatures about 230°C (depending upon the salt's composition) care must be taken to prevent it from freezing at night, especially in any of the piping system.

Heat exchangers are used to transfer the heat from the solar field heat transfer fluid to the hot tank. During discharge, the heat transfer fluid is circulated through the same heat exchangers to extract the heat from the storage and transfer it to the solar power plant steam generator. The investment cost of a two-tank molten salt system is about 40-60 €/kWh.

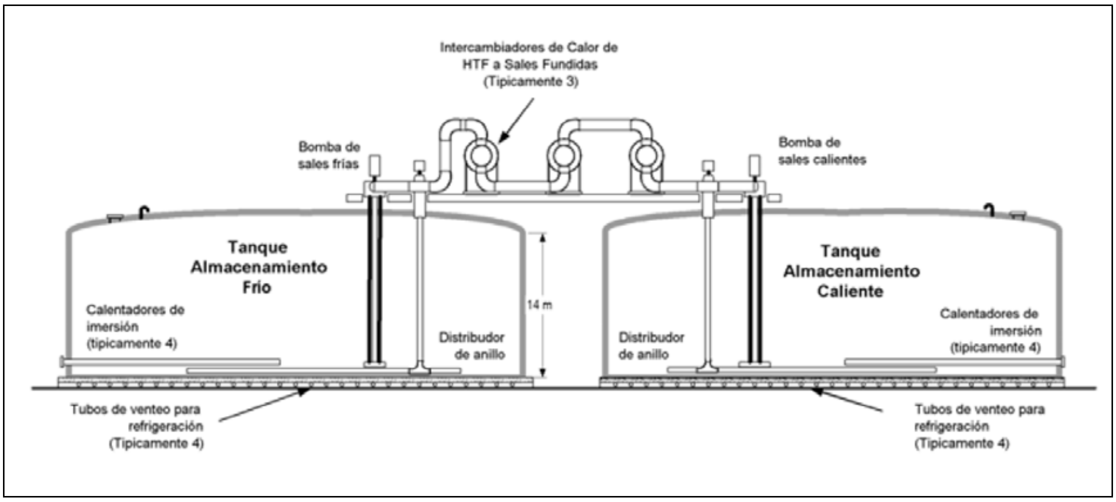


Figure 3-11: Sketch of molten salt tanks at ANDASOL 1 (ACS Cobra)

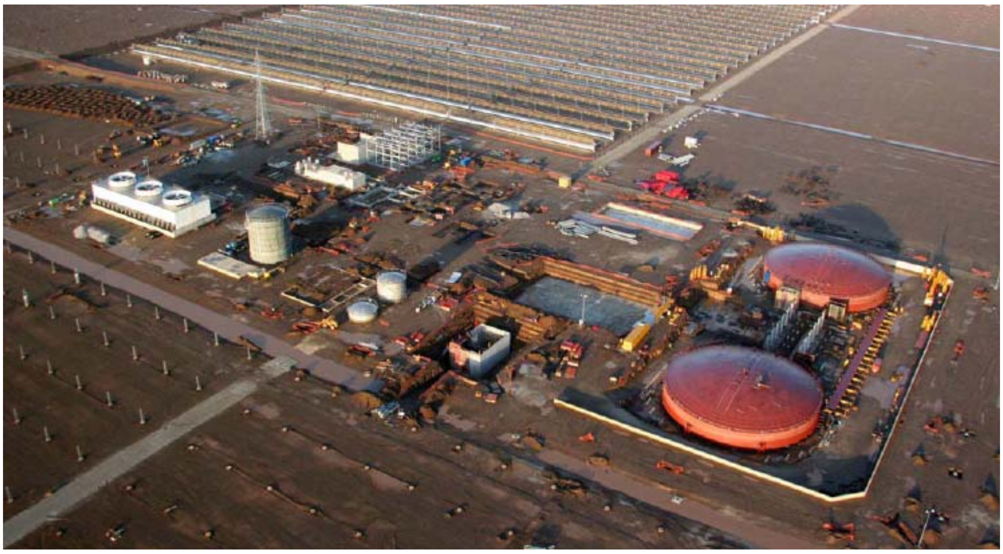


Figure 3-12: Molten salt storage tanks at ANDASOL 1 with 1010 MWh storage capacity during construction in December 2007 (ACS Cobra)

3.2.3 Sensible Heat Concrete Storage

A sensible heat storage system using concrete as storage material has been developed by Ed. Züblin AG and German Aerospace Center DLR. A major focus was the cost reduction of the heat exchanger and the high temperature concrete storage material. For live cycle tests and further improvements a 20 m³ solid media storage test module was built and cycled by an electrically heated thermal oil loop. The solid media storage test module has successfully accumulated about one year of operation in the temperature range between 300 °C and 400 °C. Investment is at present about 30-40 €/kWh with a medium term cost target of 20 €/kWh.

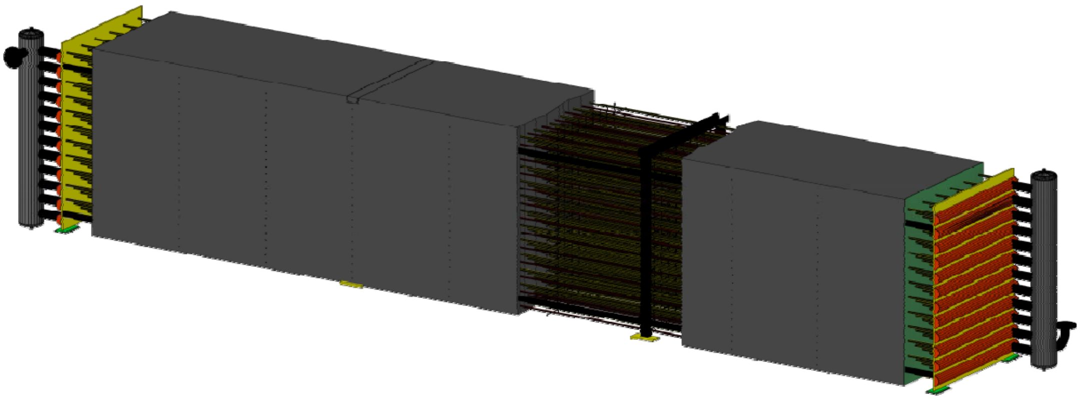


Figure 3-13: Sketch of a concrete storage with view on the tube bundle that serves as heat exchanger between the concrete and the heat transfer fluid (Laing et al. 2008)

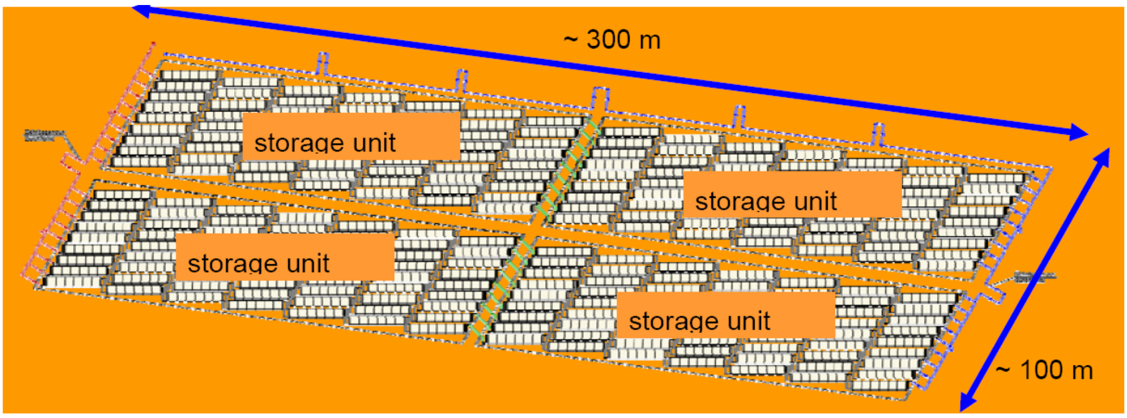


Figure 3-14: Set-up of a 1100 MWh concrete storage from 252 basic storage modules for a 50 MW concentrating solar power plant (Laing et al. 2008)

3.2.4 Latent Heat Phase Change Material Storage

A major technical problem for the implementation of high-temperature latent heat storage systems is the insufficient thermal conductivity of the available phase change materials of around 0.5 W/(mK). During the discharge process, the energy released by solidification of the storage material must be transported from the solid-liquid interface through the growing solid layer to the heat exchanger surface (Figure 3-15). Unfortunately, the thermal conductivity of the solid PCM is rather low.

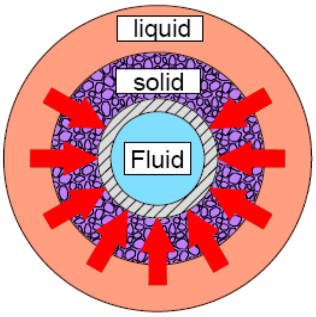


Figure 3-15: Solidification of PCM around heat exchanger tube during discharging (left) and finned tube design (right) developed to overcome the reduced heat transport through the solidified material (Laing et al. 2009)

Fins attached vertically to the heat exchanger tubes can enhance the heat transfer within the storage material. Fins can be made of graphite foil, aluminium or steel. High temperature latent heat storage with high capacity factors was demonstrated at different temperature levels. The sandwich concept using fins made either from graphite or aluminium was proven as the best option to realize cost-effective latent heat energy storage. The application of graphite is preferred for applications up 250 °C; at higher temperatures aluminium fins are used.

Feasibility was proven by three prototypes using graphite and by a further storage unit using aluminium fins. The prototype with aluminium fins filled with sodium nitrate was operated for more than 4000 h without degradation of power. PCM test storage facility with a capacity of approx. 700 kWh is currently being fabricated. Other activities aim at the thermo-economic optimization of the storage concept; further storage systems using the sandwich concept are under development (Laing et al. 2009). A cost of 40-50 €/kWh is expected for large scale storage systems.

Figure 3-16: Phase change material demonstration plant with 200 kWh storage capacity at German Aerospace Center (Laing 2008)

3.2.5 Steam Accumulator

Storage of sensible heat in pressurized liquid water (Ruths Storage) is used in several industrial applications as short term (typically 0.5 to 2 h) steam buffer. The storage is charged by condensing high temperature steam and thus raising the temperature of the water volume contained. During discharge, the pressure within the hot water vessel is decreased. Part of the water evaporates and can be withdrawn as saturated steam. The thermal capacity of the storage is proportional to the heat capacity of the contained water and to the temperature difference allowable for the steam process between charging and discharging. Investment of the pressurized steam vessel is rather high at about 180 €/kWh.

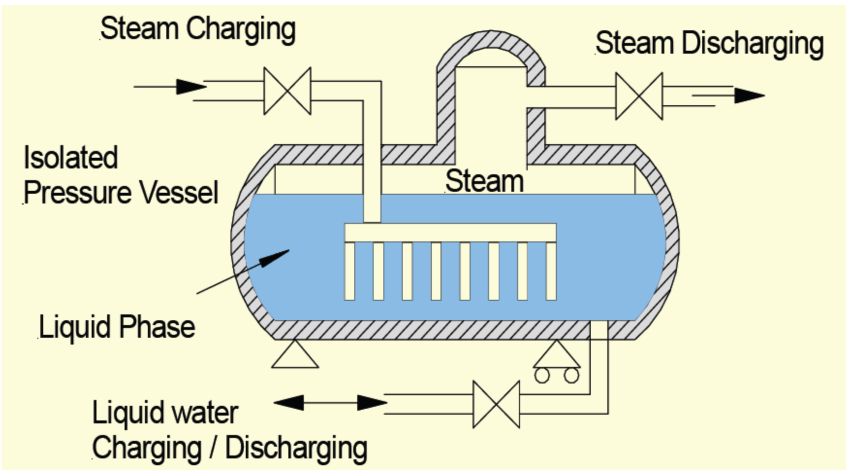


Figure 3-17: Principle of steam accumulator heat storage (Laing 2008)

Figure 3-18: Steam accumulator with 1-hour storage capacity at PS-10 concentrating solar power station (Abengoa Solar)

3.2.6 Hot Water Storage

A stratified hot water tank at normal ambient pressure can in principle be used to store low temperature heat below 100 °C required e.g. for a multi-effect thermal desalination process. In a stratified tank during discharge, cold water is returned to the bottom and hot water is taken from the top of the tank. The different temperature layers are stabilised by gravity.

Figure 3-19: Solar flat plate collectors for water heating (left) and seasonal hot water storage (right) with 6,000 m³ volume at Olympic Park, Munich (Kuckelhorn et al. 2002)

Large scale storage systems up to 20,000 m³ capacity have been developed in Germany for seasonal storage of low temperature heat from flat plate solar collectors for room heating, accumulating solar energy in the summer and releasing heat to the space heating system in winter. The storage temperature is typically cycled between a maximum of 95°C and a lower temperature of 50°C. Lower storage temperatures can be achieved if heat pumps are applied. The stored energy is proportional to the heat capacity of the water stored and to the temperature difference achieved during cycling. Investment cost is between 50 and 150 €/m³. For a temperature difference of 30 °C, this would be equivalent to a cost of storage capacity of about 2-5 €/kWh.

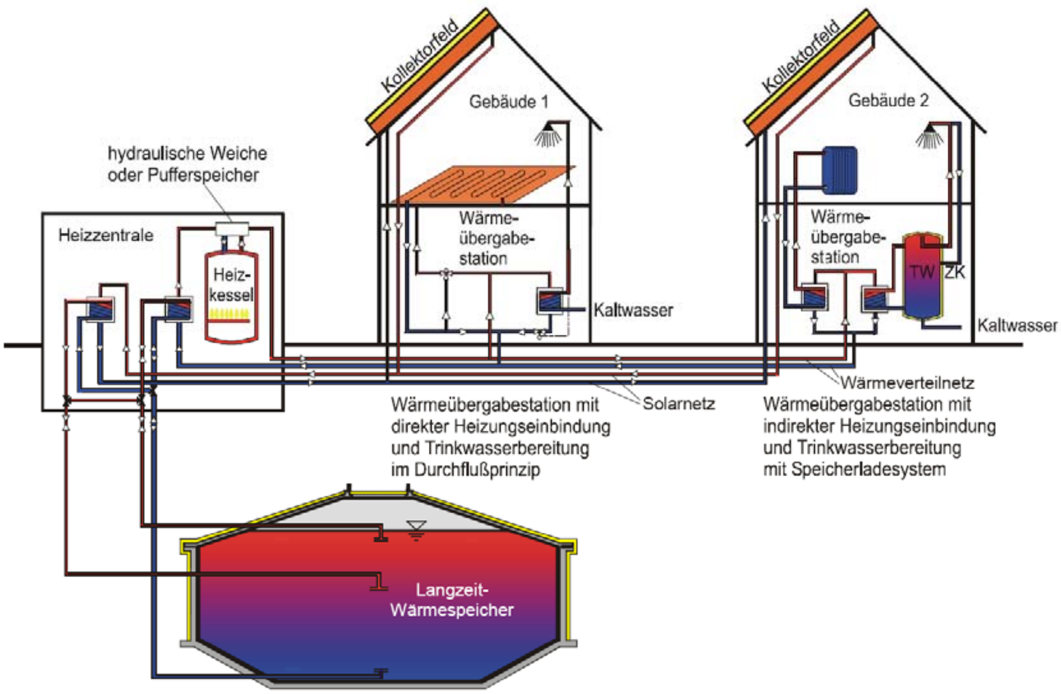


Figure 3-20: Sketch of a solar/fuel hybrid district heating system with low temperature seasonal energy storage (Mangold and Müller-Steinhagen 2002)

Technology	Molten Salt	Concrete	Phase Change Material	Water/Steam	Hot Water
Capacity Range (MWh)	500-> 3,000	1->3,000	1->3,000	1-200	1-3,000
Realized max. capacity of single unit (MWh)	1,000	2	0.7	50	1,000 (not for CSP)
Realized max. capacity of single unit (full load hours)	7.7	not yet applied to CSP plants	not yet applied to CSP plants	1.0	not yet applied to CSP plants
Capacity installed (MWh)	1,000	3	0.7	50	20,000 (not for CSP)
Annual Efficiency (%)	0.98	0.98	0.98	0.9	0.98
Heat Transfer Fluid	synthetic oil	synthetic oil, water/steam	water / steam	water / steam	water
Temperature Range (°C)	290-390	200-500	up to 350	up to 550	50-95
Investment Cost (€/kWh)	40-60	30-40 (20 projected)	40-50 projected	180	2-5
Advantages	high storage capacity at relatively low cost	well suited for synthetic oil heat transfer fluid	latent heat storage allows for constant temperature at heat transfer	latent heat storage allows for constant temperature at heat transfer	very low cost storage for process heat below 100°C
	experience in industrial applications	easily available material	low material requirements	experience in industrial applications	experience in industrial applications
	well suited for synthetic oil heat transfer fluid	well suited for pre-heating and superheating in direct steam generating collectors	well suited for evaporation/condensation process in direct steam generating collectors	well suited for evaporation/condensation process in direct steam generating collectors	
Disadvantages	sensible heat storage requires temperature drop at heat transfer	not suited for evaporation/condensation process in direct steam generating collectors	not suited for pre-heating and superheating in direct steam generating collectors	not suitable for pre-heating and superheating	sensible heat storage requires temperature drop at heat transfer
	molten salt freezes at 230°C	recent development	very early stage of development		not applicable to power generation

Table 3-3: Comparison of the principal features of solar thermal storage technologies

3.3 PARABOLIC TROUGH COLLECTORS FOR STEAM CYCLE POWER PLANTS (20 - 200 MW)

3.3.1 Parabolic Trough Collector with Synthetic Heat Transfer Fluid

As shown in Figure 3-21 and Figure 3-23, some line focusing systems use parabolic trough 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. 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. 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 & 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., 2004).

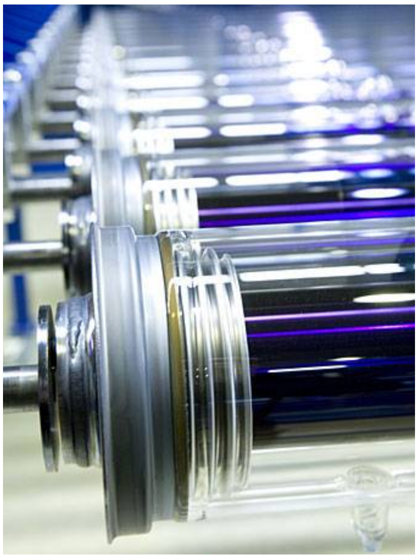


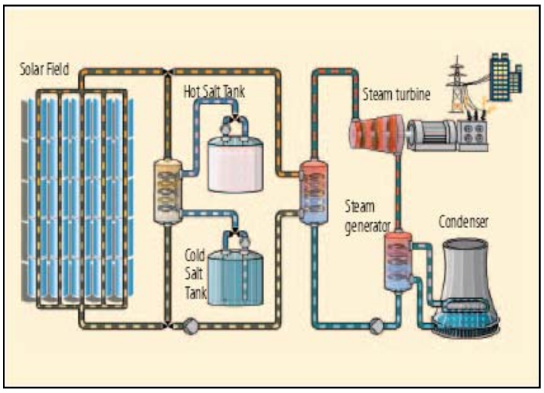
Figure 3-21: Absorber tube with selective coating and evacuated glass envelope by Schott Solar AG, Germany (left) and parabolic trough collector assembly at the Plataforma Solar de Almeria, Spain (right).

Figure 3-22: Impressions of the Californian Solar Electricity Generating Systems

The experience of parabolic trough steam cycles dates back to 1985, when the first of a series of 9 solar electricity generating systems (SEGS) was commissioned in California, with a rated capacity between 14 MW (SEGS I) and 80 MW (SEGS (IX commissioned in 1991). The plants have been run successfully since then producing more than 15,000 GWh of solar electricity up to now.

In Europe a first plant of this type with 50 MW rated power using synthetic oil as heat transfer fluid and a molten salt tank system with 7 full load hours storage capacity has been commissioned in April 2009 in the Spanish Sierra Nevada near Guadix. On July 20th 2006, construction started 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 solar electricity after a construction time of 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 over 2000 MW to be commissioned within the coming 5 years period. The investment cost amounted to 310 M€ (Schott 2006).

Heat storage consists 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 3-23 and Figure 3-24).



ANDASOL – DESIGN FEATURES	
Location	Andalucía, Spain
Nominal electrical power	49.9 MW
Annual equivalent full-load hours	3,589
Receiver technology	Parabolic trough solar field
Receiver geometry	510,120 m²
Thermal storage technology	Molten-salt
Thermal storage capacity	7.5 hr reserve
Ground area	200 ha
Annual electricity production	179 GWh

Figure 3-23: Simplified sketch and basic design parameters of the ANDASOL 1 plant (EC 2007)

Figure 3-24: Andasol-1 parabolic trough solar field, molten salt storage tanks and power station during construction in December 2007 (Source: ACS Cobra S.A., Spain).

3.3.2 Parabolic Trough for Direct Steam Generation

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 & 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 projects DISS and INDITEP 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.

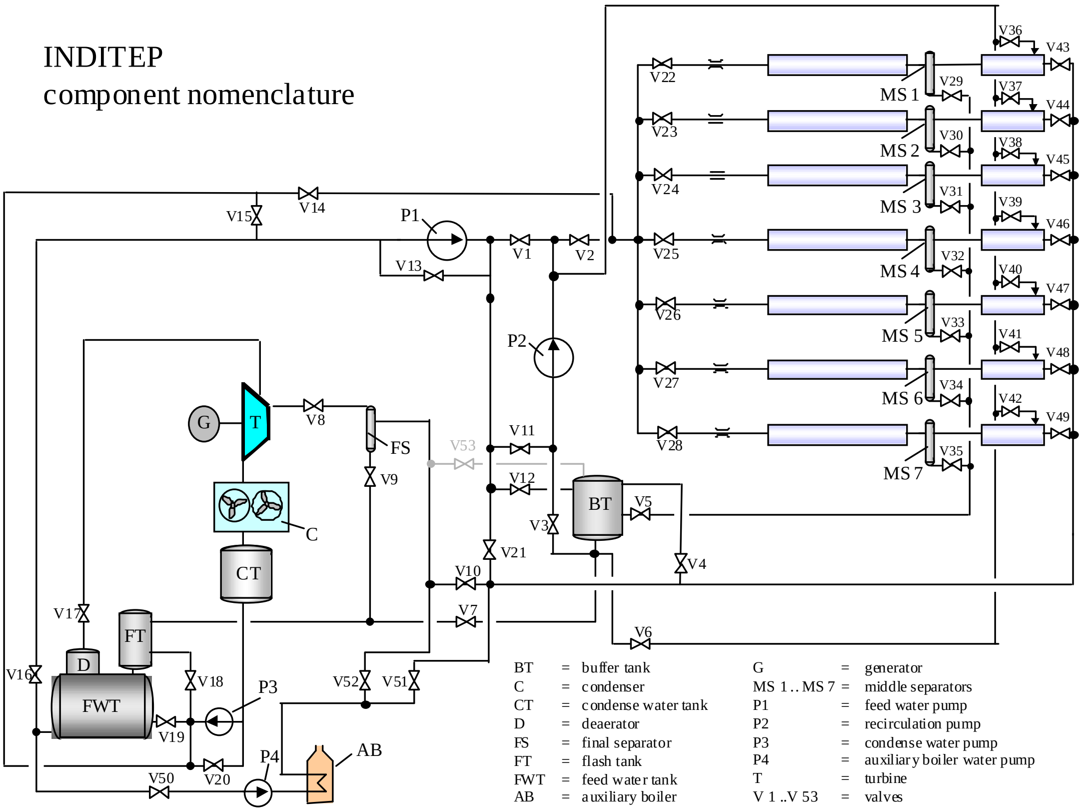


Figure 3-25: Schematic diagram of a direct steam generating solar collector field for a 5 MW pre-commercial solar thermal power plant designed by DLR (INDITEP, 2004).

