AQUA-CSP

Concentrating Solar Power for Seawater Desalination

Final Report

by

German Aerospace Center (DLR)
Institute of Technical Thermodynamics
Section Systems Analysis and Technology Assessment

Study commissioned by

Federal Ministry for the Environment,
Nature Conservation and Nuclear Safety
Germany

The Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

DLR

The full **AQUA-CSP Study Report** can be found at the website:
http://www.dlr.de/tt/aqua-csp

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Stuttgart, November 2007

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Acknowledgements:

The AQUA-CSP team thanks the German Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) for sponsoring this project, Ralf Christmann from BMU, Nadine May and Ludger Lorych from VDI/VDE/IT for their efficient project management, Dr. Jürgen Scharfe from entropie, Munich for kindly reviewing part of the report, Sabine Lattemann from Oldenburg University for providing the latest know-how on environmental impacts of desalination, the Trans-Mediterranean Renewable Energy Cooperation (TREC) for providing a very useful discussion forum, our colleagues at DLR and to everybody else who helped in making this project a success.

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Some Remarks about this Study

Thousands of years ago, prosperous conditions in fertile river locations throughout the world motivated nomadic people to form sedentary, agrarian communities. The inhabitants of these areas built cities, learned to fabricate pottery and to use metals, invented writing systems, domesticated animals and created complex social structures. In short, civilization was born when hunters and gatherers became settlers and farmers.

Except for energy: today's civilization is still based on gathering different forms of fossil energy, just like our ancestors, that collected berries and hunted animals until resources were depleted and they had to move elsewhere. Today, fossil energy resources are still sought and gathered until the last drop is spent. It becomes more and more evident that this is not a civilized behaviour, and certainly not a sustainable one, because there is no other planet in view to move to after resources are depleted and the atmosphere is spoiled.

However, our hunting and gathering ancestors found a solution to that dilemma: they became farmers, sowing seeds in springtime and harvesting corn and fruits in autumn, making use of technical know-how and the abundance of solar energy for their survival. That's exactly what is overdue in the energy sector: we must become farmers for energy, sow wind farms, wave- and hydropower stations, biomass- and geothermal co-generation plants, photovoltaic arrays, solar collectors and concentrating solar power plants and harvest energy for our demand.

The same is true for freshwater: if the freely collectable natural resources become too scarce because the number of people becomes too large, we have to sow rainwater-reservoirs, waste-water reuse systems and solar powered desalination plants, and harvest freshwater from them for our daily consumption. Maybe as a side-effect of this more "civilized" form of producing energy and water, we will also – like our ancestors – find another, more developed social structure, maybe a more cooperative and peaceful one.

The concept described within this report still leaves some open questions. A study like this cannot give all answers. However, much is gained if the right questions are finally asked, and if solutions are sought in the right direction. The AQUA-CSP study, like its predecessors MED-CSP and TRANS-CSP, is a roadmap, but not a wheel-chair: it can show the medium- and long-term goal, it can also show the way to achieve that goal, but it will not carry us there, we'll have to walk by ourselves.

Franz Trieb
Stuttgart, November 12, 2007

It is not essential to predict the future,
but it is essential to be prepared for it.

Perikles (493 – 429 a. C.)

Our world can only be developed by creating lasting values,
but neither by cultivating luxury nor by saving costs.

(lesson learned during the edition of this report)

Introduction

The general perception of "solar desalination" today comprises only small scale technologies for decentralised water supply in remote places, which may be quite important for the development of rural areas, but do not address the increasing water deficits of the quickly growing urban centres of demand. Conventional large scale desalination is perceived as expensive, energy consuming and limited to rich countries like those of the Arabian Gulf, especially in view of the quickly escalating cost of fossil fuels like oil, natural gas and coal. The environmental impacts of large scale desalination due to airborne emissions of pollutants from energy consumption and to the discharge of brine and chemical additives to the sea are increasingly considered as critical. For those reasons, most contemporary strategies against a "Global Water Crisis" consider seawater desalination only as a marginal element of supply. The focus of most recommendations lies on more efficient use of water, better accountability, re-use of waste water, enhanced distribution and advanced irrigation systems. To this adds the recommendation to reduce agriculture and rather import food from other places. On the other hand, most sources that do recommend seawater desalination as part of a solution to the water crisis usually propose nuclear fission and fusion as indispensable option.

None of the presently discussed strategies include concentrating solar power (CSP) for seawater desalination within their portfolio of possible alternatives. However, quickly growing population and water demand and quickly depleting groundwater resources in the arid regions of the world require solutions that are affordable, secure and compatible with the environment – in one word: sustainable. Such solutions must also be able to cope with the magnitude of the demand and must be based on available or at least demonstrated technology, as strategies bound to uncertain technical breakthroughs – if not achieved in time – would seriously endanger the whole region.

Renewable energy sources have been accepted world wide as sustainable sources of energy, and are introduced to the energy sector with an annual growth rate of over 25 % per year. From all available energy sources, solar energy is the one that correlates best with the demand for water, because it is obviously the main cause of water scarcity. The resource-potential of concentrating solar power dwarfs global energy demand by several hundred times. The environmental impact of its use has been found to be acceptable, as it is based on abundant, recyclable materials like steel, concrete and glass for the concentrating solar thermal collectors. Its cost is today equivalent to about 50 US$ per barrel of fuel oil (8.8 US$/GJ), and coming down by 10-15 % each time the world wide installed capacity doubles. In the medium-term by 2020, a cost equivalent to about 20 US$ per barrel (3.5 US$/GJ) will be achieved. In the long-term, it will become one of the cheapest sources of energy, at a level as low as 15 US$ per barrel of oil (2.5 US$/GJ). It can deliver energy "around the clock" for the continuous operation of desalination plants, and is therefore the "natural" resource for seawater desalination.

Main Results

The AQUA-CSP study analyses 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 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.

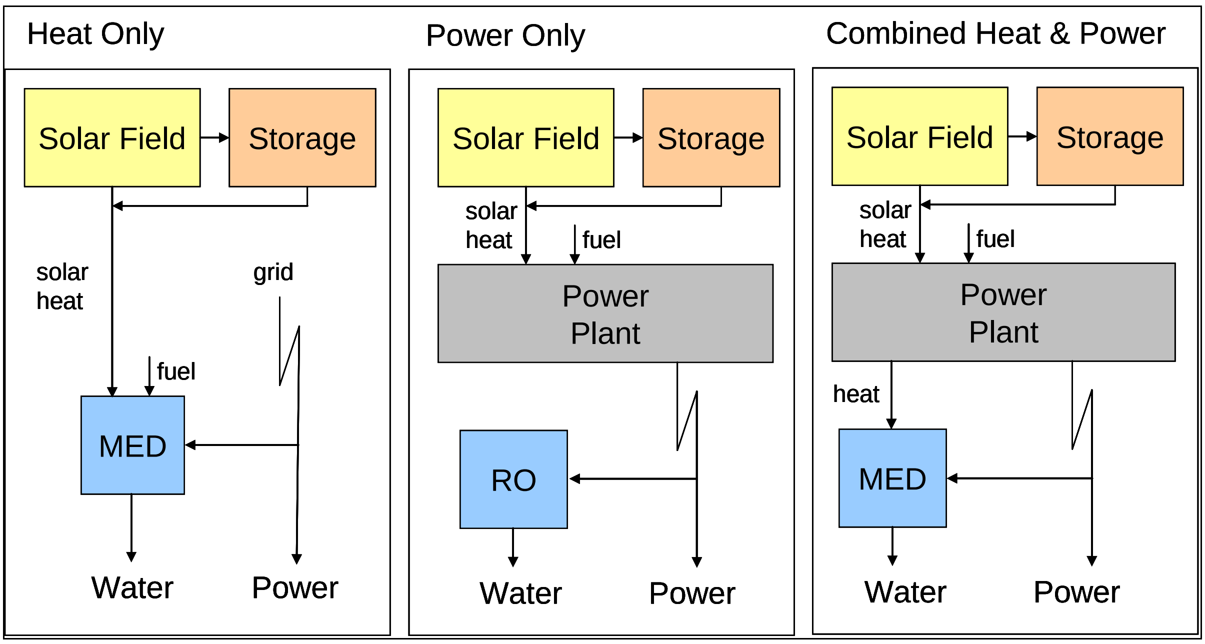


Figure 1: Different configurations for desalination by concentrated solar power. Left: Concentrating solar collector field with thermal energy storage directly producing heat for thermal multi-effect desalination. Center: Power generation for reverse osmosis (CSP/RO). Right: Combined generation of electricity 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). 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. Additional measures like re-use of waste water, advanced irrigation, better management and accountability, improved distribution systems and new, unconventional sources of water will be imperative to avoid a foreseeable collapse of water supply in the MENA region.

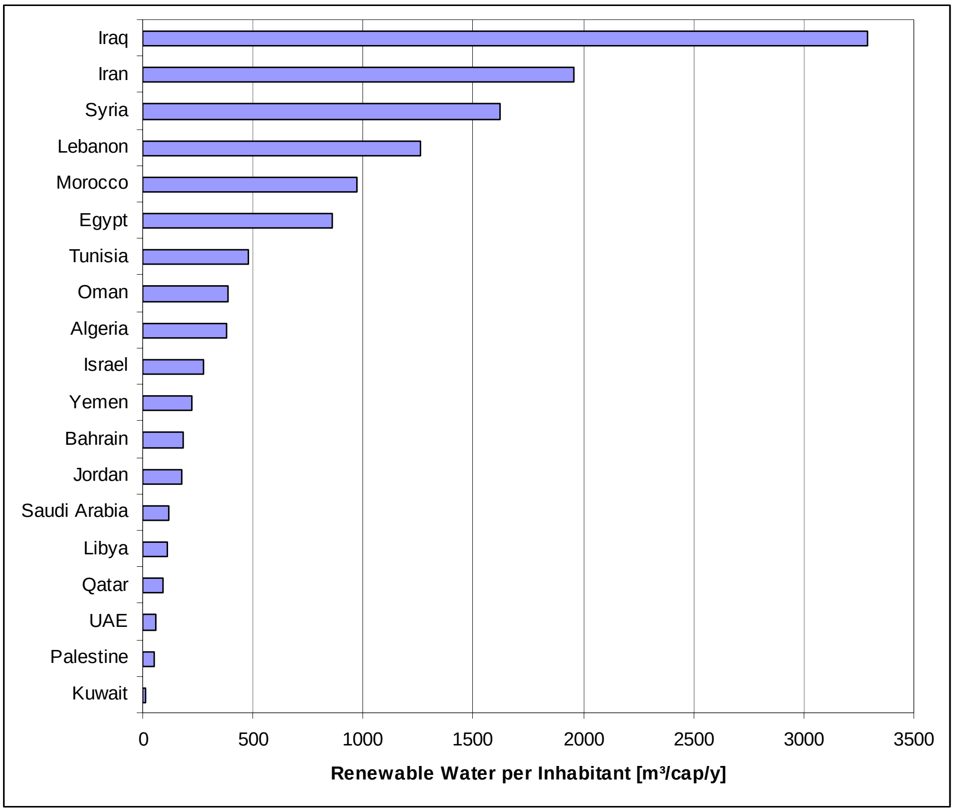


Figure 2: Total available natural renewable freshwater sources available per capita in the MENA region of the year 2000. Only four countries are beyond the water poverty threshold of 1000 m³/cap/y.

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 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.

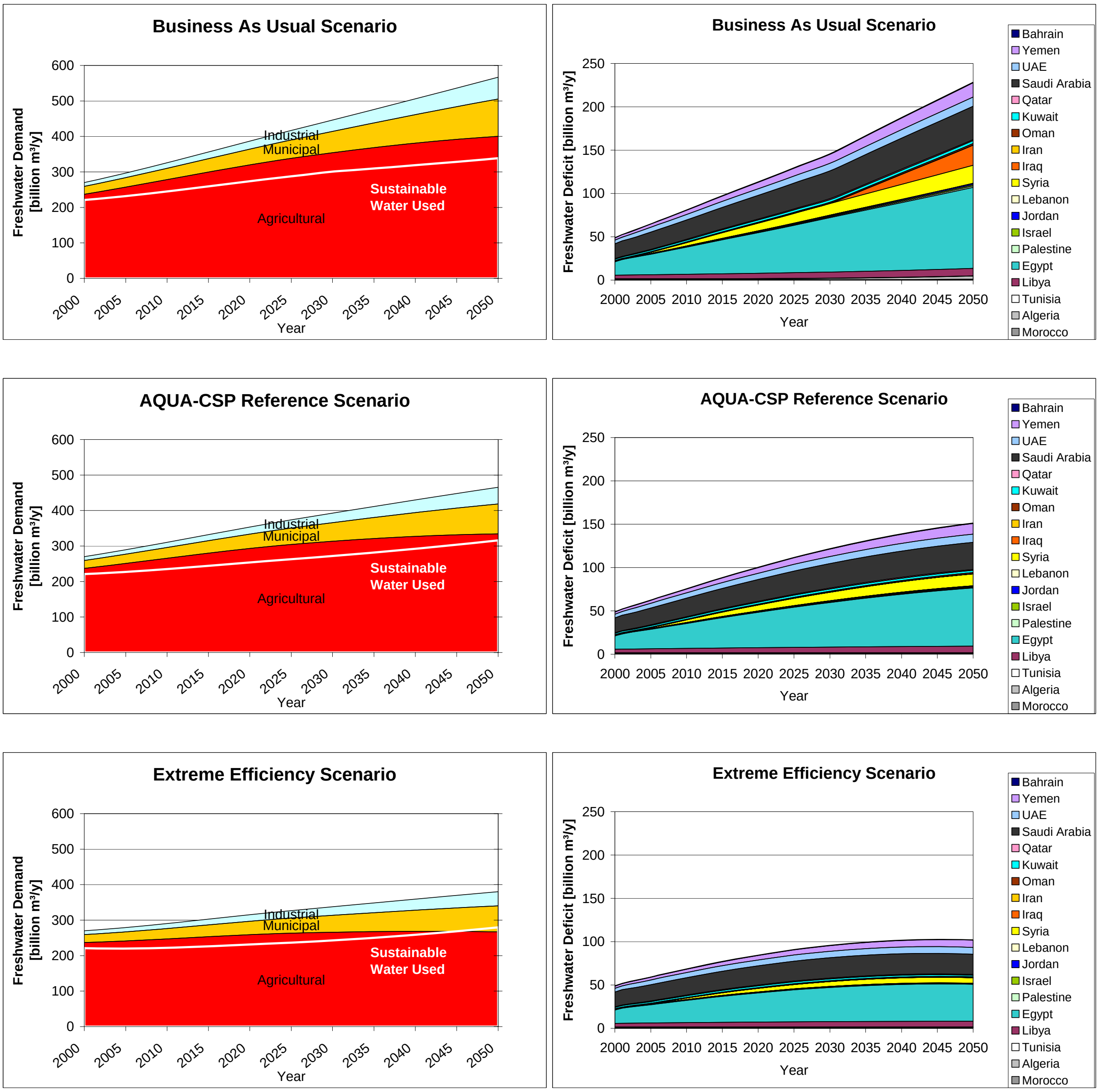


Figure 3: Results of the model calculation with minimum (top), reference (centre) and maximum (bottom) measures to increase the efficiency of water use, water distribution and irrigation and the re-use of waste-water for all MENA countries (data for individual countries is given in the annex of the main 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 4 and Table 1).

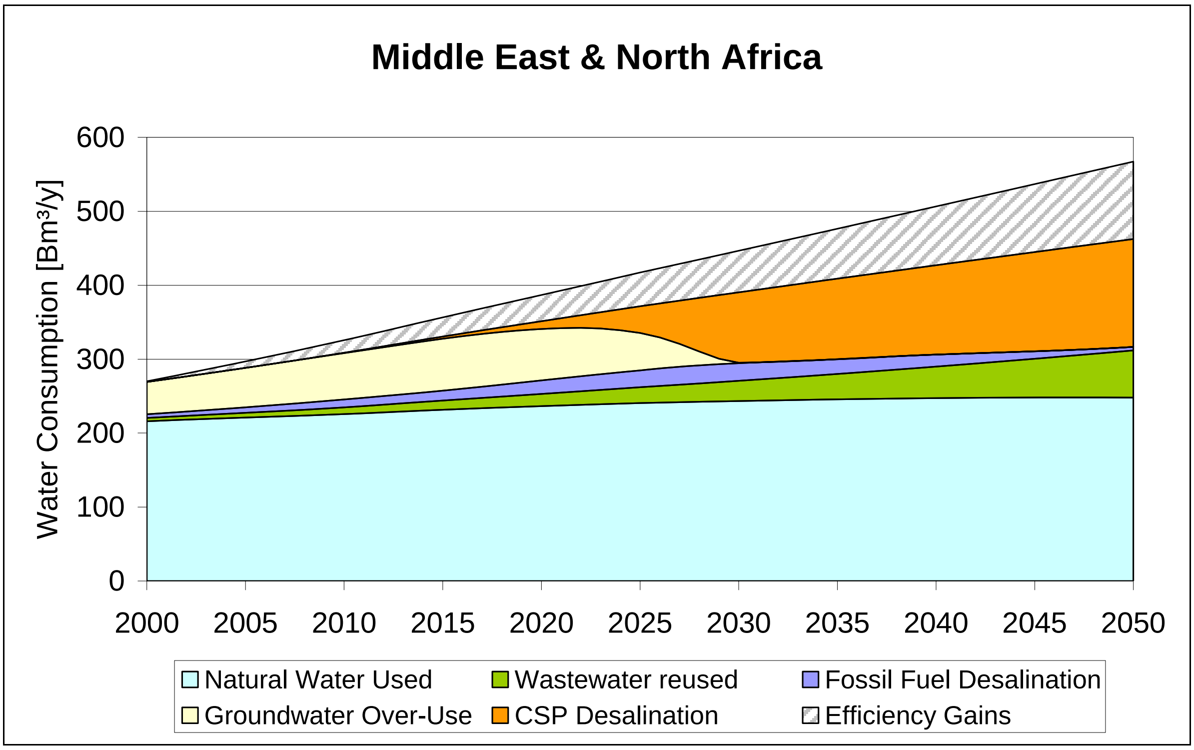


Figure 4: Water demand scenario for MENA until 2050 and coverage of demand by sustainable sources, by unsustainable sources and by solar desalination. (shaded: efficiency gains with respect to business as usual)

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 probably 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 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 5 and Figure 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.

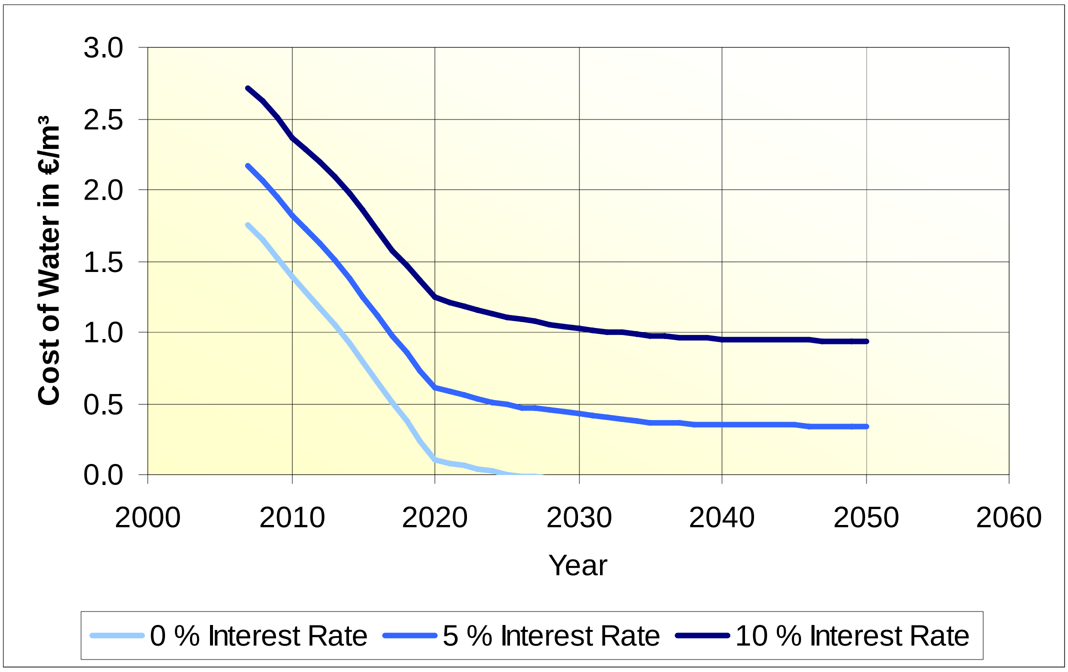


Figure 5: Cost of water from CSP/MED plants for different interest rates assuming that electricity produced by the plants will achieve a fixed revenue of 0.05 €/kWh. In the long-term, a cost of water of 0.34 €/m³ and 0.05 €/kWh for electricity can be achieved in the AQUA-CSP reference case with 5 % interest 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.

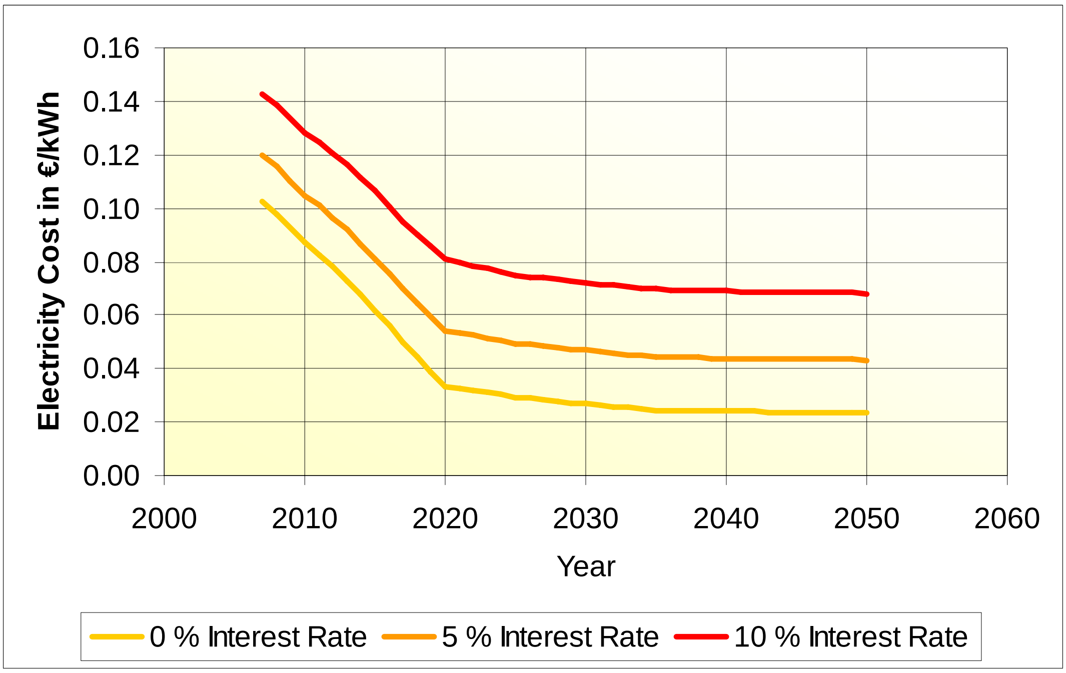


Figure 6: Cost of electricity from CSP/MED plants for different interest rates assuming that water produced by the plants will achieve a fixed revenue of 0.5 €/m³. In the long-term, a cost of electricity of 0.04 €/kWh and 0.5 €/m³ of water can be achieved in the AQUA-CSP reference case with 5 % interest 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 7).

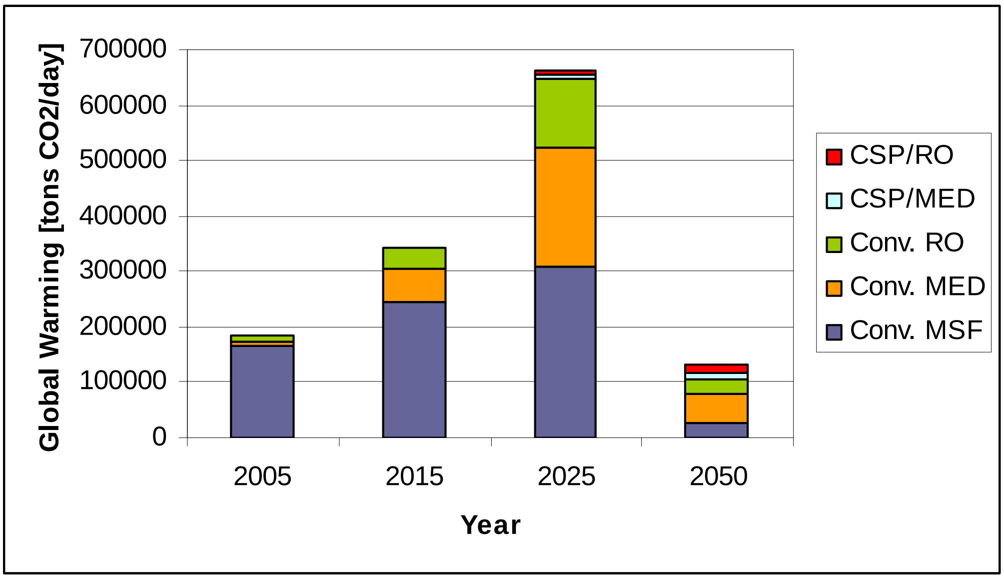


Figure 7: Greenhouse gas emissions from desalination in the AQUA-CSP scenario taking as basis for life-cycle assessment the electricity mix of the MENA countries with increasing renewable shares according to the MED-CSP study. A similar pattern results for all pollutants, showing that the introduction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

Conclusions

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.

1 Review of CSP and Desalination Technology

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

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

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

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

1.1 Seawater Desalination Technologies

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

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

1.1.1 Multi-Stage Flash Desalination (MSF)

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

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

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

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

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

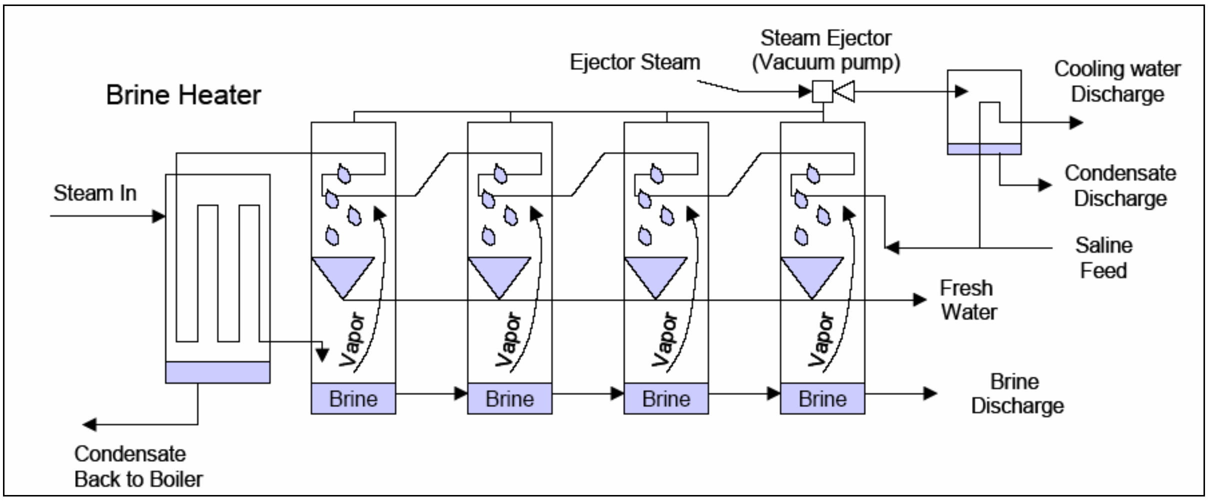


Figure 1-2: Principle of Multi-Stage Flash Desalination (MSF). Source: /Miller 2003/

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

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

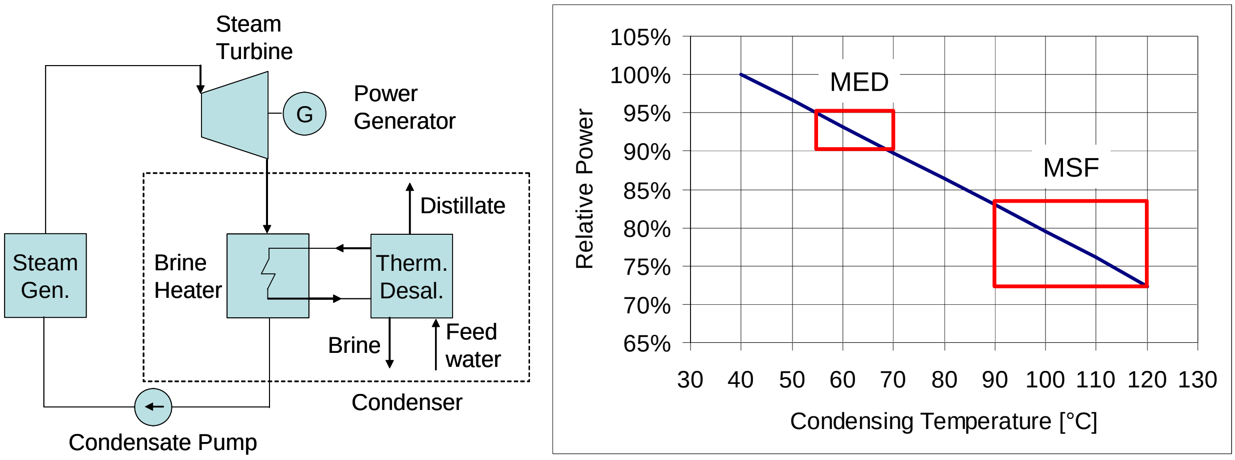


Figure 1-3: Principle of substituting the condenser of a steam cycle power plant by a thermal desalination unit (left) and typical reduction of steam turbine power capacity at increasing condensing temperature (right). The squares show the typical operating range of MED and MSF plants.

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

1.1.2 Multi-Effect Desalination (MED)

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

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

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

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

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

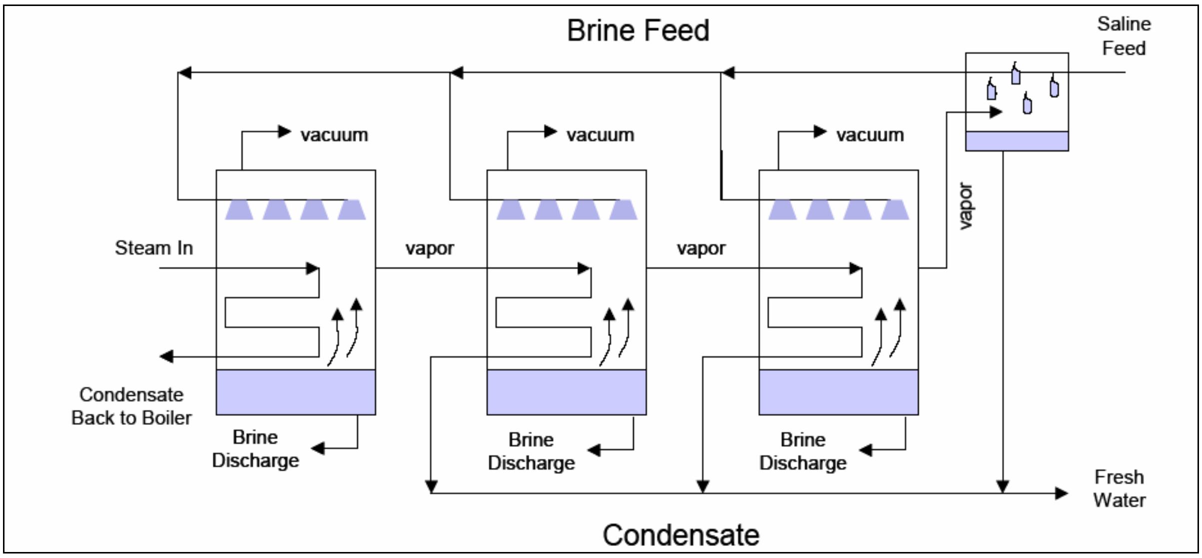


Figure 1-5: Principle of Multi Effect Desalination (MED) /Miller 2003/.

1.1.3 Reverse Osmosis (RO)

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

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

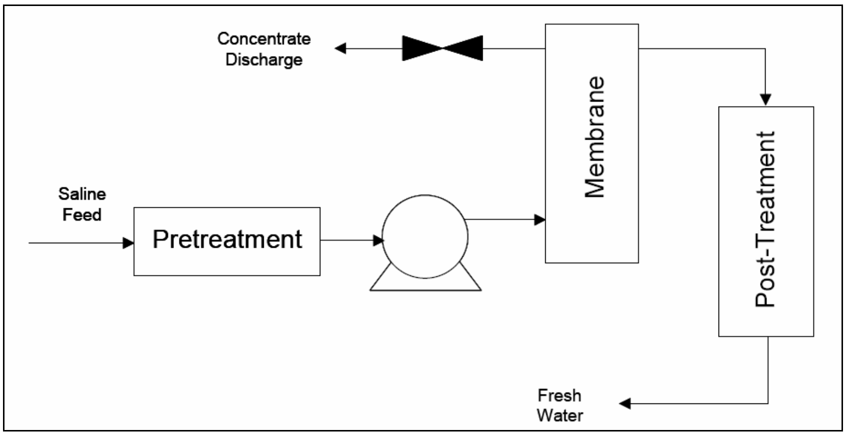


Figure 1-6: Principle of Desalination by Reverse Osmosis (RO) /Miller 2003/.

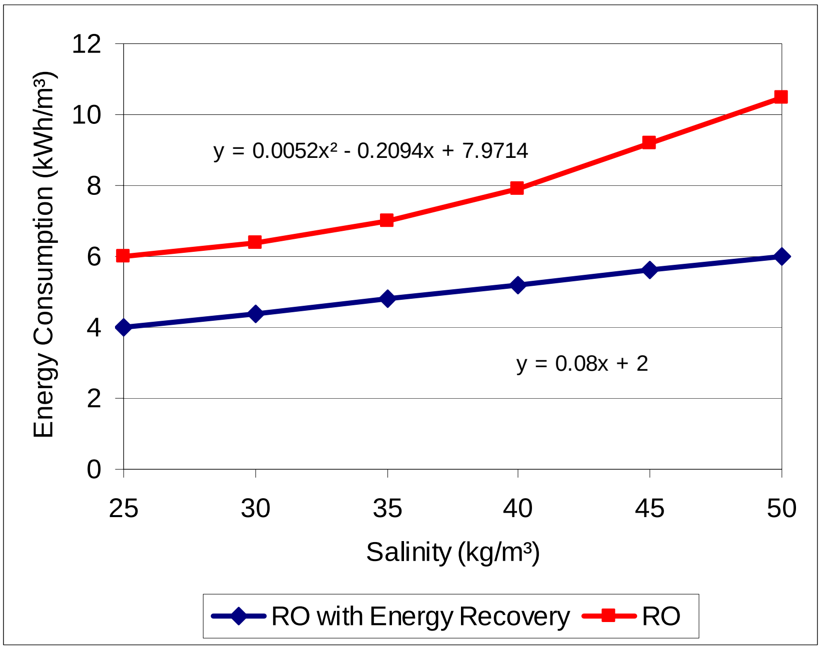


Figure 1-7: Specific electricity consumption of reverse osmosis plants with and without energy recovery system as function of raw water salinity /MEDRC 2005/

Figure 1-8: Left: Pressure cylinders containing the separation membranes of a reverse osmosis plant in Barcelona, Spain, with 30,000 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

1.1.4 Thermal Vapour Compression (TVC)

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

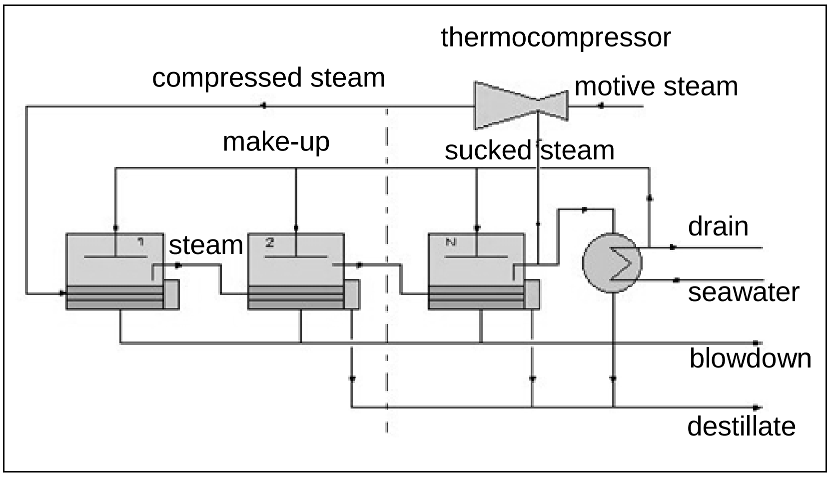


Figure 1-9: Principle of Thermal Vapour Compression (TVC) /Abu-Arabi 2005/

1.1.5 Mechanical Vapour Compression (MVC)

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

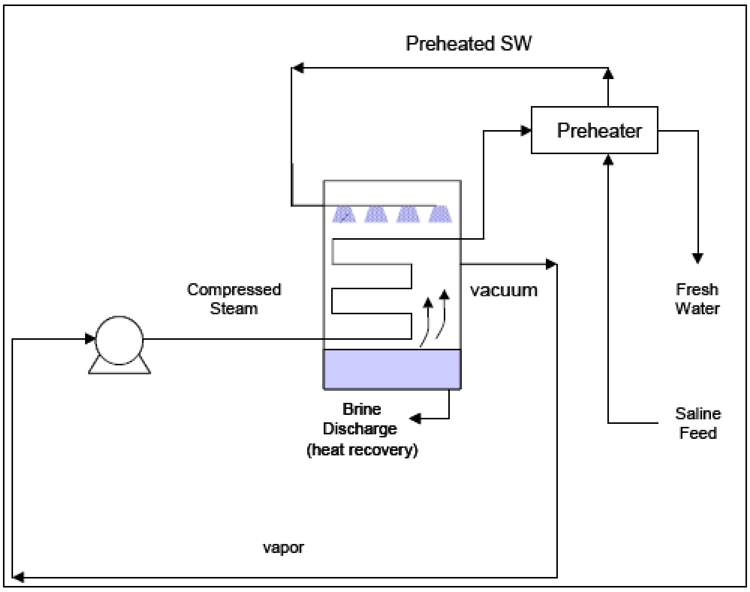


Figure 1-10: Single stage mechanical vapour compression desalination process (MVC) /Miller 2003/.

1.1.6 Pre-Selection of Desalination Technologies

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

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

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

Energy used	thermal		mechanical	
Process	MSF	MED/TVC	MVC	RO
State of the Art	commercial	commercial	commercial	commercial
World Wide Capacity 2004 (Mm³/d)	13	2	0.6	6
Heat Consumption (kJ/kg)	**250 – 330**	145 - 390	--	--
Electricity Consumption (kWh/m³)*	**3 - 5**	1.5 - 2.5	**8 - 15**	2.5 - 7
Plant Cost ($/m³/d)**	**1500 - 2000**	900 - 1700	**1500 - 2000**	900 -1500
Time to Commissioning (months)	24	18 - 24	12	18
Production Unit Capacity (m³/d)	< 76000	< 36000	**< 3000**	< 20000
Conversion Freshwater / Seawater	**10 - 25%**	23 - 33%	23 - 41%	20 - 50%
Max. Top Brine Temperature (°C)	**90 - 120**	55 - 70	70	45 (max)
Reliability	very high	very high	high	moderate (for seawater)
Maintenance (cleaning per year)	0.5 - 1	1 - 2	1 - 2	several times
Pre-treatment of water	simple	simple	very simple	demanding
Operation requirements	simple	simple	simple	demanding
Product water quality (ppm)	< 10	< 10	< 10	200 - 500

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

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

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

1.2 Concentrating Solar Power Technologies

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

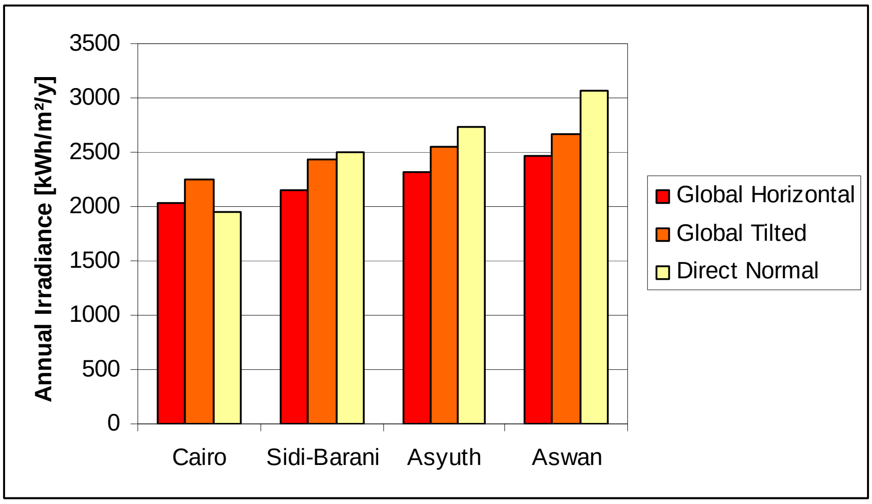


Figure 1-11: Examples of the annual sum of global horizontal irradiance, global irradiance on a surface tilted south and direct normal irradiance for several locations in Egypt (Source: meteonorm database)

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

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

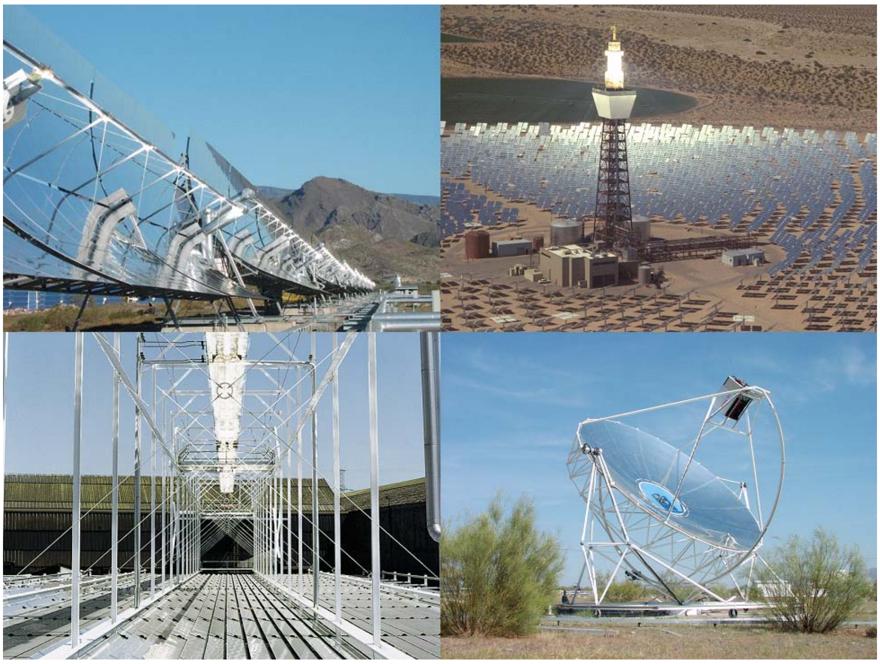


Figure 1-12: The four mainstream CSP-technologies for the production of high-temperature solar heat for power generation and process steam: parabolic trough (upper left), linear Fresnel (bottom left), solar tower (upper right) and dish Stirling (bottom right).

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

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

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

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

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

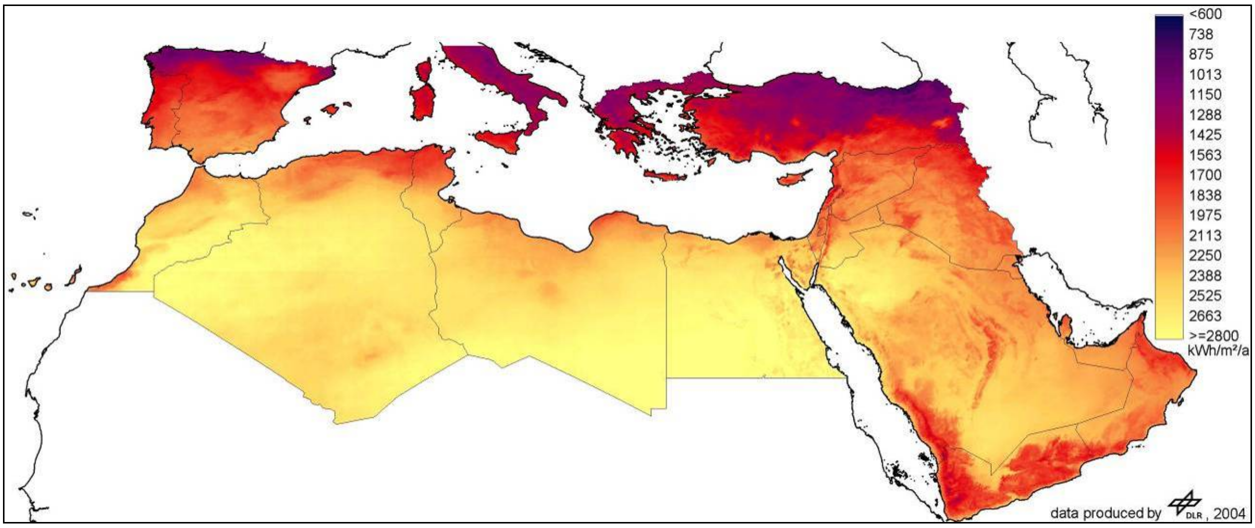


Figure 1-13: Solar energy atlas for Southern Europe, the Middle East and North Africa, showing the annual sum of direct normal irradiance in kWh/m²/y. Normal irradiance is defined as the irradiance perpendicular to a surface that continuously tracks the sun. Direct irradiance excludes the diffuse share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

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

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

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

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

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

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

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

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

3 Solar irradiance 2400 kWh/m^2/y x 1 million m^2/km^2 : 1600 kWh/bbl heating value = 1.5 million bbl/km^2/y

4 Lake Nasser has 6000 km^2 x 1.5 million bbl/km^2/y = 9 billion bbl/y = Middle East oil production

5 Solar irradiance 2400 kWh/m^2/y x 11 % CSP efficiency * 95 % Land Use : 4.2 kWh/m^3 RO power consumption : 365 days/y = 0.165 m^3/m^2/day x 1 million m^2/km^2 = 165,000 m^3/km^2/day

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

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

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

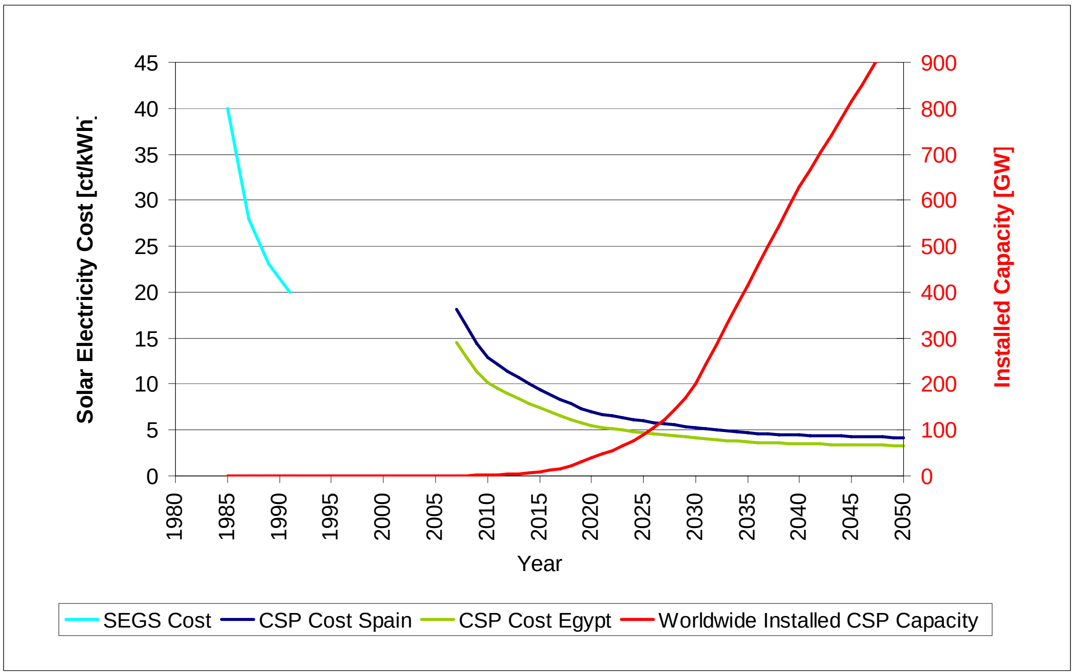


Figure 1-14: Solar electricity cost of concentrating solar power plants as function of time and world wide installed capacity; historical cost of the Californian 350 MW Solar Electricity Generating Systems (SEGS) installed between 1985 and 1991 has been converted to €2005; assumptions for new plants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

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

1.2.1 Concentrating Solar Power for Steam Turbines

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

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

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

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

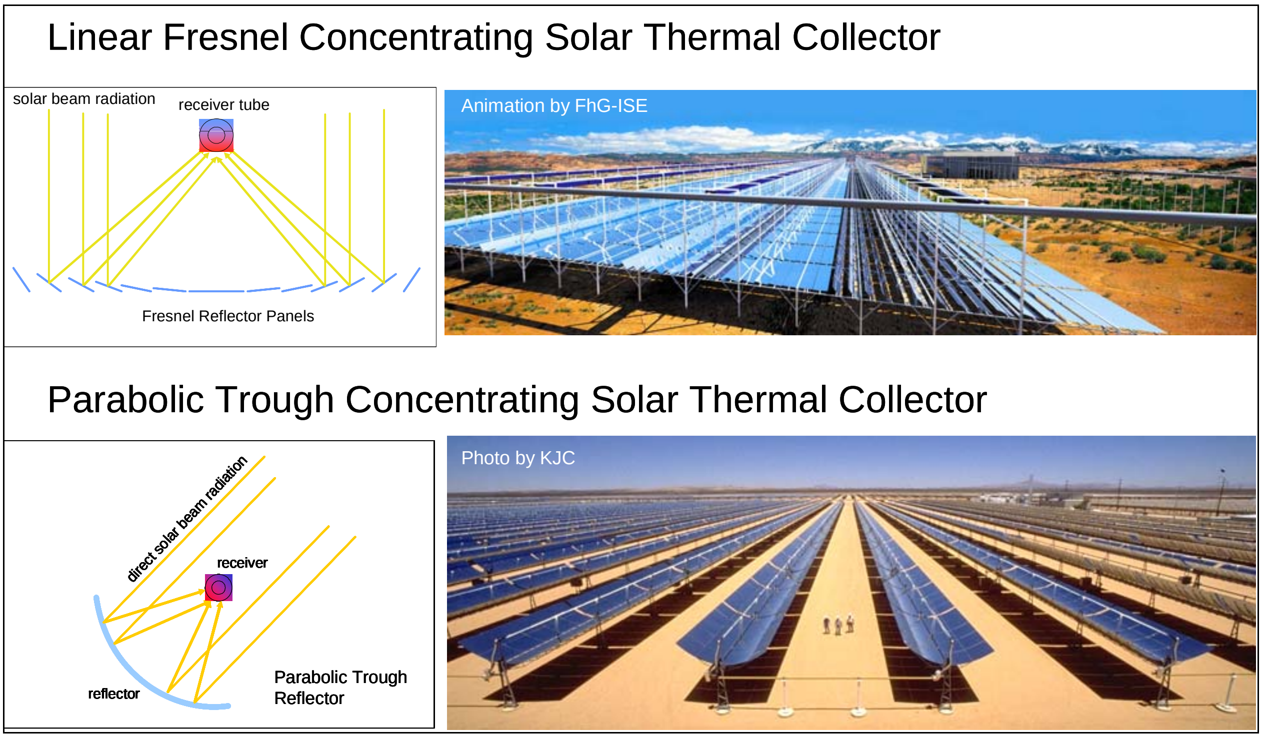


Figure 1-15: Principle of line focusing concentrating solar collector systems. Top: Animation of a Linear Fresnel type concentrating solar thermal collector field for direct steam generation as presently developed by MAN/SPG. Bottom: Parabolic trough solar field of the 5 x 30 MW solar electricity generating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

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

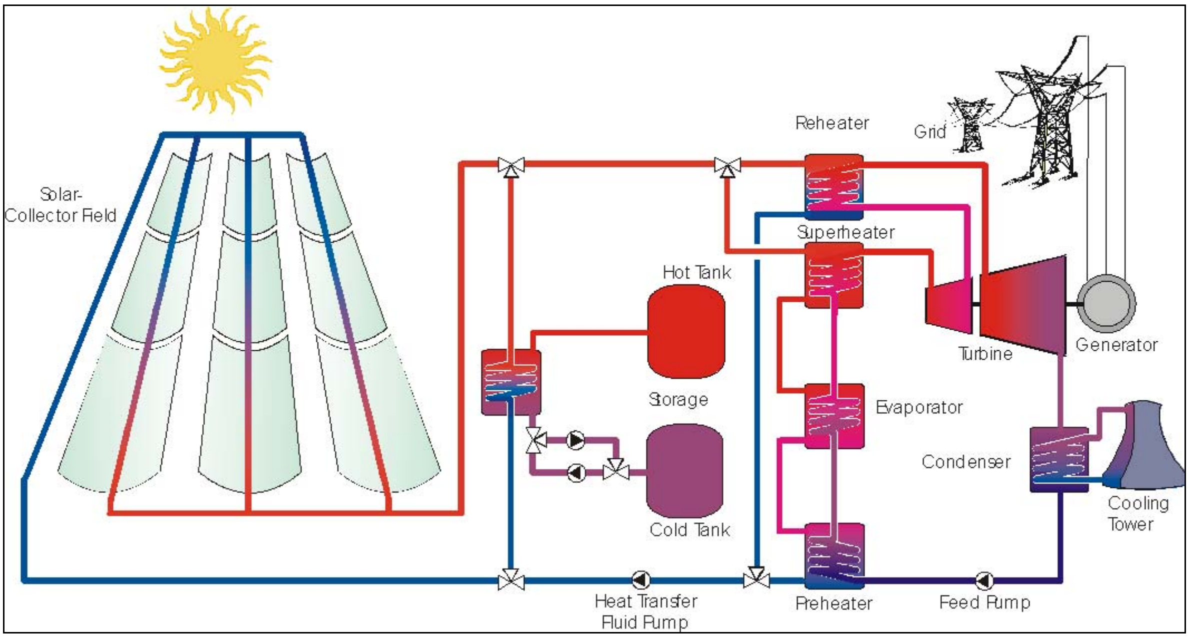


Figure 1-17: Line focusing concentrating collector coupled to a steam cycle power station

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

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

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

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

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

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

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

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

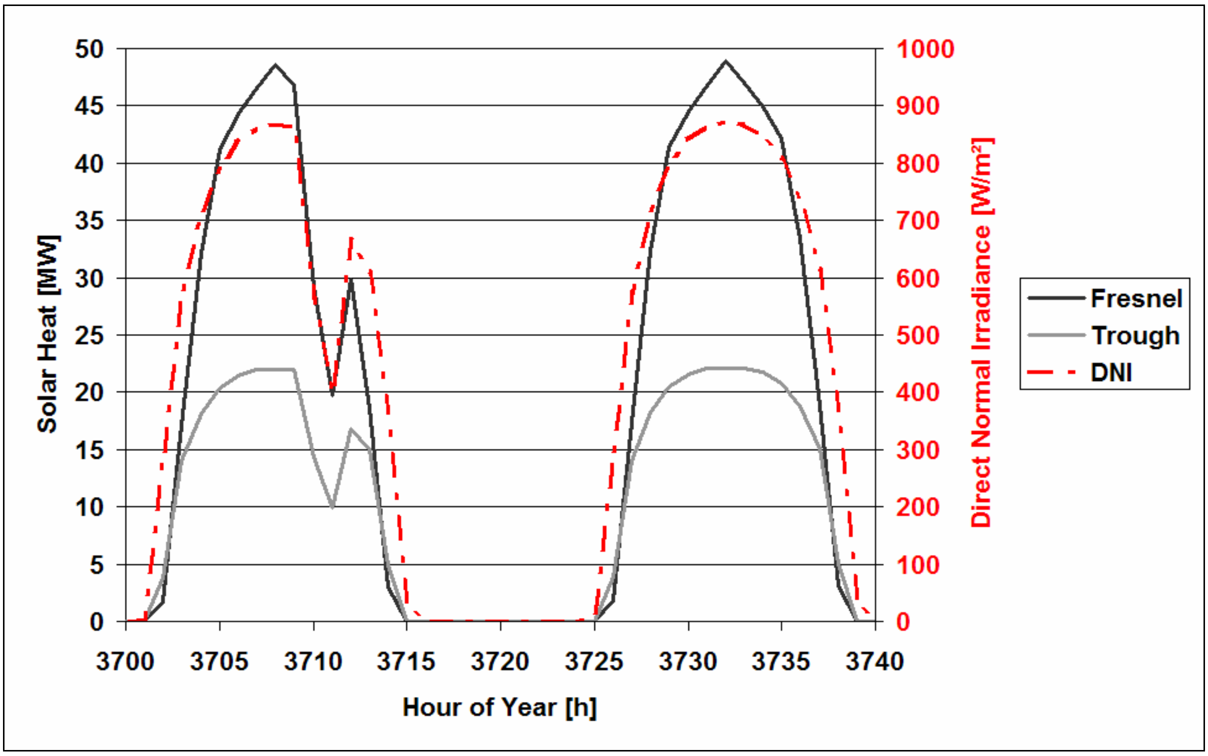


Figure 1-19: Example of the solar heat delivered from a linear Fresnel and from a parabolic trough collector field covering a land area of 110,000 m² as function of time and direct normal irradiance /SolWater 2006/

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

1.2.2 Concentrating Solar Power for Gas Turbines

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

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

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

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

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

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

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

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

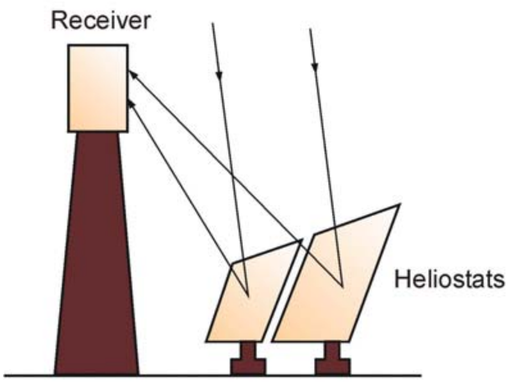


Figure 1-20: Principle of a point focusing solar tower system (Plataforma Solar de Almeria, Spain)

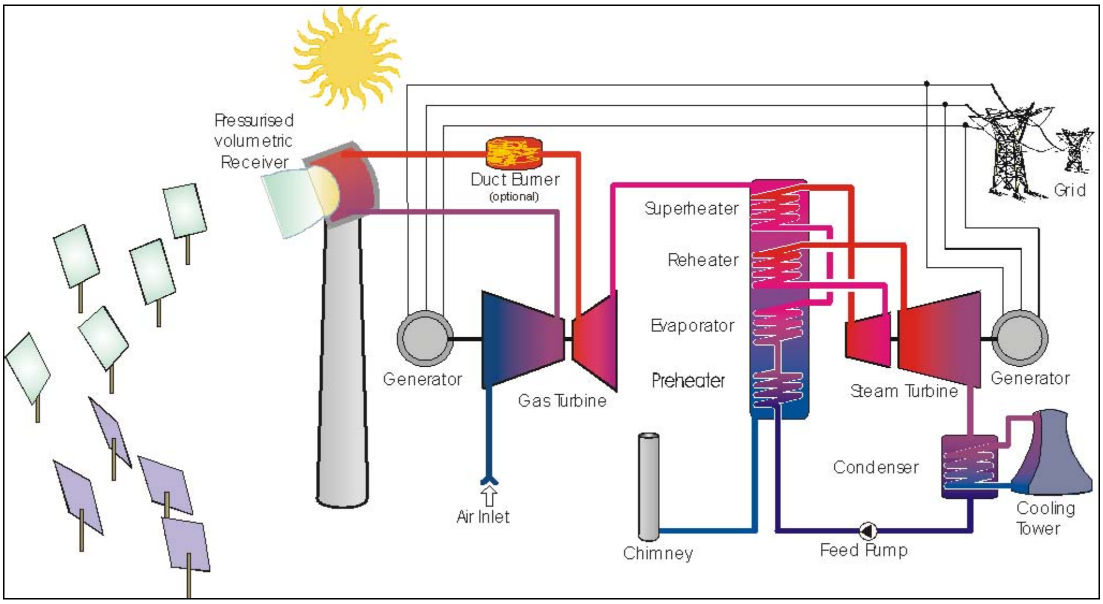


Figure 1-21: Solar tower used for gas turbine operation in a combined cycle power plant

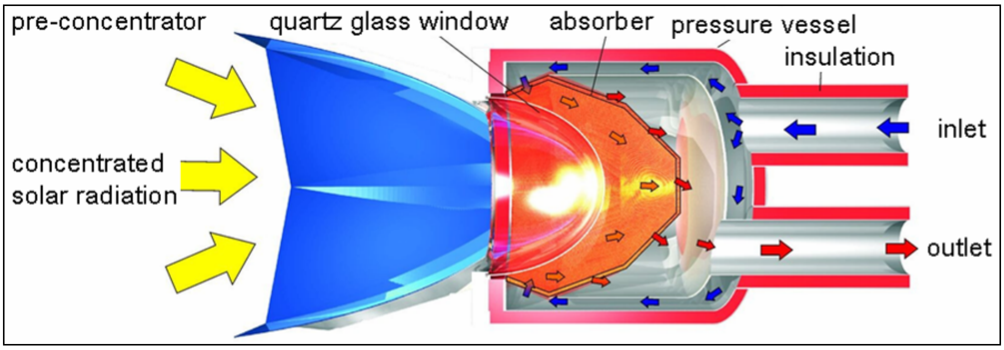


Figure 1-22: Pressurised air heated by solar energy using a volumetric receiver

1.2.3 Concentrating Solar Power for Combined Electricity and Heat

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

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

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

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

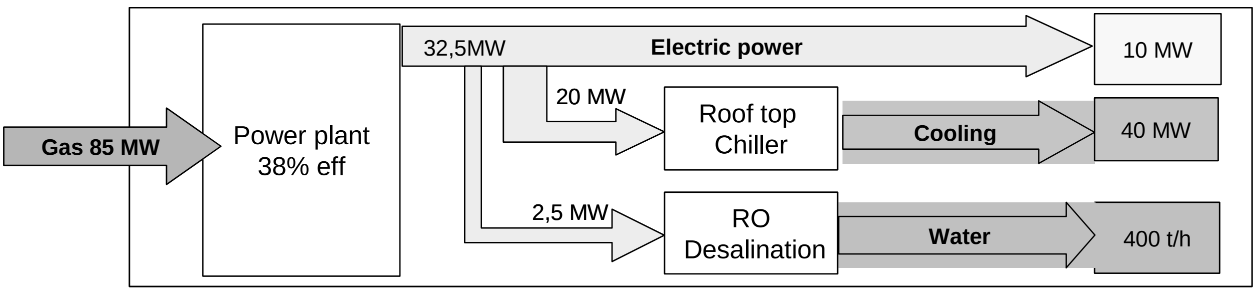


Figure 1-23: Conventional solution for power, cooling and water for a hotel resort in Aqaba /Kern et al. 2006/

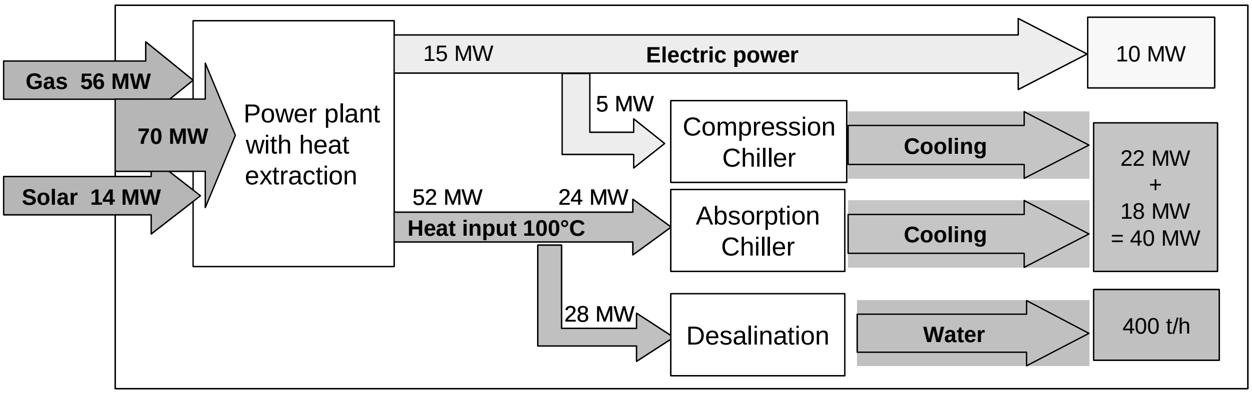


Figure 1-24: Integrated solution for power, cooling and water supported by CSP /Kern et al. 2006/

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

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

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

1.2.4 Pre-Selection of CSP Technologies

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

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

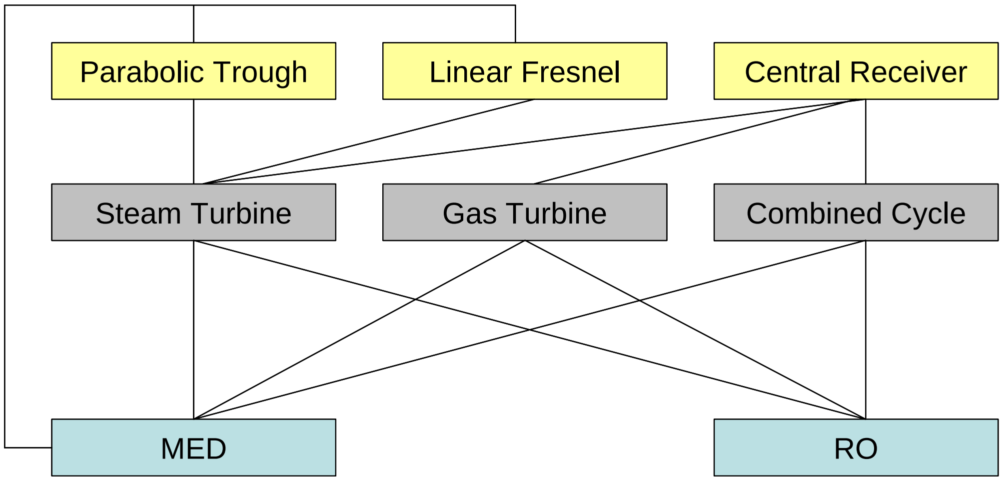


Figure 1-25: Options of combining concentrating solar power with desalination technologies

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

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

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

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

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

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

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

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

1.3 Concentrating Solar Power for Large Scale Seawater Desalination

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

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

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

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

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

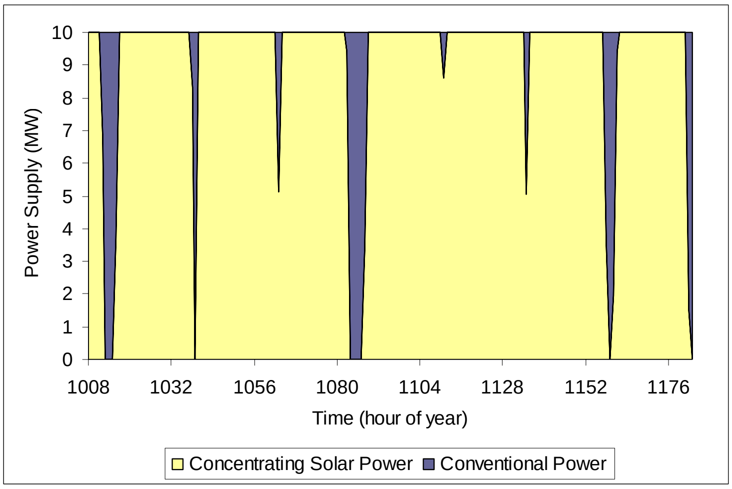


Figure 1-26: Solar power provided by a modelled CSP-plant with 16 hour thermal storage in a week in spring, and fuel consumed in hybrid mode from the same plant for constant 10 MW capacity.

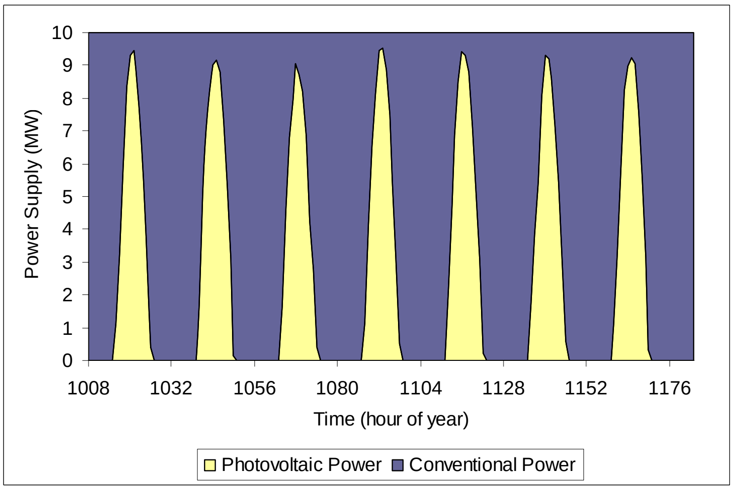


Figure 1-27: Power supplied by modelled 10 MW PV capacity and conventional backup power from the grid needed to provide constant 10 MW power supply for desalination for a week in spring.

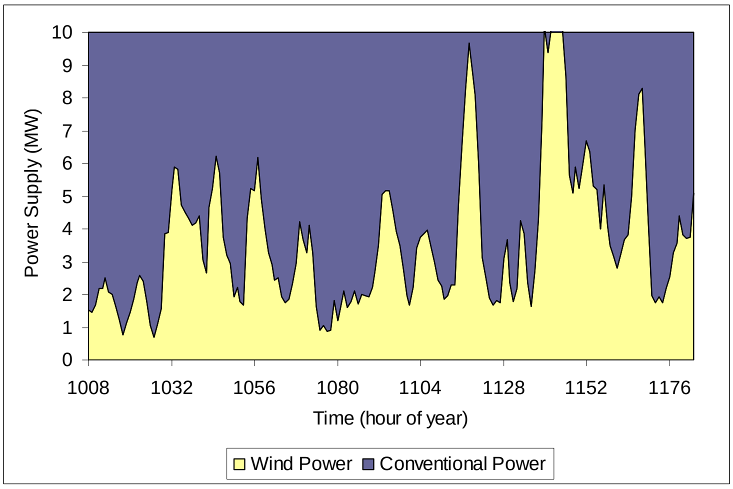


Figure 1-28: Power supplied by 10 MW installed wind capacity and conventional backup power from the grid needed to provide constant 10 MW power supply for desalination for a week in spring.

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

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

1.3.1 Comparison of Technical Performance

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

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

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

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

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

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

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

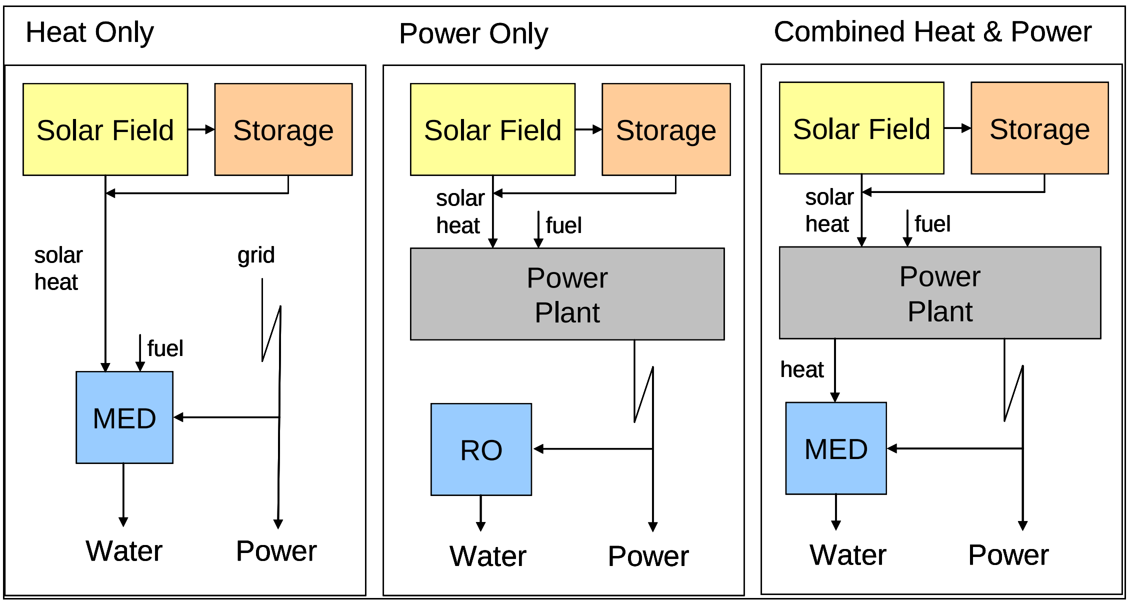


Figure 1-29: Different configurations for desalination powered by CSP. Left: Solar field directly producing heat for thermal multi-effect desalination. Center: Power generation for reverse osmosis (RO). Right: Combined generation of electricity and heat for multi-effect desalination (MED).

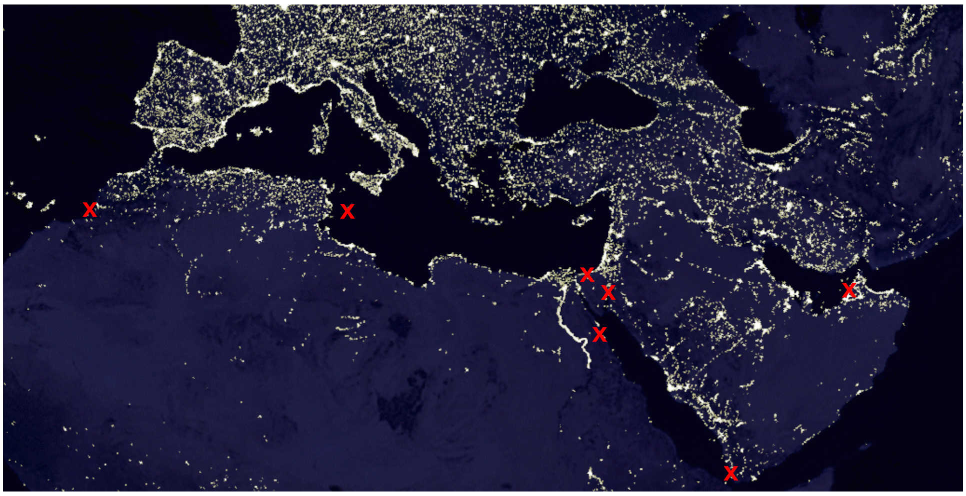


Figure 1-30: Human activities indicated by night-time light emissions in the MENA region and sites chosen for case analysis of CSP combined with seawater desalination (background map by NASA). From left to right: Agadir (Morocco), Valetta (Malta), Gaza (Palestine), Aqaba (Jordan), Hurghada (Egypt), Al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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

1.3.2 Comparison of Economic Performance

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

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

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

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

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

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

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

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

The economic performance of the combined generation of electricity and desalted water was compared by fixing the sales price for electricity at 0.07 €/kWh which would be the production cost of a gas-fired combined cycle power station and subtracting the resulting annual electricity revenue from the total annual expenditure. The remaining annual cost was charged to the annual desalted water production, yielding the average cost per cubic meter of desalted water, which resulted to be in the range of 1.55 – 1.85 €/m³.

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

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

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

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

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

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

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

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

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

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

1.4 Concentrating Solar Power for Small Scale Seawater Desalination

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

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

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

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

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

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

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

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

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

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

2 Natural Water Resources of the MENA Region

In this chapter we will quantify the renewable and exploitable freshwater resources in MENA. Basically the natural resources of freshwater are rainfall, rivers, lakes and groundwater sheds. A very comprehensive definition of the different resources is given in /FAO 2003/. The following definitions are used for the different freshwater resources (Table 2-1):

Internal renewable water resources account for the average annual surface flow of rivers and the recharge of groundwater generated from endogenous precipitation.

External renewable water resources refer to surface water and to renewable groundwater that come from other countries plus part of shared lakes and border rivers as applicable, taking into account the net consumption of the country in question. Dependency on incoming water from external sources is quantified by the **dependency ratio**.

Renewable resources are the total of internal and external surface and groundwater resources. Double counting of surface water and groundwater is avoided as far as possible.

The **exploitable water** potential was estimated if available or was set equal to the renewable water value /FAO 2007/. Exploitable water may either be limited by technical and economical reasons (e.g. if the source is very far from the demand or in a region that is difficult to access), by international treaties regulating the allocation of water from rivers that cross international borders as e.g. in Syria and Egypt, or by reasons of environmental protection.

Non-renewable groundwater resources are naturally replenished only over a very long timeframe. Generally, they have a negligible rate of recharge on the human scale (<1 percent) and thus can be considered non-renewable. In practice, non-renewable groundwater refers to aquifers with large stocking capacity in relation to the average annual volume discharged. Figures included in this table are the best estimate of annual withdrawals.

2.1 Overview of Freshwater Resources

Considerable rainfall in the MENA region with an annual precipitation of more than 300 mm/y is mainly limited to the Mediterranean coastal areas of the Maghreb (Morocco, Algeria, Tunisia), the Northern Mashreq (Syria, Lebanon, Israel) and the western mountains of Yemen and Iran (Figure 2-1, Table 2-1). Only four countries – Iraq, Iran, Syria and Lebanon – can be considered well above the water poverty limit of 1000 m³/cap/y, while all other countries in MENA must be considered as water poor (Figure 2-2). There are only a few major perennial rivers and lakes in the MENA region, namely Euphrates and Tigris in Syria and Iraq and the Nile and Lake Nasser in Egypt, and some smaller rivers in the Maghreb region (Figure 2-3). Some countries like Egypt depend almost exclusively on external freshwater resources entering the country from outside, in this case the Nile river, which accounts for 97 % of the available freshwater.

There are very large groundwater aquifers in the MENA region, that are re-charged by rainfall and by incoming rivers (Figure 2-4). Most of the water contained in those subterranean basins is however fossil water that is not renewed on an annual basis /BGR 2007/.

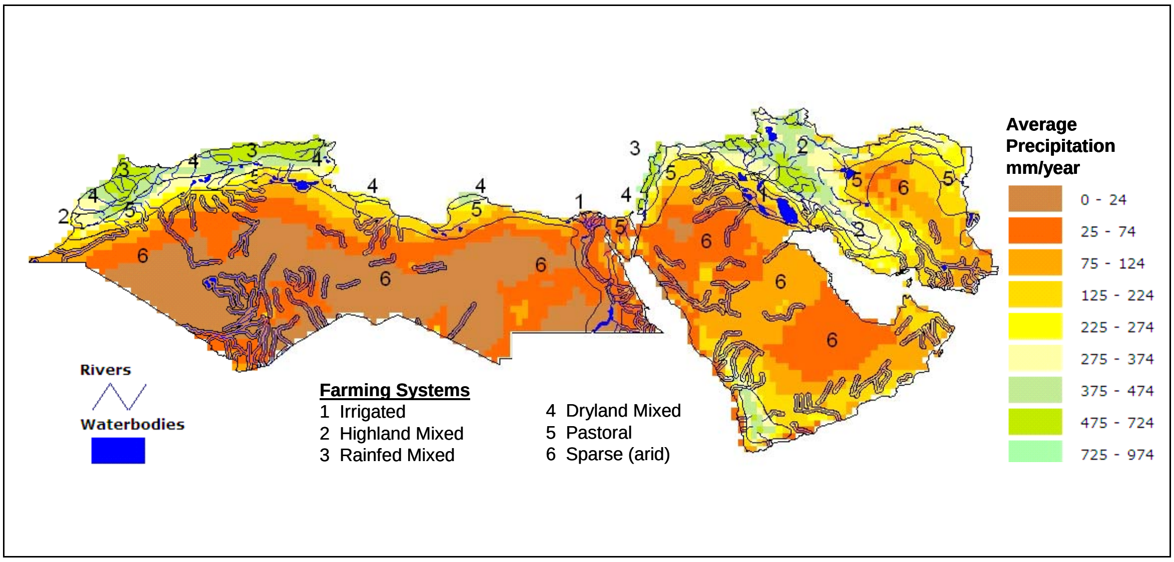


Figure 2-1: Annual Precipitation in the MENA Region /FAO 2007-2/

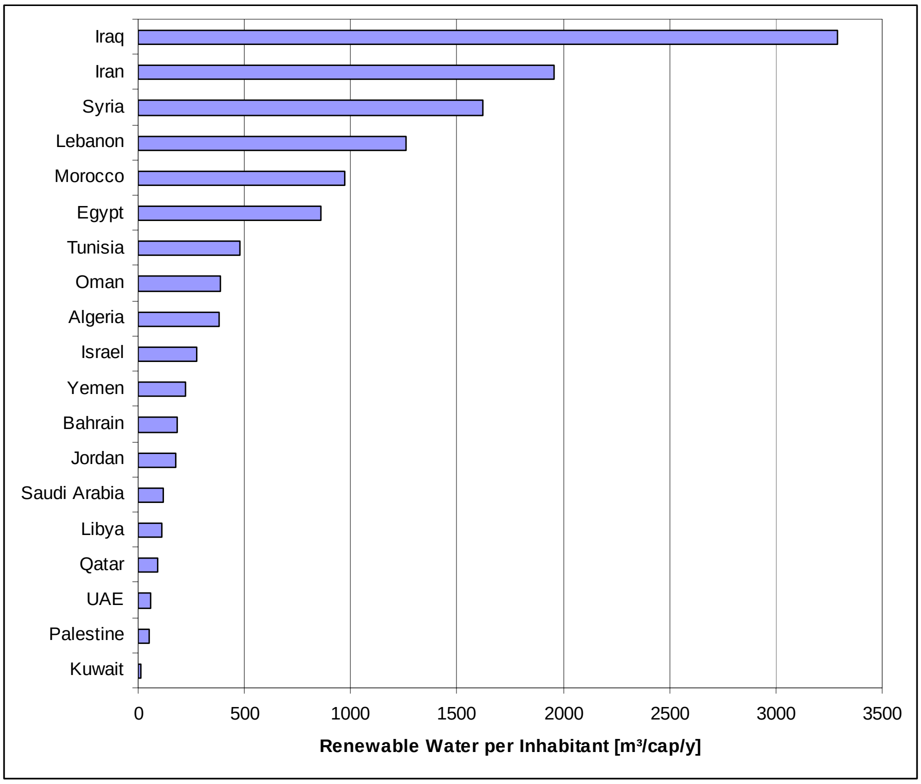


Figure 2-2: Total available natural renewable freshwater sources available per capita in the MENA region for the year 2000. Only four countries are beyond the water poverty threshold of 1000 m³/cap/y.