3.4 LINEAR FRESNEL COLLECTORS FOR STEAM CYCLE POWER PLANTS (5 - 200 MW)

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. 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.

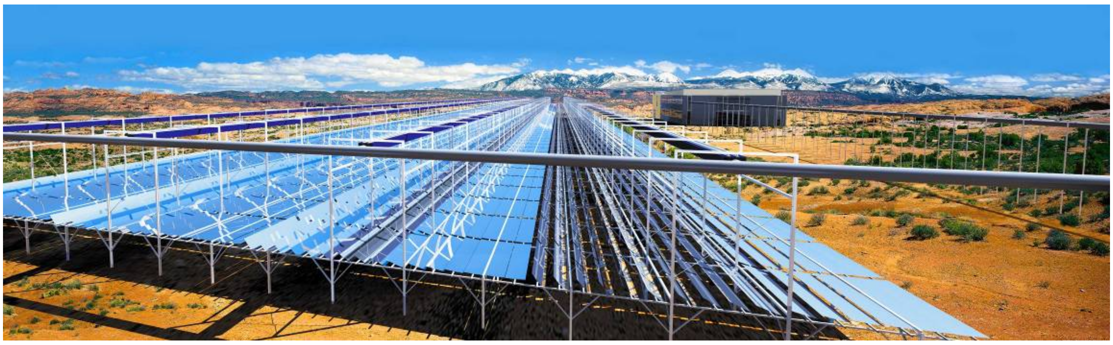


Figure 3-26: Animation of a Linear Fresnel Collector Field by FhG/ISE

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.

Compared to the existing parabolic trough, some linear Fresnel collector systems show a weight reduction per unit area of about 75%. This reflects not only a lower cost, but also leads to a lower emission of pollutants during construction. On the other hand, the simple optical design of the Fresnel system leads to a lower optical efficiency of the collector field, requiring about 33-38% 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, Fresnel systems have considerable advantages over parabolic troughs. Land use is much better, as the distances between mirrors are much smaller. The collector aperture area covers between 65 % and 90 % of the required land, while for a parabolic trough, only 33 % of the land is covered by mirrors, because the distances between the single parabolic-trough-rows required to avoid mutual shading are considerable. Land use efficiency of a linear Fresnel can thus be 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.

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.

3.4.1 Linear Fresnel Collector for Direct Generation of Superheated Steam

In July 2007 the first large scale linear Fresnel concentrating solar collector with 1500 m² collector area was inaugurated by a joint venture of Solar Power Group (SPG) and MAN at the Plataforma Solar de Almería. The collector, erected under the frame of the project FRESDEMO funded by the German government, has produced in a very stable and continuous way superheated steam at a temperature of 450°C and a pressure of 100 bar. The superheated steam was generated directly inside the absorber tube without the use of any heat transfer fluid other than water. Electricity was not generated yet.

In May 2008, the German Solar Power Group GmbH and the Spanish Laer S.L. agreed upon the joint execution of a solar thermal power plant in central Spain. This will be the first commercial solar thermal power plant in Spain based on the Fresnel collector technology of the Solar Power Group. The planned capacity of the power plant will be 10 MW. It will combine a solar thermal collector field with a fossil co-firing unit as backup system. Start of construction is planned for 2009. The project is located in Gotarrendura about 100 km northwest of Madrid, Spain.

The Fresnel-technology is a line-focussing type of concentrating solar power (CSP). It is based on large arrays of modular Fresnel reflectors which direct the sunlight to a stationary receiver several meters high. This receiver contains a steel absorber tube and a so-called second stage reflector which re-directs the rays which did not directly hit the absorber. In the absorber tube, the concentrated sunlight is converting water to superheated steam with temperatures up to 450°C driving a turbine to produce electricity (SPG 2009).

Figure 3-27: Absorber tube box (left) and linear Fresnel collector assembly (right) of the FRESDEMO project at Plataforma Solar de Almeria, Spain (Source: MAN/SPG).

3.4.2 Linear Fresnel Collector for Direct Generation of Saturated Steam

The first European linear Fresnel system for power generation was commissioned in March 2009 near Calasparra, Spain. The Puerto Errado Plant No. 1 (PE 1) has two collector units about 800 meters long with a total of 18,000 m² collector area producing enough steam for a rated power capacity of 1 MW, each. The collectors are fabricated by robots in an automated production factory in Fortuna, Spain with a capacity of 220,000 m²/y. The automated fabrication has led to a very high optical accuracy of the reflector panels, while the on-site erection of the modular system is relatively simple. The regular cleaning of the collector field segments is also done automatically by a robot. The collector field produces directly steam at 55 bar, 270 °C which is fed into a saturated steam turbine with 1.4 MW capacity. An annual electricity production of 2.9 GWh is expected.

Figure 3-28: Puerto Errado linear Fresnel power station with 2 MW capacity (Novatec 2009)

Figure 3-29: Robot automatically assembling a linear Fresnel reflector element (left) and cleaning robot in operation on the solar field (right) (Paul 2008, Novatec 2009)

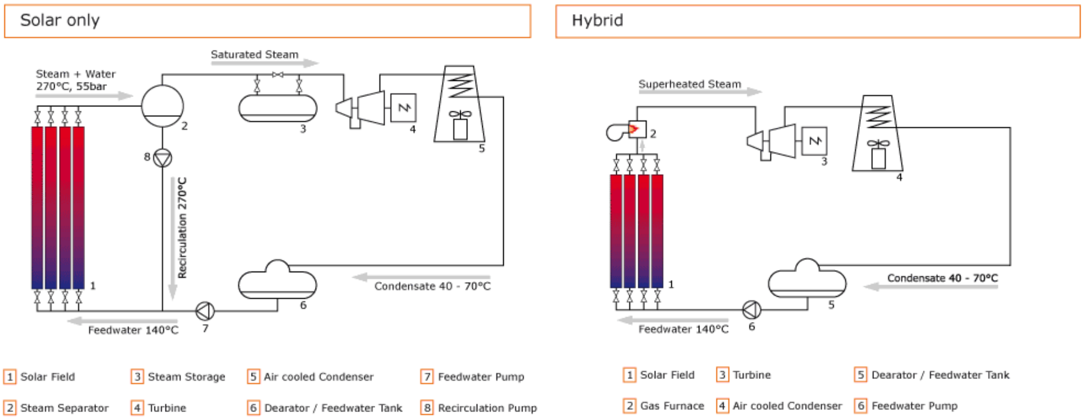


Figure 3-30: Simplified sketch of a saturated steam cycle power station with linear Fresnel collector for solar only operation (left) and with additional fossil fuel fired superheater (right) (Novatec 2009)

The implementing companies Novatec and Prointec are planning to install another facility PE-2 with a considerably higher capacity of 30 MW at Puerto Errado with a turnkey investment of 120 M€ which is presently under construction, and three further plants near Lorca.

The plants include a short term steam storage facility to compensate for cloud transients and use air-cooled condensers which can be applied anywhere without need for cooling water. There is a possibility of superheating the steam coming from the solar field by a conventional fossil fuel fired superheater (Figure 3-30). For the future, superheating of steam within the collector field to 350 °C is scheduled to be developed within the next generation of concentrating solar collectors.

3.5 CENTRAL RECEIVER SYSTEMS FOR STEAM CYCLE POWER PLANTS (10 - 100 MW)

3.5.1 PS10 Central Receiver for Saturated Steam Cycle Power Plant

The PS10 plant is a project funded by the European Community under the 5th Framework Programme (1998-2002)

The 11 MW PS10 solar power plant makes use of existing and proven technologies - as glass-metal heliostats, a saturated steam receiver, and water pressurised thermal storage.

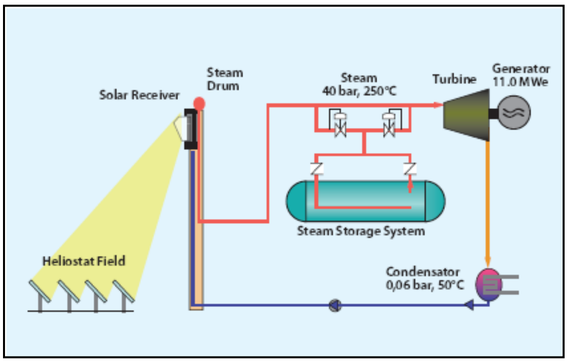
The PS10 has 624 heliostats; each one is a mobile 120m² curved reflective surface mirror. The receiver is designed to produce saturated steam at 250°C from thermal energy supplied by concentrated solar radiation. The thermal power received by the receiver is about 55MW at full load. The system has a saturated water thermal storage with a capacity of 20MWh. A part of the steam produced is used to load the thermal storage system during the full load operation of the plant.

The PS10 central receiver solar tower plant was built by Abengoa Solar after several years of research and development and began operation on March 30th, 2007. It is located in the Spanish province of Sevilla, in Sanlúcar la Mayor, and sits on 150 acres (60 ha). It is the first solar tower in the world commercially delivering electricity.

As seen in the operating schematic the plant generates saturated pressurized steam to run a conventional power cycle with 11 MW nominal power. The PS10 plant has 624 heliostats that are 120 m² each, which have an independent solar tracking mechanism that directs solar radiation toward the receiver. Heliostats have to be regularly cleaned and - when wind speed is higher than 36 km/h - they have to be set vertically to avoid structural damages. The receiver is located in the upper section of the tower. The receiver is a “cavity” receiver of four verticals panels that are 5.5 m wide and 12 m tall. The panels are arranged in a semi-cylindrical configuration and housed in a squared opening 11 m per side.

PS10 investment cost is about € 35 million. The project has been granted with some public contributions because of its highly innovative features. In this sense, 5th Framework Programme of European Commission has contributed through DG TREN (Directorate General for Transport and Energy) to PS10 investment costs with a € 5 million subvention (total eligible costs were € 16.65 million). In the same way, the regional administration through the Consejería de Innovación Ciencia y Empresa in the Junta de Andalucía Autonomic Government has supported PS10 project with € 1.2 million.

A second plant with 20 MW capacity (PS 20) is presently under construction at the same location.



PS10 – DESIGN FEATURES	
Location	Sanlúcar M., Spain
Nominal electrical power	11.02 MW
Tower height	100.5 m
Receiver technology	Saturated steam
Receiver geometry	Cavity 180°, 4 panels 5.40 m x 12.00 m
Heliostats	624 @ 120 m²
Thermal storage technology	Water/steam
Thermal storage capacity	20 MWh, 50 min @ 50% rate
Steam cycle	40 bar 250°C, 2 Pressures
Electric generation	6.3 kV, 50 Hz -> 66 kV, 50 Hz
Ground area	55 ha
Annual electricity production	23.0 GWh

Figure 3-31: PS10 central receiver schematic and design parameters (Abengoa Solar, EC 2007)

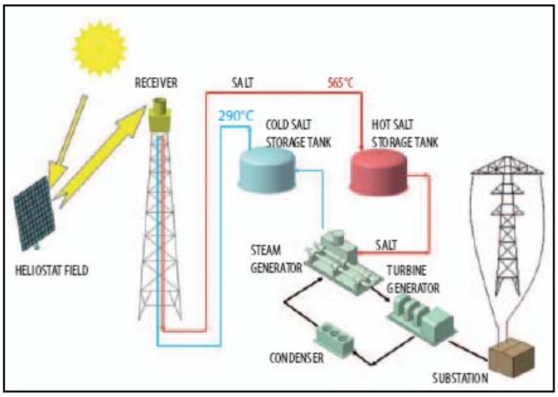
Figure 3-32: PS 10 central receiver solar tower facility near Sevilla, Spain (Abengoa Solar). In the background the PS20 facility can be seen under construction

3.5.2 The Solar Tres Central Receiver Plant Project

The main aim of the Solar Tres project is to demonstrate the technical and economic viability of molten salt solar thermal power technologies to deliver clean, cost-competitive bulk electricity.

Solar Tres consists of a 15 MW plant using the same central receiver approach as PS-10, while using innovative solutions for the energy storage system. The project total costs are about €196 million, the total eligible costs more than €15.3 million and the EC contribution is about €5 million. The partners involved in the Solar Tres project are GHERSA (Spain), Compagnie de Saint Gobain (France), CIEMAT (Spain), and Siemens (Germany). The Solar Tres project takes advantage of several technological innovations. These include:

- A larger plant with a 2,480-heliostat field and 120 m^2 glass metal heliostats – the use of a large-area heliostat in the collector field greatly reducing plant costs, mainly because fewer drive mechanisms are needed for the same mirror area.
- A 120 MW (thermal) high-thermal-efficiency cylindrical receiver system, able to work at high flux, and lower heat losses.
- A larger thermal storage system (15 hours, 647MWh, 6,250 t salts) with insulated tank immersion heaters – this high-capacity liquid nitrate salt storage system is efficient and low-risk, and high-temperature liquid salt at 565ºC in stationary storage drops only 1-2ºC/day. The cold salt is stored at 45ºC above its melting point (240ºC), providing a substantial margin for design.



SOLAR TRES – DESIGN FEATURES	
Location	Ecija, Spain
Receiver thermal power	120 MW
Turbine electrical power	17 MW
Tower height	120 m
Heliostats	2,480
Surface of heliostats	285,200 m^2
Ground area covered by heliostats	142.31 ha
Storage size	15 hr
Natural gas boiler thermal capacity	16 MW
Annual electricity production (min.)	96,400 MWh
CO_2 mitigation (best available technology)	23,000 ton/year
CO_2 mitigation (coal power plant)	85,000 ton/year

Figure 3-33: Sketch and basic design parameters of the Solar Tres central receiver plant (EC 2007).

3.5.3 The Solarturm Jülich Central Receiver Project in Germany

A central receiver demonstration plant is scheduled to be commissioned by mid 2009 in Jülich, Germany. The plant was developed by Solarinstitut Jülich and Kraftanlagen München (KAM) and has a heliostat field with roughly 20,000 m² area. The core element of the plant is an innovative open volumetric (porous) high temperature receiver (HiTRec) developed by DLR with 22 m² surface in 55 m height on the central tower, heating up ambient air that is sucked into the receiver to about 700 °C. By means of a heat exchanger, the hot air is used to produce superheated steam at 485 °C, 27 bar for a steam cycle power plant with 1.5 MW power capacity. The plant also has a ceramic packed bed as heat storage facility for about 1 hour operation to overcome cloud transients. The plant is operated by Stadtwerke Jülich GmbH. The overall investment cost of the plant is about 22 M€.

Figure 3-34: Heliostat field in front of the 1.5 MW central receiver power tower in Jülich, Germany (left) and sketch of the plant configuration (right) (STJ 2009)

3.6 CENTRAL RECEIVER SYSTEMS FOR GAS TURBINES AND COMBINED CYCLE POWER PLANTS (5 - 100 MW)

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. 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 (Figure 3-36). 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 temperature for gas turbine operation and the heat transfer using air require 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 (SOLGATE 2005).

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 3-35).

This system can heat pressurised air coming from the compressor of a gas turbine power cycle. A first pilot system (Solgate) has been installed and tested on the Plataforma Solar de Almería in Spain and the following targets have been 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.

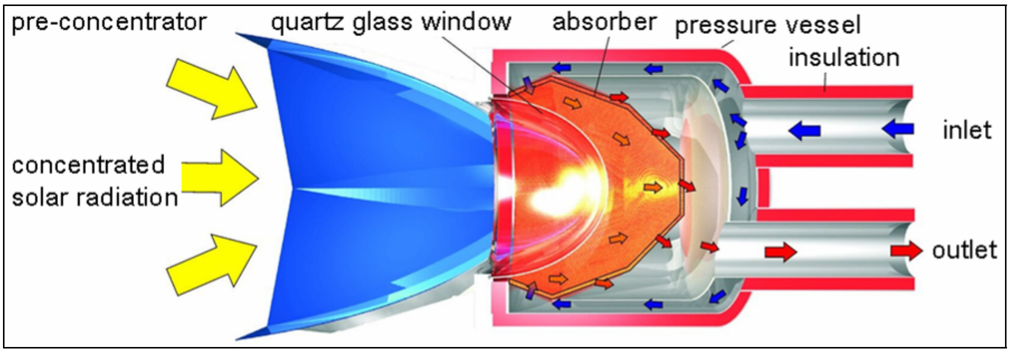


Figure 3-35: Pressurised air heated by solar energy using a volumetric receiver

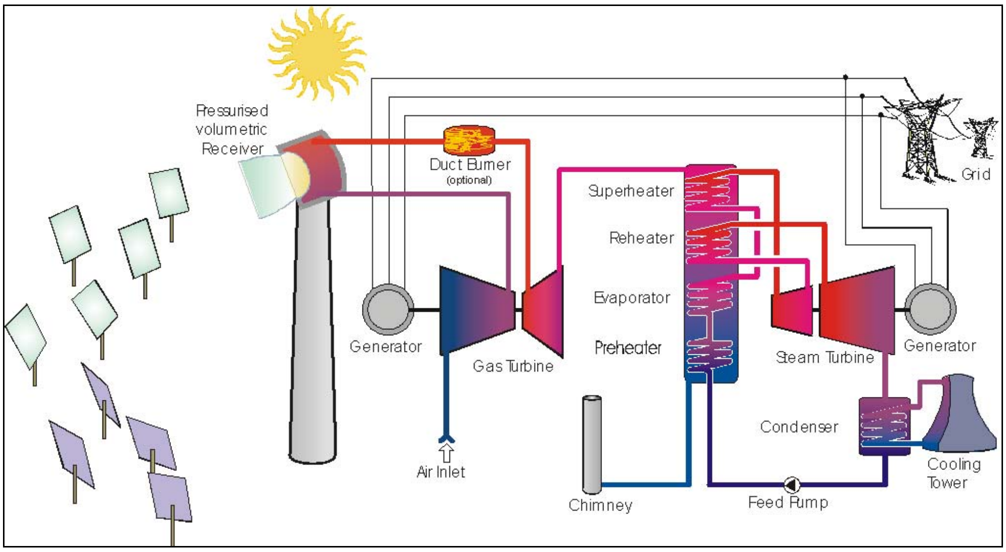


Figure 3-36: Solar tower used for gas turbine operation in a combined cycle power plant

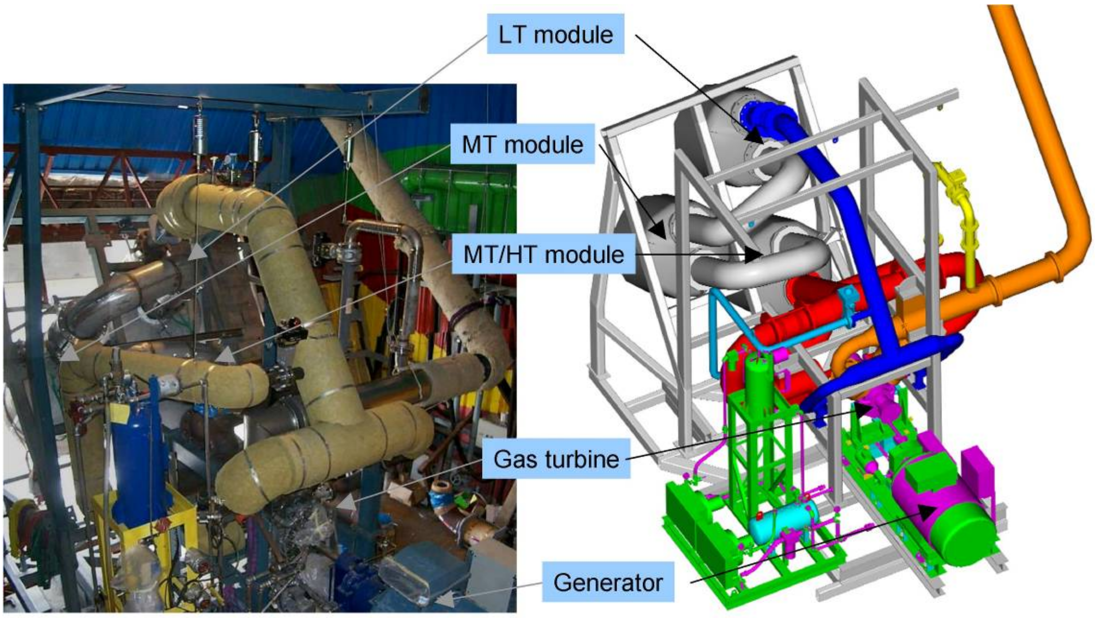


Figure 3-37: SOLGATE solar powered gas turbine test arrangement on top of the CESA-1 solar tower test facility at the Plataforma Solar de Almeria, Spain (SOLGATE 2005), LT low temperature, MT medium temperature, HT high temperature

3.7 CSP TECHNOLOGY DEVELOPMENT OUTSIDE EUROPE

3.7.1 Acciona Energia

Acciona Energia is a part of Acciona, a big Spanish infrastructure and services group. This group is active in wind energy (at the end of 2007 the company installed about 5000 MW) and also in the field of mini-hydro, cogeneration, biomass and hydrogen.[1] Acciona Energia works with all three solar technologies -CSP, PV and solar hot water - amounting to a total owned capacity of 195 MW. At the beginning of summer 2007 Acciona connected to the grid the largest CSP facility of its type in the world in the last 17 years: the 64 MW Nevada Solar One plant. Acciona is planning various CSP plants in Spain - all of which have a capacity of 50 MW, upper limit for the Spanish feed-in law for renewable energies- and participates to the major projects in the south-western United States.[2] Table 6 summarizes Acciona's already on-line projects.

Table 3-4: CSP projects of Acciona Energia in the US (by kernenergien)

Installation	**Technology**	**Location**	**On-line**	**Capacity [MW]**
APS Saguaro Project	Trough-ORC	Tucson, AZ, USA	2006	1
Nevada Solar One	Trough- ISG	Eldorado Valley, Boulder City, USA	Jun 07	64

Nevada Solar One is an Oil-ISG power plant with a gas co-firing unit that provide additional heating. The plant covers ca. 140 hectares of the desert near Boulder City in Nevada, south of Las Vegas. The German company Schott has provided 19300 PTR-70 receivers, which are vacuum tubes which absorb the reflected sunlight. They are located inside parabolic mirrors that are supplied by Flabeg, another German company.[3] The HTF contained in the receivers is heated up to 300 °C by the absorbed solar energy and is used to heat water into steam. The steam is then used to turn a turbine and generate electricity.

[1] Concentrating Solar Power: Technology, Cost and Markets. 2008 Industry Report, *Prometheus Institute*

[2] http://www.acciona-energia.com/default.asp?x=00020204

[3] http://www.reuk.co.uk/Nevada-Solar-One.htm

Figure 3-38: Nevada Solar 1 64 MW power plant supplying electricity to Las Vegas, US

The plant has an annual output of about 130 GWh: therewith it's possible to power more than 14000 households; the electricity production costs are estimated of 0.17 $/kWh and the O&M costs are about 0.05 $/kWh. Even if the price of produced electricity is higher than the electricity produced by the conventional power plants, because of tax credits, government subsides and a 20 years power purchase agreement (PPA) with Nevada Power and Sierra Pacific the plant is able to compete effectively in the peak power generation market.[4]

The APS Saguaro Project is a small (1 MW) Trough-ORC power plant located in Tucson, Arizona. A buffer tank provides storage for short periods without direct irradiation. The heated oil flows across the solar field and delivers heat an organic Rankine cycle (ORC) using pentane in a closed cycle that is cooled by a water-cooled condenser.

[4] Concentrating Solar Power: Technology, Cost and Markets. 2008 Industry Report, *Prometheus Institute*

3.7.2 Solel Solar Systems

Solel Solar Systems is a multinational company based in Israel, with subsidiaries Solel Inc. in the USA and PASCH Y CIA in Spain. Solel was the original supplier of the solar field for SEGS plants in California and has continued to implement trough technology to offer solar fields with improved performance. Actually Solel has an agreement for a 553 MW Power Purchase Agreement with California's Pacific Gas & Electric Company and is planning several 50 MW power plants in Spain. Solel manufactures evacuated receiver tubes and parabolic trough collectors for external sales, too.[5] The company has developed the vacuum receiver element for parabolic trough collectors UVAC 2008 (Figure 3-39). Table 3-5 shows Solel's CSP projects:

Figure 3-39: UVAC 2008 Solel Evacuated Receiver (From: http://solel.com)

Table 3-5: CSP projects of Solel (by kernenergien)

Installation	**Technology**	**Location**	**On-line**	**Capacity [MW]**
Solar Fields for SEGS Plants	Trough Solar Field	USA	1984	354
Receivers for Nevada Solar One	Receivers Tubes	USA	2007	64
Receivers Upgrade for FPL's Luz SEGS Plants	Receivers Tubes	USA	2007	100
Sacyr-Vallehermoso Plants	Trough Plant	Spain	Not reported	150
Aires Solar Termoeléctrica, S.L. Installations	Receivers Tubes	Spain	2008	100
Solel Mojave Solar Park	Trough Plant	USA	2011	553

[5] Concentrating Solar Power: Technology, Cost and Markets. 2008 Industry Report, *Prometheus Institute*

3.7.3 Ausra

The Ausra collector concept was born in the early 1990s at Sydney University and it was first commercialized by Solar Heat and Power Pty Ltd. in 2004 in Australia. This company implements Compact Linear Fresnel Reflector (CLFR) solar collector and steam generation systems (Figure 3-40).[6] Today, Ausra has secured significant funding, led by Khosla Ventures and Kleiner Perkins Caufield & Byers, and its main ambition is to obtain low costs with the simple CLFR solar field technology. The company started in Australia but now has headquarters in Palo Alto (California) and has stated the aim to go public by 2010. Ausra has several projects under development, as can be observed in Table 3-6. Ausra opened in June 2008 a factory in Las Vegas, in order to produce mirrors and absorber tubes for a capacity of 700 MW of power. Ausra and Pacific Gas and Electric communicated a power purchase agreement for a 177 MW solar thermal power plant for California, which will provide enough power for roughly 120000 homes. [7]

Table 3-6: List of Ausra's CSP projects

Installation	Technology	Location	On-line	Capacity [MW]
Steam production for Liddell Power Plant	LFR Solar Field	Liddell, Australia	2004	1
Kimberlina, US	LFR DSG	California	2009	5
PG&E San Luis Obispo Plant	LFR DSG	California	2010	177
FPL Plant	LFR DSG	USA	2010	300

Figure 3-40: Ausra's Compact Linear Fresnel Reflector (CLFR) (http://news.cnet.com/)

[6] http://www.ausra.com/about/

[7] http://news.cnet.com/8301-11128_3-9980815-54.html?tag=mncol;txt

3.7.4 Skyfuel

Skyfuel was founded in 2005 by Arnold Leitner, the chairman of the Solar Electric Division of the American Solar Energy Society (ASES). Skyfuel is implementing trough and LFR technology with Refletech^{TM} reflective films. The company has received a grant from the New Mexico Energy Innovations Fund and from the Solar Energy Technologies Program of the U.S. Department of Energy (DOE/SETP): therewith Skyfuel is currently developing its first installations.[8] With the DOE's support SkyFuel plans to set up the LTP by 2011.[9]

RefleTech Solar Film is a high-reflective, silver-metallised film. It is designed for CSP technologies as well as for other reflector applications that require outdoor durability. The product is an invention of RefleTech and the NREL. RefleTech Solar Film is made up of multiple layers of polymer films with an inner layer of pure silver to provide high reflectance. This special assembly defends the silver layer from oxidation.[10] Figure 3-41 shows the reflectance of RefleTech as a function of the light's wavelength.

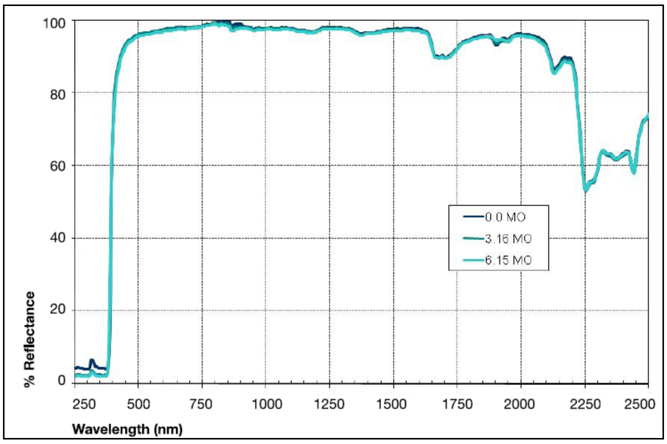


Figure 3-41: Inspection of Refletech Film Reflectors at SEGS VI and Skyfuel Refletech`s Reflectance performance over wavelength (http://www.skyfuel.com/)

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[8] Concentrating Solar Power: Technology, Cost and Markets. 2008 Industry Report, *Prometheus Institute*

[9] http://www.renewableenergyworld.com/rea/news/story?id=50739

[10] http://www.skyfuel.com/

3.7.5 Brightsource Energy / Luz II

BrightSource is a privately held company and its investors include: VantagePoint Venture Partners, Google.org, BP Alternative Energy, Chevron Technology Ventures, StatoilHydro, Draper Fisher Jurvetson, DBL Investors, and Black River. Arnold Goldman, who founded also Luz International, Ltd., created also BrightSource Energy. The Luz International was the company that built the 9 Solar Electricity Generating Stations (SEGS) in California's Mojave Desert.

Actually, Luz II is focusing on Distributed Power Towers (DPT) technology. LUZ II plants produce electrical power by using solar energy in order to convert water to superheated steam. Solar fields reflect sunlight onto a receiver located on the top of a Power Tower. Each Power Tower module is linked by pipelines to a central location where superheated steam and electricity are produced. The first installation is operating in Israel as a pilot plant (Figure 3-42). The facility produces superheated steam but not yet electricity.[11]

A series of 100 MW and 200 MW commercial solar power plants are scheduled to come on line in 2010. LUZ II's DPT technology consists of a number of solar clusters, each including a power tower surrounded by an array of heliostats. Heliostats are flat glass mirrors which track the sun and reflect sunlight onto a receiver. The receiver is located on the top of the power tower. Power towers are linked together by pipelines to a central location where electricity is generated and sent to a power grid. The DPT 550 technology heats water to superheated steam at pressures up to 160 bar and temperatures up to 565 °C. A high efficiency steam turbine converts the superheated steam to electricity, which is sent to a power grid.

Figure 3-42: Brightsource distributed power tower pilot plant

[11] http://www.luz2.com/

3.7.6 Solar Reserve

The United Technologies Corporation and the US Renewable Group joined forces in early 2008 to create Solar Reserve, a company dedicated to the development of molten salt tower power plants. UTC, trough Rocketdyn, Pratt & Whitney and Hamilton Sunstrand pioneered this technology trough the development of the now decommissioned Solar One and Solar Two tower installations. UTC has granted Solar Reserve an exclusive worldwide license to this technology and its full technical support. US Renewables Group, a $575 M private equity firm exclusively focused on the development of renewable energy and clean fuel projects, contributes its financial experience to the new company.[12]

3.7.7 eSolar

eSolar, based in Pasadena (California) is the utility-scale solar company and has developed a cost effective utility-scale CSP power plant that is based on mass manufactured components and designed for rapid construction, uniform modularity, and unlimited scalability. The eSolar approach offers a low-impact and pre-fabricated design to provide solar electricity ranging from 33 MW to over 500 MW (see Figure 3-43). The eSolar™ solution delivers cost competitive solar energy in order to meet the growing worldwide energy demands. The company is supported among other by Idealab and Google.[13] In June 2008 eSolar declared that it will build plants for Southern California Edison for a total capacity of 245 MW.[14]

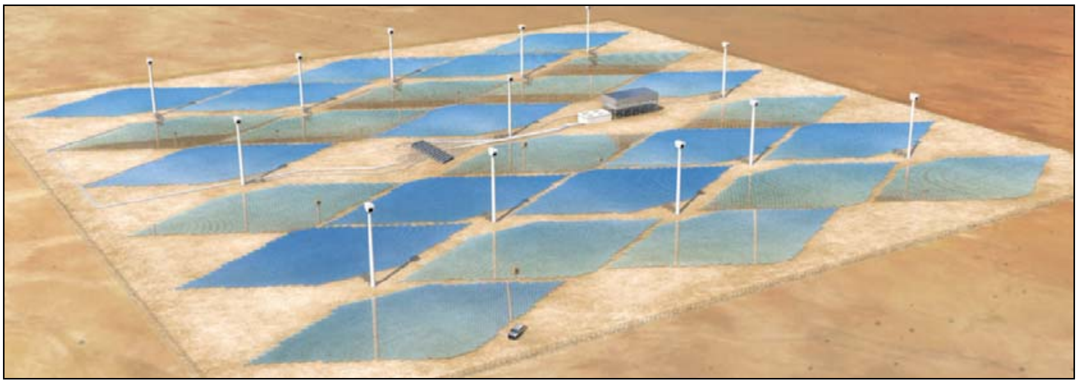


Figure 3-43: eSolarTM 33 MW Power Unit (http://www.esolar.com/esolar_brochure.pdf)

[12] Concentrating Solar Power: Technology, Cost and Markets. 2008 Industry Report, *Prometheus Institute*

[13] Concentrating Solar Power: Technology, Cost and Markets. 2008 Industry Report, *Prometheus Institute*

[14] http://news.cnet.com/8301-11128_3-9980815-54.html?tag=mncol;txt

3.8 CURRENT CSP PROJECT DEVELOPMENT (MARCH 2009)

The current development of CSP projects is very dynamic and therefore difficult to assess. At the end of 2008 approximately 482 MW capacity of commercial plants were in operation of which almost 419 MW were installed in the USA, 63 MW in Spain and another 0.36 MW in Australia. The concept mostly used is parabolic trough mirrors with an overall capacity of 468.8 MW. The remaining 13.36 MW are a tower project in Spain with 11 MW and a Fresnel reflector system with 2 MW in Spain and another one in Australia with 0.36 MW capacity (Table 3-7).

Most of the existing capacity was built in a period from the mid 1980ies to the early 1990ies. The development back then was ascribed to the oil shock in the late 70ies and the resulting rise of electricity prices. As the prices declined shortly afterwards no further CSP projects were initiated between 1991 and 2005 due to the decreased competitiveness and missing political support for this technology (Figure 3-44).

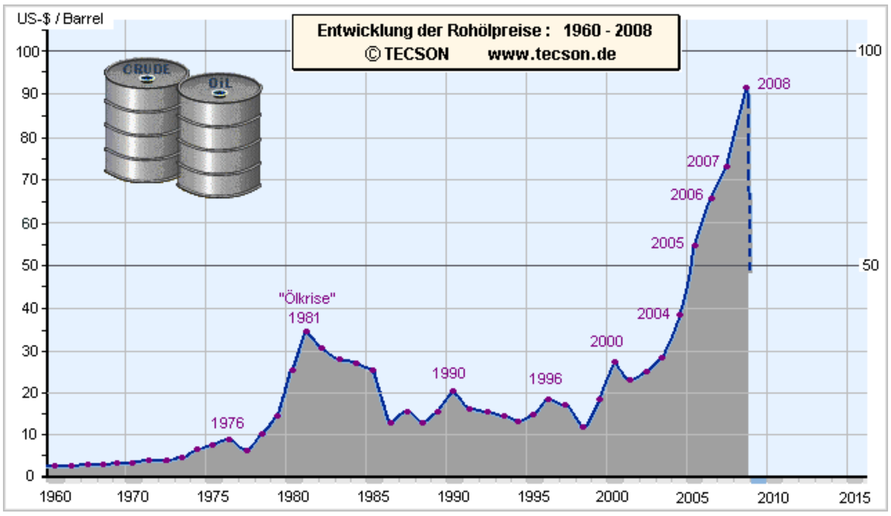


Figure 3-44: Development of Crude Oil Prices since 1960 (TECSON 2009)

With strongly increasing fuel prices the use of renewable energies became more important in recent years and several governments adopted promotion schemes. The use of CSP is now also experiencing a revival. In 2007 three installations with a total capacity of about 75 MW came into operation followed by another installation with 52 MW in 2008. After a steep fall of oil prices from over 90 $/bbl average in 2008 to 40 $/bbl starting 2009, the oil price is again steadily increasing, regaining a level of 55 $/bbl by May 2009. At the same time the cost of raw materials like steel and the capital cost (loan interest rates) for CSP plants declined considerably. Therefore, the momentum created for CSP development in the recent years will most probably continue further.

Table 3-7: CSP plants in operation in spring 2009.

Plant name	Net Power Capacity [MW_e]	Type	Constructor	Country	Year of initial operation
SEGS 1	13,8	Parabolic trough	Luz	USA	1985
SEGS 2	30	Parabolic trough	Luz	USA	1986
SEGS 3	30	Parabolic trough	Luz	USA	1987
SEGS 4	30	Parabolic trough	Luz	USA	1987
SEGS 5	30	Parabolic trough	Luz	USA	1988
SEGS 6	30	Parabolic trough	Luz	USA	1989
SEGS 7	30	Parabolic trough	Luz	USA	1989
SEGS 8	80	Parabolic trough	Luz	USA	1990
SEGS 9	80	Parabolic trough	Luz	USA	1991
Arizona Public Services Saguaro Project	1	Parabolic trough	Solargenix Energy	USA	2006
Nevada Solar One	64	Parabolic trough	Acciona/ Solargenix Energy	USA	2007
PS10	11	Tower	Abengoa Solar	Spain	2007
Liddell Power Station	0.36	Fresnel reflector		Australia	2007
Andasol 1	50	Parabolic trough	Solar Millenium and ACS/Cobra	Spain	2009
Puerto Errado 1	2	Fresnel reflector	Tubo Sol Murcia, S.A.	Spain	2009

About 16 projects were under construction in spring 2009 summing up to a capacity of 540 MW. Again Spain with 389 MW and the USA with 86 MW are the largest contributors to this development. The remaining projects are constructed in Egypt (25 MW) as well as Algeria (20 MW) and Morocco (20 MW).

Table 3-8: CSP plants under construction in Spring 2009.

Plant name	Net Power Capacity [MW_e]	Type	Constructor	Country
Martin Next Generation Solar Energy Center	75	ISCC	FPL	USA
Andasol 2	50	Parabolic trough	Solar Millenium and ACS/Cobra	Spain
Andasol 3	50	Parabolic trough	MAN Solar Millenium (JV MAN Ferrostaal + SM), Duro Felguera S.A. Energía, Gijón [2]	Spain
Extresol 1	50	Parabolic trough	ACS/Cobra	Spain
Solnova 1	50	Parabolic trough	Abengoa Solar	Spain
Solnova 3	50	Parabolic trough	Abengoa Solar	Spain
Puertollano	50	Parabolic trough	Iberdrola	Spain
La Risca 1 or Alvarado	50	Parabolic trough	Acciona	Spain
Kuraymat Plant	25	ISCC	Solar Millenium	Egypt
Hassi R'mel	20	ISCC	Abengoa Solar	Algeria
Ain Beni Mathar Plant	20	ISCC	Abengoa Solar	Morocco
PS 20	20	Tower	Abengoa Solar	Spain
Solar Tres	19	Tower	Sener/Torrosol	Spain
Esolar Demonstrator	5	Tower	Esolar	USA
Kimberlina	5	Fresnel	Ausra	USA
Keahole Solar Power	1	Parabolic trough	Sopogy	USA

The dominating technology is once again parabolic trough. Eight projects use this technology summing up to an overall installation of 351 MW. Another four projects are hybrid installations so called Integrated Solar Combined Cycle (ISCC) plants. This technology combines a solar field of parabolic trough collectors with a gas fire combined cycle plant.

Tower technology is applied in three projects under construction at the moment aiming for 44 MW of installed capacity. The Fresnel technology is currently in the process of installation in one project in the USA. Figure 3-45 shows CSP capacities currently in operation or under construction per country.

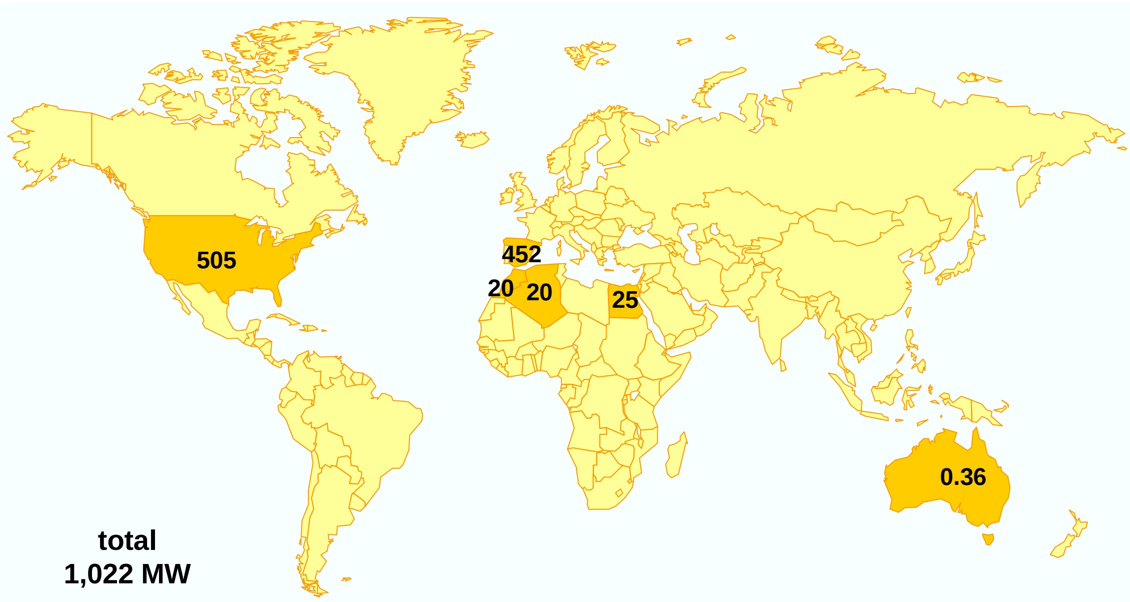


Figure 3-45: CSP capacities in operation or under construction at the end of 2008.

It is not clear how large the number of currently planned installations is. Declarations of intend can be found on many different levels regarding existing technology as well as demonstration projects of new technological developments. The status of many of these projects is constantly changing. Figure 3-46 and the following Tables give an overview of announced projects at the end of 2008 excluding political goals like Chinas target to install 1,000 MW CSP capacity until 2020.

Overall 5,975 to 7,415 MW planned capacity of CSP plants could be identified on a project level that was announced until the end of 2008 (Figure 3-46). The countries that account for the majority of these projects are once again the USA and Spain. Table 3-9 shows a detailed list of the announced installations in the USA that amounted to 3,407 to 4,847 MW. Another 1,980 MW are planned in Spain (Table 3-10). It can be observed that the list of projects in Spain is a lot larger than the one in the United States even though the overall announced capacity is smaller. The reason for this is the promotion scheme of Spain that provides a feed in tariff for installations up to 50 MW. The remaining announcements of another 588 MW planned capacity can be found in various other countries (Table 3-11).