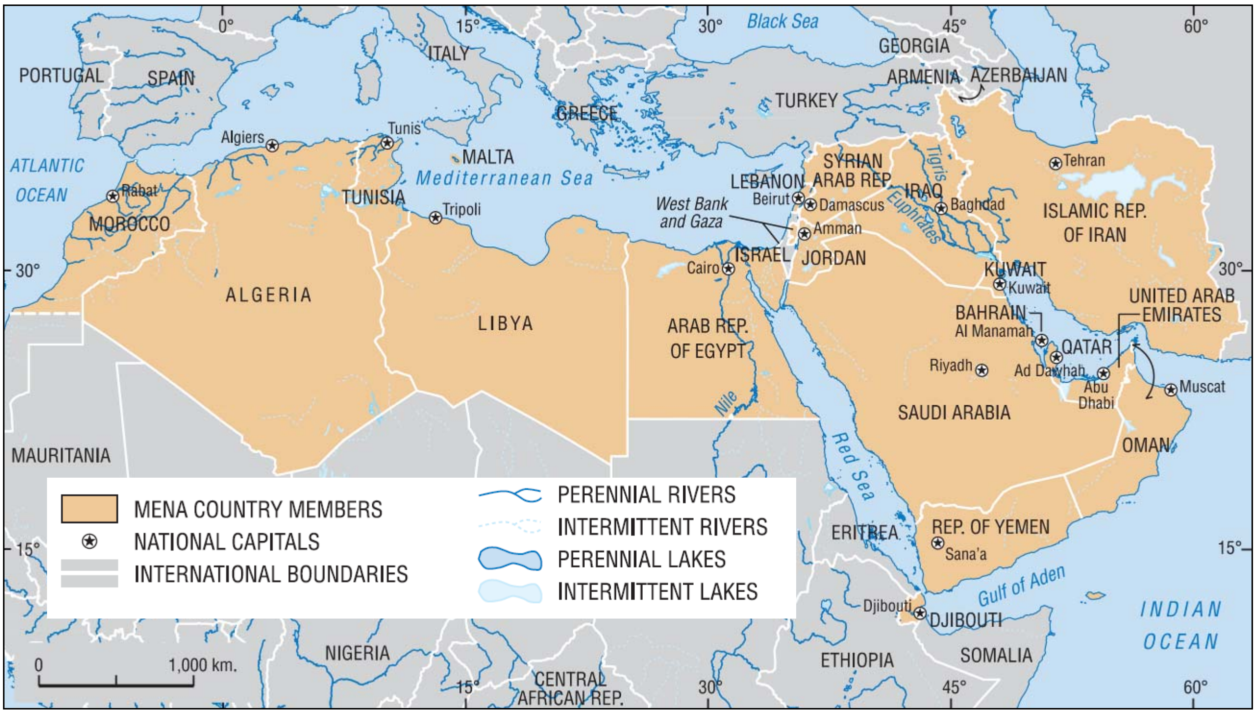


Figure 2-3: Major Rivers and Lakes in the MENA Region /World Bank 2007/

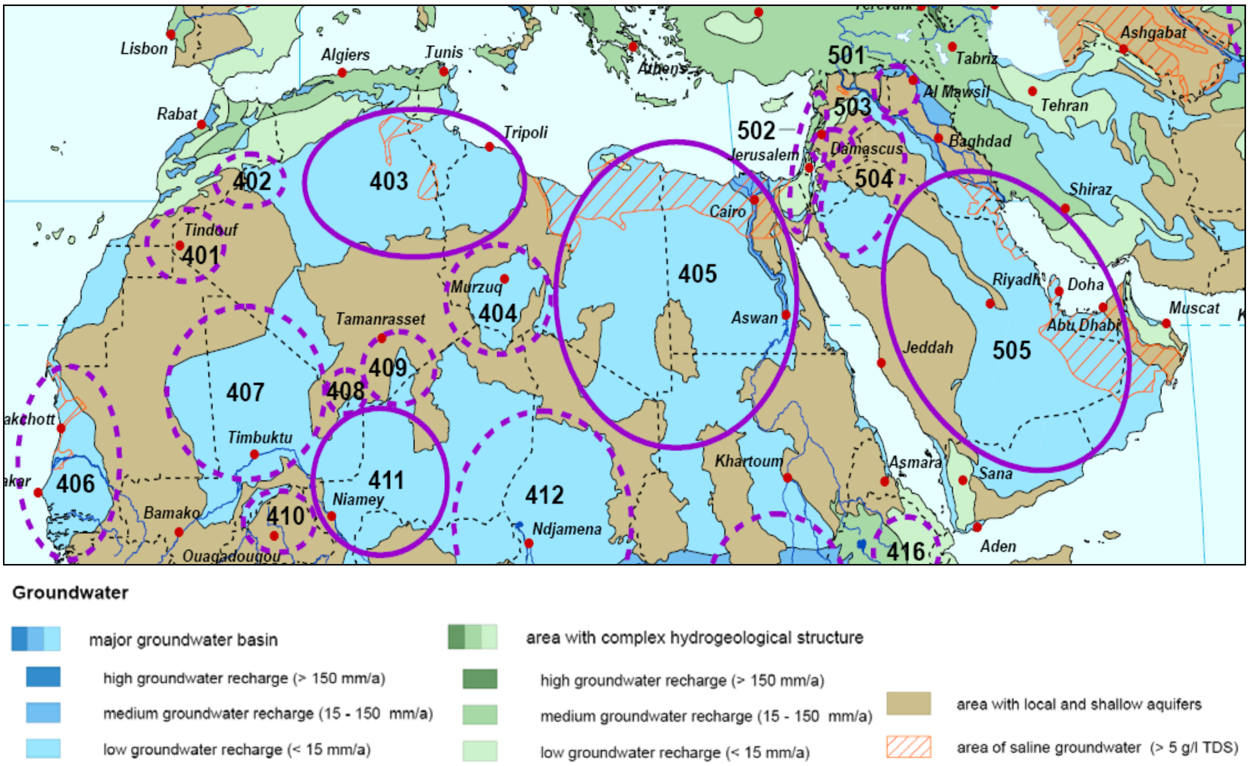


Figure 2-4: Groundwater Aquifers of the MENA Region /BGR 2006/

Renewable and Exploitable Water in MENA	Average Precipitation (mm/y)	Annual Rainfall (km^3/y)	Internal Renewable Water (km^3/y)	Internal Renewable Groundwater (km^3/y)	Internal Renewable Surface Water (km^3/y)	Overlap: Surface and Groundwater (km^3/y)	Total Renewable Water (natural) (km^3/y)	Total Renewable Water (actual) (km^3/y)	Total Population in 2000 (million)	Total Renewable Water (actual) ($m^3/cap/y$)	Dependency Ratio (%)	Exploitable Water (km^3/y)
Morocco	346	154.7	29.0	10.0	22.0	3.0	29.0	29.0	29.2	993	0	20.0
Algeria	89	211.5	11.2	1.4	9.8	0.0	11.6	11.6	30.5	380	3	7.9
Tunisia	313	51.3	4.2	1.5	3.1	0.4	4.6	4.6	9.6	475	9	3.6
Libyan Arab Jamahirija	56	98.5	0.6	0.5	0.2	0.1	0.6	0.6	5.3	113	0	0.6
Egypt	51	51.4	1.8	1.3	0.5	0.0	86.8	58.3	67.3	866	97	49.7
North Africa	**--**	**567.3**	**46.8**	**14.7**	**35.6**	**3.5**	**132.6**	**104.1**	**141.9**	**733**	**--**	**81.8**
Israel	435	9.2	0.8	0.5	0.3	0.0	1.7	1.7	6.1	274	55	1.64
Palestine	316	0.1	0.1	0.1	0.0	0.0	0.1	0.1	3.2	19	18	0.06
Jordan	111	9.9	0.7	0.5	0.4	0.2	0.9	0.9	5.0	176	23	0.88
Lebanon	661	6.9	4.8	3.2	4.1	2.5	4.8	4.4	3.4	1297	1	2.19
Syrian Arab Republic	318	58.9	7.0	4.2	4.8	2.0	46.1	26.3	16.8	1563	80	20.6
Iran, Islamic Rep. of	228	375.8	128.5	49.3	97.3	18.1	137.5	137.5	66.4	2071	7	137.51
Iraq	216	94.7	35.2	1.2	34.0	0.0	96.4	75.4	25.1	3005	53	75.42
Western Asia	**--**	**555.5**	**177.0**	**59.0**	**140.9**	**22.8**	**287.5**	**246.2**	**126.0**	**1954**	**--**	**238.3**
Oman	125	38.7	1.0	1.0	0.9	0.9	1.0	1.0	2.4	413	0	0.99
Kuwait	121	2.2	0.0	0.0	0.0	0.0	0.0	0.0	2.2	9	100	0.02
Qatar	74	0.8	0.1	0.1	0.0	0.0	0.1	0.1	0.6	83	4	0.05
Saudi Arabia	59	126.8	2.4	2.2	2.2	2.0	2.4	2.4	21.5	112	0	2.4
United Arab Emirates	78	6.5	0.2	0.1	0.2	0.1	0.2	0.2	3.2	47	0	0.15
Yemen	167	88.3	4.1	1.5	4.0	1.4	4.1	4.1	17.9	229	0	4.1
Bahrain	83	0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.7	171	97	0.12
Arabian Peninsula	**--**	**263.4**	**7.7**	**4.8**	**7.3**	**4.4**	**7.8**	**7.8**	**48.5**	**161**	**--**	**7.83**
Total MENA	**--**	**1386.2**	**231.4**	**78.4**	**183.7**	**30.7**	**427.9**	**358.1**	**316.4**	**1132**	**--**	**328.0**

Table 2-1: Renewable and exploitable freshwater resources in the MENA countries by AQUASTAT /FAO 2007/. Values of exploitable water shaded in blue were not available and have been assumed to be equal to the total actual renewable water.

2.2 Individual Country Information

(most of the following information is taken from AQUASTAT /FAO 2007/ if not stated otherwise)

Algeria

Algeria receives rain in an annual average of 89 mm/y, that allows a flow of 211 km³/y. But taking into account the aridity of the major part of the country, most of this water is evaporated, while only a small proportion constitutes the renewable water resources. The surface water resources are evaluated to net 9.8 Km³/y, distributed among 5 water sheds /UN 2005/, renewable groundwater resources are estimated at 1.4 km³/y. Internal renewable water resources are estimated at 11.2 km³/year. Incoming surface water has been estimated at 0.4 km³/year. of which 0.2 km³ from Morocco and 0.2 km³ from Tunisia. The water resources, that are potentially available for use in the northern part of the country and the high plateaux have been estimated at 7.9 km³/year, of which 6.4 km³/y is surface water to be regulated by dams and 1.5 km³/y is groundwater. In 2006, dams had been constructed or were under construction with a total dam capacity of 6 km³.

Bahrain

With only 83 mm/y of annual precipitation, the total annual rainfall in Bahrain amounts to roughly 0.1 km³/y of with only 0.004 km³/y can be considered as internal renewable source. The external renewable sources amount to 0.112 km³/y. The total renewable water has also been considered as exploitable, with a total of 0.116 km³/y.

Egypt

The Nile river is the main source of water for Egypt. Under the 1959 Nile Waters Agreement between Egypt and Sudan, Egypt's share is 55.5 km³/y. The 1959 Agreement was based on the average flow of the Nile during the 1900-1959 period, which was 84 km³/year at Aswan. The flow of the Nile at Aswan varies monthly in a proportion from 1 to 10: monthly flows are lower than 5,000 Mm³ during six months, from January to June, increase until reaching 20,000 Mm³ in July, then decrease until reaching 5,000 Mm³ in December. Average annual evaporation and other losses from the High Dam lake were estimated to be 10 km /year, leaving a net usable annual flow of 74 km³/year, of which 18.5 km³/y was allocated to Sudan and 55.5 km³/y to Egypt. Internal surface water resources are estimated at 0.5 km³/year. This brings the total (actual) surface water resources to 56.0 km³/y.

The volume of groundwater entering the country from Libya is estimated at 1 km³/year. Internal renewable groundwater resources are estimated at 1.3 km³/y. This brings the total renewable groundwater resources to 2.3 km³/y. The main source of internal recharge is percolation from irrigation water, and its quality depends mainly on the quality of the irrigation water. In the northern part of the Delta, groundwater becomes brackish to saline due to sea water intrusion. About half of the Delta contains brackish to saline groundwater. The Nubian Sandstone aquifer, located under the Western Desert and extending to Libya, Sudan and Chad, contains important non-renewable fresh groundwater resources, already developed in the oasis of the new valley. Large irrigation schemes pumping water from the Nubian aquifer are under development in the south-western part of the country (Al Aweinat).

In Egypt the Nubian ground water sheet would have a potential of 15,000 km³, non-renewable, and not exploitable because the great depth of the piezometric level. In addition, the Nile alluvial ground water sheet would have a potential of 500 km³, of which only 7.5 km³ are exploitable.

Iran

Iran can be divided into the following major river basins: the Central Plateau in the middle, the Lake Orumieh basin in the north-west, the Persian Gulf and the Gulf of Oman in the west and south, the Lake Hamoun basin in the east, the Kara-Kum basin in the north-east and the Caspian Sea basin in the north. With an area of 424 240 km², the Caspian Sea is the largest landlocked water body in the world and its surface lies about 22 metres below sea level.

All these basins, except the Persian Gulf and Gulf of Oman, are interior basins. There are several large rivers, the only navigable one of which is Karun, the others being too steep and irregular. The Karun river, with a total length of 890 km, flows in the south-west of the country to the Shatt ElArab, which is formed by the Euphrates and the Tigris after their confluence. The few streams that empty into the Central Plateau dissipate into the saline marshes. All streams are seasonable and variable. Spring floods do enormous damage, while there is little water flow in summer when most streams disappear. Water is however stored naturally underground, finding its outlet in subterranean water canals (qanats) and springs. It can also be tapped by wells.

Internal renewable water resources are estimated at 128.5 km³/year. Surface runoff represents a total of 97.3 km /year, of which 5.4 km³/year comes from drainage of the aquifers, and groundwater recharge is estimated at about 49.3 km³/year, of which 12.7 km³/year is obtained from infiltration in the river bed. Iran receives 6.7 km³/year of surface water from Pakistan and some water from Afghanistan through the Helmand river. The flow of the Arax river, at the border with Azerbaijan, is estimated at 4.63 km³/year. The surface runoff to the sea and to other countries is estimated at 55.9 km³/year. The total safe yield of groundwater (including non renewable water or unknown groundwater inflow from other countries) has been estimated at 49.3 km³/year.

The actual total renewable water resources allocated to Iran are estimated to be 137.5 km³/y which are considered as exploitable, because of lack of other information.

Iraq

There is only one river basin in Iraq, the Shatt Al-Arab basin. The Shatt Al-Arab is the river formed by the confluence downstream of the Euphrates and the Tigris and flows into the Persian Gulf after a course of only 190 km. Before their confluence, the Euphrates flows for about 1 000 km and the Tigris for about 1 300 km respectively within the Iraqi territory. Nevertheless, due to the importance of the Euphrates and the Tigris, the country is generally divided into three river basins: the Tigris, the Euphrates, and the Shatt Al-Arab (referring to the part downstream of the confluence of the two rivers).

Both the Tigris and the Euphrates are international rivers originating their source in Turkey. The Tigris river basin in Iraq has a total area of 253 000 km², or 54% of the total river basin area.

The average annual flow of the Euphrates as it enters Iraq is estimated at 30 km³/y, with a fluctuating annual value ranging from 10 to 40 km³/y. Unlike the Tigris, the Euphrates receives no tributaries during its passage in Iraq. About 10 km³ per year are drained into the Hawr al Harnmar (a marsh in the south of the country).

For the Tigris, average annual runoff as it enters Iraq is estimated at 21.2 km³. All the Tigris tributaries are on its left bank. From upstream to downstream:

- the Greater Zab, which originates in Turkey and is partly regulated by the Bakhma dam. It generates 13.18 km³ at its confluence with the Tigris; 62% of the 25 810 km² of river basin is in Iraq;
- the Lesser Zab, which originates in Iran and is equipped with the Dokan dam (6.8 km). The river basin of 21 475 km² (of which 74% is in Iraqi territory) generates about 7.17 km, of which 5.07 km³ of annual safe yield after the Dokan construction;
- the Al-Adhaim (or Nahr Al Uzaym), which drains about 13 000 km² entirely in Iraq. It generates about 0.79 km³ at its confluence with the Tigris. It is an intermittent stream subject to flash floods;
- the Diyala, which originates in Iran and drains about 31 896 km², of which 75% in Iraqi territory. It is equipped with the Darbandikhan dam and generates about 5.74 km³ at its confluence with the Tigris;
- the Nahr at Tib, Dewarege (Doveyrich) and Shehabi rivers, draining together more than 8 000 km². They originate in Iran, and bring together in the Tigris about 1 km³ of highly saline waters;
- the Al-Karkha, whose course is mainly in Iran and, from a drainage area of 46 000 km², brings about 6.3 km³ yearly into Iraq, namely into the Hawr Al Hawiza during the flood season, and into the Tigris river during the dry season.

The Karun river, originating in Iran flows with its mean annual flow of 24.7 km³ into the Shatt Al-Arab. It brings a large amount of fresh water into the Shatt Al-Arab, just before it reaches the sea.

The Euphrates and the Tigris are subject to large and possibly disastrous floods. The level of water in the Tigris can rise at the rate of over 30 cm/hour. In the southern part of the country, immense areas are regularly inundated, levees often collapse, and villages and roads must be built on high embankments. The Tharthar reservoir was planned inter alia in the 1950s to protect Baghdad from the ravages of the periodic flooding of the Tigris by storing extra water discharge upstream of the Samarra barrage.

Average precipitation in Iraq is of 216 mm/y. The internal renewable water sources are estimated to an amount of 35.2 km³/y of which 34 are surface water. Taking into account the external sources entering the country and their allocation to Iraq, about 75 km³/y are considered as total actual renewable water resources. They have also been considered as exploitable, lacking better information.

Jordan

In Jordan, rainfall is limited to 111 mm/y, and surface water resources are unevenly distributed among 15 basins. The largest source of external surface water is the Yarmouk river, at the border with Syria. Originally, the annual flow of the Yarmouk river was estimated at about 400 million m³ (of which about 100 million m³ are withdrawn by Israel). Total flow is now much lower than 400 million m³ as a result of the upstream Syrian development works which have been done in the 1980's. The Yarmouk river accounts for 40 % of the surface water resources of Jordan, including water contributed from the Syrian part of the Yarmouk basin. It is the main source of water for the King Abdullah canal and is thus considered to be the backbone of development in the Jordan valley. Other major basins include Zarqa, Jordan river side wadis, Mujib, the Dead Sea, Hasa and Wadi Araba. Internally generated surface water resources are estimated at 0.4 km³/y.

Jordan's groundwater is distributed among 12 major basins. Total internally produced renewable groundwater resources have been estimated at 0.5 km³/y, of which 0.22 km³ constitute the base flow of the rivers. Groundwater resources are concentrated mainly in the Yarmouk, Amman-Zarqa and Dead Sea basins.

The safe yield of renewable groundwater resources is estimated at 0.275 km³/year. Most of it is at present exploited at maximum capacity, in some cases beyond safe yield. Of the 12 groundwater basins, 6 are being over-extracted, 4 are balanced with respect to abstraction and 2 are under-exploited. Over-extraction of groundwater resources has seriously degraded water quality and reduced exploitable quantities, resulting in the abandonment of many municipal and irrigation water well fields, such as in the area of Dhuleil.

The main non-renewable aquifer presently exploited is the Disi aquifer (sandstone fossil), in southern Jordan with a safe yield estimated at 0.125 km^3/year for 50 years. Other non-renewable water resources are found in the Jafer basin, for which the annual safe yield is 0.018 km^3. In total it is estimated by the Water Authority of Jordan that the safe yield of fossil groundwater is 0.143 km^3/year.

Total renewable water resources in Jordan are estimated at 0.88 km^3/y which are also considered as exploitable, due to lack of other information.

Kuwait

There are no permanent surface water flows in Kuwait. Rainwater (121 mm/y) accumulates in the natural depressions where water remains for several weeks. Only a small part of this water percolates into the ground because of the high evaporation and the presence of an impervious layer in some regions.

There are two major aquifers: the Kuwait group (upper layer) and the Damman group (lower layer). Groundwater inflow has been estimated at about 20 million m^3/year through lateral underflow from Saudi Arabia.

There are three classes of groundwater: fresh water with salinity below 1000 ppm which is used for drinking and domestic purposes, slightly saline water with salinity ranging between 1 000 and 10 000 ppm which is used for irrigation, and highly saline water with salinity exceeding 10 000 ppm which is used in special cases only. In general groundwater quality and quantity are deteriorating due to the continuous pumping of water. 90% of the wells pump water with a salinity level higher than 7 500 ppm in 2000.

Lebanon

In total, there are about 40 major streams in Lebanon and, based on the hydrographic system, the country can be divided into five regions:

- the El Assi (Orontes) river basin in the north. The El Assi flows into Syria in the north-east of the country;
- the Litani river basin in the east and south. The Litani reaches the sea in the south-west of the country;
- the Hasbani river basin in the south-east. The Hasbani, which flows into Israel in the south east of the country, is a tributary of the Jordan river;

- all the remaining major coastal river basins. The northern El Kebir river basin is shared with Syria, the river itself forming part of the border between the two countries before flowing into the sea;
- all the remaining small in-between scattered and isolated sub-catchments with no noticeable surface stream flow, like some isolated coastal pockets.

Lebanon has a relatively favourable position as far as its rainfall (661 mm/y) and water resources (1260 m^3/cap/y) are concerned, but constraints for development consist of the limited water availability during the seven dry summer months. Annual internal renewable water resources are estimated at about 4.8 km^3/y. Annual surface runoff is estimated at 4.1 km^3/y and groundwater recharge at 3.2 km^3/y, of which 2.5 km^3 constitutes the base flow of the rivers. About 1 km^3 of this flow comes from over 2 000 springs with about 10-15 l/s of average unit yield, sustaining a perennial flow for 17 of the total of 40 major streams in the country.

Lebanon being at a higher elevation than its neighbours has practically no incoming surface water flow. A contribution of 0.074 km^3/year to the El Kebir river, to the north, is estimated to be generated by the 707 km^2 bordering Syrian catchments areas. There might also be some groundwater inflow from these areas, but no figures on quantities are available. Surface water flow to Syria is estimated at 510 million m^3/year through the El-Assi (Orontes)) river and the bordering El Kebir river. An agreement between Lebanon and Syria on the Orontes river has led to a share of 0.080 km^3/year for Lebanon and the remainder for Syria. Surface water flow to Israel is estimated at 0.160 km^3/y, of which about 0.138 km^3 through the Hasbani river including a contribution of 0.03 km^3 from its tributary, the Wazzani spring. Annual groundwater outflow is estimated at 1.030 km^3/y, of which 0.130 km^3/y flow to Syria, 0.180 km^3 to Israel and 0.72 km^3 to the sea.

The relative importance of groundwater flow to the sea and the difficulties related to its control, added to the difficult geological conditions of most of the investigated sites for storage dams, make the manageable resources of Lebanon certainly much lower than the global figure of 4.8 km^3/year. The most realistic figure recognized does not exceed 2.2-2.5 km /year.

Libya

The total mean annual runoff calculated or measured at the entrance of the wadis in the plains is estimated at 0.2 km^3/year, but part of it either evaporates or contributes to the recharge of the aquifers. Sixteen dams, with a total storage capacity of 0.387 km^3 and with an expected average annual volume of water controlled in the order of 0.06 km^3/y, had been constructed by 2000. This difference between the average annual runoff and the storage capacity of the dams is so that the runoff water of exceptionally wet years can be stored.

Currently, aquifers are only recharged in the northern regions, namely in the northwestern zone, Jabal Nafusah and Jifarah Plain, and in the north-eastern zone, Jabal al Akhdar. Renewable groundwater resources are estimated at 800 to 1 000 million m³/year, but part (perhaps 50%) now flows out either to the sea or to evaporative areas (sabkhas). Not all the renewable groundwater can be abstracted without affecting the environment, because of the deterioration of water quality by saline water encroachment. For this reason, the safe yield has been estimated at 0.5 km³/year. South of the 29th parallel, an important development of Palaeozoic and Mesozoic continental sandstone enabled water to be stored safely during the long period of the late Quaternary, before the climate turned extremely arid. Most water used in Libya comes from these huge fossil reserves.

Through the Great Manmade River Project about 2 km³/year of fossil water is transported from the desert to the coastal areas, mainly for irrigation but part is used for the water supply of the major cities.

Morocco

Precipitation in Morocco amounts to 346 mm/y, mostly in the coastal regions and in the Atlas mountains. There are no external water resources available. The total internal renewable water resources of Morocco have been evaluated at 29 km³/year, (19 km³/y surface water, 10 km³/y groundwater) out of which 16 km³ of surface water and 4 km³ of groundwater are considered to represent an exploitable water development potential. The most important rivers are equipped with dams, allowing surface water to be stored for use during the dry seasons. In the year 2000, dams with a total capacity of 16 km³ were operational. Over 45 % of the surface water and over 50 % of the groundwater quality of Morocco is considered bad or very bad.

Oman

A great deal of uncertainty lies in the assessment of Oman's water resources. Internal renewable water resources have been evaluated at 0.985 km³/y. Surface water resources are scarce. In nearly all wadis, surface runoff occurs only for some hours or up to a few days after a storm, in the form of rapidly rising and falling flood flows. Since 1985, 15 major recharge dams have been constructed together with many smaller structures, in order to retain a portion of the peak flows, thus allowing more opportunity for groundwater recharge. In addition, several flood control dams produce significant recharge benefits. In 1996, the total dam capacity was 0.058 km³. Groundwater recharge is estimated at 0.955 km³/year.

Qatar

There is practically no permanent surface water - annual surface runoff has been estimated at 0.001 km³/y. Direct and indirect recharge of groundwater from rainwater forms the main natural internal water resources. Two-thirds of the land surface is made up of some 850 contiguous depressions of interior drainage with catchments varying from 0.25 km² to 45 km² and with a total aggregate area of 6 942 km². While direct recharge from rainfall might take place during very rare heavy storms, the major recharge mechanism is an indirect runoff from surrounding catchments and the pounding of water in the depression floor. Surface runoff typically represents between 16 and 20% of rainfall. Of the amount reaching the depressions, 70% infiltrates and 30% evaporates.

There are two separate and distinct groundwater regions: the northern half, where groundwater occurs as a freshwater 'floating lens' on brackish and saline water and the southern half where no such lens exists and where water quality is generally brackish with only a thin veneer of freshwater at the top of the water table. Annual groundwater recharge has been estimated at 0.050 km³/y.

The two main aquifers underlying Qatar are recharged in Saudi Arabia. Over most of Qatar the Damman formation does not contain water because of its altitude. It dips lower in southwest Qatar where it contains water, but is also overlain by impervious layers. The artesian aquifer which results from this structure is called the Alat unit of the Damman. Below this aquifer is the Umm er Radhuma, which is similarly artesian. In 1981, the Master Water Resources and Agricultural Development Plan (MWRADP) estimated that in the southern part of Qatar the safe yield of the Alat aquifer is 2 million m³/year and that of the Umm er Radhuma 10 million m³/year, based on an estimate of annual flow from Saudi Arabia. However, these safe yields would be substantially reduced if the aquifer were exploited more extensively on the Saudi Arabian side of the border. In the northern and central part the Rus aquifer overlies the Umm el Radhuma aquifer, which is partly an unconfined aquifer, recharged by percolating rainfall and return flows from irrigation but losing some water to the sea and some through abstractions. The safe yield of the aquifer system in the northern and central part of Qatar is estimated at 13 million m³/year from the upper layer and 20 million m³/year from the lower layer (the latter leading to a depletion in 50 years). In total, the estimated safe yield for the whole of Qatar is 45 million m³/year.

Another potential source of groundwater is beneath the capital Doha itself. According to the MWRADP, considerable volumes of water leak from pipelines and other sources throughout much of Doha. This leakage, estimated at about 15 million m³/year, has caused the water table to rise locally, flooding basements as well as shallow excavations.

Saudi Arabia

Although the annual precipitation only amounts to 59 mm/y, heavy rainfall sometimes results in flash floods of short duration. River beds are dry for the rest of the time. Part of the surface runoff percolates through the sedimentary layers in the valleys and recharges the groundwater, some is lost by evaporation. The largest quantity of runoff occurs in the western region, which represents 60% of the total runoff although it covers only 10% of the total area of the country. The remaining 40% of the total runoff occurs in the far south of the western coast (Tahama) which covers only 2% of the total area of the country. Total surface water resources have been estimated at 2.2 km³/year, most of it infiltrating to recharge the aquifers. About 1 km³ recharges the usable aquifers. The total (including fossil) groundwater reserves have been estimated at about 500 km³, of which 340 km³ are probably extractable at an acceptable cost in view of the economic conditions of the country.

Syria

There are 16 main rivers and tributaries in the country, of which 6 are international rivers:

- the Euphrates (Al Furat), which is Syria's the largest river. It comes from Turkey and flows to Iraq. Its total length is 2 330 km, of which 680 km are in Syria,
- the Afrin in the north-western part of the country, which comes from Turkey, crosses Syria and flows back to Turkey,
- the Orontes (El-Ass) in the western part of the country, which comes from Lebanon and flows into Turkey,
- the Yarmouk in the south-western part of the country with sources in Syria and Jordan and which forms the border between these two countries before flowing into the Jordan river,
- the El-Kebir with sources in Syria and Lebanon and which forms the border between them before flowing to the sea,
- the Tigris, which forms the border between Syria and Turkey in the extreme north-eastern part.

15.75 km³ of water are entering to Syria with the Euphrates, as proposed by Turkey, 0.43 km³ of water is entering with the Orontes, as agreed with Lebanon. With the tributaries of Euphrates and Afrin, this becomes a total 18.11 km³/year (Table 2-2). The Tigris, which is the second most important river in the country, borders the country to the east and has a mean annual flow of 18 km³/y, of which 50 % can be accounted for Syria, making a total of water entering Syria of 27.1 km³/y. The total natural average outflow from Syria is 31.98 km³/year, of which an agreement exists for 9.2 km³, resulting in a total of actual external surface water resources balance for Syria of 17.9 km³/year (27.1 km³/year - 9.2 km³/year).

Although figures for water resources are very difficult to obtain due to the lack of reliable data, it can be estimated that water resources generated from rain falling within the country amount to 7 km³/year. Groundwater recharge is about 4.2 km³/year, of which 2 km³/year discharges into rivers as spring water. Total groundwater inflow has been estimated at 1.35 km³/year, of which 1.2 km³ from Turkey and 0.15 km³ from Lebanon. Although not quantified, the amount of groundwater flowing into Jordan may be significant.

The total actual renewable water sources are estimated at 26.3 km³/y of which 20.6 are considered as exploitable.

Name of river	Inflow into Syria (km³/year)			Outflow from Syria (km³/year)		
	from	natural	actual	to	natural	agreement
Euphrates *	Turkey	26.29	15.75	Iraq	30	9
Tributaries of Euphrates	Turkey	1.74	1.74		-	
Afrin	Turkey	0.19	0.19	Turkey	0.25	
Orontes, El Kebir	Lebanon	0.51	0.43		1.2	
Yarmouk		-	-	Jordan	0.4	0.2
Baniyas		-	-	Israel	0.13	
Sub-total		28.73	18.11		31.98	9.2
Bordering Tigris	50% of total	9	9			
Total	Inflow	37.73	27.11	Outflow	31.98	9.2

Table 2-2: Major rivers entering, bordering and leaving Syria, * Turkey has unilaterally promised to secure a minimum flow of 15.75 km³/year at its border with Syria

Tunisia

The hydrographic system of Tunisia is rather dense in the north where the Medjerda wadi is the most important water course. This is also the zone where the principal irrigation development and flood protection works have been carried out.

Surface water resources have been estimated at 3.4 km^3/year, of which 3.1 km^3 are produced internally. About 2.1 km^3/year are exploitable through reservoirs, by means of large water conservation works and groundwater recharge systems. At present, there are dams with a total capacity of 2.5 km^3.

Internal renewable groundwater resources have been estimated at 1.5 km^3/year. At present, there are 83000 open wells and 1830 tube wells. Two categories of groundwater resources can be distinguished in function of the depth:

- when the water table is above 50 metres, groundwater can be used for private exploitation (with some restrictions). The potential has been estimated at 0.67 km^3/year;
- below 50 metres of depth, the groundwater has been reserved for public exploitation.

The potential of the deep ground water sheets in Tunisia is estimated at 1.4 km^3, of which 0.75 km^3 of renewable resources (53.7%), and 0.65 km^3 of non-renewable resources (46.3%). The potential of ground water is better distributed in the South of the country where primarily three large deep sheets of variable quality are located:

- The Complex Terminal (40 to 700 m)

- The Continental Intercalary (from 700 to 2000 m)

- Sheet of Djeffara (on the coastal plain)

- The deep sheet of the Continental Intercalary is considered fossil and without renewal.

The actual renewable water resources of Tunisia are approximately 4.6 km^3/y, of which 3.6 km^3/y are considered exploitable.

United Arab Emirates

Rain accounts for only 78 mm/y, the total annual surface runoff produced from rain is about 0.15 km^3, but there are no perennial streams. The average annual groundwater recharge is about 0.12 km^3, most of which comes from infiltration from the river beds. Over-extraction of groundwater resources has led to a lowering of the water table by more than one metre on average during the last two decades, while sea water intrusion is increasing in the coastal areas. About 0.15 km^3/y of freshwater are considered renewable and exploitable, lacking better knowledge.

Yemen

Yemen can be subdivided into four major drainage basins, regrouping numerous smaller wadis:

- the Red Sea basin
- the Gulf of Aden basin
- the Arabian Sea basin
- the Rub Al Khali interior basin

The floods of the wadis in Yemen are generally characterized by abruptly rising peaks that rapidly recede. In between the irregular floods the wadis are either dry or carry only minor base flows.

Surface water resources have been estimated at 4 km³/year, including the runoff from major rivers and the runoff produced within the smaller catchments. Renewable groundwater resources have been estimated at l.5 km³/year, a large part probably coming from infiltration in the river beds. A major groundwater aquifer was discovered in the eastern part of the country with an estimated storage of 10 km³. This aquifer is still under study and it is not known whether the groundwater is rechargeable or whether it is all fossil water.

The surface runoff to the sea measured in some major wadis is estimated at 0.27 km³/year, the groundwater outflow to the sea at 0.28 km³/year. There might be some groundwater flowing into Saudi Arabia, but no data are available. The existence of surface drainage crossing into Saudi Arabia suggests that some sharing of surface flows could be possible, but details are not known.

The renewable and exploitable freshwater resource of Yemen is estimated at 4.1 km³/y, due to the lack of better data.

The Chapter at hand has given a brief overview of the existing freshwater resources in the single MENA countries. More information on groundwater resources and a discussion about the socio-economic consequences of water scarcity is provided within Chapter 5.

3. Freshwater Demand and Deficits in MENA

In this chapter we will quantify the growing demand for freshwater in MENA on the basis of a simple empirical model and show how water consumption will be driven by growing population and by economic development of the region.

It is well known that the renewable freshwater resources of MENA are rather limited, and that increasing shortages and deficits of freshwater are threatening economic development and social peace in some parts of MENA (Blue Plan 2005/, /IEA 2005/, /Gleick 2004/, /FAO 2003/. Comparing the existing sustainable freshwater resources with the present and future demand, we have quantified the present and also the threatening future freshwater deficits of each country of the region. Part of the presently used freshwater that is stemming from overuse of groundwater or from fossil-fuel-powered desalination must be considered unsustainable, as it is based on fading resources which are related to exploding costs and considerable environmental damage.

Efficiency of extraction, distribution and end-use of water is rather low, leaving a considerable potential for future efficiency gains, if adequate water policies are successfully implemented to foster such goal. Also the re-use of water is an important measure to reduce future water deficits in MENA. In fact, efficiency gains can be considered an additional future source of freshwater, because the water is there, but up to now, unused.

Taking into account those partially counteracting effects, we have formulated a simple empirical model for the prediction of freshwater demand which was applied to every country in MENA.

3.1 Population Prospects

Population and population growth are the major driving forces for freshwater demand. The population growth scenario used here is based on the intermediate World Population Prospect of the United Nations that was revised in the year 2004 /UN 2006/. According to that estimate, the population in the total MENA region will steadily grow from about 300 million today to over 600 million in 2050. The population in North Africa will grow from today’s 140 million to 245 million in 2050. With 125 million in 2050, Egypt will be accounting for more than 50 % of the population of the North African region. The population in the Western Asian countries will grow from 125 to almost 240 million by 2050, Iran being the country with the largest population in this region. The population on the Arabian Peninsula will increase from today’s 50 million to 130 million in 2050. The dominating countries in terms of population are Saudi Arabia and Yemen. The Saudi Arabian population will stabilize by the middle of the century around 50 million, but Yemen’s population will still be growing quickly by that time, with almost 60 million becoming the most populated country in this region (Figure 3-1).

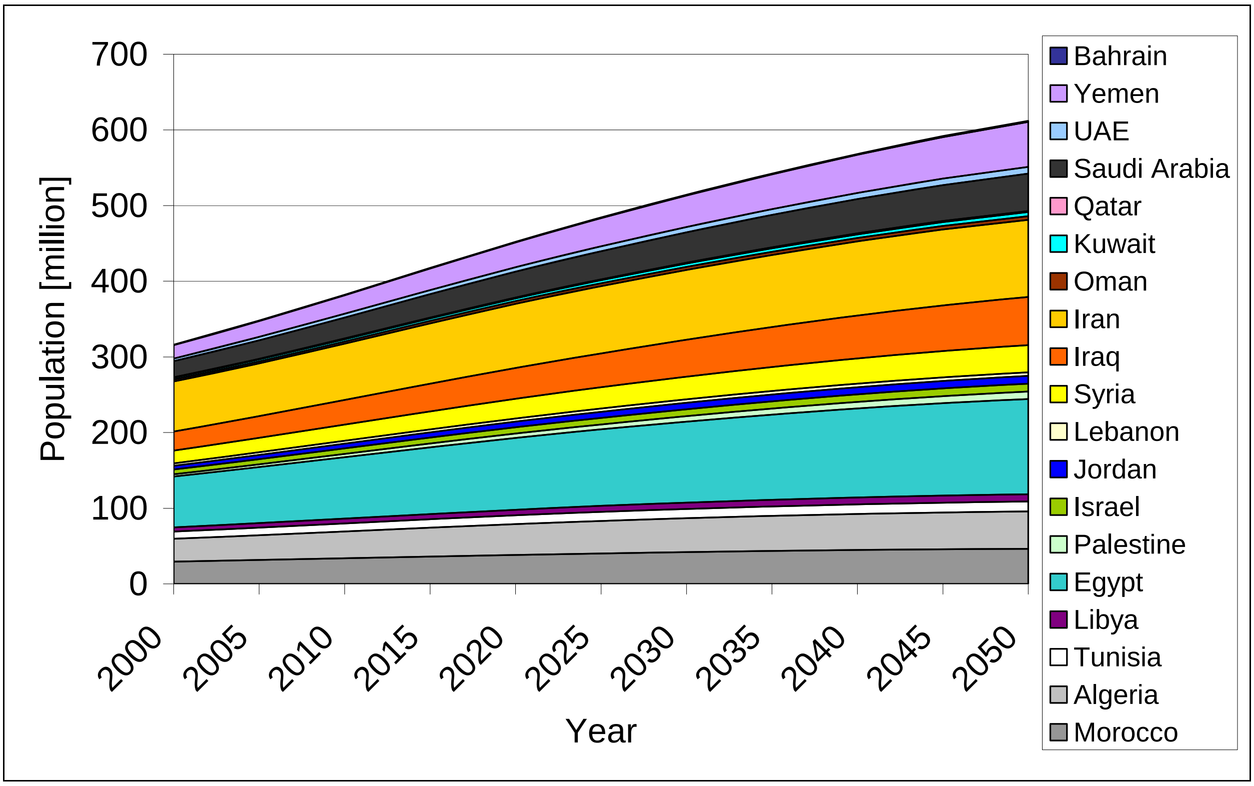


Figure 3-1: Population of the analysed countries in MENA according to the United Nations medium growth scenario revised in 2004 /UN 2006/.

Population [Million]	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Yemen	17.9	21.0	24.5	28.5	32.7	37.1	41.5	46.0	50.5	55.0	59.5
Bahrain	0.7	0.7	0.8	0.9	0.9	1.0	1.0	1.1	1.1	1.1	1.2
UAE	3.2	4.5	5.0	5.6	6.1	6.7	7.2	7.7	8.2	8.7	9.1
Kuwait	2.2	2.7	3.0	3.4	3.7	4.0	4.3	4.6	4.8	5.1	5.3
Oman	2.4	2.6	2.9	3.2	3.5	3.8	4.1	4.3	4.6	4.8	5.0
Qatar	0.6	0.8	0.9	1.0	1.0	1.1	1.2	1.2	1.3	1.3	1.3
Saudi Arabia	21.5	24.6	27.7	30.8	34.0	37.2	40.1	42.9	45.3	47.5	49.5
Arabian Peninsula	**48.6**	**56.8**	**64.8**	**73.3**	**82.0**	**90.8**	**99.4**	**107.7**	**115.8**	**123.5**	**130.7**
GCC	**30.7**	**35.9**	**40.3**	**44.8**	**49.3**	**53.7**	**57.9**	**61.8**	**65.3**	**68.4**	**71.2**
Iran	66.4	69.5	74.3	79.9	85.0	89.0	92.3	95.2	98.0	100.4	101.9
Iraq	25.1	28.8	32.5	36.5	40.5	44.7	48.8	52.8	56.7	60.3	63.7
Israel	6.1	6.7	7.3	7.8	8.3	8.7	9.2	9.5	9.9	10.2	10.4
Jordan	5.0	5.7	6.3	7.0	7.6	8.1	8.7	9.1	9.6	9.9	10.2
Lebanon	3.4	3.6	3.8	4.0	4.1	4.3	4.4	4.5	4.6	4.7	4.7
Palestine	3.2	3.7	4.3	5.0	5.7	6.4	7.2	7.9	8.7	9.4	10.1
Syria	16.8	19.0	21.4	23.8	26.0	28.1	30.0	31.7	33.3	34.7	35.9
Western Asia	**125.9**	**137.1**	**150.0**	**163.9**	**177.3**	**189.4**	**200.5**	**210.9**	**220.7**	**229.6**	**237.0**
Morocco	29.2	31.5	33.8	36.2	38.3	40.3	42.0	43.5	44.8	45.7	46.4
Algeria	30.5	32.9	35.4	38.1	40.6	42.9	44.7	46.2	47.5	48.6	49.5
Libya	5.3	5.9	6.4	7.0	7.5	8.0	8.3	8.7	9.0	9.3	9.6
Tunisia	9.6	10.1	10.6	11.1	11.6	12.0	12.4	12.6	12.8	12.9	12.9
Egypt	67.3	74.0	81.1	88.2	94.8	101.1	107.1	112.7	117.8	122.2	125.9
North Africa	**141.8**	**154.3**	**167.5**	**180.6**	**192.9**	**204.2**	**214.5**	**223.8**	**231.9**	**238.8**	**244.3**
Total MENA	**316.3**	**348.2**	**382.3**	**417.8**	**452.2**	**484.4**	**514.3**	**542.4**	**568.5**	**591.9**	**611.9**

Table 3-1: Population of the analysed countries in MENA in million persons between the years 2000 and 2050 according to the United Nations medium growth scenario revised in 2004 /UN 2006/.

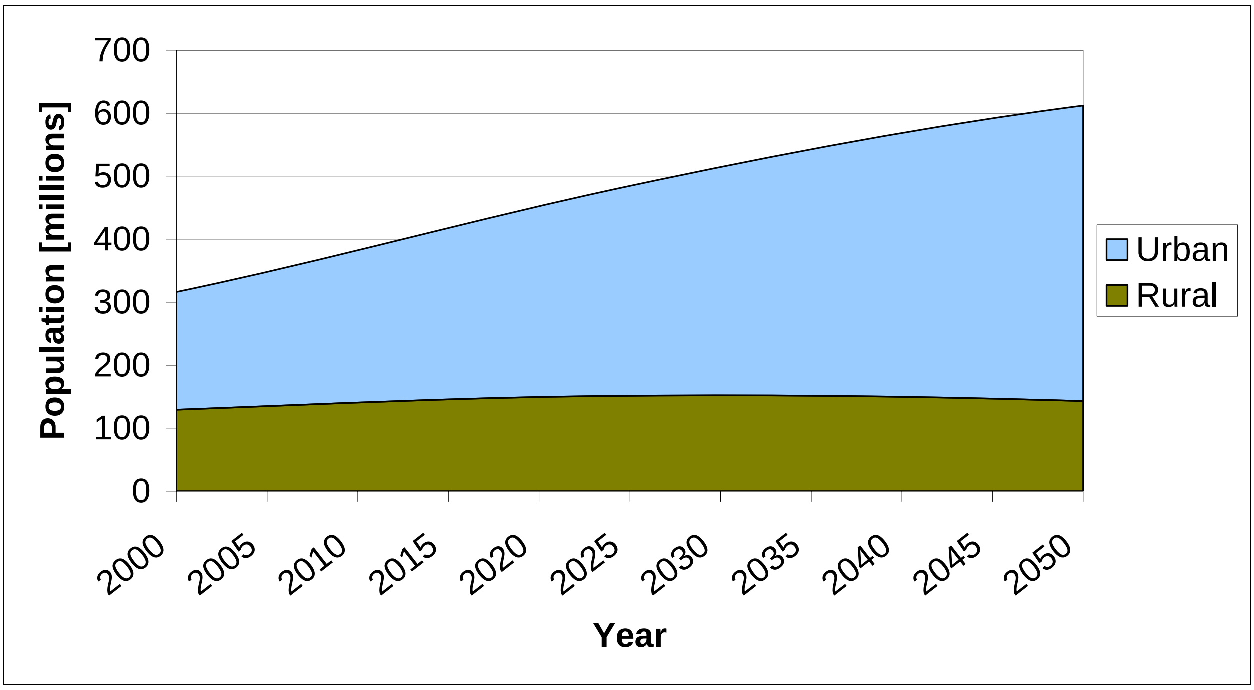


Figure 3-2: Urban and rural population prospects in MENA according to the United Nations medium growth scenario revised in 2004 /UN 2006/ (extrapolated after 2030)

Rural Share [%]	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Yemen	76.0%	73.5%	71.0%	68.3%	65.4%	62.5%	59.5%	56.3%	53.2%	50.0%	46.8%
Bahrain	7.1%	6.5%	5.9%	5.3%	4.8%	4.4%	4.0%	3.6%	3.3%	2.9%	2.7%
UAE	12.4%	11.1%	10.0%	8.9%	7.9%	7.1%	6.3%	5.6%	5.0%	4.4%	3.9%
Kuwait	3.9%	3.6%	3.4%	3.1%	2.9%	2.7%	2.5%	2.3%	2.2%	2.0%	1.9%
Oman	23.3%	21.4%	19.6%	17.9%	16.4%	15.0%	13.6%	12.4%	11.3%	10.2%	9.3%
Qatar	7.0%	6.3%	5.7%	5.2%	4.7%	4.2%	3.8%	3.5%	3.1%	2.8%	2.5%
Saudi Arabia	12.8%	11.6%	10.5%	9.5%	8.6%	7.8%	7.0%	6.3%	5.7%	5.1%	4.6%
Arabian Peninsula	**36.1%**	**34.4%**	**33.3%**	**32.3%**	**31.2%**	**30.1%**	**28.9%**	**27.6%**	**26.4%**	**25.1%**	**23.8%**
GCC	**12.7%**	**11.4%**	**10.4%**	**9.4%**	**8.5%**	**7.7%**	**6.9%**	**6.3%**	**5.7%**	**5.1%**	**4.6%**
Iran	35.2%	32.5%	29.8%	27.3%	24.9%	22.7%	20.6%	18.7%	16.9%	15.2%	13.7%
Iraq	33.7%	32.6%	31.4%	30.3%	29.2%	28.1%	27.1%	26.0%	25.0%	24.1%	23.1%
Israel	8.2%	7.6%	7.1%	6.6%	6.1%	5.7%	5.3%	4.9%	4.6%	4.2%	3.9%
Jordan	21.7%	20.6%	19.6%	18.6%	17.7%	16.7%	15.9%	15.0%	14.2%	13.4%	12.7%
Lebanon	3.9%	3.6%	3.4%	3.1%	2.9%	2.7%	2.5%	2.3%	2.2%	2.0%	1.9%
Palestine	1.0%	1.4%	1.8%	2.1%	2.5%	2.6%	2.6%	2.7%	2.7%	2.8%	2.8%
Syria	9.7%	8.9%	8.2%	7.6%	7.0%	6.5%	5.9%	5.5%	5.0%	4.6%	4.3%
Western Asia	**33.6%**	**31.5%**	**29.5%**	**27.6%**	**25.8%**	**24.2%**	**22.6%**	**21.1%**	**19.7%**	**18.4%**	**17.2%**
Morocco	44.0%	41.3%	38.6%	36.0%	33.5%	31.0%	28.7%	26.4%	24.3%	22.3%	20.4%
Algeria	42.5%	40.1%	37.5%	34.9%	32.3%	30.0%	27.9%	25.7%	23.7%	21.8%	20.0%
Libya	12.0%	11.2%	10.5%	9.8%	9.1%	8.5%	7.9%	7.3%	6.8%	6.4%	5.9%
Tunisia	33.8%	31.4%	29.2%	27.0%	25.0%	23.0%	21.2%	19.5%	17.9%	16.4%	14.9%
Egypt	58.9%	57.0%	55.0%	53.0%	51.0%	48.9%	46.9%	44.9%	42.9%	41.0%	39.0%
North Africa	**48.9%**	**46.8%**	**44.6%**	**42.5%**	**40.4%**	**38.3%**	**36.4%**	**34.5%**	**32.6%**	**30.8%**	**29.1%**
Total MENA	**40.8%**	**38.7%**	**36.8%**	**34.9%**	**33.0%**	**31.2%**	**29.5%**	**27.9%**	**26.3%**	**24.8%**	**23.3%**

Table 3-2: Rural population share of the analysed countries in MENA according to the United Nations medium growth scenario revised in 2004 /UN 2006/.

The share of rural population of the total MENA region is today about 41 %. Rural population will most probably be stagnating over the coming decades. Therefore, the share of rural population will be reduced by 2050 to about 23 % (Table 3-2 and Figure 3-2).

This trend – although at different shares of total population – can be seen in all countries and sub-regions. Countries like Yemen, Egypt, Morocco, Algeria and Iran have a rather large portion of rural population, while the rural population share of e.g. the GCC countries is rather low. The distribution of rural and urban population will be significant when analysing the markets for decentralised small-scale and centralised large-scale seawater desalination systems.

3.2 Economic Growth

After population, the second driving force for water demand is economic growth, represented by the change of the gross domestic product (GDP) over time. The GDP is expressed in US$ 2001 purchasing power parity (PPP), defined by the basket of commodities of the Penn World Tables /Heston et al. 2002/.

Long-term average per capita growth rates of the GDP for the different countries are selected in a range of reasonable values, most countries closing the gap of GDP per capita to a certain reference country with very high GDP per capita – we have selected United States as reference for this purpose – by 50 % in the year 2050 (Table 3-3). As the USA is a large country with very high GDP per capita, it represents something like an upper margin of productivity. Thus, the growth rate for the USA can be seen as reference case for a highly developed technical and organisational progress.

The countries analyzed here reach higher GDP per capita growth rates as they are able to accelerate productivity growth by imitation, subsequently reducing their gap to the U.S. and approximately reaching present central European economic standards in 2050. For example, Germany and the United Kingdom had in 2006 a per capita GDP of 31,800 $/cap/year /CIA 2007/, an order of magnitude that according to our model is achieved by most MENA countries by 2050 (Figure 3-3).

North Africa		**Western Asia**		**Arabian Peninsula**	
Morocco	4.6	Jordan	4.4	Oman	3.2
Algeria	4.0	Lebanon	4.2	Kuwait	2.1
Tunesia	3.6	Syria	4.7	Qatar	1.9
Libya	3.8	Iraq	5.6	Saudi-Arabia	2.7
Egypt	4.1	Iran	3.8	UAE	1.8
		Israel	1.9	Yemen	4.5
Reference U.S.	1.2	Palestine	4.6	Bahrain	2.3

Table 3-3: Average long-term per capita GDP growth rates in %/year selected for the scenario calculation.

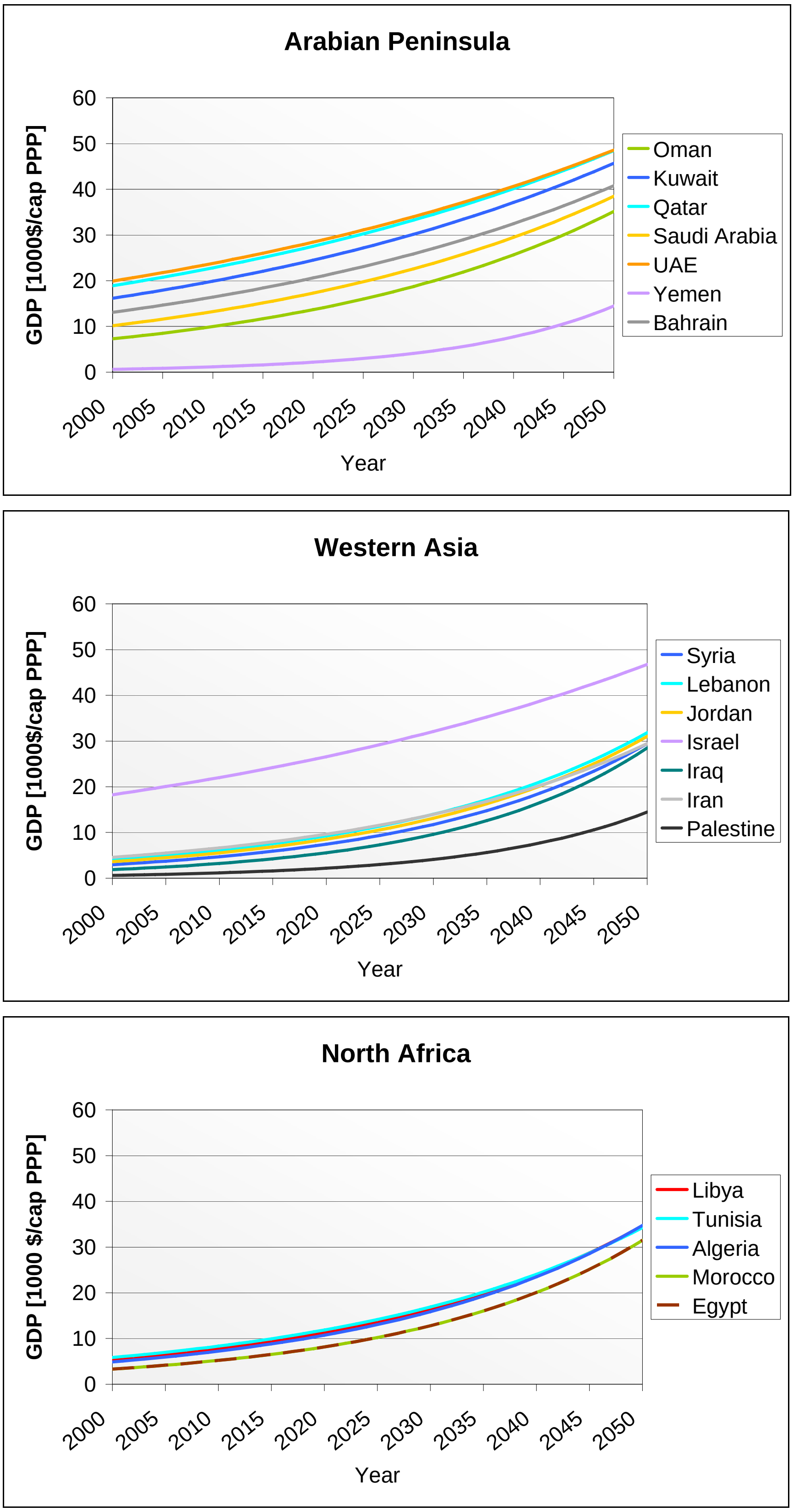


Figure 3-3: Development of the per capita GDP for the MENA countries according to the economic growth model applied in the AQUA-CSP study.

3.3 Water Demand Prospects

In the following we introduce a simple method for estimating the freshwater demand on country level /Trieb and Müller-Steinhagen 2007/. It shows how the demand for freshwater may develop under certain key assumptions for population, economic growth and increasing efficiency in the water sector. The water demand ω for irrigation (ω_{irr}), municipal use (ω_{mun}) and industrial consumption (ω_{ind}) is a function of time t:

$$\omega(t) = \omega(t-1) \cdot (1+\gamma(t)) \cdot \frac{\eta(t-1)}{\eta(t)} \cdot (1-\mu) \qquad \text{Equation (1)}$$

with the relevant driving force, the growth rate γ of the population γ_{pop} or of the gross domestic product γ_{GDP}, respectively, the efficiency of distribution η and the end use efficiency enhancement μ. The distribution efficiency departs from the present values achieved in each country $\eta(t_S)$ in the starting year of the scenario $t_S = 2001$, and develops with a linear function of the calendar year according to

$$\eta(t) = \eta(t_E) \cdot \varepsilon(t) + \eta(t_S) \cdot (1-\varepsilon(t)) \qquad \text{Equation (2)}$$

until reaching the efficiency $\eta(t_E)$ in the final year of the scenario $t_E = 2050$, which is calculated from

$$\eta(t_E) = \eta(t_S) + \alpha \cdot (\beta - \eta(t_S)) \qquad \text{Equation (3)}$$

with the best practice efficiency β and the progress factor α, that describes how much of the efficiency gap between present practice and state of the art is closed until 2050. The transition from present practice to state of the art best practice follows a linear function of time using the weighing factor ε,

$$\varepsilon = \frac{t-t_S}{t_E-t_S} \qquad \text{Equation (4)}$$

with the starting year $t_S = 2001$, the final year $t_E = 2050$ and the time variable t = 2001, 2002, ... 2050.

Sector	Irrigation	Municipal	Industrial
Driving Force	γ_{pop}	γ_{GDP}	γ_{GDP}
Best Practice	β_{irr} = 70 %	β_{mun} = 85 %	β_{ind} = 85 %
Progress Factor	α_{irr} = 50 %	α_{mun} = 65 %	α_{ind} = 65 %
General End Use Eff. Enhancement	μ_{irr} = 0	μ_{mun} = 1.8 %/y	μ_{ind} = 1.8 %/y

Table 3-4: Parameters used for demand side calculation

For the different demand sectors (irrigation, municipal use and industrial use) different sets of parameters according to Table 3-4 are used to calculate the future water demand.

For the calculation of the water demand for irrigation, the population growth rate of each country γ_{pop} that can be derived from Table 3-4 was used as driving force indicator. This implies that the present per capita water consumption for irrigation is in principle maintained also in the future, maintaining also today's level of per capita availability of water for food production in each country. The parameters α and β for irrigation imply that half of the gap between the present irrigation efficiency and best practice which is assumed to be 70 % is closed by 2050. The end use efficiency enhancement of irrigation is already considered with that, so μ is neglected. Starting values of irrigation efficiency and municipal/industrial distribution efficiency for the year 2000 for each country were taken from /FAO 2007/ and /World Bank 2007/.

For the municipal and industrial water demand we have used the GDP growth rate as driving force indicator, which is the sum of the per capita GDP growth rate γ_{GDP} from Table 3-3 and the population growth rate γ_{pop}. The model assumes that about two thirds of the gap of present water distribution efficiency and best practice distribution efficiency (85 %) is closed until 2050. The general end use efficiency is assumed to increase by relative μ = 1.8 % per year, leading to a general reduction of water consumption for constant water services of 60 % until 2050. A similar development has e.g. been experienced in Australia in the past 40 years, where the water demand doubled with a growth rate of 1.6 %/y while the GDP grew by a factor of 5 with a rate of 4.2 %/y. In this case, the general end use enhancement was 2.6 %/y including the irrigation sector. Australia as a mostly arid country, that has experienced a transition to a strong industrial country in the past 40 years, may serve as a good example for the MENA economies in terms of water management and efficiency /ABS 2006/.

Starting values for the water withdrawal in the year 2000 were taken from /FAO 2007/. If there was more in-depth information available from the MENA region itself on the freshwater demand of the starting year 2000, it was used instead of the FAO data, like e.g. in the case of Saudi Arabia, UAE and Palestine /ESCWA 2001-2/, /Shaheen 2006/.

The resulting model of the development of freshwater demand in each country is shown in Figure 3-4 and Table 3-6. All in all, the MENA freshwater demand will grow more or less proportional to the population, which could be interpreted as if a significant part of the additional growth of per capita GDP and the related additional water services can be compensated by efficiency enhancement. This demonstrates the crucial importance of water management and efficiency of distribution and end use. However, it also shows that these measures alone will not suffice to cover the future demand of the MENA region, especially if present demand is already today over-using the available natural freshwater resources.

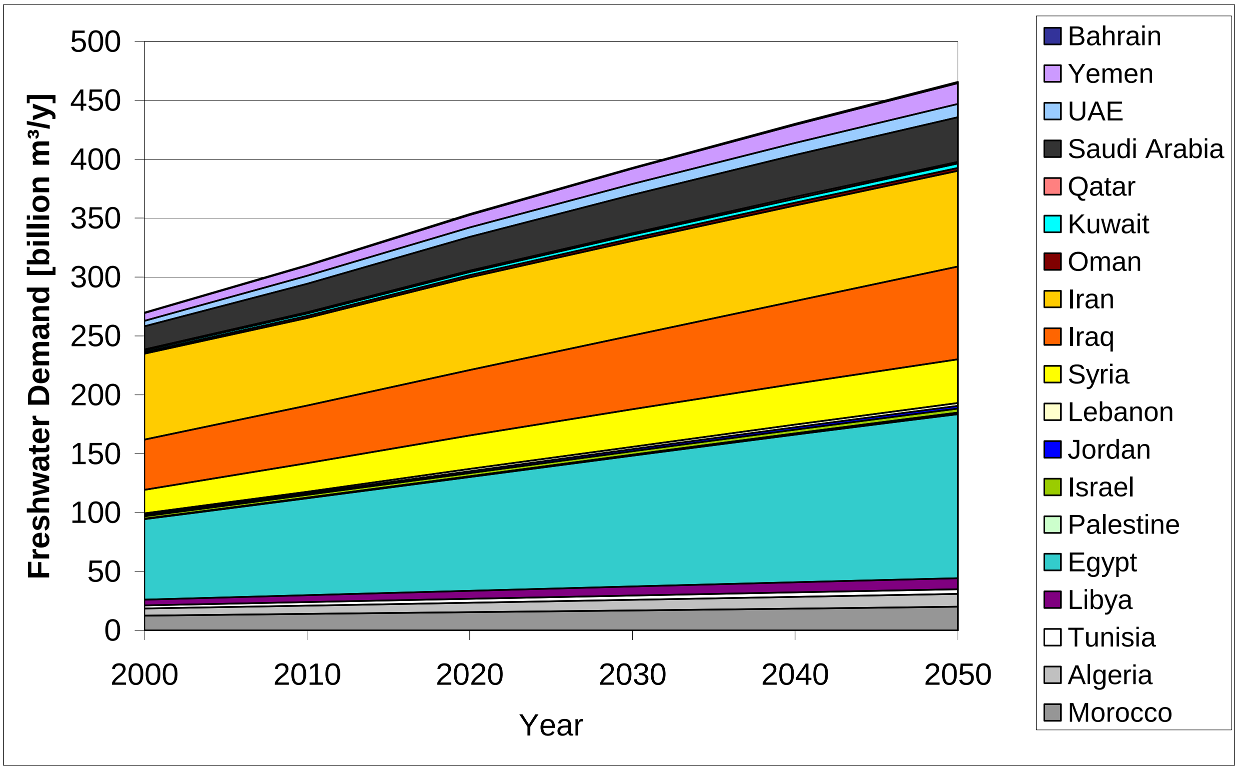


Figure 3-4: Freshwater demand derived from growth of population and economy considering increasing use of wastewater and efficiency as described in the text.

The future demand is calculated individually for every country and aggregated to the regions of North Africa, Western Asia and Arabian Peninsula as a function of population and economic growth (Table 3-6).

The future water demand of the agricultural sector was calculated as function of population. The idea behind the model is that the per capita water supply for food production purposes is maintained at least constant in every country to avoid an increasing dependency on food imports /FAO 2002/, /PRB 2002/ (Figure 3-6). In our scenario, the efficiency of irrigation technologies is enhanced with time, through change of irrigation systems and technical advance.

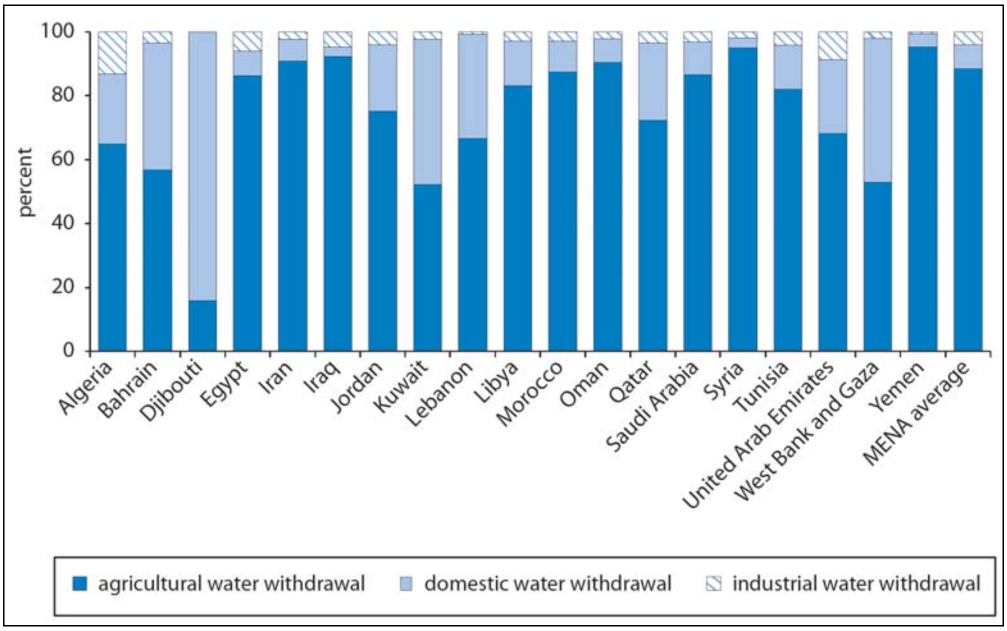


Figure 3-5: Annual water withdrawal by sector in 1998-2002 /World Bank 2007/, /FAO 2007/

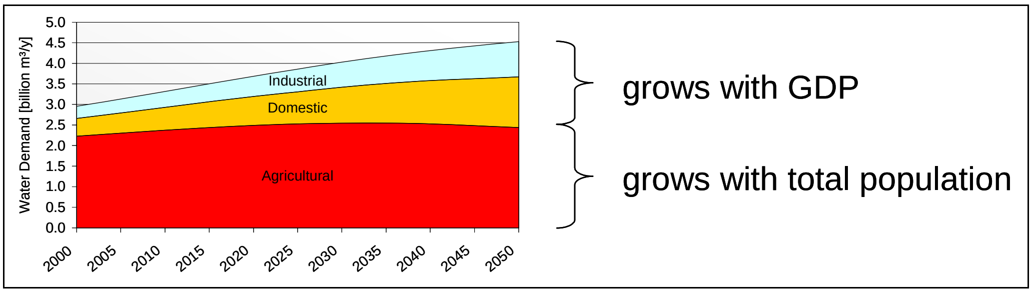


Figure 3-6: Example of the AQUA-CSP scenario showing the relation of water demand to the input parameters population and economic growth for Tunisia

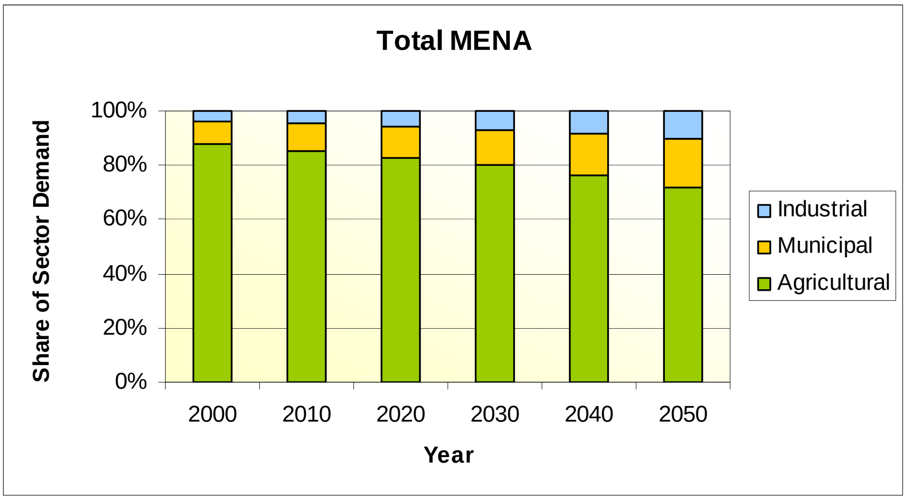


Figure 3-7: Share of water demand by sectors in the AQUA-CSP scenario

In our model the water demand of the industrial and domestic sectors grows in proportion to the national economy represented by the GDP. Efficiency enhancements of the municipal water supply system are considered. Efficiency starts with actual values in each country taken from /FAO 2007/ and reaches close to best practice values by 2050.

The water demand in the MENA region in the year 2000 consists of 88 % agricultural use, 8 % municipal use and 4 % industrial use (Figure 3-5). While the water demand of the agricultural sector will be stagnating in countries like Morocco, Algeria and the GCC with retrogressive rural population, it will still increase significantly e.g. in Yemen and Egypt. This pattern is likely to change over the years, as shown in Figure 3-7 with the municipal and industrial sectors becoming more important.

The by far strongest growth of total freshwater demand will take place in Egypt, which will make up for about 32 % of the total MENA freshwater demand in the year 2050 (Figure 3-4). Water demand will also grow significantly in Iraq, Saudi Arabia, Syria and Yemen. Taking into account the growth of population and economy and the different measures of increasing the extraction, distribution and end-use efficiency of the water sector as shown in this chapter, the freshwater demand in MENA will almost double until 2050. This will exert significant pressure on the scarce water reserves of this mainly arid region.

Nevertheless, our scenario is rather optimistic compared to other scenarios that predict a doubling of demand already for the year 2025 or a stagnation of freshwater supply after 2000, as will be shown in Chapter 3.5. In contrast to such extremes, we believe that a well balanced approach of increasing the efficiencies of water extraction, distribution and end-use, better water management and increased seawater desalination powered by renewable, mainly solar energy will lead to a satisfying result for the MENA region (Chapter 4).

3.4 Freshwater Sources and Deficits

Our analysis shows the renewable freshwater resources and compares them to the growing freshwater demand of each country. Within a specific country, there may be regions with deficits that cannot be identified on the basis of statistical country-wide data. An analysis of Spain or Italy at that level would not identify any deficits, however, we know that in Andalusia and Sicily, there is a severe water shortage, and plans are underway to build desalination plants. Most of the actual data on renewable water resources and exploitable shares has been obtained from the AQUASTAT Database of the Food and Agriculture Organisation of the United Nations /FAO 2007/. The following definitions have been used for our water balances:

- Renewable Water = Renewable Surface Water + Renewable Groundwater – Overlap
- Exploitable Water = Renewable Water · Exploitable Share

- Sustainable Water = De Facto Used Share of Exploitable Water + Reused Waste Water
- Water Demand = Agricultural + Municipal + Industrial Demand
- Deficit = Water Demand – Sustainable Water
- Non-sustainable water = Overuse of Groundwater + Desalination based on Fossil Fuels

In its recent report "Making the Most of Scarcity " the World Bank has analysed the available freshwater resources in the Middle East and North Africa /World Bank 2007/. Figure 3-8 shows the per capita available renewable freshwater sources in each country. Different to our analysis in Chapter 2, this data includes non-conventional sources of water used at present, like desalination and "virtual" water obtained from food imports. Considering the generally accepted threshold of 1000 m³/cap/year for water poverty, only five countries have sufficient water resources: Iraq, Iran, Syria, Lebanon and Morocco. Egypt is exactly at the rim, and all other MENA countries can be considered as poor in natural water resources.

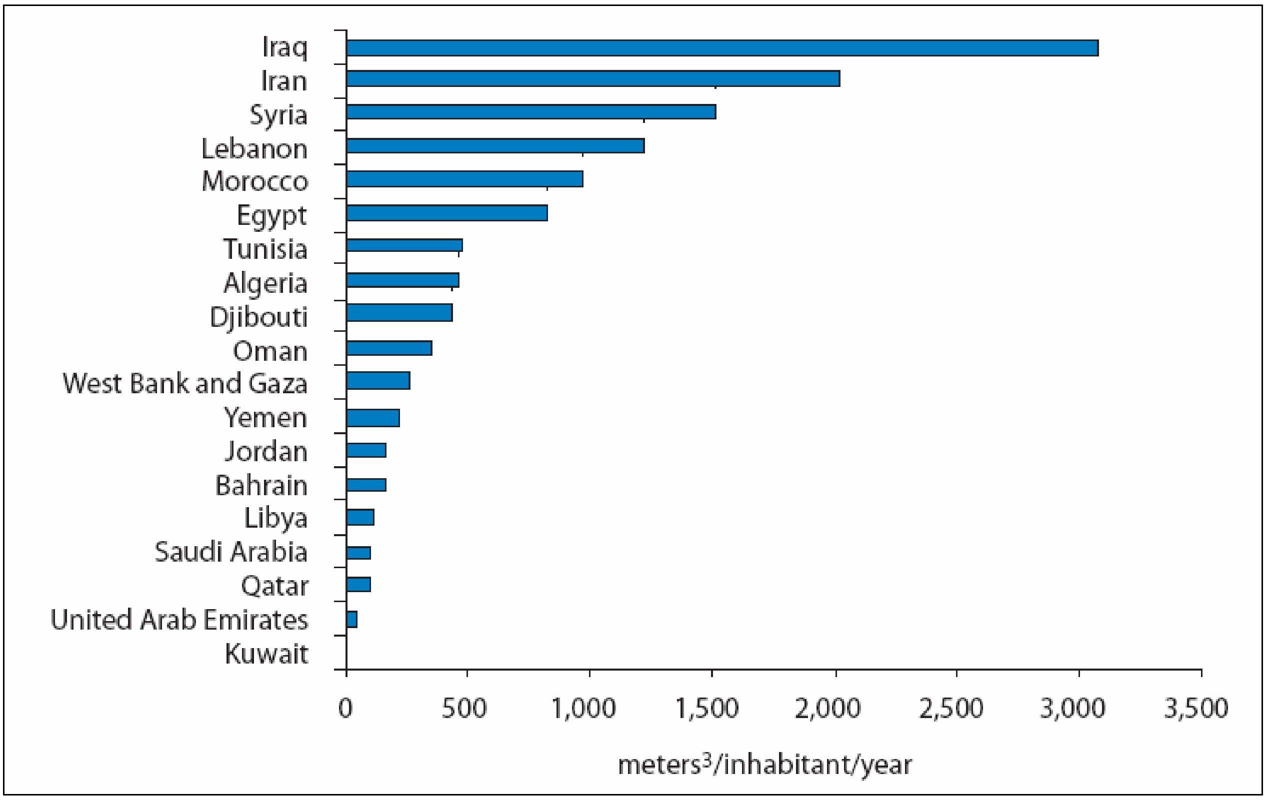


Figure 3-8: Per capita available renewable water in MENA /World Bank 2007/. Data includes non-conventional sources like desalination and "virtual water" through food imports.

	Water available by source (10^9 m^3/yr)			
Country	Internal renewable water resources	External renewable water resources	Nonrenewable groundwater	Virtual water
Algeria	13.9	0.4	1.7	10.9
Bahrain	0.1	0.1	0.1	0.5
Djibouti	0.3	0.0	0.0	0.1
Egypt	4.9	56.5	0.8	18.9
Iran	128.5	9.0	0.0	6.8
Iraq	35.2	40.2	0.0	1.4
Jordan	0.7	0.2	0.2	5.0
Kuwait	0.3	0.0	0.3	1.4
Lebanon	4.8	0.0	0.0	2.0
Libya	0.7	0.0	3.7	1.4
Morocco	29.0	0.0	0.0	5.8
Oman	1.0	0.0	0.2	1.4
Qatar	0.2	0.0	0.2	0.3
Saudi Arabia	3.2	0.0	17.8	13.1
Syria	7.6	19.3	0.0	−4.1[a]
Tunisia	4.2	0.4	0.7	4.1
United Arab Emirates	0.7	0.0	1.6	4.2
West Bank and Gaza	0.8	0.0	0.0	2.2
Yemen	2.7	0.0	1.3	1.6

Table 3-5: Water available or used by source in MENA /World Bank 2007/, /FAO 2007/

Internal renewable resources account for the average annual flow of rivers and recharge of groundwater generated from endogenous precipitation. Double counting of surface water and groundwater is avoided as far as possible. Renewable resources are a measure of flow rather than stock or actual withdrawal. They are, therefore, typically greater than the volume of exploitable water resources, for which consistent data are unavailable. In our study, the exploitable share was estimated from data from /World Bank 2007/, /FAO 2007/.

External renewable water resources refer to surface and renewable groundwater that come from other countries plus part of shared lakes and border rivers as applicable, net of the consumption of the country in question.

Non-renewable groundwater resources are naturally replenished only over a very long timeframe. Generally, they have a negligible rate of recharge on the human scale (<1 percent) and thus can be considered non-renewable. In practice, non-renewable groundwater refers to aquifers with large stocking capacity in relation to the average annual volume discharged.

Virtual water is water used to produce food products that are traded across international borders. It is the quantity of water that would have been necessary for producing the same amount of food that a country may be exporting or importing. These figures reflect both crop and livestock net imports.

In our model the amount of **reused waste water** is increased continuously from the statistical values of each country in the year 2000 until reaching a best practice rate of 50 % within the municipal and industrial sector in the year 2050. The sustainable water is shown in Figure 3-9 in comparison to the agricultural, municipal and industrial freshwater demand of the MENA region.

Sustainable water increases with time due to presently untapped resources in some countries that will be exploited in the future and due to an increased reuse of wastewater of the municipal and industrial sector. **Unsustainable water supply** from fossil fuelled desalination and from excessive groundwater withdrawal is considered as potential future deficit.

The difference of sustainable sources and water demand leads to the **water deficit** displayed in Figure 3-10 as a function of time. There is already a significant deficit today, which is covered by sea water desalination based on fossil fuels and by the over-exploitation of groundwater resources, with the consequence of subsequently dropping groundwater levels, intrusion of salt water into the groundwater reservoirs and desertification in many regions in MENA (Figure 3-11). According to our analysis, this deficit tends to increase from 50 billion m³ per year in the year 2000, which is almost the annual flow of the Nile River allocated to Egypt, to 150 billion m³ in the year 2050. Egypt, Saudi Arabia, Yemen, and Syria are the countries with the largest future deficits. The Egyptian deficit in 2050 will amount to 65 billion m³/y which is almost equivalent to the annual flow of the Nile River, the total deficit in MENA will be equivalent to three times the Nile.

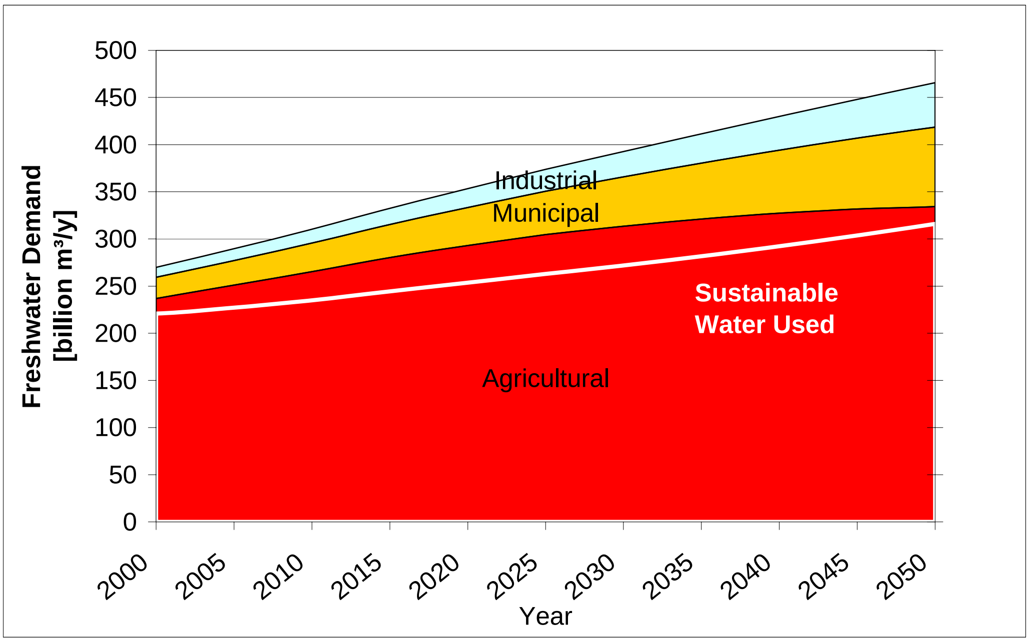


Figure 3-9: Industrial, municipal and agricultural freshwater demand in MENA in comparison to sustainable used freshwater resources of the region (white line). The increase of de-facto used sustainable water is due to enhanced re-use of water and to resources in some countries remaining untapped up to now.

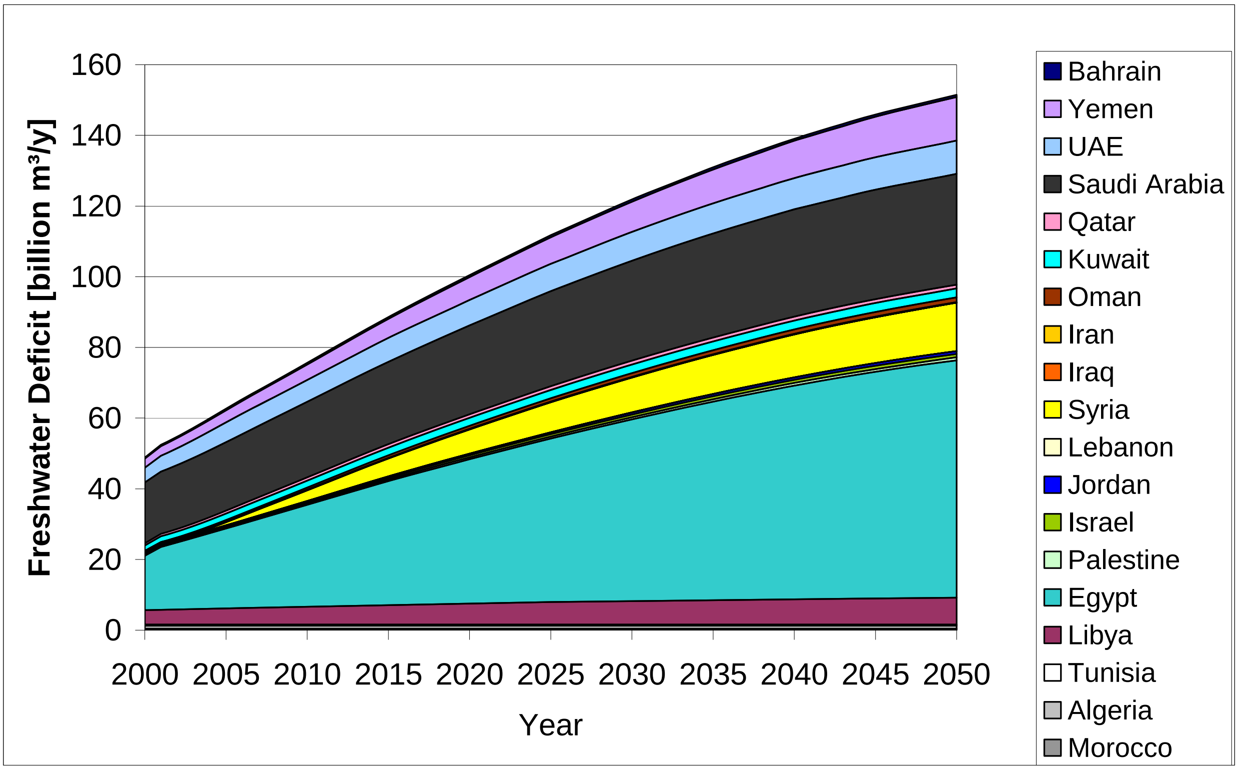


Figure 3-10: Freshwater deficit defined as the difference between water demand and sustainable freshwater for each of the MENA countries according to the AQUA-CSP scenario. Today, part of the water demand is covered by desalination powered by fossil fuels and by the exploitation of non-renewable groundwater. These are not considered as sustainable sources and thus are included as potential future deficits

Enhancement of efficiency of water distribution, water use and water management in order to achieve best practice standards by 2050 is already included in the underlying assumptions of this scenario. It is obvious that the MENA countries will be confronted with a very serious problem in the medium term future, if those and adequate additional measures are not initiated in time.

The total annual water deficits in MENA will increase from today 50 billion m^3/y that are at present supplied by excessive groundwater withdrawals and fossil fuelled desalination, to about 150 billion m^3/y by the year 2050 (Table 3-6). There is no sustainable source in sight to supply such deficits except seawater desalted by renewable energy. The cost of fossil fuels is already today too high for intensive seawater desalination and its volatility and the fact that fossil fuels are limited in time eliminates fossil fuels as a resource for sustainable water security in MENA. Nuclear power is as well a very limited and costly resource, and in addition to that faces unsolved problems like nuclear waste disposal, proliferation and other serious security issues.

It is particularly interesting to see that Syria, which – at least statistically – is not suffering from water scarcity at present, seems to enter a phase of scarcity and deficits in the coming decades, in spite of the large number of rivers entering the country. Many smaller countries in MENA do not contribute much to the total deficit, but may have serious water scarcity within their borders.

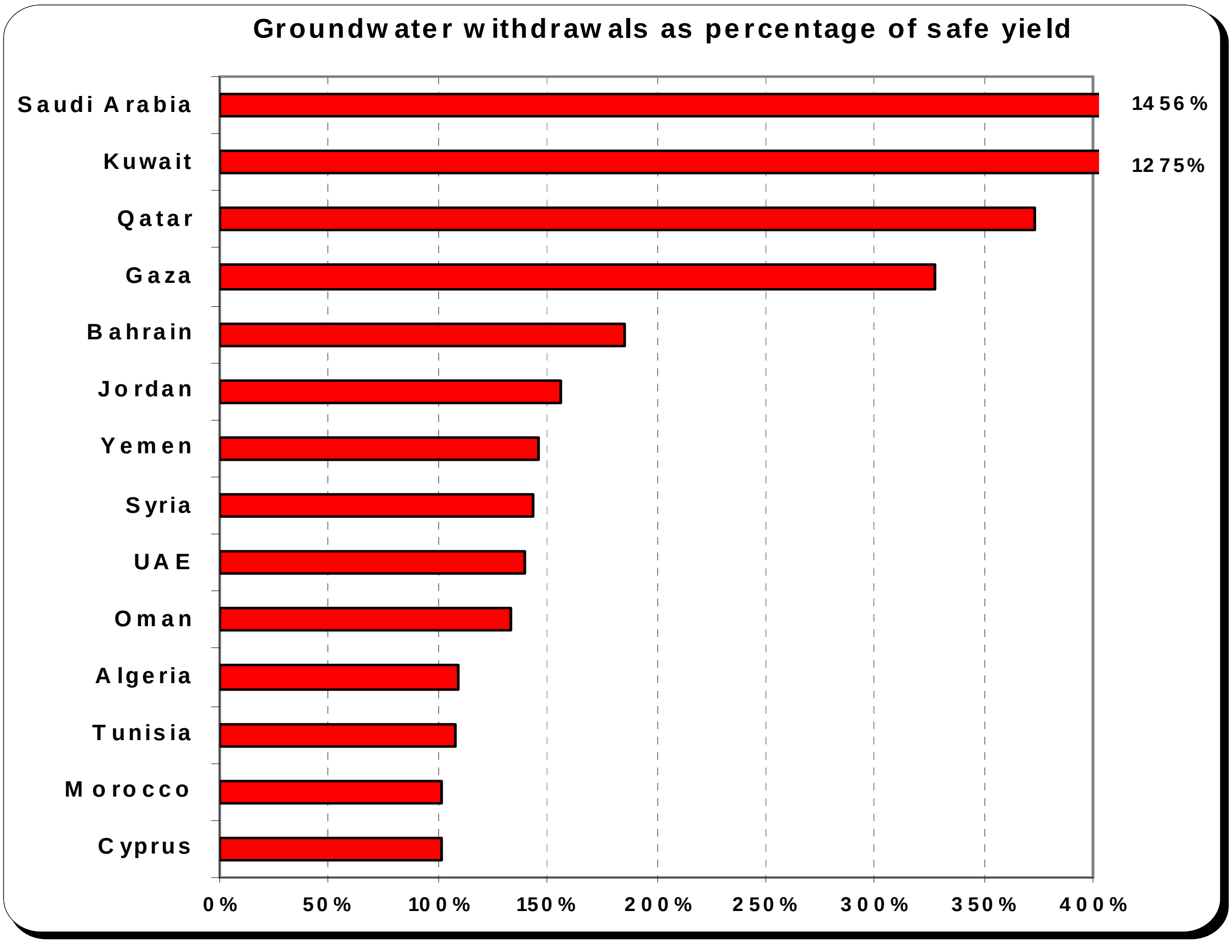


Figure 3-11: Groundwater withdrawals as percentage of save yield for selected countries /Saghir 2003/

North Africa

The sustainable sweet water resources of Northern Africa are today almost used to their limits and no considerable increase of their exploitation can be expected for the future. Unsustainable use from fossil desalination and from excessive ground water withdrawal is already taking place to a considerable extent, with a dramatic increase of this situation ahead (Table 3-6).

In spite of that, the per capita water withdrawal in North Africa will grow from 670 to about 750 m^3/cap/y which is due to a relative moderate growth of the population and an increasing importance of the municipal and industrial sector, mainly in Egypt. The scenario assumptions lead to a linear growth of the water demand in North Africa from today 95 billion m^3/y to 183 billion m^3/y in 2050. A reduction in the agricultural sector is compensated by the growth of the domestic and industrial sectors. Sustainable sources in North Africa cannot be exploited to a greater extent than today. All countries will experience growing deficits, with Egypt being by far the dominating case, due to a strong agricultural sector and large population, followed by Libya and the Maghreb countries. The deficit of Egypt expected for 2050 might arise to the present water capacity of the Nile river of about 65 billion m³/y. An official expectation of a deficit of 35 billion m³/y until 2025 was recently published.

All countries in North Africa will experience a reduction of their water demand growth rates until 2050. The per capita consumption is presently highest in Egypt and Libya (about 1000 m³/cap/y), and lowest in Algeria (200 m³/cap/y), with a slightly increasing trend in all countries. The strong economic growth of the North African countries reveals the challenge of sustainable development, as the water demand of the industrial and domestic sector will growth very quickly and overcompensate possible reductions in the agricultural sector.

Arabian Peninsula

The Arabian Peninsula is characterised by a strongly growing population and a dominating water demand of the agricultural sector, especially in Yemen. The demand will increase from 34 to 72 billion m³/y. The region's water demand is dominated by Saudi Arabia and Yemen, both relying to a great extent on non-sustainable sources, like fossil-fuelled desalination and excessive groundwater withdrawal. Due to the combination of high population and high dependency on agriculture, both countries will be facing considerable deficits, if their water supply would be persistently based on the limited resources of fossil fuels and non-renewable groundwater, as is the case today because the sustainable natural resources of this region are very limited. On the Arabian Peninsula, the relation of sustainable and unsustainable use of water is rather dramatic. The specific consumption on the Arabian Peninsula will fall from today over 700 to about 545 m³/capita and year, due to a strong growth of the population and a persisting importance of the agricultural sector, coupled with very limited natural water resources.