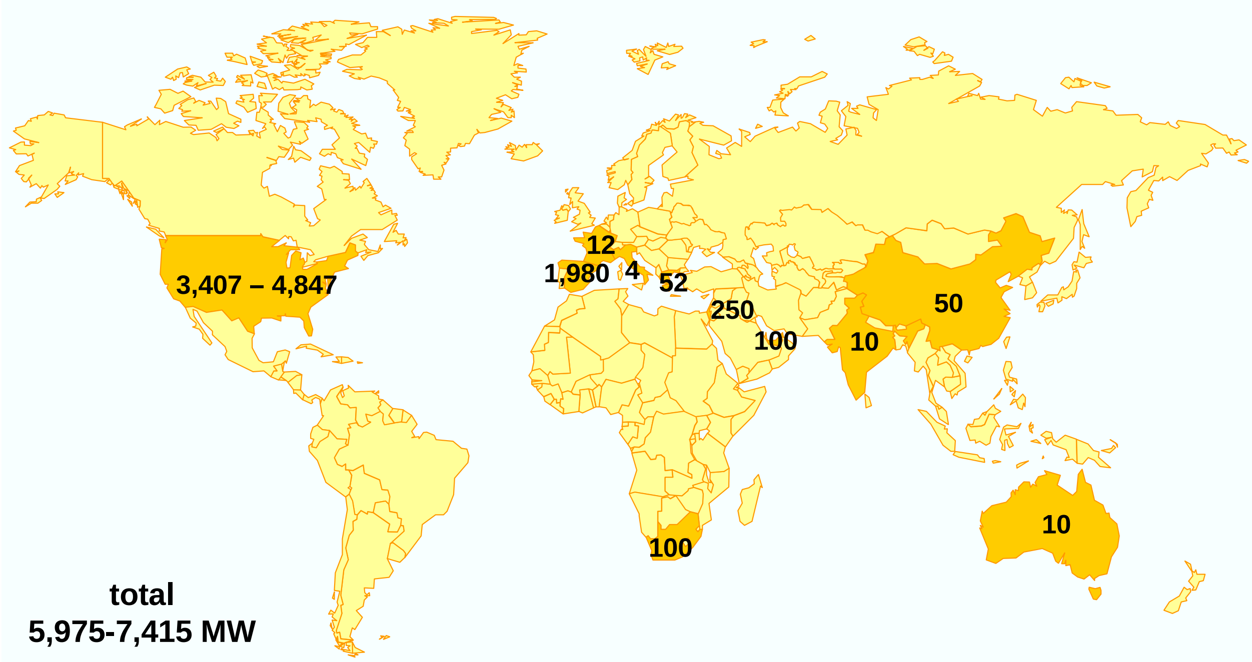


Figure 3-46: Announced CSP installations at the end of 2008.

Table 3-9: Announced CSP installations in the USA.

Plant name	**Net Power Capacity [MW_e]**	**Type**	**Constructor**	**Country**
Ivanpah 1	123	Tower	Brightsource	USA
Ivanpah 2	100	Tower	Brightsource	USA
Ivanpah 3	200	Tower	Brightsource	USA
(Brightsource other)	100 (+400)	Tower	Brightsource	USA
Mojave Solar Park	553	Parabolic trough	Solel	USA
SES Solar One	500 (+300)	Dish	Stirling Energy Systems	USA
SES Solar Two	300 (+600)	Dish	Stirling Energy Systems	USA
Solana	280	Parabolic trough	Abengoa	USA
Carrizo Solar Farm	177	Fresnel	Ausra	USA
Beacon Solar Energy Project	250	Parabolic trough	FPL	USA
Gaskell Sun Tower	105-245	Tower	Esolar	USA
San Joaquin Solar 1 & 2	107	Parabolic trough	Martifer Renewables	USA
City of Palmdale Hybrid Power Project	62	ISCC		USA
Harper Lake Energy Park	500	Parabolic trough		USA
Victorville 2 Hybrid Power Project	50	ISCC		USA

Table 3-10: Announced CSP installations in Spain.

Plant name	**Net Power Capacity [MW_e]**	**Type**	**Constructor**	**Country**
Lebrija 1	50	Parabolic trough	Solel	Spain
Andasol 4	50	Parabolic trough	ACS/Cobra	Spain
Extresol 2	50	Parabolic trough	ACS/Cobra	Spain
Extresol 3	50	Parabolic trough	ACS/Cobra	Spain
Manchasol 1	50	Parabolic trough	ACS/Cobra	Spain
Manchasol 2	50	Parabolic trough	ACS/Cobra	Spain
Andasol 5	50	Parabolic trough	Solar Millenium	Spain
Andasol 6	50	Parabolic trough	Solar Millenium	Spain
Andasol 7	50	Parabolic trough	Solar Millenium	Spain
Solnova 2	50	Parabolic trough	Abengoa	Spain
Solnova 4	50	Parabolic trough	Abengoa	Spain
Solnova 5	50	Parabolic trough	Abengoa	Spain
AZ 20	20	Tower	Abengoa	Spain
Aznalcollar TH	0,08	Dish	Abengoa	Spain
Ecija 1	50	Parabolic trough	Abengoa	Spain
Ecija 2	50	Parabolic trough	Abengoa	Spain
Helios 1	50	Parabolic trough	Abengoa	Spain
Helios 2	50	Parabolic trough	Abengoa	Spain
Almaden Plant	20	Tower	Abengoa	Spain
Termesol 50	50	Parabolic trough	Sener	Spain
Arcosol 50	50	Parabolic trough	Sener	Spain
Ibersol Badajoz	50	Parabolic trough	Iberdrola	Spain
Ibersol Valdecaballeros 1	50	Parabolic trough	Iberdrola	Spain
Ibersol Valdecaballeros 2	50	Parabolic trough	Iberdrola	Spain
Ibersol Sevilla	50	Parabolic trough	Iberdrola	Spain
Ibersol Almería	50	Parabolic trough	Iberdrola	Spain
Ibersol Albacete	50	Parabolic trough	Iberdrola	Spain
Ibersol Murcia	50	Parabolic trough	Iberdrola	Spain
Ibersol Zamora	50	Parabolic trough	Iberdrola	Spain
Enerstar Villena Power Plant	50	Parabolic trough	Enerstar	Spain
Gotasol	10	Fresnel	Solar Power Group	Spain
Aste 1 A	50	Parabolic trough	Aries	Spain
Aste 1 B	50	Parabolic trough	Aries	Spain
Aste 3	50	Parabolic trough	Aries	Spain
Aste 4	50	Parabolic trough	Aries	Spain
Astexol 1	50	Parabolic trough	Aries	Spain
Astexol 2	50	Parabolic trough	Aries	Spain
Puerto Errado 2	30	Fresnel	Tubo Sol Murcia, S.A.	Spain
La Risca 2	50	Parabolic trough	Acciona	Spain
Palma del Rio 1	50	Parabolic trough	Acciona	Spain
Palma del Rio 2	50	Parabolic trough	Acciona	Spain
Consol 1	50	Parabolic trough	Conergy	Spain
Consol 2	50	Parabolic trough	Conergy	Spain

Table 3-11: Announced CSP installations in various other countries.

Plant name	**Net Power Capacity [MW_e]**	**Type**	**Constructor**	**Country**
Ashalim	250	Parabolic trough		Israel
Uppington	100	Tower	Eskom	South Africa
Shams	100	Parabolic trough		ABU DHABI
Cloncurry solar power station	10	Tower	Ergon Energy	Australia
Archimede	3,75	ISCC	Enel etc.	Italy
Solenha	12	Parabolic trough	Solar Euromed	France
Theseus Project	52	Parabolic trough	Solar Millenium	Greece
	50	Parabolic trough	Solar Millenium	China
	10		ACME	India

As the development is rapid and many projects might have slipped through the collection displayed above a number of other publications will be referenced in the following.

3.9 REVIEW OF CSP INDUSTRY (MARCH 2009)

In a recent report titled “The CSP Industry – An Awakening Giant”, the Deutsche Bank predicts strong structural growth prospects for CSP industry in the coming decades (Deutsche Bank 2009). This view of a major global financing institution coincides very well with present project development activities, with the appearance of many new CSP designs and players all over the world, with the implementation of suitable financing instruments like feed-in tariff systems and tax credits by many governments and with the deficiencies of the fossil and nuclear energy supply system of the past century becoming more and more obvious. CSP is getting into the minds of investors and politicians as a very large renewable energy source that can deliver electricity on demand.

Table 3-12 gives an overview of companies currently involved in the project development, engineering, procurement, construction and operation of CSP plants and of their role in the CSP market.

Table 3-13 names players from research and development, investors, utilities and lobby groups presently involved in CSP deployment.

The list does not claim to be complete, as new players appear almost daily.

Table 3-12: Overview of present CSP Industries

Companies	Project Development	Financial Engineering	Engineering	Procurement, Technology	Construction	Operation & Ownership
	Site qualification, feasibility study, pre-planning, regulatory, economic and technical analysis	Devise viable financing structure and provide for financing, investor relations	Detail planning & implementation, plant layout, quality management, supervision	Supply technology - receiver, mirrors, support structure, power block, thermal storage etc.	Construction works	Hold, buy and sell shares in the power plant, operate plants
Abener			X	X	X	
Abengoa S.A.	X	X	X	X	X	X
Acciona Energía	X	X	X	(X)	X	X
ACS Cobra	X		X		X	
Albiasa Solar	X					
Alstom				X		
Aries	X		X	X	X	
Astrom			X			
Ausra	X	X	X	X		
Babcock Montajes					X	
Balcke-Dürr				X		
Bright Source Energy Inc.	X	X	X	X	(X)	X
Défi-Systémes				X		
Endesa						X
ENEL						X
Enolcon	X		X			
Enerstar	X					
Enviromission	X		X	X	(X)	(X)
Epuron	X	X				X
Eskom	X	X	(X)			X
Fichtner	X		(X)			
Flabeg				X		
Flagsol	X		X			
FPLEnergy			X	X	X	X
GE				X		
GEA Ibérica				X		
Goldman Sachs						X
Guardian				X		
Iberdrola	X					X
Iberinco			X	X	X	
KAM			X	X	X	
kernenergien	X					
Lahmeyer	X		X			
M&W Zander			X	X	X	
MAN Ferrostaal					X	
Morgan Stanley						X
NEAL	X					X
Novatec Biosol AG	(X)	(X)	X	X	X	X
Orascom			X		X	
PG&E						X
Rioglass				X		
Sacyr Vallehermoso					X	
Saint Gobain				X		
Schlaich Bergermann	(X)		X			
Schott Solar				X		
Sener	X	(X)	X		(X)	
SES	X					
Siemens				X		
Sky Fuel	X		X	X	(X)	(X)
Solar Heat and Power	(X)		(X)	X		
Solar Millenium AG	X	X	X	X	X	X
Solar Power Group	(X)	(X)		X		
Solargenix Energy LLC	X		X	X	(X)	
Solel Ltd.	X		X	X	(X)	
SPX Cooling				X		
Stirling Energy Systems	X	X	(X)	X		X
Thermodyn				X		
Torresol	X					

Sources: Deutsche Bank 2009, EuPD Research 2008, new energy finance 2008, DLR

Table 3-13: Other Players involved in CSP

Research & Development	Utilities	Investors / Creditors	Lobbies & Associations
Solar resource assessment, systems analysis, technology assessment, system and component development, basic research	Utility Services, Sales, Trade, Power Purchase Agreements	Equity Investment, Loans, Financial Engineering, Support, Grants	Lobbying, campaigning, information
CENER	APS	ADB	DESERTEC Foundation
CERTH	ENDESA	Banc Sabadell	ESTELA
CIEMAT	ENEL	Banesto	Greenpeace
CNRS	ESKOM	Caja Madrid	SEIA
DLR	Iberdrola	Calyon	SolarPaces
Fraunhofer ISE	NEAL	CAM	SW-CSP Initiative
IDAE	Nevada Solar	Cofides	TREC
INETI	ONE	Commerzbank	
IRSOLAV	Sierra Pacific	EIB	
Mines-ParisTech		Fidelity	
NASA		ING	
NREL		JBIC	
PSI		KfW IPEX	
SUNLAB		Lupus Alpha	
SUNY		Masdar	
Weizmann Inst.		Natixis	
		Piraeus Bank	
		Santander	
		SI capital	
		Societé Generale	
		Swisscanto	
		Ubibanca	
		UBS	
		Union Invest	
		West LB	
		World Bank / GEF	

Sources: EuPD Research 2008, DLR, Deutsche Bank 2009

4 TASK 2: DESALINATION TECHNOLOGY REVIEW

4.1 Introduction

Over time a lot of different desalination technologies have been invented for small and large application. The basic principle for several methods will be described. This study focuses on cogeneration of power and sea water desalination therefore a more detailed thermodynamic analysis of membrane and thermal desalination follows. The concentration of salt in water is described by the total dissolved solid content (TDS) or salinity in mg salt per l water. The following list shows the classification of saline water based on the TDS:

River water / low concentrated brackish water	500 – 3.000 mg/l TDS
Brackish water	3.000 – 20.000 mg/l TDS
Sea water	20.000 – 50.000 mg/l TDS
Brine	> 50.000 mg/l TDS

The WHO recommends water with a salinity below 1000 mg/ l for drinking water and irrigation. Industrial processes or process water for power plants require a much higher water quality with a TDS less than 10 mg/l. This can be provided by thermal distillation processes in a single step. However, if this water shall be used for drinking water minerals have to be added again. The report, starting with a short retrospection into the past, covers most of the technologies available with a strong focus on state-of-the-art for the site studies.

Already Aristotle, considered the last philosopher who was probably the last person to know everything there was to be known in his own time has written about seawater distillation. Abu al-Mansur al Muwaffak an early islamic scientist reported about distillation to produce drinking water from sea water in the 10th century. /Levey 1973/.

The first patents for seawater distillation in the history of western science have been published at the end of the 17th century, 1675 by William Wilcot and followed 1683 by Robert Fitzgerald /Forbes 1970/. This lead to an early dispute about the patents, with interests of the crown of England colliding with inventors rights /MacLeod 2002/.

The term of “osmosis” in connection with liquid phase separation by a membrane has been described in 1748 by J.A. Nollet. 200 years later “reverse osmosis” started to become the leading technology for desalination by membrane processes.

One of the first, if not the first thermal heat pump at all has been described already in 1834 by Pelletan. Pelletan published a heat pump with a steam ejector in order to recover the heat of evaporation from a salt concentrator.

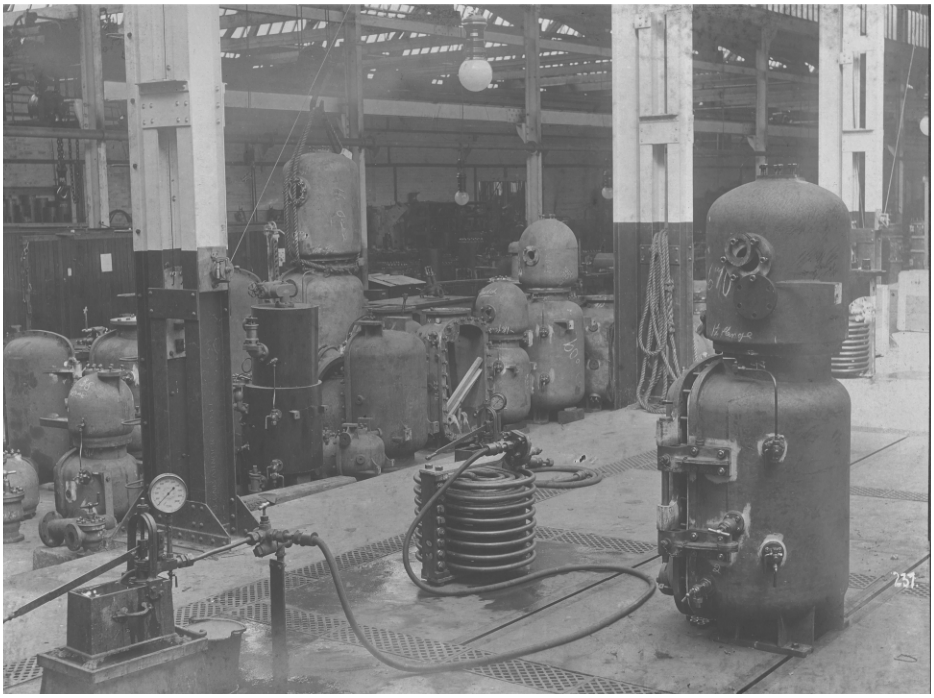


Figure 4-1: Submerge tube 1904; courtesy of Weir Westgarth, company presentation 2003

In 1879 the first patent for mechanical vapor compression has been filed. At the turn of the century, in 1900, the multi flash distillation process was invented, followed 1908 with the first patent for TVC (thermal vapor compression). The first multi effect evaporators have been built in the middle of the 19th century. A typical application for small distillation units in this time was on ships (see Figure 4-1). From this time onward sea water distillation became more and more sophisticated with the main technologies described in the following chapters.

In the following chapter the most important desalination technologies will be described. Included are well developed state of the art technologies like MSF, MED and RO as well as new developments (MEH, VMEMD). Distilled water can be produced from saline water by two main processes, evaporation and separation through membranes (Table 4-1). The driving energy for both processes can be either electrical power or thermal energy.

Thermal desalination plants use heat sources as the driving force. These heat sources can be hot water or steam from a turbine. Therefore thermal desalination is ideal for co-generation with power plants. Electrical power is only necessary for parasitical internal demands such as pumps etc.

Table 4-1: Overview of desalination technologies

Process / Driving power	Evaporation	Membrane
Thermal	Multi Stage Flash (MSF) Multi Effect Distillation (MED) Solar Stills Multi Effect Humidification (MEH)	Vacuum Membrane Distillation (VMemD)
Electrical	Mechanical Vapour Compression (MVC)	Electro Dialysis (ED) Reverse Osmosis (RO)

4.2 Evaporation Processes

4.2.1 Mechanical Vapour Compression MVC

A mechanical vapour compression MVC unit is essentially an MED unit. Like with a MED process sea water is sprayed on the tube surface. The evaporated water will be compressed in a mechanical compressor. The compressed steam is condensed and exchanging heat again with the sea water. MVC plants are driven by electrical power.

The advantage of a MED with mechanical vapour compressor is, it does not need steam and is very robust like all MED. But the compressors are expensive, though compressors with higher compression ratio are available now. Usually fans with a low compression ration are used with $p/p_0 < 1{,}3$. higher compression ratio requires axial compressors which are very expensive.

A MED-MVC requires large heat transfer surface in order to achieve low power consumption. Large pre-heaters have to be installed to maintain evaporation at roughly 55-65°C. Their size is limited by the availability of the compressors suction flow rates.

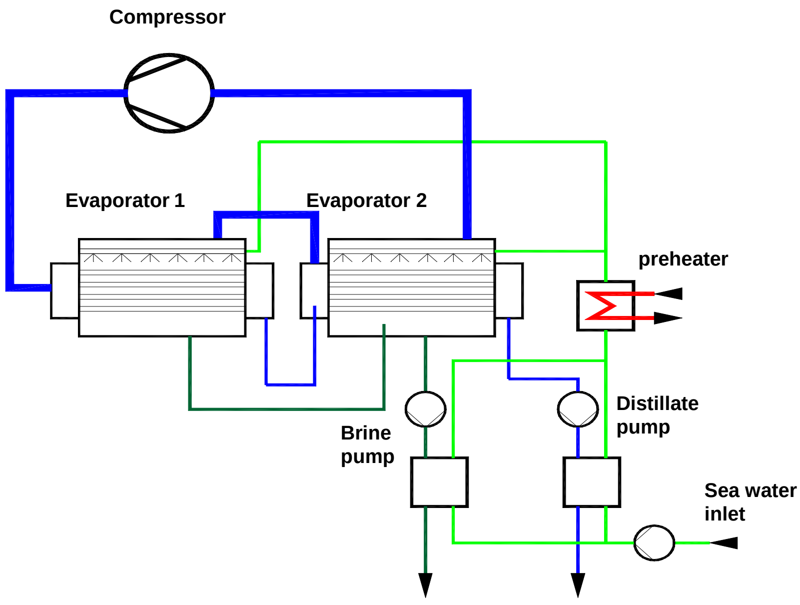


Figure 4-2: Scheme of mechanical vapour compression

4.2.2 Multi Stage Flash desalination (MSF)

A multi stage flash desalination plant consists of several serial stages of chambers/vessels. The upper parts are condensers. Each stage is operated at about 2-5 K lower temperature than the previous one. The number of flash stages can vary form 10 to 30. The sea water is heated step by step in the condenser tubes. In the last step sea water is heated by hot water or steam from an external source in the so-called brine heater. The hot sea water is then flashed into the first chamber and partly evaporated. The generated steam is condensed and collected to be used as the distillate.

MSF plants are extremely robust and have a high reliability with long running periods between cleaning (6 - 24 months). They can treat very saline raw water and still produce good distillate quality (typically 1-10 ppm TDS). Inside the condenser tubes there is only single phase heat transfer and no degassing inside heat exchangers which in turn reduces scaling. However MSF plants are rather expensive needing large specific heat transfer surfaces. Further the electrical energy consumption is quit high compared to other thermal systems (3-4 kWh/t). The MSF have been the work horse of desalination for more than 40 years.

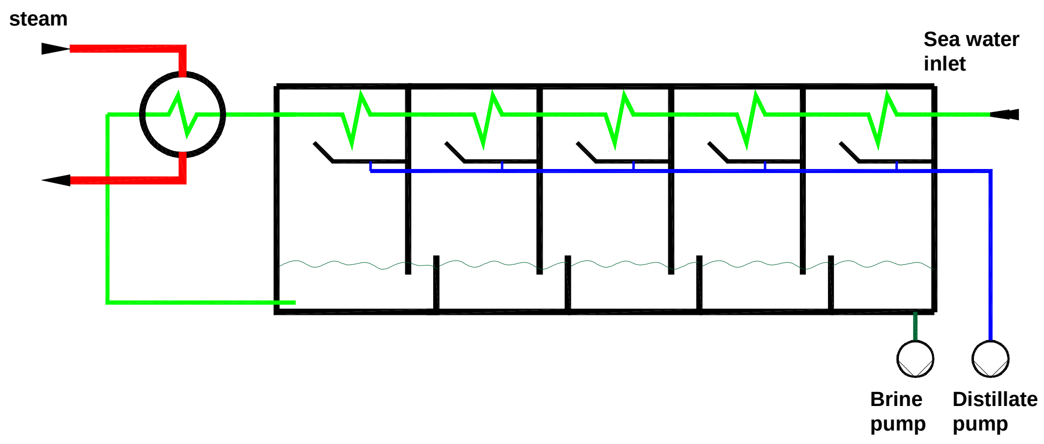


Figure 4-3: Scheme of the MSF process

4.2.3 Multi Effect Distillation (MED)

A multi effect distillation plant consists of several stages of evaporators under vacuum. Sea water is distributed on the outer surface of the tubes and partly evaporated. The driving heat of the first evaporator is hot water or low pressure steam from an external source with a maximum temperature of 70°C. All other evaporators use the evaporated water vapour of the previous stage as heat source. This steam condenses and will be used as process or drinking water.