Western Asia

Western Asia still has large sustainable water resources that will be increasingly exploited in the future. However, even in this region, non-sustainable use as from fossil fuelled desalination and from unsustainable groundwater withdrawal is already experienced on a local level and shows an increasing trend in the future.

Western Asia will reduce its per capita demand from 1110 to about 870 m³/cap/y. The water demand in Western Asia will increase from today 140 billion m³/y to about 210 billion m³/y in 2050, showing a trend for stabilisation by that time.

There are vast sustainable water resources in that region which will be increasingly exploited in the future. However, local deficits will occur in Syria, Jordan, Israel and later also in Iraq.

Total MENA

The per capita water demand and its future trend is different in the three regions. The MENA average per capita consumption will be slightly reduced from about 850 to 750 m³/capita/year. The MENA water demand situation is characterised by several facts that at a first glance seem to be rather paradox. On one hand, there is a severe water shortage, with the total region on average living beyond the commonly accepted water poverty level of 1000 m³/cap/y, while on the other hand there is a dominating agricultural production sector that due to the arid climate of the region consumes more than 85 % of the available natural renewable water resources. This situation is sharpened by a strongly growing population, which will double in the 50 years between the beginning and the middle of the 21st century.

Up to now, the proposed answers to this situation were dominated by a call for better water management, measures to increase efficiency, higher and unsubsidised water tariffs, increased accountability, re-use of wastewater, better management of groundwater, reduction of agriculture and increase of food imports. Some of the countries that had the energetic and financial means to do so, mostly the GCC countries, also took into consideration seawater desalination, using for this purpose their abundant fossil energy resources /World Bank 2007/.

However, groundwater resources are already over-used, fuel for desalination is becoming very expensive, and there is simply not enough water available, no matter if well managed or not. Of course, the above mentioned measures make a lot of sense and should be implemented as soon as possible. They will effectively stretch existing resources and delay a possible collapse. But they will not be able to avoid a collapse of water supply in the long-term, if no additional, new sources for freshwater are found and activated in time. As a consequence of scarcity, some places in MENA are already abandoned, and migration induced by water scarcity is increasing, solving nothing but creating similar problems in other regions (Chapter 4 and Chapter 5).

North Africa		2000	2010	2020	2030	2040	2050
Demand Growth Rate	%/y	1.78	1.66	1.37	1.18	1.03	1.00
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
North Africa Deficit	Bm³/y	21.6	34.7	47.6	58.9	69.0	76.9

Western Asia		2000	2010	2020	2030	2040	2050
Demand Growth Rate	%/y	0.80	1.10	0.80	0.63	0.60	0.60
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
Western Asia Deficit	Bm³/y	1.1	4.6	9.0	12.4	15.0	16.8

Arabian Peninsula		2000	2010	2020	2030	2040	2050
Demand Growth Rate	%/y	2.85	1.99	1.60	1.19	0.89	0.76
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
Arabian Peninsula Deficit	Bm³/y	26.1	34.4	41.8	48.3	53.2	56.6

Total MENA		2000	2010	2020	2030	2040	2050
Demand Growth Rate	%/y	1.41	1.43	1.13	0.92	0.81	0.78
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
Total MENA Deficit	Bm³/y	48.9	73.8	98.4	119.7	137.2	150.4

Table 3-6: Numerical data of the AQUA-CSP water demand scenario by region. For single country data please refer to the Annex.

3.5 Comparison to Other Scenarios

The results of the AQUA-CSP water demand scenario can be compared to other scenarios from the literature. The data includes the total freshwater demand for agriculture and for municipal and industrial use. We have taken into account the total withdrawal of water including transport losses. Unfortunately, we could not find a comprehensive analysis of future freshwater demand prospects for all countries of the MENA region, except for one that only gives estimates of municipal and industrial demand, and so we had to compare our results to different sources regarding different countries. Also, there was no scenario available that looks further than 2030.

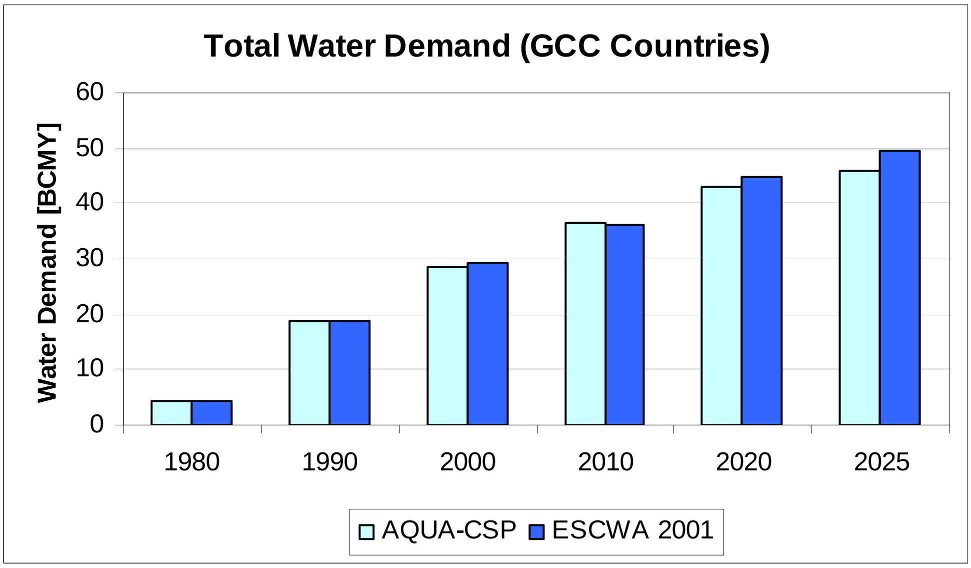


Figure 3-12: Total water demand in the GCC countries analysed by /ESCWA 2001/ compared to AQUA-CSP results. GCC = Gulf Cooperation Council = Saudi Arabia, UAE, Kuwait, Qatar, Oman, Bahrain

The results of the AQUA-CSP study compare fairly well to a forecast of the total water demand of the Economic and Social Commission for Western Asia (ESCWA) from an analysis that was done for the countries of the Gulf Cooperation Council (GCC) shown in Figure 3-12 /ESCWA 2001/. A similar good coincidence for the total Arabian Peninsula from /Al-Zubari 2002/ is shown in Figure 3-13.

For the Northern African countries, we could compare our results to data of the Blue Plan for the Mediterranean Region shown in Figure 3-14 that gives slightly lower prognostics of water demand in its reference scenario /Blue Plan 2005/.

Several other predictions for the total water demand for the year 2025 were available from different sources that differ considerably, as shown in Figure 3-15. The results of AQUA-CSP are close to the average value of those sources.

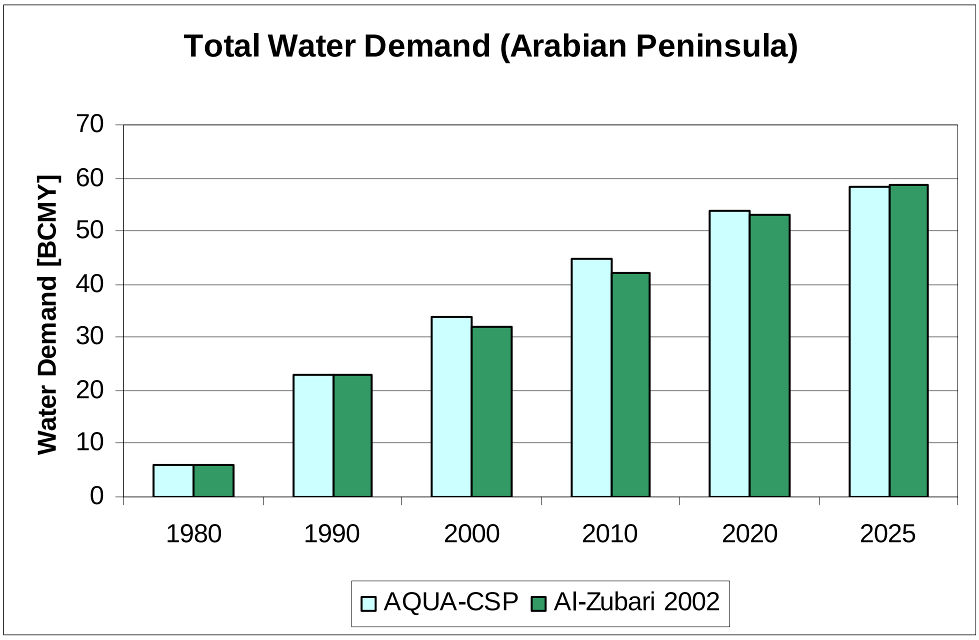


Figure 3-13: Projected water demand of the Arabian Peninsula from /Al-Zubari 2002/ compared to the results of AQUA-CSP (includes GCC and Yemen)

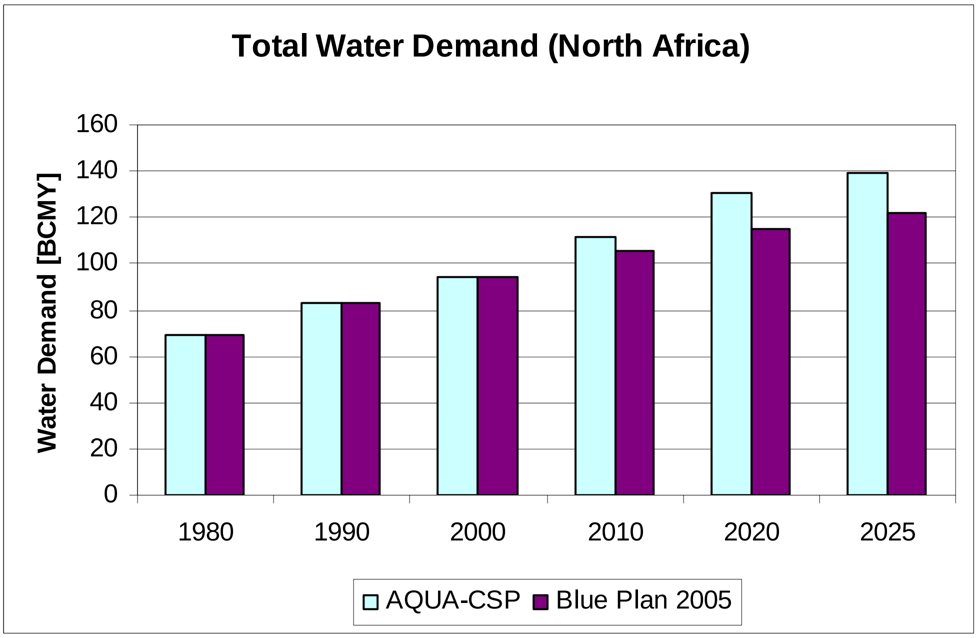


Figure 3-14: Total water demand in the North African countries /Blue Plan 2005/ compared to AQUA-CSP. Countries included: Morocco, Algeria, Tunisia, Libya, Egypt

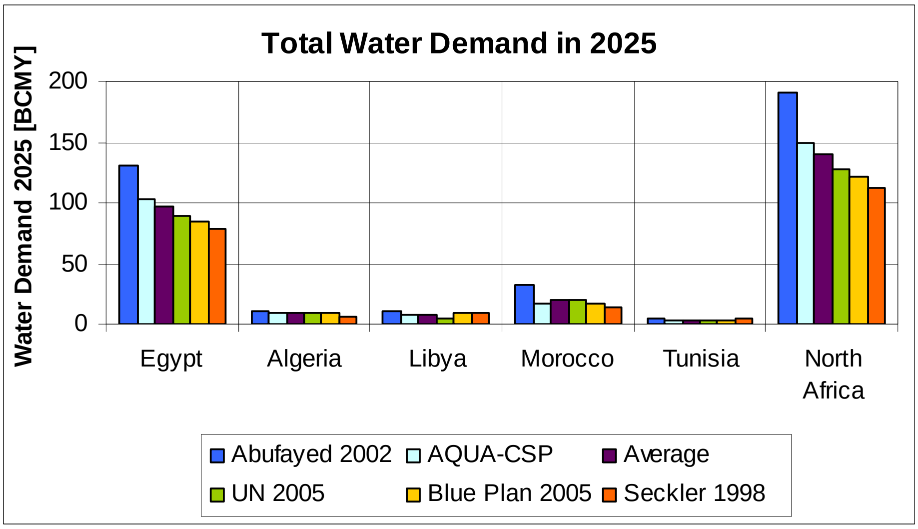


Figure 3-15: Total water demand estimates for the year 2025 from different sources compared to the results of AQUA-CSP. The average value of all sources is also given.

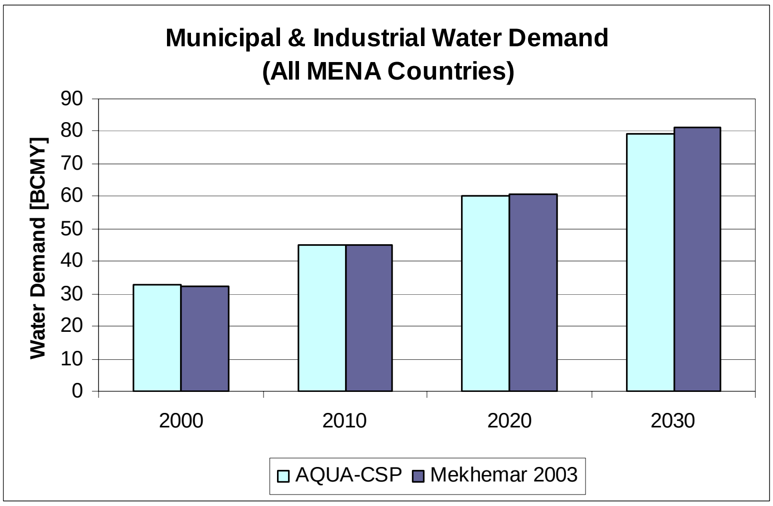


Figure 3-16: Scenario of the municipal and industrial withdrawal of freshwater for all MENA countries compared to the corresponding results of AQUA-CSP.

Furthermore we could compare our data to a scenario of the municipal and industrial water demand of all MENA countries until 2030, which is displayed in Figure 3-16. Again here, we have a fairly good accordance of both data sets (after eliminating an obvious error in the compared data from /Mekhemar 2003/ for the demand estimate of Algeria, that erroneously included agricultural demand).

Water demand prospects for some Western Asian countries were compared with forecasts from /El-Fadel 2001/ and /Al-Zubari 2002/ as shown in Figure 3-17 and Figure 3-18, also coinciding fairly well.

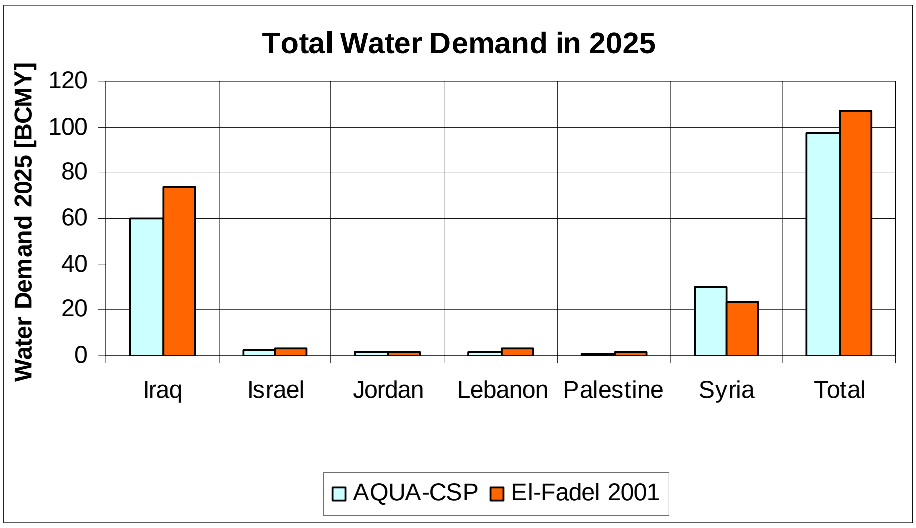


Figure 3-17: Total water demand in 2025 for some Western Asian countries predicted by /El-Fadel 2001/ compared to the results of AQUA-CSP.

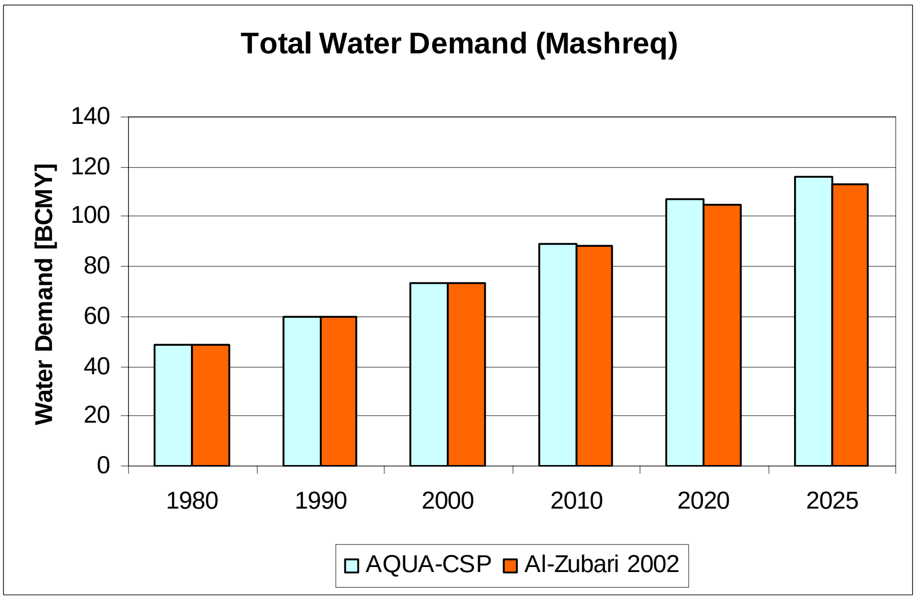


Figure 3-18: Water demand prospects of the Mashreq region by /Al-Zubari 2002/ compared with the results of AQUA-CSP (Countries included are: Egypt, Lebanon, Israel, Palestine, Jordan)

We must also mention a scenario from IEA World Energy Outlook that takes into consideration a selection of countries from the Arabian Peninsula and from North Africa /IEA 2005/. This scenario gives a rather pessimistic view, as it displays a sharp stagnation of water withdrawal from the year 2000 onwards (Figure 3-19). This would in fact lead to a severe reduction of per capita availability of freshwater in the affected countries, with the corresponding consequences for economic growth and social stability (Chapter 4).

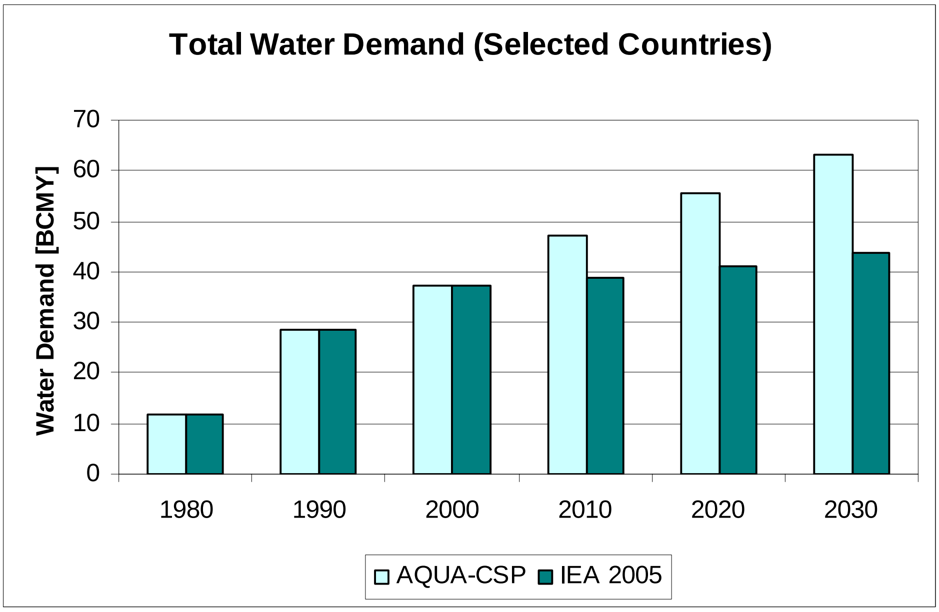


Figure 3-19: Total water demand in countries selected by /IEA 2005/ compared to AQUA-CSP and to historical data from /UNU 1997/ and /FAO 2007/. Aggregated countries selected by /IEA 2005/: Algeria, Libya, Saudi Arabia, Kuwait, Qatar, UAE

Some of the evaluated scenarios accept a significant future reduction of the per capita availability of water, taking as a given threshold the limited available sources of natural renewable water sources. Therefore, their results rather represent a more or less plausible amount of withdrawal of freshwater from those limited sources than a demand driven by the needs of population, which would rather grow proportional to population. Other predictions are based on a given per capita water demand that is extrapolated to the future considering the growth of population and economy and the increase of water transport and end-use efficiency.

There are two fundamentally different approaches for the prediction of the future water demand: on one hand scenarios of water extraction limited by the availability of natural resources, on the other hand scenarios considering only the future needs of population, which are assumed to be satisfied in any way, either by natural sources, better efficiency of water supply or seawater desalination. While in the first case, a considerable reduction of per-capita water takes place that is forced by the scarcity of freshwater, in the second, a reduction of per-capita consumption is not forced, but may be enabled by better efficiency of water distribution and end-use.

Most scenarios are based on a mixture of those assumptions, and predictions up to 2025 can differ considerably. It can be stated that the prediction of the water demand of AQUA-CSP is slightly higher than the average of other forecasts for the North African countries and very similar for the Western Asian and GCC countries when compared to the scenarios that were evaluated within this study. All in all, the AQUA-CSP freshwater demand scenario compares rather well to the medium term expectations of the Arab world until 2025.

3.6 Variations of the AQUA-CSP Scenario

In order to assess the importance of possible measures to increase the efficiency of municipal and industrial water distribution and of irrigation we have calculated two variations of the AQUA-CSP scenario, one assuming extreme efficiency gains and another basically following a business as usual strategy, with only moderate efficiency gains. The parameters of our model were set accordingly as shown in Table 3-7.

The scenario “Business as Usual” assumes that the difference between present efficiencies and best practice values of irrigation efficiency (70 %) and municipal distribution efficiency (85 %) is only reduced by 20 %, and that only 30 % of waste water is re-used by 2050. By contrast, the scenario “Extreme Efficiency” assumes a full acquaintance of best practice values by 2050 and also a 75 % re-use of waste water for all MENA countries by that time.

The model shows that the deficit of 2050 can be reduced from 150 billion m³/y to 100 billion m³/y under the “Extreme Efficiency” scenario. This is a considerable reduction of the water deficit of about 35 % with respect to the AQUA-CSP reference scenario, but it can be seen clearly that a considerable deficit will remain even under these very optimistic assumptions.

The scenario “Business As Usual” shows that a strategy following current paths would lead to a catastrophic situation for the MENA region, as the water deficit would grow to about 230 billion m³/year which would lead to severe environmental and socio-economical impacts. However, please note that even this scenario achieves efficiency gains compared to today’s situation.

The AQUA-CSP reference scenario reflects a compromise between those two extremes, with efficiency gains that are achievable within a reasonable time span. However, the challenge remains to cover a freshwater deficit of about 150 billion m³/year by 2050, and to eliminate as soon as possible the already existing unsustainable use of water of 50 billion m³/year, before irreversible environmental and socio-economic impacts take place in the most affected countries.

Type of Scenario	Business As Usual	AQUA-CSP	Extreme Efficiency
Progress Factor α_{irr} for Irrigation Efficiency	20 %	50 %	100 %
Progress Factors $\alpha_{mun, ind}$ for Distribution Efficiency	20 %	65 %	100 %
Waste Water Re-Use	30 %	50 %	75 %

Table 3-7: Input parameters for progress achievements and waste water re-use for the different scenario variations

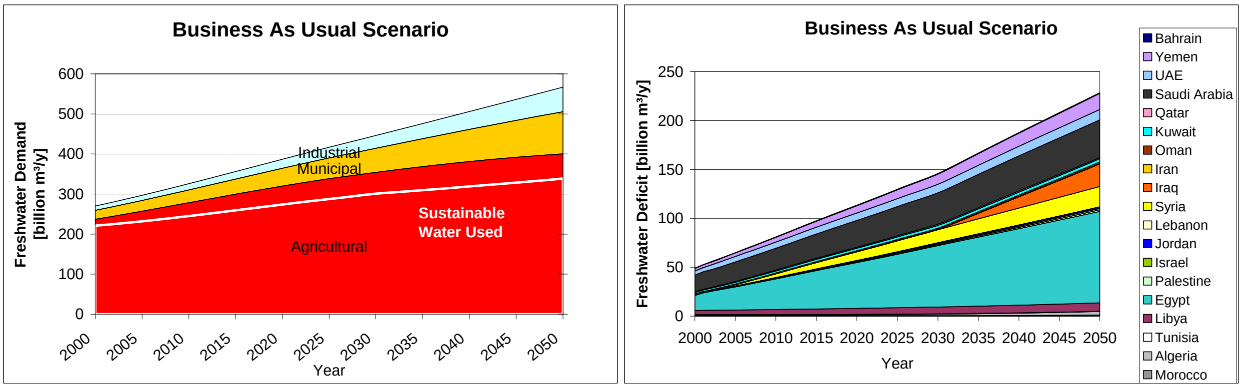


Figure 3-20: Results of the model calculation with minimum measures for increasing water distribution and irrigation efficiency and waste water re-use for all MENA countries

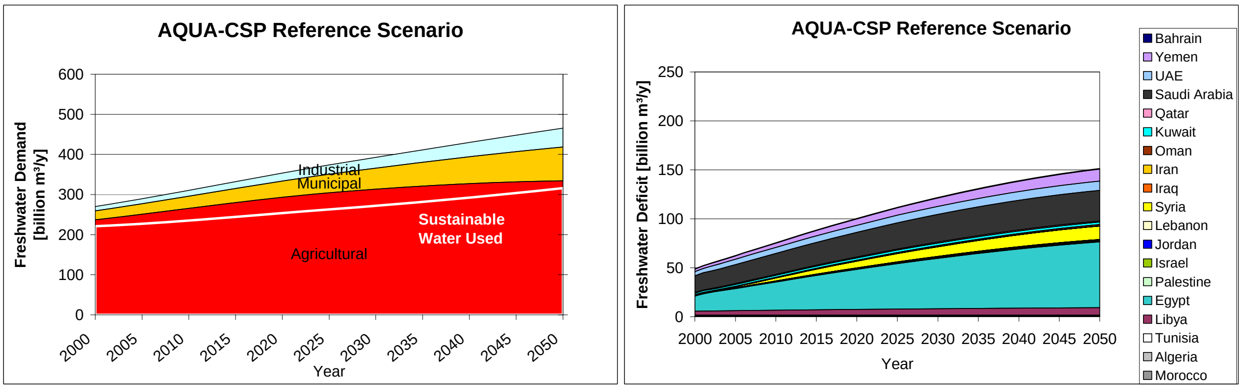


Figure 3-21: Results of the model calculation with AQUA-CSP reference parameters concerning measures for water distribution, irrigation efficiency and waste water re-use for all MENA countries

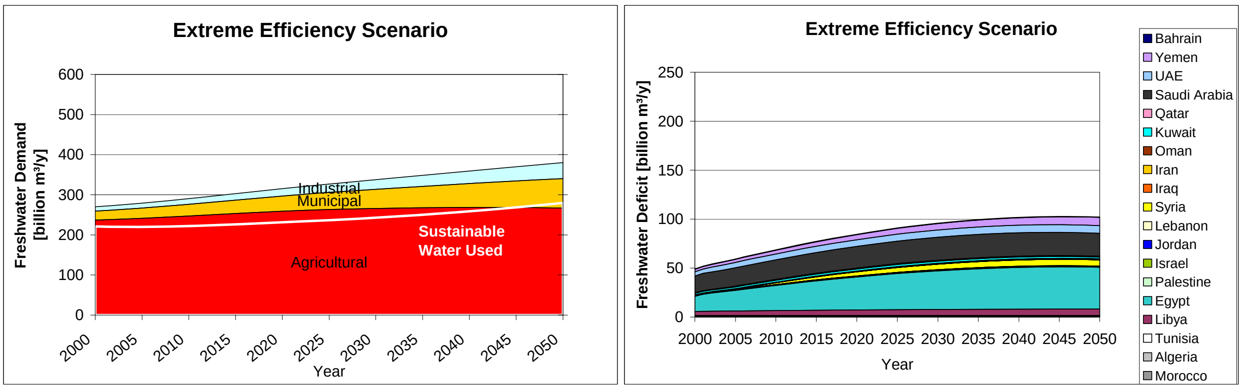


Figure 3-22: Results of the model calculation with maximum measures for increasing water distribution and irrigation efficiency and waste water re-use for all MENA countries

4. Seawater Desalination Markets in MENA

The analysis of water deficits in Chapter 3 shows that there is a pressing need for new, non-conventional, sustainable water sources in many countries of the MENA region. The hot spots can be found in North Africa (mainly Egypt and Libya) and the Arabian Peninsula (mainly Yemen and Saudi Arabia), while the situation is by far less critical in most countries of Western Asia. However, Syria, Jordan and Israel also face considerable future deficits. Although the demand of the agricultural sector, which in MENA makes up to 85 % of the total water demand, will not grow as fast as in the past decades, all countries will see a quickly growing demand of the urban centres and industry /Al-Zubari 2002/.

Today, many countries try to avoid an increasing dependency on desalination and fossil fuels by exploiting their groundwater resources. However, in many countries the exploitation rate is much higher than the rate of renewal, making this solution not more sustainable than a dependency on fossil fuels for seawater desalination. A renewable, sustainable freshwater source with low and stable cost will be required.

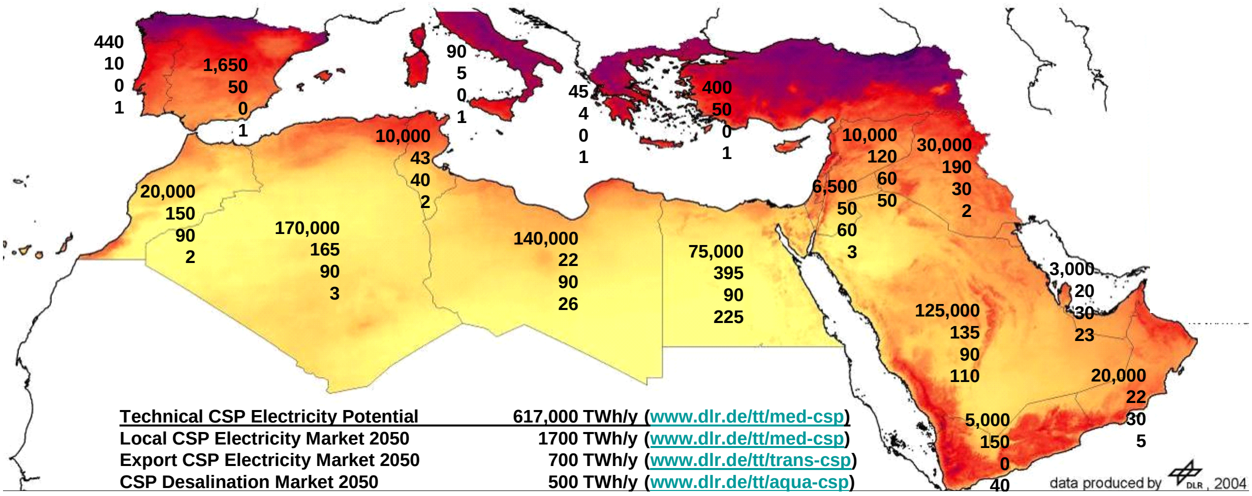


Figure 4-1: Concentrating Solar Power Potentials until 2050 in TWh/y. Techno-economic supply-side potential (top), potential for local electricity (second from top), potential for electricity export from MENA to Europe (third from top) and potential for seawater desalination (bottom). For better comparison, desalination potentials have been converted to electricity required by reverse osmosis. Background: Fig. 1-13.

Within the study at hand, we have assessed the potential of desalination powered by CSP as a possible sustainable solution for water scarcity in MENA. The goal of our analysis was to find out whether future deficits could be covered by solar thermal power plants in co-generation with thermal multi-effect desalination and by using solar electricity for reverse osmosis. Other renewable sources of heat and electricity can also be used for these purposes. However, we have concentrated our focus on direct solar energy as it is by far the most abundant renewable energy source in the MENA region. Within each country, the total technical potential of CSP for power generation and for RO and the specific coastal potential for combined generation of power and desalted water via MED has been assessed in /MED-CSP 2005/. Desalination must be seen only as one market segment of CSP, which has large market potentials for power generation, on one hand for local demand in MENA and Southern Europe, and on the other hand for solar electricity export from MENA to Europe. These potentials were assessed within the preceding studies /MED-CSP 2005/, /TRANS-CSP 2006/. The study at hand adds the potentials for seawater desalination. The results for each country and for the region as a whole are shown in Figure 4-1. For better comparison, desalination potentials have been converted to electricity as if supplied exclusively by reverse osmosis.

The general role of desalination in our developing world can be illustrated by quoting a study from the World Bank: “Desalination alone cannot deliver the promise of improved water supply. The ability to make the best use of desalination is subject to a series of wider water sector related conditions. In some countries weak water utilities, politically determined low water tariffs, high water losses and poor sector policies mean that desalinated water, just like any other new source of bulk water, may not be used wisely or that desalination plants are at risk of falling into disrepair. Under these conditions, there is a risk that substantial amounts of money are used inefficiently, and that desalination cannot alleviate water scarcity nor contribute to the achievement of the Millennium Development Goals. It may be preferable not to engage in desalination on a large scale unless the underlying weaknesses of the water sector are seriously addressed. A program to address these weaknesses should include a reduction of non-revenue water; appropriate cost recovery; limited use of targeted subsidies; sound investment planning; integrated water resources management; proper environmental impact assessments; and capacity building in desalination as well as in water resources management and utility management. In any case, desalination should remain the last resort, and should only be applied after cheaper alternatives in terms of supply and demand management have carefully been considered.

The private sector can play a useful and important role in funding and operating desalination plants, but only if the above conditions are met. If these conditions are absent, there is a risk that excessive investments in desalination become a drain to the national budget, either directly under public financing or indirectly through implicit or explicit guarantees under private financing.

Desalination technology itself has evolved substantially, making it significantly cheaper, more reliable, less energy-intensive and more environmentally friendly than it was a few decades ago. This trend is likely to continue. It is especially true for reverse osmosis, which is gaining a large share of the market outside the Gulf countries where mainly distillation technologies continue to be used. World desalination capacity is around 30 MCM/day and growing. Desalinated water costs in recent projects with Private Sector Participation verges around USD 0.70 per m^3.

Desalination has the potential to contribute to the alleviation of global water scarcity. In the past century, global water consumption levels increased almost tenfold, reaching or exceeding the limits of renewable water resources in some areas, such as in the Middle East and North Africa. This bodes well for the Southern Mediterranean countries, and indeed many other coastal countries, many of which face water shortages and have so far had limited experience with desalination. In particular, desalination can help to alleviate the pressure on coastal aquifers suffering from seawater intrusion. It can also provide an alternative to inter-basin transfers of surface water or the reallocation of water from agriculture to municipal uses whose economic and social costs have to be assessed on a case-by-case basis.

In some water scarce and poor countries, desalination may remain unaffordable in the foreseeable future. But for hundreds of millions of people living in the water-scarce coastal areas of middle income countries, desalination offers the prospect of a reliable, good quality drinking water supply, thus making a contribution to achieve the Millennium Development Goals.

Affordability for the poor is a key issue for sound water sector policies. The poor pay currently high prices to water vendors and they generally have a high willingness to pay for improved supply. No matter what kind of technologies is used to supply drinking water, targeted subsidies are needed to ensure a basic amount of water supply for the poor. In particular, subsidies and cross subsidies are necessary to increase access to water supply by the poor.

Desalination is likely to provide only a portion of the total water needs alongside with existing conventional sources. Although desalination is still more expensive than most existing conventional water sources, its cost is generally lower then the incremental cost of extra bulk supply from conventional water sources, such as dams and inter-basin transfers. Also, upward pressure on tariffs due to the incremental costs of desalination is gradual and often within the ability and willingness to pay of water users" /World Bank 2004/.

The opinion of the World Bank quoted here is based on the paradigm of fossil fuel powered desalination, and in this context, it is quite reasonable: the cost of fossil fuels is increasing steadily, and environmental concerns are becoming imperative. However, it neglects the option of solar powered desalination at large scale, which is characterised by subsequently decreasing cost of solar energy and by reduced environmental impacts. Under this new premise, desalination can adopt a totally different position within a global strategy for sustainable water.

Nevertheless, before enough capacities of CSP-desalination can be realised in the medium-term, increasing water deficits will have to be bridged by fossil fuelled desalination and by groundwater withdrawals, hoping that those limited resources will remain available and affordable. A considerable increase of non-sustainable use of water will thus occur in the coming decades. This calls for an intensive additional use of renewable energy sources for non-conventional water production by desalination, and also calls for intensive freshwater management and efficiency enhancement in urban and rural applications. Only the resolute employment and efficient combination of all possible measures will lead to a satisfactory and sustainable water supply in MENA. Seawater desalination with renewable energies must not be considered an alternative, but a complement to other measures to increase water efficiency as recommended by the United Nations and other organisations. Important factors for water sustainability are among others /FAO 2003/:

- increase irrigation efficiency (from presently less than 40 % to over 70 %)
- increase municipal water distribution efficiency (from presently less than 50 % to 85 %)
- increase general efficiency of all end uses of water by at least 1.5 % per year
- avoid upstream soil erosion by excessive logging and other activities
- concentrate agriculture on high value crops with low water demand
- avoid overexploitation of groundwater resources because this will cause the groundwater level to sink and favours the intrusion of salt water
- clean and reuse at least 50 % of municipal and industrial wastewater
- harvest rain water by small scale distributed basins and dams.

A sustainable supply can only be achieved in time if those measures are realised with high priority. Neglecting those measures would lead to an unacceptable future situation that would be worse than the one shown in our business-as-usual scenario in Chapter 3.6, which considers a moderate increase of efficiency. On the other hand, Chapter 3.6 also shows that enhanced efficiency and re-use of wastewater will be able to reduce, but not to remove the growing freshwater deficit of a population doubling until 2050. Extended seawater desalination will therefore become an imperative component of future freshwater supply in almost all MENA countries.

The future markets for seawater desalination where assessed in two ways. Firstly, a short term analysis by Global Water Intelligence /GWI 2004/ was taken as reference for an estimate of the “conventional” desalination potentials in the Middle East and the Mediterranean countries until the year 2015. For the long-term assessment, we used our own demand side assessment until 2050 shown before in Chapter 3, to estimate the future potential for CSP desalination.

4.1 Short-Term Desalination Markets until 2015

The short term desalination capacities expected in the Middle East and Mediterranean countries until 2015 are shown in Figure 4-2 for both membrane and thermal desalination technologies. In 2002, a capacity of roughly 11 million m³/d of thermal desalination plants was installed in the total region, with most of it – almost 10 million m³/d – in the Arabian Gulf area. Membrane desalination summed up to a capacity of roughly 7 million m³/d, with 4.5 million m³/d installed in the Gulf region.

In the Gulf region, both technologies are expected to double their installed capacity until 2015, to 9 million m³/d for membrane and 19 million m³/d for thermal desalination. Thus, the Gulf region will remain the dominant desalination market world wide, with a visible preference for thermal desalination technology (Figure 4-3).

In the Mediterranean region, there is a visible preference for membrane technology, 2.5 million m³/d installed in 2002 growing to 8 million m³/d by 2015. Thermal desalination is used to a lesser extend but also growing considerably, with 1 million m³/d in 2003 growing to 4 million m³/d in 2015 (Figure 4-4). The figures show that the Mediterranean desalination market is smaller, but growing much faster than the Gulf market, and that there is a visible preference for membrane technology. Therefore, looking at both regions together, membrane desalination is slowly catching up with thermal desalination, with around 17 million m³/d of membrane technology and 22 million m³/d of thermal desalination capacity expected to be installed by 2015 (Figure 4-2).

There is no evidence of RO taking over considerable market shares from thermal desalination systems within the world's largest agglomeration of desalination plants, the Gulf Region. Thus, thermal desalination will remain an important technology, with a subsequent substitution of older MSF plants by more efficient alternatives, mainly MED. To increase efficiency, most thermal desalination plants will in the future be coupled to power generation.

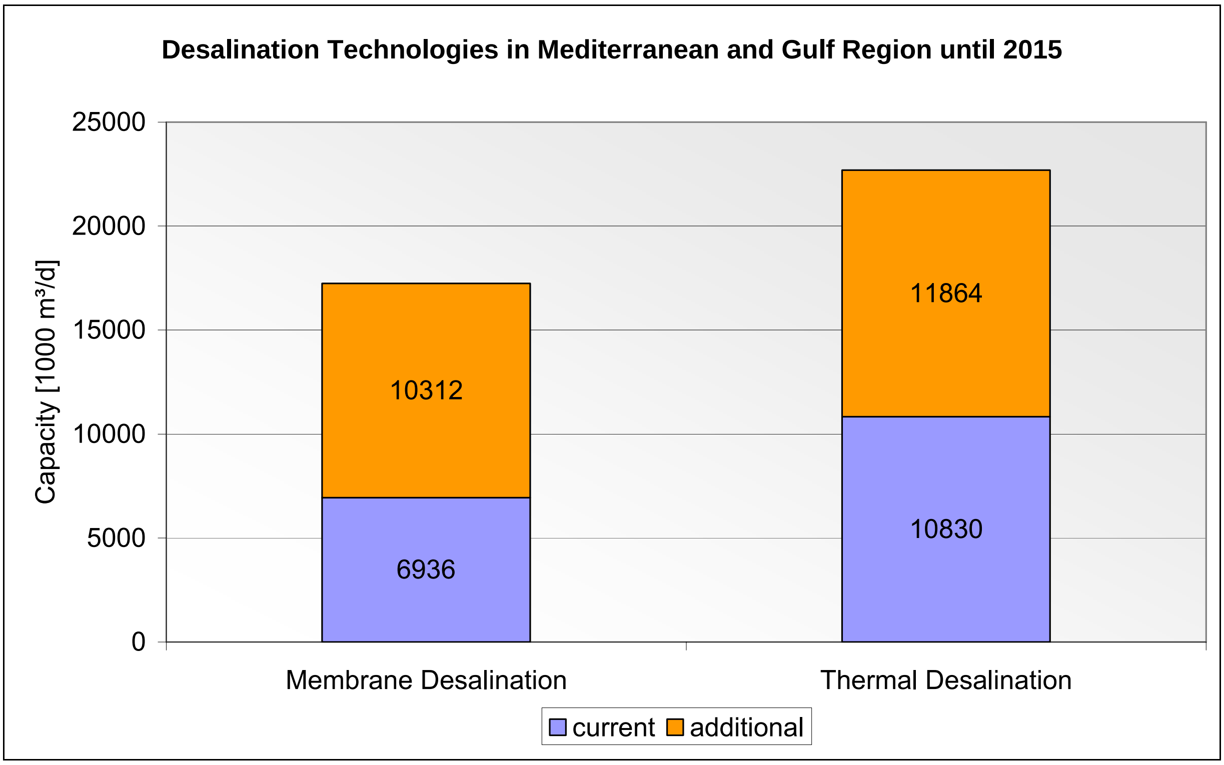


Figure 4-2: Potential of desalination capacity in MENA in 2002 (current) and 2015 /GWI 2004/

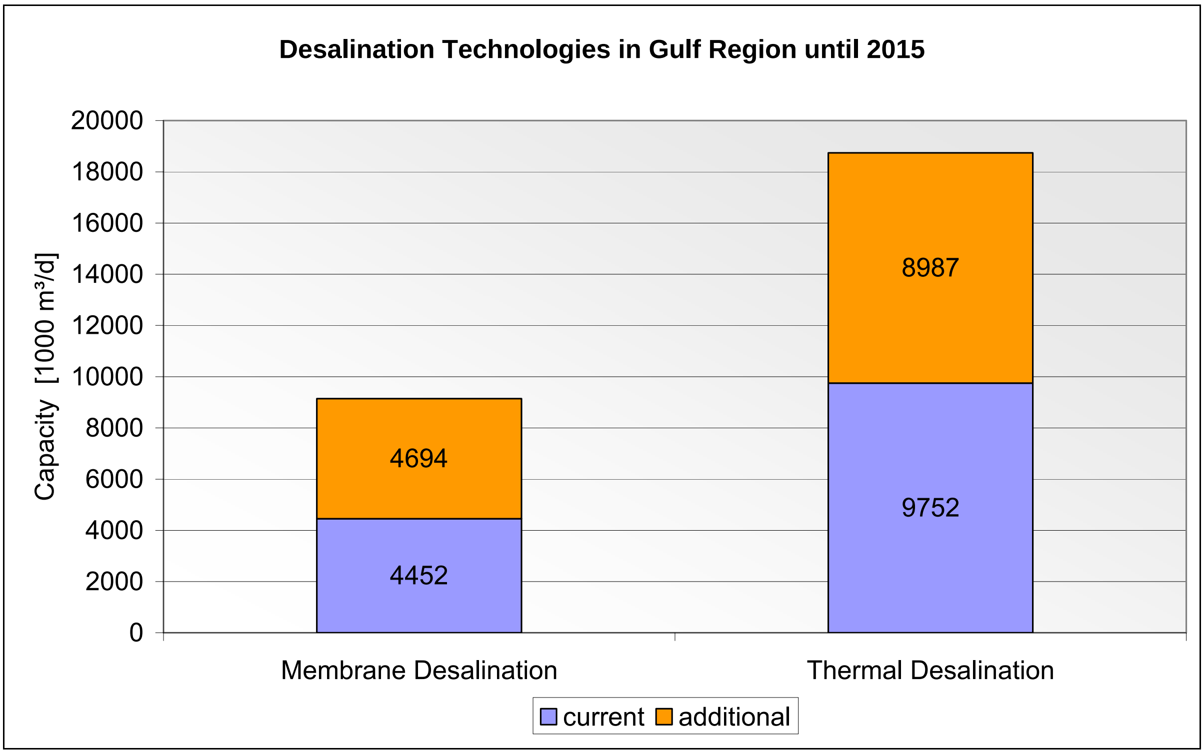


Figure 4-3: Potential of desalination capacity in the Gulf region in 2002 (current) and 2015 /GWI 2004/

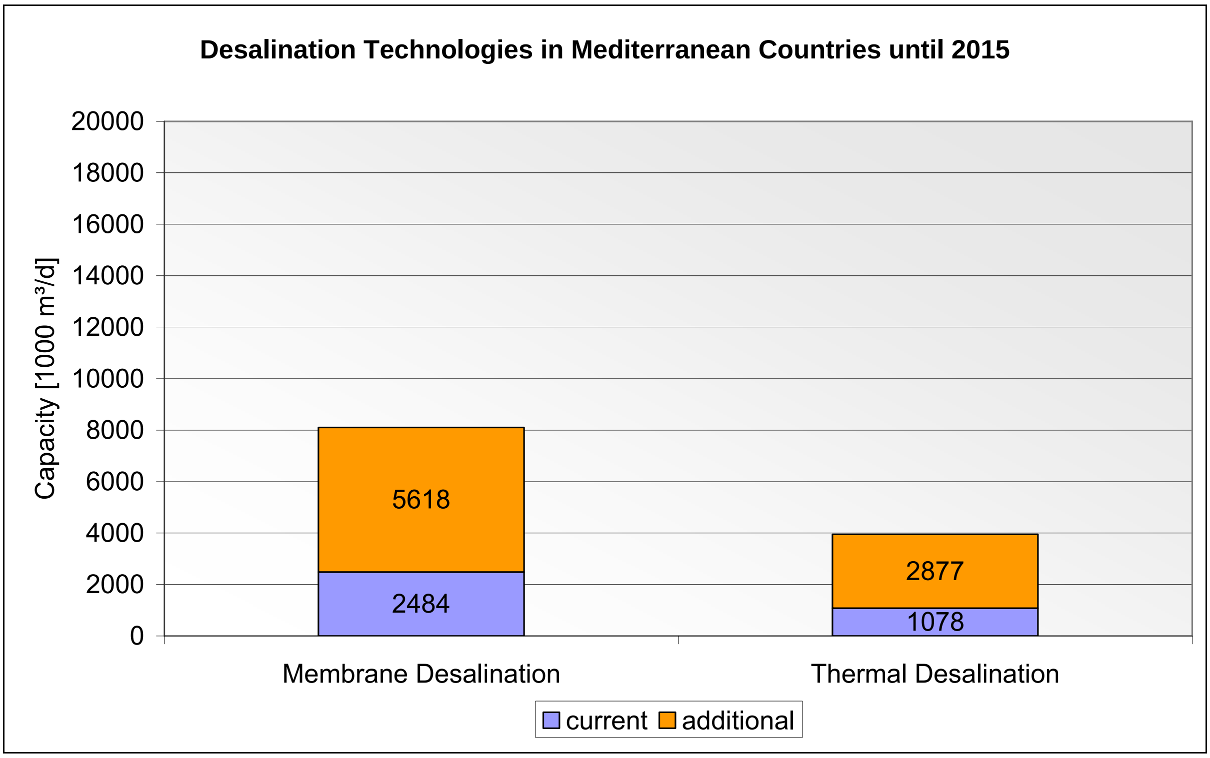


Figure 4-4: Potential of desalination capacity in the Mediterranean region in 2002 (current) and 2015 /GWI 2004/

	Current Capacity			2015 Capacity			Cost of Water	Water tariffs	Capital	Operating	Remarks
	MED, TVC, MSF	RO, ED, MVC	Total	MED, TVC, MSF	RO, ED, MVC	Total			Expenditure	Expenditure	
Country	thermal	other		thermal	other				2005-2015		
	m³/d	m³/d	m³/d	m³/d	m³/d	m³/d	\$/m³	\$/m³	M\$	M\$/y	
Algeria	95,375	79,625	175,000	870,000	1,305,000	2,175,000	-	60% of costs	1800	350	
Bahrain	445,000	55,000	500,000	630,000	270,000	900,000	-	subsidies	440	102	75% of cap.: 70% MSF, 30% RO
Cyprus	1,448	95,053	96,500	10,575	200,925	211,500	-	0.8 from the Larnaca plant	104	20	
Egypt	*45,000*	*255,000*	300,000	248,500	461,500	710,000	-	0.25 - 0.35	369	72	current cap.: Process: 79% RO; 6% VC; 12% MSF; 6% ED; 1% MED Σ 104%
Iraq	0	384,500	384,500	0	984,500	984,500	-	20% of costs	570	120	
Israel	0	439,878	439,878	89,494	1,700,384	1,789,878	-	0.25 to 1.1 (homes and industry: 1.1, but municipality pays the supplier 0.45; farmers pay 0.25 for fresh water and 0.14/0.18 for second-treatment/high quality recycled water)	1215	237	
Jordan			220,000	72,000	648,000	720,000		min. 0.42 for up to 20m³ per month, higher prices for more than 20m³, farmers: 0.11 to 0.5	350	69	
Kuwait	318,000	1,182,000	1,500,000			3,250,000	1.75	0.65	1925	447	
Libya	405,000		415,000	1,537,250	827,750	2,365,000	-	0.15 for the first 25 to 30m³ of water consumed, apply in the bigger cities	2145	463	current cap.: Wangnick: 808564 m³/d => many of old plants no longer operational, in 2000 available for use only 142500 m³/d
Morocco	3,885	11,115	15,000	107,500	107,500	215,000	-	-	180	35	
Oman	316,127	6,452	322,579	463,547	309,031	772,579	1.56	1.17	495	115	
Palestine			10,400	12,060	68,340	80,400	-	0.87 - 1.45	63	11	
Qatar	841,500	8,500	850,000	872,200	373,800	1,246,000	1.15	0.43	436	101	
Saudi Arabia	4,030,000	2,470,000	6,500,000	8,925	2,975,000	11,900,000	-	0.025 - 1.6	5,940	1,380	
Tunisia	660	54,340	55,000	51,250	153,750	205,000	-	-	135	22	
UAE	3,542,000	308,000	3,850,000	5,187,000	2,793,000	7,980,000	Abu Dhabi: 0.6	subidies are payed in the other emirates	4543	1055	
Yemen	0	76,000	76,000	0	131,000	131,000	-	if tariffs are charged at all don't cover costs	41	9	

Table 4-1: Desalination Plant Inventory in 2002 and Outlook to 2015 /GWI 2004/

4.2 Long-Term Markets for Seawater Desalination until 2050

Neither water nor energy is scarce in MENA. Both are available in abundance and forever, in form of sea water, solar radiation and other renewable energy sources. However, presently there are considerable freshwater deficits in MENA that are poorly covered by groundwater depletion and by fossil fuelled desalination. In the future, those deficits could be covered by solar thermal power plants, partially in co-generation with thermal multi-effect desalination, and also by using solar electricity for reverse osmosis. Other renewable sources of heat and electricity will also be used for these purposes. Numeric data for single countries is given in the Annex.

4.2.1 General Results for the MENA Region

Figure 4-5 shows that considerable amounts of water desalted by renewable energy cannot be achieved in the short term, because renewable production capacities have still to be build and related investments must be achieved. Until 2020, increasing deficits will have to be bridged by fossil fuelled desalination and by excessive groundwater withdrawals, hoping that those limited resources will remain available and affordable until then. This may seem optimistic, but there are no sustainable and affordable alternatives. On the other hand, it is a reassuring fact that the potential of CSP is neither limited by the solar energy resource nor by its cost, but only by the possible speed of CSP capacity expansion (starting with zero in the year 2006) and that there is a viable and affordable long-term solution for the freshwater deficits in MENA.

Once the industrial CSP production capacities will have grown to a mature level, in the time span from 2020 to 2030 the growing freshwater deficits will be increasingly covered by desalination plants powered with renewable energies, mainly CSP, reducing the non-sustainable water supply and providing most of the non-conventional water by the year 2030 and afterwards. Finally, with a strong effort, freshwater deficits could be fully removed by the middle of the century.

In the medium term until 2020, the re-use of waste-water and fossil fuelled desalination will have equal importance to reduce the increasing over-use of non-renewable groundwater resources. However, this does not imply a preference for fossil fuelled desalination for coming projects. On the contrary, the scenario assumes a rather quick expansion of CSP for desalination. However, it also shows that it will easily take 15-20 years from now until the CSP shares will attain a noticeable weight within the mix of water resources of the MENA region (Figure 4-6).

This enforces the urgency of a change of thinking and acting of the MENA governments and decision makers: only an immediate change to sustainable solutions will yield acceptable results in good time. Efficiency gains are already considered in our scenario, as explained in Chapter 3, reducing considerably the water demand with respect to business as usual. In spite of that, un-sustainable over-use of ground water will still increase, reaching a maximum of almost 70 billion m^3/y around 2020, which is equivalent to the annual flow of the Nile river.

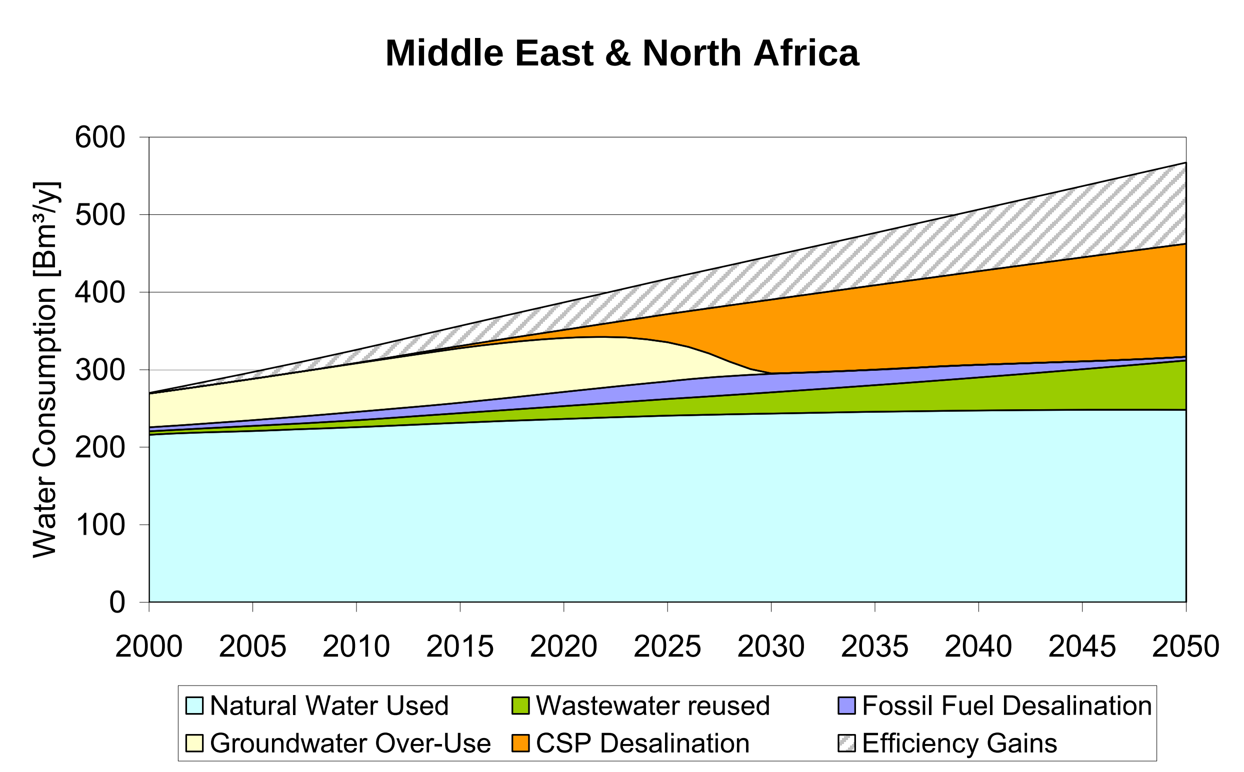


Figure 4-5: Water demand scenario for MENA until 2050 and coverage of demand by sustainable sources, by unsustainable sources and by solar desalination. (shaded: efficiency gains with respect to business as usual)

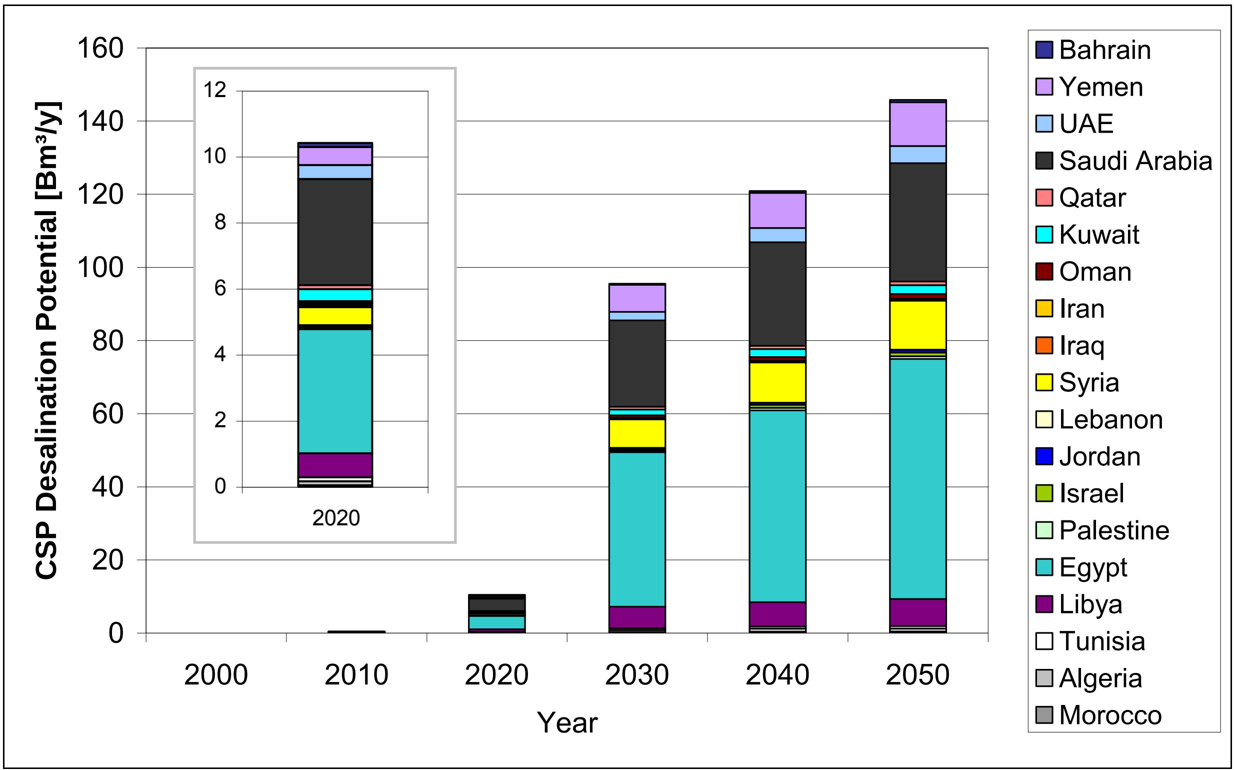


Figure 4-6: CSP potential for seawater desalination in all MENA countries until 2050.

The use of fossil fuelled desalination will increase five-fold to almost 24 billion m³/y in the same time span. Re-use of waste-water is an effective means to combat water scarcity, but limited by the available amounts of water that can be re-used. Until 2050, re-use of wastewater will provide an amount of water equivalent to the over-use of groundwater in 2010 – 62.5 Bm³/y – but in the meantime other gaps will have opened. Therefore, combining all measures including seawater desalination will be the only viable solution to get rid of the growing water deficits in MENA. On the other hand, large scale desalination only has the perspective to become environmentally and economically sustainable if powered by solar energy (Chapters 1, 5 and 6). After a phase of market introduction and demonstration that will last about 10-15 years, the most dynamic expansion of CSP for desalination will take place between 2020 and 2030, when CSP will gradually take over large shares of freshwater supply from depleting groundwater resources. In 2050 demand will be mainly covered by natural water (248 bm³/y) and by solar powered desalination (145 Bm³/y). If provided by RO with an average consumption of 3.5 kWh/m³, the desalted water would lead to an additional electricity demand of around 500 TWh/y in 2050.

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 4-2: Aggregated data of all MENA countries of the AQUA-CSP scenario until 2050

Thus, desalination powered by CSP has the potential to relieve the MENA region from one of its most pressing problems – water scarcity – with a realistic medium-term perspective until 2030. Although water scarcity can be more pronounced in other countries, in terms of quantity, five countries will dominate the CSP desalination market: Egypt, Saudi Arabia, Libya, Yemen and – astoundingly – Syria, as shown in Figure 4-6 (see Annex for country data). There will be basically three types of CSP plants, serving domestic electricity supply, electricity export or sea water desalination in different combinations:

- CSP plants for co-generation with coupled seawater desalination must be located at the coast, as the co-generated heat cannot be transferred over long distances. Their electricity can be used for additional reverse osmosis desalination (RO), for domestic electricity consumption or for export. As the coastal regions in MENA are strongly used by other human activities, this plant type will be limited to regions with appropriate site conditions and available land area.

- CSP plants used exclusively for power generation can be anywhere on the grid. Their electricity can be transmitted to any other place and used for domestic supply, export or RO-desalination. This type of plants will be placed where good irradiation coincides with good infrastructure conditions.
- CSP plants for co-generation will be limited to appropriate industrial sites or hotel resorts with sufficiently large demand of heat and power. While their heat will be used on-site for desalination and district cooling, their electricity might be used on-site too or be sold to the grid for municipal use, export or RO-desalination.

The mix of these three plant types will vary according to the regional demand of each country and the local supply side conditions. The scenario gives a rough estimate of the overall potentials of the region. However, it cannot distinguish and quantify the different plant types that will be erected in each country, which will be subject of the national strategic power expansion planning.

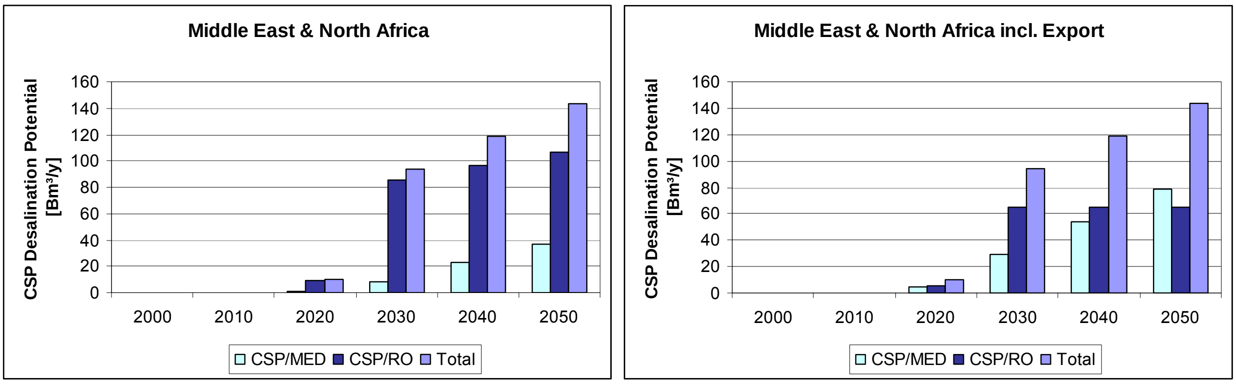


Figure 4-7: Shares of CSP plants using Multi-Effect desalination (CSP/MED) and Reverse Osmosis (CSP/RO) assuming that MED will exclusively be used in co-generation with domestic electricity demand (left) and including an additional combination of MED with solar export electricity (right).

A certain limitation for plants using Multi-Effect Desalination is given assuming that MED will only be used in co-generation with electricity. Thus, the potential for CSP electricity generation would also limit the potential for CSP/MED. If we assume a power to water ratio of typically 1 kW/m³/d and a capacity factor of 7500 full load hours per year for such plants, the share of CSP/MED (25 %) and CSP/RO (75 %) would result as given in Figure 4-7 (left). However, this neglects the direct use of concentrating solar fields for the operation of thermal desalination plants and also neglects the possibility of interconnecting MED desalination plants to power stations producing electricity for export to Europe. Allowing for a combination with electricity exports would yield a much higher share of 55 % for CSP/MED (Figure 4-7 (right). A final estimate of concrete numbers depends very much on future decisions of national policies and is in fact of secondary importance. It is therefore not given here.

To solve the immediate problem of groundwater depletion until 2030, a minimum capacity of 40 GW of CSP must be installed for seawater desalination in order to cover the freshwater deficits by that time. After that, the installation of another 20 GW until 2050 would also cover the further growing demand in a sustainable way. All plants would operate in base-load mode with 7500 full load operating hours per year and exclusively produce electricity and heat for RO and MED seawater desalination. In this configuration, about 1/5 of the water deficit would be covered by reject steam of CSP power stations combined with thermal MED, while 4/5 of the water would be covered by electricity from CSP powering RO membrane desalination.

4.2.2 North African Markets

The demand for freshwater in North Africa will almost double in 50 years from 95 Bm^3/y in 2000 to 184 Bm^3/y in 2050 (Figure 4-8), while only 82 Bm^3/y of exploitable natural water resources are available in the region. Although the agricultural sector will decrease it's share of consumption with time, it will still make up for 65 % of the total water demand in 2050 (Table 4-3). Efficiency gains in irrigation and municipal water distribution, re-use of waste water and solar powered seawater desalination will allow to slightly increase the per capita water consumption, from 660 to 750 $m^3/cap/y$, in spite of a strongly growing population that will increase from 140 to 240 million people.

Unsustainable over-use of groundwater will continue and even increase from about 22 Bm^3/y in 2000 to a maximum of 38 Bm^3/y around 2020 until it can be alleviated earliest by 2030. Fossil fuel powered desalination will be developed in the first years in parallel to solar powered desalination using CSP and other renewable sources, but – due to its elevated cost – will loose importance in the medium and long term. CSP desalination will become visible to a larger extent by 2020 producing 5 Bm^3/y of freshwater, and will achieve an annual production of 75 Bm^3/y in 2050. To this end, a minimum CSP capacity of 2 GW must be installed in MENA for desalination by 2020, and 32 GW in 2050. This will add to the peak electricity demand of about 200 GW expected for this region in 2050 and to 100 GW of capacity installed for solar electricity exports in the total MENA region as scheduled by the prior studies /MED-CSP 2005/ and /TRANS-CSP 2006/.

Re-used waste water will cover about 9 Bm^3/y in 2020 and over 30 Bm^3/y by 2050, making up by then for about 17 % of the water supply, while 75 Bm^3/y will come from CSP desalination as well as from natural resources, making up for 41 % of the water supply, each. By 2050, only a minor share will still be provided by fossil fuelled desalination.

The most dynamical development of the CSP desalination market will take place between 2020 and 2030, with a new desalting capacity of 45 Bm³/y built within that time-span of only 10 years. This is in fact a challenge, and the required industrial production capacities for the components of CSP desalination plants can only be achieved in time if market expansion according to our scenario starts immediately in the MENA region. Otherwise, market introduction may be delayed, and the use of unsustainable sources of water will continue and increase. However, it is not clear for how long this unsustainable use can continue in any case, as the groundwater sources may be totally depleted in many areas of MENA, with severe negative impacts on environment and society.

North Africa will be the largest future market for CSP desalination, with Egypt and Libya being the main candidates for installing large plant capacities, even surpassing the demand for desalination on the Arabian Peninsula. For this region, there is no alternative for CSP desalination in view, and gladly, there is no alternative required. The immense solar radiation potential, easily available seawater and land and the option of combining solar electricity exports to Europe with seawater desalination for local use, makes CSP the most logical, economical and environmental friendly solution for the threat of freshwater scarcity. The end of groundwater overuse scheduled in our scenario by 2030 may look optimistic and will require a tremendous effort from policy, investors and technology providers, but may result as imperative for survival of the whole region, because the exploitable groundwater resources may already be depleted by that time (Chapter 5).

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

Table 4-3: Aggregated data of the AQUA-CSP scenario for North Africa until 2050

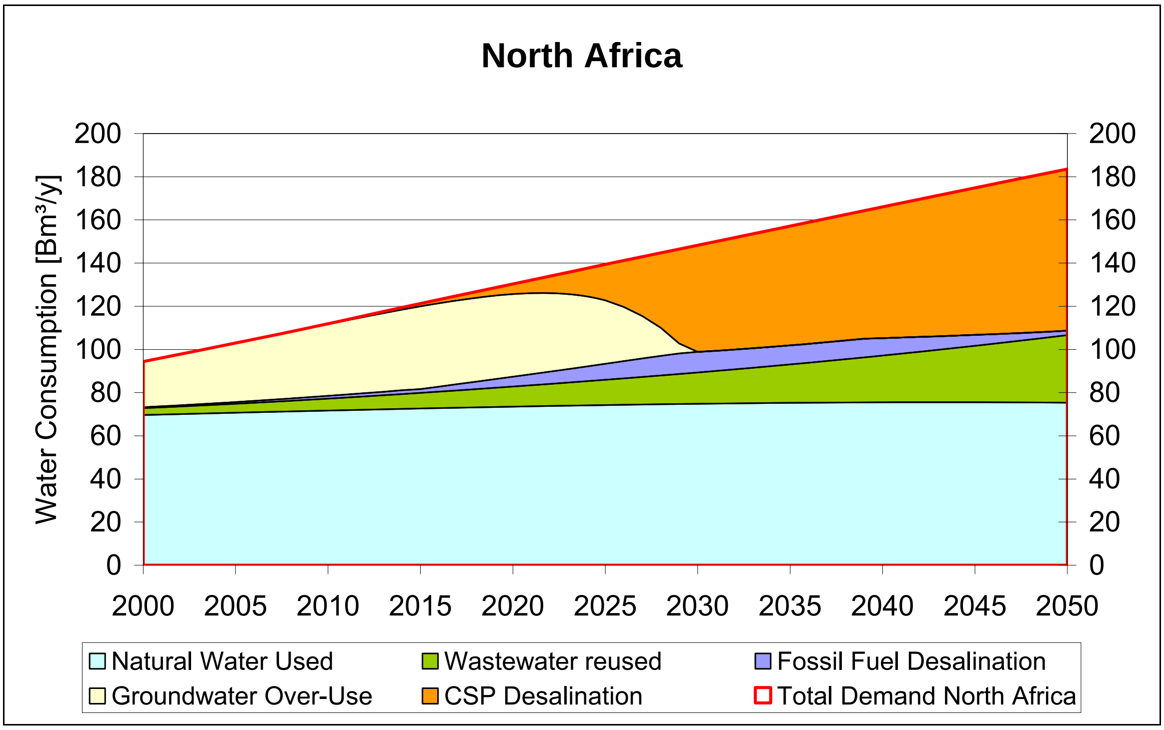


Figure 4-8: Water demand scenario for North Africa until 2050 and coverage of demand by sustainable sources, by unsustainable sources and by solar desalination, including efficiency gains.

4.2.3 Western Asian Markets

Western Asia has the highest exploitable natural water resources of the MENA region, which today make up for 99 % of water supply (Table 4-4 and Figure 4-9). Up to now, there are only few regions that suffer from an over-exploitation of groundwater, and seawater desalination is hardly an issue. However, this pattern has been changing recently in Jordan, Israel and Palestine, and in a few years, deficits will also increasingly become visible in Syria and Iraq.

Efficiency gains in agriculture, industry and municipal distribution and the re-use of waste water are the most important measures to prevent the region from water scarcity. Desalination, no matter if based on fossil or solar energy, will only be used as last resource, and only in the regions where deficits are highest, like Syria and Iraq.

However, even in this relatively water-abundant region, CSP desalination will become an important contribution to freshwater sustainability, avoiding an increasing over-exploitation of groundwater and the use of fossil fuels for desalination. Nevertheless, the over-use of groundwater will reach a maximum of 5 Bm^3/y in 2020 and fossil fuelled desalination will increase to about 3 Bm^3/y by 2030. After that, desalination using CSP and other renewable energy sources will alleviate the region from unsustainable use of water, which will take a time span of about 10-15 years. A completely sustainable supply can be achieved by 2050, if the necessary measures are taken in time.

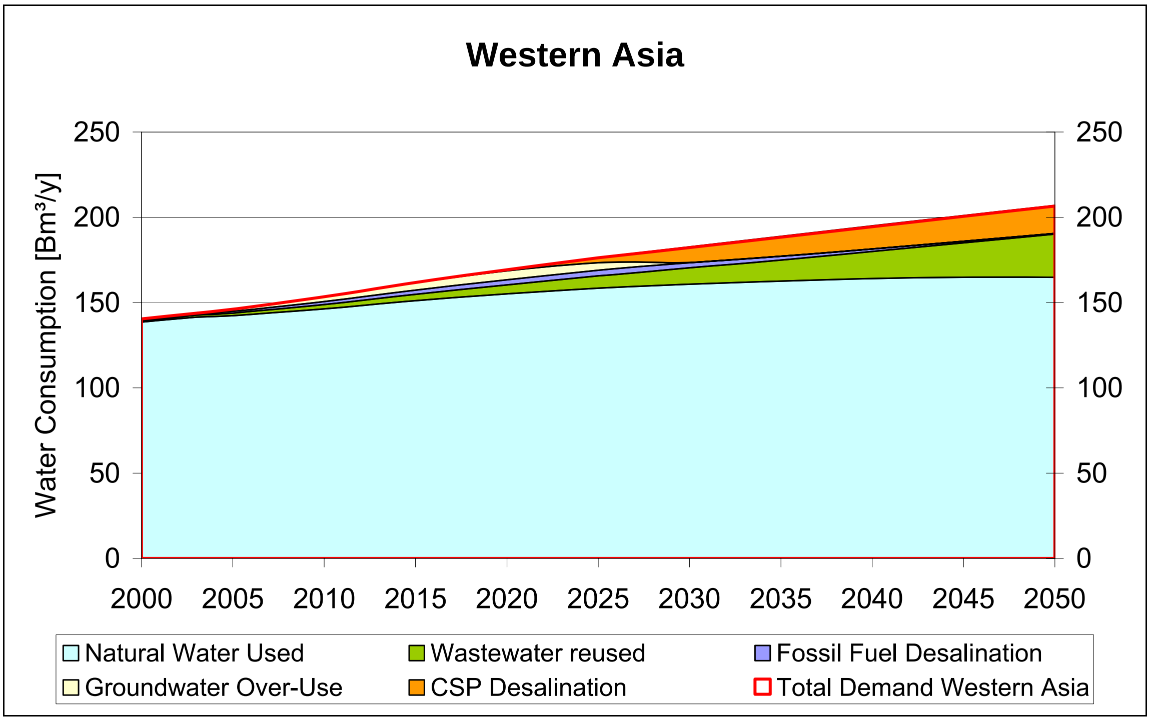


Figure 4-9: Water demand scenario for Western Asia until 2050 and coverage of demand by sustainable sources, by unsustainable sources and by solar desalination, including efficiency gains.

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

Table 4-4: Numerical data of the AQUA-CSP scenario for Western Asia until 2050

4.2.4 Markets on the Arabian Peninsula

On the Arabian Peninsula, the non-sustainable over-use of groundwater makes up for the largest portion of freshwater supply, with a maximum of 25 Bm³/y (Figure 4-10 and Table 4-5). Today's total demand of about 35 Bm³/y will at least double until 2050, which must be compared to a natural exploitable water resource of only 7.8 Bm³/y. Until 2020, fossil-fuel-powered desalination will become the second most important source of freshwater, which is also a source that is not considered sustainable in economical and environmental terms. This makes the Arabian Peninsula the most critical region in MENA, not because of its absolute deficits (which are smaller than those of North Africa), but in terms of dependency on non-sustainable water, that makes up for 75 % of the total supply.

With the Masdar initiative, the United Arab Emirates have recently started to build up a sustainable solution for energy and water based on renewable energy sources including concentrating solar power /Masdar 2007/. However, it will take at least 15 years until visible shares of CSP desalination can be build up in the energy and water sectors of the region, today starting with zero. Until 2020, the expansion of CSP desalination will still be over-compensated by the annual growth of demand for freshwater. By 2025 global industrial CSP production capacities will finally have become large enough to cope with the growing demand, and the freshwater deficits can and must then be alleviated within a time span of 10-15 years. Fossil fuelled desalination will remain until 2050, as new plants built until 2025 will most probably be operated until the end of their economic life time which is about 20-25 years.

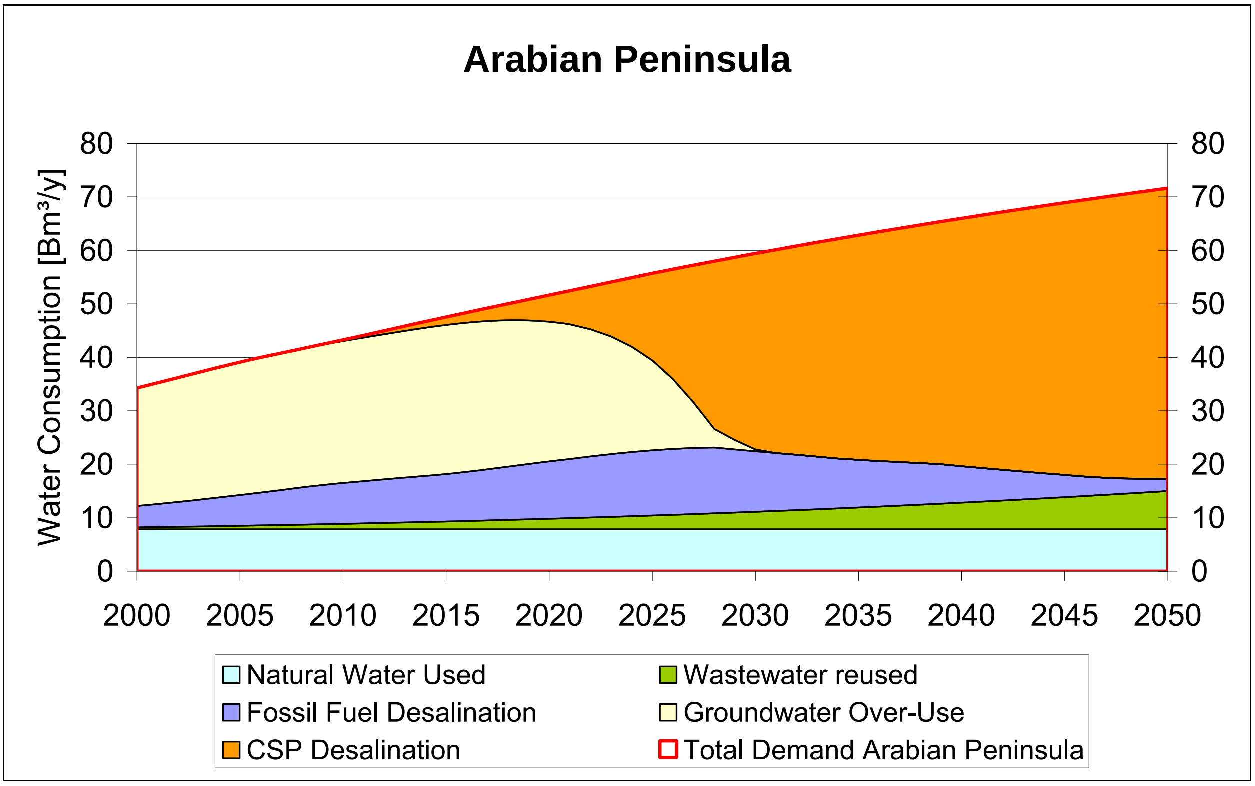


Figure 4-10: Water demand scenario for the Arabian Peninsula until 2050 and coverage of demand by sustainable sources, by unsustainable sources and by solar desalination, including efficiency gains.

In order to achieve a fast elimination of un-sustainable supply of water, a minimum capacity of 2 GW of CSP desalination systems must be installed until 2020, and 22 GW until 2050. The share of agricultural water on the Arabian Peninsula is relatively high, with 83 % today and 77 % in

2050. Due to an only moderate share and growth of industrial and municipal water demand and a presently low efficiency of those sectors, the option of re-using waste water is rather limited. However, in the long term it will be an important factor of security and sustainability and will approximately supply the same amount of freshwater as the natural exploitable water resources.

In absolute numbers, Saudi Arabia and Yemen are the countries with the largest deficits on the Arabian Peninsula. However, all countries of the region suffer from severe water scarcity and a high dependency on non-sustainable sources. Therefore, the Arabian Peninsula has the highest priority, and absolutely no alternative to immediately start market introduction and market expansion of CSP desalination systems.

Having an important potential domestic market for CSP desalination, the necessary financial means due to its oil and gas exports, and with the Masdar initiative already started in the United Arab Emirates, the Arabian Peninsula has a very good chance to become a technology- and market leader for CSP desalination in the medium term future. In 2050, CSP desalination on the Arabian Peninsula can make up for over 50 Bm³/y of freshwater, which is almost the annual volume of the Nile river allocated to Egypt. There will be a considerable environmental impact on the coasts around the Peninsula from such large amounts of seawater desalination. The necessary measures of environmental impact prevention will have highest priority, but can be solved satisfyingly, as will be described in Chapter 6.

In spite of this optimistic perspective and in spite of considerable future efficiency gains that were postulated in our scenario as described before, the per capita supply of water on the Arabian Peninsula will have to be reduced from today about 680 m³/cap/y to less than 550 m³/cap/y in 2050. This is due to a rapidly growing population from about 50 million in 2000 to over 130 million in 2050, with the highest growth rates in Yemen and Saudi Arabia.

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

Table 4-5: Numerical data of the AQUA-CSP scenario for the Arabian Peninsula until 2050

4.3 Method Applied for Market Assessment

The aim of this work package was to find a consistent scenario for the expansion of concentrating solar power for seawater desalination in the analysed countries until 2050. The emphasis of the study lies on CSP technology in the context of other renewable and non-renewable energy technologies and other available sources of freshwater. As shown in Chapter 3.5, a number of water supply scenarios on regional level can be found in the literature /Seckler 1998/, /ESCWA 2001/, /Al-Zubari 2002/, /Abufayed 2002/, /Mekhemar 2003/, /UN 2005/, /Blue Plan 2005/, /IEA 2005/. No consistent long-term scenarios for the total MENA region and for all water sectors are available. However, a long-term approach is necessary, as sustainability cannot be achieved with short-term measures. If limited to short-term measures and perspectives, most efforts would fail to achieve the sustainability goal, and short-sighted analysis of the situation would lead to misleading recommendations.

Therefore, we have tried to build a consistent, long-term scenario of the water demand of all MENA countries until 2050, and compared this "prediction" to the available, exploitable freshwater resources of the region. Our analysis was based on statistical data on country level.

A scenario is not a prediction. A scenario is one of many possible ways to reach a certain future situation. It will require a social and political effort to reach that goal, it will not happen spontaneously. A scenario should be free of inconsistencies or it shall be disregarded. With a scenario, one can examine if a preset goal is desirable or not, if a consistent way to that goal exists and what kind of measures could or must be taken to reach or to avoid it. One can vary the input parameters of a scenario to see if there are different, maybe better ways to reach the goal. A scenario represents a span of possible futures of which one may become reality if the preconditions are fulfilled. No economic or otherwise optimisation of the scenario was performed. Optimisations over a time span of 50 years would be rather questionable, as the input parameters for any optimisation would be a function of time and thus would have a wide range of insecurity. Moreover, most optimisation methods neglect singularities that may change the course of history in an unforeseeable way, like e.g. the market introduction of renewable energy.

With respect to sustainability our scenario leads to a desirable goal, which is characterised by

- affordable cost of water from seawater desalination based on low energy cost from concentrating solar power as shown in Chapter 1 and Chapter 5,
- low environmental impact of power generation and seawater desalination, due to the use of renewable energy for desalination and due to the substitution of chemicals by renewable energy, as explained in Chapter 6,
- low conflict potential due to water scarcity, and fair access to water for everybody due to the exploitation of a new, domestic source of water (seawater) and using a domestic energy source (solar energy) for desalination, as will be shown in Chapter 5,

- economic stability due to low and stable cost of water for the economic development of arid regions, as will be explained in Chapter 5,
- energy and water security, as shown in Chapter 4.

There are technical, economical, social and environmental barriers that limit the expansion of any energy technology. As drafted in Figure 4-11, an overlay of such "guard rails" can be defined as a function of time, limiting market expansion by subsequently changing factors. As an example, market expansion of most renewable energy or desalination technologies can be characterised in a simplified way by four main phases of market expansion:

- Phase 1: Technology cost is high and expansion requires preferential investment
- Phase 2: Prices become competitive but production capacities are still limited
- Phase 3: Production catches up and the market is defined by demand
- Phase 4: As demand grows the availability of resources may become limiting

Phase 1 is characterised by a situation where research and development has lead to innovative technologies ready for commercial application, but still with a high investment cost due to their limited number of projects and lack of mass production. A rather high risk perception by potential investors is usually associated with new technologies, further elevating their cost.

Technological progress and economies of scale will certainly lead to subsequent cost reductions, but this can only be achieved if market expansion takes place at least at a certain minimum rate in niche markets with limited investment opportunities.

First pilot plants will usually not be competitive with existing technologies. The 10th or 20th plant probably would, but it would never come to this because nobody would start. The only possibility to overcome this situation is setting economic frame parameters that guarantee a preferential investment into the new technology. This can only be done by governments or international organisations like the European Commission or the World Bank capable of recognising the chance of a future sustainable supply, and willing to introduce this new option into the existing technology portfolio.

Good examples for such measures are the German, Spanish and lately also the Algerian renewable energy acts that by law guarantee feed-in tariffs for renewable electricity that initially cover the relatively high initial cost of renewables, creating a niche market for those technologies. Another example is the Aqaba Solar water Project described in Chapter 1, where the self-generation of power, cooling and water of a hotel resort by a combined generation plant using solar energy is cheaper and more cost-stable than conventionally buying those services from the public grid.

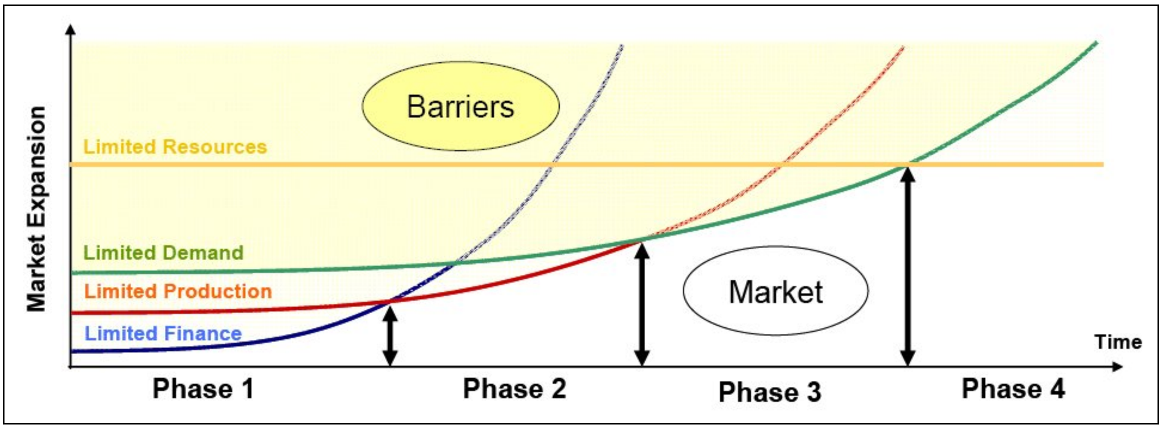


Figure 4-11: Finding a market scenario with the Guard-Rail-Principle. Subsequently, different factors limit technology expansion. The potential market volume is represented by the white area while the different overlapping guard-rails are represented by the coloured lines.

Phase 2 is initiated once the cost of a new technology becomes competitive under conventional economic market conditions. Then, it can expand beyond the initial niche markets. In that phase the production capacities must be extended considerably in order to cope with the increased market volume. For industry this is a very attractive phase, as it is only limited by the industrial production growth rates that can be achieved.

Initially, production growth rates can exceed 100 %/year, because the volumes are still small in absolute terms. However, as the production volumes increase, growth rates are limited. Over a long term of e.g. ten years, a maximum growth rate not exceeding 30 % can be used as a thumb rule for a first estimate. In the renewable energy sector, growth rates of this order of magnitude have been experienced by wind power and photovoltaic systems in the past years.

Phase 3 starts once the industrial production capacities reach eye-to-eye level with demand. In this phase, the demand becomes the limiting factor for market expansion. In competition to other technologies and solutions, the demand for a certain source of water is also coupled to its cost.

The water demand structure of a country will certainly change with time and with economic development, as described in the previous chapter. It will also change with a country's – and its politician's – awareness of the external (societal) costs of water like those induced by pollution, climate change, or groundwater depletion, e.g. accepting higher tariffs for clean, environmentally friendly sources of water than for those that pollute the ambient.

Phase 4 finally describes a situation where the resource itself becomes the limiting factor for market development. Fortunately in our case neither seawater nor solar energy are scarce resources in the MENA region.

The following potential barriers and frame conditions have been taken into account to narrow down the course of the CSP desalination market in the MENA region:

- maximum growth rates of CSP desalination capacities
- annual water demand
- replacement of old desalination plants
- cost of water in comparison to competing technologies

Those parameters were not treated as static constants, but are analysed in their dynamic transition towards a sustainable supply scheme.

In the first place we have assessed the available natural **renewable water resources** of each of the analysed countries as described in Chapter 2. These are well documented by international institutions like the United Nations or the World Bank, and consist of surface and groundwater that is renewed either by rainfall or by rivers or underground flows coming from outside the country /FAO 2007/, /World Bank 2007/, /BGR 2006/. Only a part of the available natural water resources is renewable, while some of the existing groundwater aquifers consist of fossil water that is not renewed in a sufficiently short time span to be considered renewable. Of the renewable water, only a part is exploitable. This is due to different reasons, e.g. the economic feasibility of their exploitation, the fact that sources may be very dispersed or remote, or to environmental or other restrictions. The **exploitable share** of natural water sources in each country has been taken from literature if available or assumed to be equal to renewable water /FAO 2007/.

In a second place, we have analysed the **demand of water** for agricultural, municipal and industrial use and formulated a consistent method to predict its future development as function of population and economic growth as described in Chapter 3. In this model we have taken into account **efficiency gains**, based on a possible transition from the present average efficiency of irrigation and municipal distribution to a long-term best practice value. In addition to the AQUA-CSP reference scenario that may be considered as “desirable and realistic”, we have assessed two further scenarios, one oriented at a business-as-usual strategy with relatively low future efficiency gains, and another with extreme efficiency gains. Finally, we made a balance of exploitable water and water demand as function of time, resulting in the potential future **freshwater deficits** for each country up to the year 2050.

In a third place, in Chapter 4 we have developed a **long-term scenario** showing how the growing freshwater demand in each MENA country can be covered in a sustainable way, by using the different available water resources that consist of exploitable natural surface and groundwater, limited use of non-renewable groundwater, fossil fuel powered desalination, solar powered desalination and re-use of municipal and industrial waste-water. The scenario shows the present and future deficits of freshwater and the pressing need to change to a sustainable form of supply before groundwater resources are totally depleted. Fossil fuelled desalination markets in several countries have been assessed up to 2015 by /GWI 2004/ and up to 2030 by /IEA 2005/. These values have been taken as given. Once the over-use of fossil groundwater will be eliminated by solar and fossil fuelled desalination between 2020 and 2030, a further growth of desalination capacity is only allowed within our model on the basis of solar desalination. However, the average life-time of the existing fossil desalination plants is taken into account to derive their remaining share of water supply after that time. The share of re-used waste water in each country starts with the historical value of the year 2000 and is linearly extended to a maximum value of 50 % of the municipal and industrial water demand by 2050. In the “Extreme Efficiency” scenario this value has been augmented to 75 %, in the “Business-As-Usual” scenario it was set to only 30 %.

5. Socio-Economic Impacts of CSP Desalination

Figure 5-1 shows the market perspectives of CSP in terms of total installed capacity resulting from the scenarios developed in the MED-CSP study for the coverage of the domestic electricity demand in the EU-MENA countries, from the TRANS-CSP study that quantifies the potential of solar electricity exports from MENA to Europe, and finally, found within the prior chapters of this report, the potential for seawater desalination. The addition of capacities of those three sectors leads to a total installed CSP capacity of about 28 GW by 2020, 140 GW by 2030 and 520 GW by 2050 in the total EUMENA region. Over 90 % of this capacity will be installed in MENA (please compare to Figure 4-1).

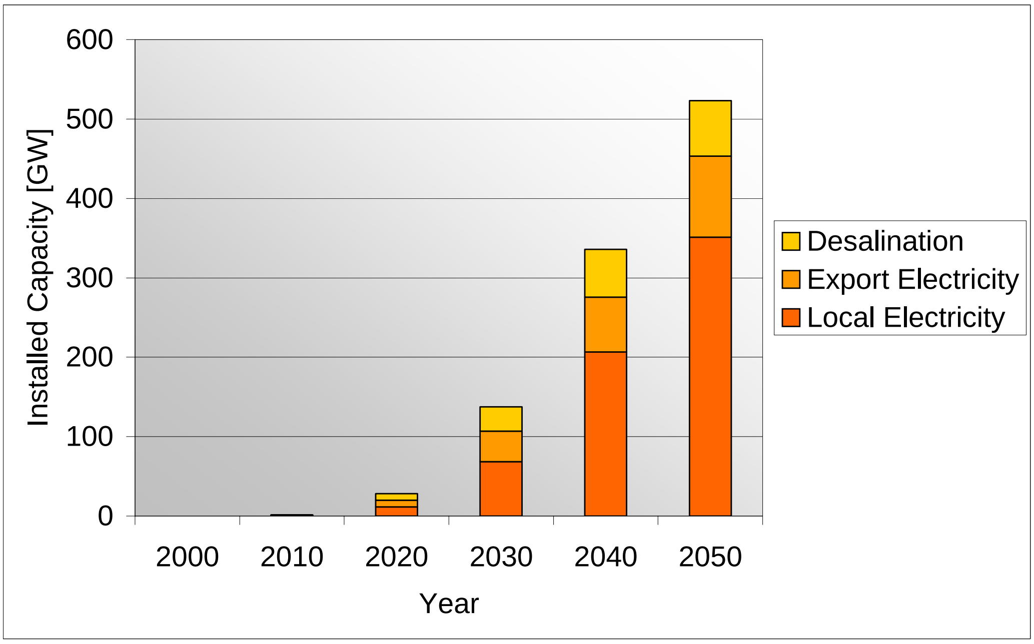


Figure 5-1: Market perspectives of concentrating solar power for local electricity supply, export electricity from MENA to Europe and seawater desalination /MED-CSP 2005/, /TRANS-CSP 2006/

The expansion of CSP in the electricity sector of Europe and MENA will have considerable socio-economic and environmental impacts, most of them positive, that have already been described in the previous studies /MED-CSP 2005/ and /TRANS-CSP 2006/. Within this chapter, we will describe the socio-economic impacts of a broad dissemination of CSP desalination plants in the MENA region. First of all, we will try to quantify the cost of water that can be expected in the medium and long-term from such systems, and compare it to the present and expected cost of water in the MENA region. The main question is, will the MENA countries enter a never ending spiral of subsidies for water and energy or can water scarcity be solved in a sustainable way?

Certainly, a low production cost is only one part of the challenge, as its benefits are often lost if the efficiency of distribution and use of water is well below state of the art. In that case, a lot of the extracted water may be lost and useless on one side, or a cheap source of water may be rapidly depleted on the other side. Many MENA countries are already on such a track, and the cost of not-acting is becoming visible in many areas, affecting economic development and often even social peace. A phenomenon appearing recently is the growing competition of urban and rural population for water, in most cases being the rural population the losers, moving as a consequence to the rapidly growing Mega-Cities of the region and sharpening the problem there. This context will be described here.

Finally, after analysing the problem of water scarcity and summarising the presently discussed portfolio of solutions, we will add the AQUA-CSP concept of cultivating the desert for a growing population in MENA, using the natural resources that have always been there but are still totally untapped: desert land, salty water and solar energy.

5.1 Cost Perspectives of CSP Desalination

Within this chapter, we will analyse the future cost perspectives of freshwater produced by CSP-powered desalination taking into account the expected capacity expansion of CSP as a total and the related cost learning curves resulting from research and development, from mass production, from economies of scale of larger plant units and from the integration of solar thermal storage capacities into the power plants. The different effects that lead to a cost reduction of electricity from CSP as function of the total installed capacity have been described in numerous publications /NEEDS 2007/, /TRANS-CSP 2006/, /MED-CSP 2005/, /Ecostar 2004/, /Sargent & Lundy 2003/, /Sokrates 2003/.

Learning curves describe the cost reduction of a product as function of the total amount of that product sold on the world market, in our case the total installed capacity of CSP plants /Neij 2003/. A cost learning curve is described by the following equation as function of the progress ratio (PR):

$$c = c_0 \cdot \left(\frac{P}{P_0}\right)^{\frac{\log(PR)}{\log(2)}} \qquad \text{Equation 5-1}$$

As an example, a progress ratio of PR = 90 % means that the specific cost (c) is reduced with respect to the initial value (c_0) by 10 % every time the total installed capacity (P) is doubled with respect to the initial value (P_0). Several analysis predict a progress ratio of 86 % for concentrating solar power technology /Sokrates 2003/, /Ecostar 2004/, /Needs 2007/. The cost learning curve for solar electricity resulting from an analysis in the frame of the European NEEDS project is shown in Figure 5-2.

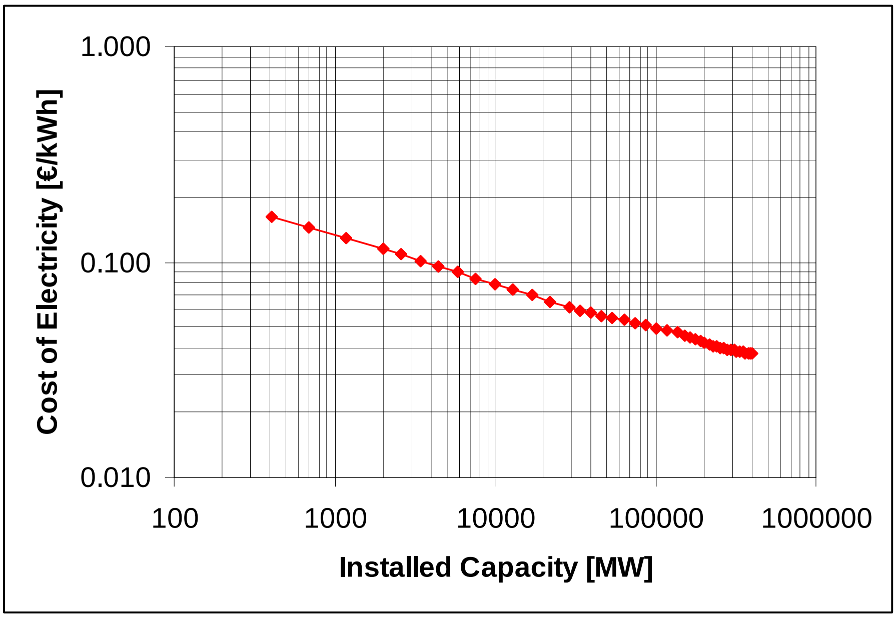


Figure 5-2: Cost of electricity from CSP as function of installed capacity according to the optimistic-realistic scenario variant of /NEEDS 2007/ for sites with an annual irradiance of 2500 kWh/m²/y, 8000 full load hours per year. The learning curve corresponds to a progress ratio of 0.862 for solar electricity, which is equal to the progress ratio found in /Sokrates 2003/.

The curve starts with a solar electricity cost of 0.163 €/kWh in 2007 with presently installed 410 MW and ends with 0.037 €/kWh in 2050 with over 400 GW installed capacity. In spite of a higher total installed capacity in our predictions as shown in Figure 5-1, we will use a more conservative cost scenario, as shown in Figure 5-3, calculated on the basis of a lower annual solar irradiance of 2400 kWh/m²/y and less operating hours. This represents an average value, as direct normal irradiance in MENA may vary from 2000 to 2800 kWh/m²/y (Figure 1-13). Figure 5-3 shows the learning curve for the AQUA-CSP reference scenario as function of time instead of installed capacity. We have also calculated the cost of electricity generated by conventional, gas-fired power stations, and the mixed cost taking into consideration the solar share of our scenario, which increases from initially roughly 20 % today to over 95 % after 2025, which can be achieved by the increased use of solar thermal energy storage for night-time operation (Figure 5-5). At the same time, the cost of fossil fuel increases from 25 €/MWh in 2007 to 40 €/MWh in 2050, equivalent to about 60 $/bbl of fuel oil. This cost represents the average fuel cost over the total lifetime of the plants installed in the respective year. It stands for the present and expected cost of natural gas.

As has been described in Chapter 1, CSP plants can produce both electricity and water, and the resulting cost of one product has a strong influence on the cost of the other. Therefore, in order to get a reliable definition of the cost of water from CSP desalination, we have opted in a first step for separating the plant into two parts, one that produces exclusively solar electricity and another one that uses this solar electricity for seawater desalination.

In fact, this is exactly the definition of a CSP/RO configuration. As we have seen in Chapter 1, the cost of CSP/MED is expected to be only slightly below the values resulting for CSP/RO, and therefore it would theoretically suffice to calculate the long-term learning curve of CSP/RO systems as representative cost learning curve for both options.

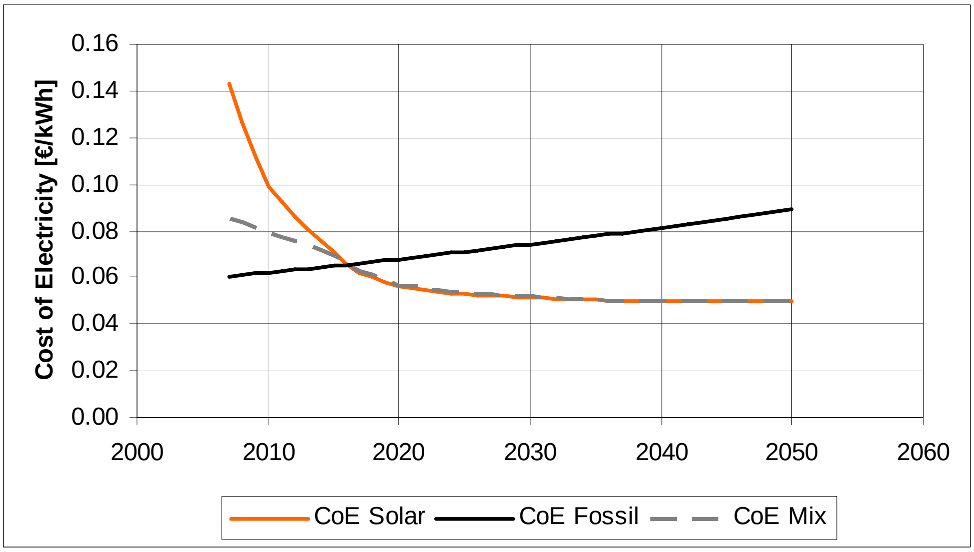


Figure 5-3: Projected cost of electricity (CoE) from CSP, from gas fired power stations and from hybrid systems in the AQUA-CSP reference scenario (prices in real €2007, 5 %/y interest rate, 25 years economic life, solar irradiance 2400 kWh/m²/y, initial fuel cost 25 €/MWh, fuel cost escalation 1 %/y, gas power plant efficiency 47%, power plant investment 500 €/kW, O&M rate 2%/y, 7500 full load hours per year, long-term exchange rate €/$ = 1.0). Cost break-even can occur much earlier if fossil fuel costs escalate faster.

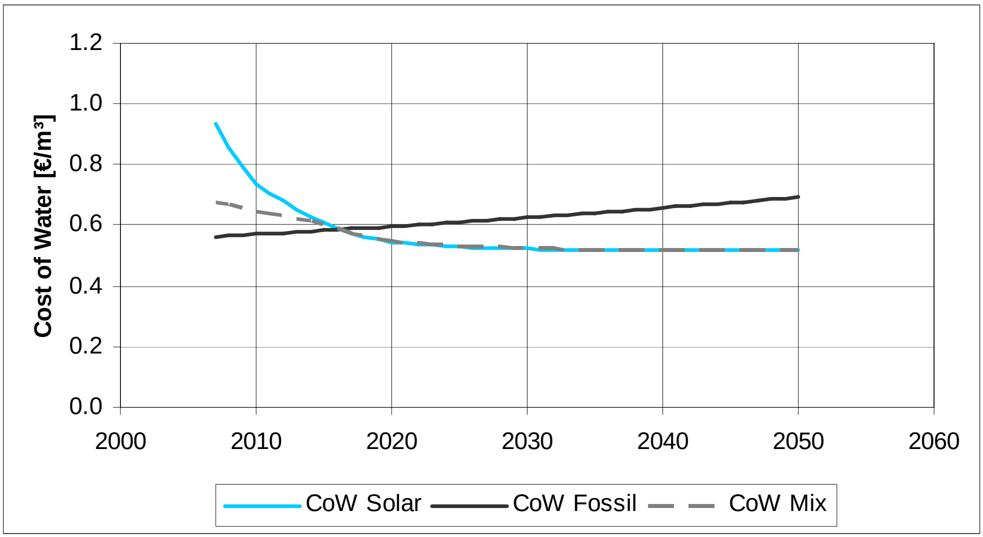


Figure 5-4: Projected cost of water (CoW) from RO using conventionally generated power or solar electricity in the AQUA-CSP reference scenario (RO investment 900 €/m³/d, RO power demand 4.5 kWh/m³, electricity cost and other economic frame parameters as given in Figure 5-3 and Figure 5-5).

The resulting learning curve is shown in Figure 5-4 for CSP/RO, for an interest rate of 5 %/y and 25 years of economic lifetime. The learning curve starts around 0.9 €/m³ today and quickly falls down to 0.55 €/m³ by 2020. In the long-term, a value below 0.5 €/m³ is achieved. At the same time, the cost of conventional seawater desalination rises from initially 0.55 €/m³ today to 0.6 €/m³ in 2020 and up to 0.7 €/m³ in 2050. That means that before 2020, solar desalination will become considerably cheaper than conventional desalination driven by fossil fuel fired power plants, provided that the expansion of CSP takes place as scheduled.

Figure 5-3 and Figure 5-4 show another very important fact: the future cost difference of fossil and solar production of electricity and water leaves a considerable margin for the pricing of both commodities. As CSP plants can produce both power and water, the sales-price for one commodity can be adjusted closer to the – competing – price of fossil generation. This results in a lower cost of the other commodity, that now can be sold at lower price. The cost reduction acquainted by CSP in time can either be fully accounted to both commodities as shown in Figure 5-3 and Figure 5-4, or it can be allocated preferentially to one commodity, while the other one is priced as high as the market allows. As an example, if the revenue achieved for solar electricity in 2020 would be 0.070 €/kWh as for fossil generation instead of 0.057 €/kWh which would be its cost according to Figure 5-3, the water produced by such plants could be sold at 0.26 €/m³ as shown in Table 1.9, Chapter 1, instead of 0.55 €/m³ as shown in Figure 5-4.

The combination of solar power and water would allow to produce water at prices that would be competitive even in the irrigation sector. This is only possible because the primary energy source, solar power, becomes cheaper with time, while its competitors, conventional fuels, become more expensive, thus elevating the achievable market prices for energy and water. The visibility of this unique opportunity may be distorted by existing energy subsidies, and MENA governments must individually analyse their situation very carefully in order to see the real chance of acting behind the curtain of illusion created by subsidised prices for energy and water.

The economic frame parameters used for this calculation can also be varied. As an example, the real interest rate of 5 %/y used here as reference represents the average internal rate of return of the modelled power and desalination projects. It is in the same order of magnitude as a typical average discount rate of a national economy. It is also in the same order of magnitude of what can be expected as project return e.g. investing in the frame of the German Feed-In Law for renewable energies. Therefore, this value may be a useful indicator for the economical feasibility of such projects, but other values are possible. For example, many water utilities in the MENA region do not have a positive return on investment at all, but either zero or even a negative return, which means they are heavily subsidizing water by public funding from taxes and from other sources of income, or by increasing their national debt. Energy sources used for desalination are also often subsidised, and the resulting water prices do not necessarily represent the real market value.

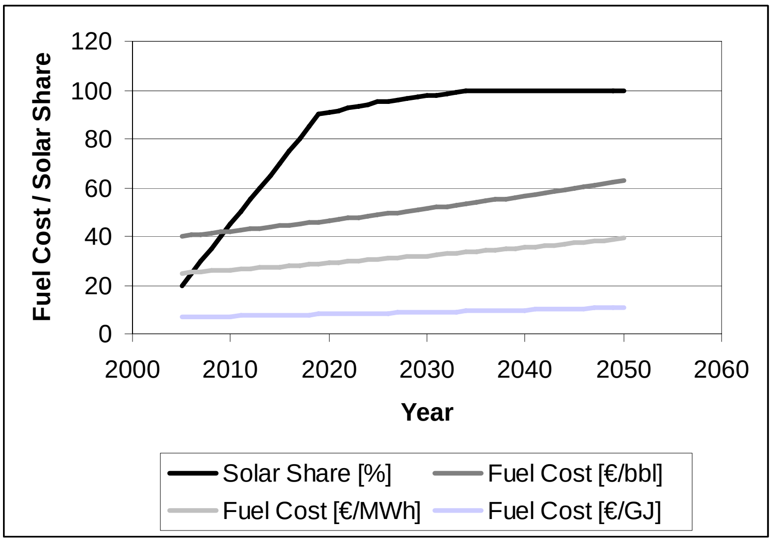


Figure 5-5: Solar share and average lifetime fuel cost of CSP and conventional plants built in the respective year assumed for the AQUA-CSP cost scenario as function of time

In addition to the calculations for CSP/RO we have made a scenario calculation for CSP/MED type plants, fixing the revenues for electricity at 0.05 €/kWh and calculating the resulting cost of water, as shown in Figure 5-6. Furthermore, we have calculated the cost of electricity for a fixed revenue for water of 0.5 €/m³, as shown in Figure 5-7. The plants are operated at full load for 7500 hours per year and have a solar share and fuel cost according to Figure 5-5.

In the case of the CSP/MED plants we have also varied the project interest rate in order to show its potential significance for irrigation and agriculture. After 2020, a cost of desalted water from CSP of less than 0.10 €/m³ is possible if the respective interest rate would be zero. This would be comparable to present prices of water for irrigation, that often lead to negative rates of return. Such a low cost of water can be obtained if governments decide to build and operate such plants without interest rates, custom duties, taxes or other duties that would elevate their cost, only expecting such projects to pay back for investment and operation cost in order to facilitate new investments. Governments would not necessarily have to subsidise the produced water or the construction of those plants, because revenues as low 0.10 €/m³ for water and 0.05 €/kWh for the generated electricity would just suffice to pay back for the cost of construction and operation (but would not yield additional gains – interest rates – in that case).

A possibility of achieving low costs of water for agriculture and at the same time attractive interest rates for investors would be to elevate the sales price of electricity as it would be defined by the generation of electricity from competing fossil fuel fired plants. This will be possible in the medium term future, as electricity prices from fossil fuel fired plants will quickly escalate and create a rather high level of energy costs world wide. Following electricity cost development of conventional gas-fired power plants, the revenue for electricity would slowly escalate from 0.060 €/kWh today to 0.068 €/kWh in 2020 and 0.088 €/kWh in 2050 (Figure 5-8).

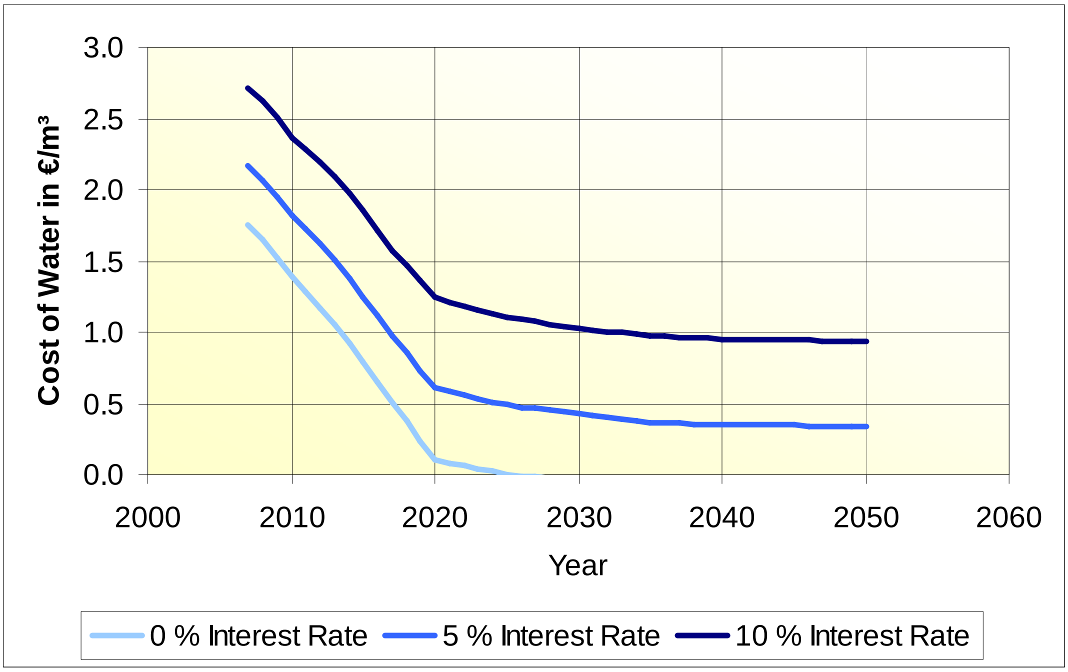


Figure 5-6: Cost of water from CSP/MED plants for different interest rates assuming that electricity produced by the plants will achieve a fixed revenue of 0.05 €/kWh. In the long-term, a cost of water of 0.34 €/m³ and 0.05 €/kWh for electricity can be achieved in the AQUA-CSP reference case with 5 % interest rate (annual real project rate of return).

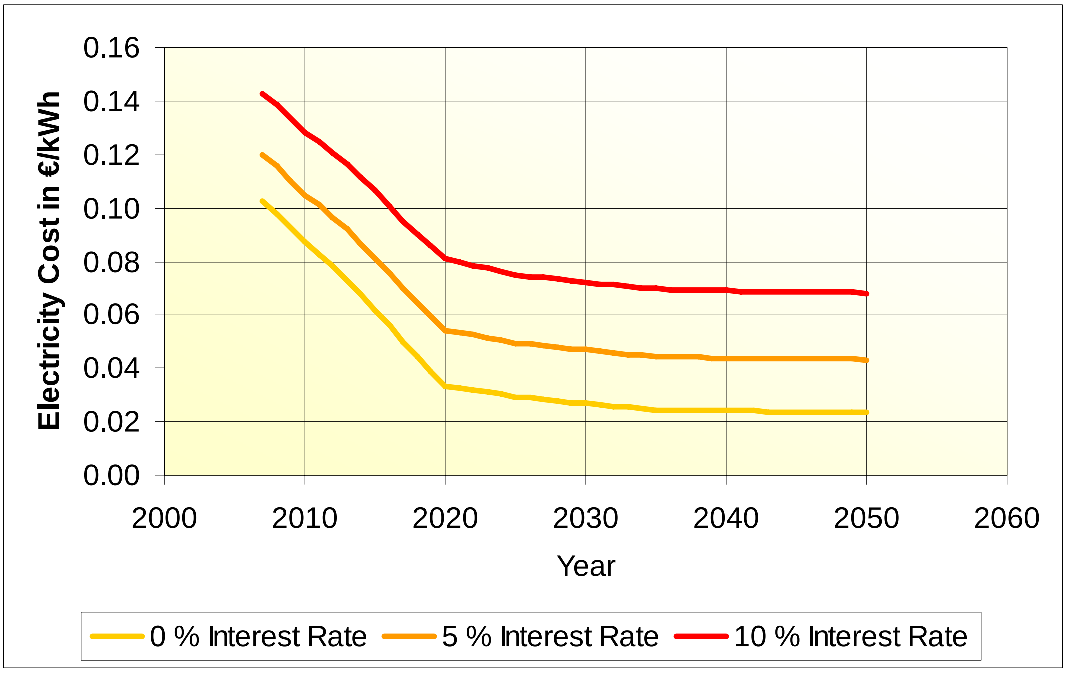


Figure 5-7: Cost of electricity from CSP/MED plants for different interest rates assuming that water produced by the plants will achieve a fixed revenue of 0.5 €/m³. In the long-term, a cost of electricity of 0.04 €/kWh and 0.5 €/m³ of water can be achieved in the AQUA-CSP reference case with 5 % interest rate (annual real project rate of return).

In 2020, this would lead to a higher revenue for power and thus to a much lower cost of water of only 0.28 €/m³ in spite of 5 % rate of return, without having to rely on any subsidies (see also Chapter 1, Table 1-9). This model is rather attractive, as – mostly urban – electricity consumers will be more readily able to pay for the real costs of electricity, thus allowing for a rather low, however unsubsidised cost of water for irrigation in rural areas. Another option for combining water and electricity prices will be the export of solar electricity from MENA to Europe, which may allow for a relatively high revenue for clean solar electricity and at the same time be a very attractive means of inter-regional cooperation /TRANS-CSP 2006/.

On the other hand, if CSP plants would have to compete with subsidised electricity without being subsidised themselves, a situation as shown in Figure 5-9 will occur, with revenues from electricity being too low to achieve an acceptable cost of water for irrigation. However, even assuming revenues for electricity as low as 0.035 €/kWh today growing very slowly to 0.05 €/kWh in 2050, the equivalent cost of water from combined CSP desalination would be in the order of 1.00 €/m³ in 2020 and 0.5 €/m³ in 2050, that would be acceptable even today in the municipal supply sector. In this case, to achieve costs that would be low enough for irrigation, subsidies or reduced interest rates would be required for desalting water with CSP.

Figure 5-10 and Table 5-1 show contemporary prices for water in the MENA countries and compare them to the real cost of extracting water in some selected countries. The data was obtained in the year 2000, so we can assume a considerably higher cost today. For simplicity and lack of better data, we may assume a similar situation for water costs as in those examples in the total MENA region. At least in those countries that are using water beyond the renewable rate, desalination would define the marginal cost of producing water. Looking at the water production cost of some selected countries in the year 2000 in Figure 5-10, and comparing this figure to the cost of CSP in Figure 5-10, it can be seen that water from CSP desalination will in the medium-term become very attractive when compared to other water sources with costs of 0.5-0.75 $/m³ in the municipal sector and 0.10-0.40 $/m³ for irrigation.

Due to increasing water shortage and escalating energy prices, water prices are steadily climbing upwards, and investment into alternatives must start right now. However, Figure 5-10 shows that cost and pricing of water in MENA is rather unbalanced. Pricing of power and water in MENA is and will remain a political issue, and will probably remain relying on subsidies for some time. In any case, our analysis shows clearly that trying to solve the water scarcity problem with conventional desalination based on fossil fuels would lead to a subsequently higher cost of water that will be unaffordable in the short and medium term, while a timely investment into CSP will certainly lead to steadily falling, attractive costs of generating electricity and desalted water. Compared to today's situation, it may even become possible to achieve a long-term reduction and elimination of subsidies in both the energy and water sector, a target that will certainly be impossible to achieve relying further on fossil fuels.

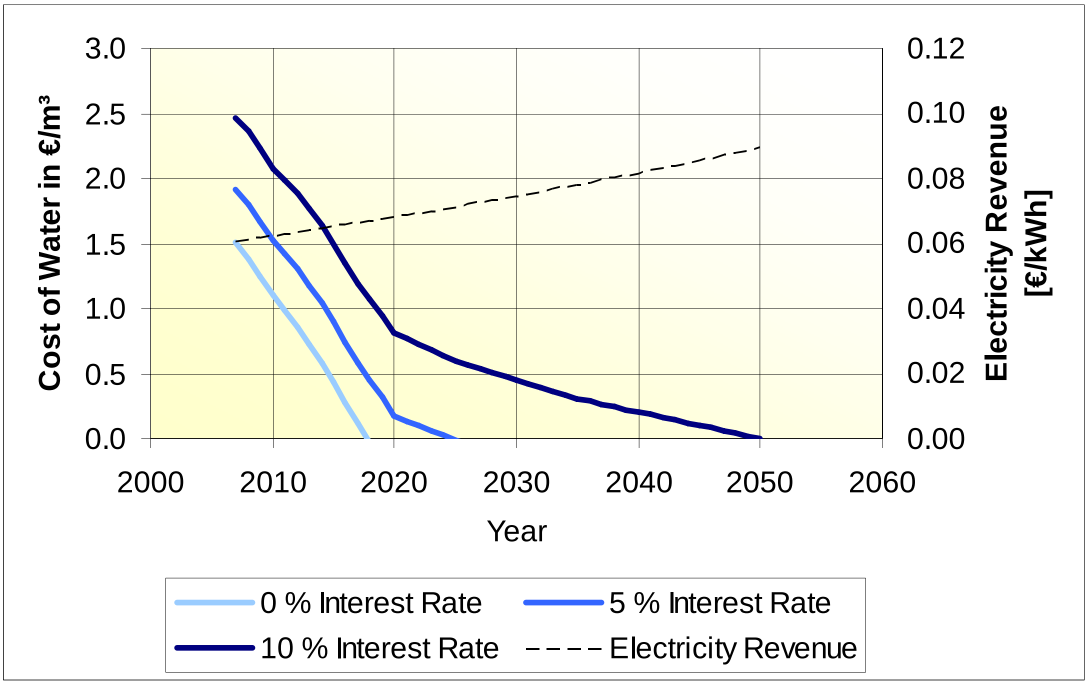


Figure 5-8: Cost of water from CSP/MED plants for different interest rates assuming that electricity produced by the plants will achieve a revenue equivalent to the unsubsidised cost of gas power stations. Please note that with 0 %/y interest rate (but covering construction and operation cost) and a revenue for water of 0.067 €/kWh, before 2020 water could already be produced as bye-product without cost.

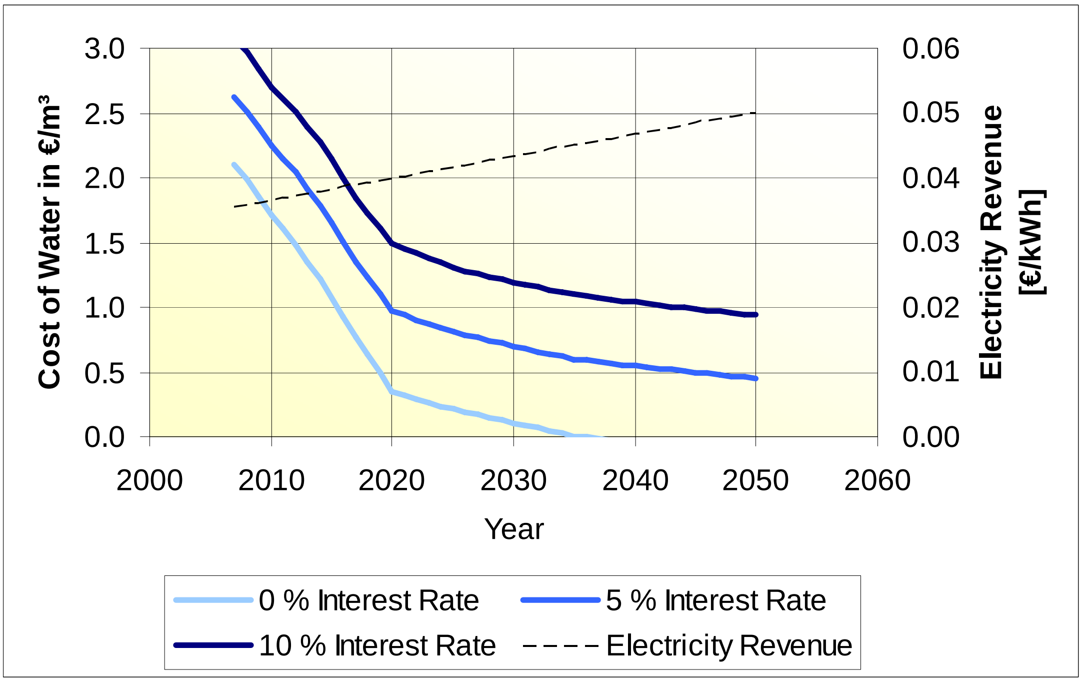
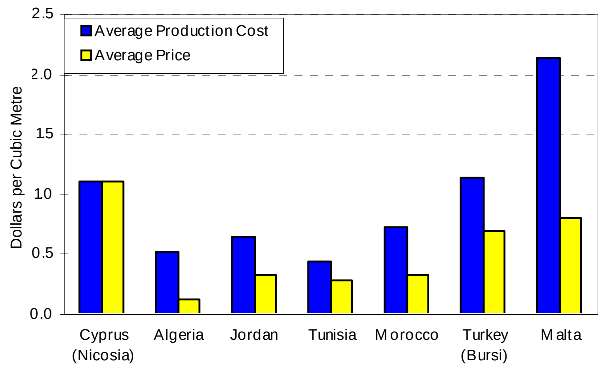


Figure 5-9: Cost of water from CSP/MED plants for different interest rates assuming that electricity produced by the plants will achieve only low revenues competing with subsidised electricity prices.



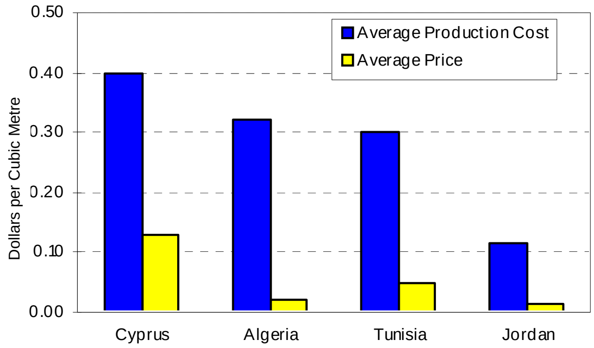


Figure 5-10: Water pricing in US$ per cubic metre versus real costs in the municipal (left) and irrigation sector (right) in selected MENA countries /Saghir 2000/

Country / City	Sector	Water Tariff in \$/m³	Year	Source	Comment
Saudi Arabia	Average	0.03	2003	IEA 2005	
Saudi Arabia	Range	0.025 – 1.6	2003	GWI 2004	
Kuwait	Average	0.65	2003	IEA 2005	
Qatar	Average	0.43	2003	GWI 2004	
Qatar	Average	1.20	2003	IEA 2005	
Egypt	Average	0.03 – 0.05	2000	Saghir 2000	
Egypt	Average	0.25 – 0.35	2003	GWI 2004	
Israel	Municipal	0.25 – 1.1	2003	GWI 2004	+0.45\$/m³ sub.
Israel	Irrigation	0.14 – 0.25	2003	GWI 2004	
Jordan	Municipal	0.42 +	2003	GWI 2004	
Jordan	Irrigation	0.11 – 0.5	2003	GWI 2004	
Amman	Municipal	0.62	2000	Saghir 2000	
Libya	Municipal	0.15 +	2003	GWI 2004	
Oman	Average	1.17	2003	GWI 2004	
Palestine	Range	0.87 – 1.45	2003	GWI 2004	
Ramallah	Municipal	1.10	2000	Saghir 2000	
Khan Younis, Gaza	Irrigation	0.46	2000	Saghir 2000	
Gaza City	Municipal	0.29	2000	Saghir 2000	
Kuwait	Average	0.65	2003	GWI 2004	
Sana’a, Yemen	Municipal	0.28	2000	Saghir 2000	
Tunisia	Irrigation	0.022-0.077	2000	Bahri 2001	
Tunisia	Re-use	0.015	2000	Bahri 2001	
Tunisia	Average	0.22	2000	Saghir 2000	
Morocco	Municipal	0.20 – 0.55	2000	Saghir 2000	
Lebanon	Average	0.32	2000	Saghir 2000	
Algiers	Municipal	0.18	2000	Saghir 2000	
Syria	Average	0.08	2000	Saghir 2000	
United States	Average	1.30	2003	IEA 2005	
Germany	Average	2.00	2006	Lexikon.Wasser.de	
France	Average	3.15	2003	IEA 2005	

Table 5-1: Average water tariffs in selected countries in MENA from different sources. Please note the substantially higher water tariffs in water-rich countries like Germany and France (bottom). Exchange rate €/\$ = 1.

In the MENA region there is a – slightly reluctant – trend to achieve a better **accountability** for energy and water and to reduce subsidies in both sectors. In terms of sustainability it is very important that prices reflect the real cost of any product, including externalities like environmental or socio-economic damages that may be caused by the use of those commodities. If prices and costs are unbalanced, there will be on one hand a careless, inefficient use, and on the other hand there will be no money available on the provider's side to invest in efficiency of supply and distribution. This leads to a vicious circle of increasing losses and at the same time increasing societal costs and subsidies. Because of subsidies, these costs will not be paid by consumers, but by all tax payers and eventually by the whole society, in form of deceases, conflicts and economic constraints.

Therefore, a better accountability for water and energy is of high priority in the MENA region to increase the quality of water management and supply /World Bank 2007/. However, a change to more realistic prices of water and energy must occur gently and socially compatible, and it will take time.

The question is, how should a reduction of subsidies and a more realistic tariff system be achieved in view of energy prices that have been multiplying within a time-span of only a few years? In the year 2000, crude oil was still at 20 $/barrel, but its price jumped to 60 $/barrel in 2006, which is three times higher. Natural gas was around 2 $/GJ in 2000 and at 6 $/GJ in 2006, also three times higher. Coal prices doubled in the same time-span, starting with 30 $/ton in 2000 and ending up with an average cost of 60 $/ton in 2006. Since 2000 the price of uranium has even become fourfold /oilnergy 2007/, /Thomson 2006/, /Cameco 2006/.

Even if energy costs would escalate much slower in the future as assumed conservatively in the AQUA-CSP reference scenario – at only 1 %/y – the economic performance of CSP will be much better than that of conventional power generation and seawater desalination, as has been shown before in this chapter.

Triple costs within 6 years is equivalent to a **cost escalation** rate of 20 %/y. Such an escalation of water and electricity prices would not be acceptable for most energy and water consumers in MENA, because their per capita income is growing much slower. Thus, any possibility for reducing energy or water subsidies is eliminated by rising energy costs. In reality, the subsidised gap between costs and prices is even becoming larger.

Money for investments that would be necessary to change the situation will increasingly be consumed by exploding running-costs, with no way out of that dilemma, except the change to a source of energy and water that instead of escalating in cost becomes cheaper with time and use. This source is already there and available, and it must now be activated: solar energy from concentrating solar power, using the desert sun for energy and seawater for desalination. In terms of technology, the necessary production capacities must be build in order to satisfy a significant share of demand as shown in Chapter 4, and in terms of economy, the production capacities must become large enough to achieve the necessary economies of scale and mass production to reduce production costs to really low levels as shown within this chapter. This still remains a challenge, as it will require significant investment, political will, international cooperation and clever and efficient implementation, but is the only way out of the dilemma of energy and water scarcity.

Subsidies for power and water should slowly be reduced. As long as CSP plants will have to compete with subsidised fuel, electricity or water, they should obtain an equivalent subsidy in order to be able to be introduced to the market. In the short term, they will require less subsidies than conventional production, and in the long-term, subsidies for power and water may even be reduced to zero.

To achieve this goal, there is absolutely no alternative in sight. We therefore strongly recommend an immediate start of investment in CSP technology for power and seawater desalination in MENA, without any delay. The resource is waiting to be tapped, the technology is ready for the market, and MENA has now the chance to make the best use of this option. Any waiting will increase the problem – in the worst case causing irreversible damage – and subsequently deprive the MENA governments from the economical means to react properly to this critical situation. Even in the case of strong efforts and decided action, the achievement of considerable, visible shares of sustainable water from CSP will at least take 10-15 years.

Each country in MENA can develop its individual strategy for market introduction according to the technical and economic frame conditions available. Some countries have sites with a solar irradiance well over 2800 kWh/m²/y and very steady conditions all around the year, and of course, due to that climatic situation, those are the countries with the sharpest water scarcity. Governments can decide ether to subsidise electricity or water or just provide investment at low interest rates, taxes and custom duties for CSP projects. **Niche markets** like feed-in tariffs for solar electricity as in Spain or Germany or auto-generation of power and water for hotel resorts as in the Aqaba case described in Chapter 1.2.3 should be strongly supported and implemented by the MENA governments, because those are the most efficient forms of market introduction.

Last but not least, we should mention the phenomenon of **marginal costs**. The marginal cost is the cost of producing a commodity without considering the investment and capital cost for building new plants. In case of any conventional power or desalination plant, this cost includes the cost of operation and maintenance and a large amount of fuel. In case of a solar plant, only operation and maintenance must be considered, as solar energy is used as “fuel”. That means that after having paid back for the initial investment of such plants, power and water from CSP plants will see a cost reduction of 90 % with respect to their initial cost, while power and water from conventional plants relying on fossil fuel will only see a cost reduction of about 10-20 %, if any. Operators of CSP plants will be awarded in case of careful maintenance of their system that will lead to a longer economic lifetime, while conventional plant operators will be punished by escalating fuel prices, no matter if they carefully maintain their system or not.

5.2 Exploitation of Fossil Groundwater

Exploitation of groundwater is taking place world wide and is one of the most important sources of freshwater. However, in the arid regions of the world, groundwater is only renewed to a marginal extent. In the MENA region, there are very large bodies of groundwater that are made up of fossil water, that means water that was deposited there tens of thousands of years ago, when there still was significant rainfall in the region. As an example, the Nubian Sandstone Aquifer System (NSAS) is one of the largest freshwater deposits of the world, but is hardly renewed and thus considered mostly fossil water. The extraction of that water must be considered as mining of a fossil resource, just like oil, coal or natural gas.

COUNTRY	AQUIFER SYSTEM	EXTENSION (km^2)	ACCESSIBLE RESERVES (Mm^3)	CURRENT EXTRACTION (Mm^3/y)	STATIC DURATION (y)
Egypt, Libya	Nubian Sandstone	2,200,000	10,220,000	4,500	2271
Algeria, Libya, Tunisia	North Western Sahara	1,000,000	1,280,000	2,560	500
Saudi Arabia, Bahrain, Qatar, UAE	Various	250,000	2,185,000	18,200	120
Jordan	Qa Disi Aquifer	3,000	6,250	170	37

Table 5-2: Main aquifer systems containing fossil water in the MENA region. Accessible reserves are compared to the present extraction rate, yielding as indicator the "static duration" of the resource under theoretical constant rates of withdrawal. /UNESCO 2006/

COUNTRY	AQUIFER SYSTEM	Extraction 2050 BAU (Mm^3)	Extraction as Percentage of Reserve	Extraction AQUA-CSP (Mm^3)	Extraction as Percentage of Reserve
Egypt, Libya	Nubian Sandstone	2,500,000	24.5%	675,000	6.6%
Algeria, Libya, Tunisia	North Western Sahara	350,000	27.3%	87,000	6.8%
Saudi Arabia, Bahrain, Qatar, UAE	Various	2,800,000	128.1%	860,000	39.4%
Jordan	Qa Disi Aquifer	31,000	496.0%	3,200	51.2%

Table 5-3: Main aquifer systems in the MENA region. Accessible reserves are compared to the cumulated future extraction scheduled in the Business As Usual (BAU) Scenario (Chapter 4) and the AQUA-CSP Reference Scenario until 2050.

The **Nubian Sandstone Aquifer System** in Egypt, Libya, Chad and Sudan has a thickness of up to 3500 m, an extension of 2.2 million km² (Figure 5-11), and a total stored water volume of

373,000 Bm³ of which 14,500 Bm³ are considered to be accessible[1] /UNESCO 2006/. The accessible share in Egypt and Libya is reported to be 10,220 Bm³. Present extraction is reported to be from around 2.2 Bm³/y /UNESCO 2006/ to 4.5 Bm³/y /AQUASTAT 2005/, which is equivalent to an extraction rate of only 0.02-0.05 % per year. Theoretically, the accessible reserve would still last about 2270 years if used at current rates of extraction. Until the year 2000 about 40 Bm³ had been extracted from the aquifer, which is less than 0.4 % of the total. Nevertheless, by that time the groundwater level had already fallen by 60 meters since 1960, with 97 % of the existing natural shallow wells in the region falling dry /UNESCO 2006/.

If the extraction would come to 24.5 % of the accessible reserve as scheduled in the business as usual scenario for Egypt and Libya developed in Chapter 4 (Table 5-3), freshwater would probably have to be pumped from a depth of around 1000 meters. This however would require about 4-6 kWh/m³ of electricity which would be more than required by equivalent seawater desalination.

Even in the case of the AQUA-CSP reference scenario, 6.6 % of the accessible reserve of the aquifer equivalent to 675 Bm³ would be used until 2050 (Table 5-3). This would still have serious consequences for the groundwater level, but not nearly as sharp as for the business as usual case.

The **North Western Sahara Aquifer** will suffer similar consequences if following a business-as-usual strategy (Table 5-3 and Figure 5-12). Libya has already initiated a significant withdrawal of fossil groundwater with the Great Man-Made River Project. According to /UNESCO 2006/, current extraction from the aquifer amounts to about 2.6 Bm³/y, which theoretically would allow a continuous extraction for about 500 years. However, taking into consideration growth of demand and following a business-as-usual scenario, about 27 % of the reserve would have been withdrawn by 2050, while the AQUA-CSP reference scenario leads to an extraction of only 6.8 % by that time.

The **Aquifers on the Arabian Peninsula** are facing an even more serious situation: at present rate of withdrawal, the theoretical duration of the aquifers would only be 120 years (Table 5-2 and Figure 5-13), with some sources even predicting a total depletion within a time span of only 35 years /EoEarth 2007/. Even in the case of the AQUA-CSP reference scenario, 40 % of the reserves would be extracted until 2050. This will have dramatic consequences for the groundwater level and for the environment, probably affecting most existing wells and oasis in the region. There may also be a serious intrusion of salt water into the coastal groundwater reserves, in the worst case making them useless. The good news is that there is a source of freshwater available as a bridge from current unsustainable supply to a future sustainable water production based on solar energy. However, it is unclear if this source of groundwater is

1 In the original literature, the terms “exploitable” or “recoverable” are used instead of „accessible“. However, those terms are misleading as they suggest that the reserves are renewable, which is not the case.

sufficiently large and stable in order to last long enough to achieve sustainability without major negative consequences for the natural environment and for the society of the Arabian Peninsula. The countries of the Arabian Peninsula would therefore be wise to immediately initiate a transition to a sustainable supply based on CSP seawater desalination, re-use of waste water, water management, efficient distribution and efficient use of water in all sectors of demand.

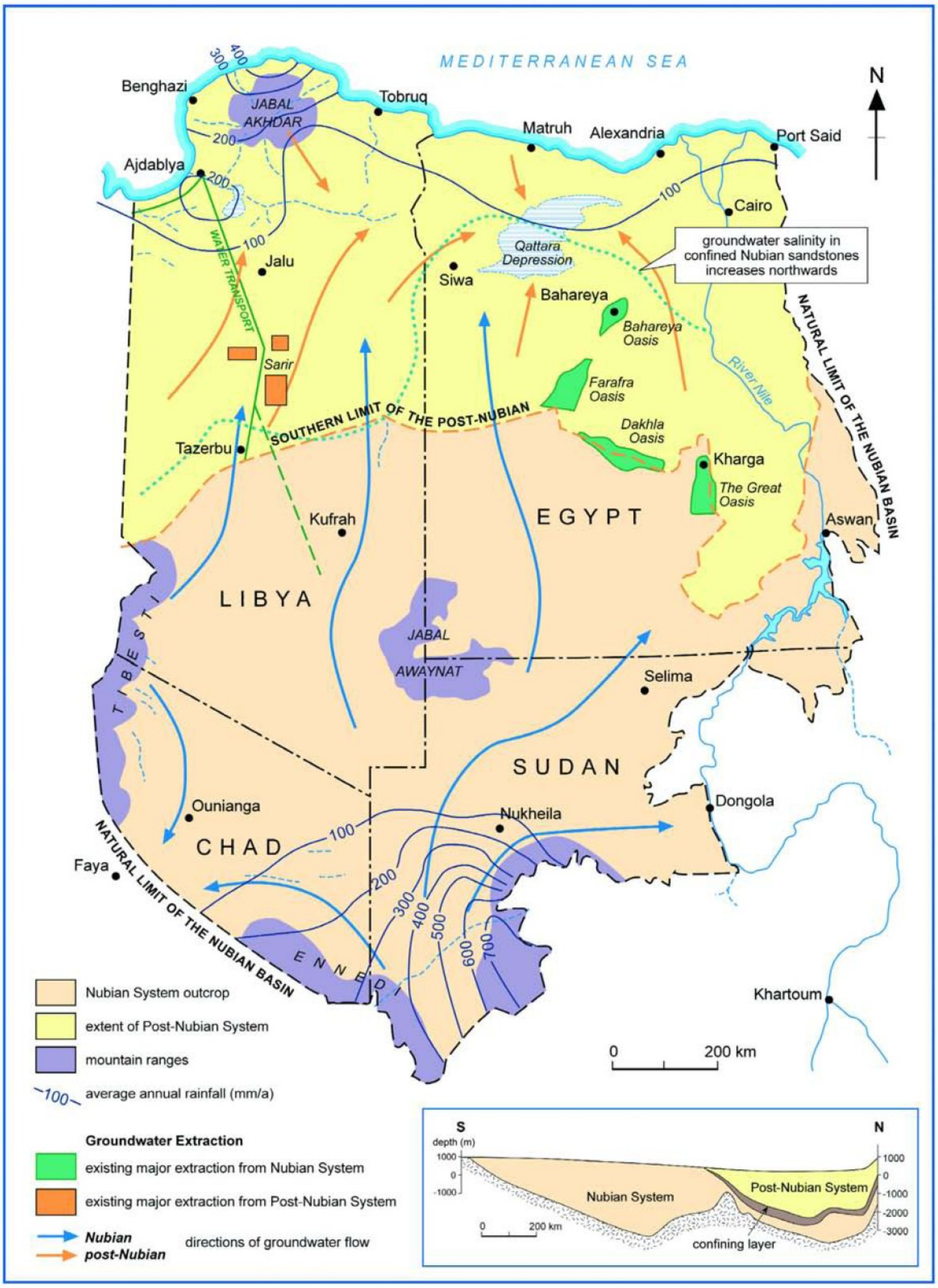


Figure 5-11: Extension of the Nubian Sandstone Aquifer System /UNESCO 2006/

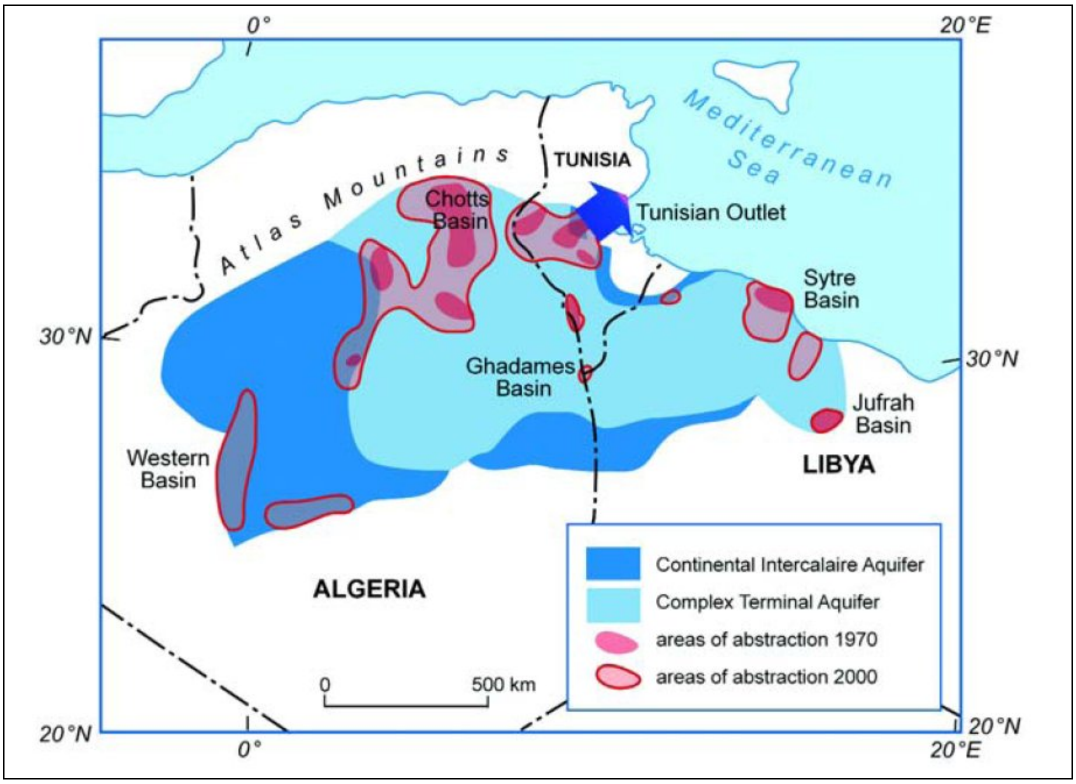


Figure 5-12: North-Western Sahara Aquifer System /UNESCO 2006/

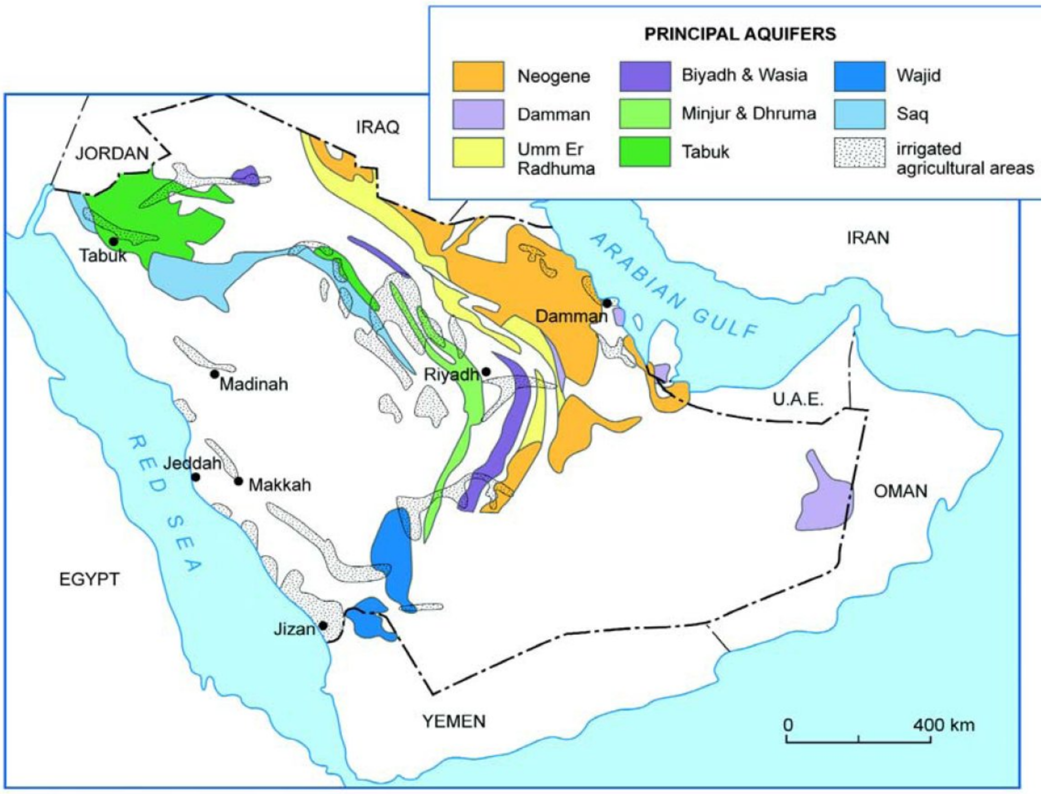


Figure 5-13: Saudi Arabian Aquifer Systems /UNESCO 2006/

The **Sustainable Groundwater Potential**, as used in /IWRM 2007/, refers to the total rates that can be abstracted on a sustainable base; for future uses the term reserves is utilized. Sustainability, on the other hand, can be given several definitions. However, in all cases, the quality of the resource base should be maintained suitable to the originally allocated sector (i.e. no deterioration) and the environment enhanced. Three distinct examples are given below.

- In the case of ***renewable groundwater from external sources*** (e.g. coastal aquifers and shallow wadi aquifers), the permissible development should be equal to the rate of recharge. This may not imply that the time span be restricted to a season or a year.
- In the case of ***renewable groundwater from internal sources*** (e.g. the Nile alluvium), the permissible development should be equal to the recharge without affecting flow in surface water channels and the river. Again, this does not imply specific time spans.
- In the case of ***non-renewable groundwater*** (e.g. the Nubian sandstone, Moghra), the permissible development is made to satisfy the economy of developmental activities and to ensure that groundwater will serve several generations (up to e.g. 500 years).

Based on the previous criteria, the Egyptian groundwater potential, uses and reserves have been assessed, as summarized in Table 5-4. The total sustainable potential is reported to be in the order of 12.5 Bm^3/y, of which 7 Bm^3/y were already used in the year 2000. With respect to that year, groundwater resources in Egypt offer an additional sustainable potential of only 5.5 Bm^3/y. In our reference scenario, the sustainable groundwater potential is already fully exploited by 2010. In the business-as-usual case, exploitation would exceed in the long-term 50 Bm^3/y. In the AQUA-CSP reference scenario, exploitation reaches a maximum of 17.5 Bm^3/y by 2020 and is later reduced to zero. This means that in Egypt – like in most MENA countries – the threshold of sustainable groundwater exploitation is likely to be overshot significantly in the coming decades, even in the case of the AQUA-CSP reference scenario, but worse in a business-as-usual case. Figure 3-11 in Chapter 3 shows the most critical groundwater withdrawals as percentage of save yield for the countries in MENA (see Annex for scenario data for all MENA countries).

Region	**Potential (million m^3/year)**	**Usage in 2000 (million m^3/year)**	**Reserves (million m^3/year)**
Delta	5,220	4,195	1,025
Valley	3,170	1,932	1,238
Western Desert	3,748	817	2,931
Eastern Desert	90	8	82
Sinai	210	89	121
North-West Coast	80	2	78
Total Egypt	**12,518**	**7,043**	**5,475**

Table 5-4: Sustainable Groundwater Potentials in Egypt /IWRM 2007/

5.3 Performance of Water Utilities and Irrigation

Table 5-5 shows current indicators of the water sector in the analysed countries in MENA:

Water Scarcity is the ratio of total water use to water availability. Water scarcity will generally range between zero and hundred percent, but can in exceptional cases (e.g. groundwater mining) be above a hundred percent.

Water Dependency Ratio measures the share of total renewable water resources originating from outside the country. It is the ratio of the amount of water flowing in from neighbouring countries to the sum of total internal renewable water resources plus the amount of water flowing in from neighbouring countries expressed as percentage.

Access to Save Water gives the percentage of the total population of a country with reasonable access to an adequate amount of water from an improved source such as household connection, public standpipe, borehole, protected well or spring or rainwater collection.

Public Utility Performance is water sold as percentage of water supplied by utilities. The difference is caused by leaks or uncontrolled withdrawal from the distribution systems.

Agricultural Water Requirement Ratio is the ratio of the irrigation water requirement to the total agricultural water withdrawals of a country. It measures the efficiency of irrigation.

Country	Water Scarcity (%)	Dependency Ratio (%)	Access to Save Water (%)	Public Utility Performance (%)	Agricultural Water Requirement Ratio (%)
North Africa					
Algeria	40	3	76	49	37
Morocco	42	0	80	75	37
Egypt	106	97	72	50	53
Tunisia	57	9	87	82	54
Libya	720	0	68	(70)	60
Western Asia					
Lebanon	34	1	99	60	40
Jordan	115	23	95	55	38
Palestine	--	18	45	47	(20)
Syria	75	80	69	55	45
Iran	53	7	92	68	32
Iraq	55	53	--	(40)	32
Israel	110	55	100	(69)	(60)
Arabian Peninsula					
Bahrain	236	97	100	77	(60)
Yemen	157	0	30	36	40
UAE	1488	0	100	70	(60)
Oman	132	0	92	65	(50)
Qatar	538	4	100	65	(60)
Saudi Arabia	714	0	82	72	43
Kuwait	2070	100	100	62	(60)
Goal	**--**	**--**	**100**	**85**	**70**

Table 5-5: Water indicators for the analysed MENA countries: ( ) own estimate, -- no data. Sources: /FAO 2003/, /AQUASTAT 2007/, /World Bank 2007/, /Blue Plan 2005/.

A study by the Center for Environment and Development for the Arab Region and Europe (CEDARE) has thoroughly analysed the potential water savings until the year 2025 for most of the countries analysed in AQUA-CSP except for Iran, Israel and Palestine (Table 5-6). The results show an astounding conformity with the results of the AQUA-CSP model scenario for the year 2025, although both results were obtained by very different approaches (compare Chapter 3 with /Abu-Zeid et al. 2004/.

Country	Potential Total Irrigation Savings M m3/year	Potential Total Domestic Savings M m3/year	Potential Total Indust./Com. Savings M m3/year	Potential Treated Wastewater For Reuse M m3/year	Total Potential Water Savings M m3/year
ALGERIA	422	567	13.2	1785	2,787
BAHRAIN	20	44	0.2	80	144
EGYPT	6,733	1510	78.3	7298	15,620
IRAQ	7,139	743	48.5	4332	12,263
JORDAN	179	167	0.9	292	638
KUWAIT	49	96	0.2	126	271
LEBANON	111	146	0.8	299	557
LIBYA	975	391	2.8	751	2119
MOROCCO	1,358	246	5.5	744	2,353
OMAN	296	51	0.8	109	457
QATAR	32	31	0.2	39	102
SAUDI ARABIA	3,189	1014	4.4	1803	6,010
SYRIA	2,201	302	5.9	507	3,016
TUNISIA	387	129	1.7	298	815
U.A.E.	179	203	3.0	431	816
YEMEN	582	148	0.8	286	1017
Total	**23852**	**5787**	**167**	**19180**	**48985**
AQUA-CSP	**22902**	**4389**	**3144**	**18467**	**48902**

Table 5-6: Potential for water savings in the MENA countries except Iran, Israel and Palestine until 2025 from /Abu-Zeid et al. 2004/ and savings resulting from the AQUA-CSP Reference Scenario compared to the Business-As-Usual Scenario as described in Chapter 3. The difference in "Industrial Savings" is probably due to a different aggregation of measures (municipal distribution is included in both "domestic" and "industrial" in case of AQUA-CSP, while in /Abu-Zeid et al. 2004/ it is allocated to the domestic sector.

Irrigation efficiency can be increased by adopting proper irrigation scheduling, precision land levelling, use of modern on-farm irrigation systems (sprinkler & drip irrigation), cleaning and maintaining furrows, canal lining, use of dikes to prevent undesirable surface drainage, improved crop management and use of low water consumption crop varieties /FAO 2002/.

Domestic/Municipal water efficiency can be increased by reducing leakages from the municipal distribution grid in- and outside buildings, by improving the maintenance of supply networks, by introducing reliable metering devices to increase accountability, by introducing water saving devices like low flow shower heads, washing machines, dish-washers and low-volume toilets, and by landscape water conservation like planting plants native to the region, rainwater harvesting from rooftops in cisterns and gray-water reuse for the irrigation of parks and other public areas. Delivering water for urban uses and expanding delivery networks to surrounding sub-urban and rural neighbourhoods can benefit greatly from improved regional delivery technologies /Sandia 2005/.

Industrial and commercial water efficiency can be improved by avoiding leakages in the industrial distribution systems for water and steam, self closing faucets, low flow toilets, and a multitude of potential water savings within the specific production processes, including the multiple use of water for different cascaded processes and the recycling of waste water. Infrastructure improvements include the addition of grey water plumbing to facilitate reuse on a grand scale within individual buildings and process chains /Sandia 2005/, /Tropp 2006/.

Reuse of wastewater is a possibility of water saving common to all water sectors. Sewage treatment facilities in MENA tend to lag behind water provision. There are human health risks of discharges of untreated sewage to surface and groundwater. There is also a threat of discharges of untreated sewage to the oceans, seas and on marine ecosystems and wetlands. Wastewater treatment provides opportunities to increase the use of waste water in agriculture. The percentage of population served with water supply and sanitation varies from one country to another. As more water supply and sanitation coverage is provided, the potential for reuse of treated wastewater increases. It has to be noted that domestic wastewater can reach up to 80 % of domestic use if efficiently collected and if countries are fully equipped with sewage treatment facilities /Sandia 2005/, /Tropp 2006/.

Unaccounted for Water (UFW) is a major loss term in municipal water distribution systems. UFW is the difference between the amount of water sold and the amount of water supplied, expressed as a percentage of the amount of water supplied. Well managed systems achieve values of 10-15 percent. In developing nations UFW values can range from 39 to 52 percent /Sandia 2005/. UFW is a function of leakage from old transmission systems, poor metering and/or poor management. Reducing UFW in developing nations generally calls for modernization of pumping and distribution systems – which could be considered more of a governance and economic problem than a technical problem /World Bank 2007/. New technologies designed to monitor and detect system weaknesses (breaks, leakages) could help eliminate some water loss. These monitoring technologies would be linked to distribution management centres located at key nodes around the distribution system, and could allow for the quick identification and repair of system weaknesses. Improvements to all these technologies would lead to greater volumes of conserved municipal water, but in these cases the real bottleneck is not at the technological level but at the policy level. Development of various kinds of fiscal incentives to drive the conversion to low-volume appliances, water harvesting and reuse are likely to have much larger impacts on water conservation than will marginal improvements to domestic water conservation technologies. Reducing water subsidies to farmers and factories would create further economic incentives to adopt water-efficient agricultural practices. In turn, public education and marketing campaigns to sway the public's perception on the necessity of such measures will also be necessary. The political will necessary to enact such changes has proven to be the most formidable barrier in their implementation /Sandia 2006/, /World Bank 2007/.

Investment for achieving water savings is estimated to be around 2.6 €/m³ for irrigation, 4.9 €/m³ for domestic use, 2.8 €/m³ for industrial and commercial use and 1.75 €/m³ for recycled and treated wastewater reuse /Abu-Zeid et al. 2004/. Using a capital recovery factor of 7.1 %/y (5 %/y discount rate, 25 years life), this translates to a cost per cubic metre of saved water of 0.19 €/m³ for irrigation, 0.35 €/m³ for domestic water, 0.20 €/m³ for industrial water and 0.12 €/m³ for wastewater reuse. These figures compare favourably with a desalination cost of around 0.50-0.70 €/m³ and even with the cost of overexploiting groundwater, as will be shown in Chapter 5.4, and demonstrate the natural priority of efficiency measures in the water sector.

However, comparing the saving potentials to the growing gap opening between sustainable natural sources and freshwater demand as shown in Chapters 3 and 4, it becomes clear that increasing efficiency alone will not solve the problem. New sources of freshwater must be found, and they must be secure, sustainable and affordable for municipal use as well as for agriculture.

5.4 The Cost of Doing Nothing

The arid basin of Sana'a possesses a Quaternary alluvial aquifer locally overlying a deeper Cretaceous Sandstone aquifer for which there is no evidence of significant recharge and which presently contains mainly fossil groundwater (Figure 5-14). In the absence of regulation some 13,000 water wells have been constructed for urban and rural water supply and to irrigate some 23,000 ha. These wells extract groundwater in part from the deep aquifer. As a consequence groundwater levels are falling by 3-5 metres per year as a result of the imbalance between groundwater extraction and recharge /UNESCO 2006/.

Options for resolving the imminent Sana'a water crisis have been investigated by members of the Trans-Mediterranean Renewable Energy Cooperation (refer to the Annex). According to a preliminary analysis, lasting solutions can be achieved by seawater desalination at the Red Sea coast using solar energy from concentrating solar power. There are 2 fundamentally different solutions for Sana'a:

- Seawater is desalinated and pumped to Sana'a using CSP plants located near Al-Hudaydah at the Red Sea coast ("Saving Sana'a" solution)
- The large majority of Sana'a population is relocated to coastal regions like Al-Hudaydah and others ("Sana'a Relocation" solution)

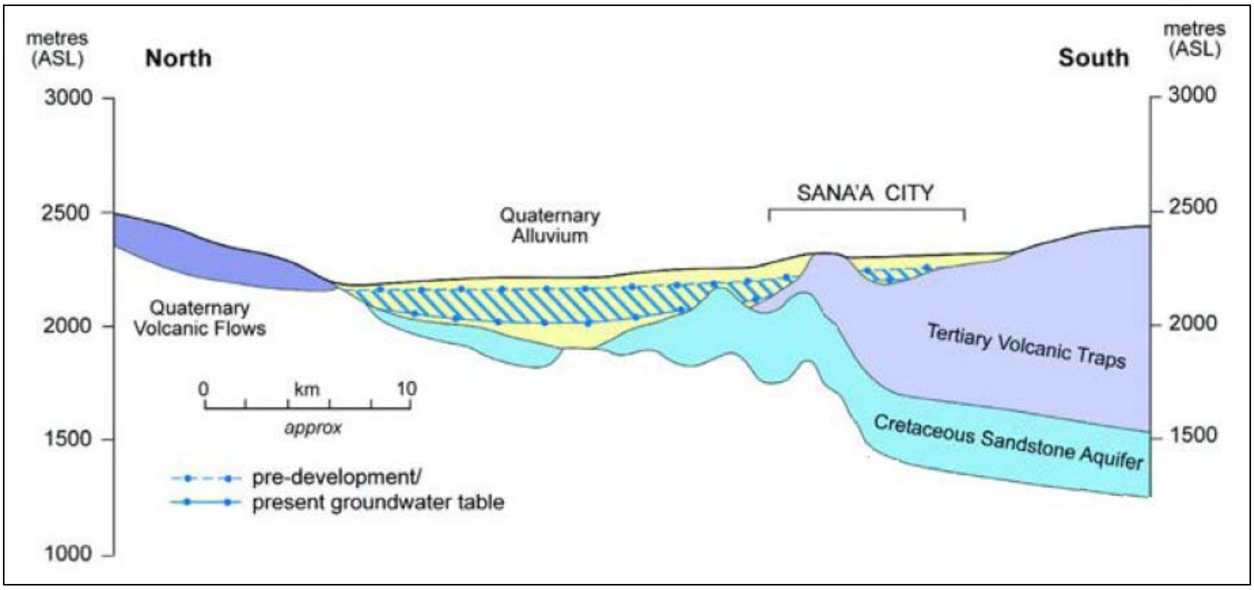


Figure 5-14: Sana'a Basin Aquifer System /UNESCO 2006/

In both cases, desalination plants with a cost of 4 Billion US$ would have to be installed at the sea shore to supply additional water for 2 million people. Building new settlements for 2 Million relocated people will cost over 35 Billion US$, while the costs for a pipeline and a concentrating solar power plant for desalting and pumping 1 Billion m³ water per year to Sana'a will require about 6 Billion US$ /TREC 2006/. The amount needed for "Saving Sana'a" is equivalent to the world market value of 2 % of the proven Yemeni oil reserves. Operating costs will be around 1US$/m³. Construction of the pipeline can be well controlled, while relocation of 2 Million people can lead to conflicts and surprises and can induce uncontrollable developments including armed hostilities (see the following box from /World Bank 2007/). Socially, logistically, financially, politically and internationally a continuation of Sana'a by supplying freshwater through a pipeline from the Red Sea is preferable to relocating its population. In spite of that, the Yemeni government has not reacted up to now to that proposal.

The UNESCO World Heritage of the old city of Sana'a may be a rather spectacular case of water crisis in the Middle East and North Africa, but unfortunately it is no exception. Many cities in MENA suffer from water shortage and there is an increasing competition of rural and urban areas for water, as will be discussed later in Chapter 5.5. Water scarcity is becoming a major barrier for economic development.

Table 5-7 (left) shows an estimate of the impact of groundwater depletion originating from **overuse of groundwater** on the gross domestic product (GDP) of several MENA countries /World Bank 2007/. If these numbers are used to calculate the cost of those excessive water withdrawals (Table 5-7, right), the resulting cost of water including the cost of production and the loss of GDP ranges between 0.58 $/m³ and 1.86 $/m³, which is already today higher than the cost of seawater desalination, and much higher than the cost of efficiency measures.

Water and Land Disputes Leave Many Dead, According to the Yemeni Press

"Six people were fatally shot and seven injured in tribal clashes in Hajja which broke out two weeks ago and continued till Tuesday between the tribes of al Hamareen and Bani Dawood. Security stopped the fighting and a cease fire settlement for a year was forged by key shaykhs and politicians. The fighting was triggered by controversy over agricultural lands and water of which both sides claim possession. Meanwhile...there is speculation of retribution attacks on government forces which used heavy artillery and tanks to shell several villages in al-Jawf..." (*Al Thawra* 1999).

"Sixteen people have been killed and tens injured since the outbreak of armed clashes between the villagers of Qurada and state troops, who used heavy artillery and rockets to shell the village. Scores of villagers were arrested and hundreds fled their homes. The incident began when Qurada refused to share well water with neighboring villagers" (*Al Shoura* 1999).

	Cost of Groundwater Depletion % GDP	GDP 2005 B$/y	GDP Lost M$/y	Overuse Bm³/y	Cost of Groundwater Depletion $/m³	Cost of Production $/m³	Total Cost $/m³
Algeria	1.2	90	1080	0.7	1.54	0.32	1.86
Egypt	1.3	85	1105	4.0	0.28	0.30	0.58
Jordan	2.1	12.5	263	0.2	1.31	0.25	1.56
Tunisia	1.2	33	396	0.6	0.66	0.30	0.96
Yemen	1.4	15	210	2.5	0.08	0.50	0.58
Total		**532**	**3054**	**8.0**	**0.38**	**0.36**	**0.74**

Table 5-7: Cost of groundwater depletion in some MENA countries from /World Bank 2007/ and own calculations of the resulting cost of water (blue section)

To this adds a loss of water and GDP due to **environmental degradation** in the same order of magnitude (Table 5-8). The countries analysed in those two tables alone suffer a loss of GDP of over 11 billion US$/year due to groundwater overuse and environmental degradation. It is obvious that almost any measure, ranging from efficiency enhancement to reuse of wastewater and seawater desalination would be more cost effective than the presently ongoing depletion. Unfortunately, this simple truth is often hidden by subsidies, either of energy for groundwater pumping or directly by subsidizing the water supplied.

However, these numbers also show the trap in which many MENA countries find themselves at present: the loss of GDP creates a scarcity of funds that avoids investment into new, more sustainable sources. It becomes more and more difficult to find a budget for investment in innovations, because increasing production cost and increasing budget losses due to depletion bind public funding that would be required for a change. This trap is quickly closing, and some countries may already be beyond the point of being able to free themselves, even if they realised the situation. On the other hand, there are also countries that would in principle be capable of changing, but are structurally unable or unwilling to do so or uninformed about alternatives /World Bank 2007/.

	Cost of Environmental Degradation % GDP	GDP 2005 B$/y	GDP Lost M$/y
Algeria	0.8	90	720
Egypt	1	85	850
Iran	2.7	193	5211
Jordan	1.2	12.5	150
Lebanon	1	20	200
Morocco	1.3	58	754
Syria	0.9	25	225
Tunisia	0.6	33	198
Yemen	0.6	15	90
Total		**532**	**8398**

Table 5-8: Cost of environmental degradation of water sources in MENA /World Bank 2007/ and own calculations

5.5 Urbanisation versus Rural Development

The Middle East and North Africa has one of the fastest growing populations in the world with an average annual growth rate of 2.1 percent in the past decade. The population is growing from around 100 million in 1960, through a present 311 million to a projected 430 million in 2025, bringing the available amount of water per capita in many countries to far below the scarcity level. Most of population growth has occurred in urban areas, where the population share is expected to exceed 70 percent by 2015. The urban growth rate has been around 4 percent per year during the last twenty years /World Bank 2005/.

The region’s 25 largest cities are expected to grow with 2.7 percent per year between 2000 and 2010 /UN-Habitat 2004/. Whereas Bahrain, Kuwait and Qatar were already 80 percent urban in the 1970s, the region’s lesser urbanized nations all have experienced sharp urban population increases – a trend expected to continue (see also Figure 3-2).

Statistically Egypt, Sudan and Yemen will be the only MENA nations less than 50 percent urbanized in 2015. However, the Nile Valley could already today be considered a large single urban structure (Figure 5-15) and it is likely that single settlements will slowly grow together, if they have not done so already. Around 2030 nine MENA countries will likely be more than 90 percent urban: Bahrain (95.8 percent), Israel (94.5 percent), Kuwait (98.4 percent), Lebanon (93.9 percent), Libya (92.0 percent), Oman (95.2 percent), Qatar (95.9 percent), Saudi Arabia (92.6 percent) and the United Arab Emirates (93.3 percent) /Tropp 2006/.

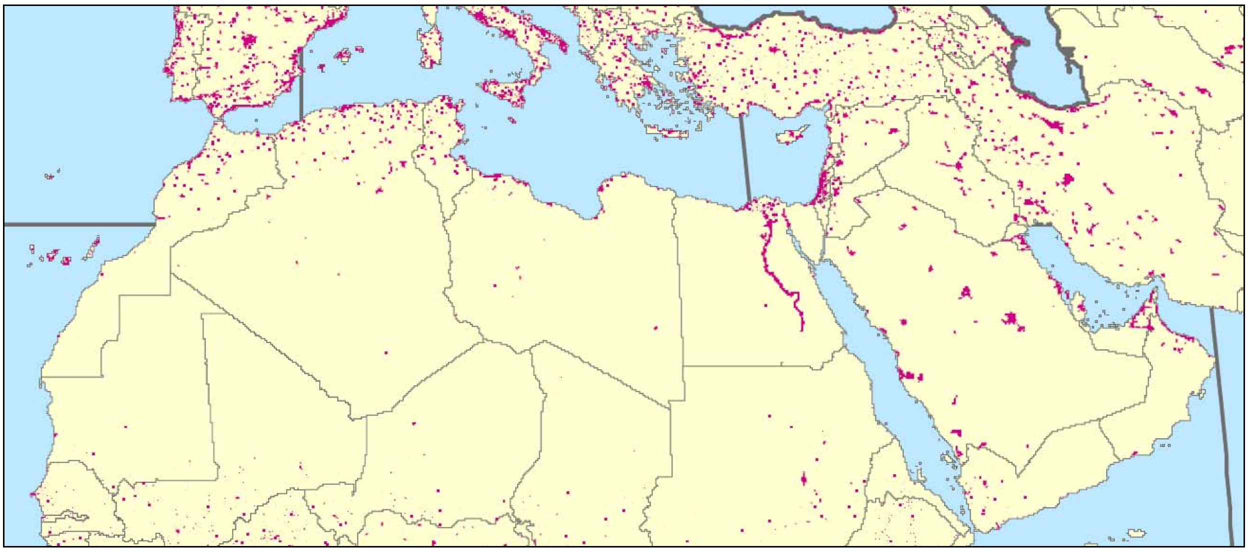


Figure 5-15: Urban settlements with more than 5000 inhabitants in MENA (red areas) /CIESIN 2005/

According to /Tropp 2006/ "a common feature of urban transition in most developing countries is that the relative urban growth is higher in small- and medium-sized urban areas as compared to mega cities. The MENA region is no exception. In 2000, the MENA region had 16 cities of over 1 million inhabitants, with only Cairo, Istanbul and Tehran exceeding 5 million. By 2010, there will probably be 24 cities of over 1 million within the region. It is forecast that by 2015, six cities will be larger than 5 million, with Cairo and Istanbul both exceeding 11 million. Tehran and Baghdad will remain the third and forth largest cities, with 6.9 and 4.8 million /UN-Habitat 2004/. Small- and medium sized cities tend to have lower levels of services compared to bigger cities. It is thus essential that more focus is put on those cities that currently are below or around 1 million inhabitants. Such a focus presents opportunities to apply innovative water technologies and practices more widely and to avoid past mistakes of unplanned development in mega cities."

As a conclusion of his analysis of the water situation in MENA, Tropp states that "there is evidently no blueprint solution to the challenges related to water and irrigated agriculture in the region. Most countries in the region face acute problems related to water scarcity that are amalgamated by the highly complex political map of the region and difficulties to re-think agricultural policies. Many countries in the region are at a crossroads over their future use of water for irrigated agriculture. A critical question for many countries in the region is: ***Is agriculture an economically viable option?*** Despite that some countries have managed to shift into more high-value crops, such as fruits and flowers, it is not realistic to perceive that all countries will be able to follow such a path. It is also required to resolve the insufficient provision of drinking water supply and sanitation. Some countries in the region, for example Egypt, seem to be on track to meet the Millennium Development Goals (MDGs) on water supply and sanitation, while Yemen is far off the MDG mark.