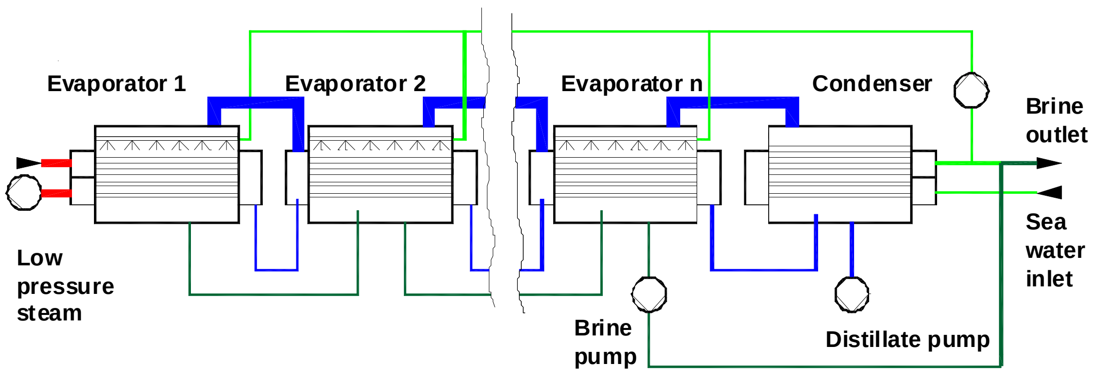


Figure 4-4: Scheme of the MED process

Like the MSF, MED plants can treat very saline raw water and produce good distillate quality. They are also highly reliable with long running periods between cleaning (6 - 24 months). MEDs are less expensive than MSF since they need a much smaller heat transfer surface. Further no sophisticated equipment is required. MEDs have a better thermal efficiency and very low electrical consumption (0.5-0.6 kWh/t). The heat transfer in MED is with dual phase flow, thus degassing occurs during evaporation. However the tube surface can only be cleaned chemically. The maximum steam temperature is limited to 70°C due to scaling, i.e. the number of stages is also limited.

Recent developments for both MSF and MED include upstream removal of Ca and Mg by nano-filtration (NF) as well as degassing and acid dosing to remove CO2 and reduce vacuum pumping, which may have a potential to increase. The downside, however is a significant increase in complexity.

4.2.4 Multi Effect Distillation with Thermal Vapor Compression (MED–TVC)

If high pressure steam from a power plant is available, the output of a MED plant can be further enhanced using a steam ejector. The high pressure steam is the motive steam, providing the energy for recompression of the product vapour from the evaporator. This vapour leaving the thermo-compressor, which will be at an intermediate pressure level, is again used as driving heat for the first evaporator.

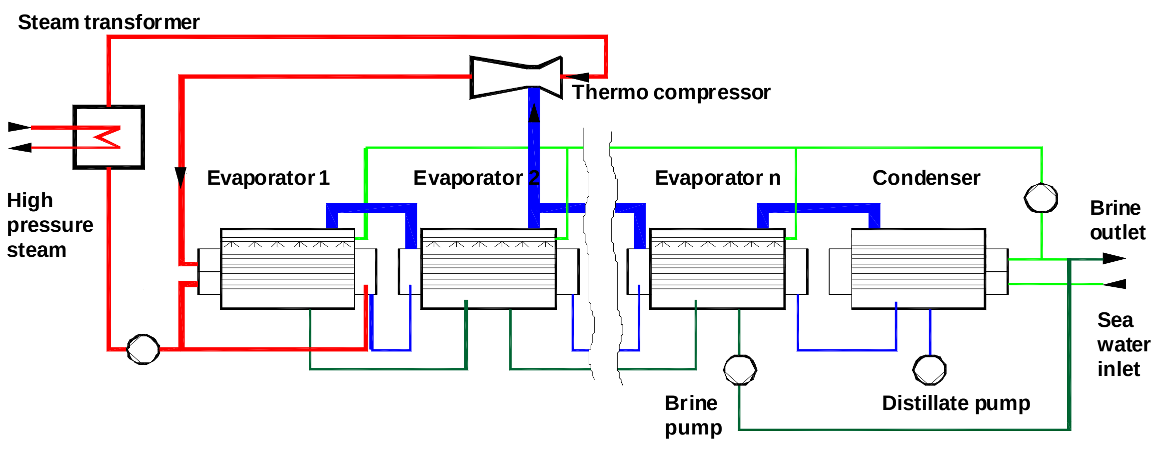


Figure 4-5: Scheme of a MED-TVC

A MED with thermal vapour compressor can benefit of heat at higher temperatures, without increasing the top brine above the critical scaling temperature of 65-70°C. There are very simple and robust skid mounted units with smaller size steam piping available. However, MED-TVCs have a lower thermodynamic efficiency than a simple MED. A steam transformer is mandatory if clean distillate in first cell is required. Recently, steam compressors with low motive steam pressure (1-2 bar abs.) have been developed. All systems are quite robust. The operation is simple and fault tolerant to a very high degree.

4.2.5 Solar Stills

A rather simple technology is the so called “solar still” using the solar energy directly./Holland 1999/

The glas roof covers the basin of saline water (see figure 6). Water volatilises under the influence of solar radiation. A dark underground of the pond enhances the evaporation. The water is then condensed underneath the glass surface, which is cooled by the ambient air. The condensate is recovered on both sides of the construction. These stills are used for small scale applications, the daily production being limited to about 5 l per square meter.

Solar stills do not require any auxiliary power nor any control and can be erected with a minimum of materials of construction. Feed flow can be kept very low as solar stills operate up to high salt concentrations including crystallisation. This technology is also called “solar distillation”. This can be confused with the expression of “solar powered desalination”. The later term describes in particular desalination processes in co- generation with solar power plant, as studied in this and other projects /Trieb 2007/.

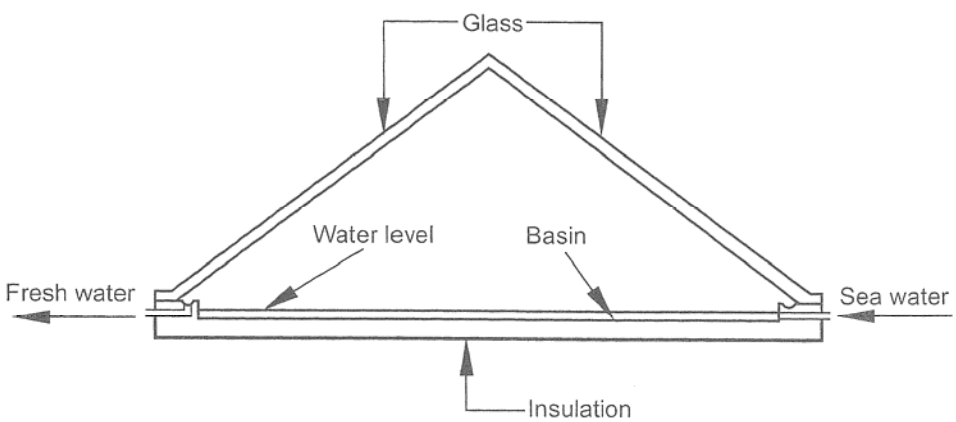


Figure 4-7: Principle of a solar still

4.2.6 Multi Effect Humidification (MEH)

Multi effect humidification is based upon the principle of solar stills /Müller-Holst 2002/. An isolated chamber consists of an evaporator section and a condenser section. Hot sea water is distributed on top of the evaporator section, which is constructed with parallel plates. Part of the water evaporates while flowing downward and cooling down. At the same time air flows up through natural convection and becomes more humid through absorbing the water vapor.

Cold sea water flows from bottom to top in the condenser section exchanging heat with the down flowing air. Water condenses on the heat exchanger surface and is collected at the bottom. Brine is collected at the bottom of the evaporator section. The sea water is further heated up to 85 °C by an external heat source like hot water or steam.

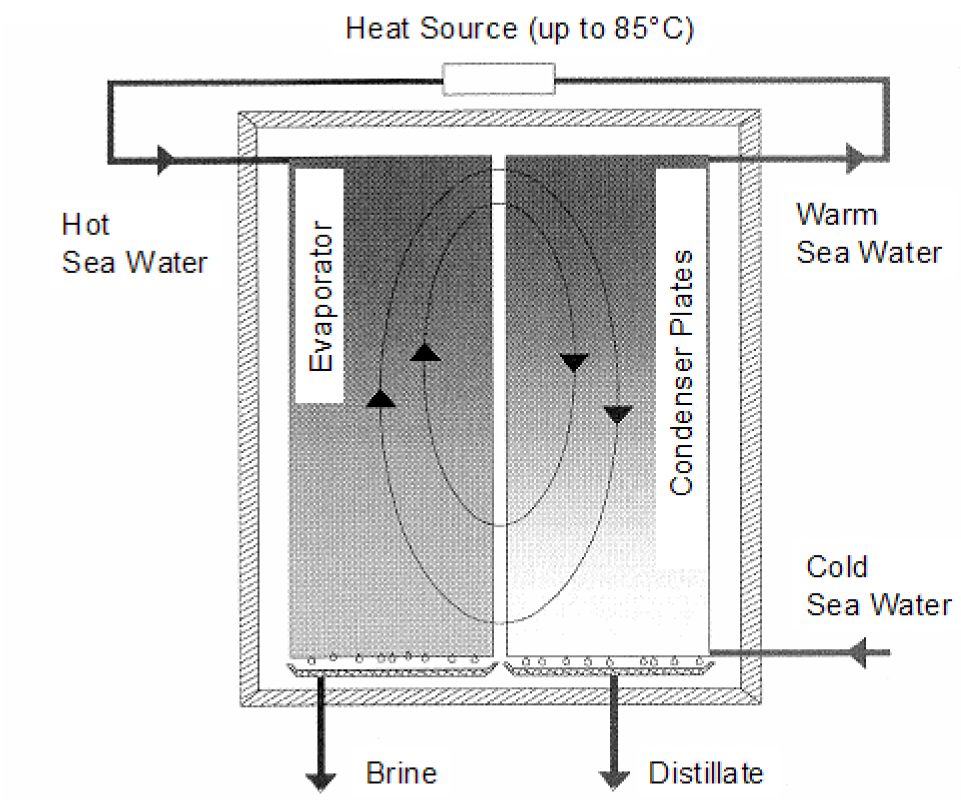


Figure 4-8: Principle of humid air distillation

Facts about the system and its advantages:

- Low temperature heat of 85°C is used for evaporation
- ·Absence of moving parts within the distillation chamber ensure low maintenance demand

- The self-controlling natural convection loop enables best energy recovery ratios of up to GOR 8
- Sophisticated geometrical design allows easy maintenance and optimum performance at the same time
- No pre-treatment of raw water is needed. The process is insensitive to high salt contents.
- Modular set-up, available sizes comprise units with 1000, 5000 and 10000 litres per day capacity

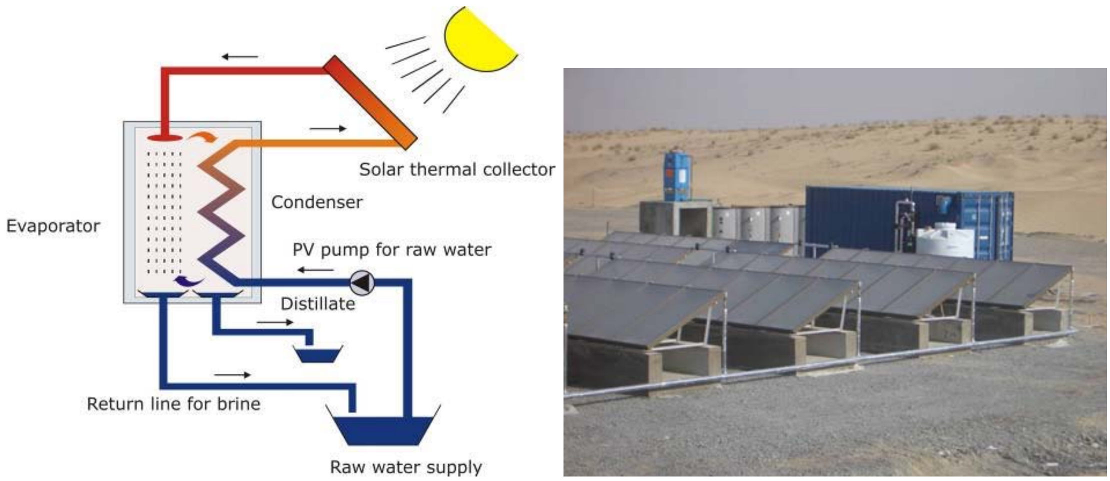


Figure 4-9: MEH field study near Dubai; pictures courtesy of Almeco-Tinox GmbH

A complete autonomously driven desalination system is operating since July 2008 in the middle of the desert south of Dubai, using fossil high alkaline brackish water as raw water source. /Müller-Holst 2009/. The system is equipped with solar thermal collector field of 156 m² absorber area and a PV electrical energy supply of 4.8 kW peak. The System is running in 100% stand alone operation mode, as no grid connection is available.

4.3 Membrane Processes

The purpose of membranes is the separation of phase (liquid/ vapour) or molecules and ions. For phase change membranes the driving force is heat. Evaporation occurs in the membrane because of vapour pressure difference on either side of the membrane and thus dividing the liquid from the vapour.(see chapter 2.2.3 VMEMD). The other separation process is diffusion. Only Molecules or ions which are small enough can pass through the pores of a membrane. The driving force is a difference of chemical potential, which can be either pressure or electrical voltage. Electrodialysis separates the ions from water by using direct current across the membrane which an ion conductor. The membrane selectively lets pass the ions leaving distilled water behind.

The membrane in the reverse osmosis acts like a filter, letting pass the water molecules and leaving the ions of the brine behind. Electric pumps generate the necessary high pressure up to 70 bar for sea water desalination in RO while a differential voltage is applied across an ED membrane.

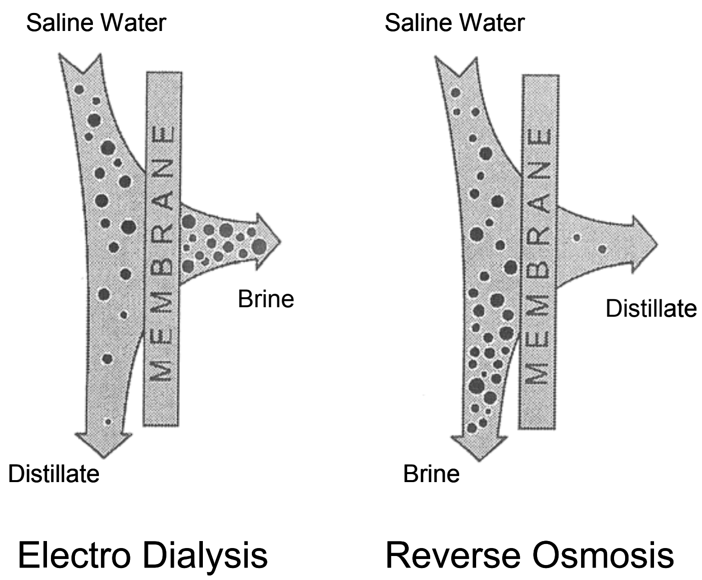


Figure 4-10: Comparison of electro dialysis and reverse osmosis

4.3.1 Electro Dialysis

Figure 10 shows the schematic process of the electro dialysis process. The cathode and anode envelope a block of membranes. Two different kind of membranes alternate – one selective for anions the other for cations.

Saline water is distributed into the channels between the membranes. The salt in the water then ionises when the electrical field is applied. In every second channel the water is enriched salt other channel depleted with salt. The two streams, distillate and brine, are collected at the bottom of the cell.

Electrodialysis processes are used for brackish water desalination only. Newest plants have output rates over 20.000 m³/d. To date there do not seem to be any SW ED plants./IDA 2008/.

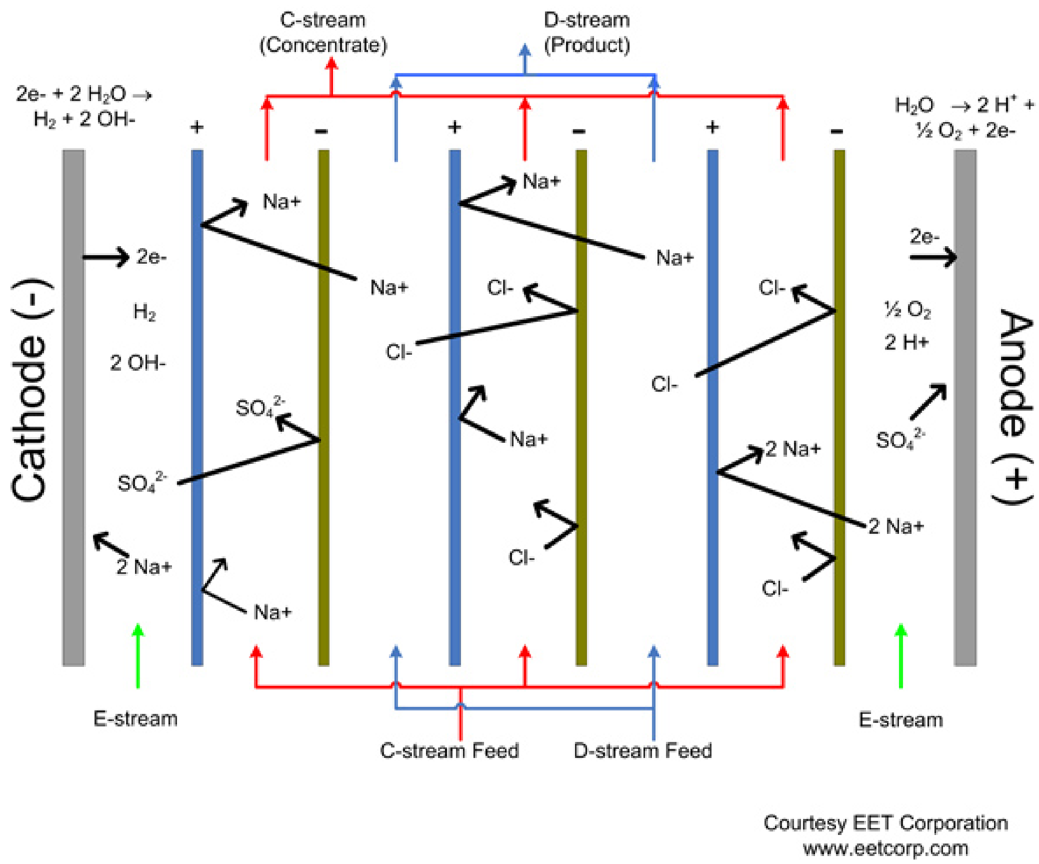


Figure 4-11: Electrodialysis process

4.3.2 Reverse Osmosis

Since their introduction in the late 1950's, reverse osmosis, nano-filtration, ultra-filtration and micro-filtration have been increasingly used in the field of water treatment. From the early development by Sourirujan and Loeb on the spiral wound cellulose acetate membrane and the invention of capillary technology, has improved performance, reliability and lower operating cost, making membranes the preferred technology for desalination of seawater, brackish water and waste water.

In the last decade RO seawater desalination has gone through a significant transformation. Currently most of implemented seawater desalination plants use RO technology. System of 300,000 m^3/day and recently even larger, have been build and are in operation in many parts of the world. Desalted water cost decreased from 2.0 $/$m^3$ to 0.5 $/$m^3$ and world wide capacity is continuously increased

In Israel, same as in the Mediterranean region, reverse osmosis (RO) is almost exclusively the leading technology. A considerable advancement was achieved in many areas of this technology: in the pre-treatment in the membranes and in the pumping and energy recovery systems. Osmosis is a physical process, which takes place when two solutions of different salt concentrations are separated by a semi permeable membrane.

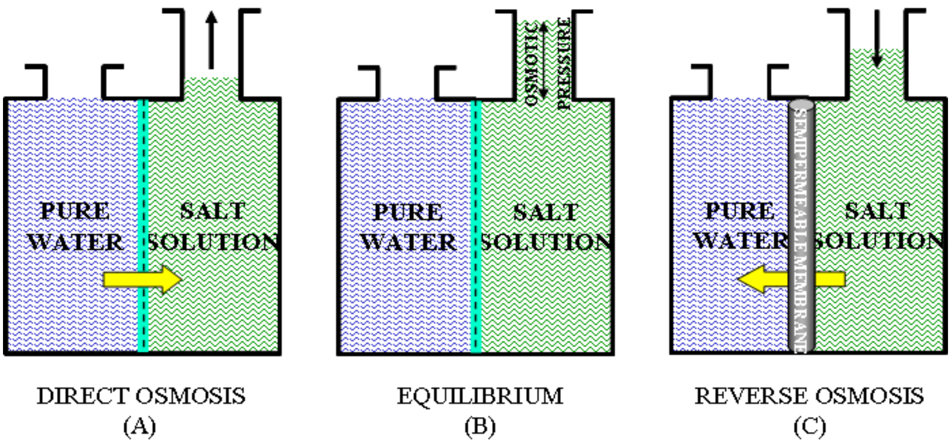


Figure 4-12: Explanation of Reverse Osmosis

Under normal conditions (A) (see Figure 4-12) water will pass from the solution whose salt concentration is higher until the hydrostatic pressure difference is equalized, or more precisely, the passage of water through the membrane in both directions will be equal. The pressure difference between distilled water and any saline solution, when the flow of water in both directions is identical, is equal to the osmotic pressure of the solution (B). The application of an external pressure on the concentrated solution (C), which is larger than the osmotic pressure will cause water flow from the concentrated solution to the dilute solution through the membrane, this process is called reverse osmosis. This osmotic pressure is proportional to the salt concentration. In the Mediterranean waters it is approximately 30 atmospheres.

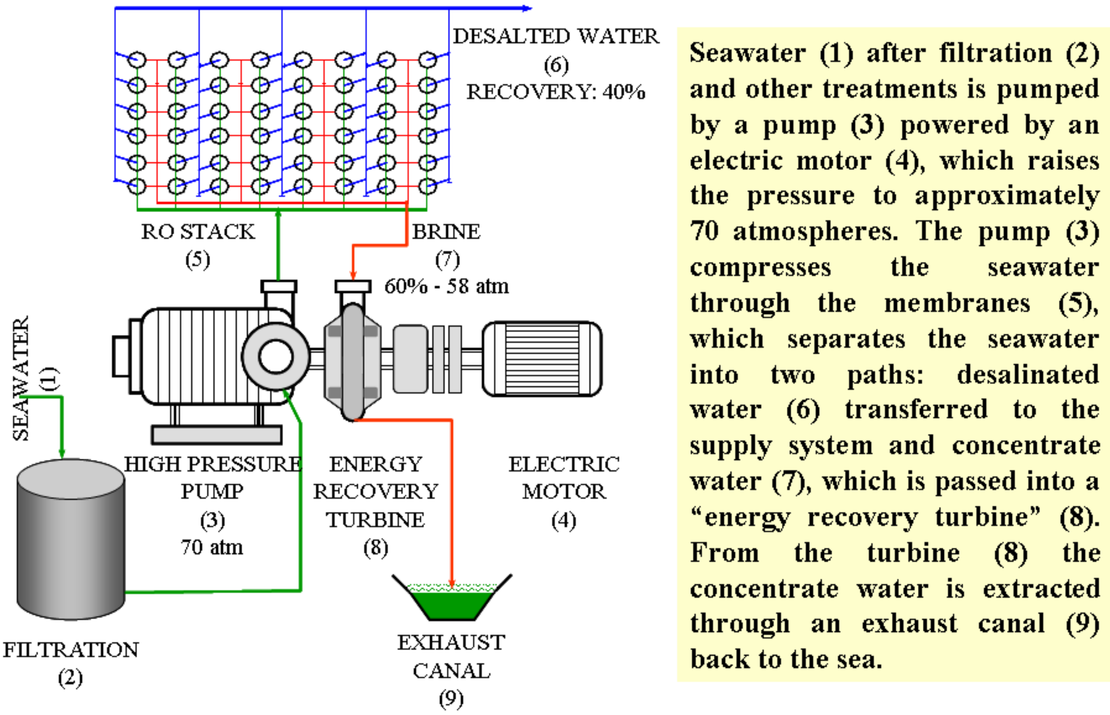


Figure 4-13: Principle of Operation of Seawater RO (SWRO) Desalination Plant - Process Flow Diagram

4.3.3 Vapor Membrane Distillation (VMEMD)

The main principle of membrane distillation is the following: two chambers are divided by a micro-porous, hydrophobic membrane. One chamber contains the saline water. The other side only water vapour. If heat is applied to the water side of a pressure difference occurs between the chambers – the lower pressure being on the vapour side – and water vapour permeates though the membrane. Up to now membrane distillation is a process similar to the MSF.