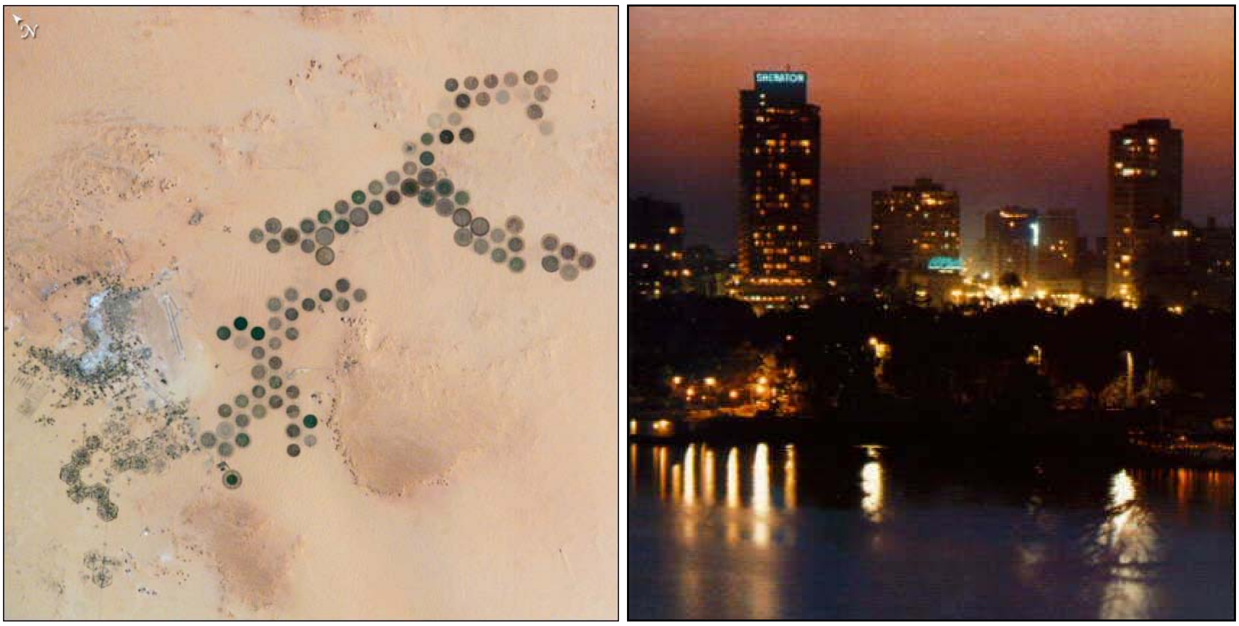


Figure 5-16: Astronaut view of agricultural fields using centre pivot irrigation at Al Khufrah Oasis in South-Eastern Libya (left) and a view of Cairo from the Nile River at night (right)

The most water-scarce countries in the region will thus have to pose some very serious questions related to irrigated agriculture. ***Can current levels of irrigated agriculture be maintained in the long run?*** What are the environmental, social and political costs of maintaining current levels of water allocation? There is increasing evidence that unless countries apply economic policies that shift away from increased water use, water will continue to fuel political tensions between and within countries. It is somewhat hopeful that the much-hyped “water wars” are increasingly being replaced by a new type of thinking: Water for long-term stability in the region. However, much remains to be done before such a way of perceiving shared waters impacts political levels and the practice of politics in the region.

In developing local and national financing and adaptive strategies to water scarcity and climate variability, the ***role of virtual water*** (water virtually provided with food imports) should also be considered. Alternatively, or as a supplementary measure, countries can diversify economies and shift away from water intensive agriculture and industries to reduce water scarcity as well as drastically reduce investment needs. Structural shifts away from water-intensive irrigated agriculture and industries could decrease economic vulnerability to droughts and land degradation. Equally and sometimes even more important is the shift towards sectors where the country or a community has a comparative advantage in terms of water use efficiency. Relying on trade in virtual water to meet a country's power supply and food needs could drastically reduce unsustainable water use. Furthermore, it could also mitigate the need for diverting national resources as well as foreign direct investment and aid towards costly water supply projects to support water intensive activity in areas that do not have the necessary water resources" (end of quotation of /Tropp 2006/).

The message is clear: stop consuming a lot of water by growing plants in the deserts and rather import virtual water by directly importing food from places that have better resources available.

However, problems arising from international marketing of agricultural products are well known: countries importing virtual water in form of food will also import virtual and actual subsidies from rich countries against which their own farmers will have to compete in local markets. Virtual water markets suffer from the same distortions as the markets for the products that facilitate water exchange /World Bank 2007/. This and the reduction of domestic market volumes would directly impact rural economy and livelihood, and consequently aggravate urbanisation. A shift of farmers to high income - low water crops could alleviate some of those impacts, but markets for "fruits and flowers" are usually risky and limited and could collapse if everybody jumped into.

Another major concern is the interaction of food imports and food security, as imports will have to be financed by other sources of income. Therefore, food imports may be an attractive option e.g. for oil-producing countries with huge foreign income, but may be a considerable challenge for countries that depend on food imports and energy imports as well.

5.6 Cultivating the Desert

In general, seawater desalination is not considered a viable option for resolving water scarcity in arid regions like the Middle East and North Africa. The Human Development Report 2006 /HDR 2006/ states that "A major constraint on commercial desalinization is the cost of energy. Due to innovation and development, production costs have fallen and output increased. However, the sensitivity of production costs to **energy prices**, allied to the high costs of pumping water over long distances (to cities lying further inland[1]), creates restrictive conditions. For oil-rich countries and relatively wealthy cities close to the sea, desalinization holds out promise as a source of water for domestic consumption, but the potential for addressing the problems of poor cities in low-income countries is more limited, and desalinization is unlikely to resolve the fundamental mismatch between supply and demand in water. It currently contributes only 0.2 % to global water withdrawals and holds limited potential for agriculture or industry (Figure 5-17).

1 note from the author

“If we could ever competitively, at a cheap rate, get fresh water from saltwater, this would be in the long-range interests of humanity and really dwarf any other scientific accomplishment”, observed US President John F. Kennedy. Practiced since biblical times, the creation of fresh water by extracting salt from sea water is not recent human endeavour. But does it offer a solution to problems of water stress and scarcity?” (end of quotation).

The answer is clearly “no”, if water supply by desalination would depend on fossil fuels, because fuel prices could escalate further to an unaffordable level and finally fuels could be depleted on a world wide scale. Loosing those primary fossil resources for energy supply would be bad enough, but loosing the related freshwater resources as well would be catastrophic.

However, the answer is clearly “yes”, if desalination is based on a renewable and secure resource of energy that is compatible with the environment and becomes cheaper with time. This is reflected in our reference scenario in Chapter 4, where fossil-fuel-based desalination disappears in the long-run after reaching a maximum share of 6 % by 2030, while CSP-desalination achieves major shares of freshwater supply after being introduced to the market. Unfortunately, present decision makers within the water sector are not yet familiar with this option, and consequently exclude seawater desalination from their portfolio of possible solutions to the MENA water crisis or only consider it as a marginal element of supply.

Desalinization is a technical option for creating fresh water from sea water. Distilling sea water by boiling it and collecting the vapour is an age-old activity—an activity transformed over the past 20 years through new technologies. But there are limits to its scope.

In 2002 the global market for desalinization stood at $35 billion. There are now more than 12,500 plants operating in 120 countries. Traditionally, desalinization has taken place through thermal heating, using oil and energy as the source. The most modern plants have replaced this technology with reverse osmosis—forcing water through a membrane and capturing salt molecules. The costs of producing water from this source have fallen sharply, from more than $1 per cubic metre a decade ago to less than half that today. The energy to drive the conversion is a significant part of the cost.

Israel provides the gold standard in water desalinization. Following implementation of a planning strategy launched in 2000—the Desalinization Master Plan—the country now generates about a quarter of its domestic fresh water through desalinization. The $250 million Ashkelon Plant, which began operation in 2005, is the world’s largest and most advanced reverse osmosis facility, producing fresh water at a cost of $0.52 per cubic metre. It supplies about 15% of Israel’s fresh water used for domestic consumption. Current plans envisage an increase in production from desalinization plants from 400 million cubic metres today to 750 million cubic metres by 2020.

Current desalinization capacity is heavily concentrated. The Gulf states account for the bulk of capacity, with Saudi Arabia accounting for one-tenth of total output. Elsewhere, Tampa Bay in Florida and Santa Cruz in California have adopted reverse osmosis plants, and China has announced plans for a plant in Tianjin, its third largest city. In Spain the new government abandoned plans to pump water across the country from the wet north to the arid south in favour of 20 reverse osmosis plants (enough to meet 1% of needs), though the costs of desalinized water may not entice farmers from their current groundwater irrigation sources. In the United Kingdom the water utility serving London has a reverse osmosis plant that will come into operation in 2007.

This pattern of distribution highlights both the potential and the limits of desalinization. While costs are falling, the capital costs of new plants are considerable and operating costs are highly sensitive to energy prices. Recent projects in Israel and other countries demonstrate this, with tenders for water supply rising to $0.80–$1.00 per cubic metre. The cost of pumping water rises sharply with distance as well, so that inland cities would face higher cost structures. These factors help to explain why oil-rich states and coastal cities in water-stressed areas will probably remain the main users.

Overall use patterns are likely to change slowly. In some countries desalinization can be expected to account for an increased share of domestic and industrial water use. Municipalities currently account for two-thirds of use and industry for a quarter. The potential in agriculture is limited by cost. That is especially so for producers of low value-added staple crops that require large volumes of water.

Source: Rosegrant and Cline 2003; Schenkeveld and others 2004; Rijsberman 2004a; BESA 2000; Water-Technology.net 2006.

Figure 5-17: Desalinization – And its Limits. Source: Human Development Report 2006 /HDR 2006/

Cultivating the desert is an old dream of humanity. Vast areas are there, soils are rather fertile, but cannot be used due to the lack of water. Today, considerable areas in the MENA deserts are already cultivated, most of them using (fossil) groundwater or water from rivers coming from outside into the country, like the Nile (Figure 5-18). In the previous chapters we have seen that in terms of water consumption, the region is now reaching or surpassing its natural limits.

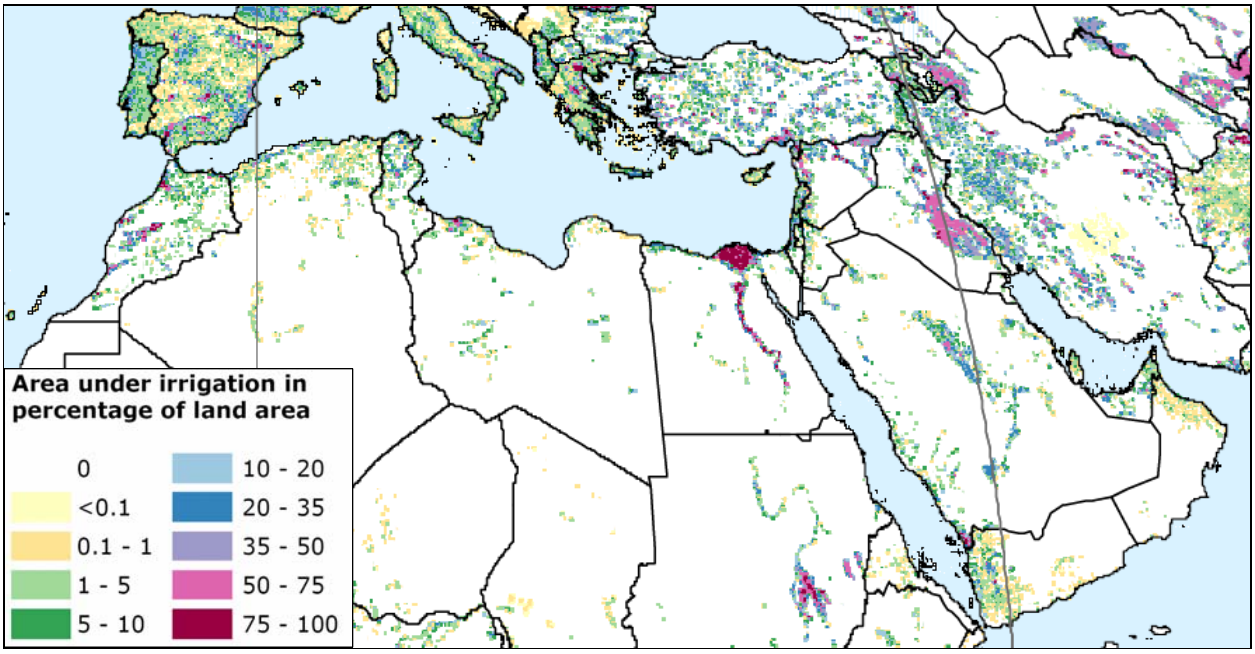


Figure 5-18: Irrigated areas in the MENA region. The map depicts the area equipped for irrigation in percentage of cell area. For the majority of countries the base year of statistics is in the period 1995-2000 /FAO 2005/. Al-Khufra Oasis from Figure 5-16 (left) is the point located in the lower right corner of Libya.

But what if the vision of John F. Kennedy became true and we could cheaply obtain freshwater from saltwater? The consequences for MENA would be striking: MENA could become self-sufficient in food production in spite of its growing population and without having to deplete its fossil energy and water resources. Using solar energy for seawater desalination would effectively fight the problem of water scarcity by making use of the main cause of this problem itself: the intensive solar irradiance in the MENA region.

Concentrating solar power can already today compete with unsubsidised world market prices of fuel oil and is heading for competitiveness with natural gas by 2010. Ten years later, around 2020, it will be even cheaper than coal. After that, costs will further decline, due to technological learning, competition and economies of scale, and as we have seen in Chapter 5.1, the combination of seawater desalination with power generation could allow for water prices that would even become competitive for irrigation.

What if seawater could be desalted on a large scale for municipal use and for irrigation, and if at the same time the best use of water would be achieved by increasing the efficiencies of distribution, waste-water recycling and end-use of water? On a large-scale, this could have the effect of re-filling existing or already depleted groundwater resources by seepage and thus increasing the – in that case renewable – groundwater resources in the MENA region, that could be further used in the traditional way by groundwater pumping. This would be something like a natural recycling of part of the desalted seawater.

What if the only reason why seawater desalination is today not considered sustainable by most decision makers – its high energy consumption – is removed by a sustainable form of energy from the MENA region itself? What if imports of food, virtual water and energy could be replaced by a resource that is domestic to MENA: by solar energy? The AQUA-CSP study shows that such a source is available and the necessary technology is ready for the market in form of concentrating solar power for seawater desalination.

Concentrating solar power (CSP) is a unique source of energy in the MENA region. It is available everywhere in very large amounts. It is a very concentrated, easily controllable and storable form of energy. It is already affordable today and becoming cheaper with time. It is compatible to the environment and can be used for multiple purposes like power generation, seawater desalination, cooling and even for shading, if linear Fresnel technology is applied (Figure 5-19).

As proposed by the Trans-Mediterranean Renewable Energy Cooperation /TREC 2006/, concentrating solar thermal power stations in MENA could be used for export electricity to Europe and for providing regional freshwater from combined thermal desalination of sea water. In the TRANS-CSP study /TRANS-CSP 2006/, we have analysed the potential of combining CSP exports to Europe with local sea water desalination for the MENA region.

The combination of export solar electricity with sea water desalination will have only a moderate contribution to the coverage of the water deficit, because CSP exports will start relatively late, compared to the extremely pressing situation in the water sector. CSP plants exclusively producing water with reverse osmosis and thermal multi-effect desalination and MED plants coupled to domestic solar power generation will provide the core of the desalination capacity in MENA. In the year 2050, a maximum 30 billion m³/y could be desalted by about 40 % of the installed CSP export plants, covering roughly 20 % of the freshwater deficit. 25 billion m³/y would be desalted by domestic CSP plants, while 110 billion m³/y must be desalted by exclusive CSP desalination plants with RO and MED.

Electricity produced in CSP plants can be used for domestic needs and export, as well as for additional desalination of sea water through reverse osmosis (RO), if required. The design of such combined solar power and desalination plants can be flexibly adapted to any required size and need. The advantages of this concept lay at hand:

Figure 5-19: Photo of the top of a Linear Fresnel Concentrating Solar Collector and artist view of a greenhouse installed underneath to protect the plants from excessive irradiance and evaporation. This could be a concept for multi-purpose plants for power, water and horticulture. Other local uses include shade for parking and the production of steam for cooling and process heat. (Source: Solarmundo, DLR)

- outstanding overall conversion efficiency of over 80 % for both solar heat and fuel,
- outstanding economic efficiency through the second valuable product freshwater,
- energy, water and income for the sustainable development of arid regions.

Concentrating solar multipurpose plants in the margins of the desert could generate solar electricity for domestic use and export, freshwater from seawater desalination, and in addition provide shade for agriculture and other human activities. Such plants could turn waste land into arable land and create labour opportunities in the agriculture and food sector. Tourism and other industries could follow. Desertification could be stopped (Figure 5-20).

A brief introduction to the possibilities of integrated multi-purpose plants using CSP for energy, water and agriculture in the MENA region is given in the Annex. The brief study shows options for combination, suitable crops and the conditions required to achieve sustainable agriculture based on renewable sources in desert environments. The concept is being developed by members of the Trans-Mediterranean Renewable Energy Cooperation (TREC) and the German Section of the Club of Rome (CoR) and proposed in combination with an export strategy for solar electricity from the Middle East and North Africa to Europe (www.trec-eumena.net).

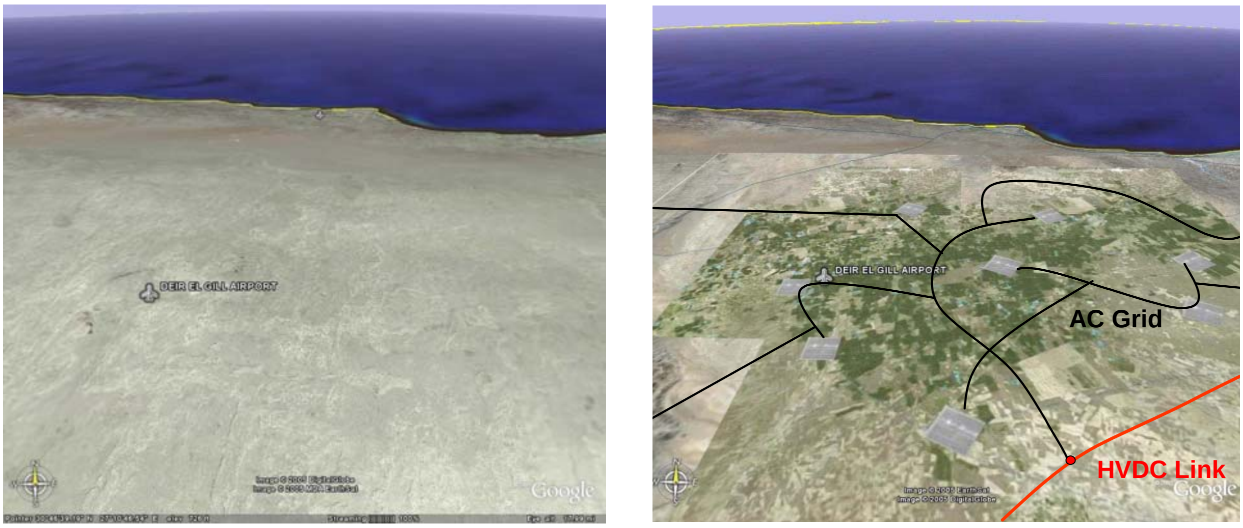


Figure 5-20: Left: typical region at the Mediterranean coast in Northern Egypt from Google Earth (left). Right: artist impression of the same region with large CSP plants for power and desalination connected to the national utility grid and to a trans-continental HVDC link that could be a key for the economic development of desert regions along the coasts of the Mediterranean Sea, the Red Sea and the Persian Gulf.

6. Environmental Impacts of CSP Desalination

Impacts of seawater desalination to the environment, which will be explained in this section, are caused by feed water intake, material and energy demand, and by brine discharge.

The selection of the seawater intake system depends on the raw water source, local conditions, and plant capacity. The best seawater quality can be reached by beach wells, but in these cases the amount of water that can be extracted from each beach well is limited by the earth formation, and therefore the amount of water available by beach wells is very often far below the demand of the desalination plant. For small and medium reverse osmosis plants, a beach well is often used. For seawater with a depth of less than 3 m, short seawater pipes or an open intake are used for large capacities. Long seawater pipes are used for seawater with depths of more than 30 m.

The seawater intake may cause losses of aquatic organisms by impingement and entrainment. The effects of the construction of the intake piping result from the disturbance of the seabed which causes re-suspension of sediments, nutrients or pollutants into the water column. The extent of damage during operation depends on the location of the intake piping, the intake rate and the overall volume of intake water. Alternative techniques of feed water intake will be identified in Chapter 6.5.

The second impact category is linked to the demand of energy and materials inducing air pollution and contributing to climate change. The extent of impact through energy demand is evaluated by life cycle assessment, LCA. The impacts of this category can be mitigated effectively by replacing fossil energy supply by renewable energy and using waste heat from power generation for the thermal processes.

The third impact category comprises effects caused by the release of brine to the natural water body. On one hand the release of brine stresses the aquatic environment due to the brine's increased salinity and temperature. On the other hand the brine contains residuals of chemicals added during seawater pre-treatment and by-products formed during the treatment. These additives and their by-products can be toxic to marine organisms, persistent and/or can accumulate in sediments and organisms. Apart from the chemical and physical properties the impact of the brine depends on the hydrographical situation which influences brine dilution and on the biological features of the discharge site. For instance, shallow sites are less appropriate for dilution than open-sea sites and sites with abundant marine life are more sensitive than hardly populated sites. But dilution can only be a medium-term mitigation measure. In the long run the pre-treatment of the feed water must be performed in an environmentally friendly manner. Therefore alternatives to conventional chemical pre-treatment must be identified.

The environmental impacts of seawater desalination will be discussed separately for each technology because of differences in nature and magnitude of impacts. The technologies regarded here are MSF, MED and RO as they are, at least at the moment, the predominant ones of all desalination technologies and therefore these plants are responsible for almost all impacts on the environment caused by desalination. An excellent and highly recommendable compendium of environmental impact of MSF and RO desalination technologies is /Lattemann and Höpner 2003/. Much of the data used here has been taken from that source.

6.1 Multi-Stage Flash Desalination (MSF)

6.1.1 Seawater Intake

Due to their high demand of cooling water, MSF desalination plants are characterized by a low product water conversion rate of 10 to 20 %. Therefore the required volume of seawater input per unit of product water is large, i.e. in the case of a conversion rate of 10 %, 10 m³ of seawater are required for 1 m³ of produced freshwater (see Figure 6-1). Combining the high demand of seawater input in relative terms with the high demand of seawater input in absolute terms due to the large average MSF plant size the risks of impingement and entrainment at the seawater intake site must be regarded as high. Therefore, the seawater intake must be designed in a way that the environmental impact is low.

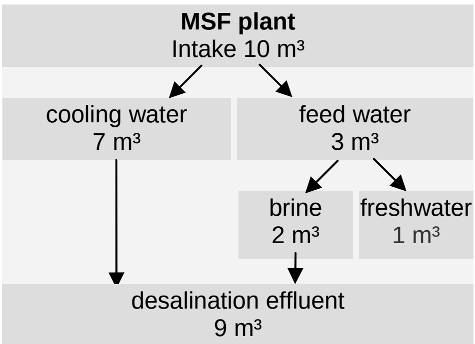


Figure 6-1: Flow chart of reference MSF process

6.1.2 Discharge of Brine Containing Additives

The discharge of brine represents a strong impact to the environment due to its changed physical properties, i.e. salinity, temperature and density, and to the residues of chemical additives or corrosion products. In MSF plants common chemical additives are biocides, anti-scalants, anti-foaming agents, and corrosion inhibitors. The conditioning of permeate to gain palatable, stable drinking water requires the addition of chlorine for disinfection, calcium, e.g. in form of calcium hydroxide, for remineralisation and pH adjustment /Raluy 2003/, /Delion et al. 2004/. In case of acidification as pre-treatment removal of boron might be necessary /Delion et al. 2004/.

Figure 6-2 shows where the chemicals are added, and indicates the concentrations as well as the characteristics of the brine and its chemical load.

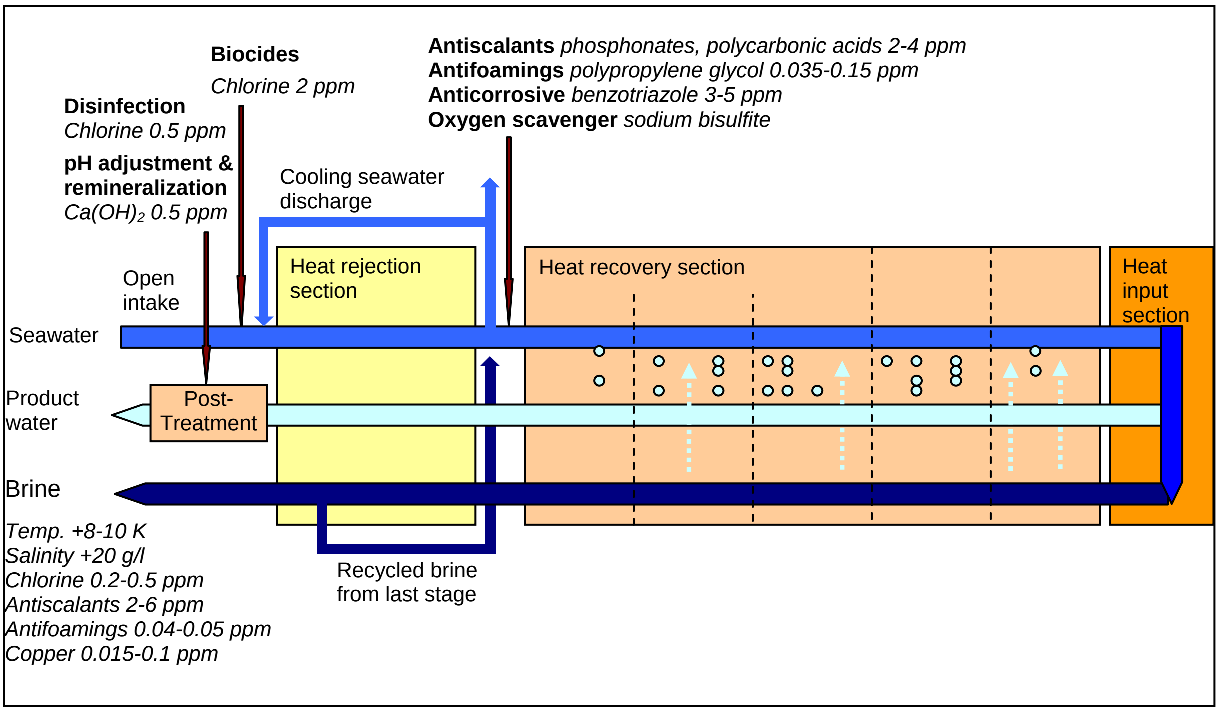


Figure 6-2: MSF process scheme with input and output concentrations of additives and brine characteristics, /Lattemann and Höpner 2003/, modified

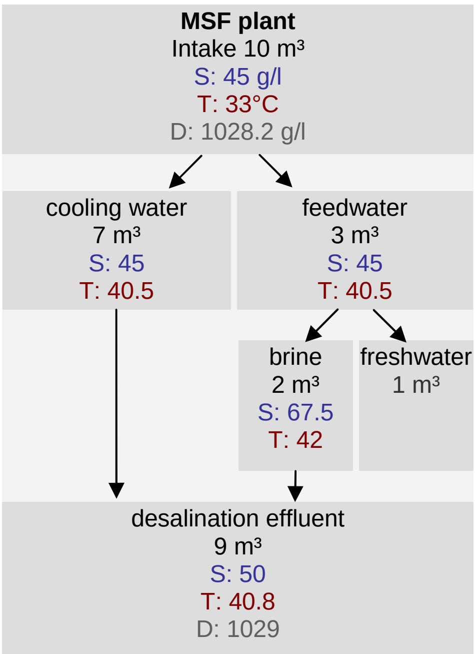


Figure 6-3: Flow chart of reference MSF process with salinity (S, in g/l), temperature (T, in °C) and density (D, in g/l), /Lattemann and Höpner 2003/, modified

Physical Properties of Brine

The physical parameters of the brine are different compared to the intake seawater. During the distillation process the temperature rises and salt accumulates in the brine. Taking the reference process (Figure 6-1) with a conversion rate of approx. 10 % (related to the seawater flow) as example the salinity of the brine rises from 45 g/l to 67.5 g/l (Figure 6-3). Brine and cooling water temperature rises by 9 and 7.5 K, respectively. Salinity of the brine is reduced by blending with cooling water, but still reaches a value of 5.4 g/l above ambient level. The resulting increase of density is small what can be attributed to balancing effects of temperature and salinity rise. In general, the increase of the seawater salinity in the sea caused by solar evaporation is normally much higher than by desalination processes. However, the brine discharge system must be designed in a way that the brine is well distributed and locally high temperature and salinity values are avoided.

Biocides

Surface water contains organic matter, which comprises living or dead particulate material and dissolved molecules, leads to biological growth and causes formation of biofilm within the plant. Therefore the seawater intake flow is disinfected with the help of biocides. The most common biocide in MSF plants is chlorine. A concentration of up to 2000 µg/l in the seawater intake flow is sustained by a continuous dosage. Chlorine reacts to hypochlorite and, in the case of seawater, especially to hypobromite. Residual chlorine is released to the environment with the effluents from cooling and distillation where it reaches values of 200-500 µg/l, representing 10-25 % of the dosing concentration. Assuming a product-effluent-ratio of 1:9 the specific discharge load of residual chlorine per m³ of product water is 1.8-4.5 g/m³. For a plant with a desalination capacity of 24,000 m³/day, for instance, this means a release of 43.2-108 kg of residual chlorine per day.

Further degradation of available chlorine after the release to the water body will lead to concentrations of 20-50 µg/l at the discharge site. Chlorine has effects on the aquatic environment because of its high toxicity, which is expressed by the very low value of long-term water quality criterion in seawater of 7.5 µg/l recommended by the U.S. Environmental Protection Agency (EPA 2006, cited in /Lattemann and Höpner 2007a/) and the predicted no-effect concentration (PNEC) for saltwater species of 0.04 µg/l determined by the EU environmental risk assessment (ECB 2005, cited in /Lattemann and Höpner 2007a/). In Figure 6-4 the occurring concentrations near the outlet and at a distance of 1 km are compared to ecotoxicity values determined through tests with different aquatic species and to the EPA short-term and long-term water quality criteria. It is striking that most of the concentrations at which half of the tested populations or the whole population is decimated at different exposure times or show other effects are exceeded by the concentrations measured near the outlet and even at the distance of 1 km. The values are quoted in /Lattemann and Höpner 2003/ who took them from Hazardous Substance Databank (HSDB, http://toxnet.nlm.nih.gov).

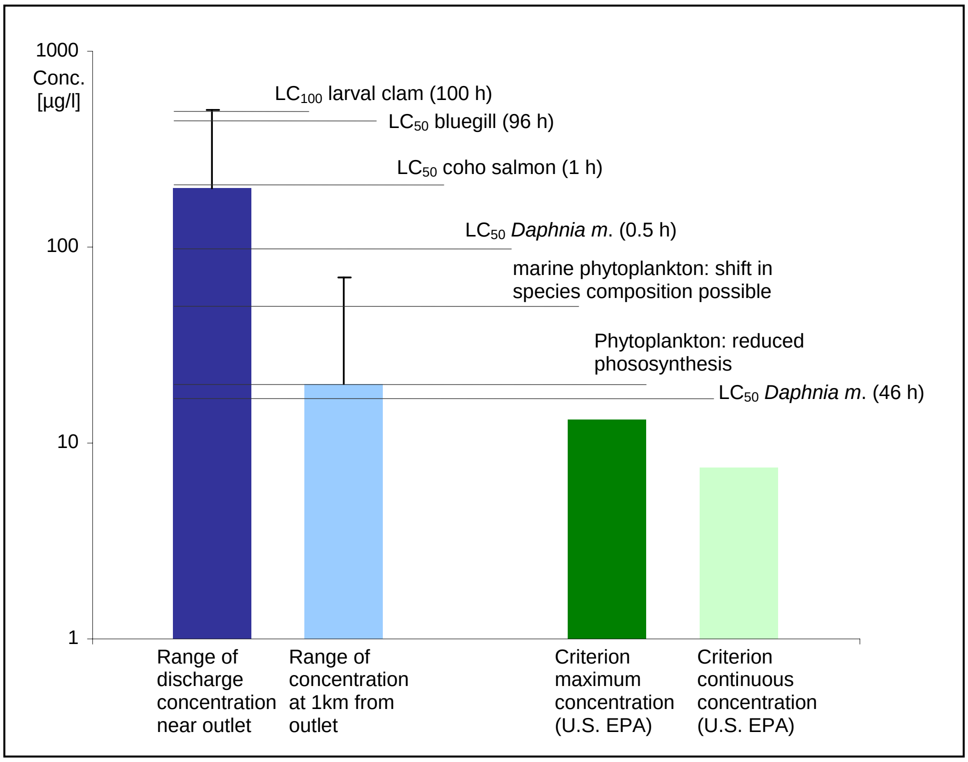


Figure 6-4: Chlorine: Ecotoxicity (LC50 = mean lethal concentration) compared to ranges of brine concentration and water quality criteria, /Lattemann and Höpner 2003/, modified

Another aspect of chlorination is the formation of halogenated volatile liquid hydrocarbons. An important species is bromoform, a trihalomethane volatile liquid hydrocarbon. Concentrations of up to 10 µg/l of bromoform have been measured near the outlet of the Kuwaiti MSF plant Doha West /Saeed et al. 1999/. The toxicity of bromoform has been proven by an experiment with oysters which have been exposed to a bromoform concentration of 25 µg/l and showed an increased respiration rate and a reduced feeding rate and size of gonads (Scott et al. 1982, cited in /Saeed et al. 1999/). Larval oysters are even more sensitive to bromoform, as significant mortality is caused by a concentration of 0.05-10 µg/l and acute, 48 h exposures.

Antiscalants

A major problem of MSF plants is the scale formation on the heat exchanger surfaces which impairs heat transfer. The most common scale is formed by precipitating calcium carbonates due to increased temperatures and brine concentration. Other scale forming species are magnesium hydroxide calcium sulphate, the latter being very difficult to remove as it forms hard scales. Therefore sulphate scaling is avoided in the first place by regulating the operation parameters temperature and concentration in such a way that the saturation point of calcium sulphate is not reached. Calcium carbonates and magnesium hydroxides, again, are chemically controlled by adding acids and/or antiscalants.

In the past, acid treatment was commonly employed. With the help of acids the pH (acidity value) of the feed water is lowered to 2 or 3 and hereby the bicarbonate and carbonate ions chemically react to carbon dioxide which is released in a decarbonator.. Thus, the $CaCO_3$ scale forming ions are removed from the feed water. After acid treatment the pH of the seawater is re-adjusted. Commonly used acids are sulphuric acid and hydrochloric acid, though the first is preferred because of economic reasons. High concentrations and therefore large amounts of acids are necessary for the stoichiometric reaction of the acid.. Apart from a high consumption of acids further negative effects of using acids are the increased corrosion of the construction materials and thus reduced lifetimes of the distillers as well as handling and storage problems. The negative effects mentioned above have led to the development of alternatives: Nowadays antiscalants are replacing acids during operation. But before talking about antiscalants, the use of acids as cleaning agents needs to be mentioned because that’s when significantly acidic effluents occur. During this periodic cleaning procedure the pH is lowered to 2-3 by adding citric, sulfamic or sulphuric acid, for instance, to remove carbonate and metal oxide scales. In this context Mabrook (1994, in /Lattemann and Höpner, 2003/) explained an observed change in density and diversity of marine organisms by a decreased pH of 5.8 compared to 8.3 in coastal waters. Eco-toxic pH values range from 2-2.5 for starfish (LC_{50}, HCl, 48 h) to 3-3.3 for salt water prawn (LC_{50}, H_2SO_4, 48 h) and show the sensitivity of marine organisms to low pH values. Little mobile organisms, like starfish, are especially affected by an acid plume as they cannot avoid this zone. To mitigate these possible effects the cleaning solution should be neutralized before discharge or at least blended with the brine during normal operation.

An antiscalant can suppress scale formation with very low dosages, typically below 10 ppm. Such low dosages are far from the stoichiometric concentration of the scaling species. Hence inhibition phenomena do not entail chemical reactions and stem from complex physical processes involving adsorption, nucleation and crystal growth processes. Scale suppression in the presence of minute concentrations of antiscalants is believed to involve several effects:

- Threshold effect: An antiscalant can slow down the nucleation process occurring in a supersaturated solution. Thereby, the induction period, which precedes crystal growth, is increased. The inhibition effect of anti-scalants is based on their ability to adsorb onto the surfaces of sub-microscopic crystal nuclei, which prevents them from growing any further or, at least, substantially slows down the growth process. Since anti-scalant molecules with a low molecular weight are more mobile, the extension of the induction period is more pronounced with molecules of comparatively low molecular weight.

- Crystal distortion effect: Adsorbed antiscalant molecules act to distort the otherwise orderly crystal growth process. A different degree of adsorption and retardation of the growth process on different crystal faces results in alteration of the crystal structure. The scale structure can be considerably distorted and weakened. The distorted crystals are less prone to adhere to each other and to metal surfaces. When crystallisation has started either further growth is inhibited or the precipitates form a soft sludge that can be easily removed rather than hard scales /Al-Shammiri et al. 2000/.
- Dispersive effect: Antiscalants with negatively charged groups can adsorb onto the surfaces of crystals and particles in suspension and impart a like charge, hence repelling neighbouring particles, thereby preventing agglomeration and keeping the particles suspended in solution.
- Sequestering effect: Antiscalants may act as chelating agents and suppress the particle formation by binding free Ca^{2+} or Mg^{2+} ions in solution. Anti-scalants with strong chelating characteristics cannot work at the sub-stoichiometric level, as the anti-scalant is consumed by the scale-forming ions. Sequestration is affected by chemicals that require relatively high concentrations and is not a physical inhibition effect.

Polyphosphates represent the first generation of antiscalant agents with sodium hexametaphosphate as most commonly used species. A procedural disadvantage is the risk of calcium phosphate scale formation. Of major concern to the aquatic environment is their hydrolytic decomposition at 60°C to orthophosphate which acts as a nutrient and causes eutrophication. The development of algae mats on the water body receiving the discharge could be ascribed to the use of phosphates /Abdel-Jawad and Al-Tabtabaei 1999/, in /Lattemann and Höpner 2003/). Because of these reasons they have partly been substituted by thermally stable phosphonates and polycarbonic acids, the second generation of antiscalants. Where phosphates have been replaced by these substances the problem of algae growth could be solved completely. Main representatives of polycarbonic acids are polyacrylic and polymaleic acids. Especially polyacrylic acid has to be dosed carefully if precipitation is to be avoided. The reason for this is that, at lower concentrations, it enhances agglomeration and therefore also serves as a coagulant in RO plants (see below). Discharge levels of phosphonates and polycarbonic acids are classified as non-hazardous, as they are far below concentrations with toxic or chronic effects. They resemble naturally occurring humic substances when dispersed in the aquatic environment which is expressed by their tendency to complexation and their half-life of about one month, both properties similar to humic substances. Though they are generally assumed to be of little environmental concern, there is a critical point related to these properties. As they are rather persistent they will continue to complex metal ions in the water body. Consequently, the influence on the dissolved metal concentrations and therefore metal mobility naturally exerted by humic substances is increased by polymer antiscalants. The long-term effect induced hereby requires further research.

Experimental data on the bioaccumulation potential of polycarboxylates are not available. However, polymers with a molecular weight > 700 are not readily taken up into cells because of the steric hindrance at the cell membrane passage. Therefore a bioaccumulation is unlikely. Copolymers have a favourable ecotoxicological profile. Based upon the available short-term and long-term ecotoxocity data of all three aquatic trophic levels (fish, daphnia, algae) for a variety of polycarboxylates, it is considered that exposure does not indicate an environmental risk for the compartments water, sediment and sewage treatment plants.

A MSF plant with a daily capacity of 24,000 m³ releases about 144 kg of antiscalants per day if a dosage concentration of 2 mg per litre feedwater is assumed. This represents a release of 6 g per cubic meter of product water.

Antifoaming Agents

Seawater contains dissolved organics that accumulate in the surface layer and are responsible for foaming. The use of antifoaming agents is necessary in MSF plants, because a surface film and foam -increase the risk of salt carry-over and contamination of the distillate. A surface film derogates the thermal desalination process by increasing the surface viscosity. An elevated surface viscosity hampers deaeration. Furthermore, if the surface tension is too high, brine droplets will burst into the vapour phase during flashing. Deaeration is essential for thermal plants as it reduces corrosion; salt carry-over with brine droplets must be avoided for a clean distillation..

As the antifoaming agents are organic substances, too, they must carefully be chosen and dosed. Blends of polyglycol are utilized, either containing polyethylene glycol or polypropylene glycol. These substances are generally considered as non-hazardous and low discharge concentrations of 40-50 µg per litre of effluent further reduce the risk of environmental damage. However, highly polymerized polyethylene glycol with a high molecular mass is rather resistant to biodegradation. On this account it has been replaced in some industrial applications by substances, such as dialkyl ethers, which show a better biodegradability. Addition of usually less than 0.1 ppm of an antifoaming agent is usually effective. Concentrations in the discharge were found to be half this level, which is mainly due to mixing of brine with cooling water /Lattemann and Höpner 2003/. While the brine contains residual antifoaming agents, the cooling water is not treated and thereby reduces the overall discharge concentration.

Under the assumption of a product-feedwater-ratio of 1:3 and 0.035-0.15 ppm dosing 0.1-0.45 g per cubic meter of product water are released.

Corrosion Inhibitors and Corrosion Products

An important issue for MSF plants is the inhibition of corrosion of the metals the heat exchangers are made of. The corrosive seawater, high process temperatures, residual chlorine concentrations and corrosive gases are the reason for this problem. Corrosion is controlled by the use of corrosion resistant materials, by deaeration of the feed water, and sometimes by addition of corrosion inhibitors . Especially during acidic cleaning corrosion control by use of corrosion inhibitors is essential for copper-based tubing. In a first step oxygen levels are reduced by physical deaeration. The addition of chemicals like the oxygen scavenger sodium bisulfite can further reduce the oxygen content. Sodium bisulfite should be dosed carefully as oxygen depletion harms marine organisms.

Corrosion inhibitors generally interact with the surfaces of the tubes. Ferrous sulphate, for example, adheres to the surface after having hydrolized and oxidized and hereby protects the alloy. Benzotriazole and its derivates are special corrosion inhibitors required during acid cleaning. They possess elements like selenium, nitrogen, sulphur and oxygen with electron pairs which interact with metallic surfaces building a stable protective film. However, it is assumed that in the end the major amount is discharged with the brine. Due to the slow degradation of benzotriazole, it is persistent and might accumulate in sediments if the pH is low enough to allow adsorption to suspended material. Acutely toxic effects are improbable because the expected brine concentrations are well below the LC_{50} values of trout and Daphnia magna. Still the substance is classified as harmful for marine organisms. The release of benzotriazole per cubic metre product water, corresponding to a continuous dosage of 3-5 ppm to the feed water, amounts to 9-15 g.

The most important representative of heavy metals dissolved from the tubing material is copper, because copper-nickel heat exchangers are widely used. In brines from MSF plants it represents a major contaminant. Assuming a copper level of 15 ppb in the brine and a product-brine-ratio of 1:2 /Höpner and Lattemann 2002/, the resulting output from the reference MSF plant with a capacity of 24,000 m³/d is 720 g copper per day. Generally, the hazard to the ecosystem emanates from the toxicity of copper at high levels. Here, levels are low enough not to harm the marine biota, but accumulation of copper in sediments represents a latent risk as it can be remobilised when conditions change from aerobic to anaerobic due to a decreasing oxygen concentrations. To illustrate the latent risk posed by discharge of untreated brine Figure 6-5 compares reported discharge levels to eco-toxicity values and the EPA water quality criteria. The eco-toxicity values have been derived from values which have been determined during tests with copper sulphate under the assumption that copper sulphate is of less concern for saltwater organisms /Lattemann and Höpner 2003/. Diluting discharge water with cooling water does not produce relief as reported levels are still above water quality criteria and total loads stay the same.

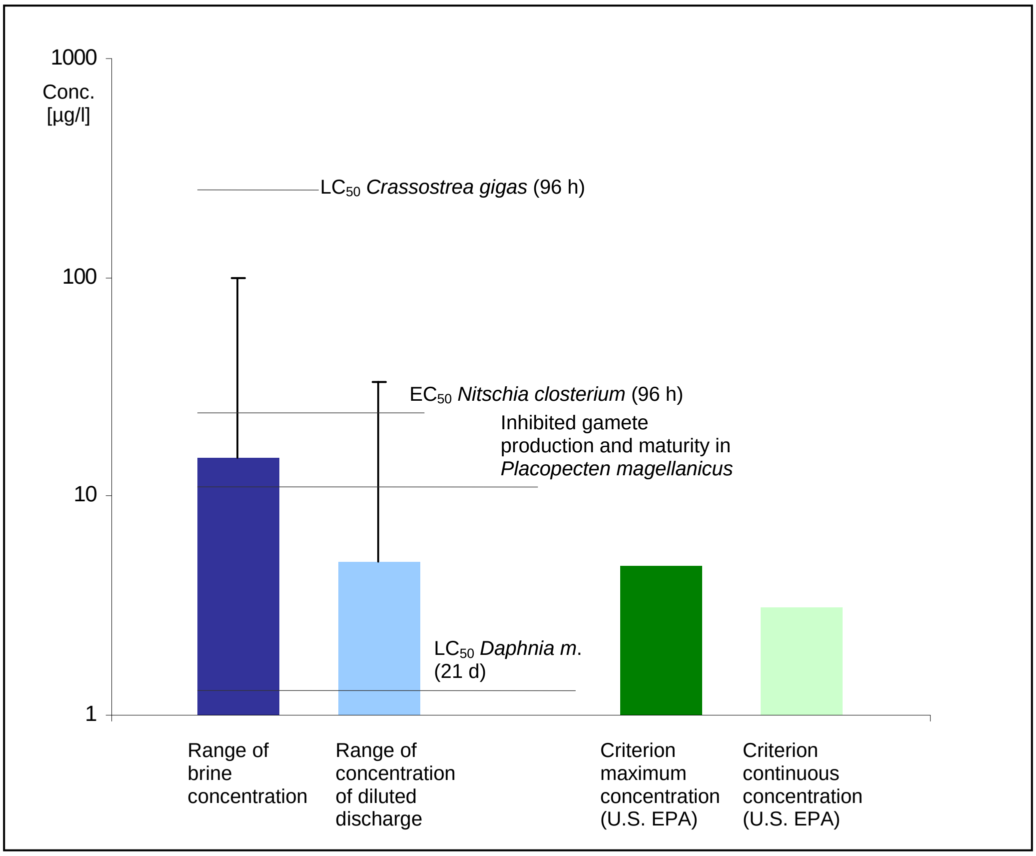


Figure 6-5: Copper: Eco-toxicity (LC50 = mean lethal concentration, EC50 = mean effective concentration) compared to ranges of brine concentration and water quality criteria, /Lattemann and Höpner 2003/, modified

6.2 Multi-Effect Distillation Desalination (MED)

6.2.1 Seawater Intake

The flow rate of the cooling water which is discharged at the outlet of the final condenser depends on the design of the MED distiller and the operating conditions. In the case of a conversion rate of 11 % (related to the seawater intake flow), 9 m³ of seawater are required for 1 m³ of fresh water (Figure 6-6). Due to the smaller unit sizes the seawater intake capacity for a single MED unit would be lower than for a single MSF unit, but in the majority of cases the required distillate production is reached by installing several units in parallel. Thus, the seawater intake capacity for MED plants and MSF plants would be similar. Nevertheless, the potential damage caused by impingement and entrainment at the seawater intake must be regarded as high.

6.2.2 Discharge of Brine Containing Additives

The discharge of brine represents a strong impact to the environment due to its changed physical properties and to the residues of chemical additives or corrosion products. In MED plants common chemical additives are biocides, antiscalants, antifoaming agents at some plants, and corrosion inhibitors at some plants. The conditioning of permeate to gain palatable, stable drinking water requires the addition of chlorine for disinfection, calcium, e.g. in form of calcium hydroxide, for remineralization and pH adjustment /Raluy 2003/, /Delion et al. 2004/. Figure 6-7 shows where the chemicals are added and at which concentrations as well as the characteristics of the brine and its chemical load.

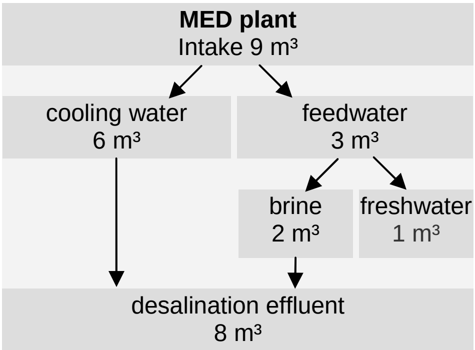


Figure 6-6: Flow chart of reference MED process

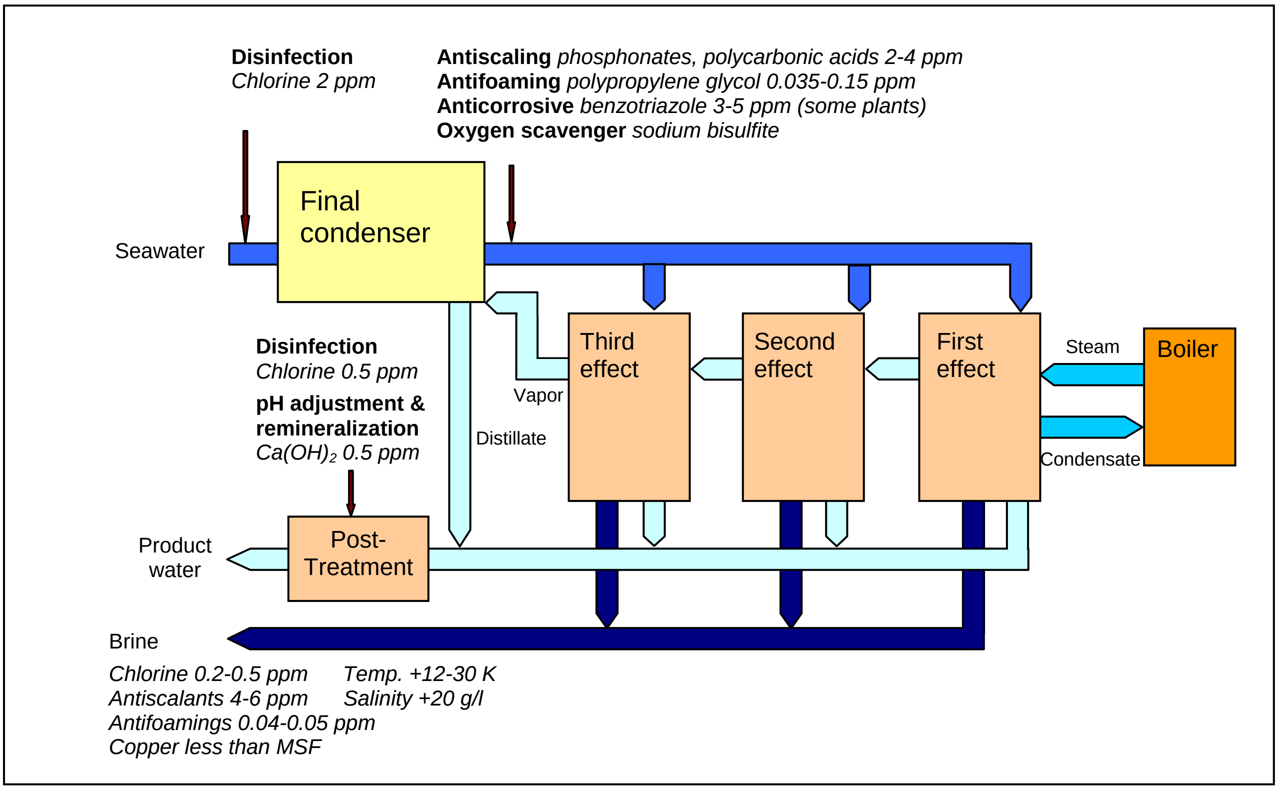


Figure 6-7: MED process scheme with input and output concentrations of additives and brine characteristics

Physical Properties of Brine

The physical parameters of the brine are different compared to the intake seawater. During the distillation process the temperature rises and salt accumulates in the brine. Taking the reference process (Figure 6-6) with a conversion rate of approx. 11.2 % as example the salinity rises from 45 g/l to 66 g/l (Figure 6-8). Brine and cooling water temperature rises by about 14 and 10 K, respectively. Salinity of the brine is reduced by blending with cooling water, but still reaches a value of 5.6 g/l above ambient level. The resulting decrease of density is very small what can be attributed to balancing effects of temperature and salinity rise.

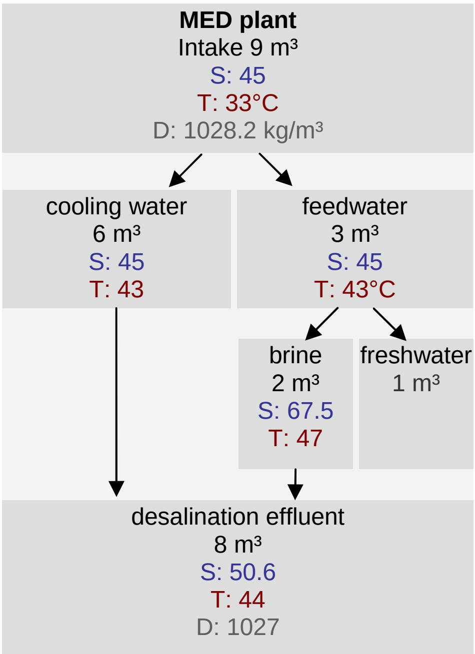


Figure 6-8: Flow chart of reference MED process with salinity (S, in g/l), temperature (T, in °C) and density (D, in g/l), /Lattemann and Höpner 2003/, modified

Biocides

Surface water contains organic matter, which comprises living or dead particulate material and dissolved molecules, leads to biological growth and causes formation of biofilm within the plant. Therefore both the feed water and the cooling water are disinfected with the help of biocides. The most common biocide in MED plants is chlorine. A concentration of up to 2000 µg/l is sustained by a continuous dosage. Chloride reacts to hypochlorite and, in the case of seawater, especially to hypobromite. Residual chloride is released to the environment with the brine where it reaches values of 200-500 µg/l, representing 10-25 % of the dosing concentration. Assuming a product-effluent-ratio of 1:8 the specific discharge load of residual chlorine per m³ of product water is 1.6-4.0 g/m³. For a plant with a daily desalination capacity of 24,000 m³, for instance, this means a release of 38.4-96.0 kg of residual chlorine per day. The effects of chlorine are described in Chapter 6.1.2.

Antiscalants

A major problem of MED plants is the scale formation on the heat exchanger surfaces which impairs the heat transfer. The most common scale is formed by precipitating calcium carbonates due to increased temperatures and brine concentration. Other scale forming species are magnesium hydroxide, and calcium sulphate, the latter being very difficult to remove as it forms hard scales. Therefore sulphate scaling is avoided in the first place by regulating the operation parameters temperature and concentration in such a way that the saturation point of calcium sulphate is not reached. Calcium carbonates and magnesium hydroxides, again, are chemically controlled by adding acids and/or antiscalants.

In the past, acid treatment was commonly employed. With the help of acids the pH (acidity value) of the feed water is lowered to 2 or 3 and hereby the bicarbonate and carbonate ions chemically react to carbon dioxide which is released in a decarbonator. Thus, the $CaCO_3$ scale forming ions are removed from the feed water. After acid treartment the pH of the feed water is re-adjusted. Commonly used acids are sulphuric acid and hydrochloric acid, though the first is preferred because of economic reasons. High concentrations and therefore large amounts of acids are necessary for the stoichiometric reaction of the acid. Apart from a high consumption of acids further negative effects of using acids are the increased corrosion of the construction materials and thus reduced lifetimes of the distillers as well as handling and storage problems. The negative effects mentioned above have led to the development of alternatives: Nowadays antiscalants are replacing acids during operation. But before talking about antiscalants, the use of acids as cleaning agents needs to be mentioned because that's when significantly acidic effluents occur. During this periodic cleaning procedure the pH is lowered to 2-3 by adding citric or sulfamic acid, for instance, to remove carbonate and metal oxide scales. In this context Mabrook (1994, in /Lattemann and Höpner, 2003/) explained an observed change in density and diversity of marine organisms by a decreased pH of 5.8 compared to 8.3 in coastal waters. Ecotoxic pH values range from 2-2.5 for starfish (LC_{50}, HCl, 48 h) to 3-3.3 for salt water prawn (LC_{50}, H_2SO_4, 48 h) and show the sensitivity of marine organisms to low pH values. Little mobile organisms, like starfish, are especially affected by an acid plume as they cannot avoid this zone. To mitigate these possible effects the cleaning solution should be neutralized before discharge or at least blended with the brine during normal operation.

The mode of action of antiscalants is described in Chapter 6.1.2. They react substoichiometrically which is the reason why they are effective at very low concentrations. Polyphosphates represent the first generation of antiscalant agents with sodium hexametaphosphate as most commonly used species. A procedural disadvantage is the risk of calcium phosphate scale formation. Of major concern to the aquatic environment is their hydrolytic decomposition at 60°C to orthophosphate which acts as a nutrient and causes eutrophication. The development of algae mats on the water body receiving the discharge could be ascribed to the use of phosphates

(Abdel-Jawad and Al-Tabtabaei 1999, in /Lattemann and Höpner 2003/). Because of these reasons they have partly been substituted by thermally stable phosphonates and polycarbonic acids, the second generation of antiscalants. Where phosphates have been replaced by these substances the problem of algae growth could be solved completely. Main representatives of polycarbonic acids are polyacrylic and polymaleic acids. Especially polyacrylic acid has to be dosed carefully if precipitation is to be avoided. The reason for this is that, at lower concentrations, it enhances agglomeration and therefore also serves as a coagulant in RO plants. Discharge levels of phosphonates and polycarbonic acids are classified as non-hazardous, as they are far below concentrations with toxic or chronic effects. They resemble naturally occurring humic substances when dispersed in the aquatic environment which is expressed by their tendency to complexation and their half-life of about one month, both properties similar to humic substances. Though they are generally assumed to be of little environmental concern, there is a critical point related to these properties. As they are rather persistent they will continue to complex metal ions in the water body. Consequently, the influence on the dissolved metal concentrations and therefore metal mobility naturally exerted by humic substances is increased by polymer antiscalants. The long-term effect induced hereby requires further research.

A MED plant with a daily capacity of 24,000 m³ releases about 144-288 kg of antiscalants per day if a dosage concentration of 2-4 mg per litre feedwater is assumed. This represents a release of 6 g per cubic meter of product water.

Antifoaming Agents

MED plants also use antifoaming agents, but compared to MSF plants, it’s less usual. The use of antifoaming agents can be necessary if foam forms in the presence of organic substances concentrated on the water surface which derogates the thermal desalination process by hampering the falling film flow onto the horizontal evaporator tubes and thus the wetting of the tubes.

As the agents are organic substances, too, they must carefully be chosen and dosed. Blends of polyglycol are utilized, either containing polyethylene glycol or polypropylene glycol. These substances are generally considered as non-hazardous and low discharge concentrations of 40-50 µg/l per litre brine further reduce the risk of environmental damage. However, highly polymerized polyethylene glycol with a high molecular mass is rather resistant to biodegradation. On this account it has been replaced in some industrial applications by substances, such as dialkyl ethers, which show a better biodegradability.

Under the assumption of a product-feedwater-ratio of 1:3 and 0.035-0.15 ppm dosing 0.1-0.45 g per cubic meter of product water are released.

Corrosion Inhibitors and Corrosion Products

The corrosion inhibitors that are used in MSF plants are also necessary in MED plants. However, it is assumed that the copper load is smaller compared to MSF plants as operation temperatures are lower and piping material with lower copper contents are used, such as titanium and aluminium-brass.

6.3 Reverse Osmosis (RO)

6.3.1 Seawater Intake

The conversion rate of RO processes ranges between 20 and 50 % /Goebel 2007/, signifying an intake volume of less than 5 m³ of seawater per cubic meter of freshwater. Therefore, compared to the thermal processes the mechanical process of RO requires significantly less intake water for the same amount of product water. Consequently the loss of organisms through impingement and entrainment is lower. The flows, shown in Figure 6-9, result from a conversion rate of 33 %.

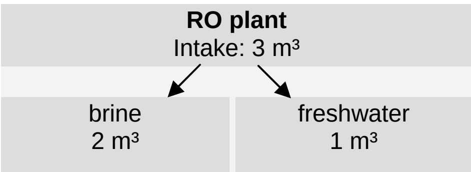


Figure 6-9: Flow chart of reference RO process

6.3.2 Discharge of Brine Containing Additives

The discharge of brine represents a strong impact to the environment due to its changed physical properties and to the residues of chemical additives or corrosion products. In RO plants common chemical additives are biocides, eventually acids if not yet substituted by antiscalants, coagulants, and, in the case of polyamide membranes, chlorine deactivators. The conditioning of permeate to gain palatable, stable drinking water requires the addition of chlorine for disinfection, calcium, e.g. in form of calcium hydroxide, for remineralization and pH adjustment /Raluy 2003/, /Delion et al. 2004/. Figure 6-10 shows where the chemicals are added and at which concentrations as well as the characteristics of the brine and its chemical load.

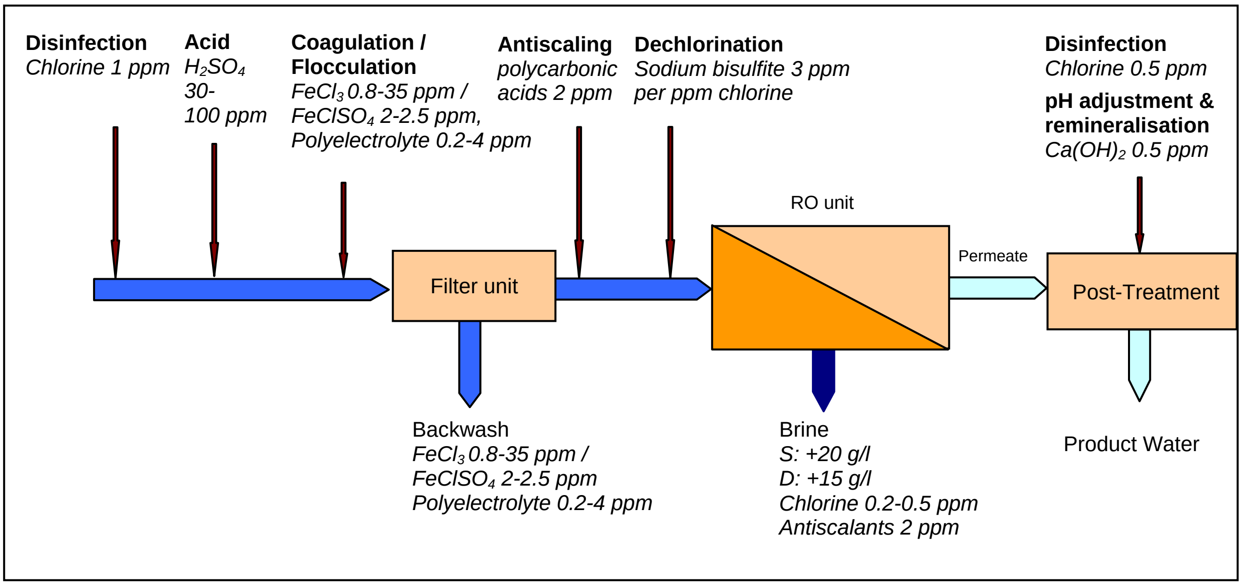


Figure 6-10: RO process scheme with input and output concentrations of additives and brine characteristics, /Lattemann and Höpner 2003/, modified

Physical Properties of Brine

The salinity of the brine is increased significantly due to high conversion rates of 30 to 45 %. The conversion rate of 32 % of the process presented in Figure 6-9 leads to a brine salinity of 66.2 g/l (Figure 6-11). As the temperature stays the same during the whole process, also density increases significantly from 1028 g/l to 1044 g/l. If the RO process is coupled with electricity generation and the effluent streams are blended, the warmed cooling water from the power plant reduces the overall density slightly compared to the ambient value and the overall salinity is almost reduced to the ambient level.

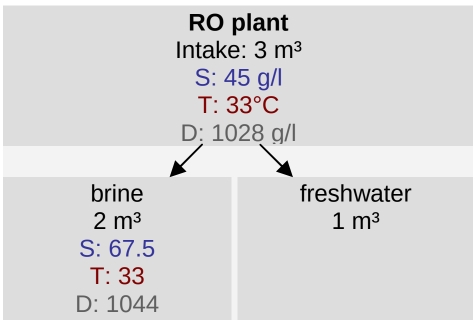


Figure 6-11: Flow chart of reference RO process with salinity (S, in g/l), temperature (T, in °C) and density (D, in g/l), /Lattemann and Höpner 2003/, modified

Biocides

Surface water contains organic matter, which comprises living or dead particulate material and dissolved molecules, leads to biological growth and causes formation of biofilm within the plant.

Therefore the RO feed water is disinfected with the help of biocides. The most common biocide in RO plants is chlorine. A concentration of up to 1000 µg/l is sustained by a continuous dosage. Chloride reacts to hypochlorite and, in the case of seawater, especially to hypobromite. In RO desalination plants operating with polyamide membranes dechlorination is necessary to prevent membrane oxidation. Therefore the issue of chlorine discharge is restricted to the smaller portion of plants which use cellulose acetate membranes. Regarding these plants residual chlorine is released to the environment with the effluents where it reaches values of 100-250 µg/l, representing 10-25 % of the dosing concentration. Assuming a product-effluent-ratio of 1:2 the specific discharge load of residual chlorine per m^3 of product water is 0.2-0.5 g/m^3. For a plant with a daily desalination capacity of 24,000 m^3, for instance, this means a release of 4.8-12 kg of residual chlorine per day. Again, the problem of chlorine discharge is restricted to plants with cellulose acetate membranes. In contrast, the release of chlorination by-products is an issue at all RO plants regardless of the material of their membranes, as by-products form up to the point of dechlorination. The effects of chlorine are described in chapter 6.1.2.

Coagulants

The removal of suspended material, especially colloids, beforehand is essential for a good membrane performance. For this purpose coagulants and polyelectrolytes are added for coagulation-flocculation and the resulting flocs are hold back by dual media sand-anthracite filters. Coagulant substances are ferric chloride, ferrous sulphate, and ferric chloride sulphate or aluminium chloride. To sustain the efficiency of the filters, they are backwashed regularly. Common practice is to discharge the backwash brines to the sea. This may affect marine life as the brines are colored by the coagulants and carry the flocs (see Figure 6-12). On the one hand the decreased light penetration might impair photosynthesis. On the other hand increased sedimentation could bury sessile organisms, especially corals. The dosage is proportional to the natural water turbidity and can be high as 30 mg/l. This extreme dosage results in a specific load of 90 g per m^3 of product water and a daily load of a 24,000 m^3/d plant of 2200 kg which adds to the natural turbidity.

Polyelectrolytes support the flocculation process by connecting the colloids. Possible substances are polyphosphates or polyacrylic acids and polyacrylamides respectively, which are also used as antiscalants. The concentration decides whether they have a dispersive or coagulative effect. Compared to their use as antiscalants the dosage of polyelectrolytes is about a tenth of the concentration required for dispersion. These substances are not toxic; the impact they cause is connected to the increased turbidity. A dosage of 500 µg/l implies a discharge of 1.5 g per m^3 of product water and a daily load of a 24,000 m^3/d plant of 36 kg which adds to the natural turbidity.

Figure 6-12: Red brines containing ferric sulphate from filter backwash at Ashkelon RO desalination plant; backwash with 6,500 m³ in 10-15 minutes every hour. Photo: Rani Amir, Director of the Marine and Coastal Environment Division of the Ministry of the Environment, presented by Iris Safrai, Ministry of the Environment, at the EDS Conference on Desalination and the Environment, Halkidiki, Greece, April 2007.

Antiscalants

The main scale forming species in RO plants are calcium carbonate, calcium sulphate and barium sulphate. Acid treatment and antiscalant dosage are used for scale control. Here, sulphuric acid is most commonly used and dosed with a range of 30-100 mg/l. During normal operation the alternative use of antiscalants, such as polyphosphates, phosphonates or polycarbonic acids, has become very common in RO plants due to the negative effects of inorganic acid treatment explained in Chapter 6.1.2. As it is explained there, these antiscalants react substoichiometrically and therefore low concentrations of about 2 mg/l are sufficient.

A RO plant with a daily capacity of 24,000 m³ releases about 144 kg of antiscalants per day if dosage concentration of 2 mg per litre feedwater and product-feedwater-ratio of 1:3 are assumed /Höpner and Lattemann 20002/. This represents a release of 6 g per cubic meter of product water.

Membrane Cleaning Agents

Apart from acid cleaning, which is carried out with citric acid or hydrochloric acid, membranes are additionally treated with sodium hydroxide, detergents and complex-forming species to remove biofilms and silt deposits.

By adding sodium hydroxide the pH is raised to about 12 where the removal of biofilms and silt deposits is achieved. Alkaline cleaning solutions should be neutralized before discharge, e.g. by blending with the brine.

Detergents, such as organo-sulfates and –sulfonates, also support the removal of dirt particles with the help of both their lipophilic and hydrophilic residues. Regarding their behaviour in the marine environment, organo-sulfates, e.g. sodium dodecylsulfate (SDS), and organo-sulfates, e.g. sodium dodecylbenzene sulfonate (Na-DBS), are quickly biodegraded. Apart from the general classification of detergents as toxic no further information is available on toxicity of Na-DBS, but it's assumed to be relatively low once the decomposition has started with cutting off the hydrophilic group. In contrast, LC50 for fish, Daphnia magna and algae are available in the case of SDS confirming the categorization as toxic substance. But, again, fast degradation reduces the risk for marine life. This risk could be further reduced by microbial waste treatment which destroys the surface active properties and degrades the alkyl-chain.

Complex-forming species, such as EDTA (Ethylendiamine tetraacetic acid) are employed for the removal of inorganic colloids and biofouling. From comparing the calculated maximum estimate of discharge concentration (46 mg/l) and an LC50 for bluegill (159 mg/l, 96 h) it can be deduced that in the case of EDTA direct toxicity is of minor concern. In contrast, persistent residual EDTA in the marine environment might provoke long-term effects in connection with its chelating and dispersing properties. Consequences of increased metal solubility and mobility and thereby reduced bioavailability still need further investigation. Generally, total amounts are of bigger interest than concentrations.

During the periodic membrane cleaning process also further disinfectants such as formaldehyde, glutaraldehyde, isothiazole, and sodium perborate, are used. These substances are toxic to highly toxic and reach toxic concentrations if discharged all at once. Therefore deactivation should be compulsory. Several deactivation substances are available: formaldehyde can be deactivated with hydrogen peroxide and calcium hydroxide or sodium hydroxide and isothiazole is neutralized with sodium bisulfite. Sodium perborate has to be handled carefully as it breaks down to sodium borate and hydrogen peroxide. The latter is the actual biocide and therefore may not be overdosed, also for reasons of membrane protection as it has an oxidizing effect.

Corrosion Products

In RO plants corrosion is a minor problem because stainless steels and non-metal equipment predominate. There are traces of iron, nickel, chromium and molybdenum being released to the water body, but they do not reach critical levels /Lattemann and Höpner 2007a/. Nevertheless, an environmentally sound process should not discharge heavy metals at all; therefore alternatives to commonly used material need to be found.

Dechlorination

The removal of chlorine is performed with sodium bisulfite, which is continuously added to reach a concentration three to four times higher than the chlorine concentration, the former amounting to 1500-4000 µg/l. The corresponding amount per cubic metre of product water is 4.5-12 g/m³. As this substance is a biocide itself and harms marine life through depletion of oxygen, overdosing should be prevented. Alternatively sodium metabisulfite is used.

6.4 Life-Cycle Assessment of Materials and Emissions

6.4.1 Methodology of LCA and Material Flow Networks

Generally accepted guidelines for carrying out a Life Cycle Assessment (LCA) can be found in ISO 14040 ff. /Guinée 2002/. In an LCA the *production*, the *operation*, and the *dismantling* of the considered products are modelled. Included are the upstream processes of the most important fuels and materials. In Figure 6-13 this is demonstrated by the example of a solar thermal power plant's life cycle. Starting with the production of the solar thermal power plant the upstream processes of both the used materials and the used electricity are modelled up to the mining processes of the crude materials. To operate the plant, some more materials are used (for example reimbursement of broken mirrors, make-up heat transfer fluid, water for cleaning the mirrors). For the time being the plant's end of life is only considered partly because there does not exist adequate data and concepts up to now.

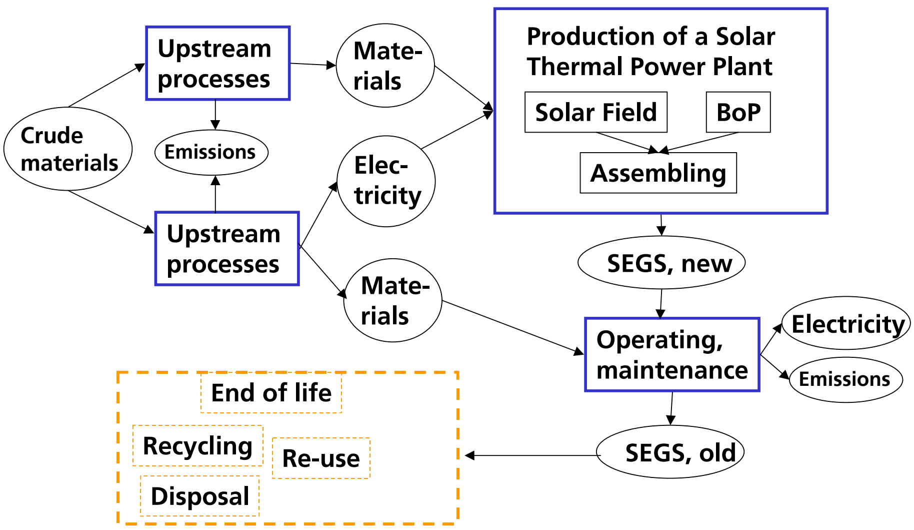


Figure 6-13: Life cycle of a solar thermal power plant (type SEGS)

After modelling the relevant material and energy flows in a material flow net the life cycle inventory is created. The input-output balance of the whole system is calculated using upstream processes taken from commercial LCA databases. Finally, the environmental impacts are calculated by allocating the resulting emissions to different impact categories (global warming potential, acidification, or resource consumption, for example). By scaling the results to a functional unit (1 kWh electricity or 1 m^3 water) different production processes can be compared and the best technology with regard to an impact category can be selected.

6.4.2 Frame conditions and data sources

In a broad sense the question should be answered if environmental impacts associated with the provision of desalted water using fossil primary energy carriers can be reduced by a system using concentrated solar power. Furthermore, it is also interesting to what extent a changed electricity mix for the production of the facilities could have an effect on the balance, like e.g. the electricity mix in MENA used for RO or heat and power provided by a gas-fired combined generation (CHP) plant for MED and MSF.

The LCA considers exploration, mining, processing and transportation of the fuels, especially for the electricity mix as well as materials for the required infrastructure. Furthermore, the production of single components is considered. This comprises the solar field, steam generator, mechanical and electrical engineering, constructional engineering, thermal energy storage, steam turbine and the desalination plant. Modelling of the facility operation includes maintenance, i.e., cleaning and material exchange. The disposal of the facility is composed of the demolition, depository and recycling.

The function studied in the LCA is that of cleaning seawater with a salinity of 45 g/l to produce freshwater with 200 ppm salt included. The *functional unit* has been defined as 1 m^3 of freshwater delivered from the plant.

In the following paragraphs it is differentiated between materials, modules, and components. While a *material* means stainless steel or molten salt an *(LCA) module* means the process of manufacturing these materials (and representing this process as LCA data). A *component* consists of different materials and modules, for example the solar field of a power plant.

The *reference period* for this study is the year 2007 that means the most actual available LCA modules are used. *Reference area* is the MENA region. Since LCA modules are not available for this region modules representing the European situation are used. This means that the results are based on production processes with a better performance and efficiency than usually available in the MENA region.

The MENA electricity mix is modelled to be able to compare RO using MENA electricity with RO using solar electricity. Notwithstanding the former assumptions it is modelled regarding a possible situation in 2010. This means that the results of RO using MENA electricity become better than today's situation because the 2010 electricity mix considers more renewable energies than used today.

As sources for the LCA modules in general the Swiss LCA database ECOINVENT® /ecoinvent 2007/ is used. For some modules not available in /ecoinvent 2007/ the LCA tool UMBERTO® /IFEU/IFU 2007/ is used. The material and energy flow network as well as the life cycle impact assessment is modelled with Umberto.

The study uses the most recent inventory data available both for solar thermal power plants and the desalting processes:

Solar thermal power plant

As CSP plant a direct steam based trough is chosen. As reference the pre-commercial 5 MW INDITEP power plant planned to be built in Spain is taken and scaled up to 20 MW. The data is taken from /NEEDS 2007/. Instead of using parabolic troughs as designed for INDITEP the solar field is exchanged by a linear Fresnel collector field. Data for one m^2 solar field provided by the company Novatec-Biosol who developed Fresnel mirrors with a very light design was implemented /Novatec 2007/. The solar field is linearly scaled up to the necessary extent.

Since for direct steam technology a latent heat storage medium is needed for evaporation, DLR provided data for a 6 hours 50 MW_{el} storage system using phase change materials (PCM) based on PCM developments in laboratory scale. The storage system is linearly scaled up to the necessary extent. It operates in three steps /Michels and Pitz-Paal 2007/: During the *preheating* step a conventional concrete storage is used which is heated up (sensible heat storage). This step is followed by the *evaporation* phase served by a (cascaded) latent heat storage. The increasing heat causes (several) phase changes (e.g. from solid to liquid) but does not increase the storage temperature by itself. In the last step, the *superheating* phase, a concrete storage is used again. For the applied storage system $NaNO_3$ is used, but in general different mixtures of $NaNO_3$, KNO_3 and KCL are possible. To increase the thermal conductivity aluminium plates are placed into the salt.

To refer the resulting emissions to one kWh the yearly expected output has to be multiplied with the expected life time of the power plant. The following lifetimes are assumed: solar field and power block: 30 years, storage system 25 years, building 60 years.

Desalination plants

The same desalination plants as described in the former chapters are modelled within the LCA. The inventory data is taken from /Raluy et al. 2006/. Table 6-1 shows the relevant energy consumptions of the desalting plants based on 46 000 m^3/d capacity. The lifetime of the desalination plants is assumed to be 25 years, that of the building to be 50 years.

Energy source	Unit	MED	MSF	RO
Electricity	kWh / m^3 desalted water	2	4	4
Heat	MJ / m^3 desalted water	237	300	

Table 6-1: Energy consumption of seawater desalination plants. MSF Multi-Stage Flash, MED Multi-Effect Desalination, RO Reverse Osmosis

MENA electricity mix

The MENA electricity mix was built using electricity production modules available in the ecoinvent database and suitable to the MENA situation assumed for 2010. For example, the electricity generation from oil was modelled using the Greek module because of its low energy efficiency. Table 6-2 presents details on the assumed MENA mix.

Energy source	Share		LCA module (ecoinvent name)	Efficiency
	%	TWh/a		%
Renewables	6	50	electricity, hydropower, at power plant [GR]	
Oil	63	500	electricity, oil, at power plant [GR]	37.9
Natural Gas	25	200	electricity, natural gas, at power plant [IT]	37
Hard Coal	6	40	electricity, hard coal, at power plant [ES]	35.8

Table 6-2: Composition of the modelled MENA electricity mix

Natural gas fired power plants

Both natural gas fired power plants (the combined cycle power station as well as the combined heat and electricity power station) are taken from ecoinvent representing the best available technology within this group. Figure 6-14 shows the evaluated seawater desalination technologies and their possible combination with energy from solar thermal power plants and fossil fuels. The Reverse Osmosis (RO) Membrane Technology is combined with electricity from the solar thermal power plant and compared with the same technology using electricity from the MENA mix and – as best available technology – electricity from a gas-fired combined cycle power station. Multi-Effect-Distillation (MED) and Multi-Stage Flash Desalination both need power and steam. MED is combined with electricity and steam delivered by the CSP plant. This combination is compared with MED and MSF both using electricity and steam from a natural gas fired CHP plant using the best available technology.

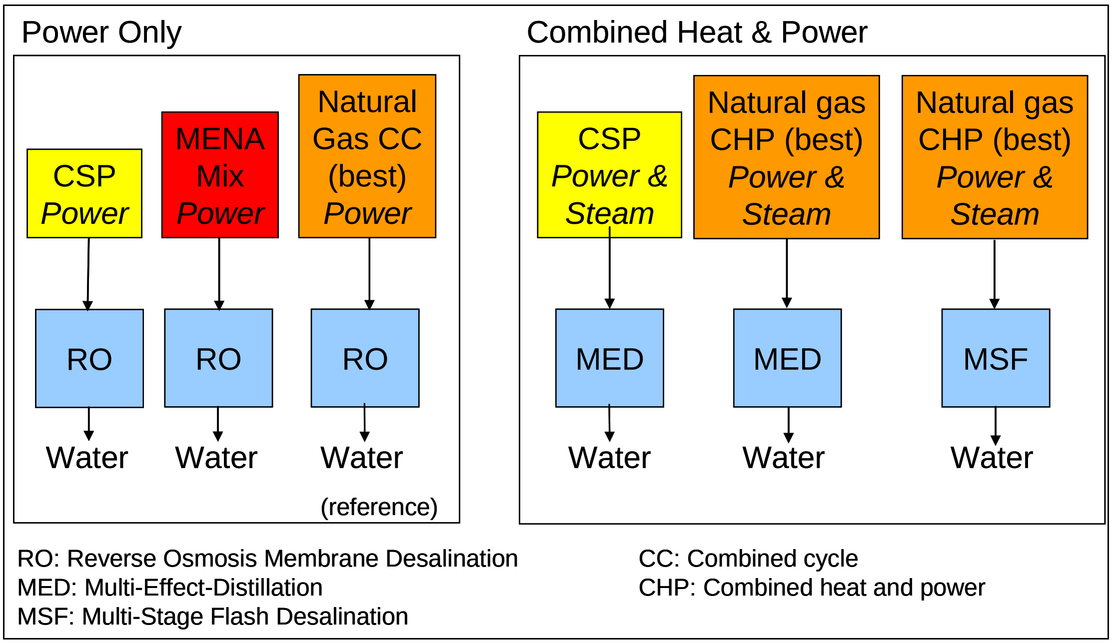


Figure 6-14: Considered seawater desalination technologies based on solar energy or fossil fuels

Impact category	Inventory parameter	Aggregated impact parameter	Ratio
Resource consumption	Cumulated Energy Demand (CED)	MJ (inventory parameter)	
Global warming [a]	CO_2	g CO_2-Equivalents	1
	CH_4		21
	N_2O		310
Acidification	SO_2	mg SO_2-Equivalents	1
	NO_X		0.7
	NH_3		1.88
	HCl		0.88
Eutrophication	NO_X	mg PO_4^{3-}-Equivalents	0.13
	NH_3		0.33
Summer Smog (Photochemial oxidant)	NMHC	mg Ethen-Equivalents	0.416
	CH_4		0.007
Cancerogenic potential, human-toxicity	Particles and dust	mg (inventory parameter)	
[a] Time horizon 100 years			

Table 6-3: Impact categories and inventory parameters applied in this study.

The results are compared to desalted water stemming from a reverse osmosis plant that receives electricity from a gas-fired combined cycle power station (third version in the figure below) because in terms of environmental impact it represents the best possible conventional solution for desalination based on fossil fuel available today. According to ISO 14 042 requirements impact categories have to be chosen to assess the results of the inventory analysis (so called life cycle impact assessment). The impact categories applied in this study are taken from the method

"UBA-Verfahren" provided by the German Federal Environmental Agency (UBA) /UBA 1995, UBA 1999/. The parameters result from the impact categories and are shown in Table 6-3.

6.4.3 Results

Figure 6-15 shows the results for the six impact categories. They are scaled to the best possible conventional solution (reverse osmosis plant combined with a gas-fired combined cycle power station, 100 % line). The figure clearly shows that the environmental impact of MSF, even if operated by steam stemming from combined heat & power (CHP), would have a five-fold impact with respect to energy and global warming, and even an eleven-fold impact with respect to eutrophication when compared to the best conventional case. The next strongest impact is caused by MED operated with steam from fossil fuel fired CHP which is still three- to seven-fold with respect to the best case. Reverse osmosis powered by the electricity mix available in MENA has also considerably higher emissions than the best case and even represents the worst case in the category acidification due to high consumption of electricity, rather low efficiencies of power generation, and the intensive use of fuel oil in the MENA electricity mix.

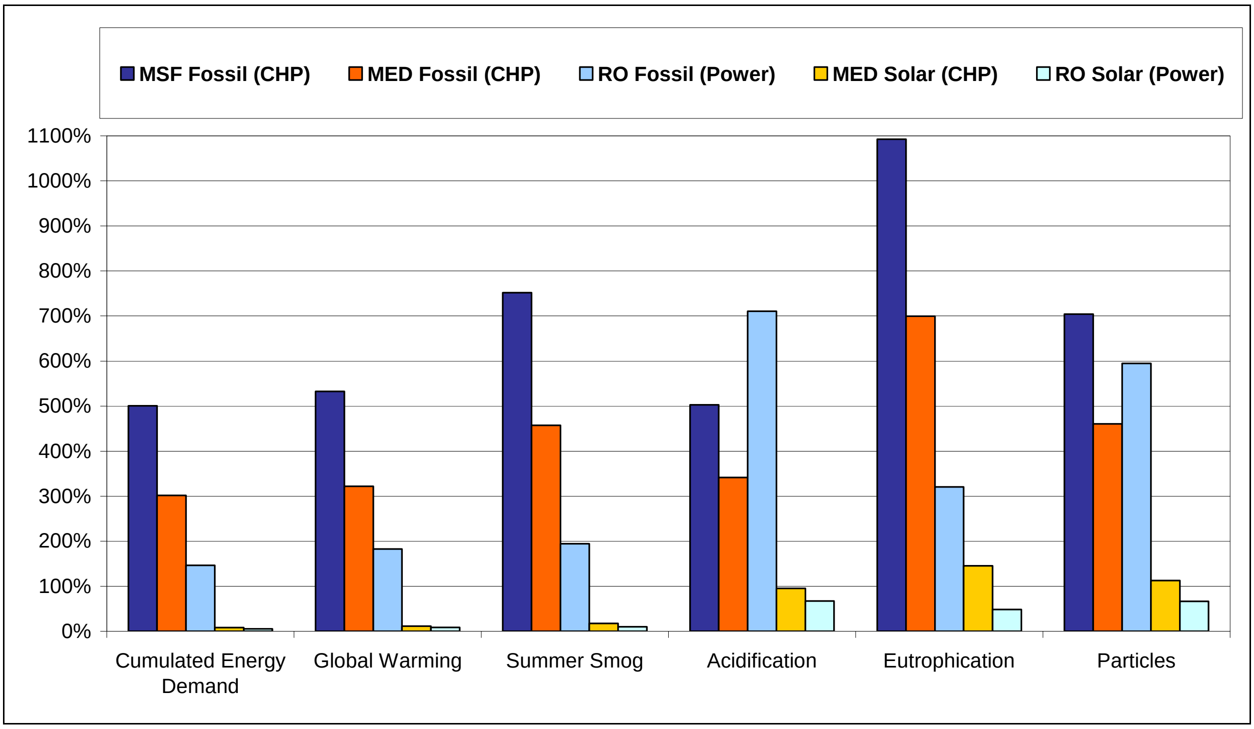


Figure 6-15: Life-cycle emissions of seawater desalination technologies in the MENA region based on fossil fuel and concentrating solar power compared to the best possible conventional solution based on a gas-fired combined cycle power plant providing electricity for reverse osmosis (100%). MSF Multi-Stage Flash, CHP Combined Heat & Power, MED Multi-Effect Desalination, RO Reverse Osmosis.

The figure shows clearly that for all categories conventional reverse osmosis has lower impacts than conventional MSF and MED, and that MED is also considerably better than MSF. It also shows that, depending on the category, in case of operating RO and MED using concentrating solar power as energy source, between 90 % and 99 % of the overall emissions can be eliminated. Therefore, CSP eliminates one of the major causes of environmental impact of seawater desalination: the emissions related to its large energy demand.

Impact Category	Unit	MED Solar (CHP)	RO Solar (Power)	RO Fossil (Power)	MED Fossil (CHP)	MSF Fossil (CHP)
Cumulated Energy Demand	kJ/m³	3,579	2,298	63,790	131,767	218,417
Global Warming	kg CO2/m³	0.27	0.21	4.41	7.75	12.83
Summer Smog	kg Ethen / m³	5.89E-05	3.30E-05	6.53E-04	1.54E-03	2.53E-03
Acidification	kg SO2 /m³	4.48E-03	3.16E-03	3.35E-02	1.61E-02	2.37E-02
Eutrophication	kg PO4 / m³	4.50E-04	1.49E-04	9.90E-04	2.16E-03	3.38E-03
Particles	kg PM10/ m³	1.01E-03	5.97E-04	5.33E-03	4.13E-03	6.31E-03

Table 6-4: Life-cycle emissions of seawater desalination plants in the MENA region based on fossil fuel vs. plants based on concentrating solar power. MSF Multi-Stage Flash, CHP Combined Heat & Power, MED Multi-Effect Desalination, RO Reverse Osmosis.

In case of the CSP/RO plant, the remaining emissions related to the construction of the solar field, the thermal energy storage and the power block are comparable to those related to the construction of the RO plant itself (Figure 6-16). The same is true for CSP/MED, in fact in this case the emissions related to the construction of the solar field, the thermal energy storage and the power block are clearly smaller than those related to the MED plant itself, due to its large material demand (Figure 6-18). It can be appreciated in Figure 6-19 that emissions related to the MED plant have a higher contribution to the overall emissions than in the case of RO, due to the same reason.

Compared to the presently used standard solution for seawater desalination in the MENA region, a multi-stage flash plant connected to a combined heat and power station, CSP/RO and CSP/MED reduce the cumulated energy consumption and the emission of greenhouse gases to about 1 %. Thus, CSP desalination offers a cost-effective and environmental-friendly solution for the MENA water crisis and can solve the problem of water scarcity in a sustainable way, taking also into account all necessary measures for water efficiency and re-use.

If the electricity mix used for the production of the plants can be changed to more renewable energy in the future, the overall emissions will be reduced even further.

However, there are also considerable environmental impacts related to the concentrated brine and to the chemicals contained in the effluent of both RO and MED seawater desalination plants. In the following we will investigate a series of possible solutions to mitigate those emissions to a compatible level.

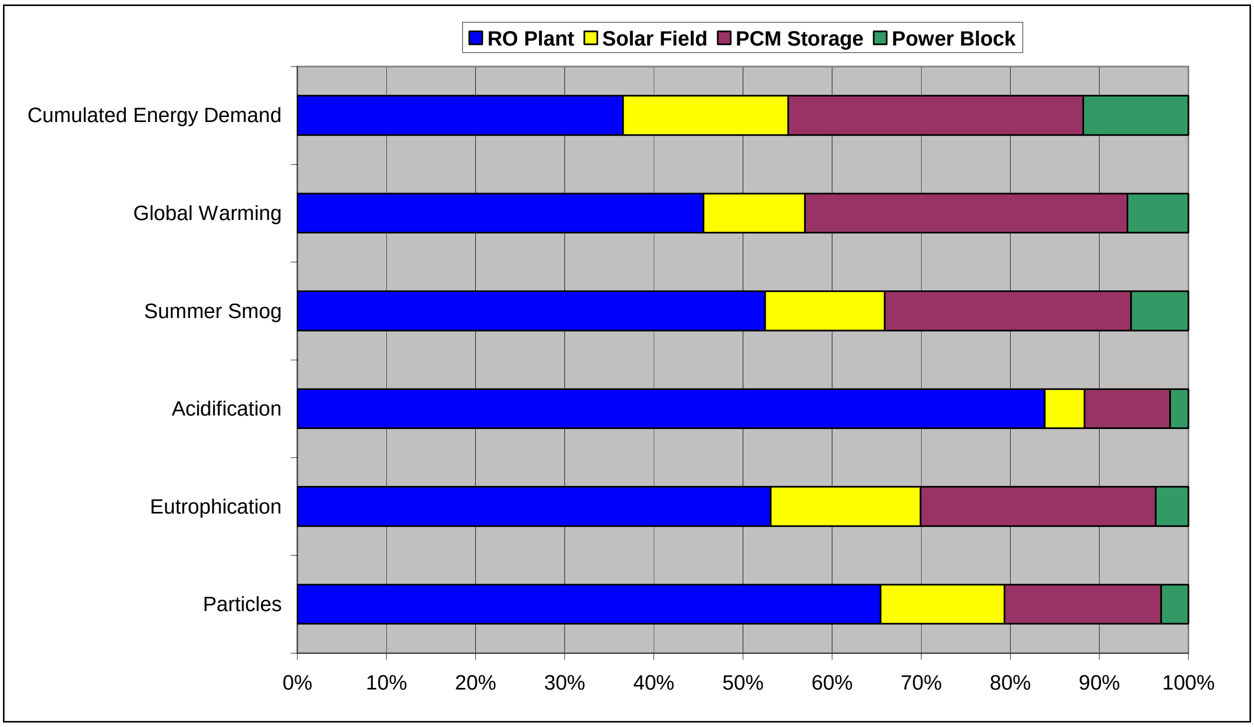


Figure 6-16: Contribution of the different components of a solar CSP/RO plant to life-cycle emissions.

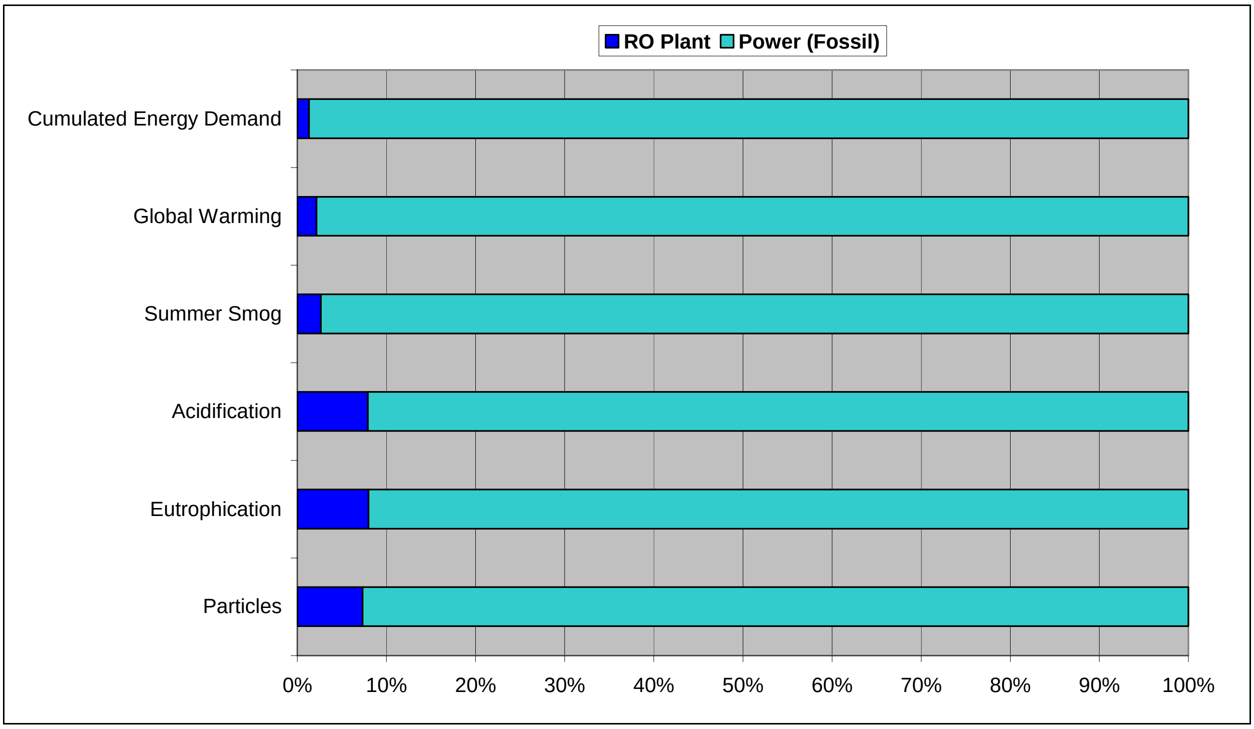


Figure 6-17: Contributions to the life-cycle emissions of a conventional RO plant receiving power from the MENA electricity grid.

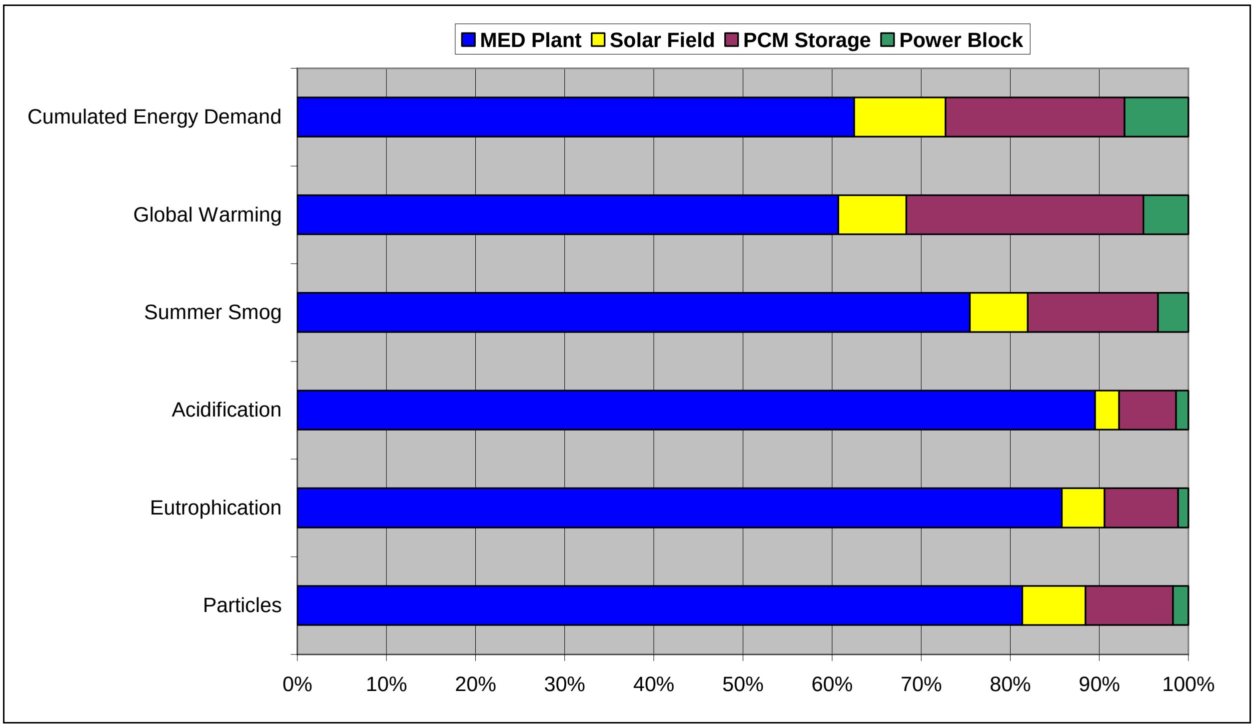


Figure 6-18: Contribution of the different components of a solar CSP/MED plant to the total life-cycle emissions.

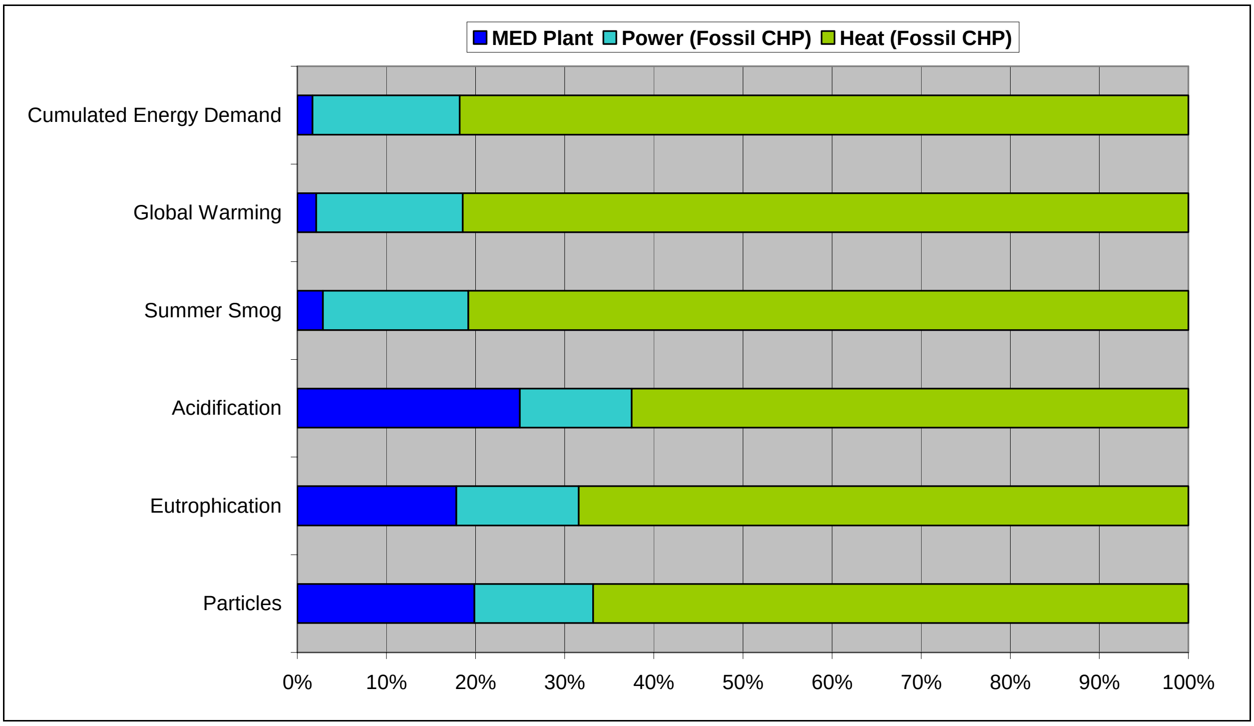


Figure 6-19: Contributions to the life-cycle emissions of a conventional MED plant receiving energy from a natural gas fired combined heat & power station (CHP).

6.5 Mitigation Measures

Capacities of seawater desalination are expected to rise significantly in the short- and medium term. The growing impacts caused by increasing numbers of desalination plants cannot be accepted. Therefore mitigation measures have to be taken to reduce the impacts drastically. In this chapter possible mitigation measures are identified and finally an outlook for an environmentally sound desalination plant will be presented.

The first step is to stop generating desalted water with fossil energy and to switch to renewable energy. As explained earlier in this report concentrated solar power is the ideal alternative to fossil fuels, especially in the context of desalination. By using concentrated solar power for desalination the impact categories energy demand and air pollution are mitigated strongly. Analogically, the impacts caused by seawater intake and brine discharge need to be mitigated. Apart from impact-specific measures there are general measures such as environmental impact assessment and site selection that need to be taken into account in the course of planning desalination plants.

6.5.1 General Measures

During the planning process, all impacts the desalination project could have on the environment should be evaluated and mitigation measures should be taken into account. By carrying out an Environmental Impact Assessment (EIA) all potential impacts can be identified and evaluated and adequate mitigation measures and process alternatives can be developed in a systematic manner /Lattemann and Höpner 2007a,c/. An EIA is a project- and location specific instrument.

In order to regard and evaluate the cumulative impacts of all plants in a region a regional water management is necessary. Strategic Environmental Assessment (SEA) is the instrument for such a purpose, because it helps to achieve sustainable development in public planning and policy making.

An important mitigation measure is the careful selection of the plant site. There are environmental, technical and economic aspects that should be taken into account.

Regarding the environmental aspects, the WHO recommends to avoid ecosystems or habitats that are unique within a region or globally worth protecting, that are inhabited by protected, endangered or rare species, that are important feeding or reproduction areas or that are highly productive or biodiverse (WHO in review, cited in /Lattemann and Höpner 2007a/).

Technical requirements are sufficient capacities for dilution and dispersion of the discharged brine. Here, apart from the discharge practice, the main factors of influence are the oceanographic features of the site, such as currents, tides, surf, water depth, and shoreline morphology (WHO in review, cited in /Lattemann and Höpner 2007a/).

An important economic aspect is the distance of the site to the sea, to infrastructure, such as water distribution networks, power grid, road and communication network, and to the consumers. A co-use of existing infrastructure is both economically and environmentally desirable. Another aspect is the potential of conflicts with other uses and activities /Lattemann and Höpner 2007a/.

6.5.2 Seawater Intake

The practice of water intake influences both the direct impacts on marine organisms and the quality of intake water, which defines the pre-treatment steps. A modification of open source water intake consists in the reduction of the intake velocity and a combination of differently meshed screens, but also in locating the intake in deeper waters or offshore /Lattemann and Höpner 2007a/. Desirable alternatives to open source water intake represent beach well intake and seabed filters with directed drilled horizontal drains, the latter being applicable in aquifers, i.e. permeable, porous and fractured geological formations, e.g. sandy and karstic formations, and for capacities of up to several 100,000 m³/d /Peters et al. 2007/ (see Figure 6-20).

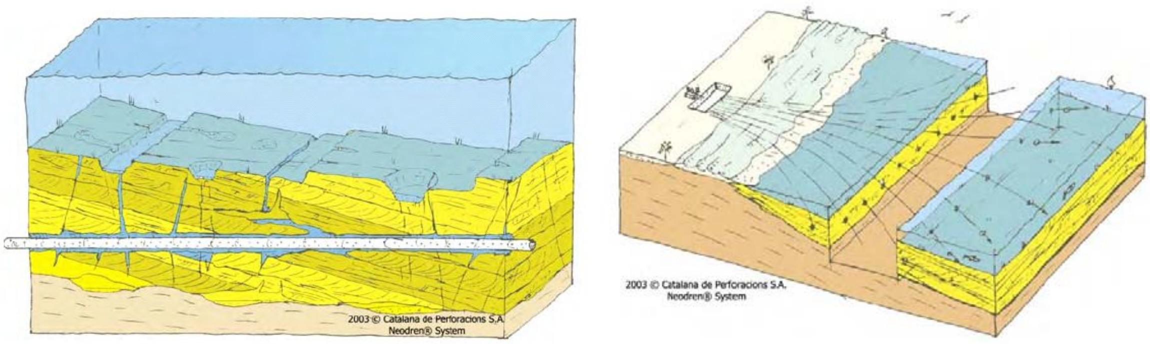


Figure 6-20: Single horizontal drain (left) and fan of horizontal drains in the sea bed /Peters et al. 2007/

On the one hand, these measures decrease the loss of organisms through impingement and entrainment of both larger organisms and smaller plankton organisms. On the other hand multimedia and cartridge filters are not necessary and the amount of pre-treatment chemicals can be reduced or chemical pre-treatment becomes dispensable at all as the seabed acts as a natural pre-filter. This accounts especially to the technique of horizontal drain seabed intake, offered for example by Catalana de Perforacions, Fonollosa, Spain, under the trade name Neodren, which is equipped with high efficient filtering devices. The filtration pipes run in separate boreholes executed from the back of the coastline into the subsoil under the sea /Catalana de Perforacions 2007/. However, these alternative locations of source water intake mean a higher impact during construction due to unavoidable soil disturbance if drilling or excavation is necessary.

Co-location of desalination and power plant reduces overall intake water volume as cooling water from the power plant can be used as feed water to the desalination plant. Therefore impacts from entrainment and impingement, as well as from construction and land use are minimized. Reduced volumes of intake water also mean reduced chemicals in case they are still necessary. Less pre-treatment chemicals in turn represent less negative effects. The concept still has to be proven for large scale applications.

6.5.3 Pre-treatment

As shown in Chapter 6.1 conventional pre-treatment of input seawater including media filtration requires a variety of chemicals partially at concentrations harming the environment. Thus, alternative pre-treatment methods need to be identified allowing to reduce or to avoid the use of hazardous chemicals. A possibility is to substitute the chemical additives by electricity from renewable energies needed for additional filtration steps. Another way to avoid environmental impacts represents the substitution of hazardous chemicals by environmentally sound, so-called green additives.

Filtration Technologies

Common filtration technologies in desalination plants are media filters, e.g. dual-media or single-medium filters retaining sand particles and macrobacteria. They rely on gravity removal mechanism and require the addition of coagulants for maximum efficiency. However, scaling and fouling of tubes and RO membranes is caused by particles mostly of smaller size, such as microbacteria, viruses, colloids, dissolved salts and dissolved organics. Adequate filter technologies for these small fractions are membrane filtration systems. These systems are further divided into microfiltration, ultrafiltration and nanofiltration respectively. Figure 6-21 shows which filters apply for which particle classes.

As a first step of filtration pre-treatment microfiltration (MF) can be applied to remove colloids and suspended matter larger than 0.1 µm. For metal membrane MF system ozone backwashing is applicable having proven to be more effective than permeate or air backwashing /Kim et al. 2007/.

Ultrafiltration (UF) can be an effective pre-treatment against fouling of RO membranes as it retains colloids and dissolved organics. Depending on the operation scheme, a benefit for the environment is the reduction of RO membrane cleaning frequency and therefore the consumption of chemical /Vedavyasan 2007/. Another benefit can be the elimination of chlorine, sodium bisulfite for dechlorination and coagulants /Wilf and Klinko 1998/. No usage of chlorine means any formation of hazardous trihalomethanes, thus in this context, the impacts on marine organisms are significantly reduced. If the UF membrane is backwashed regularly and thoroughly with permeate, the use of chemicals both in the UF and the RO step can be eliminated completely /Xu et al. 2007/. In the pilot plant tested here the UF shows excellent performance with a backwash executed every 40 minutes lasting for 30 seconds and a backwash flow rate of 1800 l/h. Apart from a sand filter upstream of the UF no further pre-treatment step was required.

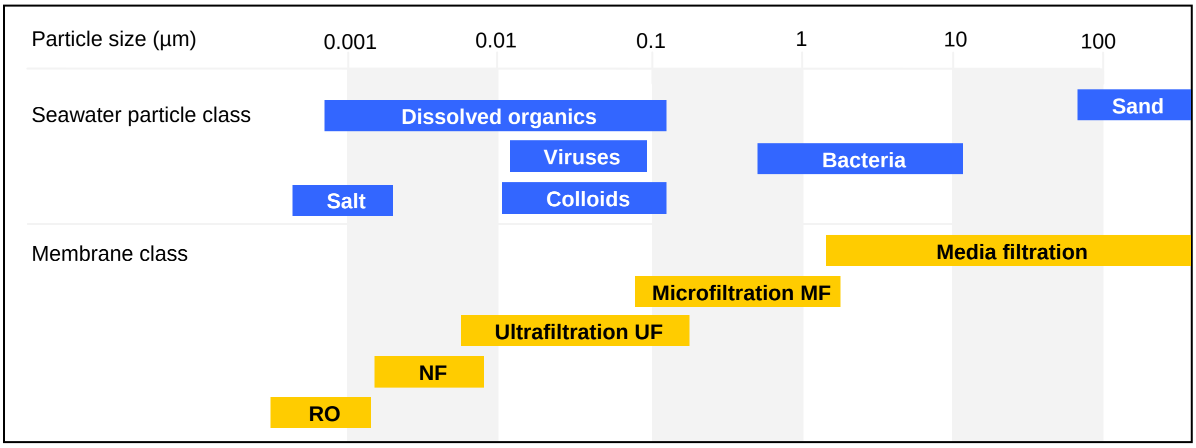


Figure 6-21: Typical seawater particles and filtration technologies compared in size (RO = reverse osmosis, NF = nanofiltration), /Goebel 2007/, modified.

Pre-treatment with MF/UF is recommendable if the intake is designed as open water intake, as in this case the water contains bacteria and colloids. However if the feed water intake is designed as beach well intake, a pre-treatment with MF/UF is not necessarily required /Pearce 2007/.

In combination with horizontal drain seabed intake UF pre-treatment including an upstream micro-bubble flotation is recommended /Peters and Pintó 2007/. Micro-bubble flotation uses a nozzle-based system for micro-bubbles with a narrowly distributed diameter. The UF unit is suggested to operate in dead-end modus.

Nanofiltration (NF) removes very fine suspended matter and residual bacteria, but above all it is a water softening treatment as it retains divalent ions. As these ions, e.g. Ca^{2+} and SO^{2-}, contribute significantly to scaling, nanofiltration prevents the formation of scales and replaces the conventional softening treatment /Hassan et al. 1998/. According to /Al-Shammiri et al. 2004/ nanofiltration can be considered as revolution in scale inhibition, as it prevents scale formation like no other treatment method. But NF does not only reduce hardness ions by up to 98 %, it also lowers the values of total dissolved solids by more than 50 % /Hassan et al. 1998./. Consequently, NF substitutes antiscalants, no matter which desalination process, and antifoamings in the case of thermal processes. Additionally it raises the performance of RO membranes as the RO feed water from nanofiltration contains less total dissolved solids.

Even though chemicals can be reduced or even avoided in the actual desalination process, pre-treatment filters need to be cleaned periodically as fouling occurs on the filtration membranes themselves. However, the use of chemicals at this point of the process would, again, mean impact to the environment. Therefore the development of filtration pre-treatment needs to lead into the direction that has been shown by /Xu et al. 2007/ through proving that filter cleaning can be carried out effectively by backwashing without chemicals. A higher overall consumption of electricity, e.g. due to additional pumping capacities required for membrane filtration or due to loss of permeate for membrane backwashing, can easily be accepted if it is generated from renewable energies such as concentrating solar power.

In the literature, membrane filtration systems are mentioned mainly in the context of RO desalination systems. However, they should definitely be considered for thermal processes, too, as they contribute to a reduction of chemical usage and therefore to the mitigation of impacts to the marine environment.

Nano-filtration would add 300-350 $/m³/d to the investment of a desalination plant and 1 ct/m³ to the operating cost for labour, 2 ct/m³ for the replacement of membranes and 1.5 ct/m³ for chemicals, adding a total of 10-15 ct/m³ to the cost of water. To this the cost of 1.2 kWh/m³ for additional power consumption would add /MEDRC 2001/.

Green Additives

In single cases, where chemicals cannot be avoided through additional filtration steps, they need to be substituted by so-called “green” chemicals. Criteria for the classification of chemicals are set by the Oslo and Paris Commission (OSPAR, cited in /Ketsetzi et al. 2007/):

- Biodegradability: > 60 % in 28 days

  Chemicals with a biodegradability of < 20 % in 28 days should be substituted.
- Toxicity: LC_{50} or EC_{50} > 1 mg/l for inorganic species, LC_{50} or EC_{50} > 10 mg/l for organic species
- Bioaccumulation: Log_{pow} < 3, pow = partition in octanol/water

A chemical, that fulfils two out of three requirements and whose biodegradability is higher than 20 % in 28 days, is qualified for the PLONOR list (Pose little or no risk). In the future, only PLONOR listed additives should be allowed.

A step into that direction is made by /Li et al. 2006/ by developing the non-toxic, rapidly biodegradable antiscalant PAP-1, synthesized from polyaspartic acid and further polycarboxylic acids. It showed very good results in the efficiency of magnesium and calcium scale inhibition as well as a fast biodegradability with 38.25 % reached at day 8 and 58.3% at day 20 (Figure 6-22). Furthermore its impact on organisms has been tested with an algae growth inhibition test. Figure

6-23 shows the results of the measurements of chlorophyll-a concentration as an indicator of algae growth. As no limitation of growth by PAP-1 can be observed the authors classified it as environmentally friendly.

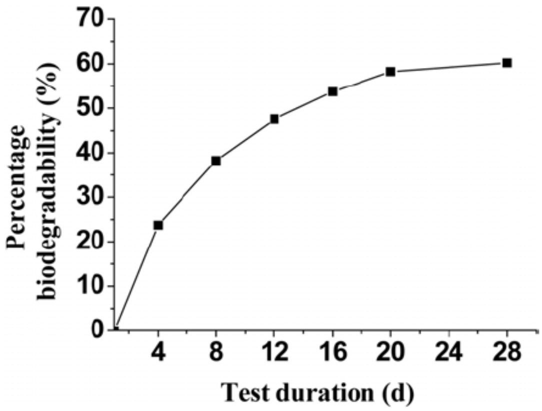


Figure 6-22: Biodegradability of PAP-1 as a function of time /Li et al. 2006/

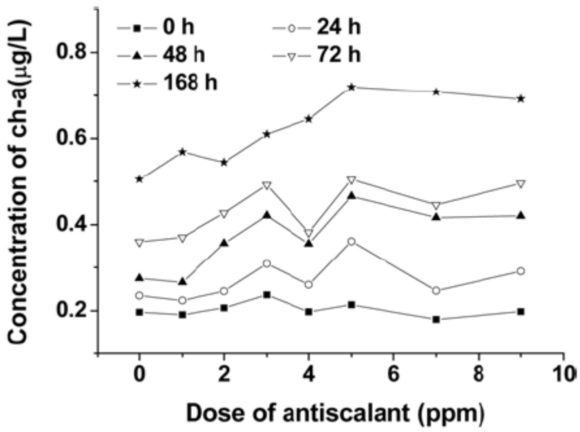


Figure 6-23: Concentration of chlorophyll-a (µg/l) as a function of antiscalant dosing concentration (ppm) with a varying test duration /Li et al. 2006/

Another approach to green antiscalants is presented by /Ketsetzi et al. 2007/. They tested the efficiency of silica scale inhibition of cationic macromolecules, i.e. inulin-based polymers modified with ammonium. The tested inhibitors showed the highest efficiency at a relatively high dosage of 40 ppm and were able to keep silica soluble at a concentration of about 300 ppm depending on the design of the polymeric inhibitor, i.e. on the average number of cationic groups per monomeric unit. There is no statement on the environmental compatibility of the inhibitor. However, inulin is of vegetable origin; therefore negative impacts on the environment are not expected.

6.5.4 Tubing Material

The heavy metal discharge of thermal desalination plants needs also to be eliminated. This can be achieved by substituting less corrosion-resistant tubing materials, such as copper alloys, aluminium brass and low alloyed stainless steel by more resistant materials. Among stainless steel grades the high alloyed austenitic grades and austenitic-ferritic grades possess the highest corrosion resistance /Olsson and Snis 2007/. The latter is a new generation of stainless steel, which is called duplex stainless steel due to its austenitic-ferritic microstructure. Titanium is already a commonly used tube material with a high corrosion resistance, but the prices and the lead times have significantly increased in the last years. A third alternative are polymeric materials, provided that their thermal conductivity can be increased by innovative solutions or that polymer films with a very low wall thickness can be used in order to reduce the heat transfer resistance. At present polymers are sometimes used for pipes, nozzles and droplet separators /El-Dessouky and Ettouney 1999/. By contrast, duplex steel and titanium are already used in various plants. A mid- to long-term solution could be the development of protective coatings.

A high corrosion resistance of stainless steel is achieved by either a high grade of alloying, such as the 254SMO grade with 6 % of molybdenum, or by the austenitic-ferritic microstructure of duplex stainless steel (DSS). Due to its structure DSS possesses higher strength, at least twice as high as austenitic steel enabling gauge, weight and cost reductions /Olsson and Snis 200/). With rising prices of alloying elements DSS is less costly than highly alloyed austenitic grades. Therefore DSS represents a real alternative to 254SMO for the replacement of corroding low alloyed stainless steel. In Table 6-5 some DSS grades and their possible locations in desalination plants are listed. In SWRO plants the high pressure parts require the most resistant grade S32750 with the highest grade of alloying. Where pressure and salinity is lower, e.g. in the second pass parts, the lower alloyed grades S32205, S32101, and S32304 are sufficient. In MSF evaporator shells a dual duplex design has been implemented consisting of the more resistant grade S32305 for hostile conditions and of less resistant grades (S32101, S32304) for less hostile conditions.

	SWRO			MSF		MSF & MED	
steel designation (ASTM)	High pressure parts, energy recovery system	second pass		condensers (heat recovery)	brine heater	Evaporator shells Dual duplex design	
		TDS: >500 ppm	TDS: 300-500 ppm			more hostile	less hostile
S32750	x						
S32205		x		x		x	
S32101			x		x		x
S32304			x		x		x
examples	Singapore			Aruba	Aruba	Taweelah B, Jebel Ali, Ras Abu Fontas	

Table 6-5: Duplex stainless steel grades and their possible applications /Olsson and Snis 2007/

Under conditions occurring in SWRO plants, i.e. at temperatures of 25°C and 45°C and salinities of 35,000 and 55,000 mg/l, titanium shows the highest corrosion resistance compared to austenitic stainless steels and nickel alloys /Al-Malahy and Hodgkiess 2003/. Consequently the use of titanium for the high pressure parts of a SWRO plant is recommended.

Polymeric materials, e.g. PTFE, show many advantages compared to steel and to copper alloys, such as easy construction, lower construction and installation costs and the ability to operate at higher top brine temperatures without the risk of effects of scale formation /El-Dessouky and Ettouney 1999/. The major advantage, of course, is the corrosion resistance making corrosion inhibitors dispensable, thus reducing the environmental impact twofold. However, there are drawbacks on the engineering side due to certain properties of polymeric, such as a thermal expansion ten times higher than metals requiring special design considerations and material aging especially at high operation temperatures that has to be taken into account. At present, the use of polymeric heat exchangers is limited by lack of practice codes, fouling concerns, limited choice and also the conservative nature of users. However, experience is made with polymeric material in a single-effect mechanical vapour compression desalination plant and described in /El-Dessouky and Ettouney 1999/. In contrast to thermal processes, polymeric materials have already entered RO plants. Here their use represents a reliable and cost effective strategy, but the high pressure parts are in the focus of the durability issue /Al-Malahy and Hodgkiess 2003/. Table 6-6 summarises which alternative materials can be used for the critical components of the different desalination processes.

Material	MSF	MED	RO
high alloyed stainless steel	x	x	x
DSS	x	x	x
Titanium	x	x	x
Polymers	prospective	prospective	x

Table 6-6: Overview of suitability of alternative materials for the processes MSF, MED, and RO

6.5.5 Treatment of Effluent before Discharge

Dechlorination

If chlorine cannot be substituted as biocide right from the start, it is indispensable for environmentally friendly desalting to dechlorinate the brine before discharge. This can be carried out with the help of the chemicals described in Chapter 6.3.2. Further chemicals in discussion for dechlorination are sulphur dioxide and hydrogen peroxide. The former yields hydrochloric and sulphuric acid, which will be neutralized by seawater alkalinity, and should be of no concern if dosage is low. The latter yields water, oxygen, and chloride and is of concern if overdosed as it is an oxidant like chlorine. Additionally residual chlorine can be depleted by activated carbon filters.

Removal of Metal Cations

Releasing heavy metal to the sea represents a risk to the environment that needs to be avoided. Therefore heavy metal cations should be removed from the effluent before discharge, if corrosion cannot be stopped by the substitution of conventional piping material by material resistant to corrosion. From various industries producing wastewater polluted by heavy metals different techniques for metal ion recovery are known. Possible techniques are precipitation, complexation, adsorption, biosorption, and ion exchange. Apart from the latter these techniques require an integrated filtration step to separate the bound metal from the brine, which can be carried out by either micro- or ultrafiltration.

Precipitation of certain heavy metals can be achieved by adding lime /Masarwa et al. 1997/. In their test iron and manganese is coprecipitated in the course of removing silica.

Another method of heavy metal removal is complexation-ultrafiltration. A possible complexing agent is carboxyl methyl cellulose (CMC), a water-soluble metal-binding polymer /Petrov and Nenov 2004/. CMC possesses good complexation ability especially towards Cu^{2+} but also towards Ni^{2+}, the quantitatively most important elements in the context of corrosion in desalination plants. A metal:CMC mole ratio of 1:6 is suggested for low metal concentrations characterising thermal desalination brines. A high retention rate of complexed, ultrafiltrated copper of up to 99 % is reached. For metal recovery decomplexation and subsequent ultrafiltration proves to be highly effective at pH 2.

A method of combined complexation and filtration is the filtration with chelating membranes made of polyvinyl alcohol (PVA) as polymer matrix and polyethyleneimine and polyacrylic acid as chelating poly-electrolytes /Lebrun et al. 2007/.

The process of adsorption is a commonly applied technique in the field of wastewater and exhaust air treatment. A well-known example is activated carbon which might be an adequate adsorbent for the treatment of desalination discharge.

Removal of heavy metals by adsorption using a powdered synthetic zeolite as bonding agent is described by /Mavrov et al. 2003/. The advantages of this new bonding agent are its high bonding capacity and its selectiveness even in the presence of other metal ions, such as Ca^{2+}, Mg^{2+}, and Na^{+}. Depending on the contamination grade of the discharge the bonding agent separation is carried out either by cross-flow microfiltration (for concentrations of up to 60 ppm) or by membrane microfiltration followed by flotation (for concentrations of up to 500 ppm). The membrane material is polypropylene and aluminium oxide respectively.

The possibility of biosorption has been tested with *Streptomyces rimosus* biomass /Chergui et al. 2007/ obtained as waste from an antibiotic production plant. The biomass samples were prepared by washing with distilled water, drying at 50°C for 24 h, grinding, and sieving to receive the fraction between 50 and 160 µm of particle diameter. The biosorption of Cu^{2+} has been most efficient in the sodium form, i.e. after NaOH treatment of the biomass. Desorption and regeneration showed to be most efficient with sulphuric acid reducing the biosorption capacity by 17 % in the case of copper. This method needs further research concerning the influence of surface-active and complexing agents or other metal ions, which might be present in desalination effluents.

Furthermore, metal ions can be removed with the help of ion exchangers. A laboratory-scale treatment system with a strongly acidic cation resin showed high removal efficiencies for chromium and zinc /Sapari et al. 1996/.

Natural evaporation and disposal as solid waste

An interesting approach to avoiding the impacts through brine discharge is natural evaporation and disposal as solid waste. A laboratory-scale test has been conducted by /Arnal et al. 2005/ showing the possibility of natural evaporation enhanced by capillary adsorbents, especially for plants where discharge to the sea is impossible or difficult, e.g. brackish water desalination plants. The comparison with the reference sample without adsorbent showed that the capillary adsorbents lead to significantly higher evaporation rates. However, a general drawback is the low evaporation rate, thus requiring large areas.

6.5.6 Enhanced Practice of Discharge to the Water Body

To eliminate the negative effects of strongly elevated temperature (thermal processes) and salinity (mechanical processes) in the mixing zone of the desalination discharges the increase of temperature and salinity should be limited to 10 % /Lattemann and Höpner 2007c/. There are several ways to achieve this goal. First of all, maximum heat dissipation before entering the mixing zone and effective dilution in the mixing zone are essential. As mentioned in chapter 6.5.1 the oceanographic properties of the site influence the dilution capacities of a site. Dilution requires good natural mixing conditions and transport. Therefore ideal discharge sites are on high energy coasts or offshore. In the case of horizontal drain seabed intake, an elegant solution to the problem of discharge is the combination of intake pipes and discharge pipes, the latter designed with a smaller diameter running inside the intake drain /Peters and Pintó 2007/. Due to the possible length of horizontal drains the point of discharge can be situated in sufficient distance to the coast line where mixing conditions are good.

Dilution can be enhanced further by the installation of diffuser systems. The type of diffuser system needed depends on the characteristics of the discharge jet, i.e. a buoyant effluent diffuser for a buoyant jet and a dense effluent diffuser for a dense jet respectively /Cipollina et al. 2004/. Another effective measure is to dilute the desalination effluents by blending with the waste streams of other industrial activities. An example is the common practice of blending with cooling water from power plants. The temperature of the effluents can be reduced with the help of evaporation cooling towers.

To achieve optimal dilution it is recommendable to carry out field investigations in the course of the site selection. Hydrodynamic modelling can be useful to predict impacts and to find the adequate discharge system /Bleninger and Jirka 2007/. During plant start-up and operation an effect and compliance monitoring should be carried out /Lattemann and Höpner 2007a/.

6.5.7 Changing Operation Parameters

The best solution to a problem is to avoid it right from the start. In the context of seawater desalination this means to change the operation parameters is such a way, that scaling, fouling and corrosion do not occur or at least that they can be reduced. Fossil fuelled plants are optimized in respect to their energy efficiency; therefore efforts were made to increase the water recovery rate. But high recovery rates lead to the problems mentioned above which need then to be solved by chemicals. By using renewable energies, however, the water recovery rate can be reduced to facilitate the desalination process.

An example following this approach is the concept of RO desalination using wind energy with a reduced water recovery rate that does not require any chemicals at all /Enercon 2007/. Disinfection of source water happens merely with the help of UV rays. With the help of an integrated energy recovery system energy efficiency is increased.

6.6 Options for Environmentally Enhanced Seawater Desalination

In this chapter we describe how future desalination plants could be optimized for minimum environmental impact. By using heat and electricity from concentrating solar power plants the major impacts from energy consumption and air pollution are avoided. Enhancing the practice of seawater intake and hereby achieving higher quality input seawater leads to less chemical-intensive or even chemical-free pre-treatment and consequently less potential waste products in the effluents. The pre-treatment process itself can be advanced to further reduce the use of chemicals. Finally the practice of discharge needs to be improved in such a way that optimum dilution is guaranteed. Among the market-dominating desalination technologies, MSF performs worst regarding efficiency, costs and overall impact, which is why it falls out of consideration. Therefore future concepts will only be illustrated for MED and RO.

6.6.1 Enhanced CSP/MED plant

The future advanced MED plant would run completely with heat and electricity from concentrating solar power (CSP/MED). The impacts from energy consumption are reduced to a minimum originating from the upstream processes of the CSP plant, i.e. production and installation of collector field, heat storage and conventional steam power station. The related emission can only be reduced by increasing the renewable share of power generation of the total energy economy. During operation of the plant there is no use of fossil energy carriers and there are no emissions to the atmosphere. The features characterizing the future MED plant are summarized schematically in Figure 6-24 and are presented in the following.

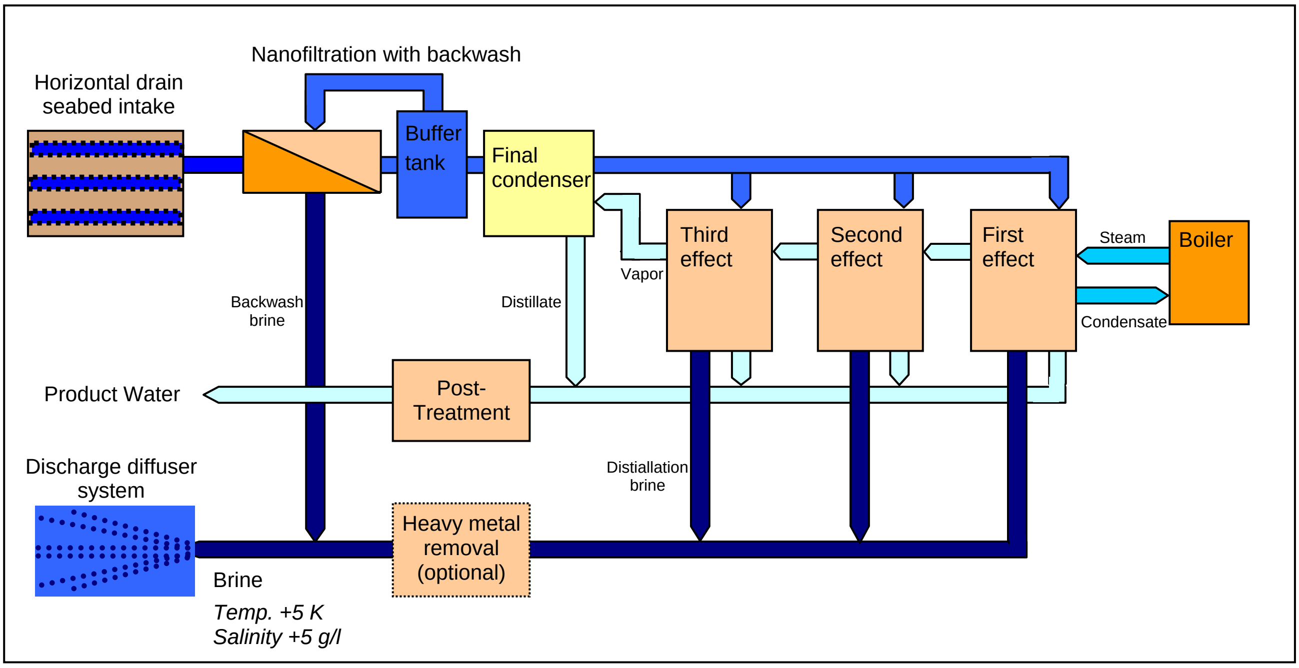


Figure 6-24: Scheme of A-MED process including horizontal drain seabed intake, nano-filtration unit, buffer tank for backwash of nano-filtration membranes and discharge diffuser system

The seawater intake is designed as a seabed filter intake through directed drilled horizontal drains. This system is environmentally compliant, because it does not affect aquatic organisms neither through impingement nor through entrainment. Where this system cannot be realised beach wells are the suggested alternative. Open source water intake is considered only on sites where neither horizontal seabed filters nor beach wells are possible. Due to the filtrating effect of seabed intake the source water is largely free from suspended inorganic and organic matter.

Optimally, the pre-filtered seawater does not require chlorination due to the long passage through the subsoil. In that case the pre-treatment consists of a nano-filtration system to eliminate colloids, viruses and hardness, i.e. divalent ions. As these ions are largely removed no antiscalants are necessary. Furthermore anti-foaming is dispensable as hardly any organic matter passes the nano-filtration membranes. The nano-filtration system comprises a permeate buffer tank where the NF permeate is stored for membrane backwashing. Backwashing is the essential measure to retain the performance of the NF membrane and has to be done regularly with a sufficient backwash flow rate. The backwash brine is blended with the distillation brine.

In case of sub-optimally pre-filtered source water and unfiltered open source water, further pre-treatment steps consisting of micro-filtration and ultra-filtration become necessary each with a backwashing facility.

The tubing is made of corrosion-resistant material, such as titanium, or of conventional material coated with a durable protection film respectively. Anyway, the risk of corroding tubes is reduced by the enhanced pre-treatment that does not require acid cleaning anymore. However, to guarantee effluents free from heavy metals a post-treatment step can be inserted optionally where the heavy metals are removed applying one of the techniques described in Chapter 6.1. The practice of effluent discharge is enhanced with a diffuser system providing optimal and rapid dilution.

In the future advanced CSP/MED plant, the use of chemicals and the concentration of brine will be avoided to a great extent by increased filtering and diffusion. Additional energy for this process will be obtained from solar energy. For a first estimate, we will assume that the chemicals required per cubic metre of desalted water will be reduced to about 1 % of present amounts and that on the other hand an additional 40 % of electricity will be required for pumping.

6.6.2 Enhanced CSP/RO Plant

A future advanced RO plant would run completely with electricity from concentrating solar power plants. The impacts from energy consumption are reduced to a minimum originating from the upstream processes of the CSP plant, i.e. production and installation of collector field, heat storage and conventional steam power station. During operation there is no use of fossil energy carriers and there are no emissions to the atmosphere. The features characterizing the future RO plant are summarized schematically in Figure 6-25 and are presented in the following.

The seawater intake is designed as a seabed filter intake through directed drilled horizontal drains. Where this system cannot be realised beach wells are the suggested alternative. Open source water intake is considered only on sites where neither horizontal seabed filters nor beach wells are possible.

Optimally, the pre-filtered seawater does not necessitate chlorination due to the long passage through the subsoil. In that case the pre-treatment consists of a nano-filtration system to eliminate colloids, viruses and hardness, i.e. divalent ions. As these ions are largely removed no antiscalants are necessary. The nano-filtration system comprises a permeate buffer tank where the NF permeate is stored for membrane backwashing. Backwashing is the essential measure to retain the performance of the NF membrane and has to be done regularly with a sufficient backwash flow rate. The backwash brine is blended with the RO brine.

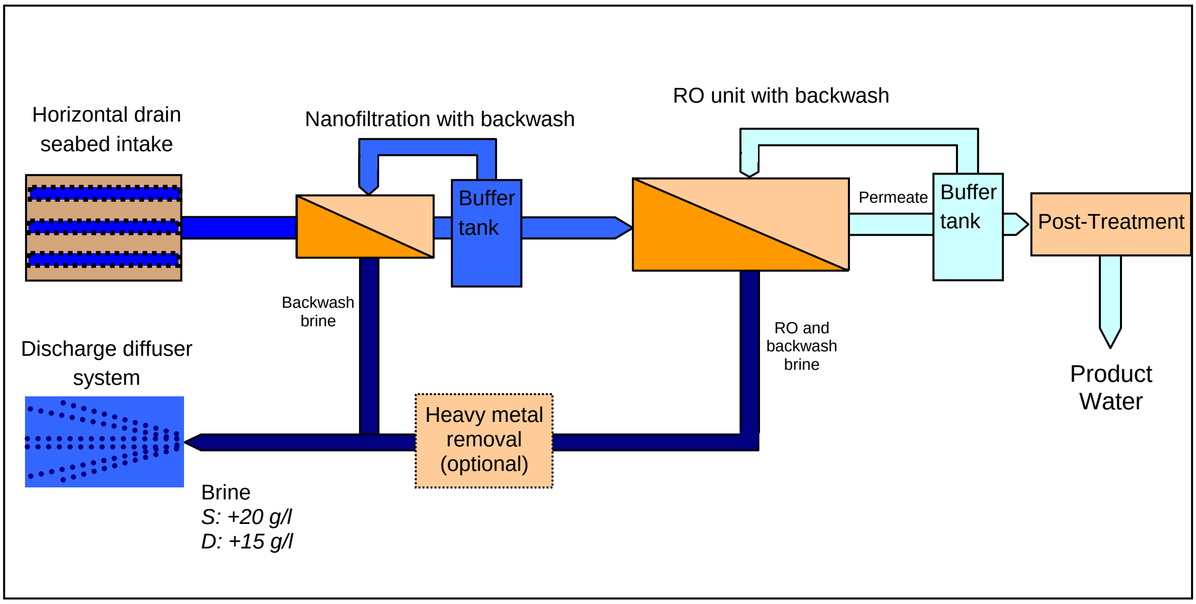


Figure 6-25: Scheme of A-RO process including horizontal drain seabed intake, nano-filtration unit, buffer tank for backwash of nano-filtration membranes and discharge diffuser system

In case of sub-optimally pre-filtered source water and unfiltered open source water further pre-treatment steps consisting of micro-filtration and ultra-filtration become necessary each with a backwashing facility. Thanks to the high quality of NF permeate, i.e. the feed to the RO membranes, the number of RO stages can potentially be decreased /Hassan et al. 1998/ thus reducing the investment costs and energy consumption of the RO. In analogy to the NF system, the RO unit requires a backwashing facility including a RO permeate buffer tank

The piping is made of corrosion-resistant material, such as stainless steel and PVC for high and low pressure piping respectively, or of conventional material coated with a durable protection film respectively. Anyway, the risk of corroding tubes is reduced by the enhanced pre-treatment that does not require acid cleaning anymore. However, to guarantee effluents free from heavy metals a post-treatment step can be inserted optionally where the heavy metals are removed applying one of the techniques described in chapter 6.1. The practice of effluent discharge is enhanced with a diffuser system providing optimal and rapid dilution.

In the future advanced CSP/RO plant, the use of chemicals and the concentration of brines will be avoided to a great extent by increased filtering and diffusion, and energy input will be delivered by solar energy. For a first estimate, we will assume that the chemicals required per cubic metre of desalted water will be reduced to about 1 % of present amounts and that on the other hand an additional 20 % of electricity will be required for pumping.

6.7 Impacts of Large-Scale Desalination in the MENA Region

In this chapter we will assess to total absolute emissions and impacts of seawater desalination in the Middle East and North Africa as for today and for the AQUA-CSP scenario until 2050. The world wide desalination capacity rising rapidly reached 24.5 million m^3/d by the end of 2005 (IDA 2006, cited in /Lattemann and Höpner 2007a/). With 87 % of all plants the EUMENA region is by far the most important region in the context of desalination. “The largest number of desalination plants can be found in the Arabian Gulf with a total seawater desalination capacity of approximately 11 million m^3/day (Figure 6-27) which means a little less than half (45 %) of the worldwide daily production. The main producers in the Gulf region are the United Arab Emirates (26 % of the worldwide seawater desalination capacity), Saudi Arabia (23 %, of which 9 % can be attributed to the Gulf region and 13 % to the Red Sea) and Kuwait (< 7 %)” (cited from /Lattemann and Höpner 2007a/). Regarding the emissions through the brine discharge, from all MSF plants the Arabian Gulf receives a daily load of copper of 292 kg, amounting to more than 100 t/y. The chlorine load emitted daily by MSF and MED plants reaches up to 23 t/d and more than 8000 t/y.

The Red Sea region shows the third highest concentration of desalination plants worldwide with an overall capacity of 3.4 million m^3/day (Figure 6-28, /Lattemann and Höpner 2007a/). With a capacity share of 23 % RO plays a significant role compared to the Arabian Gulf, where this technology reaches only 5 %. Still enormous amounts of copper and chlorine are released yearly: 28 t of copper and 2100 t of chlorine from both MSF and MED plants.

In the Mediterranean, the total production from seawater is about 4.2 million m^3/day, representing 17 % of the worldwide capacity /Lattemann and Höpner 2007a/. The largest producer of this region is Spain with 30 % of the capacity not including its RO plants on the Canary Islands with an additional capacity of 411,000 m^3/d (Figure 6-29). While in the Gulf region thermal processes account for 90 % of the production, the predominant process in the Mediterranean is RO with almost 80 % of the capacity. The only exception to this trend is Libya where the dominating process is MSF. Consequently the release of copper and chlorine is less of concern compared to the Arabian Gulf.

According to /IDA 2006/ the MENA region had in 2005 a total desalination capacity of about 16.3 Mm^3/day. If we consider the specific air pollutants from Table 6-4 for conventional MSF, MED and RO taking as reference background the MENA electricity mix according to Table 6-2, and the chemicals typically contained in the effluents of each desalination system as shown before, we obtain the daily emissions of pollutants from desalination in the MENA region in the year 2005. For simplicity, MSF and MED plants have been calculated as if always coupled to power generation (Table 6-7). Therefore, estimates for 2005 are rather optimistic.

The AQUA-CSP scenario foresees an increase of desalination capacity in the MENA region from today 7 billion m³ per year to 145 billion cubic metres per year by 2050. This means a twenty-fold increase of desalted water within a time span of about 40 years. In 2050 almost all desalination plants will be of the type of advanced plants powered by CSP (and to a lesser extent by other renewable sources) with only 1 % of energy related emissions and only 1 % of the chemicals contained in the effluents compared to present standards. Roughly, this means that the overall load to the environment from power consumption and from chemicals can be reduced to about 20 % of the present load in spite of dramatically increasing desalination volumes.

However, with the growth perspectives for desalination until 2015, all pollutants will approximately double by that time (Table 6-7). It will take until 2025 to achieve a majority of 55 % of solar powered, advanced desalination plants, and pollution by that time will increase by 3-4 times compared to 2005. This would only be acceptable if it would be a transitional effect. Luckily, this is the case in our scenario, and by 2050, when advanced, solar powered desalination will provide the core of desalted water, pollutants like carbon dioxide can be brought back below present levels (Figure 6-26).

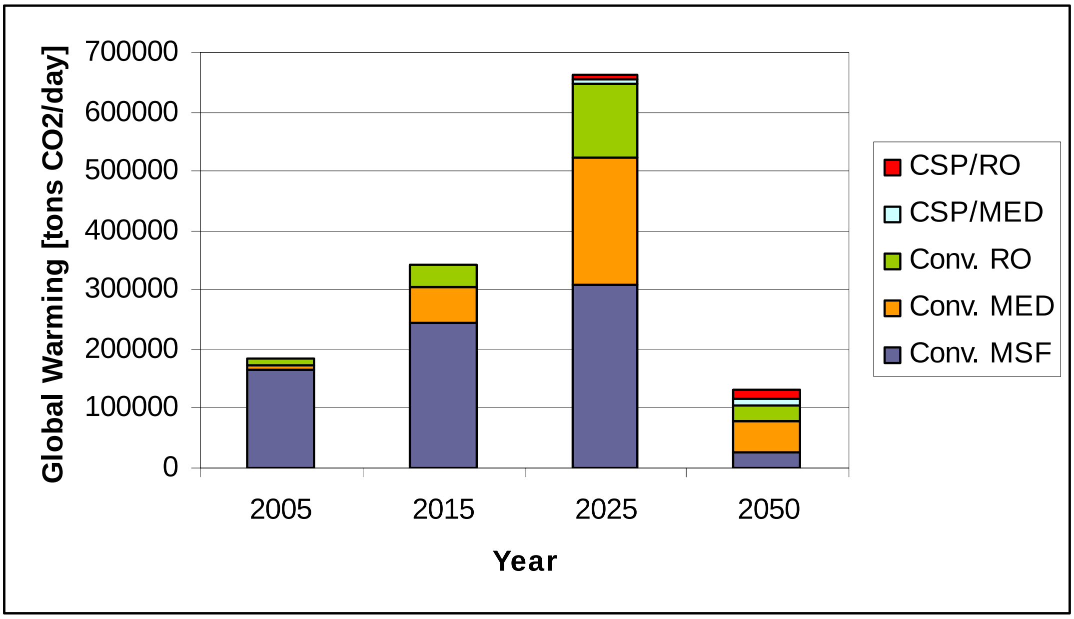


Figure 6-26: Greenhouse gas emissions from desalination in the AQUA-CSP scenario taking as basis the electricity mix of the MENA countries according to /MED-CSP 2005/. A similar pattern results for all pollutants, showing that the introduction and large scale implementation of advanced CSP/MED and CSP/RO plants is imperative.

Pollutants from CSP/RO and CSP/MED remaining in 2050 would be mainly caused by the construction of the plants. However, if the composition of the electricity mix in MENA would change to a mainly renewable supply according to the scenario dveloped in /MED-CSP 2050/, most of these pollutants would also be removed to a large extent, leading to an almost clean desalination system by that time (Table 6-7). The remaining conventional desalination plants using fossil fuels, which will cause most environmental impacts by that time, will subsequently be replaced by advanced systems.

The only chemical pollutants that would increase by 2050 with respect to 2005 would be antiscalants and coagulants, that are however not considered as toxic substances. Nevertheless, their environmental impacts by causing turbidity and sediments could become critical (Chapter 6.1) and should be totally removed by further research and development. Also it must be considered that the advanced CSP/MED and CSP/RO concepts described here – and their low environmental impacts – are not yet state of the art today and their development and commercialization should be a primary target of R&D for desalination.

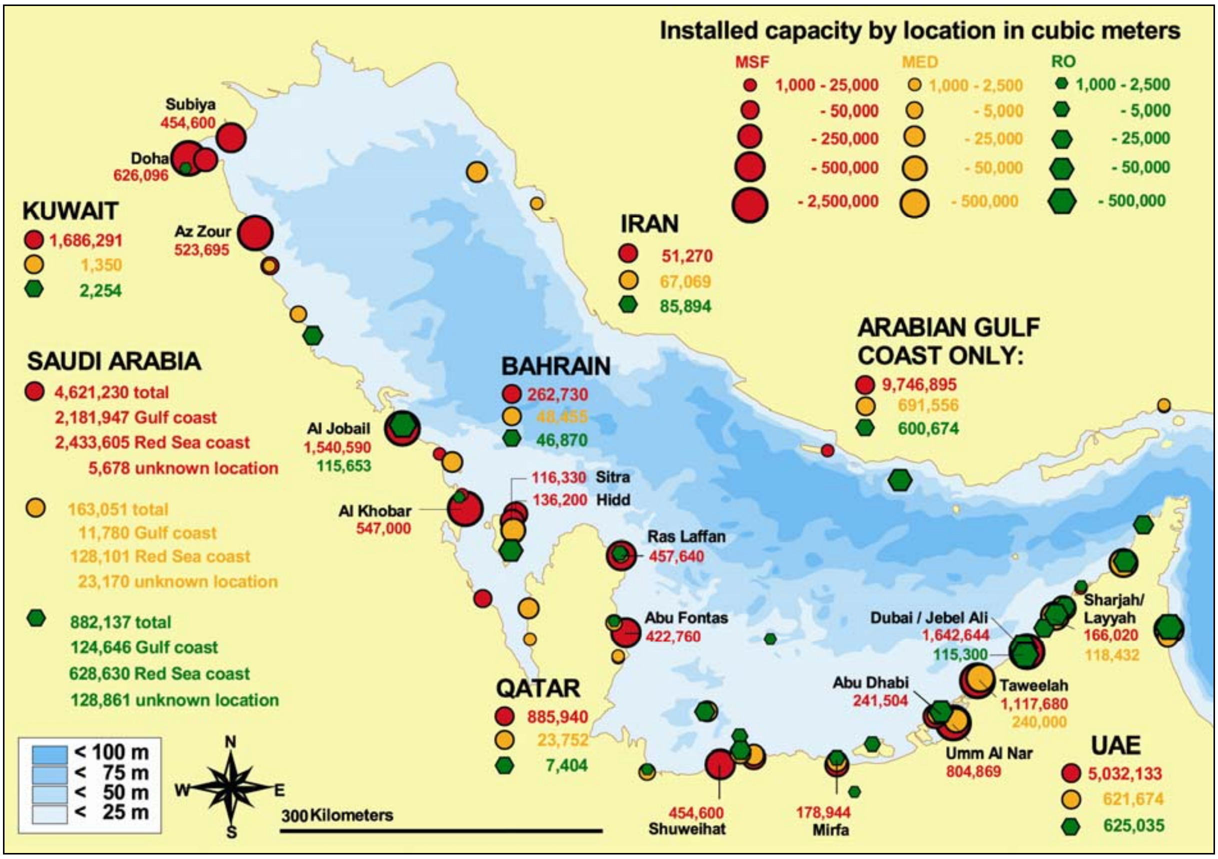


Figure 6-27: Capacity of seawater desalination in the Arabian Gulf in m³/d /Lattemann and Höpner 2007a/

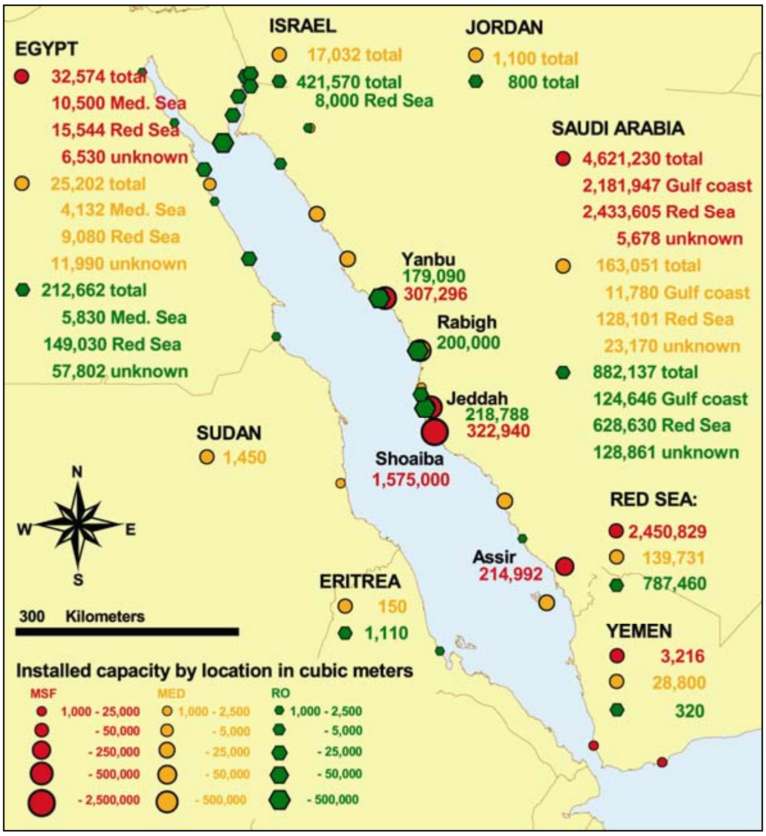


Figure 6-28: Capacity of seawater desalination in the Red Sea in m³/d, /Lattemann and Höpner 2007a/

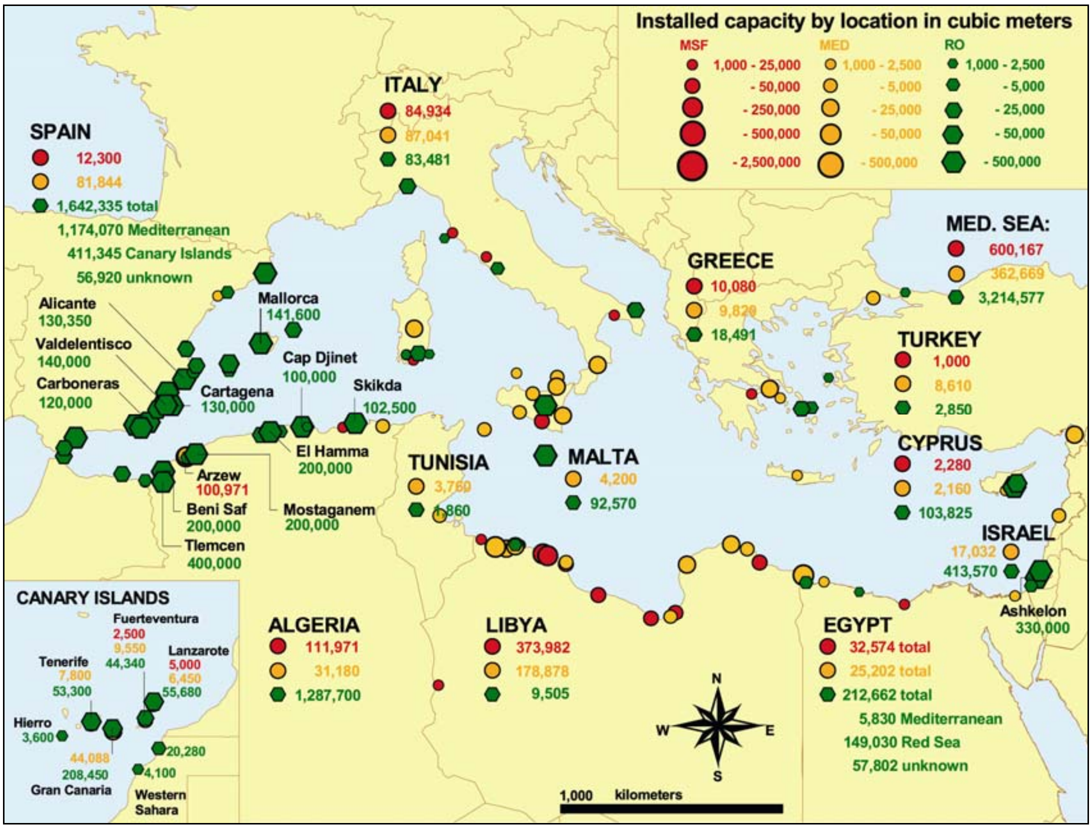


Figure 6-29: Capacity of seawater desalination in the Mediterranean in m³/d, /Lattemann and Höpner 2007a/

Specific	Unit	Conv. MSF	Conv. MED	CSP/MED	Conv. RO	CSP/RO
Desalting Capacity	m^3	1	1	1	1	1
Global Warming	kg CO_2 / m^3	12.83	7.75	0.378	4.41	0.252
Summer Smog	kg Ethen /m^3	2.53E-03	1.54E-03	8.25E-05	6.53E-04	0.0000396
Acidification	kg SO_2 / m^3	2.37E-02	1.61E-02	6.27E-03	3.35E-02	0.003792
Eutrophication	kg PO_4 / m^3	3.38E-03	2.16E-03	6.30E-04	9.90E-04	0.0001788
Particles	kg PM10 / m^3	6.31E-03	4.13E-03	1.41E-03	5.33E-03	0.0007164
Chlorine	kg Cl / m^3	2.50E-03	2.30E-03	2.30E-05	5.00E-04	5.00E-06
Antiscalants	kg A / m^3	6.00E-03	6.00E-03	6.00E-05	6.00E-03	6.00E-05
Antifoamings	kg AF / m^3	1.00E-04	5.00E-05	5.00E-07	0	0
Metals	kg M / m^3	3.00E-05	1.80E-05	1.80E-07	0	0
Coagulants	kg Co /m^3	0	0	0	9.00E-02	9.00E-04

Status 2005	Unit	Conv. MSF	Conv. MED	CSP/MED	Conv. RO	CSP/RO	Total
Desalting Capacity	1000 m^3/d	12886	1150	0	2313	0	16349
Global Warming	tons/day	165327	8913	0	10200	0	184440
Eutrophication	tons/day	32.6	1.8	0.0	1.5	0.0	35.9
Acidification	tons/day	305.4	18.5	0.0	77.5	0.0	401.4
Smog	tons/day	43.6	2.5	0.0	2.3	0.0	48.3
Particles	tons/day	81.3	4.7	0.0	12.3	0.0	98.4
Chlorine	tons/day	32.2	2.6	0.0	1.2	0.0	36.0
Antiscalants	tons/day	77.3	6.9	0.0	13.9	0.0	98.1
Antifoamings	tons/day	1.3	0.1	0.0	0.0	0.0	1.3
Metals	tons/day	0.4	0.0	0.0	0.0	0.0	0.4
Coagulants	tons/day	0	0	0	208.2	0.0	208.2

Status 2015	Unit	Conv. MSF	Conv. MED	CSP/MED	Conv. RO	CSP/RO	Total
Desalting Capacity	1000 m^3/d	19000	8000	2500	8000	2500	40000
Global Warming	tons/day	243770	62000	737	35280	491	342279
Eutrophication	tons/day	48.1	12.3	0.2	5.2	0.1	65.9
Acidification	tons/day	450.3	128.8	12.2	268.0	7.4	866.7
Smog	tons/day	64.2	17.3	1.2	7.9	0.3	91.0
Particles	tons/day	119.9	33.0	2.8	42.6	1.4	199.7
Chlorine	tons/day	47.5	18.4	0.1	4.0	0.0	70.0
Antiscalants	tons/day	114.0	48.0	0.2	48.0	0.2	210.3
Antifoamings	tons/day	1.9	0.4	0.0	0.0	0.0	2.3
Metals	tons/day	0.6	0.1	0.0	0.0	0.0	0.7
Coagulants	tons/day	0	0	0	720.0	2.3	722.3

Status 2025	Unit	Conv. MSF	Conv. MED	CSP/MED	Conv. RO	CSP/RO	Total
Desalting Capacity	1000 m^3/d	24000	28000	35000	28000	75000	190000
Global Warming	tons/day	307920	217000	6483	123480	9261	664144
Eutrophication	tons/day	60.7	43.1	1.4	18.3	1.5	125.0
Acidification	tons/day	568.8	450.8	107.6	938.0	139.4	2204.5
Smog	tons/day	81.1	60.5	10.8	27.7	6.6	186.7
Particles	tons/day	151.4	115.6	24.3	149.2	26.3	466.9
Chlorine	tons/day	60.0	64.4	0.8	14.0	0.4	139.6
Antiscalants	tons/day	144.0	168.0	2.1	168.0	4.5	486.6
Antifoamings	tons/day	2.4	1.4	0.0	0.0	0.0	3.8
Metals	tons/day	0.7	0.5	0.0	0.0	0.0	1.2
Coagulants	tons/day	0	0	0	2520.0	67.5	2587.5

Status 2050	Unit	Conv. MSF	Conv. MED	CSP/MED	Conv. RO	CSP/RO	Total
Desalting Capacity	1000 m^3/d	2000	7000	155000	6000	310000	480000
Global Warming	tons/day	25660	54250	11132	26460	14843	132345
Eutrophication	tons/day	5.1	10.8	2.4	3.9	2.3	24.5
Acidification	tons/day	47.4	112.7	184.7	201.0	223.3	769.2
Smog	tons/day	6.8	15.1	18.6	5.9	10.5	56.9
Particles	tons/day	12.6	28.9	41.6	32.0	42.2	157.3
Chlorine	tons/day	5.0	16.1	3.6	3.0	1.6	29.2
Antiscalants	tons/day	12.0	42.0	9.3	36.0	18.6	117.9
Antifoamings	tons/day	0.2	0.4	0.1	0.0	0.0	0.6
Metals	tons/day	0.1	0.1	0.0	0.0	0.0	0.2
Coagulants	tons/day	0	0	0	540.0	279.0	819.0

Table 6-7: Daily load of pollutants at the Southern Mediterranean Coast, the Red Sea and the Arabian Sea in the year 2005, 2015, 2025 and 2050. The yellow shaded area shows air pollutants from energy consumption, while the orange shaded area shows water pollution from chemical additives. The blue area shows the installed desalination capacity according to the AQUA-CSP scenario. Life cycle assessment of emissions was calculated for each year on the basis of the subsequently changing electricity mix from /MED-CSP 2005/.

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Annex 1: Selection of Reference Plant Configuration

Option A1.1: Central Receiver with Combined Cycle

HTF Options:	compressed air
Advantages:	high efficiency for electricity
	can be placed in difficult terrain
Disadvantages:	not yet demonstrated
Storage:	not yet available but possible (ceramics)

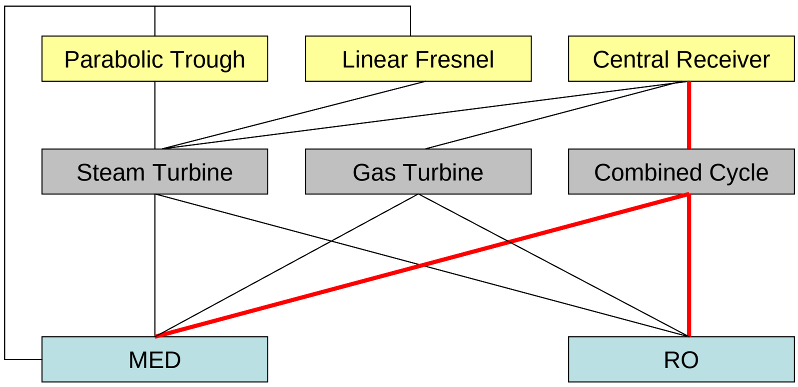

Figure A1.1: Central Receiver with Combined Cycle

Option A1.2: Central Receiver with Gas Turbine

HTF Options:	compressed air
Advantages:	can be placed in difficult terrain
	no water consumption of power block
	low cost power block
Disadvantages:	reject heat at very high temperature for MED
	low efficiency for electricity
	high space requirement
	only prototypes available (REFOS, Empoli)
Storage:	not yet available but possible (ceramics)

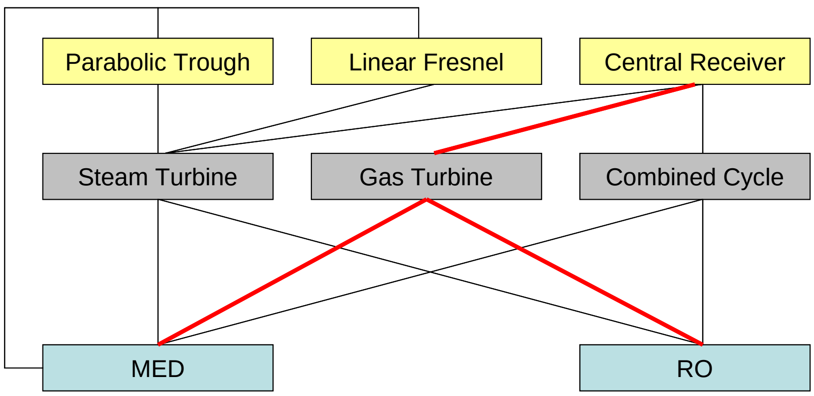

Figure A1.2: Central Receiver with Gas Turbine

Option A 1.3: Central Receiver with Steam Turbine

HTF Options: molten salt, direct steam, air

Advantages: can be placed in difficult terrain

Disadvantages: steam more expensive than by linear concentrators

high space requirement

only prototypes available (PS10, KAM, Solucar)

Storage: molten salt and ceramics demonstrated

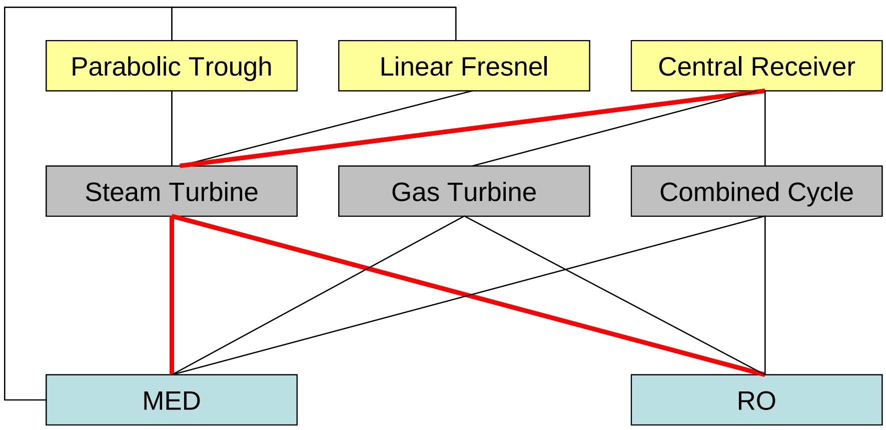

Figure A1.3: Central Receiver with Steam Turbine

Option A 1.4: Linear Fresnel with Steam Turbine

HTF Options: direct steam (oil or molten salt possible)

Advantages: low cost collector

low space requirement

easy integration (buildings, agriculture)

Disadvantages: only prototypes available (Novatec, MAN/SPG, SHP)

Storage: phase change or molten salt

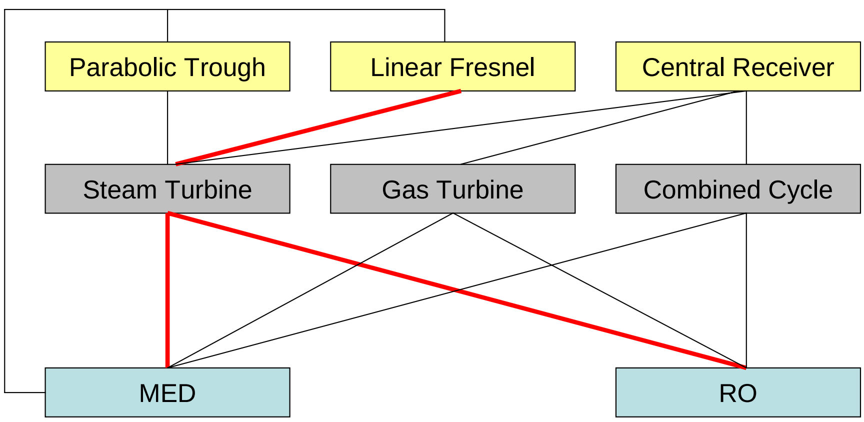

Figure A1.4: Linear Fresnel with Steam Turbine

Option A1.5: Linear Fresnel for Direct Heat

HTF Options: direct steam

Advantages: low space requirement

easy integration (buildings, agriculture)

Disadvantages: only prototypes available (Novatec, MAN/SPG, SHP)

Storage: very easy (hot water)

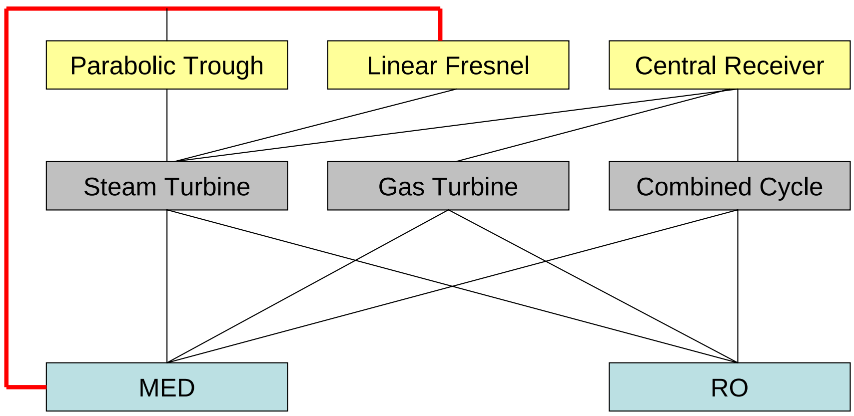

Figure A1.5: Linear Fresnel for direct heat

Option A 1.6: Parabolic Trough with Steam Turbine

HTF Options: oil, direct steam, molten salt

Advantages: most mature technology (Skal-ET, Schott, Flabeg, SMAG)

large plants build in Spain and USA (Acciona, Cobra)

Disadvantages: high precision required

high cost

high land requirement

no easy integration to buildings or agriculture)

Storage: concrete, phase change or molten salt

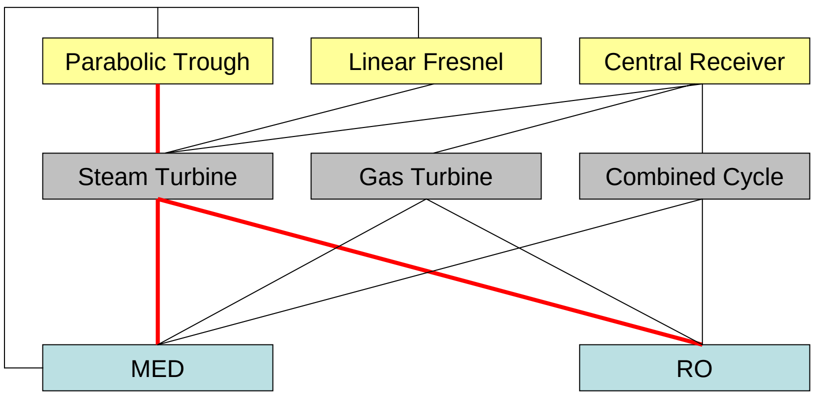

Figure A1.6: Parabolic Trough with Steam Cycle

Parabolic Trough for Direct Heat

Advantages: direct steam generation

low temperature collector available (Solitem)

Disadvantages: high cost

Storage: very easy (hot water)

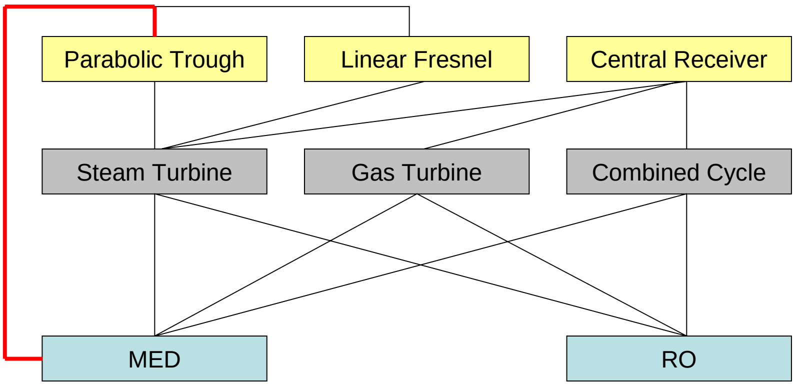

Figure A1.7: Parabolic Trough for Direct Heat

Annex 2: Controversial Publications on CSP/RO and CSP/MED

Several publications have recently appeared stating that a combination of CSP with RO is much more productive and cost-efficient than CSP/MED, creating a rather controversial and unfruitful discussion within the CSP and desalination community. As they contain methodical errors, they are not quoted within our main report, but only within this annex, and errors are explained.

Reference A 2.1:

G. Burgess and K. Lovegrove. Solar thermal powered desalination: membrane versus distillation technologies. Proceedings of the 43rd Conference of the Australia and New Zealand Solar Energy Society, Dunedin, November 2005.

http://engnet.anu.edu.au/DEresearch/solarthermal/pages/pubs/DesalANZSES05.pdf

The authors state that the specific water output per square meter of collector area of a CSP (Parabolic-Dish-Steam-Cycle) system coupled to RO is much higher than that of a CSP/MED plant. This is in principle correct, as the electricity produced by the CSP plant will be fully used by RO, while MED will only use low-temperature steam extracted from the turbine and about 2 kWh/m³ of electricity for pumping, leaving most of the electricity generated by the CSP plant for other purposes. Therefore, a comparison on the basis of collector area only makes sense taking into account both products of the CSP plant (power and water).

Furthermore, the low values assumed by the authors for RO power consumption of 1.0 – 3.5 kWh/m³ suggest that not all the relevant components of the RO process have been taken into account, and that the delivered water quality is probably not comparable. The effect that MED replaces the cooling system of a CSP plant together with all its parasitic electricity consumption has been neglected. Therefore, the above mentioned conclusion of the authors generalising an advantage of CSP/RO is based on a miss-interpretation of their results and on incomplete input parameters for their comparison.

Reference A 2.2:

O. Goebel. Solar thermal co-generation of power and water – some aspects to be considered. 13th International Symposium on Concentrated Solar Power and Chemical Energy Technologies, SolarPaces, Sevilla, Spain 2006

This paper compares a CSP/MSF (Multi-Stage-Flash) configuration with CSP/RO and comes to the conclusion that the combination of CSP with RO would lead to a higher electricity output than combined generation when producing the same amount of desalinated water.

This statement is in principle correct, as MSF is a process that requires a lot of energy and operates with high temperature steam, resulting in a painfully reduced electricity output of the connected steam turbine. In fact, for those reasons MSF was discarded from our pre-selection in favour of MED. Unfortunately, the author does not mention that coupling MED instead of MSF to a CSP-plant would lead to a much better performance of solar thermal co-generation due to a lower internal electricity demand and lower operating temperature of the MED process. A CSP/MSF process cannot be considered representative for a modern solar powered co-generation system of this type, as suggested by the author.

Reference A 2.3:
O. Goebel, A. Wiese, SOWELSI – Solar Water and Electricity for Sinai, International Desalination Association BAH03-069

This paper compares a CSP (Parabolic Trough Steam Cycle with Storage) system with MED and one with RO seawater desalination, and comes to the conclusion that the distillation process clearly leads to higher power and water costs than RO, because RO requires less investment and energy.

The authors compare two CSP steam cycle power plants with identical parabolic trough solar fields, one coupled with RO and the other with MED that produce identical amounts of potable water. In design point, the CSP/MED variant produces 10 MW of extra net power, while the CSP/RO system produces 11 MW of extra power. This small difference of net power output, multiplied with the annual operating hours of the plant, finally leads to a seeming advantage of CSP/RO in terms of internal rate of return.

The comparison is based on the assumption that MED consumes 3 kWh electricity per m³ of water. This is equivalent to 3.5 MW of required capacity which is subtracted from the rated output capacity of the power plant. A generally accepted value of power consumption of a modern MED would however be around 2 kWh/m³ equivalent to less than 2.5 MW capacity.

The fact that a MED plant substitutes the cooling system of the CSP plant and its parasitic power consumption of 1-2 MW was neglected. A more realistic appraisal of input parameters would thus eliminate the seeming advantage of CSP/RO and lead on the contrary to an advantage of CSP/MED yielding at least 12 MW of extra net power compared to CSP/RO with only 11 MW.