A newly developed technique is the vacuum membrane distillation. I combines the distillation via membrane with a MED process./Heinzl 2009/.

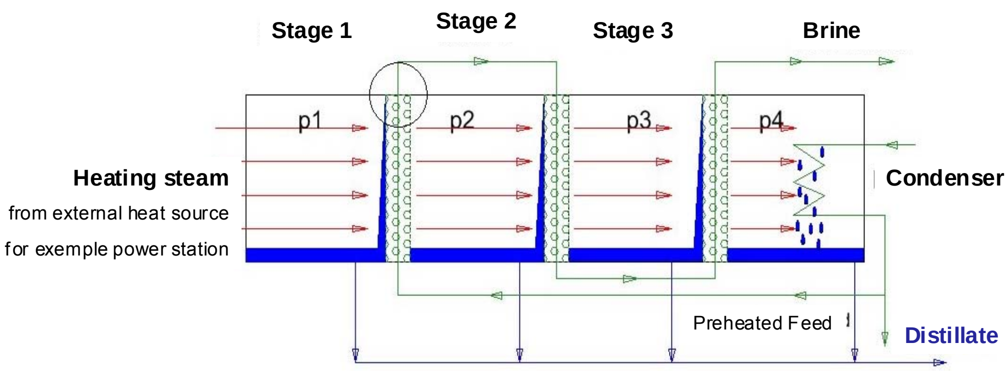


Figure 4-14: Vapour membrane distillation process

Preheated sea water enters into the channel of stage 1, which is enclosed on one side by a condensing non-permeable membrane and on the other side by a hydrophobic but permeable membrane. The condensing membrane of the first stage is heated by hot water or steam. Thus heat is transferred to the sea water. The pressure p2 of the second stage is lower than in the first stage. Water evaporates through the membrane into the second chamber. This vapour condensates again at the condensing membrane of the second stage transferring heat to the sea water chamber. The thermal and electrical power consumption are the same as for MEDs. The next steps are analogue. Latest developments promise an easy modular system. Capacities of up to 10.000 m³/d and more can be achieved with serial and parallel arrays of modules.

Advantages

- no formation of inert gas
- modular design with plate modules
- modules completely pre-manufactured with polymeric material
- pre- and post treatment necessary similar to MED
- high durability of membranes
- non-sensitive against longer stand-still periods
- low investment costs

4.4 Desalination in the Mena-Region

The figure in Annex 1 show the cumulated number of desalination plants going online in the last 10 years in the MENA region and their cumulated capacities. This study is focuses on industrial sized seawater desalination, therefore only plants with an installed capacity higher than 2000 m³/d are looked at.

The four diagrams in Annex 1 show a comparison of the three main technologies RO, MSF and MED /DW&R databank/. The characteristics are

- the installed plants per year
- cumulated number of installed plants
- installed capacity per year in m³/d
- cumulated capacity in m³/d.

Clearly most new plants in the last 10 years have been build with RO technology. The cumulated number of installed plants for MSF and MED are almost the same, each about half as many as RO plants. However the trend of the last few years shows an increasing preference of MED plants to MSF. Looking at the installed capacities gives another perspective. Now the MSF technology is in lead. hat the average capacity of a MSF plant is much higher than of a RO.

The peak capacity of MSF in 2002 is due the installed plants at Shoaiba, Saudi Arabia, with a capacity of 390.000 m³/d. In 2008 the MSF plant for the extension at Al Taweelah, United Arab Emirates, came online with a capacity of 315.000 m³/d. The largest MED plant currently in operation since 2007 is in Al Hidd, Bahrein with a capacity of 275.000 m³/d. The first RO plant with a capacity larger than 300.000 m³/d is installed at Ashkelon, Israel since 2005. For the construction of desalination plants in the future, still the tendency is to build bigger and bigger. The following table shows some selected projects:

Table 4-2: Selected desalination projects in the MENA region.

Technology	Location	Daily capacity [m³/d]	Planned online date
RO	Hadera, Isreal	330.000	2010
MED	Marafiq Jubail, Saudi Arabia	800.000	2009
MSF	Jebel Ali, United Arab Emirates	637.000	2011
MSF	Shuaiba North, Kuwait	273.000	2010

4.5 Thermodynamics

4.5.1 Irreversibilities

In theory the work required to desalinate sea water is only 0.6 kWh/m³. But all real desalination plants, membrane and thermal, are consuming at least 5-10 times as much work than this figure due to a number of important irreversibilities in any of the processes available.

Irreversibilites are a measure of second law efficiency, i.e. loss of power production in the associated power process is proportional to the irreversibilities and the resp. temperature.

While the nature of irreversibilites are different for membrane and thermal systems, the impact is the same, once the system is viewed including the generation of power.

Thermal processes

The temperature difference between two evaporation stages can be divided into the following terms:

- pressure drop of heating steam inside tubes
- heat transfer of condensing steam
- heat transfer across tube wall
- heat transfer form tube wall into sea water
- boiling point elevation 0.35 K for raw sea water
  0.7 K for concentrated sea water
- pressure drop of vapour across tube bundle
- pressure drop across demister

In practice the temperature difference between two stages varies between 2 K and 7 K while the thermodynamic minimum is 0.35 K

Reverse Osmosis

- raw water pump efficiency
- pressure drop in pre-filtration
- pressure drop in cross flow membrane
- polarization on membrane surface
- permeability of membrane
- osmotic pressure 23 bar for raw sea water
  up to 35 bar for brine
- pressure recovery system efficiency (turbine or pressure transformer)

The realistic work required for RO desalination is 3 – 5 kWh/m³ while the thermodynamic minimum is 0.6 kWh/m³.

4.6 Reverse Osmosis

4.6.1 Main Characteristics of RO Membranes

The two main characteristics of RO membranes are salt rejection and membrane permeability.

a. Salt Rejection (Rej, %) is defined according to the following formula:

$Rej(\%) = 100(1 - C_p/Cf_{avg})$

C_p = permeate concentration

$Cf(b)_{avg}$ = feed(brine) average concentration

Example

C_p = 100 ppm; C_f = 5,000 ppm; C_b = 10,000 ppm

Rej = 100 x (1-100/7,500) = 98.67%

b. Membrane permeability (Ka) is defined according to the following formula:

$K_a = J_p/NDP$

Jp = average permeate flux: Jp = gpd/A

NDP = net driving pressure: NDP = Pf – Π – dP/2

Pf = feed pressure; Π = average osmotic pressure difference between the concentrating salts; dP/2 = average hydraulic pressure losses

Example:

CPA2 – 10,000 gpd = 1,580 l/h   A = 365 ft2 = 33.9 m2

J_p = 1,580/33.9 =46.6 lmh   Pf = 225 psi = 15.85 bar

Π= 1.35 bar (1500 ppm)   NPD = 15.85–1.35–0.3 = 14.5 bar

dP/2 = 0.3 bar

K_a = 46.6/14.5 = 3.2 l/m^2-hr-bar

4.6.2 Brackish Water Reverse Osmosis (BWRO)

Desalination of BW is typically implemented for water of 1,500 - 12,000 mg/l TDS. Unlike seawater where product recovery is limited by high osmotic pressure, brackish water desalination is limited by the precipitation potential of sparingly soluble salts such as: $CaSO_4$, SiO_2, $BaSO_4$, C_2F, $SrSO_4$.

By use of special antiscalants, operation condition of about 300% over-saturation of $CaSO_4$ and up to 200 ppm SiO_2 could be achieved. In most of the cases the product recovery is in the range of 80 - 90%.

Since energy recovery in BW desalination is not economical in most of the cases, the product recovery is the most significant parameter determining the energy requirement. This parameter importance is reflected also in the feed supply and brine disposal capacities.

The membrane type and flux define the performance of the plant. For surface water and secondary effluents the membrane flux is usually limited to 18 - 20 lmh, while for ground water with low SDI - usually lmh of 22 - 24 is applied.

Regarding membranes performance, the main development efforts for the BWRO application are towards higher module capacity, achieved by a combination of larger membranes' area and higher permeability. Typical membrane characteristics of BWRO membrane modules, developed by two major membranes suppliers: Hydranautics and Filmtec, are shown in Figure 4-16.

Because of the wide range of feed water types 1,500 - 12,000 mg/l, a relatively wide range of product recovery (70% - 90%) and use of high and low pressure membrane types (permeability 3 - 8 lmh/bar), the specific energy of BWRO desalination varies between low value of 0.4 kWh/m^3 to a high value of about 1.7 kWh/m^3, as can be seen in Table 3.

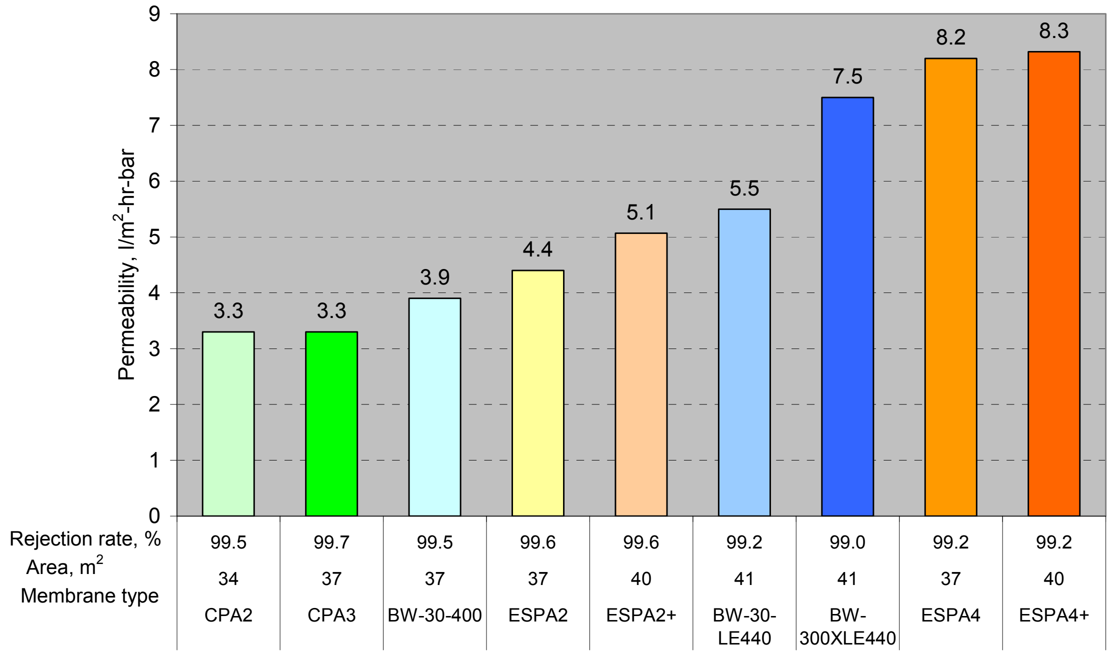


Figure 4-16: Typical performance of RO membranes of two major membranes suppliers

Table 4-3: Comparative BWRO system performance for two brackish water types and two membrane types.

<u>Feed water:</u>		
Salinity, mg/l	1,500	12,000
Pressure, bar	10.4	30.8
<u>Product:</u>		
Recovery, %	90	70
Salinity, ppm TDS	300	360
<u>Membrane type:</u>		
Hydranautics	ESPA4$^+$	CPA3
- Area,m^2	40	37
- Permeability, lmh/bar	8.3	3.3
<u>Specific energy</u>, kWh/m^3	0.47	1.73

4.6.3 Seawater Reverse Osmosis (SWRO)

A system desalination typical Mediterranean water of about 40,000 mg/l TDS at 25 ^{0}C, by standard 37.2 m^2 spiral wound membranes with permeability of about 0.9 lmh/bar operating at a recovery of 40% and flux of 14.0 lmh uses a pressure of 64.4 bar.

Assuming η_P X η_M = 0.8, the specific energy required without ERD.

$$SE = \frac{0.0286 \times 64.4}{0.4 \times 0.8} = 5.76 kWh/m^3$$

However, by use of an ERD of a typical Pelton turbine, the specific energy requirement is reduced by about 40%, to about 3.46 kWh/m^3.

In case a more advanced membrane type, such as 9,000 gpd with a permeability of 1.31 lmh/bar will be used, with more efficient process pump (η_P = 89%, η_M = 96%) and more efficient Pelton turbine (89%), the specific energy consumption will be further reduced to about 3.0 kWh/m^3 for a lmh of 18 and to about 2.82 kWh/m^3 for a flux of 14 lmh.

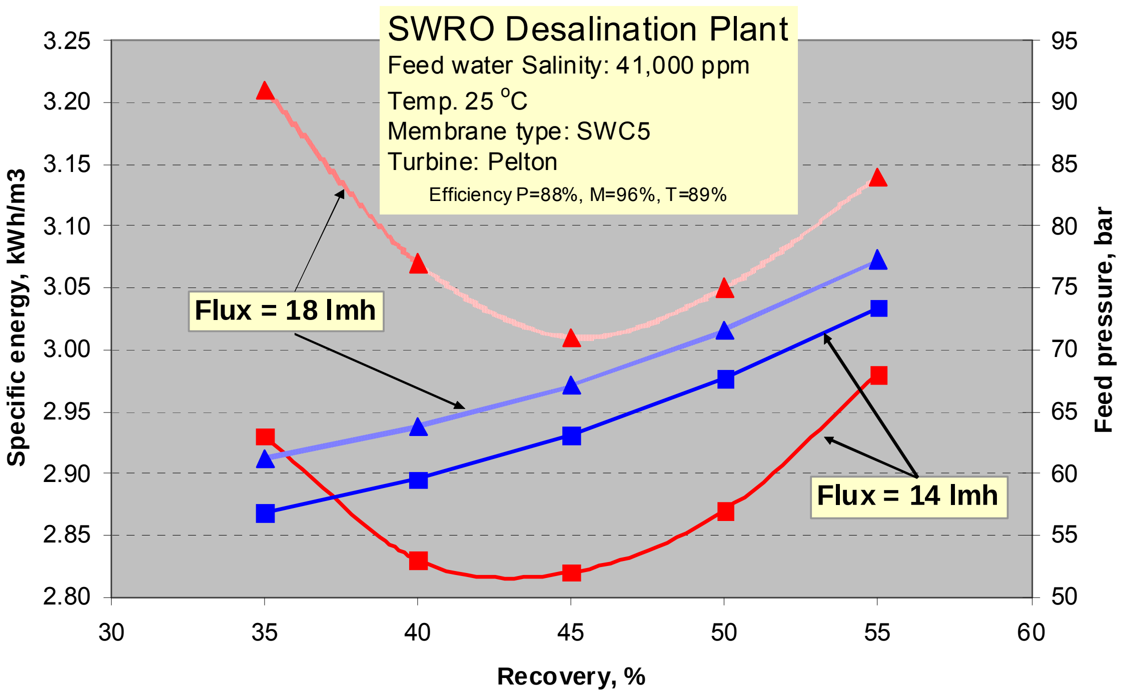


Figure 4-17: The effect of the product recovery and the membrane flux on the required pressure and on the specific energy requirement.

The effect of the product recovery and the membrane flux on the required pressure and on the specific energy requirement are shown in Figure 4-17.

The above analysis does not include the energy for the feed water supply and the power supply for plant auxiliaries. This additional power is roughly estimated to amount of 0.5 kWh/m^3. Therefore, the total energy requirement for a large SWRO plant, operating at a Mediterranean site, is in the range of 3.3 - 3.5 kWh/m^3.

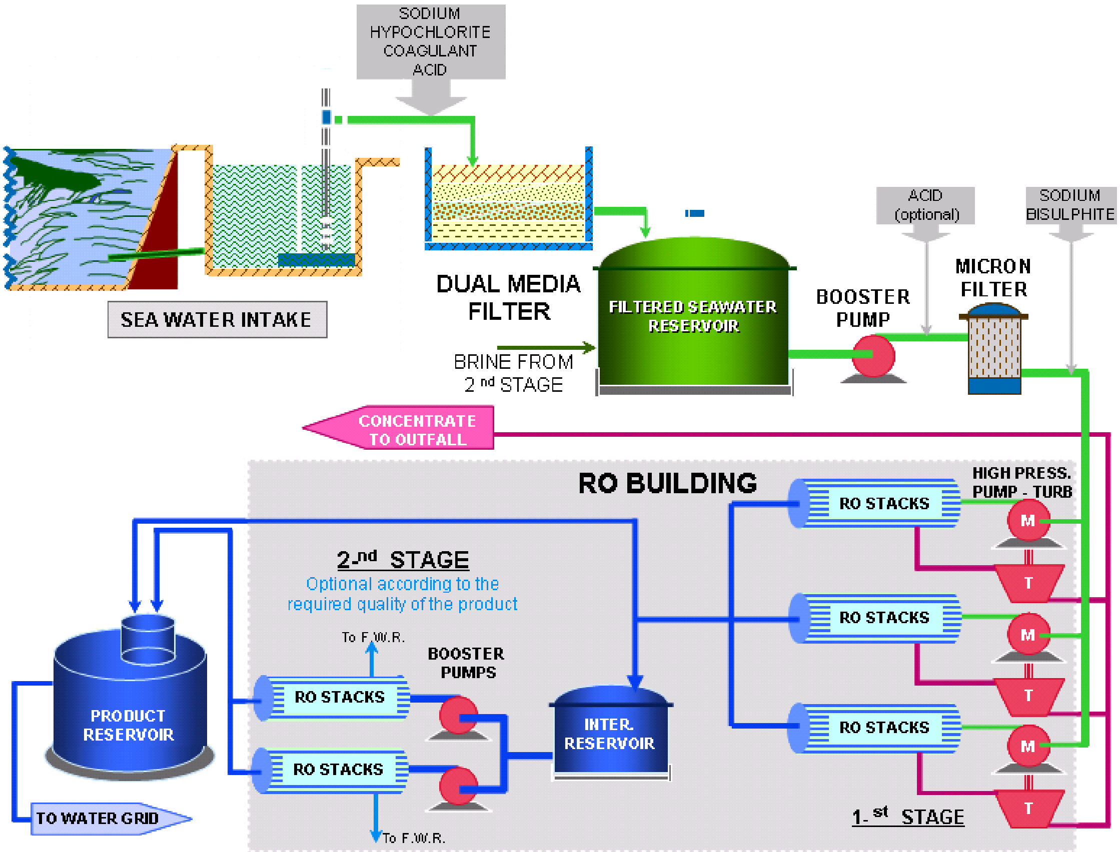


Figure 4-18: Principle flow diagram of SWRO plant

Evolution of Seawater RO Membranes

Table 4-4: *Recent characteristics of seawater RO membranes Type: Spiral wound 8" – Hydranautics*

Year	Membrane type	Area ft^2	Capacity gpd	Rejection %
1995	SWC1/2	315	5,000	99.6
2001	SWC3	370	5,900	99.7
2003	SWC3+	400	7,000	99.8
2003	SWC4+	400	6,500	99.8
2004	SWC5	400	8,000	99.8
2005	SWC5	400	9,000	99.8

Main design and operating parameters

- **Optimization** between: energy consumption, required quality of the product, raw water supply cost and pretreatment cost
- **Membrane flux**
  - High membrane flux is more economic (less investment in membranes) but the energy consumption is higher and can produce fouling
  - Decline in the membrane flux as function of their age:
    - Hydranautics: flux decline = 5% - 10% per year
    - Filmtec, Toray: fouling index = 0.8 – 1.0
- **Salt passage** increase: 5 - 10%
- **Polarization** minimum brine = 5 X product
- **Recovery** for a single membrane:
  - Seawater: 8% - 10%
  - Brackish water: 15%
  - Pass two: 20%

<u>Energy recovery systems</u>

The three major ERD (Energy recovery device) technologies include an impulse turbine (Pelton – Figure 4-19), an isobaric pressure exchanger (PX – Figure 4-20) and a hydraulic turbo charger (TC – Figure 4-21).