The difference between CSP/MED and CSP/RO in terms of technical and economic performance is rather small. Although Goebel and Wiese admit using rough estimates of input parameters for their analysis, they neglect that a small variation (like e.g. power demand of MED and consideration of parasitic losses) would lead to an opposite result of their comparison. A general preference for one or the other technology, and especially for CSP/RO as suggested by the authors of the paper, is therefore not scientifically sound.

Annex 3: Integrated Solar Combined Cycle System (ISCCS)

A **combined cycle (CC)** power station consists of a gas turbine (Brayton Cycle) and a steam turbine (Rankine Cycle). Fuel is used to provide hot, pressurized gas that directly drives the gas turbine for power generation. The residual gas leaving the gas turbine is still relatively hot and can be used to generate high pressure steam to drive a steam turbine for power generation with approximately half the capacity of the gas turbine. The gas turbine will provide 65-70 %, the steam turbine about 30-35 % of the total capacity of the CC plant. Today, this system has the highest efficiency of power generation from fossil fuel of well over 50 %.

An **integrated solar combined cycle systems (ISCCS)** has a parabolic trough solar field that additionally provides steam for the Rankine cycle of a combined cycle system. The steam turbine must be oversized to about 50 % of total capacity, because during daytime it will have to take both the flue gas from the gas turbine and additional solar heat, while it will be partially idle at night when no solar heat is available. During night time there will be a lower efficiency of power generation, either due to part load of the turbine or because of additional steam generation by fuel.

The solar share in design point operation is limited to the extra capacity of the steam turbine that is 20 % of total. A base load plant with 8000 operating hours per year will operate for about 2000 hours (a quarter of the time) with 20 % solar share and for 6000 hours (three quarters) on 100 % fuel. This translates to an annual solar share of only 5 %. This relatively small solar share will in any case be partially and in the worst case totally compensated by the lower efficiency during night time operation, as explained before.

If the system is build in a remote area because of higher solar irradiance, 95 % of the input energy – fuel – will have to be transported there, and electricity will have to be brought back to the centres of demand, causing additional energy losses. There is a considerable risk that an ISCCS would consume more fuel per net delivered electric kWh than a standard fuel-fired combined cycle on a usual site.

When Gottlieb Daimler invented the automobile, he took a horse wagon and a combustion motor, and put them together. Putting a concentrating solar field, a steam turbine and a desalination plant together would be something like that. If Daimler would have left the horse on the wagon when building his first car, he would have invented something like an ISCCS.

For those reasons, ISCCS has not been taken here into consideration as possible representative combination of CSP with seawater desalination.

Annex 4: Current Project Proposals for CSP Desalination

In the following we will shortly present some statements on presently ongoing project developments for CSP desalination:

Libya – MAN / Solar Power Group

The initial Libyan project is a R&D plant to expand and demonstrate the feasibility of solar thermal electricity and desalinated water production for Libya. It is expected that there will be a large demand for water desalination in Libya in the future, and solar powered systems could be a perfect fit for this situation. This is also expressed in the fact that the Libyan government has signed a cooperation agreement with SPG/MAN for 3,000 MW installed capacity of solar thermal power plants to be built within the next decade. The pilot plant will be build at the Center for Solar Energy Studies near Tripoli.

The technology to be applied will be of Fresnel-type solar thermal collectors with direct steam generation. The mirror area will be about 140,000 m^2. The rated output of the steam turbine will be about 15 MW while the maximum output of the multiple effect desalination plant is about 700 m^3/h (http://www.solarpowergroup.com).

Water for Sana'a from Solar Desalination at the Red Sea

The City of Sana'a is the Capital of the Republic of Yemen and it is one of the oldest and World Heritage City (see Fig.1). It is situated in the north west part of the country having an elevation of 2,400 meters above sea level. The population of Sana'a city according to 2004 census was 1.75 million (Total population of Yemen stands at about 20 Million inhabitants) with a population growth rate of 5.5% (2004 national census).

Fig. 1: Window on UNESCO World Heritage City of Sana'a

The water supply of the city and its surroundings is mainly extracted from the ground water reserves and from harnessing rain water. The ground water comes from a water basin which has a surface area of 3,250 km^2 while the rain water harnessing comes from the average annual rainfall of 200 – 400 mm that falls over the region.

The present water situation of Sana'a shows that the total ground fossil water reserve is at best in the region of 2 - 3 Billion m^3. The extraction rate for both domestic and irrigation purposes has been quoted at 260 Million m^3 per year [(1)], while the ground recharge rate has been averaging at about 52 Million m^3 per year[1]. It is therefore, been estimated that Sana'a Basin will be depleted between the years 2015 and 2020.

The Water Demand

The water supply for Sana'a is approaching a critical point since about 80% comes from the extracted fossil reserves of its basin. As the basin is estimated to deplete by the year 2020 and the population of the city expected to exceed the 2.5 Million figure, it is imperative that the demand will be to supply enough water for at least 2 Million inhabitants by this time as the rechargeable water will only be enough for about 0.4 Million inhabitants. Therefore, it is proposed strategically that a water supply project targeting a supply of Solar Desalinated Water from the Red Sea in the region of 1.0 Billion m^3/year before the year 2020.

The Sana'a Solar Desalination Water Project Proposal

The proposed Solar Desalination Water for Sana'a from the Red Sea Project is aimed at desalinating water using Concentrating Solar Power (CSP) from the Red Sea close to the coastal city of Hudaidah. The quantity of the desalinated water would then be transported a distance of about 250 km with an elevation of 2,700 m (Fig.2).

Even though Yemen is in the lucky situation of having oil and gas fields, of 3 Billion barrels of oil and of 480 Billion m^3 gas according to present estimates, their reach into the future is too limited for a water supply system: with the present production rate the oil reserves will be depleted in about 2022. If gas takes over however most of oil services after 2020, it is unlikely that gas supplies will last much beyond 2040, unless new fields are discovered.

The bottom line on desalination with fossil energy is: the domestic reserves may cease to be available after 2040. This will then lead to a nation-wide collapse of desalination and of power generation with fatal implications for the existence of Sana'a and with dramatic implications for the whole country.

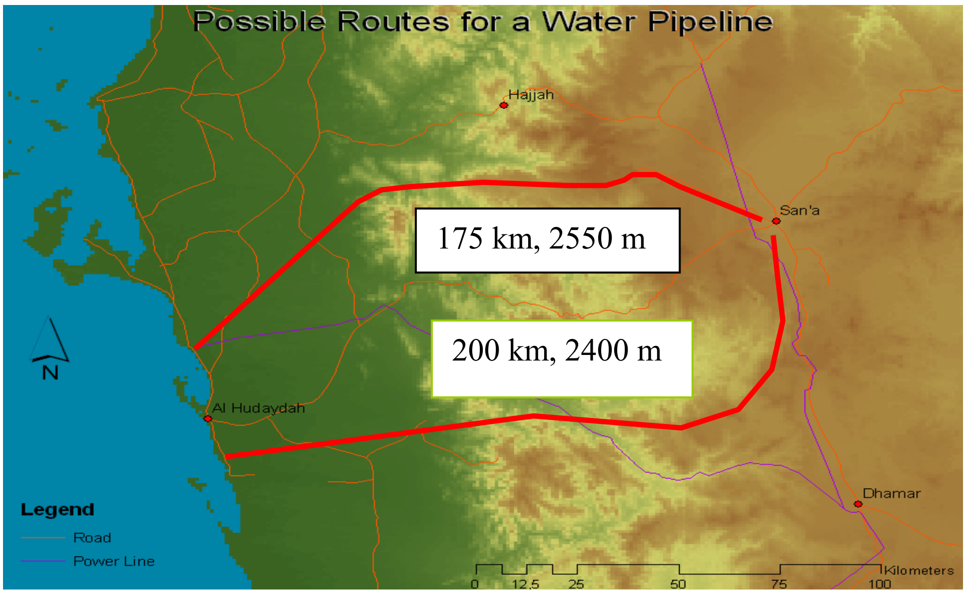

Fig.2: Sana'a Water Project Pipeline Routes

For above reasons the option of solar energy as the basis for a water and energy supply system with long-term security was chosen. Table 1, Fig. 3 and Fig. 4 shows that Solar Energy has great potential in Yemen, much larger than would be needed to accommodate the desalination and power generation needs of the country for the foreseeable future. For desalinating and pumping 1 Billion m³/year, a collector area of about 20 km² is needed. Therefore, "Solar Power Generation and Desalination of Seawater" as the preferred strategy for Water and Energy Security for Sana'a and for Yemen, and thus was considered for the "Sana'a Solar Water Project Proposal".

Technical Potential	14,150 TWh/y **(DNI > 1800 kWh/m²/y)**
Economic Potential	10,230 TWh/y **(DNI > 2000 kWh/m²/y)**
Power Demand 2000 (Yemen)	3 TWh/y
Power Demand 2050 (Yemen)	383 TWh/y
Tentative CSP 2050	300 TWh/y
Coastal Potential	390 TWh/y **(<20m a.s.l.)**
Water Demand 2050	62 TWh/y (Power for Desalination)
Sana'a Solar Water Project	10 TWh/y (Desalination and Pumping)

<u>Table 1:</u> The Solar Thermal Power Potential in Yemen[(2)]

<u>The Sana'a Solar Water Project Components</u>

The Sana'a Solar Water Project is composed of three main components and these are the Solar Thermal Power Plant with a 1,250 MW power capacity which will provide enough electrical energy for the Desalination Processes and the Pumping Machinery, the Desalination Plants and the Transportation hardware such as Pipes, Pumps etc.. These components are described below:

Solar Thermal Power Plants	**1,250 MW**
Solar Field Size	21,120,000 m² (75% solar, 16 h storage)
Electricity Production	10,000 GWh/y
Electricity for RO & MED	2,700 GWh/y
Electricity for Pumping	7,300 GWh/y
Desalination	
Multi-Effect-Desalination	700 Mill. m³/year
Reverse Osmosis	300 Mill. m³/year
Transport	
Pipeline:	250 km steel pipeline, dia. 3000 mm
Pumping:	4 pump stations and buffer basins
Infrastructure:	roads, power lines, …

The Sana'a Solar Water Project Investment Costs

The Sana'a Solar Water Project investment is estimated to reach near the 11 Billion US$ covering the cost of all the three components of the project. The details of the share of the investment cost of each component are shown below:

• Solar Thermal Power Plants 1,250 MW	4.0 Bill. US$
• Multi-Effect-Desalination 300 Mill. m³/year	1.5 Bill. US$
• Desalination Reverse Osmosis 700 Mill. m³/year	2.5 Bill. US$
• Infrastructure Pipeline/Pumping	3.0 Bill. US$
Total Investment	**11.0 Bill. US$**

The Sana'a Solar Water Project Water Costs

The Sana'a Solar Water Project using CSP as compared to using an alternative energy such as the normal fossil fuels proves its economic viability as illustrated below:-

Fuel price in 2015	**42 $**	**60 $**	**80 $/bbl.**
CSP / Solar with MED/RO	**Investment 11.0 Bill. $**		
Water production costs	0.7 $/m³	0.8 $/m³	0.8$/m³
Pumping costs	1.0	1.0	1.2
Water costs in Sana'a	**1.7**	**1.8**	**2.0**
(after 20 year depreciation)	*0.7*	*0.8*	*1.0*
Fossil with MED/RO	**Investment 7.0 Bill. $**		
Water costs in Sana'a	**2.2**	**2.7**	**3,4**
Fossil CC with RO	**Investment 6.7 Bill. $**		
Water costs in Sana'a	**1.8 $/m³**	**2.3 $/m³**	**2.8 $/m³**

- (est.: interest 6 % p.a., dept period 20 years, 40 years pipe & plant life)
- Sana'a WSS Corporation Tariff of 2004: about 160 Y.Rial / 0.86 $/m³)

<u>The Sana'a Solar Water Project Schedule of Phases (as of May 2007)</u>

- **-now- Kick-off: establish teams and base**
- **2007 Pre-Feasibility (6 months)**
- **2008 Feasibility (12 months)**
- **2009-12 Pilot Projects Yemen Al Hudaidah**
- **2009 EPC of the Pipeline**
- **2012 Operation of the Pipeline**
- **2010-17 Lighthouse 'Sana'a Solar Water'**

Edited by Towfik Sufian, University of Sana'a and Hussein Altowaie, University of Aden, Yemen.

References

(1) Source: Sana'a Water and Sanitation Local Corporation (SWSLC), Yemen

(2) Source: DLR MED-CSP Study, see: www.TRECers.net

Annex 5: Individual Country Data

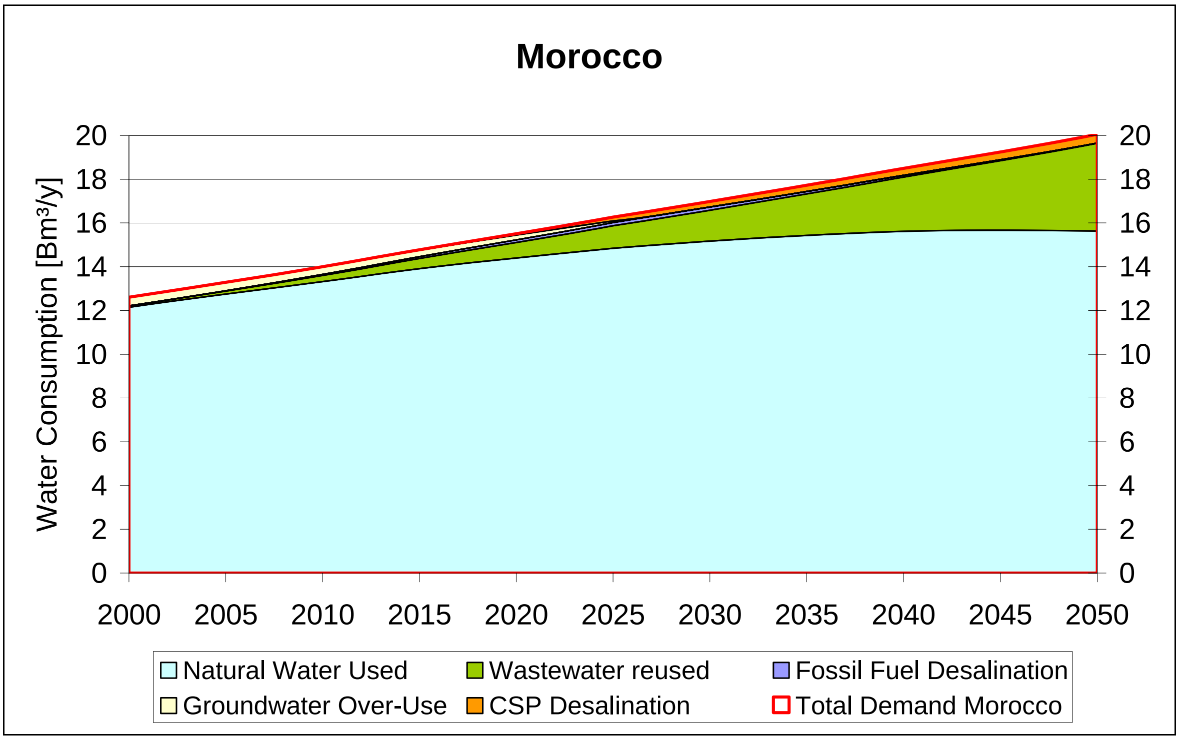

Figure A- 1: Water supply scenario until 2050 in Morocco

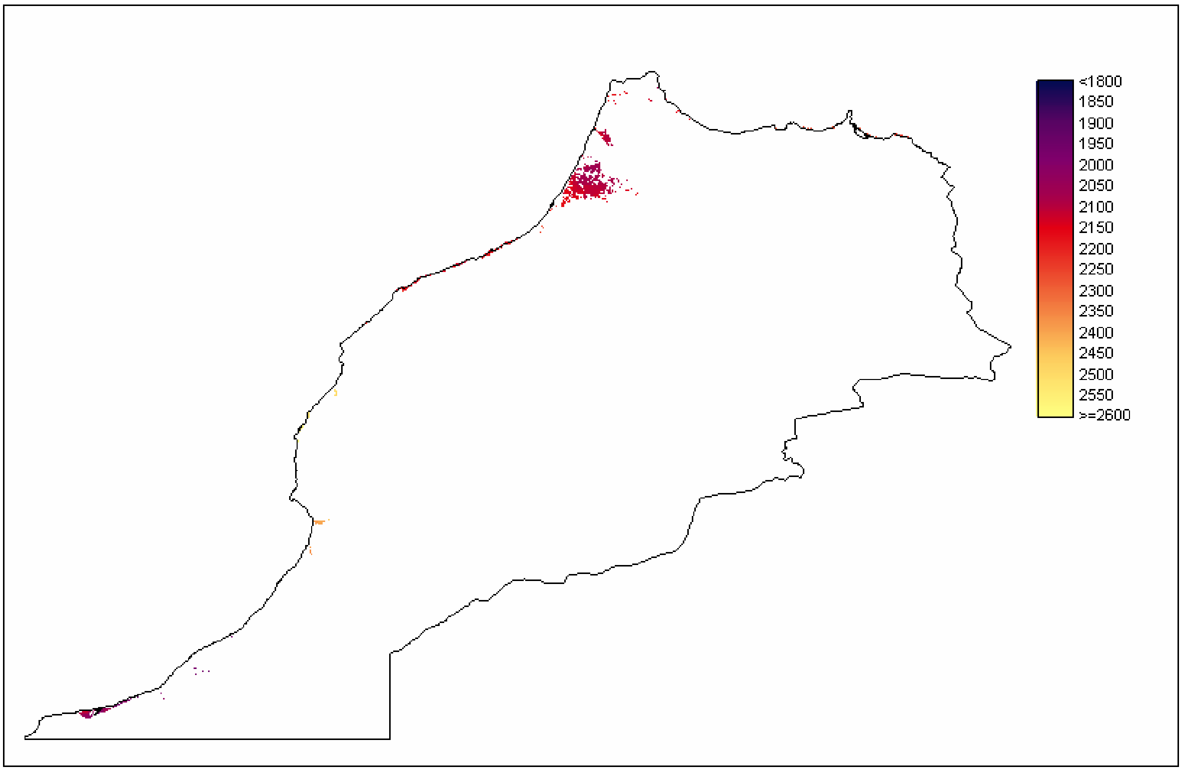

Figure A- 2: Direct normal irradiance in kWh/m²/y at potential coastal sites for CSP desalination plants

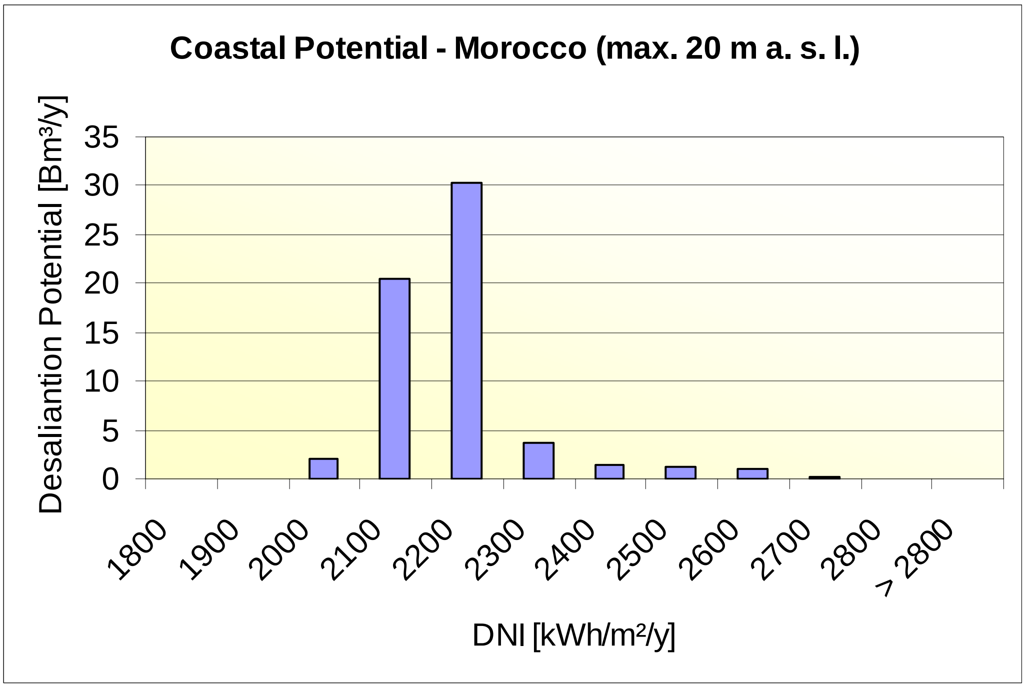

Figure A- 3: Statistical analysis of the DNI map for CSP-desalination in Morocco

Morocco		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Population MP	Mp	29.2	33.8	38.3	42.0	44.8	46.4
Exploitable Water	Bm³/y	20	20	20	20	20	20
Sustainable Water	Bm³/y	12.21	13.67	15.27	16.83	18.43	20.05
Irrigation Efficiency	%	0.37	0.40	0.44	0.47	0.50	0.54
Agricultural Use	Bm³/y	11.01	11.7	12.2	12.4	12.4	12.0
Municipal Efficiency	%	0.66	0.69	0.71	0.74	0.76	0.79
Municipal Use	Bm³/y	1.2	1.79	2.55	3.52	4.74	6.22
Industrial Use	Bm³/y	0.4	0.52	0.74	1.03	1.38	1.81
Total Demand Morocco	Bm³/y	12.6	14.0	15.5	17.0	18.5	20.1
per capita Consumption	m³/cap/y	432	414	405	405	413	432
Wastewater reused	Bm³/y	0.06	0.3	0.7	1.4	2.5	4.0
Non-sustainable Water	Bm³/y	0.4	0.4	0.3	0.1	0.1	0.0
CSP-Desalination Potential	Bm³/y	0.00	0.00	0.06	0.26	0.32	0.40
Fossil Fuel Desalination	Bm³/a	0.0	0.0	0.1	0.1	0.1	0.0
Groundwater Over-Use	Bm³/y	0.4	0.3	0.2	0.0	0.0	0.0

Table A- 1: Main scenario indicators until 2050 for Morocco

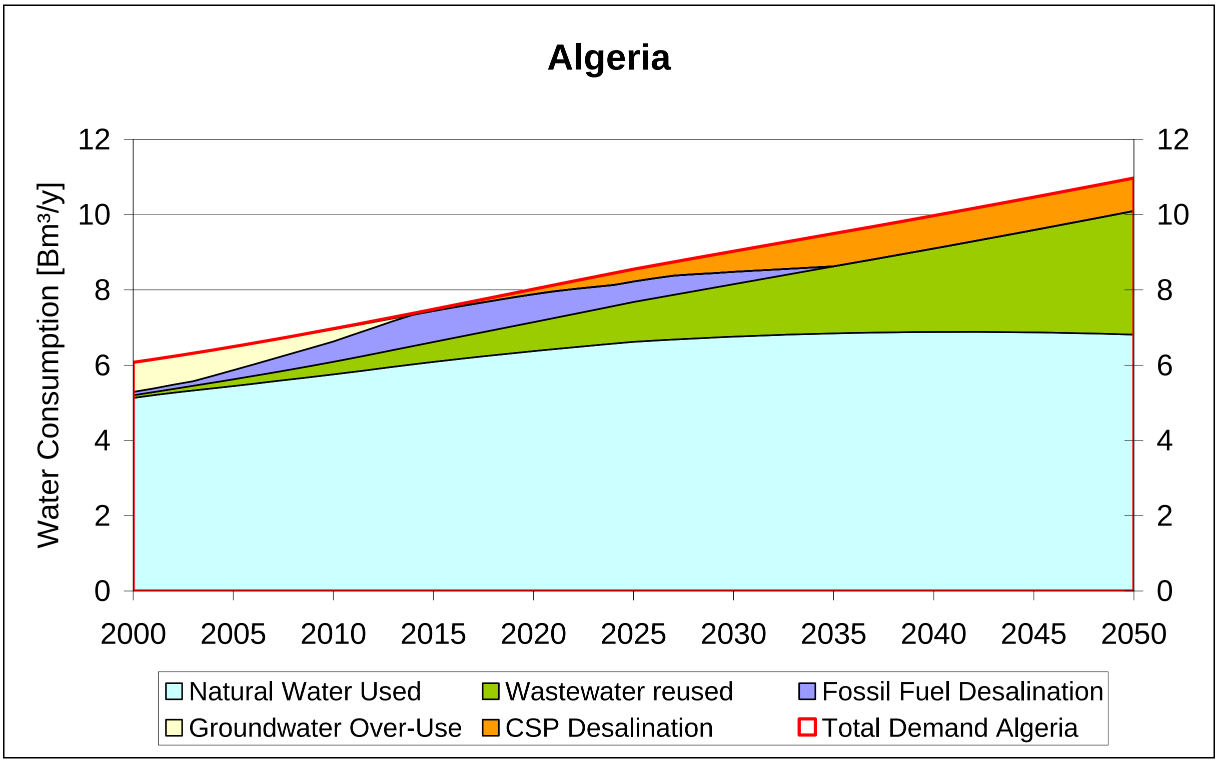

Figure A- 4: Water supply scenario until 2050 in Algeria

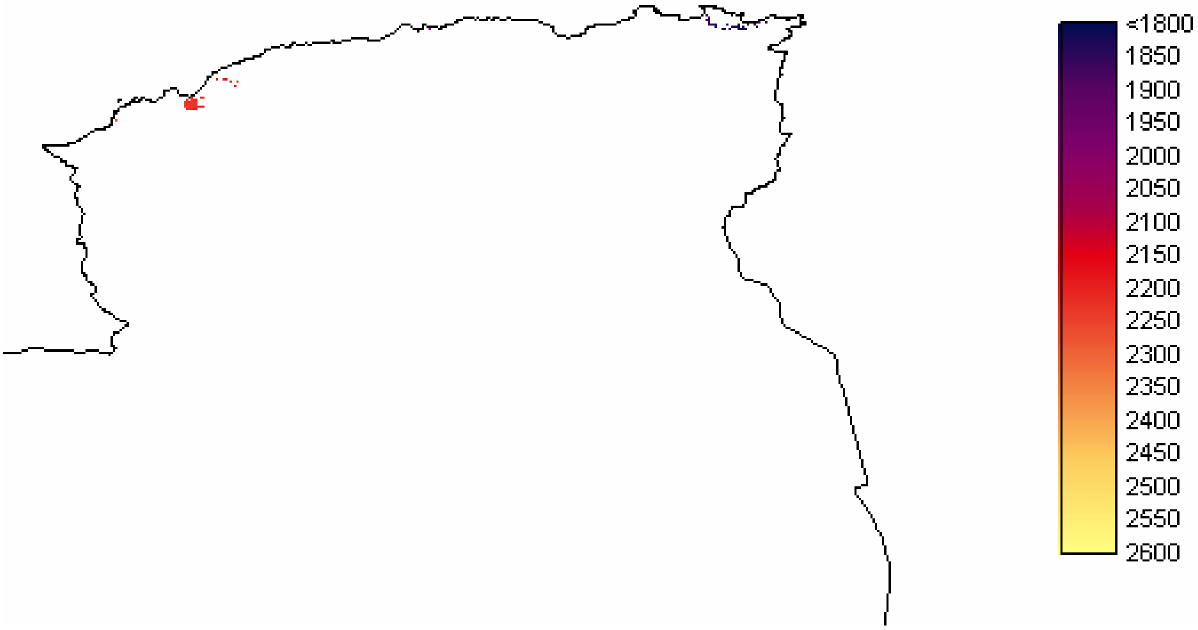

Figure A- 5: Direct normal irradiance in kWh/m²/y at potential coastal sites for CSP desalination in Algeria

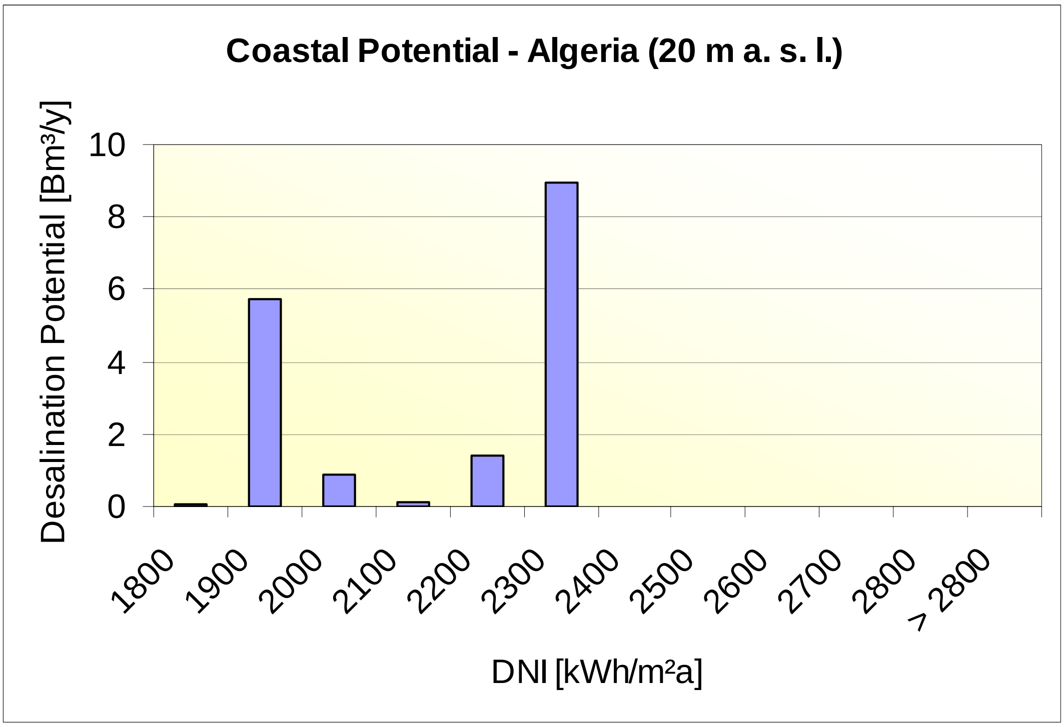

Figure A- 6: Statistical analysis of the DNI map for CSP-desalination in Algeria

Algeria		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Population MP	Mp	30.5	35.4	40.6	44.7	47.5	49.5
Exploitable Water	Bm³/y	7.9	7.9	7.9	7.9	7.9	7.9
Sustainable Water	Bm³/y	5.20	6.24	7.48	8.67	9.79	10.97
Irrigation Efficiency	%	0.37	0.40	0.44	0.47	0.50	0.54
Agricultural Use	Bm³/y	3.94	4.2	4.4	4.5	4.5	4.4
Municipal Efficiency	%	0.49	0.54	0.59	0.63	0.68	0.73
Municipal Use	Bm³/y	1.3	1.73	2.24	2.81	3.42	4.11
Industrial Use	Bm³/y	0.8	1.04	1.35	1.69	2.06	2.47
Total Demand Algeria	Bm³/y	6.1	7.0	8.0	9.0	10.0	11.0
per capita Consumption	m³/cap/y	199	197	198	202	210	222
Wastewater reused	Bm³/y	0.07	0.3	0.8	1.4	2.2	3.3
Non-sustainable Water	Bm³/y	0.9	0.9	0.7	0.3	0.0	0.0
CSP Desalination	Bm³/y	0.00	0.01	0.14	0.55	0.87	0.87
Fossil Fuel Desalination	Bm³/a	0.1	0.5	0.7	0.3	0.0	0.0
Groundwater Over-Use	Bm³/y	0.8	0.3	0.0	0.0	0.0	0.0

Table A- 2: Main scenario indicators until 2050 for Algeria

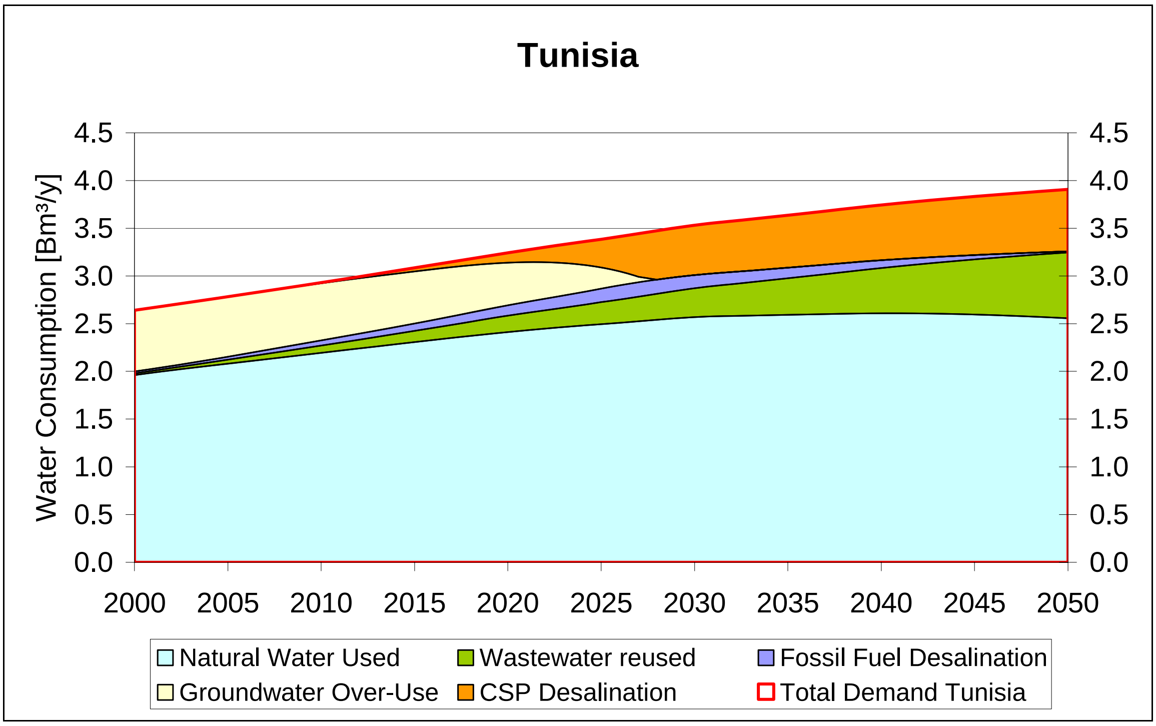

Figure A- 7: Water supply scenario until 2050 in Tunisia

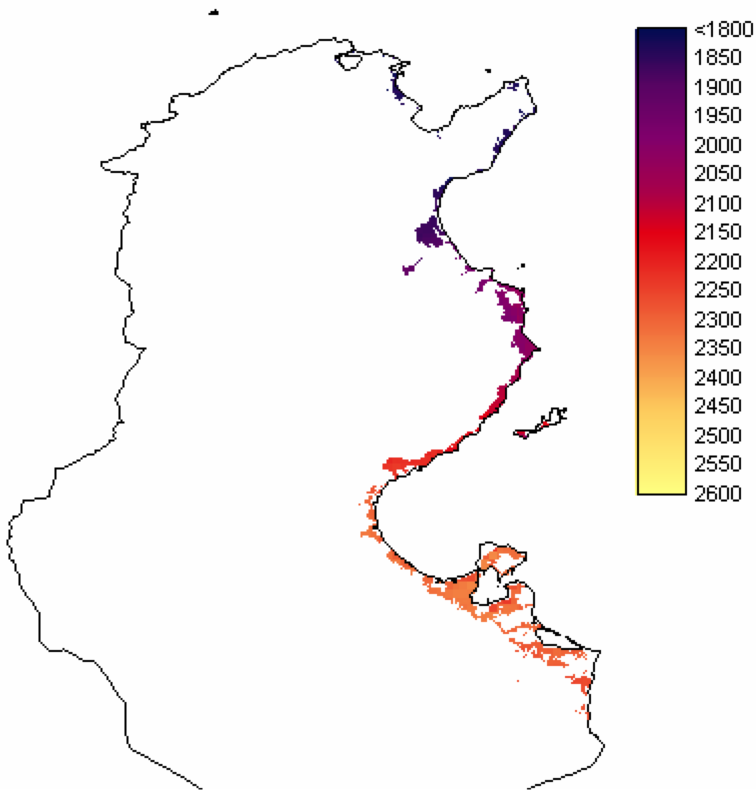

Figure A- 8: Direct normal irradiance in kWh/m²/y at potential coastal sites for CSP desalination in Tunisia

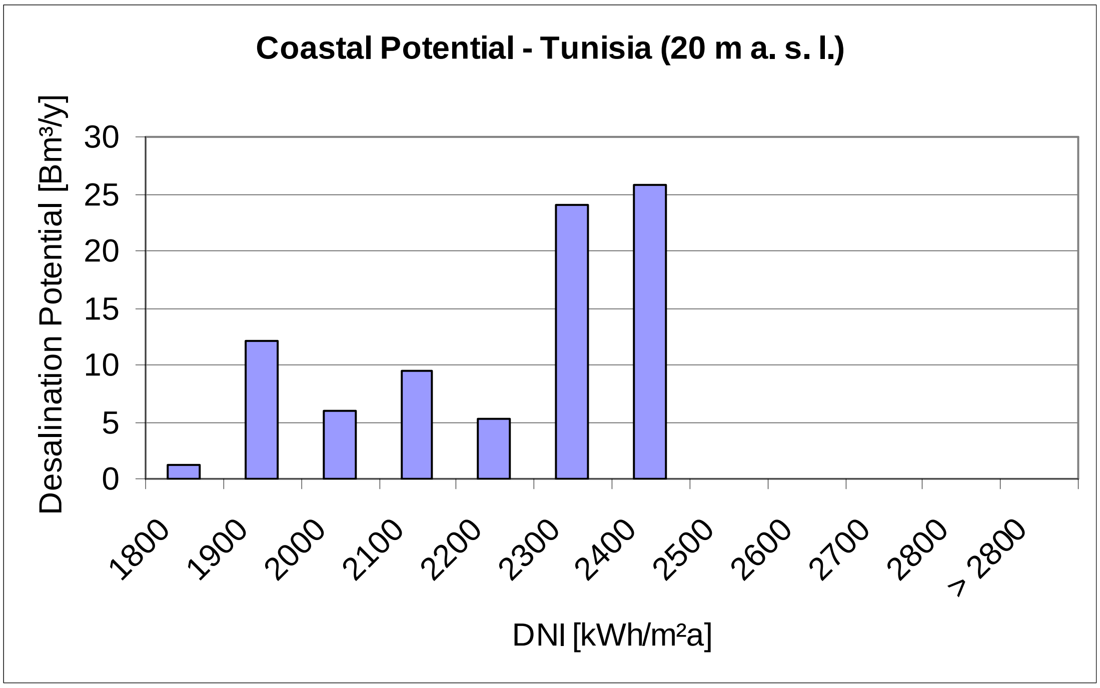

Figure A- 9: Statistical analysis of the DNI map for CSP-desalination in Tunisia

Tunisia		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Population MP	Mp	9.6	10.6	11.6	12.4	12.8	12.9
Exploitable Water	Bm³/y	3.6	3.6	3.6	3.6	3.6	3.6
Sustainable Water	Bm³/y	1.98	2.39	2.84	3.26	3.61	3.91
Irrigation Efficiency	%	0.54	0.56	0.57	0.59	0.61	0.62
Agricultural Use	Bm³/y	2.2	2.3	2.5	2.6	2.6	2.5
Municipal Efficiency	%	0.75	0.76	0.78	0.79	0.80	0.82
Municipal Use	Bm³/y	0.4	0.47	0.60	0.74	0.90	1.06
Industrial Use	Bm³/y	0.1	0.14	0.18	0.22	0.27	0.32
Total Demand Tunisia	Bm³/y	2.6	2.9	3.2	3.5	3.7	3.9
per capita Consumption	m³/cap/y	275	276	280	285	293	303
Wastewater reused	Bm³/y	0.02	0.1	0.2	0.3	0.5	0.7
Non-sustainable Water	Bm³/y	0.7	0.7	0.6	0.1	0.1	0.0
CSP Desalination	Bm³/y	0.00	0.01	0.10	0.52	0.58	0.65
Fossil Fuel Desalination	Bm³/a	0.0	0.1	0.1	0.1	0.1	0.0
Groundwater Over-Use	Bm³/y	0.6	0.6	0.4	0.0	0.0	0.0

Table A- 3: Main scenario indicators until 2050 for Tunisia

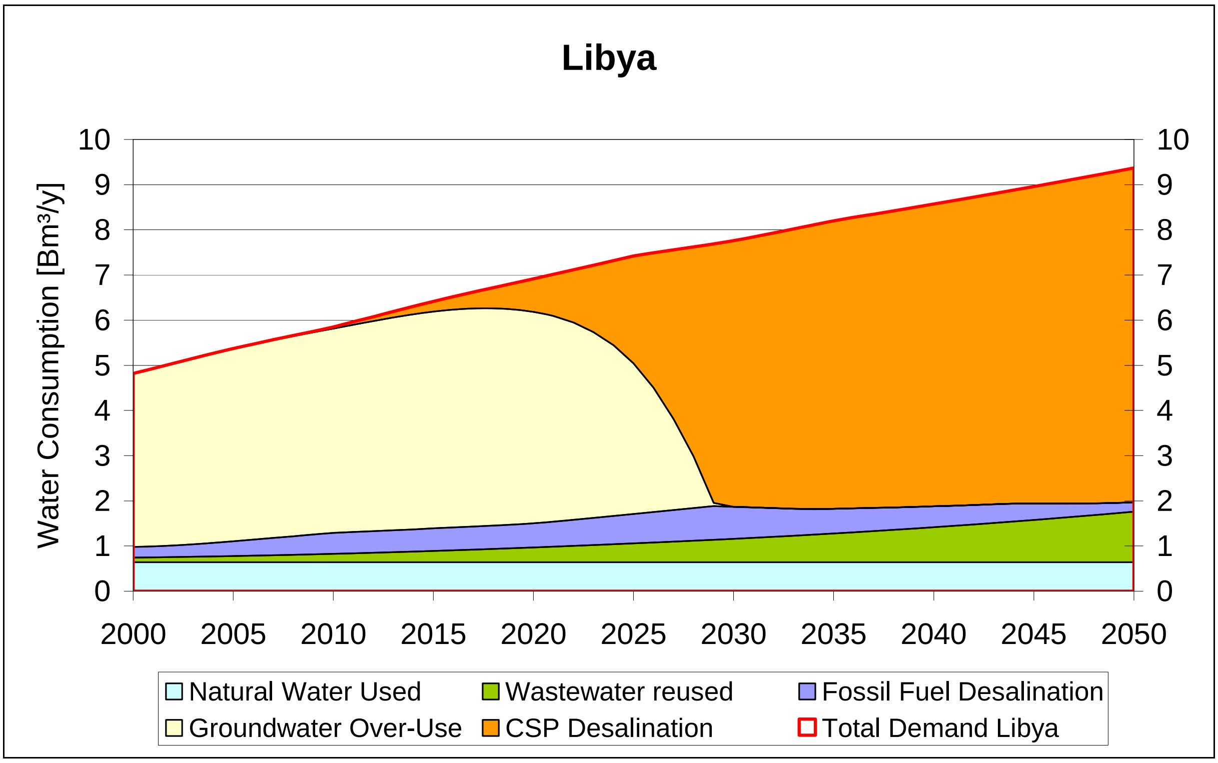

Figure A- 10: Water supply scenario until 2050 in Libya

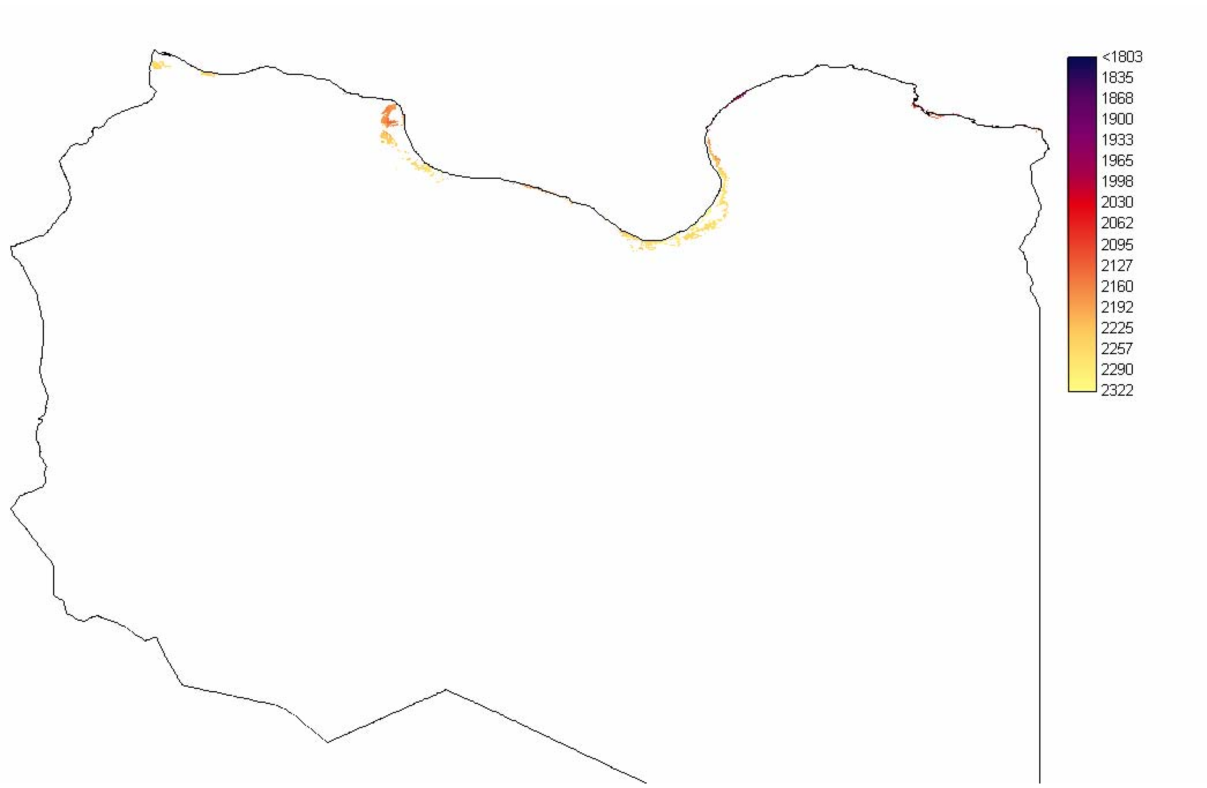

Figure A- 11: Direct normal irradiance in kWh/m²/y at potential coastal sites for CSP desalination in Libya

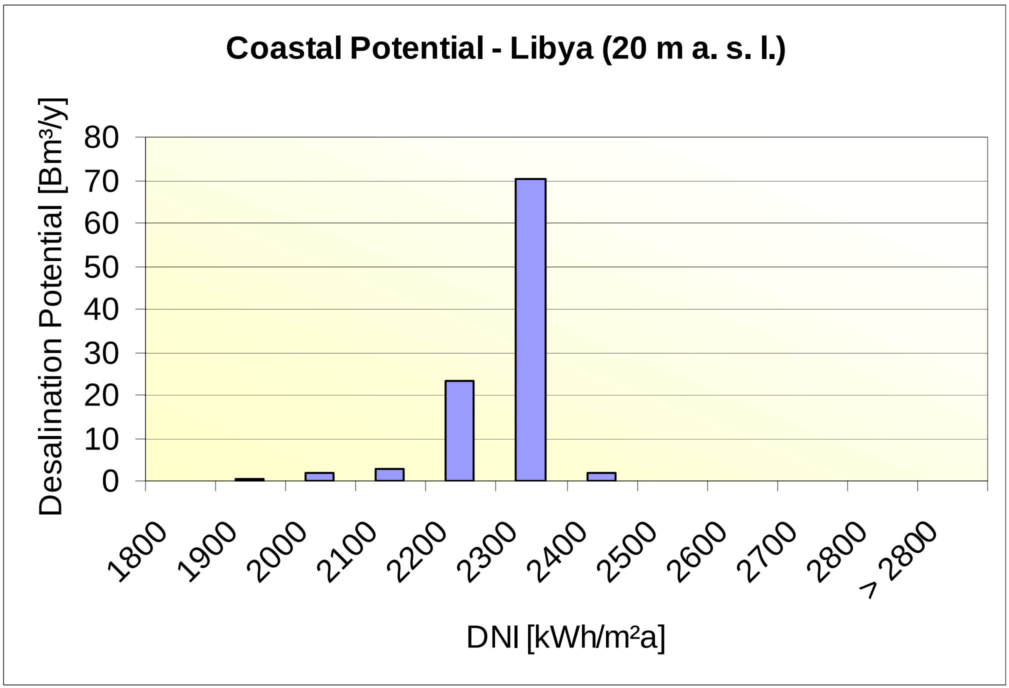

Figure A- 12: Statistical analysis of the DNI map for CSP-desalination in Libya

Libya		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Population MP	Mp	5.3	6.4	7.5	8.3	9.0	9.6
Exploitable Water	Bm³/y	0.64	0.64	0.64	0.64	0.64	0.64
Sustainable Water	Bm³/y	0.74	0.83	0.97	1.16	1.41	1.76
Irrigation Efficiency	%	0.60	0.61	0.62	0.63	0.64	0.65
Agricultural Use	Bm³/y	4.3	5.1	5.8	6.4	6.8	7.1
Municipal Efficiency	%	0.70	0.72	0.74	0.76	0.78	0.80
Municipal Use	Bm³/y	0.4	0.57	0.78	1.02	1.30	1.63
Industrial Use	Bm³/y	0.2	0.21	0.29	0.38	0.49	0.61
Total Demand Libya	Bm³/y	4.8	5.8	6.9	7.8	8.6	9.4
per capita Consumption	m³/cap/y	909	914	922	935	952	976
Wastewater reused	Bm³/y	0.10	0.2	0.3	0.5	0.8	1.1
Non-sustainable Water	Bm³/y	4.1	5.0	5.2	0.7	0.5	0.2
CSP Desalination	Bm³/y	0.00	0.04	0.73	5.89	6.69	7.40
Fossil Fuel Desalination	Bm³/a	0.2	0.5	0.5	0.7	0.5	0.2
Groundwater Over-Use	Bm³/y	3.8	4.5	4.7	0.0	0.0	0.0

Table A- 4: Main scenario indicators until 2050 for Libya

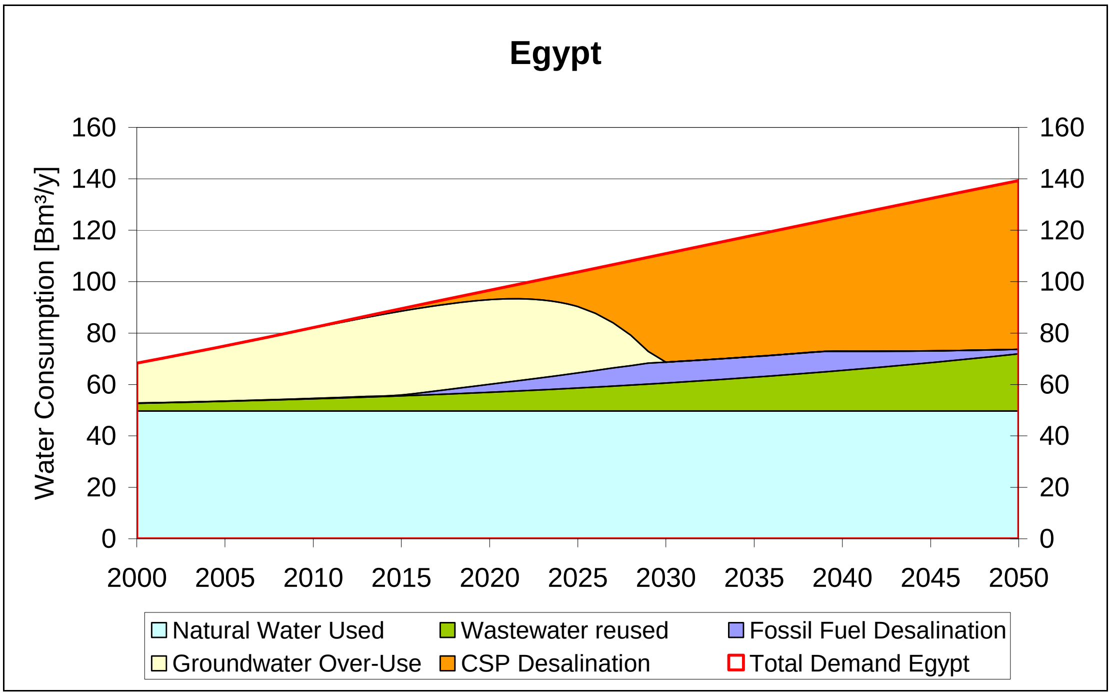

Figure A- 13: Water supply scenario until 2050 in Egypt

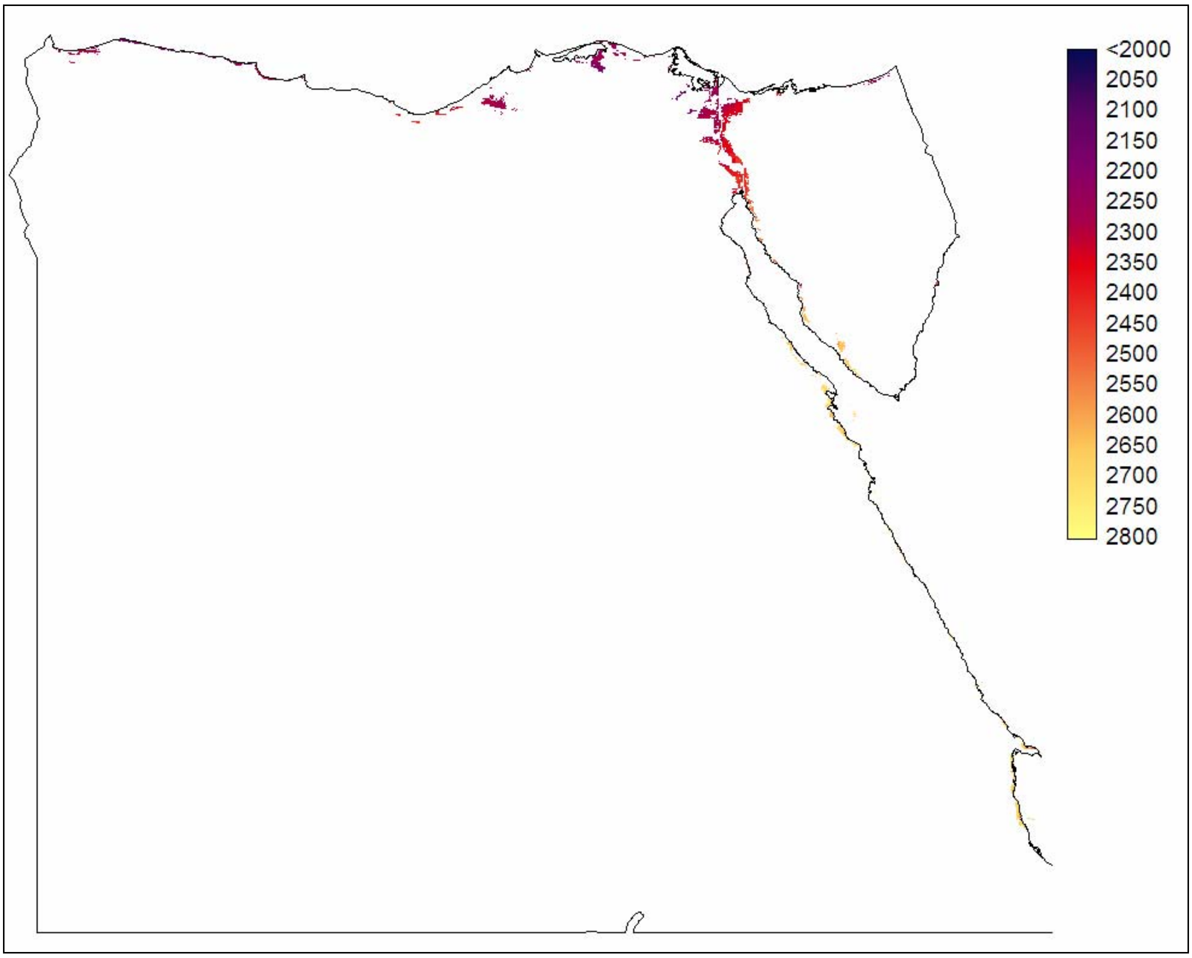

Figure A- 14: Direct normal irradiance in kWh/m²/y at potential coastal sites for CSP desalination in Egypt

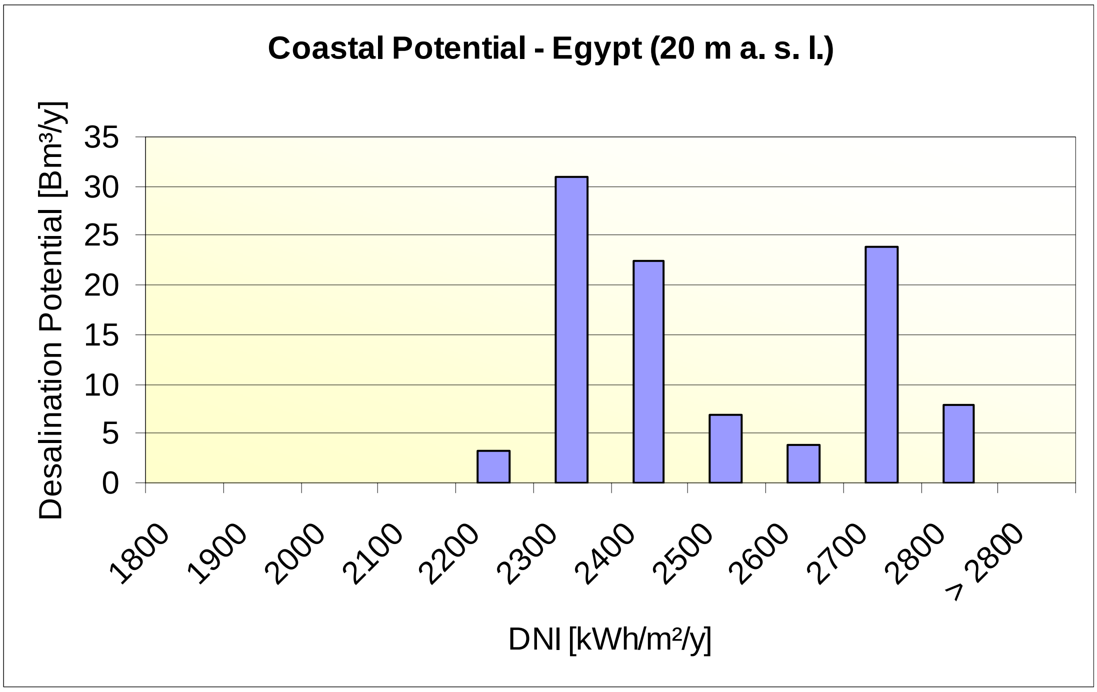

Figure A- 15: Statistical analysis of the DNI map for CSP-desalination in Egypt

Egypt		2000	2010	2020	2030	2040	2050
Population MP	Mp	67.3	81.1	94.8	107.1	117.8	125.9
Exploitable Water	Bm³/y	49.7	49.7	49.7	49.7	49.7	49.7
Sustainable Water	Bm³/y	52.68	54.40	56.97	60.56	65.46	71.93
Irrigation Efficiency	%	0.53	0.55	0.56	0.58	0.60	0.62
Agricultural Use	Bm³/y	59.0	68.8	78.0	85.5	91.3	94.9
Municipal Efficiency	%	0.50	0.55	0.59	0.64	0.69	0.73
Municipal Use	Bm³/y	5.3	7.59	10.63	14.51	19.39	25.34
Industrial Use	Bm³/y	4.0	5.73	8.02	10.95	14.64	19.12
Total Demand Egypt	Bm³/y	68.3	82.2	96.7	111.0	125.3	139.3
per capita Consumption	m³/cap/y	1015	1013	1020	1036	1064	1107
Wastewater reused	Bm³/y	3.0	4.7	7.3	10.9	15.8	22.2
Non-sustainable Water	Bm³/y	15.6	27.6	36.0	8.1	7.4	1.8
CSP Desalination	Bm³/y	0.00	0.13	3.66	42.26	52.45	65.63
Fossil Fuel Desalination	Bm³/a	0.1	0.2	3.1	8.1	7.4	1.8
Groundwater Over-Use	Bm³/y	15.5	27.4	32.9	0.0	0.0	0.0

Table A- 5: Main scenario indicators until 2050 for Egypt

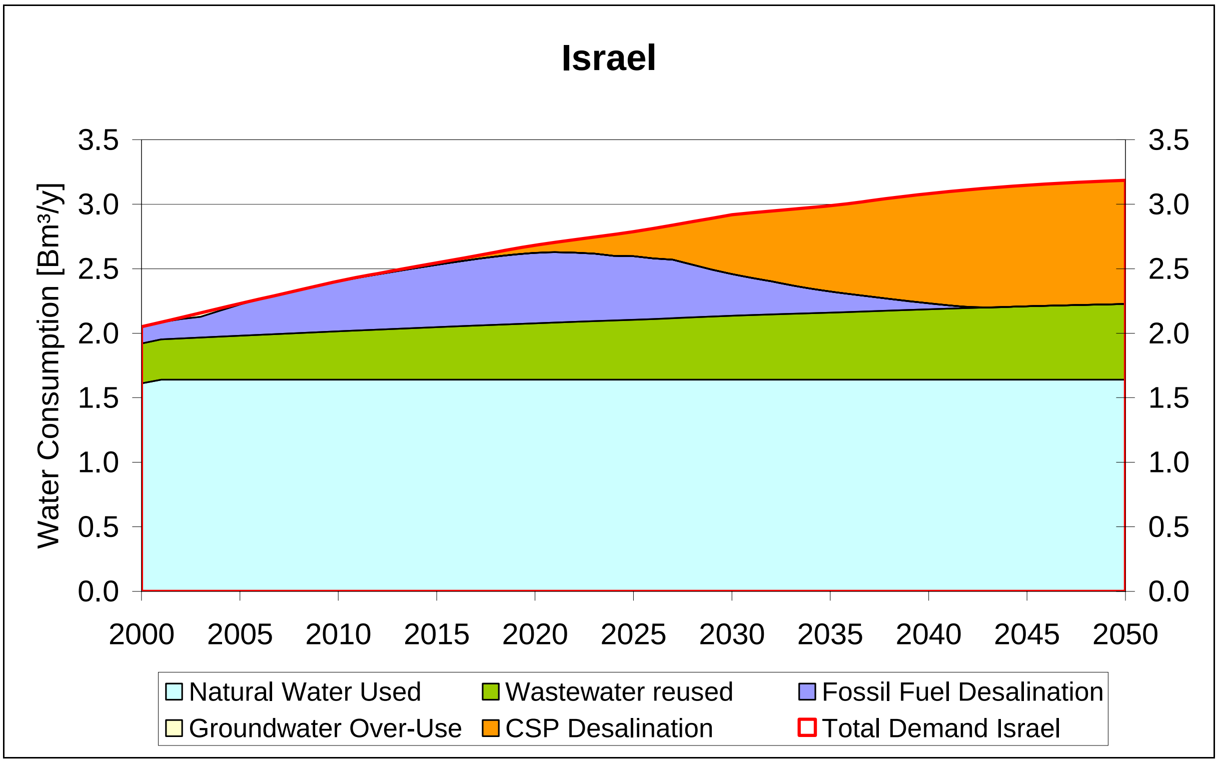

Figure A- 16: Water supply scenario until 2050 in Israel

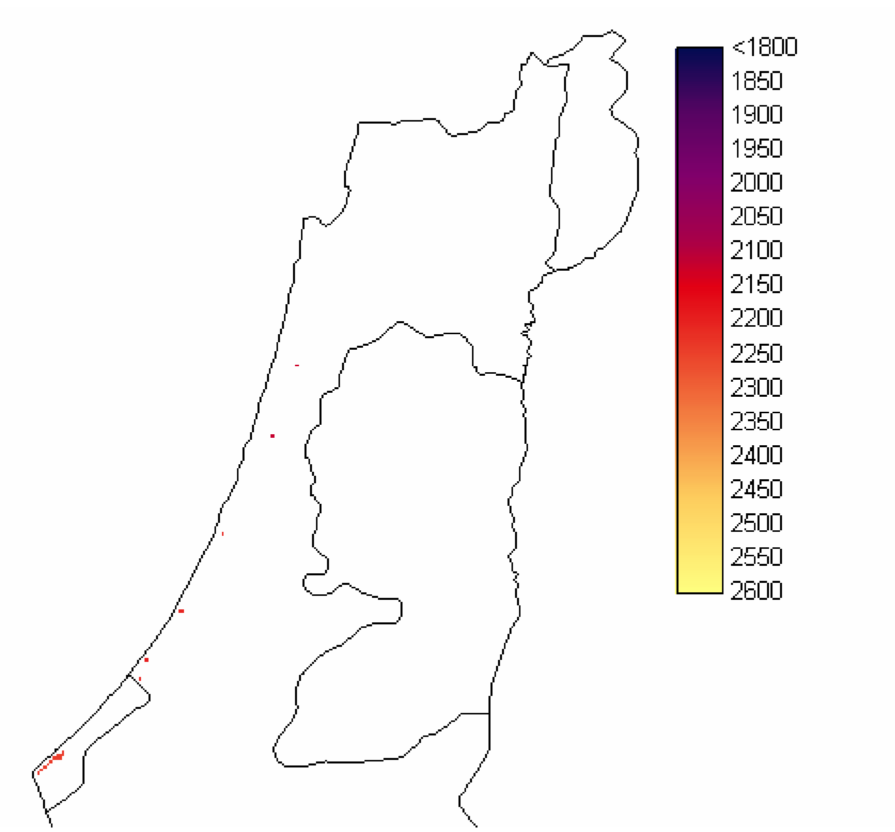

Figure A- 17: Direct normal irradiance in kWh/m²/y at potential coastal sites for CSP desalination in Israel

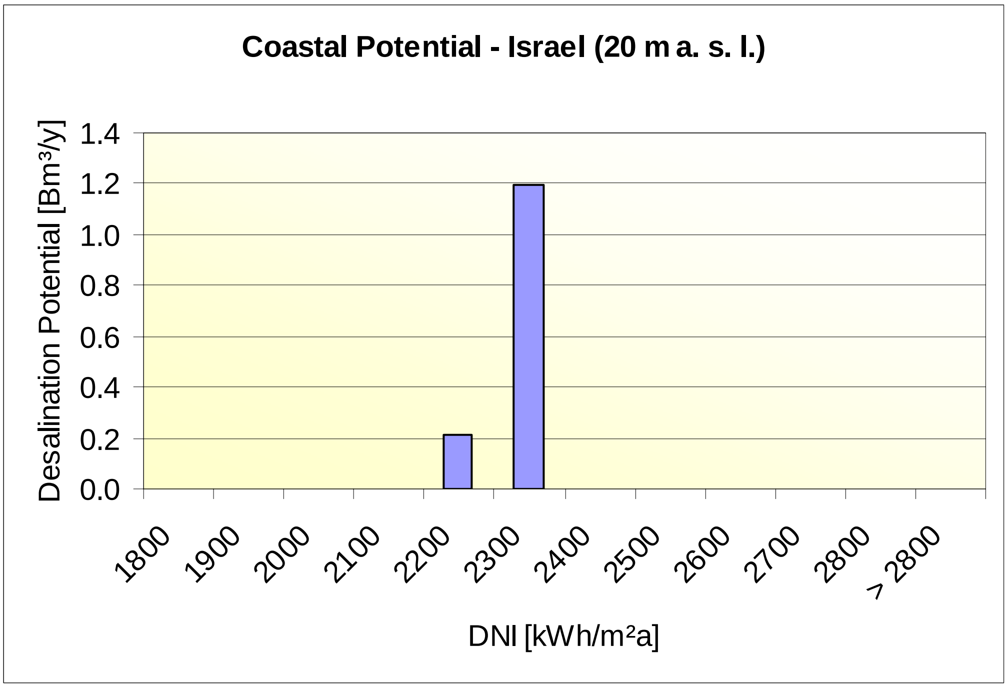

Figure A- 18: Statistical analysis of the DNI map for CSP-desalination in Israel

Israel		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Population MP	Mp	6.1	7.3	8.3	9.2	9.9	10.4
Exploitable Water	Bm³/y	1.64	1.64	1.64	1.64	1.64	1.64
Sustainable Water	Bm³/y	1.92	2.02	2.08	2.14	2.19	2.23
Irrigation Efficiency	%	0.60	0.61	0.62	0.63	0.64	0.65
Agricultural Use	Bm³/y	1.3	1.5	1.7	1.8	1.9	2.0
Municipal Efficiency	%	0.69	0.71	0.73	0.75	0.77	0.80
Municipal Use	Bm³/y	0.6	0.73	0.82	0.88	0.93	0.96
Industrial Use	Bm³/y	0.1	0.16	0.18	0.20	0.21	0.21
Total Demand Israel	Bm³/y	2.1	2.4	2.7	2.9	3.1	3.2
per capita Consumption	m³/cap/y	336	329	323	317	311	306
Wastewater reused	Bm³/y	0.308	0.4	0.4	0.5	0.5	0.6
Non-sustainable Water	Bm³/y	0.13	0.4	0.5	0.3	0.0	0.0
CSP Desalination	Bm³/y	0.00	0.00	0.06	0.46	0.85	0.96
Fossil Fuel Desalination	Bm³/a	0.1	0.4	0.5	0.3	0.0	0.0
Groundwater Over-Use	Bm³/y	0.0	0.0	0.0	0.0	0.0	0.0

Table A- 6: Main scenario indicators until 2050 for Israel

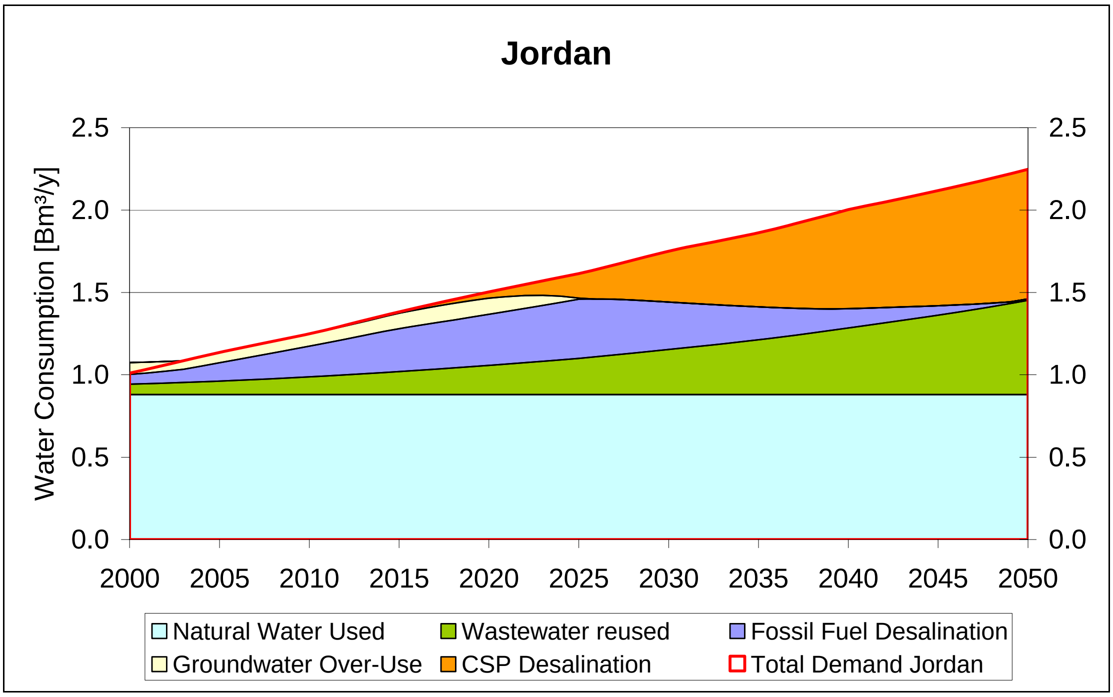

Figure A- 19: Water supply scenario until 2050 in Jordan

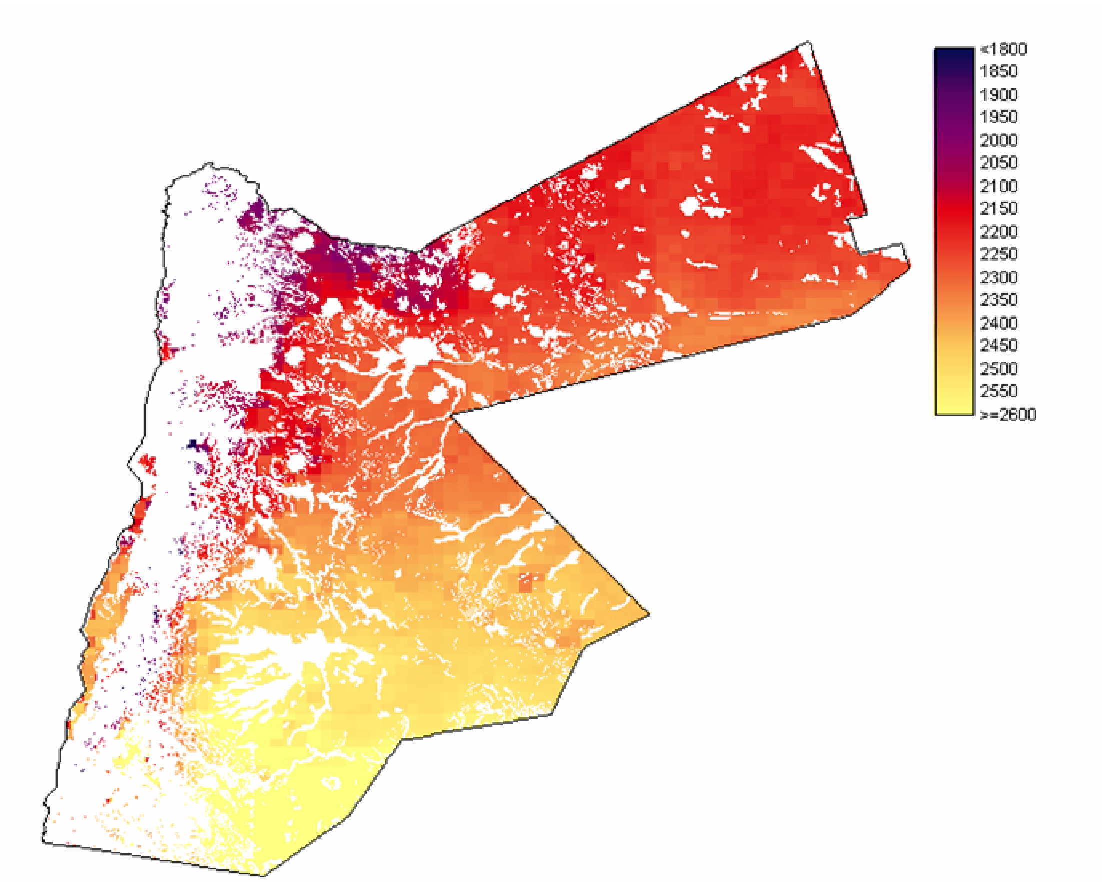

Figure A- 20: Direct normal irradiance in kWh/m²/y at potential sites for CSP power generation in Jordan. There is almost no coastal potential below 20 m a. s. l. except for the Red Sea Shore near Aqaba.

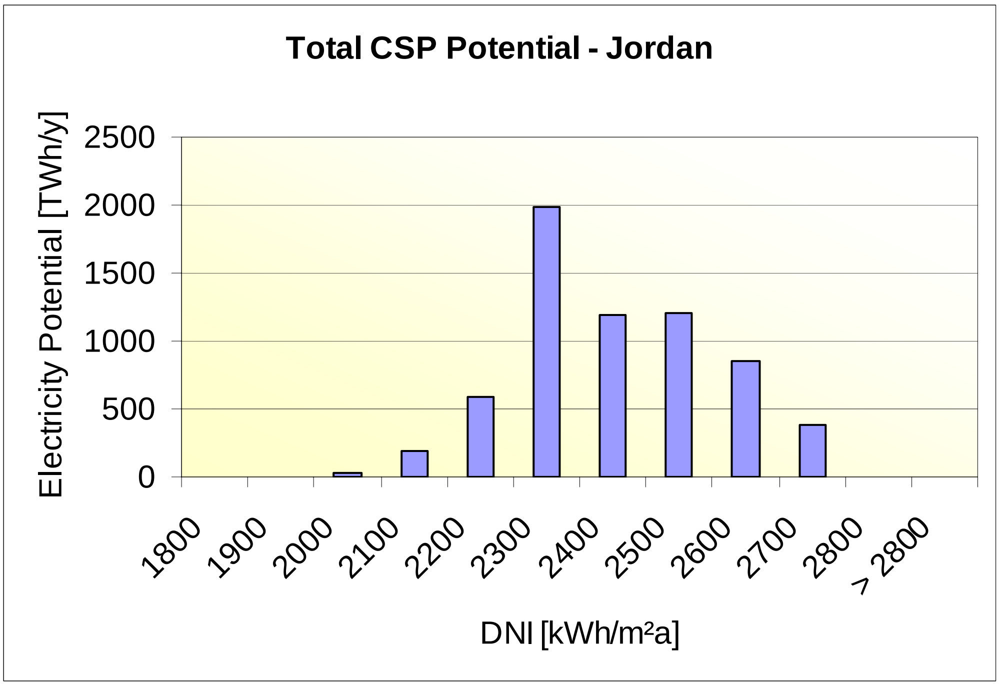

Figure A- 21: Statistical analysis of the DNI map for CSP-power generation in Jordan. There is almost no coastal potential available in Jordan except for the Red Sea coast at Aqaba. To cover the demand for CSP desalination 4 TWh/y of electricity will be required from CSP.

Jordan		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Population MP	Mp	5.00	6.30	7.60	8.70	9.60	10.20
Exploitable Water	Bm³/y	0.88	0.88	0.88	0.88	0.88	0.88
Sustainable Water	Bm³/y	0.88	0.99	1.06	1.15	1.28	1.45
Irrigation Efficiency	%	0.39	0.42	0.45	0.48	0.52	0.55
Agricultural Use	Bm³/y	0.8	0.9	1.0	1.1	1.1	1.1
Municipal Efficiency	%	0.48	0.53	0.58	0.63	0.68	0.73
Municipal Use	Bm³/y	0.2	0.30	0.43	0.58	0.76	0.96
Industrial Use	Bm³/y	0.0	0.06	0.08	0.11	0.14	0.18
Total Demand Jordan	Bm³/y	1.0	1.2	1.5	1.8	2.0	2.2
per capita Consumption	m³/cap/y	202	198	198	201	209	220
Wastewater reused	Bm³/y	0.063	0.1	0.2	0.3	0.4	0.6
Non-sustainable Water	Bm³/y	0.13	0.3	0.4	0.3	0.1	0.0
CSP Desalination	Bm³/y	0.00	0.00	0.04	0.31	0.60	0.79
Fossil Fuel Desalination	Bm³/a	0.1	0.2	0.3	0.3	0.1	0.0
Groundwater Over-Use	Bm³/y	0.1	0.1	0.1	0.0	0.0	0.0

Table A- 7: Main scenario indicators until 2050 for Jordan. Most of the desalination potential will have to be powered by electricity from CSP plants inside the country.

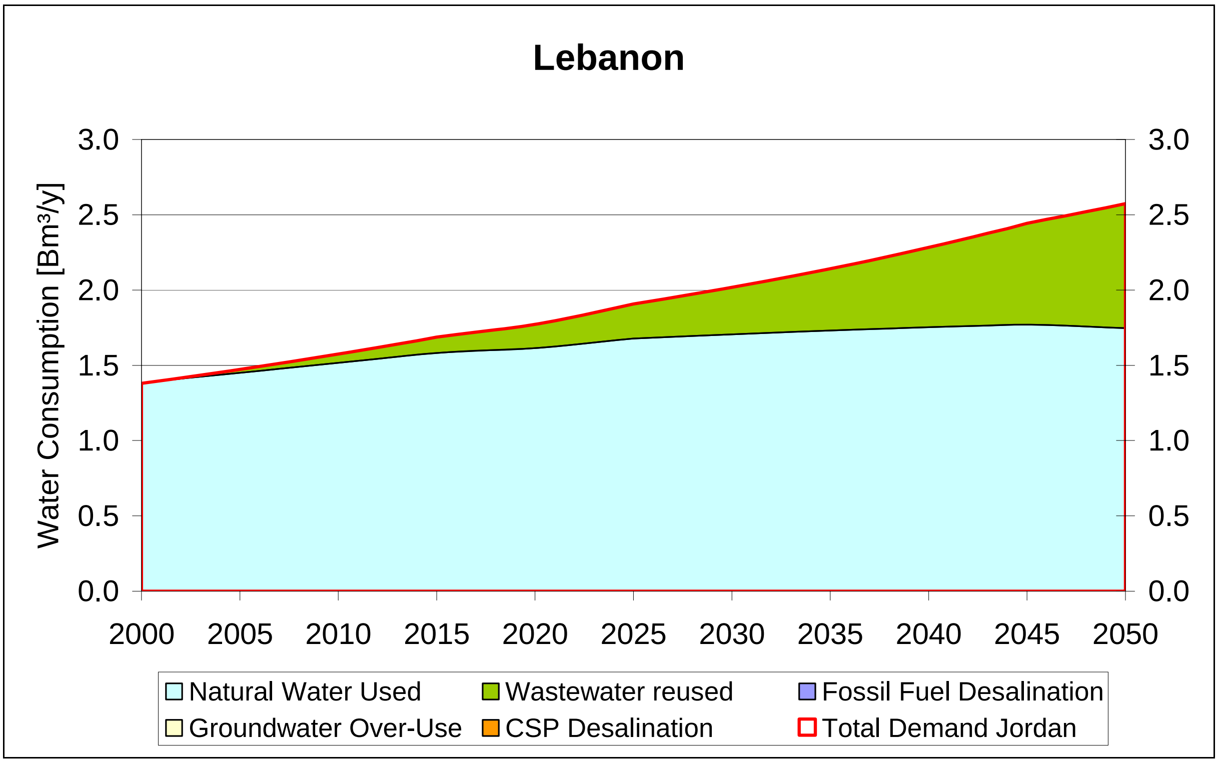

Figure A- 22: Water supply scenario until 2050 in Lebanon. No obvious demand for desalination if the potentials for wastewater re-use and the remaining natural resources are efficiently exploited.

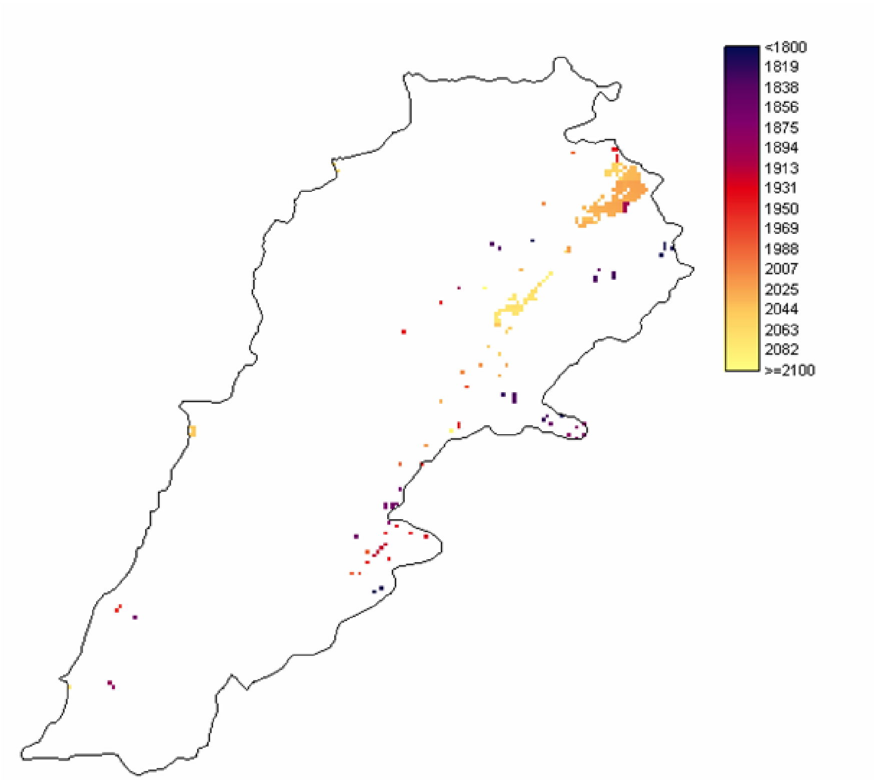

Figure A- 23: Direct normal irradiance in kWh/m²/y at potential sites for CSP power generation in Lebanon. Due to agriculture and topography there is almost no coastal potential below 20 m a.s.l.