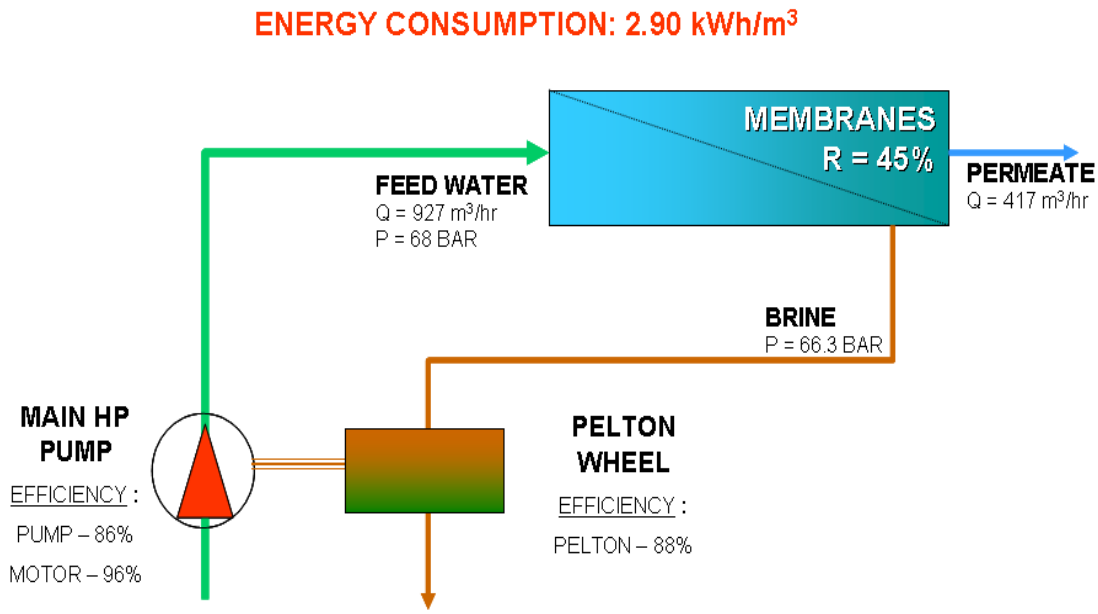


Figure 4-19: Pelton impulse turbine

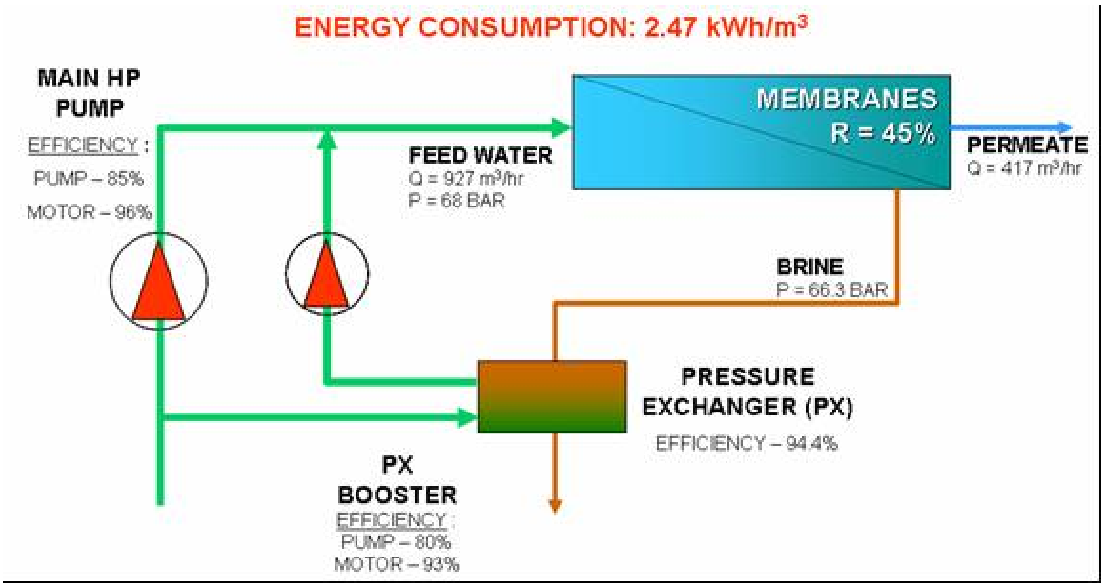


Figure 4-20*: Isobaric pressure exchanger (PX)*

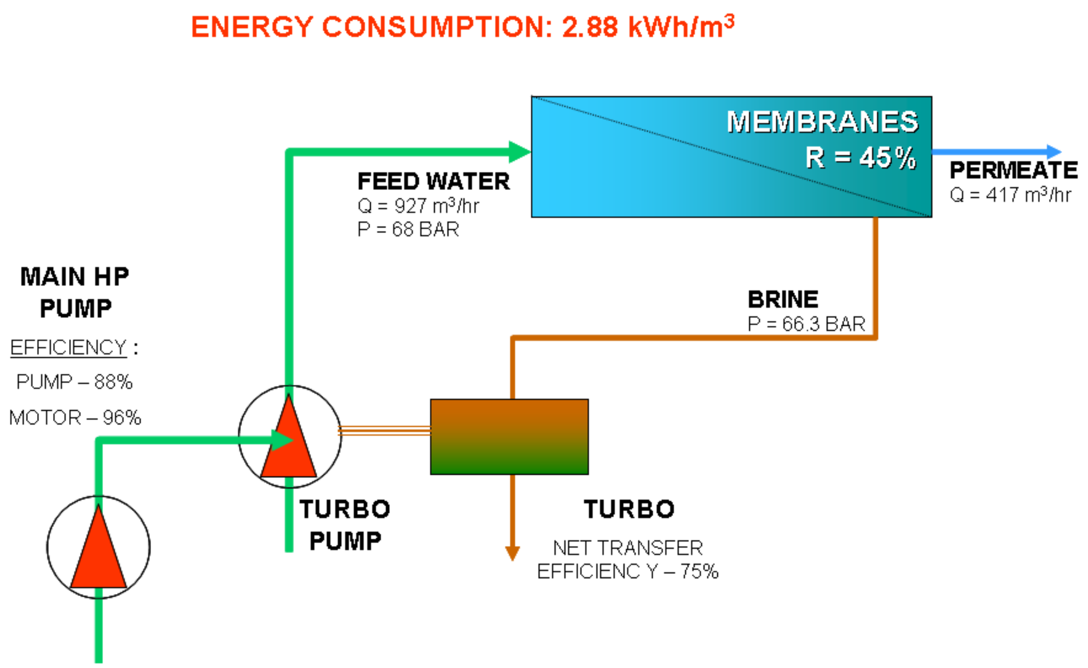


Figure 4-21*: Hydraulic turbo charger (TC)*

Table 4-5 presents the assumptions and the comparison between the efficiencies of the three alternative technologies for a 20,000 m^3/day SWRO desalination system, operating at a recovery of 45%.

Table 4-5: Comparative ERD performance

	Turbine Pelton	Pressure exchanger (PX)	Turbo charger (TC)
EFFICIENCY, %			
- Main HP pump	88	88	88
- Motor	96	96	96
- Net transfer	89	96.1	75
System power results			
Total power, kW	2,303	1,945	2,400
Specific energy, kWh/m^3	2.76	2.33	2.88

According to these results, the PX yields a lower specific energy of about 0.43 kWh/m^3. However, according to a recent publication the turbo charger net transfer efficiency for very large units could be increased to about 83% and in this case, this technology is competitive or even superior to the Pelton technology. /Moch 2005/

It should be noted that the above estimate does not include energy requirement of a second SWRO pass required in case higher permeate quality regarding salinity and boron has to be achieved.

On the other hand, a more efficient ERD such as an isobaric pressure exchanger reduces the specific energy consumption by about 0.3 – 0.5 kWh/m^3 - enough to compensate for the additional specific energy required for high quality permeate.

Table 4-6: Characteristics and performance comparison between SWRO and BWRO

	Seawater	**Brackish water**
Raw water source availability	unlimited	limited
Raw water type	Surface water	Underground water
Raw water salinity, ppm TDS	35,000 – 45,000	1,000 – 10,000
NaCl, %	~ 85%	30% - 80%
$CaSO_4$ saturation, %	~25%	2% - 50%
Osmotic pressure, bar	25 - 32	0.6 – 7.5
Changes of raw water salinity	Not relevant	Can be significant
Sparingly solved salts	Not relevant	Can be significant
Brine disposal cost	Not relevant	Expensive
Design options	exists	▪ Numerous membr. type ▪ Flexible configuration ▪ brine desalination ▪ inter-stage pumps ▪ hybrid membranes
Specific energy consumption, kWh/m^3	3 - 4	0.5 – 3.0
Desalinated water cost, \$/m^3	0.6 – 1.0	0.2 – 1.0
Raw water economic value	-	high
Cost effectiveness of the recovery	Not significant	Can be very significant

4.7 Characteristics of Thermal Processes

For thermal processes the energy consumption is independent of the salinity, which makes it ideal for sea water desalination. A typical characteristic for thermal desalination units is the GOR (gained output ratio), which is defined as the net distillate output vs. steam consumption.

$$GOR = \frac{\dot{M}_{Dist}}{\dot{M}_{Steam}}$$

4.7.1 Multi-Effect Desalination (MED)

For a MED the Gain Output Ratio (GOR) per cell is constant. As a first approximation the number of stages translates into the GOR with a correction factor of roughly 0.85. This means that a 10 stage MED unit will have a GOR of roughly 8.4. The difference is a result of imperfect pre-heating and internal heat recovery as well as the energy consumption of the vacuum system. Looking at the GOR only, the efficiency of the MED increases linearly with larger cell number N (). A MED-TVC has even a better GOR with the same number of stages, e.g. 2 stages + TVC has a GOR around 6.

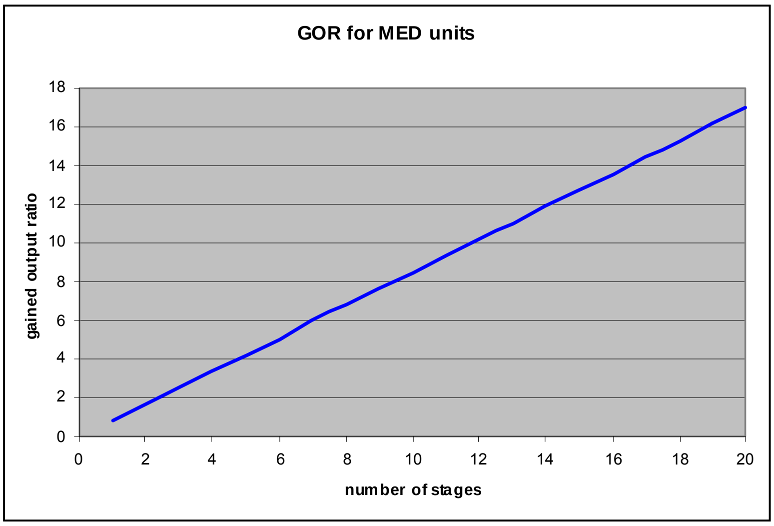


Figure 4-22: typical values of GOR vs number of stages for a MED

The limitation of efficiency lies in the exponential increase of the heat transfer surface, i.e. number and size of tubes and consequently irrational high investment costs. A simple equation correlates the key parameters of an MED. Assuming almost identical distillate production (M_{dist}/N) in each stage and the same heat transfer area in each stage including the condenser, a simple relation can be obtained /Scharfe 2006/: The boiling point elevation dT_{BPE} and other irreversibilities dT_{irr} can not be reduced as they are inherent to physical properties and mechanical constraints.

$$T_{Steam} - T_{SWR} = N \cdot (dT_{BPE} + dT_{irr}) + \frac{(N+1)^2}{N} \cdot \frac{M_{dist} \cdot r}{k \cdot A_{total}}$$

The steam temperature T_{steam} is limited by risk of scaling and the sea water return temperature must always be some degrees above sea water temperature. Hence, the only relevant parameters are the number of stages N and the specific heat transfer surface A/M.

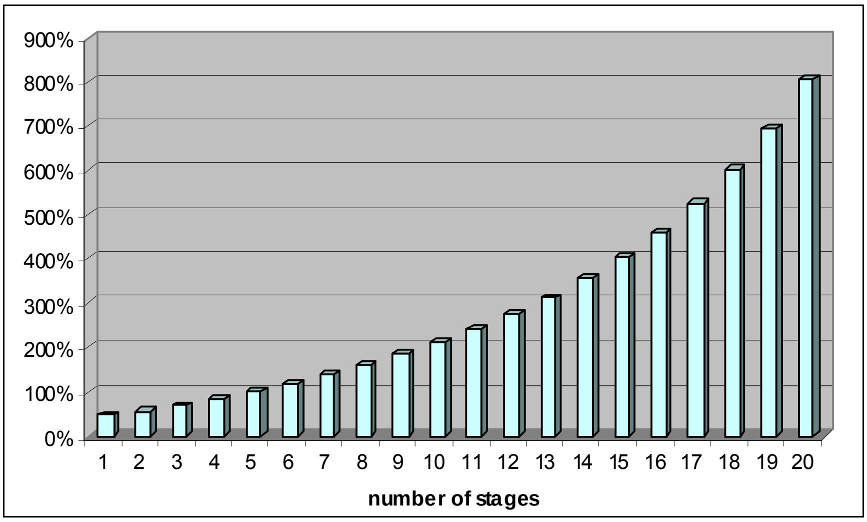


Figure 4-25: Heat Transfer Surface of a MED Unit as function of the number of effects

As shown in the increase of heat transfer is exponential. Increasing the stages from 5 to 10 results in a surface about the double size, but then double again the stages from 10 to 20 gives a heat transfer surface 8 times higher that with 5 stages. The GOR is very practical in use but has little thermodynamic value. Further it is not possible to make a realistic comparison with processes consuming electrical energy like RO. Therefore a much better number to describe the efficiency of desalination is the loss of electrical production kWh per t of distillate.

4.8 Summary

MSF:

MSF is a mature technology but not competitive in terms of power consumption due to high recirculation of brine. For high efficiency plants it should not be considered.

MED:

MED is the most competitive thermal process. It requires heat at 70°C – and not higher – for optimum second law efficiency, which can be close to efficiencies of membrane processes.

RO:

RO is a mature technology. It has every good second-law efficiency. Anyhow it requires very careful pretreatment. Usually the chemical consumption is much higher than for thermal processes. RO is clearly the winning technology for lower salinities.

Others:

The others are niche and research processes.

Table 4-7: Overview of characteristics for the main desalination technologies

	MED	**MSF**	**MED-TVC**	**MVC**	**RO**
Raw water qualtity	not critical	not critical	not critical	not critical	very specific pre-treatment
Filter mesh	3 mm	3 mm	3 mm	3 mm	< 50 µm
Distillate quality (ppm TDS)	1-10 pmm	1-10 pmm	1-10 pmm	1-10 pmm	1stage: 300 ppm 2stage: 10-50 ppm
Heat consumption	60-100 kWh/t @ 70°C	60–100 kWh/t @ 120°C	50-100 kWh/t @ 150°C	---	---
Power consumption	< 0,5 kWh/t	3-4 kWh/t	<0,6 kWh/t	8-10 kWh/t	3 – 6 kWh / t
Maintenance cost	low	low	low	low	medium

4.9 Suppliers

The following list shows suppliers for desalination plants in the MENA region. They are selected from a list of the top suppliers since 2000 with the characteristic value of the ranking being the installed production capacity. Anyhow this list only gives an overview of companies which have already installed reference plants in the Middle East and is not at all complete. It does not judge on the quality of products or recommends any particular company. There may be smaller and newer companies worthy of consideration.

Veolia Water Solutions & Technologies

www.veoliawaterst.com

Fisia Italimpianti

www.fisiait.com

Doosan Hydro Technology, Inc

www.doosangydro.com

GE Infrastructure Water & Process Technologies

www.ge.com

Suez Energy International

www.suezenergyint.com

IDE Technologies Ltd.

www.ide-tech.com

5 TASK 3: INTEGRATION OF CSP AND DESALINATION TECHNOLOGY

5.1 PRE-SELECTION OF DESALINATION TECHNOLOGIES

Table 5-1 shows some of the characteristics of the leading desalination technologies. The purpose of this comparison is to select the most appropriate thermal or mechanical desalination method for the combination with CSP, and to find a combination that could be representative for large scale dissemination.

MED is more efficient than MSF 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 for combined 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 reduces power cycle efficiency as it requires steam at higher pressure (Figure 5-1).

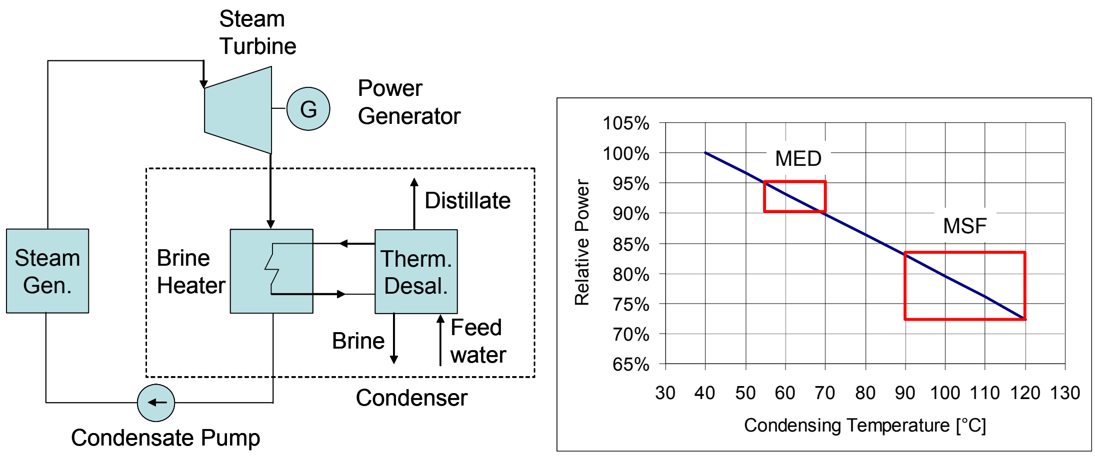


Figure 5-1: Principle of substituting the condenser of a steam cycle power plant by a thermal desalination unit (left) and typical reduction of steam turbine power capacity at increasing condensing temperature (right). The squares show the typical operating range of MED and MSF plants.

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.

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. Within this study the MED and RO processes will be considered as reference technologies for thermal and for mechanical desalination processes, respectively.

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) Heat Consumption (kJ/kg)	13 **250 – 330**	2 145 - 390	0.6 –	6 –
Electricity Consumption (kWh/m^3)*	**3 - 5**	0.6 - 1.3 *	**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) Conversion Freshwater / Seawater	< 76000 **10 - 25%**	< 36000 23 - 33%	**< 3000** 23 - 41%	< 20000 20 - 50%
Max. Top Brine Temperature (°C) Reliability	**90 - 120** very high	55 - 70 very high	70 high	45 (max) moderate (for seawater)
Maintenance (cleaning per year) Pre-treatment of water	0.5 - 1 simple	1 - 2 simple	1 - 2 very simple	several times demanding
Operation requirements	simple	simple	simple	demanding
Product water quality (ppm)	< 10	< 10	< 10	200 - 500

Table 5-1: 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 for cooling in conventional power plant required for RO, and does not include power losses induced by cogeneration due to increasing outlet temperature at the turbine in case of MED; ** plant cost increases with product water quality and energy efficiency). Source: AQUA-CSP 2007

5.2 PRE-SELECTION OF CSP TECHNOLOGIES

In principle, all CSP technologies can be used for the generation of electricity and heat and are suited to be combined with mechanical as well as with thermal desalination systems (Figure 5-2). 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.

At present, 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.

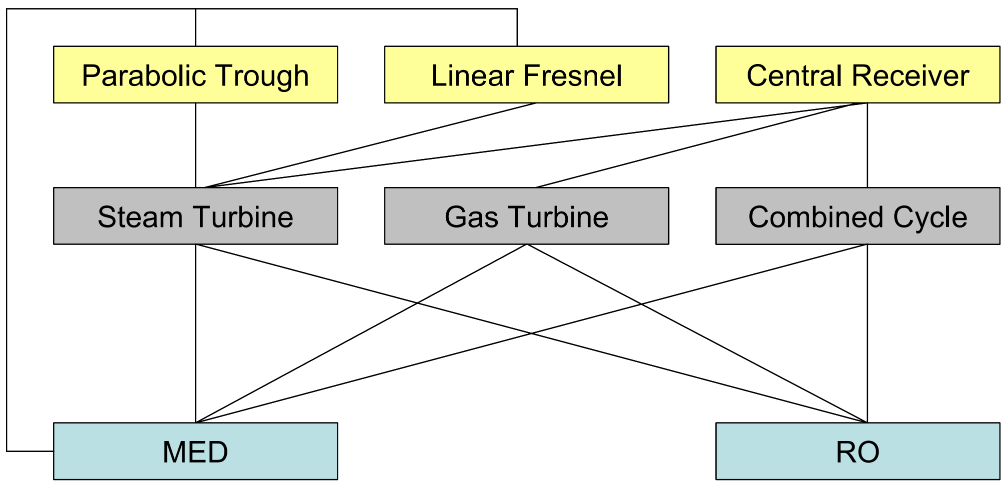


Figure 5-2: Options of large scale concentrating solar power and desalination systems

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 are not 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 an addendum.

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	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 5-2: Characteristics of current concentrating solar power technologies (PCM: Phase Change Materials)

Discarding point concentrating systems leaves parabolic trough and linear Fresnel concentrators as candidates for a CSP reference technology. Looking at Table 5-2 the linear 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. However, recently Fresnel systems have been established commercially and will be observed for comparison.

Technology	Oil-Cooled Trough for Steam Cycle Power Plant	Direct Steam Generating Trough for Steam Cycle	Linear Fresnel for Steam Cycle Power Plant	Central Receiver for Steam Cycle Power Plant	Central Receiver for Gas Turbine & Combined Cycle
Providers	Cobra, Abengoa, Acciona	not yet commercial	Novatec, AUSRA, MAN/SPG	Abengoa, KAM, Brightsource	n.a.
Collector Field	parabilic trough mirrors with evacuated tube receiver	parabilic trough mirrors with evacuated tube receiver	linear Fresnel with receiver tube in stratified air box	tube cavity or open volumetric receiver	tube cavity and pressurized volumetric receiver
Heat Transfer Fluid	Synthetic Oil	Water/Steam	Water/Steam	Water/Steam, Air	Pressurized Air
Power Cycle	Superheated steam turbine	Superheated steam turbine	Saturated and superheated steam turbine	Saturated and superheated steam turbine	Gas turbine or combined cycle system
Storage Options	Molten Salt, Concrete	Concrete, PCM	Concrete, PCM	all	High temperature ceramics
Heat Reject (Cooling) Options	Seawater, evaporation tower, dry cooling, Heller, CHP	Seawater, evaporation tower, dry cooling, Heller, CHP	Seawater, evaporation tower, dry cooling, Heller, CHP	Seawater, evaporation tower, dry cooling, Heller, CHP	Seawater, evaporation tower, dry cooling, Heller, CHP
Collector Cleaning	Spraying	Spraying	Robots, rinse & brush	Spraying	Spraying
Water Demand	low with dry cooling	low with dry cooling	very low with dry cooling and robot cleaning	low with dry cooling	low with dry cooling
Desalination Options	RO or MED	RO or MED	RO or MED	RO or MED	RO or MED
Experience	long-term commercial	experimental	recently commercial	recently commercial	experimental
Annual Efficiency (%)	up to 15%	up to 17% expected in future	up to 12%	up to 16% expected in future	up to 25% expected in future
Investment Cost (€/kW)	3,500-6,500	n.a.	2,500-4,500	4,000-6,000	n.a.
General Comments	Commercially proven technology for 20 years	Expected better cost and performance than oil-cooled trough, but not yet commercial	Lower optical efficiency but also lower collector cost compared to trough	A theoretically better thermal efficiency than trough has not yet been demonstrated	Theoretically better performance and cost than central receiver steam cycle power plant, but not yet commercial
Advantages	most experienced system	direct steam, no temperature limitation from HTF	direct steam, no temperature limitation from HTF	no temperature limitation from heat transfer fluid	very high temperatures possible > 1000°C
	several providers	water/steam is low cost and environmental friendly heat transfer fluid	water/steam is low cost and environmental friendly heat transfer fluid	water/steam or air is low cost and environmental friendly heat transfer fluid	very high efficiency possible
	reliability proven		reliability demonstrated	reliability demonstrated	
Disadvantages	risk of molten salt freezing	no commercial provider	storage options for direct steam generation not yet commercial	complex construction	no commercial provider
	complex construction	complex construction	simple construction		very complex construction
	risk of HTF leakage				high temperature materials
	temperature limitation below 390°C due to heat transfer fluid				

Table 5-3: Comparison of the principal features of current CSP systems applicable to seawater desalination

5.3 INTEGRATION OF CSP AND DESALINATION PLANTS

There are basically two options of combining CSP with seawater desalination that will be investigated within the MED-CSD project:

5.3.1 Case 1: Reverse Osmosis Powered by Electricity from a CSP Plant (CSP/RO)

The plant configuration of the ANDASOL 1 plant can be considered the status quo of a modern CSP installation. The plant uses the modern European parabolic trough collector design SKAL-ET and the new receiver tube Schott Solar PTR-70 for its solar field. The heat transfer fluid used to transfer the solar heat to the power block is synthetic oil Monsanto VP-1 operating between 292 °C and 386 °C. The collector field has an aperture area of 510,000 m² and requires about 2 km² of land. The total investment is about 310 million Euro.

The plant uses two large tanks containing 28,500 tonnes of molten nitrate salts (60% NaNO3 + 40% KNO3) to store solar energy received during the day for night time operation of the turbine. The tanks are 14 metres high and have a diameter of 38.5 metres. The molten salt can store an amount of heat of 1010 MWh which is sufficient for 7.5 hours of full load operation of the turbine, with a charging capacity of 131 MWth and a discharging capacity of 119 MWth. The heat from the solar field is transferred to the molten salt tanks via HTF/salt heat exchangers and from the solar field and the storage to the power cycle via a HTF steam generator. The power cycle is comprised by a 50 MW steam turbine SST-700RH from Siemens operating with superheated steam at a pressure of 100 bar and a temperature of 377 °C. A condenser cooled by a wet cooling tower rejects the heat from the power cycle.

The plant has a gas-fired backup system (HTF Heater) to provide a maximum of 15% of the required heat when no solar energy is available. It will be used to avoid transients from clouds and to support start-up in the morning. Under the solar irradiation conditions given at the plant site in Spain, Andasol 1 will produce about 180 GWh of electricity per year. The plant was build by ACS Cobra and engineered by Grupo SENER, both well known Spanish companies.

The ANDASOL plant configuration is very well applicable to a CSP/RO concept producing maximum electricity during the day for RO operation and for surplus power delivered to the grid, while during night time the plant will operate in part load and only serve the RO system which will be operated continuously during 24 hours. A configuration with an RO input power capacity of about 30% of the turbine output capacity should fit well to the ANDASOL configuration. This must still be confirmed by hourly time series modelling of plant performance under the concrete conditions for the sites under consideration. The following pictures give same examples of the equipment that may be used in this configuration:

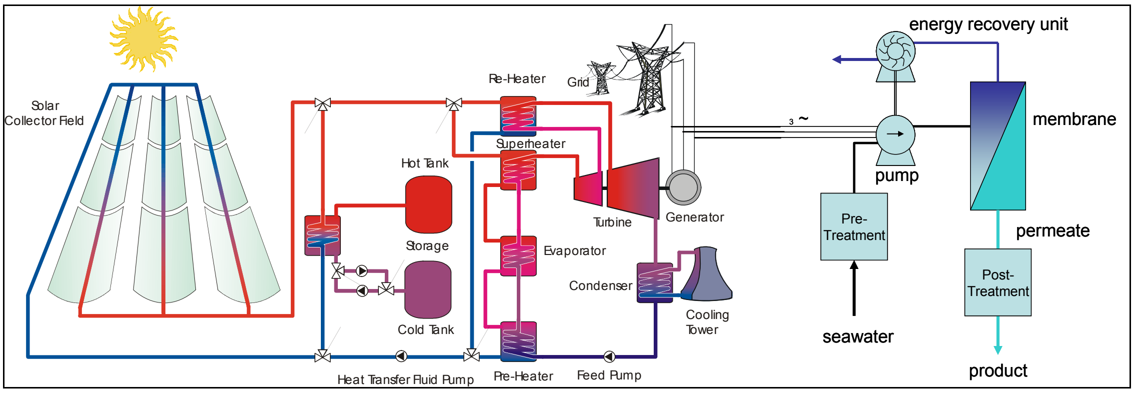


Figure 5-3: Combined CSP desalination plant with reverse osmosis (CSP/RO)

Figure 5-4: SKALET parabolic trough collector with 150 metres length.

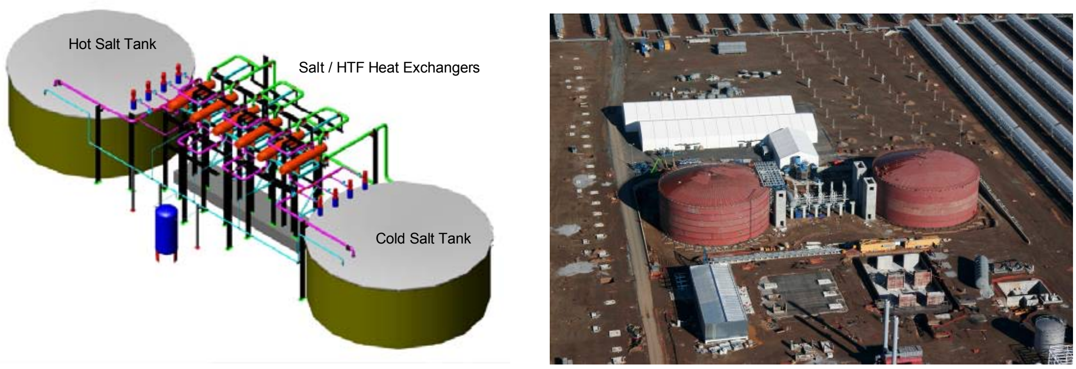


Figure 5-5: Molten Salt Heat Storage at ANDASOL 1

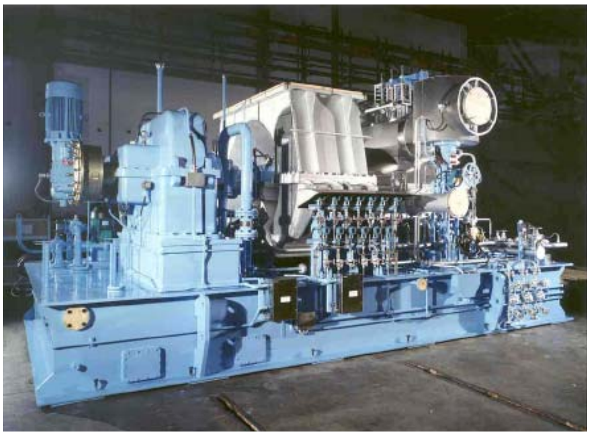
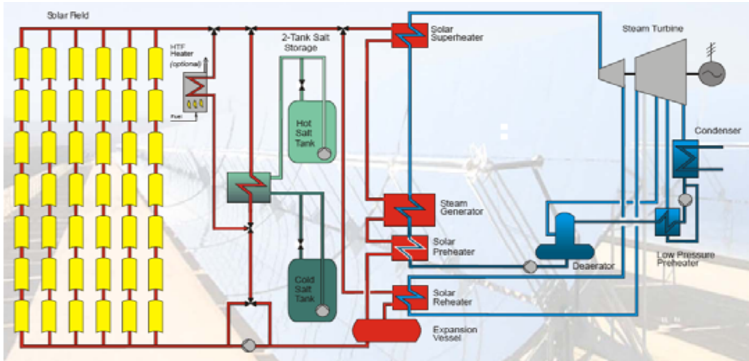


Figure 5-6: Photograph showing a 20 MW steam turbine with gearbox (left), low pressure steam flange (centre, top) and high pressure steam inlet (right, top), Dimensions L=7m , W= 3m , H=3m. Generator will be connected on the left (Length 5 m).

Figure 5-7: Backup HTF Heaters and Field Piping at SEGS VI, Kramer Junction, USA

Figure 5-8: Left: Pressure cylinders containing the separation membranes of a reverse osmosis plant in Barcelona, Spain, with 30,000 m³/day desalting capacity; Right: RO-stacks and high pressure pumps of a 30,000 m³/day desalination plant in Gran Canaria, Canary Islands. Source: Mertes, DME

Power Plant Design Data	**ANDASOL 1**	**CSP/RO**
Turbine Type	Superheated	Superheated
Steam Pressure to Turbine	100 bar	100 bar
Steam Temperature to Turbine	377 °C	377 °C
Backup Concept	HTF-Heater	HTF-Heater
Backup Fuel Type	Natural Gas	Fuel Oil
Cooling System	evaporation	seawater
Gross Turbine Capacity	50 MW	16.5 MW
Equivalent Annual Full Load Hours	3269 h/y	3269 h/y
Forecast Gross Electricity	163 GWh/y	54 GWh/y
Peak Electric Efficiency	28 %	26 %
Annual Electric Efficiency	15 %	15 %
Expected Lifespan	40 years	40 years
Plant Parasitics	14.0 GWh/y	4.6 GWh/y
Solar Field Design Data		
Parabolic Trough Technology	SKAL-ET	SKAL-ET
Absorber Tube	PTR-70	PTR-70
Heat Transfer Fluid	Synthetic Oil	Synthetic Oil
Solar Field Collector Area	510120 m²	168340 m²
Number of Parabolic Mirrors	209664 mirrors	69189 mirrors
Number of Receivers (@ 4 m length each)	22464 pipes	7413 pipes
Number of Solar Sensors	624 sensors	206 sensors
Annual Direct Normal Irradiation (DNI)	2136 kWh/m²/y	2136 kWh/m²/y
Annual Solar Heat	545 GWh_th/y	180 GWh_th/y
Solar Field Peak Efficiency	70 %	70 %
Solar Field Annual Efficiency	50 %	50 %
Land Use	2.00 km²	0.66 km²
Storage Design Data		
Type:	2-Tank	2-Tank
Storage Fluid:	Molten Salt	Molten Salt
Charging Capacity:	131 MW_th	43 MW_th
Discharging Capacity:	119 MW_th	39 MW_th
Storage Capacity in Heat Units:	1010 MWh_th	333 MWh_th
Storage Capacity in Full Load Hours:	7.5 h	7.5 h
Storage Tank Volume:	15870 m³	5237 m³
Storage Tank Height:	14 m height	8 m height
Storage Tank Diameter:	38 m diameter	23 m diameter
Cold Tank Temperature:	292 °C	292 °C
Hot Tank Temperature:	386 °C	386 °C
Melting Point of Fluid:	223 °C	223 °C
Salt Mass:	28500 tons	9405 tons
NaNO3 Share	60 % weight	60 % weight
KNO3 Share	40 % weight	40 % weight
Flow Rate:	953 kg/s	314 kg/s
Annual Storage Efficiency:	95 %	95 %



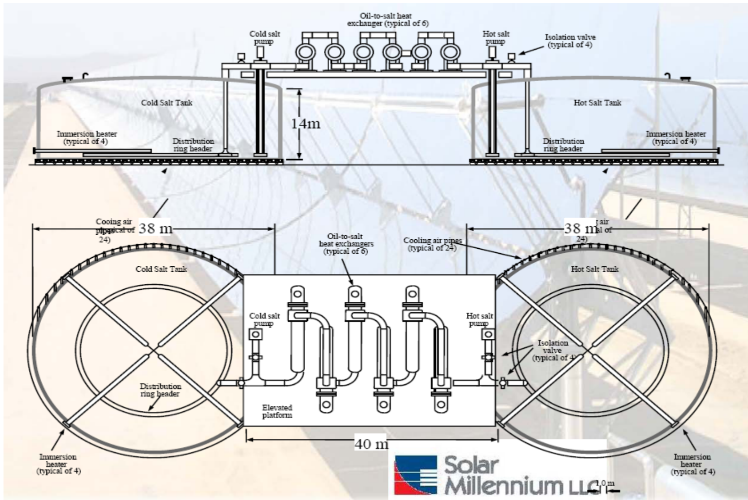


Figure 5-9: Design parameters of Andasol 1 (50 MW) vs. an equivalent smaller 16.5 MW plant for power and desalination of type CSP/RO.

5.3.2 Case 2: Multi-Effect Desalination Using Heat & Power from a CSP Plant (CSP/MED)

An appropriate concept for such a plant must still be developed. A possible configuration could use a linear Fresnel collector field directly generating saturated steam at 270 °C, 55 bar. An intermediate heat transfer fluid and respective heat exchangers are not required in that case. A saturated back-pressure steam turbine would be used for power generation. Heat storage would consist of a concrete block with a high temperature and a low temperature section. The high temperature section would serve to store heat at around 270-250°C for saturated steam generation for the turbine, while the low temperature section would serve to store heat at around 250-75 °C for low temperature steam generation for the MED plant.

During daytime, excess steam from the oversized solar field that is not required for the turbine is used to heat up the concrete storage. While passing through the storage, the saturated steam entering at 270°C is condensed in the hot section of the storage. The condensate then enters the cold section of the storage and leaves ideally at about 73°C. The pressure of the condensate is then reduced to the backpressure of the steam turbine via a throttle valve. Then it is mixed with the condensate from the MED header and returned to the solar field by the feed pump of the power cycle.

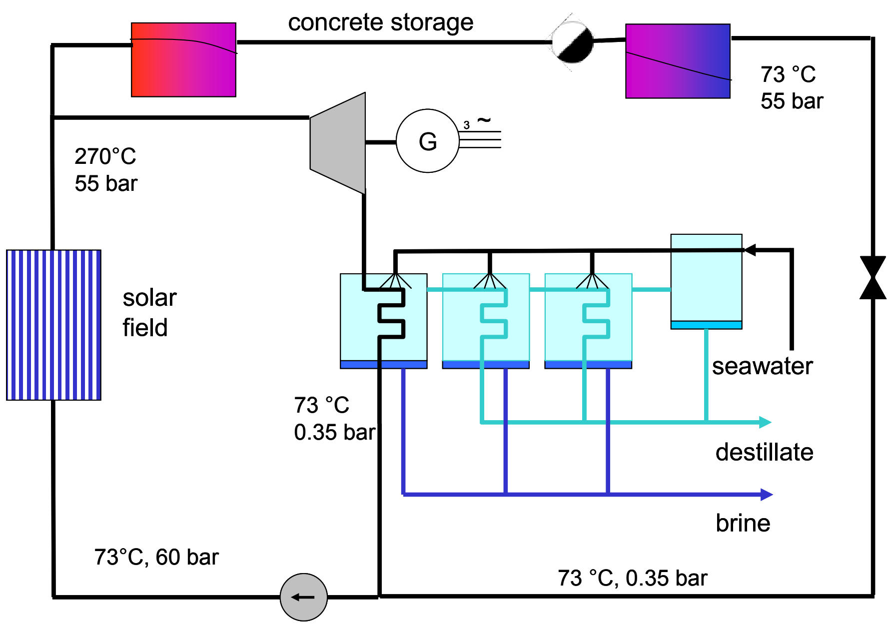


Figure 5-10: CSP/MED plant during daytime operation

During night time, the solar field is by-passed and the condensate directly enters the cold end of the hot section of the concrete storage. There, its temperature is increased to the evaporation temperature – which will be lower than at daytime – of about 250 °C at a pressure of 40 bar. During discharge, pressure may be reduced to as low as 11 bar, 185°C. Passing through the hot section of the storage, the water evaporates and is then used to drive the turbine. During night, only the amount of electricity required for the parasitic power demand of the power block and the power for the MED pumps will be produced. Therefore, the turbine will be operating in partial load, thus not generating enough steam for the MED process. The difference will be taken from condensate pumped through the low temperature storage section and evaporating at backpressure level, which will be added to the steam from the turbine. For reasons of security and control, this addition will take place through intermediate heat exchangers between the power cycle and the desalination cycle not displayed here for simplicity. After condensation in the MED header, the condensate will be fed back to the high-temperature and to the low temperature storage.

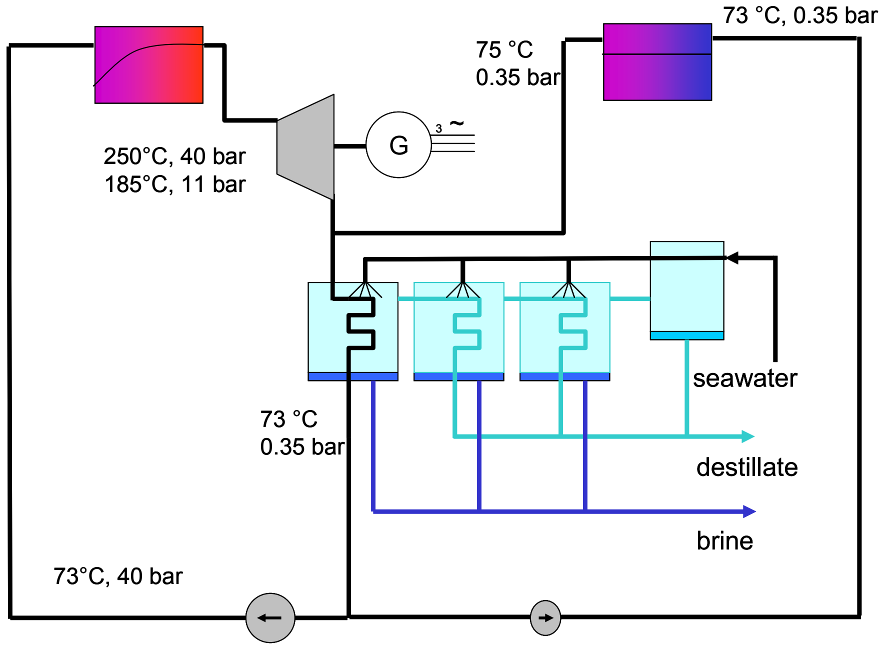


Figure 5-11: CSP/MED plant during night time operation

A possible advantage of this configuration is the independent control of power generation and seawater desalination, which allows for a certain load-following of the power generator while maintaining constant desalination capacity. Another advantage is the simplicity both of the components and of the configuration, which may help to reduce costs of electricity and water. There also seem to be several options for heat integration and efficiency enhancement that still must be exploited. This must still be confirmed by a more detailed plant design and by hourly time series modelling of plant performance under the specific conditions for the sites under consideration. A general advantage of this configuration is that the lower operation temperature within the solar field will yield higher thermal collector efficiency. On the other hand, the efficiency of power generation will be lower than in Case 1.

The following pictures give same examples of the equipment that may be used in this configuration:

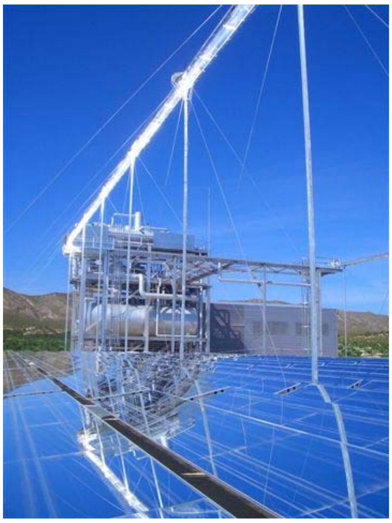



Figure 5-12: Linear Fresnel demonstration power plant at Puerto Errado (PE 1), Spain with 2 x 900 metre collector lines and 2 MW saturated steam turbine (NOVATEC)


Figure 5-13: Concrete storage without insulation for a maximum temperature of 400 °C mounted at the DLR test site in Stuttgart (left) and pre-fabricated tube bundle before adding concrete (right) (Züblin, DLR)

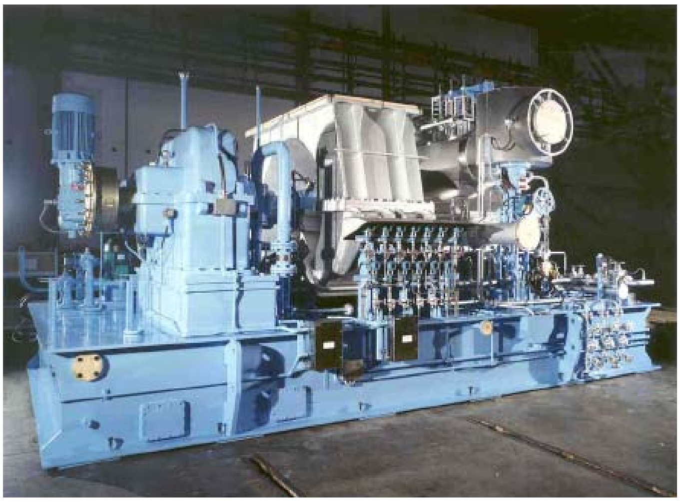


Figure 5-14: Photograph showing a 20 MW steam turbine with gearbox (left), low pressure steam flange (centre, top) and high pressure steam inlet (right, top), Dimensions L=7m , W= 3m , H=3m. Generator will be connected on the left (Length 5 m).

Figure 5-15: Optional backup steam boiler (source: inven)

Figure 5-16: Multi-effect desalination unit with thermal vapour compression (left) and complete plant (right) Source: /entropie 2006/

6 REFERENCES

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ANNEXES

ANNEX 1 : Units and Abbreviations

Abbreviation

BWRO	brackish water reverse osmosis
ERD	energy recovery device
GOR	gained output ratio
MED	Multi effect distillation
MSF	Multi stage flash
NF	Nano filtration
RO	Reverse osmosis
PX	pressure exchanger
SDI	solid dispersion index
SWRO	Sea water reverse osmosis
TC	turbo charger
TVC	Thermal vapour compression
WHO	World Health Organisation

Units

Symbol	**Unit**	**Definition**
A	m²	area
C	ppm	concentration
J	m³ / m² s	flux, also expressed in
	liter x meter² / hour	
Ka	m / Pa s	membrane permeability, also expressed in l/(m²*h*bar)
M	t/h	mass flow rate
NDP	bar	Net driving pressure

P	bar	pressure
Rej	-	salt rejection ratio
SE	kWh/m^3	specific energy
TDS	mg/l	total disolved solids
	kWh/t	power consumption
T	°C	temperature
	m^3/d	flow rate
Π	bar	osmotic pressure difference
η	-	efficiency

Subscripts

Avg	average
b	brine
Dist	distillate
f	feed
P	pump
M	mechanic

ANNEX 2 : Market Development of Desalination Plants