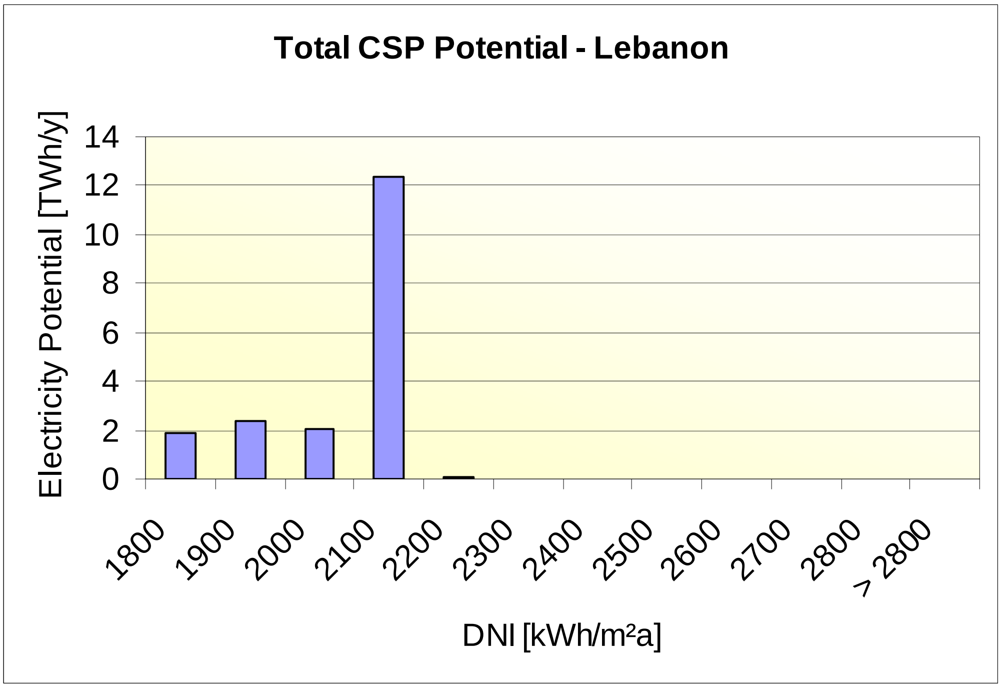

Figure A- 24: Statistical analysis of the DNI map for CSP-desalination in Lebanon

Lebanon		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Population MP	Mp	3.4	3.8	4.1	4.4	4.6	4.7
Exploitable Water	Bm^3/y	2.2	2.2	2.2	2.2	2.2	2.2
Sustainable Water	Bm^3/y	1.38	1.57	1.77	2.02	2.28	2.57
Irrigation Efficiency	%	0.40	0.43	0.46	0.49	0.52	0.55
Agricultural Use	Bm^3/y	0.9	1.0	1.0	1.0	1.0	0.9
Municipal Efficiency	%	0.65	0.68	0.70	0.73	0.76	0.78
Municipal Use	Bm^3/y	0.5	0.61	0.79	1.03	1.30	1.62
Industrial Use	Bm^3/y	0.0	0.01	0.02	0.02	0.03	0.04
Total Demand Lebanon	Bm^3/y	1.4	1.6	1.8	2.0	2.3	2.6
per capita Consumption	$m^3/cap/y$	406	414	432	459	496	548
Wastewater reused	Bm^3/y	0.001	0.1	0.2	0.3	0.5	0.8
Non-sustainable Water	Bm^3/y	0.0	0.0	0.0	0.0	0.0	0.0
CSP Desalination	Bm^3/y	0.00	0.00	0.00	0.00	0.00	0.00
Fossil Fuel Desalination	Bm^3/a	0.0	0.0	0.0	0.0	0.0	0.0
Groundwater Over-Use	Bm^3/y	0.0	0.0	0.0	0.0	0.0	0.0

Table A- 8: Main scenario indicators until 2050 for Lebanon

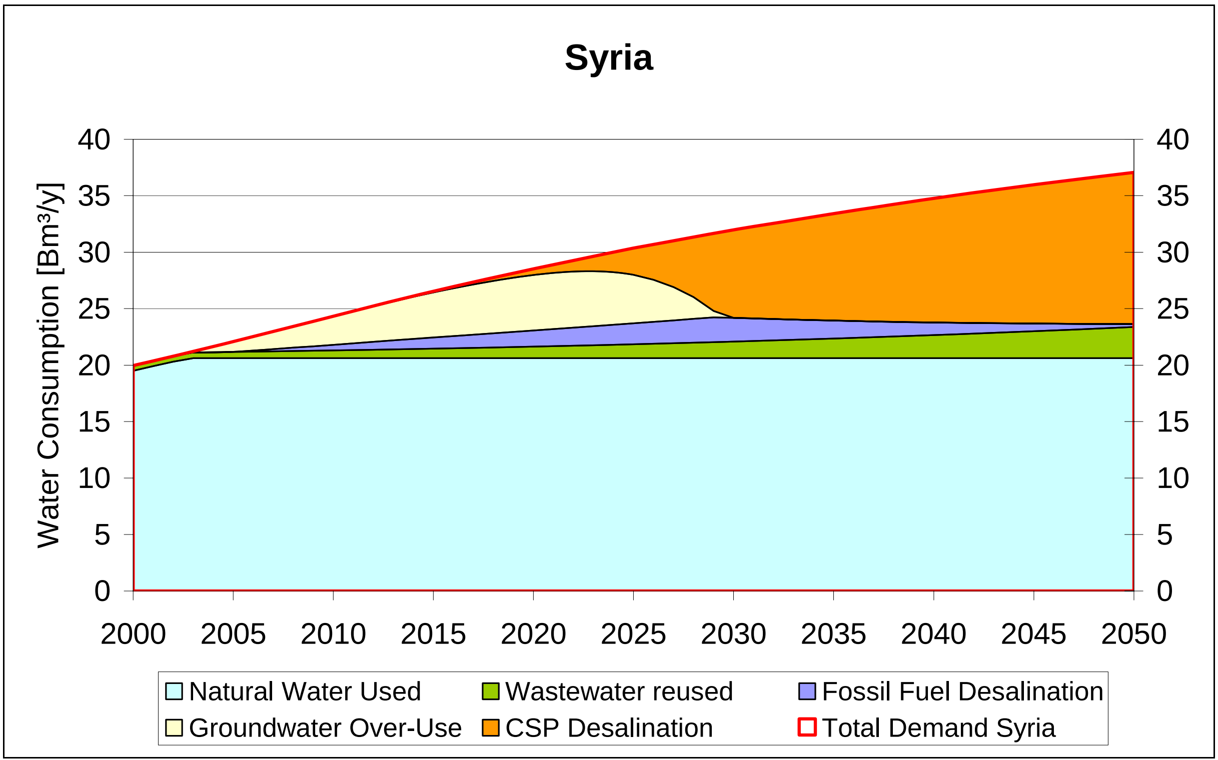

Figure A- 25: Water supply scenario until 2050 in Syria

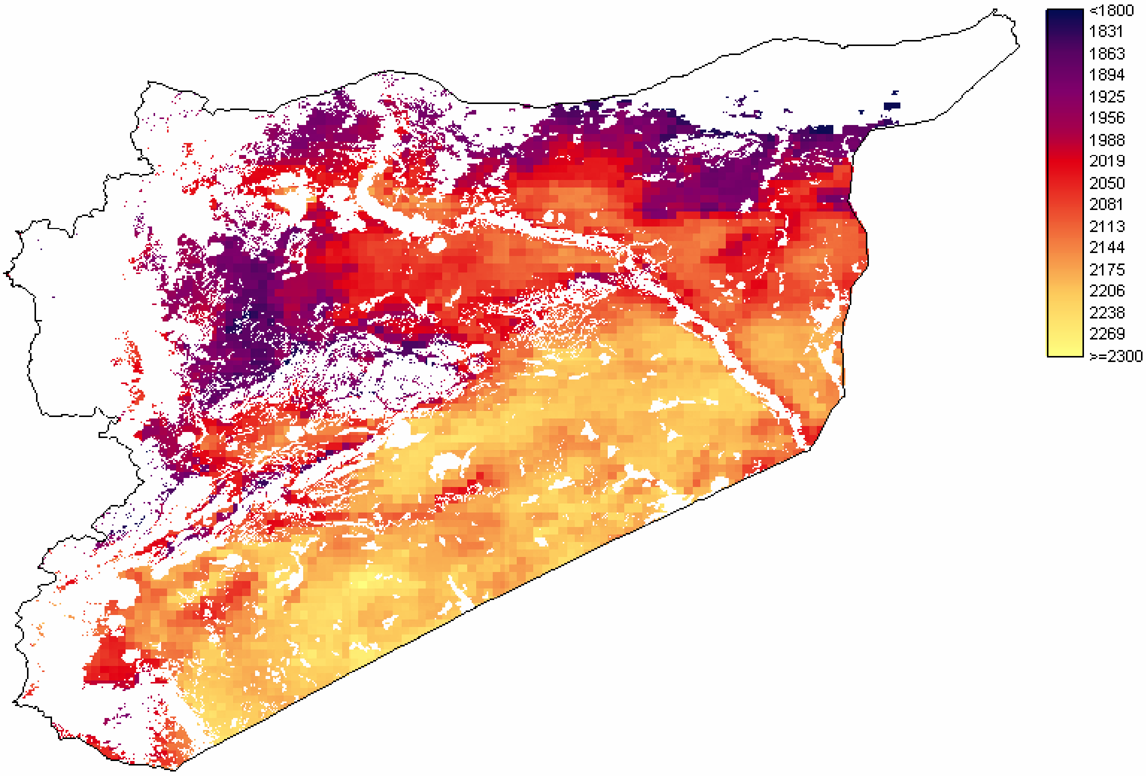

Figure A- 26: Direct normal irradiance in kWh/m²/y at potential sites for CSP power generation in Syria. Due to agriculture and topography there is almost no coastal potential below 20 m a.s.l.

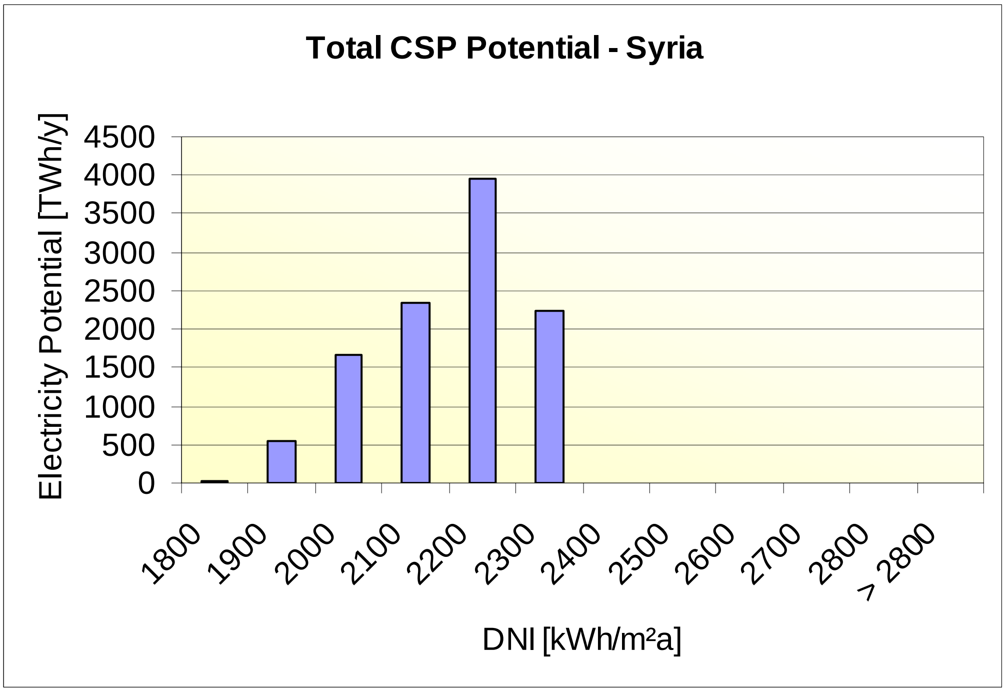

Figure A- 27: Statistical analysis of the DNI map for CSP-desalination in Syria

Syria		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Population MP	Mp	16.8	21.4	26.0	30.0	33.3	35.9
Exploitable Water	Bm³/y	20.6	20.6	20.6	20.6	20.6	20.6
Sustainable Water	Bm³/y	19.95	21.30	21.64	22.08	22.65	23.38
Irrigation Efficiency	%	0.45	0.48	0.50	0.53	0.55	0.58
Agricultural Use	Bm³/y	18.9	22.8	26.3	28.9	30.6	31.5
Municipal Efficiency	%	0.48	0.53	0.58	0.63	0.68	0.73
Municipal Use	Bm³/y	0.7	0.98	1.43	2.00	2.71	3.59
Industrial Use	Bm³/y	0.4	0.54	0.78	1.09	1.48	1.96
Total Demand Syria	Bm³/y	20.0	24.3	28.5	32.0	34.8	37.1
per capita Consumption	m³/cap/y	1188	1137	1097	1066	1044	1033
Wastewater reused	Bm³/y	0.459	0.7	1.0	1.5	2.1	2.8
Non-sustainable Water	Bm³/y	0.0	3.0	6.3	2.1	1.1	0.3
CSP Desalination	Bm³/y	0.00	0.01	0.54	7.80	11.01	13.44
Fossil Fuel Desalination	Bm³/a	0.0	0.5	1.4	2.1	1.1	0.3
Groundwater Over-Use	Bm³/y	0.0	2.5	4.9	0.0	0.0	0.0

Table A- 9: Main scenario indicators until 2050 for Syria. Most of the desalination potential will have to be powered by electricity from CSP plants inside the country or some of the coastal agricultural areas will have to be used for this purpose.

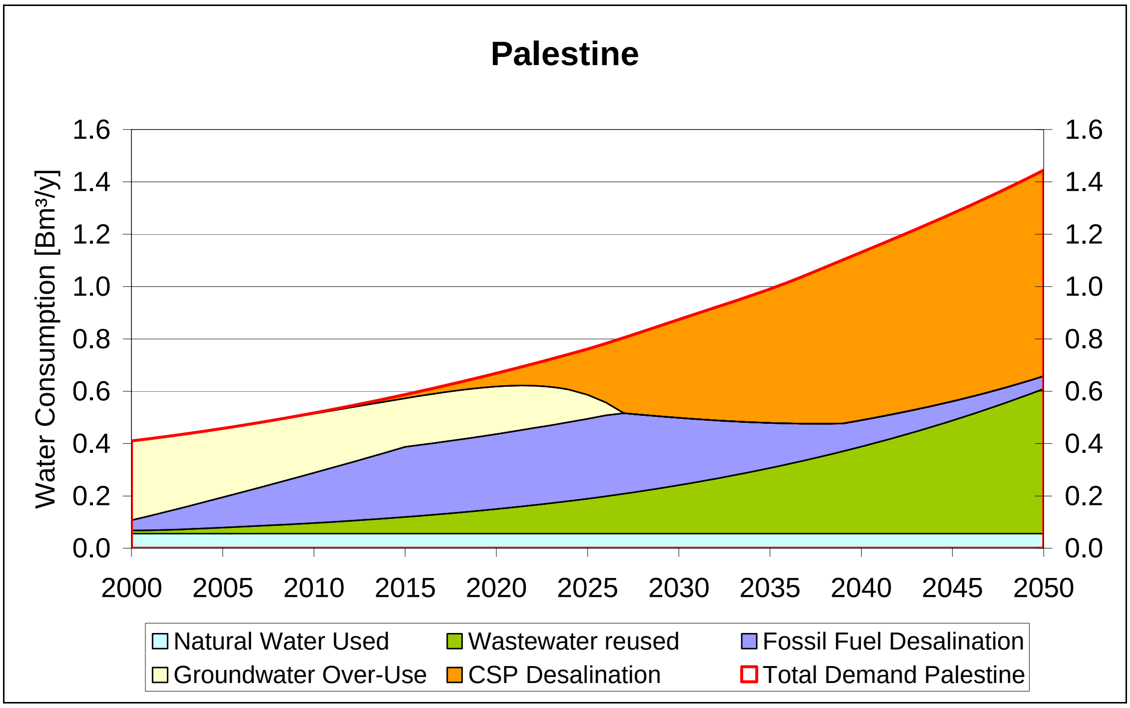

Figure A- 28: Water supply scenario until 2050 in Palestine.

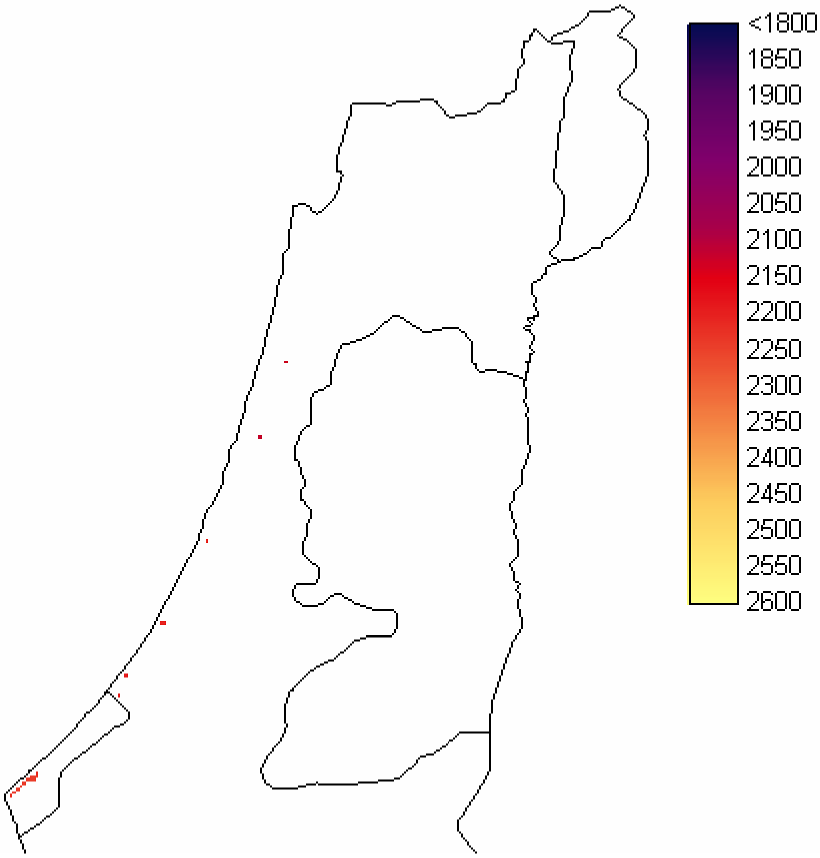

Figure A- 29: Direct normal irradiance in kWh/m²/y at potential coastal sites for CSP desalination in Palestine. There are only very limited potentials in Gaza.

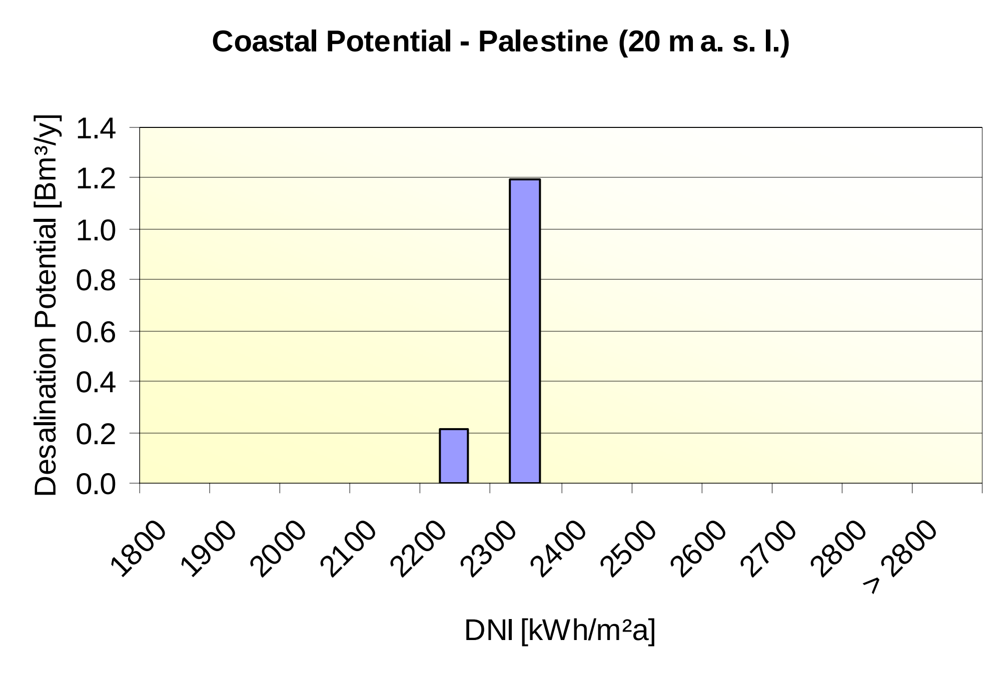

Figure A- 30: Statistical analysis of the DNI map for CSP-desalination in Palestine

Palestine		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Population MP	Mp	3.2	4.3	5.7	7.2	8.7	10.1
Exploitable Water	Bm³/y	0.056	0.056	0.056	0.056	0.056	0.056
Sustainable Water	Bm³/y	0.07	0.10	0.15	0.24	0.39	0.61
Irrigation Efficiency	%	0.30	0.34	0.38	0.42	0.46	0.50
Agricultural Use	Bm³/y	0.2	0.2	0.3	0.3	0.3	0.3
Municipal Efficiency	%	0.30	0.37	0.45	0.52	0.59	0.66
Municipal Use	Bm³/y	0.2	0.26	0.36	0.51	0.71	0.96
Industrial Use	Bm³/y	0.0	0.04	0.05	0.08	0.11	0.14
Total Demand Palestine	Bm³/y	0.410	0.516	0.668	0.874	1.132	1.445
per capita Consumption	m³/cap/y	128	120	117	121	130	143
Wastewater reused	Bm³/y	0.012	0.040	0.093	0.186	0.333	0.553
Non-sustainable Water	Bm³/y	0.3	0.4	0.5	0.3	0.1	0.0
CSP Desalination	Bm³/y	0.00	0.00	0.05	0.38	0.64	0.79
Fossil Fuel Desalination	Bm³/a	0.0	0.2	0.3	0.3	0.1	0.0
Groundwater Over-Use	Bm³/y	0.3	0.2	0.2	0.0	0.0	0.0

Table A- 10: Main scenario indicators until 2050 for Palestine. A potential cooperation of Israel, Palestine and Egypt has been assessed by TREC (www.trec-eumena.net)

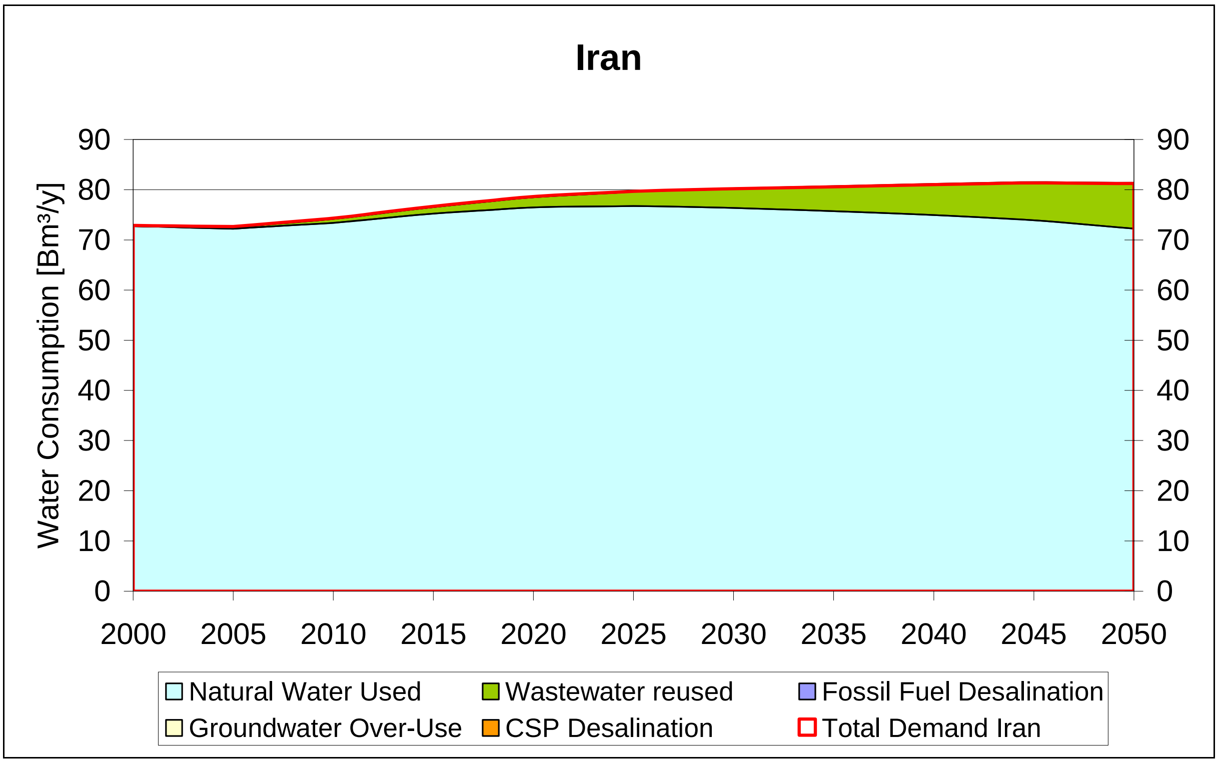

Figure A- 31: Water supply scenario until 2050 in Iran. No obvious demand for desalination if the potentials for wastewater re-use and the remaining natural resources are efficiently exploited.

Iran		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Population MP	Mp	66.40	74.30	85.00	92.30	98.00	101.90
Exploitable Water	Bm³/y	137.5	137.5	137.5	137.5	137.5	137.5
Sustainable Water	Bm³/y	72.72	74.16	78.56	80.15	81.00	81.21
Irrigation Efficiency	%	0.32	0.36	0.40	0.44	0.48	0.51
Agricultural Use	Bm³/y	66.2	66.1	68.2	67.5	65.8	63.3
Municipal Efficiency	%	0.50	0.55	0.59	0.64	0.69	0.73
Municipal Use	Bm³/y	5.0	6.11	7.77	9.47	11.33	13.36
Industrial Use	Bm³/y	1.7	2.08	2.65	3.23	3.86	4.55
Total Demand Iran	Bm³/y	72.9	74.3	78.7	80.2	81.0	81.2
per capita Consumption	m³/cap/y	1098	1000	925	869	827	797
Wastewater reused	Bm³/y	0.007	0.8	2.0	3.8	6.0	9.0
Non-sustainable Water	Bm³/y	0.2	0.2	0.1	0.1	0.0	0.0
CSP Desalination	Bm³/y	0.00	0.00	0.03	0.10	0.15	0.16
Fossil Fuel Desalination	Bm³/a	0.2	0.2	0.1	0.1	0.0	0.0
Groundwater Over-Use	Bm³/y	0.0	0.0	0.0	0.0	0.0	0.0

Table A- 11: Main scenario indicators until 2050 for Iran

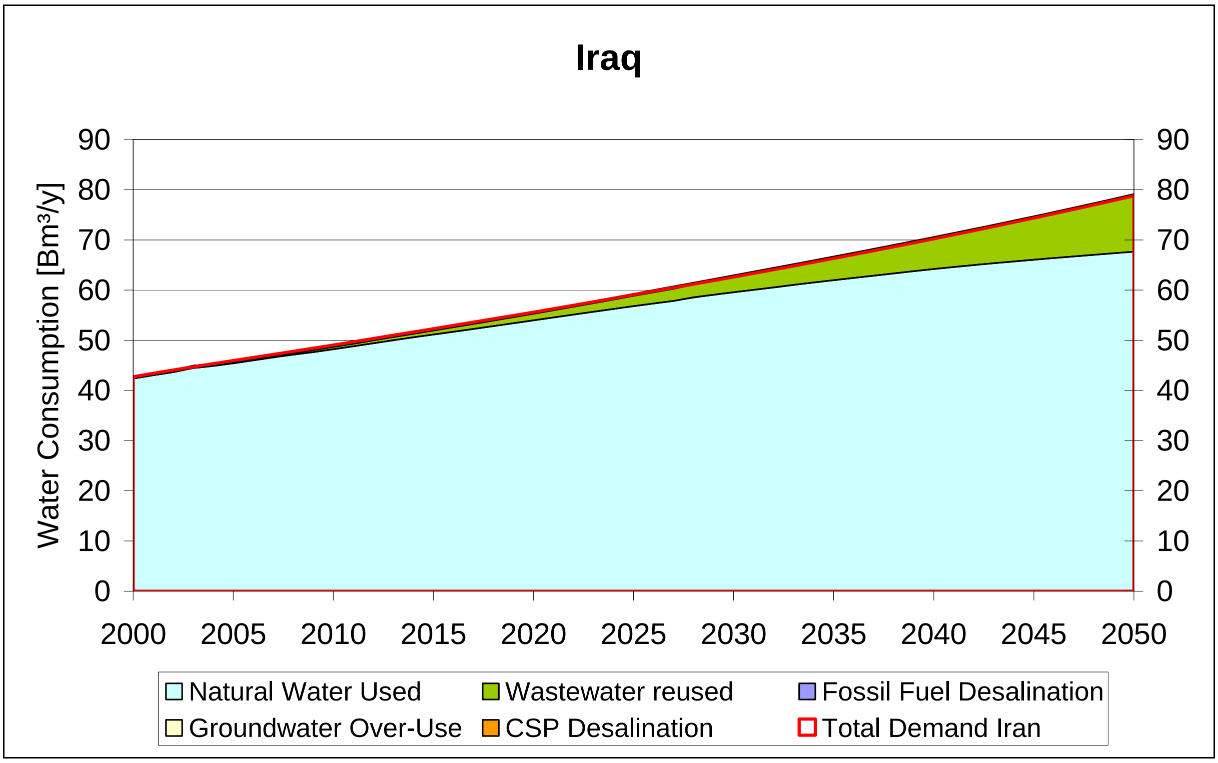

Figure A- 32: Water supply scenario until 2050 in Iraq. Only small demand for desalination if potentials for wastewater re-use and remaining natural resources are efficiently exploited.

Figure A- 33: Direct normal irradiance in kWh/m²/y at potential coastal sites for CSP desalination in Iraq

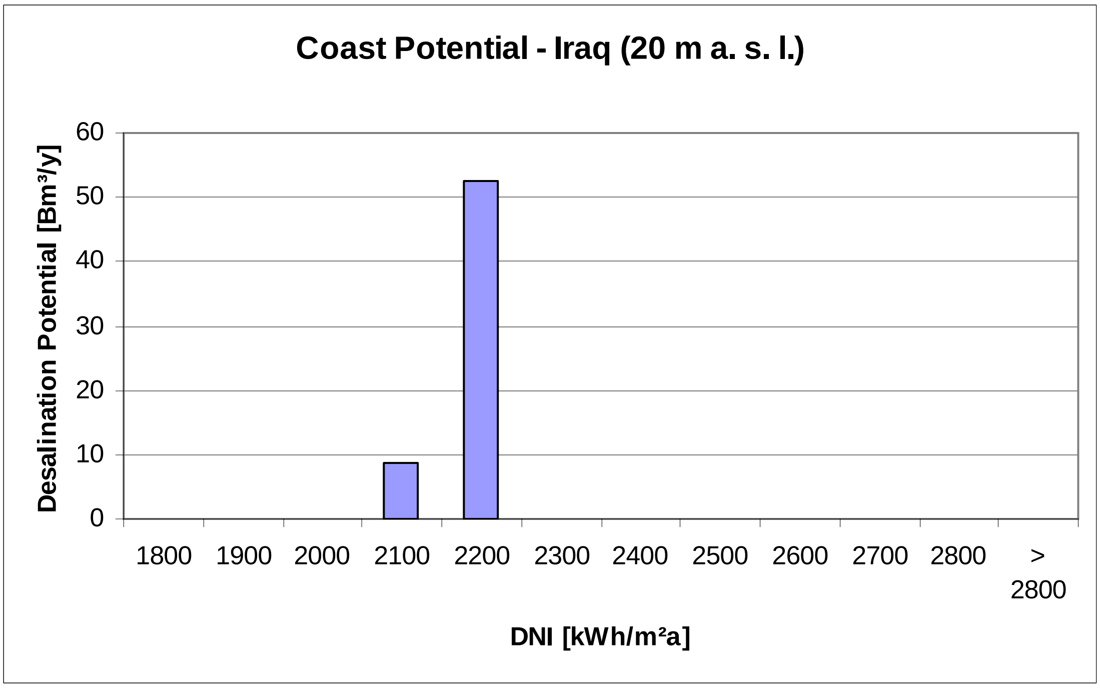

Figure A- 34: Statistical analysis of the DNI map for CSP-desalination in Iraq

Iraq		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Population MP	Mp	25.10	32.50	40.50	48.80	56.70	63.70
Exploitable Water	Bm^3/y	75.4	75.4	75.4	75.4	75.4	75.4
Sustainable Water	Bm^3/y	42.36	48.69	55.34	62.47	70.19	78.78
Irrigation Efficiency	%	0.28	0.32	0.37	0.41	0.45	0.49
Agricultural Use	Bm^3/y	39.4	44.2	48.7	52.5	55.2	56.6
Municipal Efficiency	%	0.40	0.46	0.52	0.58	0.64	0.70
Municipal Use	Bm^3/y	1.4	1.93	2.80	4.12	6.12	9.00
Industrial Use	Bm^3/y	2.0	2.81	4.08	6.01	8.93	13.14
Total Demand Iraq	Bm^3/y	42.7	49.0	55.6	62.6	70.3	78.8
per capita Consumption	$m^3/cap/y$	1702	1507	1372	1283	1239	1237
Wastewater reused	Bm^3/y	0.003	0.4	1.3	3.0	6.0	11.1
Non-sustainable Water	Bm^3/y	0.4	0.4	0.3	0.0	0.0	0.0
CSP Desalination	Bm^3/y	0.00	0.00	0.06	0.36	0.36	0.36
Fossil Fuel Desalination	Bm^3/a	0.4	0.4	0.3	0.1	0.1	0.1
Groundwater Over-Use	Bm^3/y	0.0	0.0	0.0	0.0	0.0	0.0

Table A- 12: Main scenario indicators until 2050 for Iraq

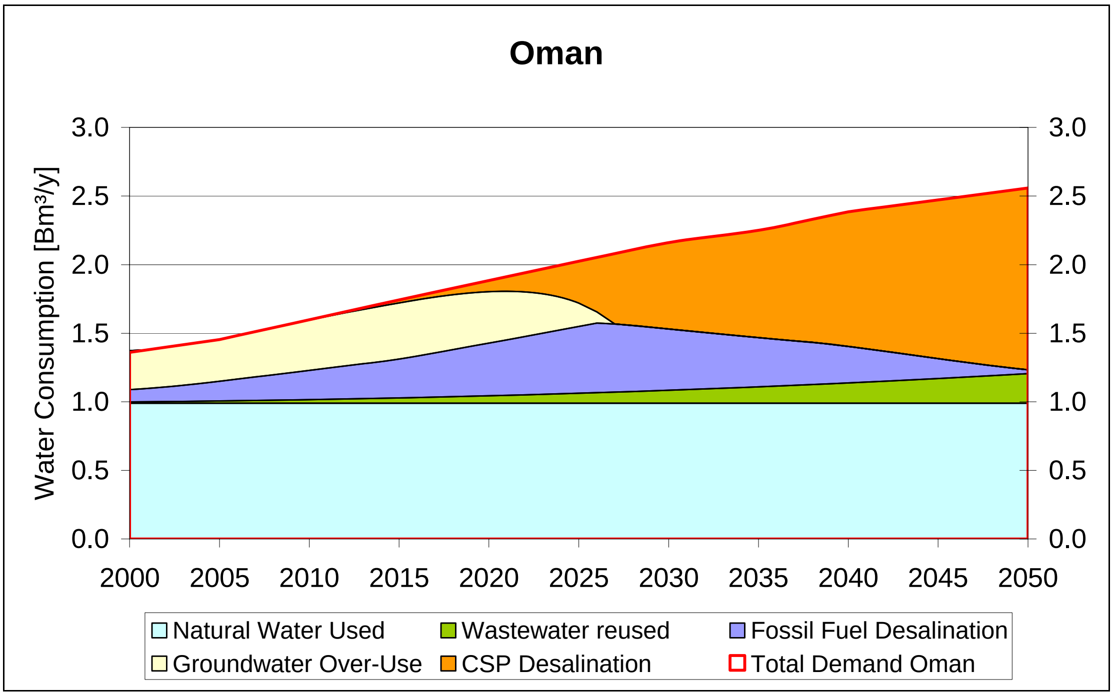

Figure A- 35: Water supply scenario until 2050 in Oman

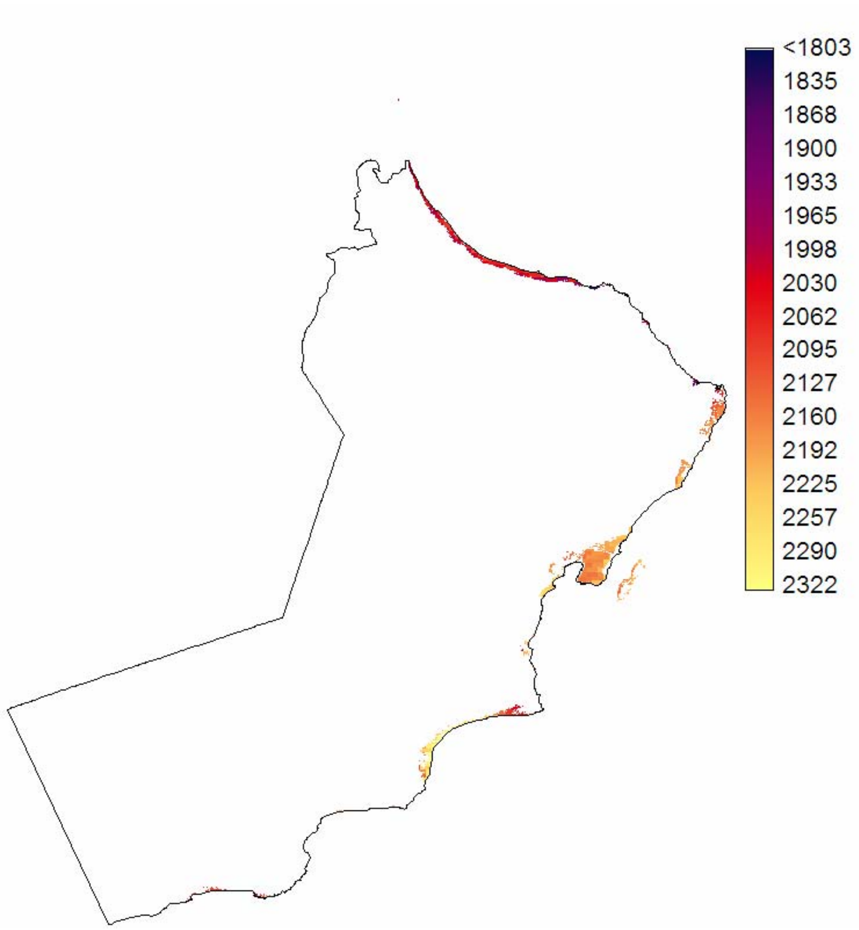

Figure A- 36: Direct normal irradiance in kWh/m²/y at potential coastal sites for CSP desalination in Oman

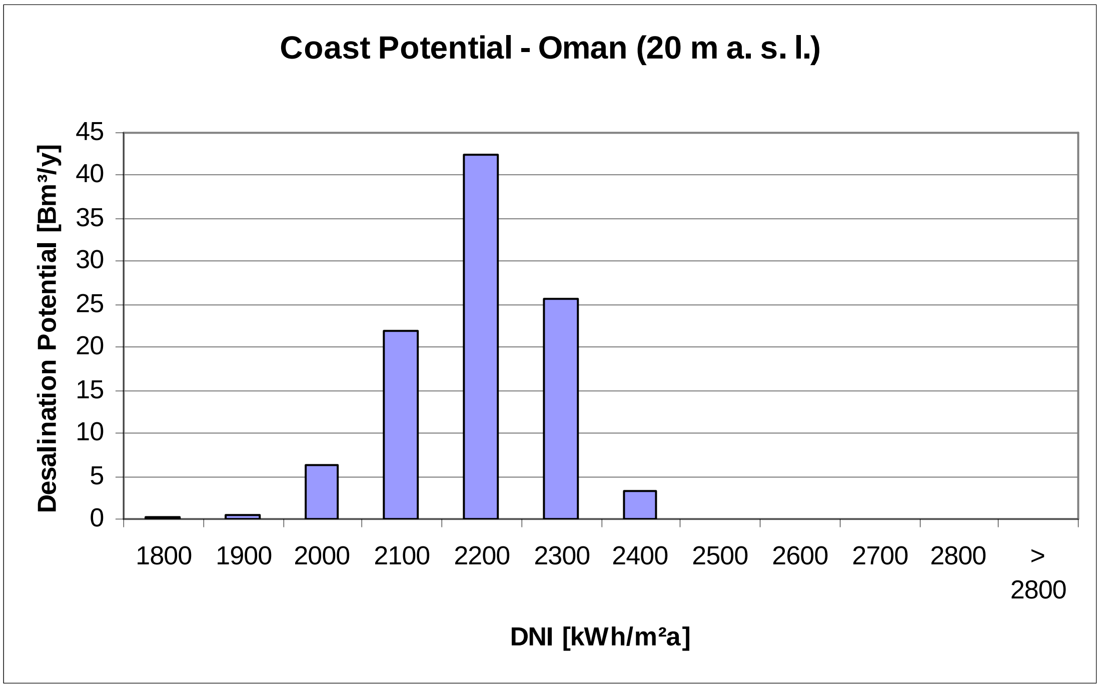

Figure A- 37: Statistical analysis of the DNI map for CSP-desalination in Oman

Oman		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Population MP	Mp	2.4	2.9	3.5	4.1	4.6	5.0
Exploitable Water	Bm³/y	0.99	0.99	0.99	0.99	0.99	0.99
Sustainable Water	Bm³/y	0.99	1.02	1.04	1.08	1.14	1.21
Irrigation Efficiency	%	0.50	0.52	0.54	0.56	0.58	0.60
Agricultural Use	Bm³/y	1.2	1.4	1.7	1.9	2.0	2.1
Municipal Efficiency	%	0.65	0.68	0.70	0.73	0.76	0.78
Municipal Use	Bm³/y	0.1	0.13	0.17	0.22	0.28	0.33
Industrial Use	Bm³/y	0.0	0.04	0.05	0.07	0.08	0.10
Total Demand Oman	Bm³/y	1.4	1.6	1.9	2.2	2.4	2.6
per capita Consumption	m³/cap/y	567	551	538	527	519	512
Wastewater reused	Bm³/y	0.009	0.0	0.1	0.1	0.1	0.2
Non-sustainable Water	Bm³/y	0.4	0.6	0.8	0.4	0.3	0.0
CSP Desalination	Bm³/y	0.00	0.00	0.08	0.63	0.98	1.32
Fossil Fuel Desalination	Bm³/a	0.1	0.2	0.4	0.4	0.3	0.0
Groundwater Over-Use	Bm³/y	0.3	0.4	0.4	0.0	0.0	0.0

Table A- 13: Main scenario indicators until 2050 for Oman

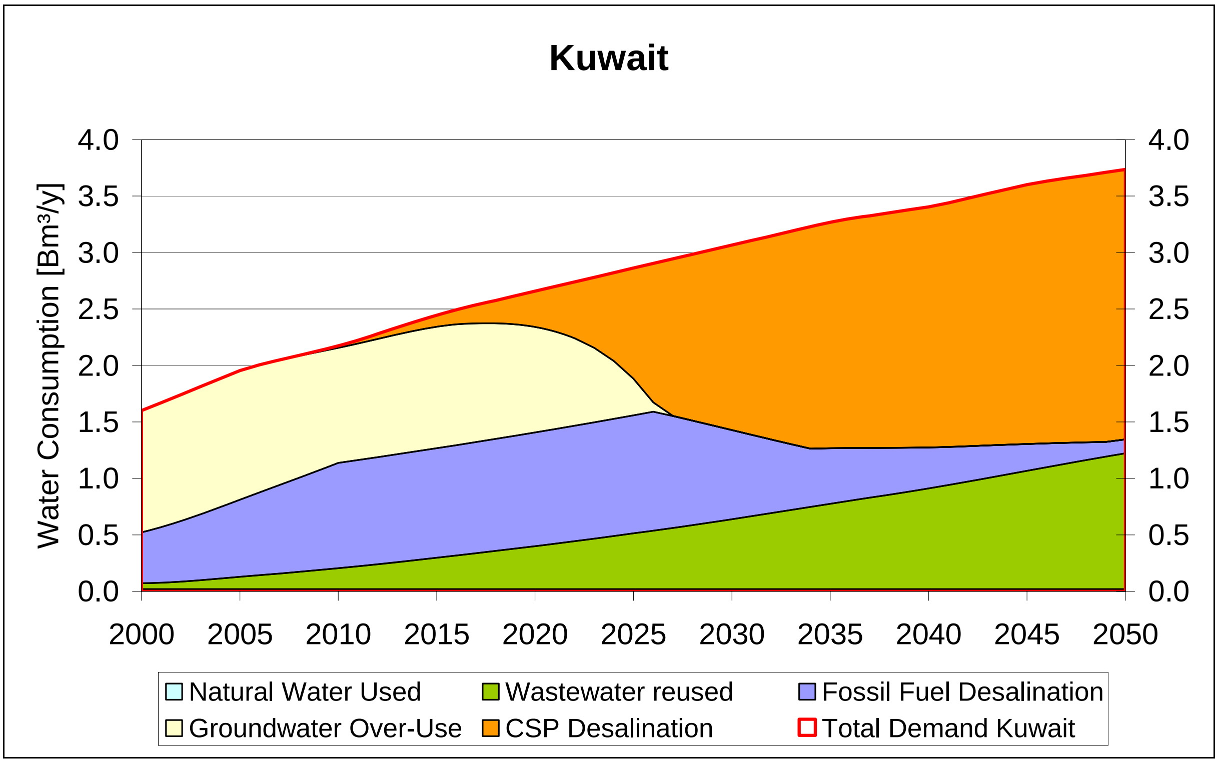

Figure A- 38: Water supply scenario until 2050 in Kuwait

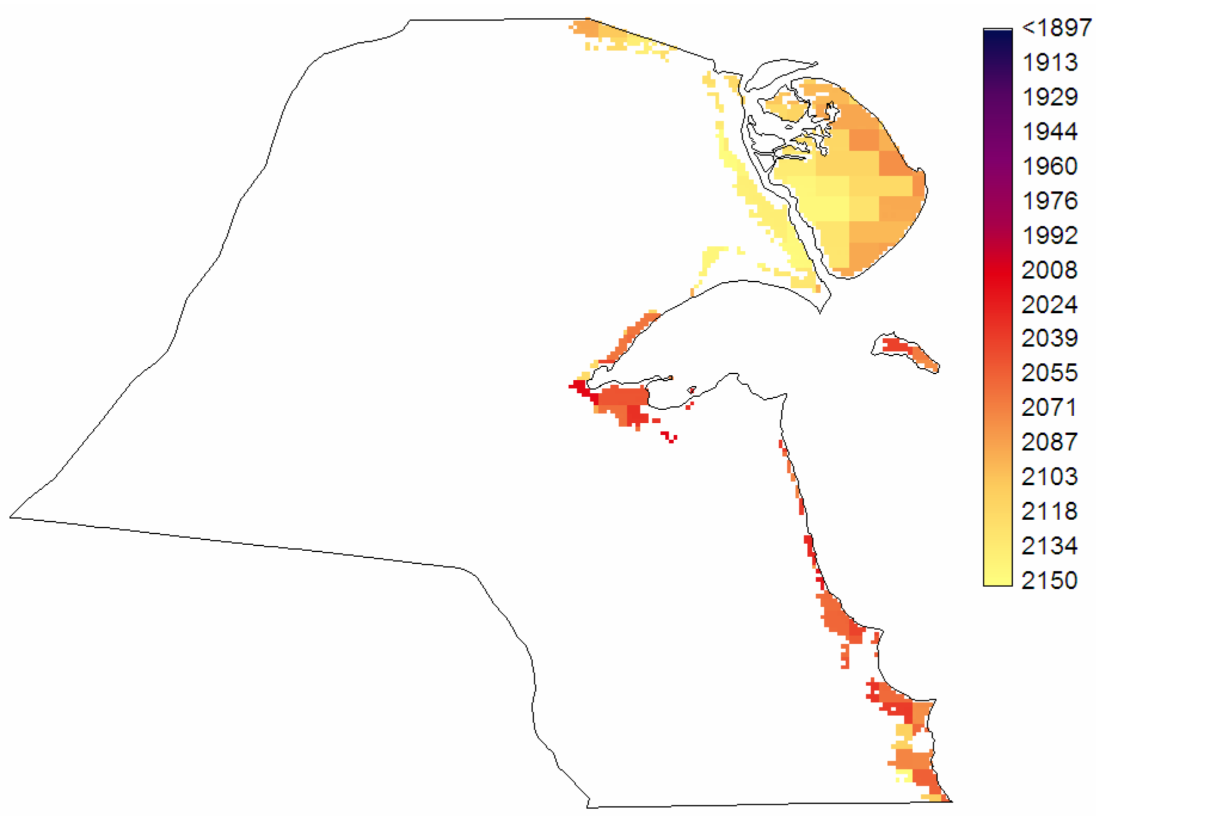

Figure A- 39: Direct normal irradiance in kWh/m²/y at potential coastal sites for CSP desalination in Kuwait

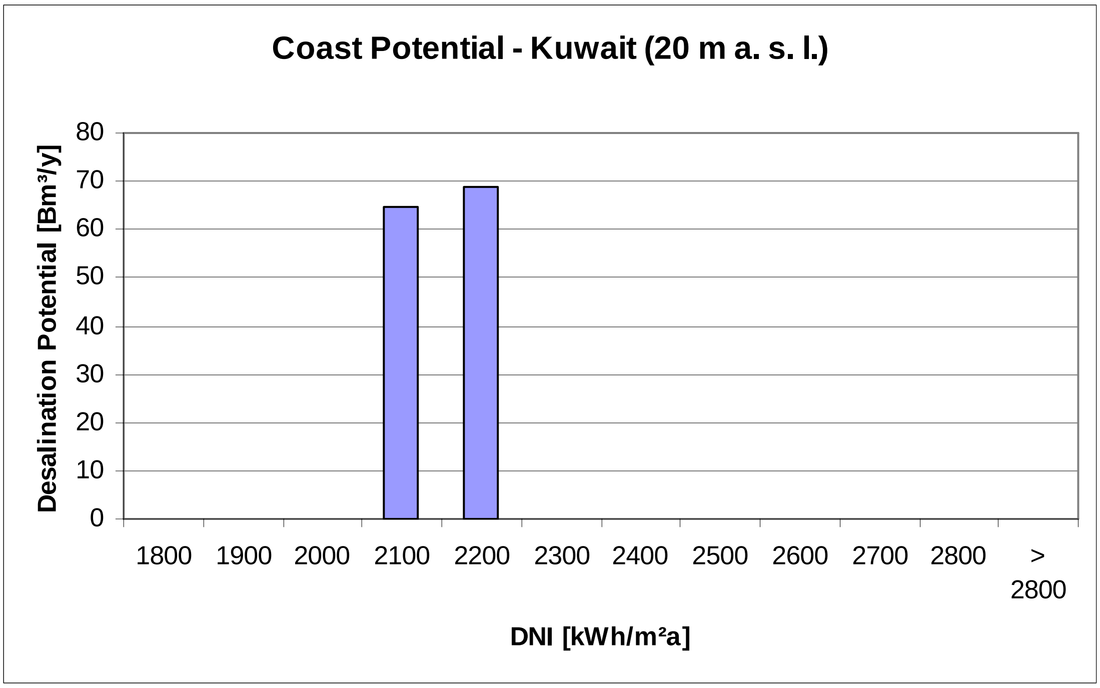

Figure A- 40: Statistical analysis of the DNI map for CSP-desalination in Kuwait

Kuwait		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Population MP	Mp	2.2	3	3.7	4.3	4.8	5.3
Exploitable Water	Bm³/y	0.02	0.02	0.02	0.02	0.02	0.02
Sustainable Water	Bm³/y	0.07	0.20	0.40	0.64	0.91	1.22
Irrigation Efficiency	%	0.60	0.61	0.62	0.63	0.64	0.65
Agricultural Use	Bm³/y	0.60	0.8	1.0	1.1	1.2	1.3
Municipal Efficiency	%	0.70	0.72	0.74	0.76	0.78	0.80
Municipal Use	Bm³/y	0.90	1.23	1.51	1.76	1.96	2.16
Industrial Use	Bm³/y	0.10	0.14	0.17	0.20	0.22	0.24
Total Demand Kuwait	Bm³/y	1.60	2.2	2.7	3.1	3.4	3.7
per capita Consumption	m³/cap/y	727	724	718	713	709	705
Wastewater reused	Bm³/y	0.052	0.2	0.4	0.6	0.9	1.2
Non-sustainable Water	Bm³/y	1.5	2.0	1.9	0.8	0.4	0.1
CSP Desalination	Bm³/y	0.00	0.02	0.32	1.64	2.13	2.39
Fossil Fuel Desalination	Bm³/a	0.5	0.9	1.0	0.8	0.4	0.1
Groundwater Over-Use	Bm³/y	1.1	1.0	0.9	0.0	0.0	0.0

Table A- 14: Main scenario indicators until 2050 for Kuwait

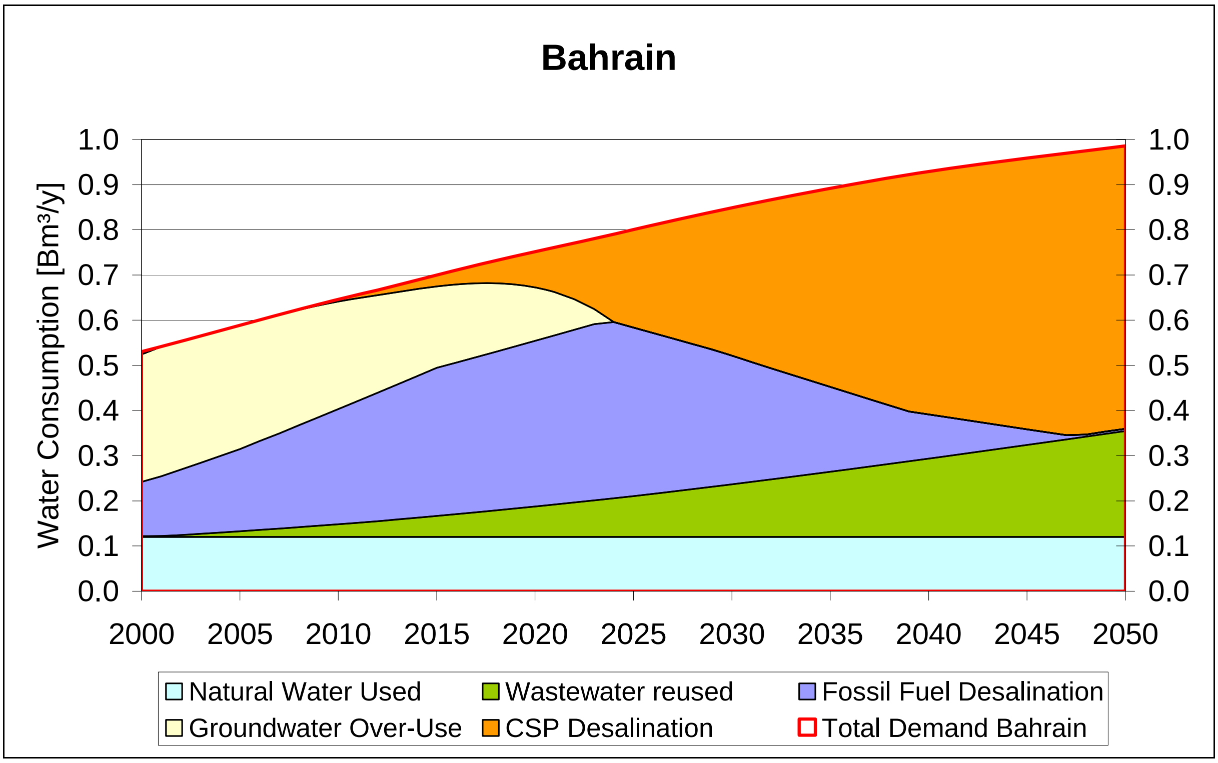

Figure A- 41: Water supply scenario until 2050 in Bahrain

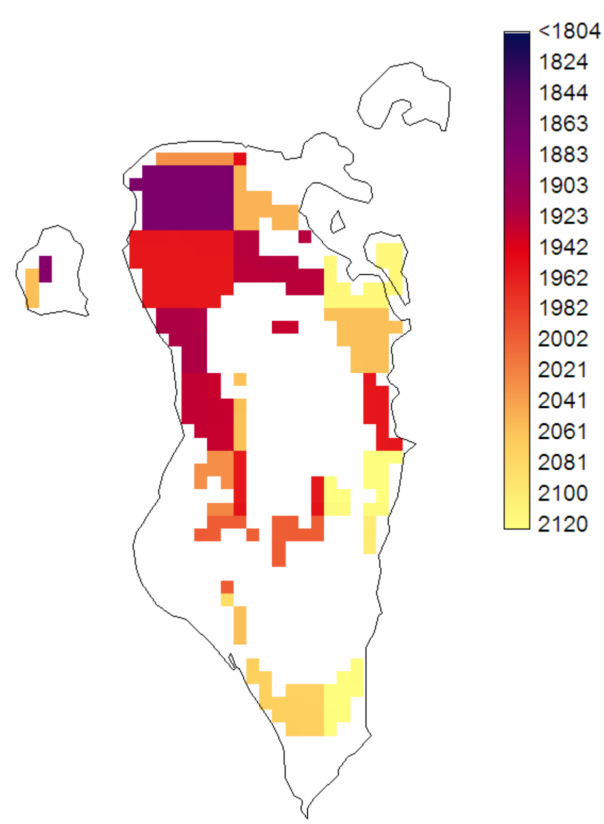

Figure A- 42: Direct normal irradiance in kWh/m²/y at potential coastal sites for CSP desalination in Bahrain

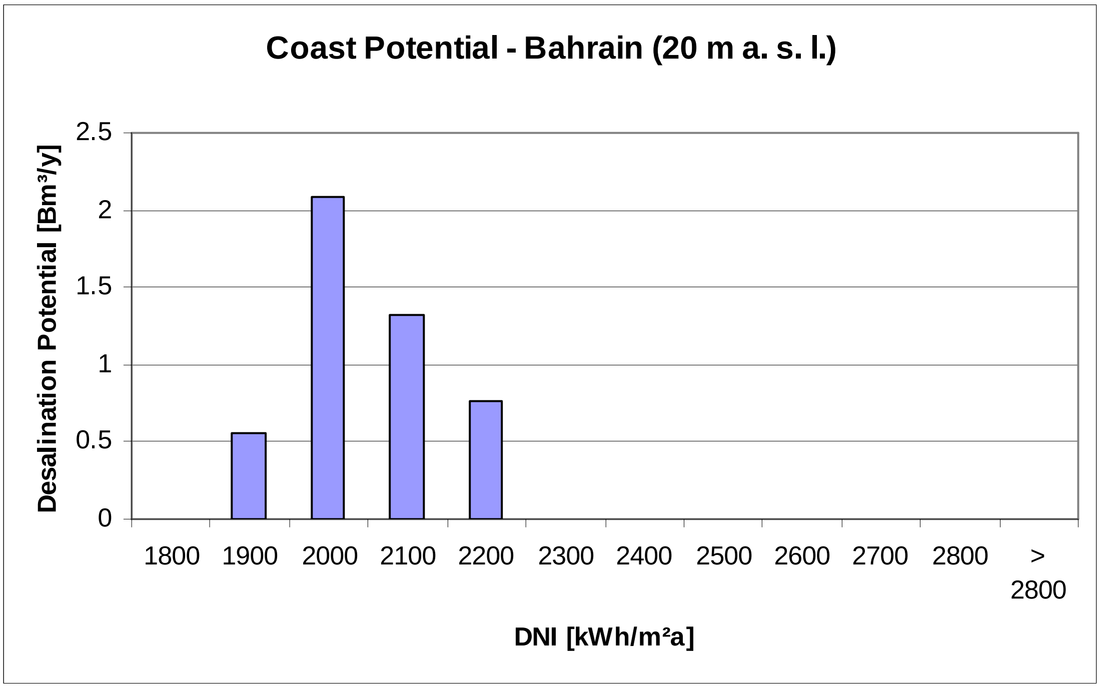

Figure A- 43: Statistical analysis of the DNI map for CSP-desalination in Bahrain

Bahrain		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Population MP	Mp	0.7	0.8	1.0	1.1	1.2	1.3
Exploitable Water	Bm³/y	0.12	0.12	0.12	0.12	0.12	0.12
Sustainable Water	Bm³/y	0.13	0.15	0.19	0.24	0.29	0.35
Irrigation Efficiency	%	0.60	0.61	0.62	0.63	0.64	0.65
Agricultural Use	Bm³/y	0.3	0.4	0.4	0.5	0.5	0.5
Municipal Efficiency	%	0.70	0.72	0.74	0.76	0.78	0.80
Municipal Use	Bm³/y	0.2	0.25	0.29	0.34	0.38	0.41
Industrial Use	Bm³/y	0.0	0.04	0.04	0.05	0.06	0.06
Total Demand Bahrain	Bm³/y	0.5	0.6	0.8	0.8	0.9	1.0
per capita Consumption	m³/cap/y	783	781	780	779	779	780
Wastewater reused	Bm³/y	0.002	0.0	0.1	0.1	0.2	0.2
Non-sustainable Water	Bm³/y	0.4	0.5	0.5	0.3	0.1	0.0
CSP Desalination	Bm³/y	0.00	0.00	0.08	0.33	0.54	0.63
Fossil Fuel Desalination	Bm³/a	0.1	0.3	0.4	0.3	0.1	0.0
Groundwater Over-Use	Bm³/y	0.3	0.2	0.1	0.0	0.0	0.0

Table A- 15: Main scenario indicators until 2050 for Bahrain

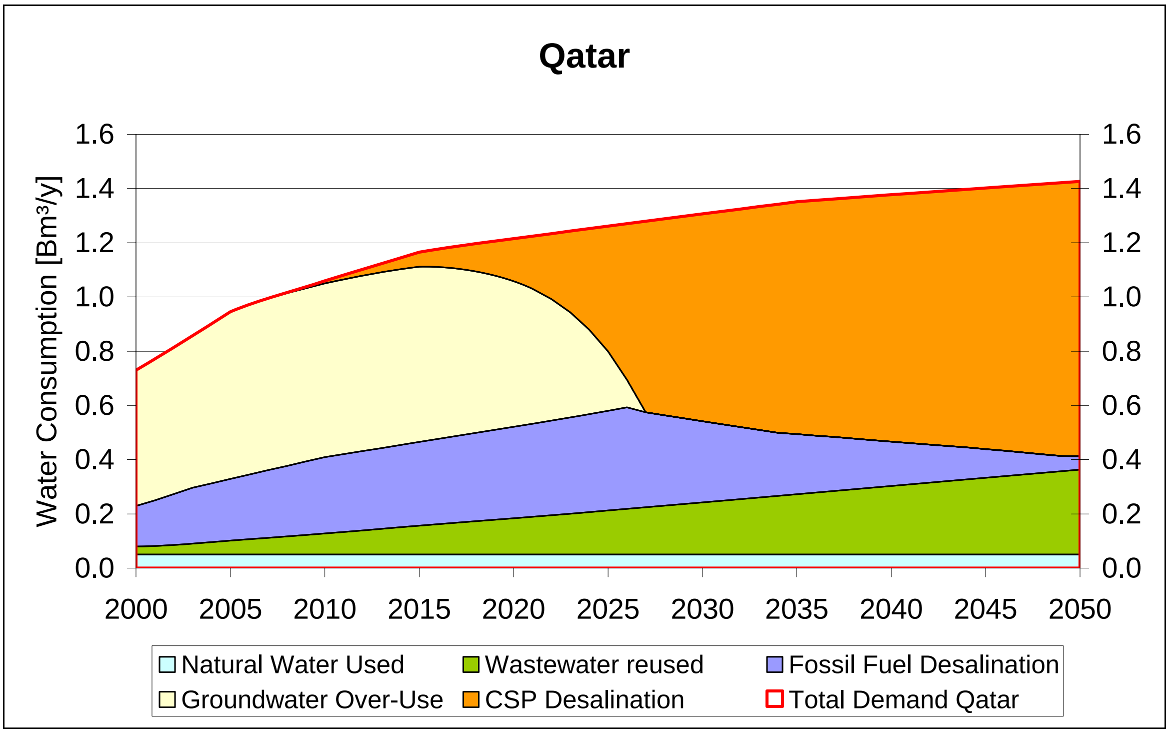

Figure A- 44: Water supply scenario until 2050 in Qatar

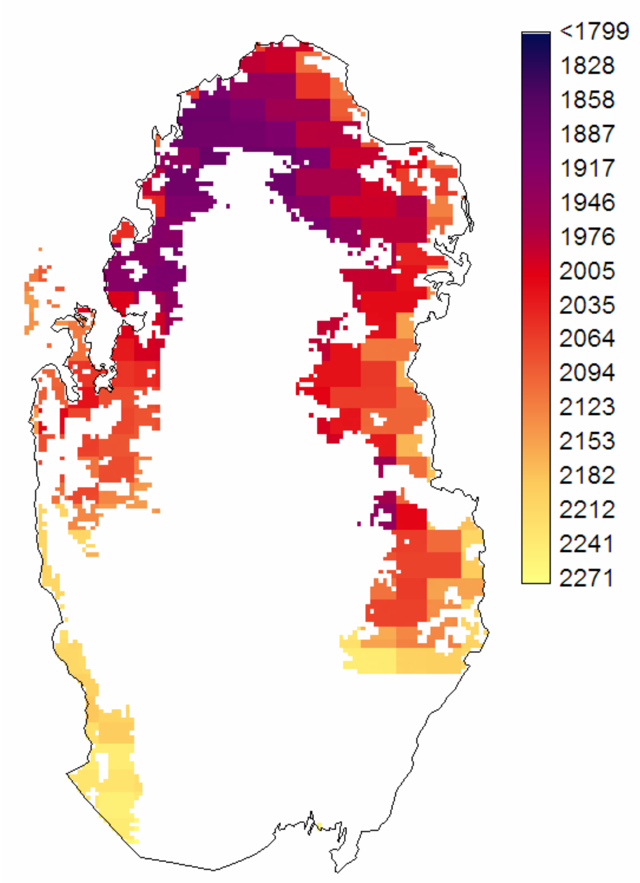

Figure A- 45: Direct normal irradiance in kWh/m²/y at potential coastal sites for CSP desalination in Qatar

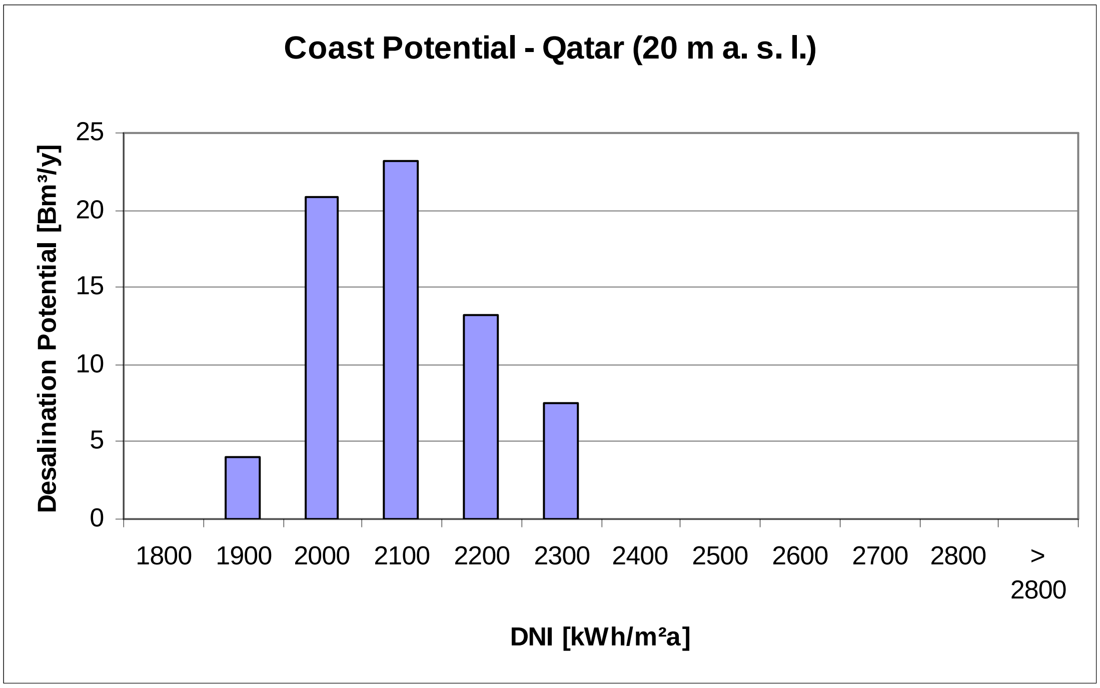

Figure A- 46: Statistical analysis of the DNI map for CSP-desalination in Qatar

Qatar		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Population MP	Mp	0.6	0.9	1.1	1.2	1.2	1.3
Exploitable Water	Bm³/y	0.05	0.05	0.05	0.05	0.05	0.05
Sustainable Water	Bm³/y	0.08	0.13	0.18	0.24	0.30	0.36
Irrigation Efficiency	%	0.60	0.61	0.62	0.63	0.64	0.65
Agricultural Use	Bm³/y	0.4	0.6	0.7	0.7	0.8	0.8
Municipal Efficiency	%	0.70	0.72	0.74	0.76	0.78	0.80
Municipal Use	Bm³/y	0.3	0.43	0.49	0.52	0.55	0.57
Industrial Use	Bm³/y	0.0	0.04	0.05	0.05	0.06	0.06
Total Demand Qatar	Bm³/y	0.7	1.1	1.2	1.3	1.4	1.4
per capita Consumption	m³/cap/y	1217	1177	1157	1136	1116	1097
Wastewater reused	Bm³/y	0.030	0.1	0.1	0.2	0.3	0.3
Non-sustainable Water	Bm³/y	0.7	0.9	0.9	0.3	0.2	0.0
CSP Desalination	Bm³/y	0.00	0.01	0.16	0.76	0.91	1.01
Fossil Fuel Desalination	Bm³/a	0.2	0.3	0.3	0.3	0.2	0.0
Groundwater Over-Use	Bm³/y	0.5	0.6	0.5	0.0	0.0	0.0

Table A- 16: Main scenario indicators until 2050 for Qatar

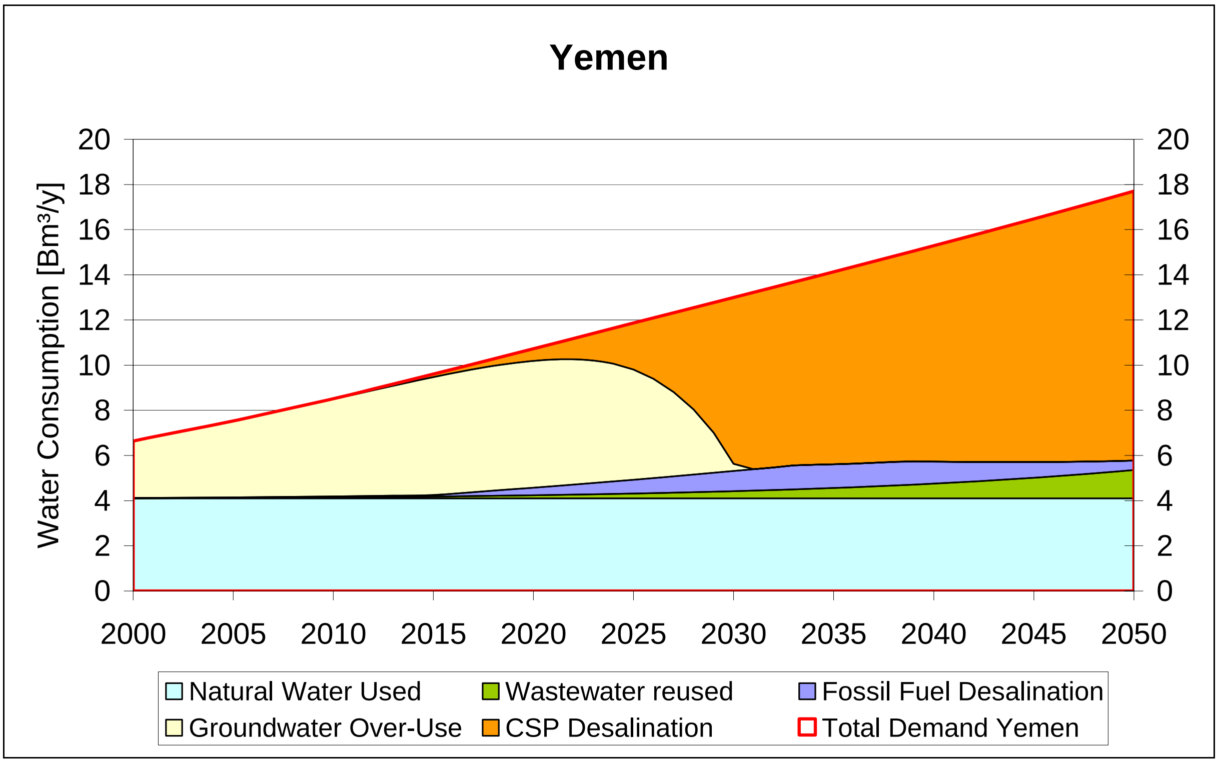

Figure A- 47: Water supply scenario until 2050 in Yemen

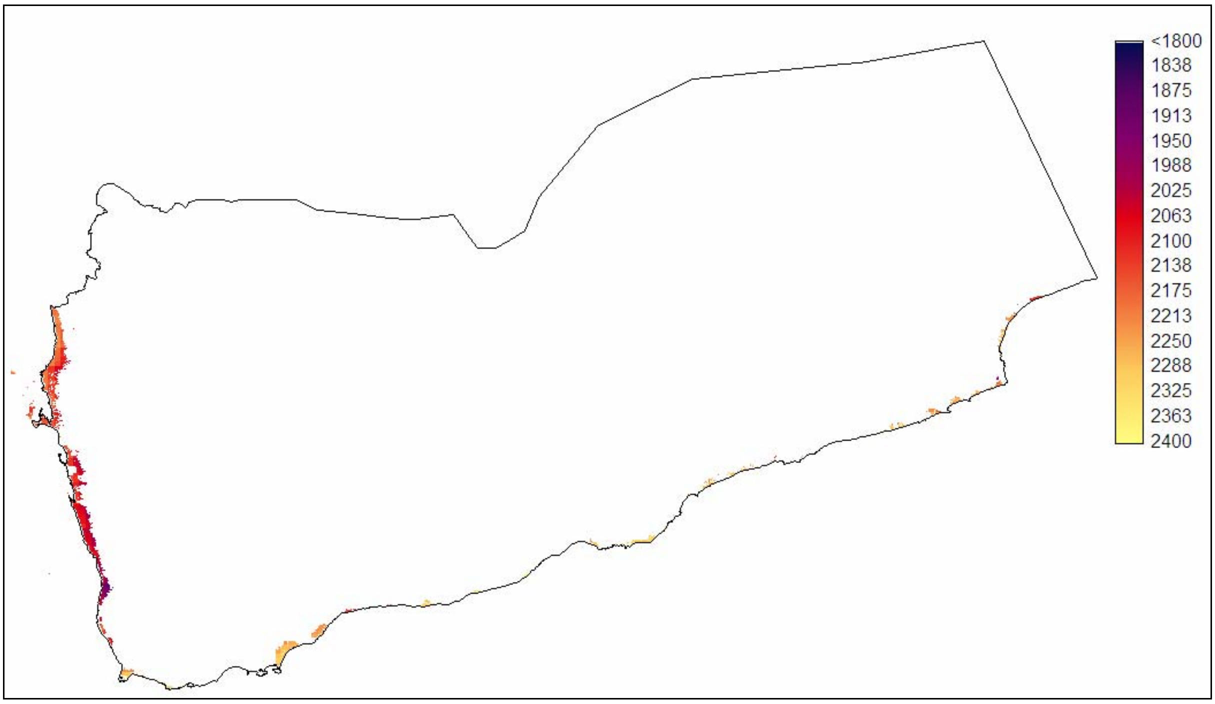

Figure A- 48: Direct normal irradiance in kWh/m²/y at potential coastal sites for CSP desalination in Yemen

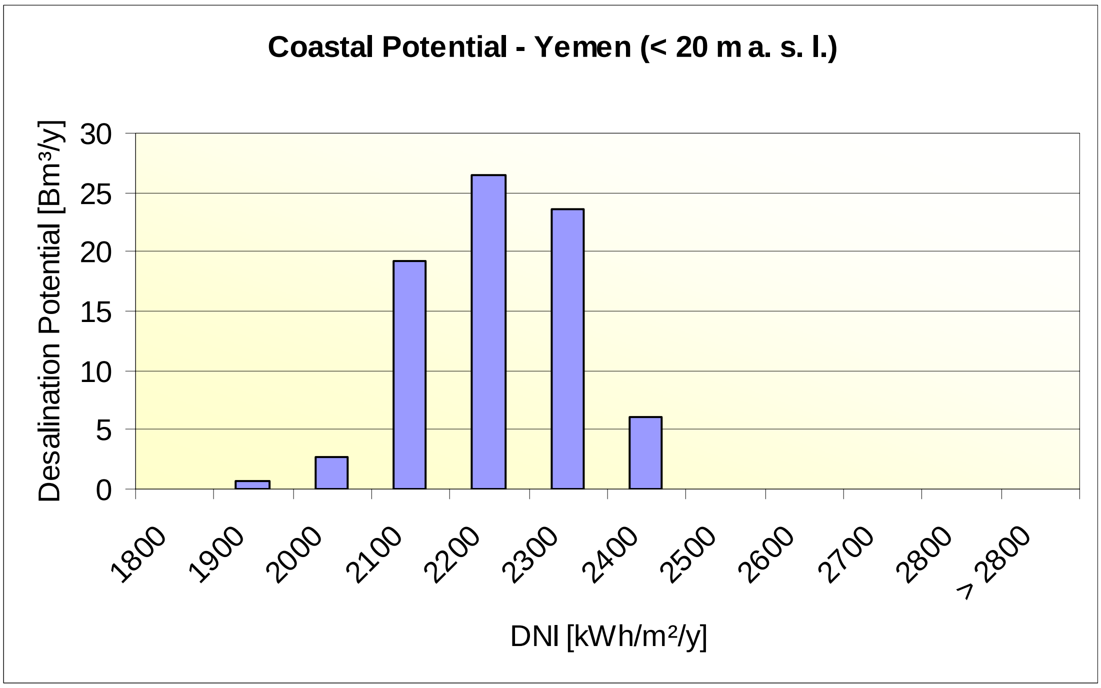

Figure A- 49: Statistical analysis of the DNI map for CSP-desalination in Yemen

Yemen		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Population MP	Mp	17.9	24.5	32.7	41.5	50.5	59.5
Exploitable Water	Bm³/y	4.1	4.1	4.1	4.1	4.1	4.1
Sustainable Water	Bm³/y	4.10	4.14	4.24	4.42	4.75	5.36
Irrigation Efficiency	%	0.40	0.43	0.46	0.49	0.52	0.55
Agricultural Use	Bm³/y	6.3	8.0	10.0	11.9	13.7	15.2
Municipal Efficiency	%	0.50	0.55	0.59	0.64	0.69	0.73
Municipal Use	Bm³/y	0.3	0.41	0.61	0.93	1.43	2.19
Industrial Use	Bm³/y	0.0	0.06	0.09	0.14	0.21	0.32
Total Demand Yemen	Bm³/y	6.6	8.5	10.7	13.0	15.3	17.7
per capita Consumption	m³/cap/y	370	347	328	313	303	298
Wastewater reused	Bm³/y	0.000	0.0	0.1	0.3	0.7	1.3
Non-sustainable Water	Bm³/y	2.5	4.3	5.9	1.2	1.0	0.4
CSP Desalination	Bm³/y	0.00	0.02	0.53	7.36	9.56	11.94
Fossil Fuel Desalination	Bm³/a	0.0	0.0	0.3	0.9	1.0	0.4
Groundwater Over-Use	Bm³/y	2.5	4.3	5.6	0.3	0.0	0.0

Table A- 17: Main scenario indicators until 2050 for Yemen

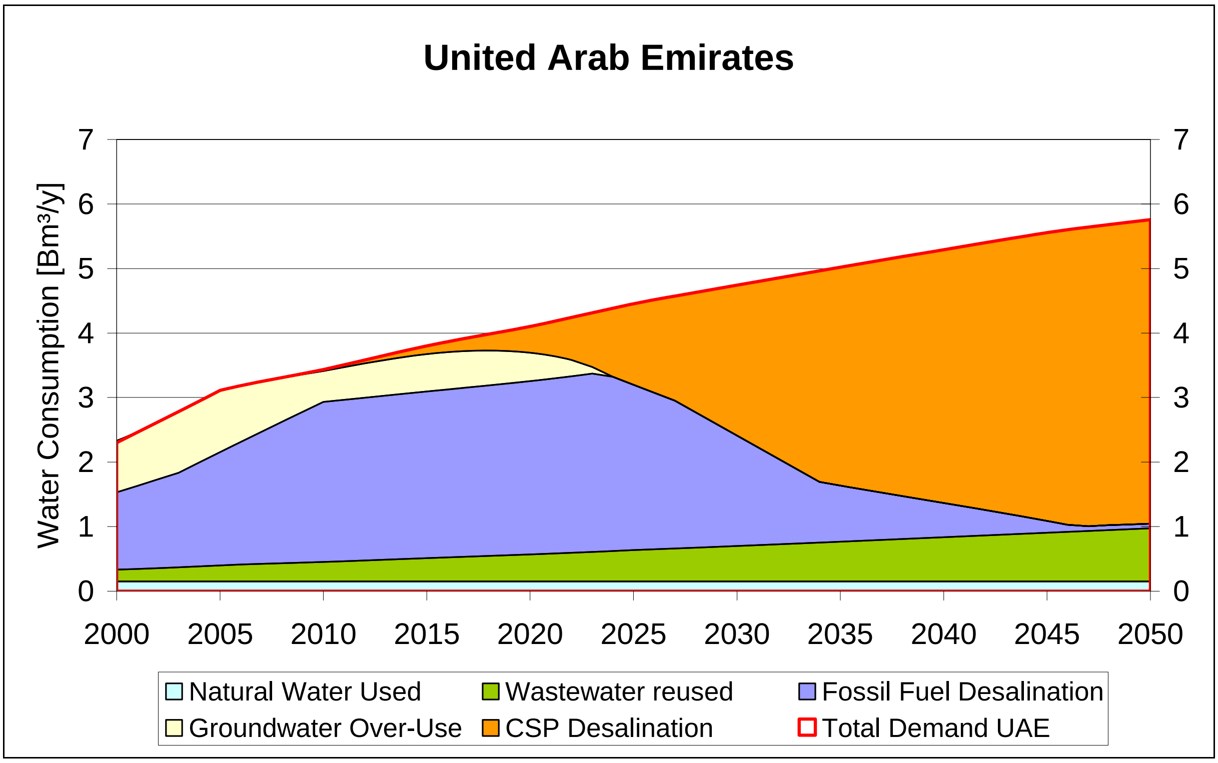

Figure A- 50: Water supply scenario until 2050 in UAE

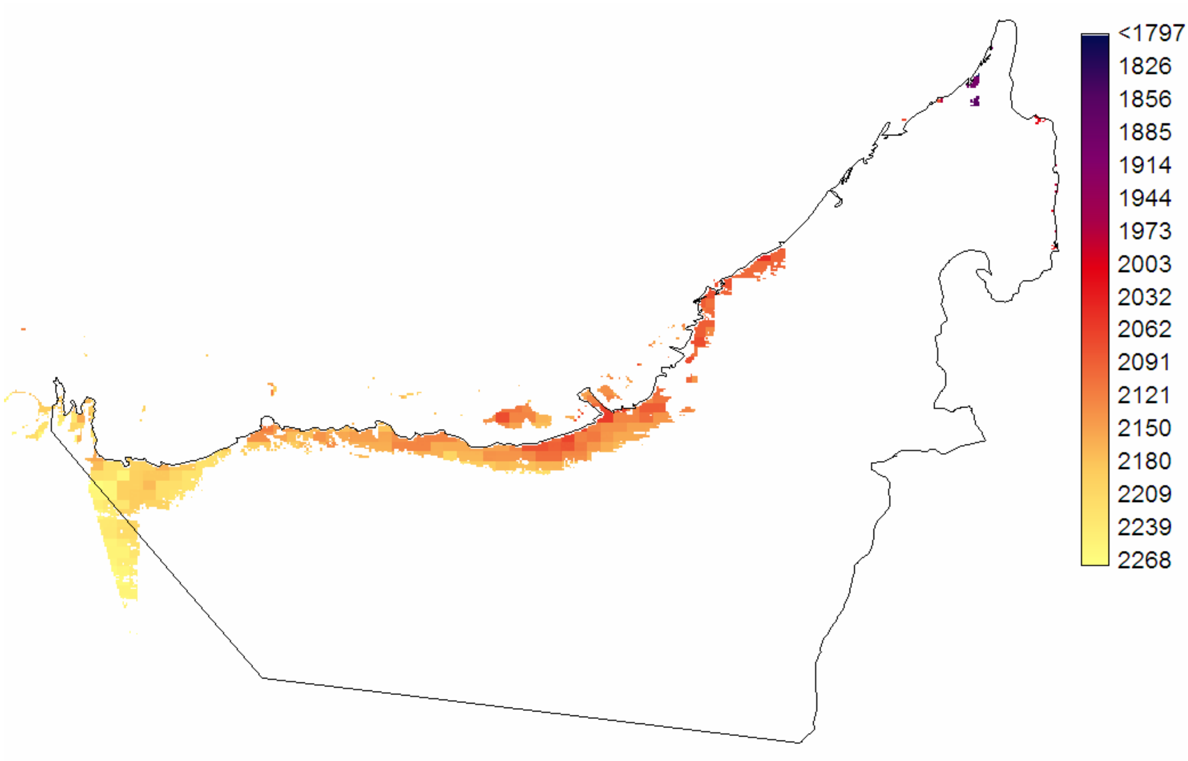

Figure A- 51: Direct normal irradiance in kWh/m²/y at potential coastal sites for CSP desalination in UAE

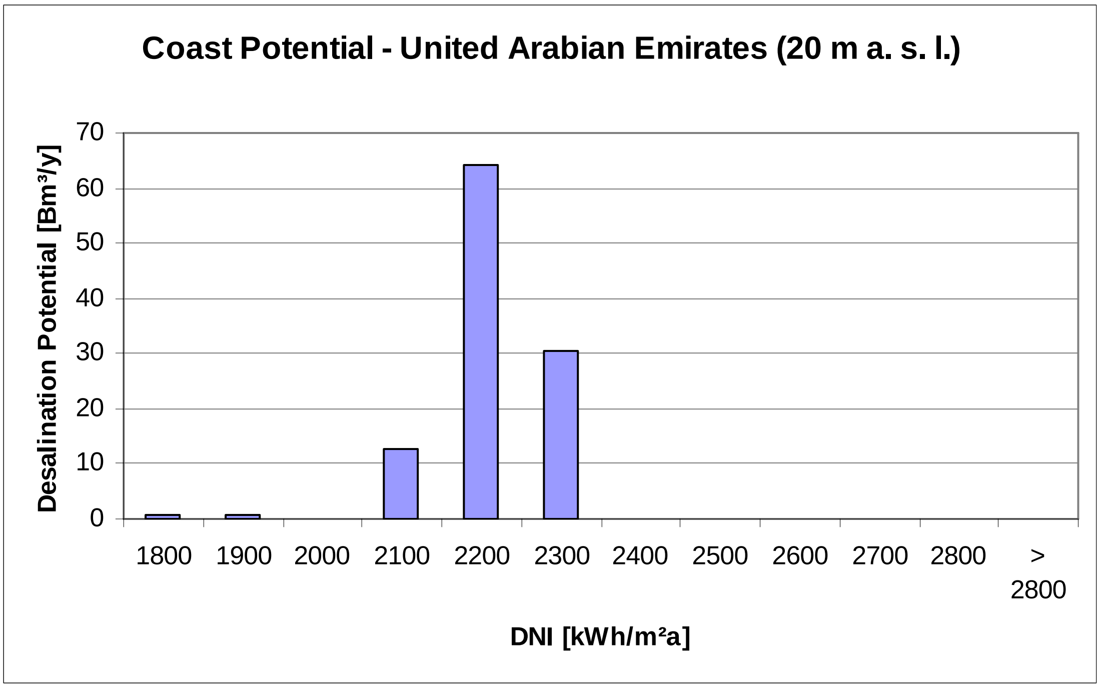

Figure A- 52: Statistical analysis of the DNI map for CSP-desalination in UAE

UAE		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Population MP	Mp	3.2	5.0	6.1	7.2	8.2	9.1
Exploitable Water	Bm³/y	0.150	0.15	0.15	0.15	0.15	0.15
Sustainable Water	Bm³/y	0.30	0.45	0.57	0.70	0.83	0.97
Irrigation Efficiency	%	0.60	0.61	0.62	0.63	0.64	0.65
Agricultural Use	Bm³/y	1.6	2.4	2.9	3.4	3.8	4.1
Municipal Efficiency	%	0.70	0.72	0.74	0.76	0.78	0.80
Municipal Use	Bm³/y	0.5	0.74	0.88	1.00	1.11	1.19
Industrial Use	Bm³/y	0.2	0.28	0.33	0.38	0.42	0.45
Total Demand UAE	Bm³/y	2.3	3.4	4.1	4.7	5.3	5.8
per capita Consumption	m³/cap/y	719	687	672	659	645	633
Wastewater reused	Bm³/y	0.183	0.3	0.4	0.5	0.7	0.8
Non-sustainable Water	Bm³/y	2.0	3.0	3.1	1.7	0.5	0.1
CSP Desalination	Bm³/y	0.00	0.02	0.41	2.33	3.93	4.71
Fossil Fuel Desalination	Bm³/a	1.2	2.5	2.7	1.7	0.5	0.1
Groundwater Over-Use	Bm³/y	0.8	0.5	0.4	0.0	0.0	0.0

Table A- 18: Main scenario indicators until 2050 for UAE

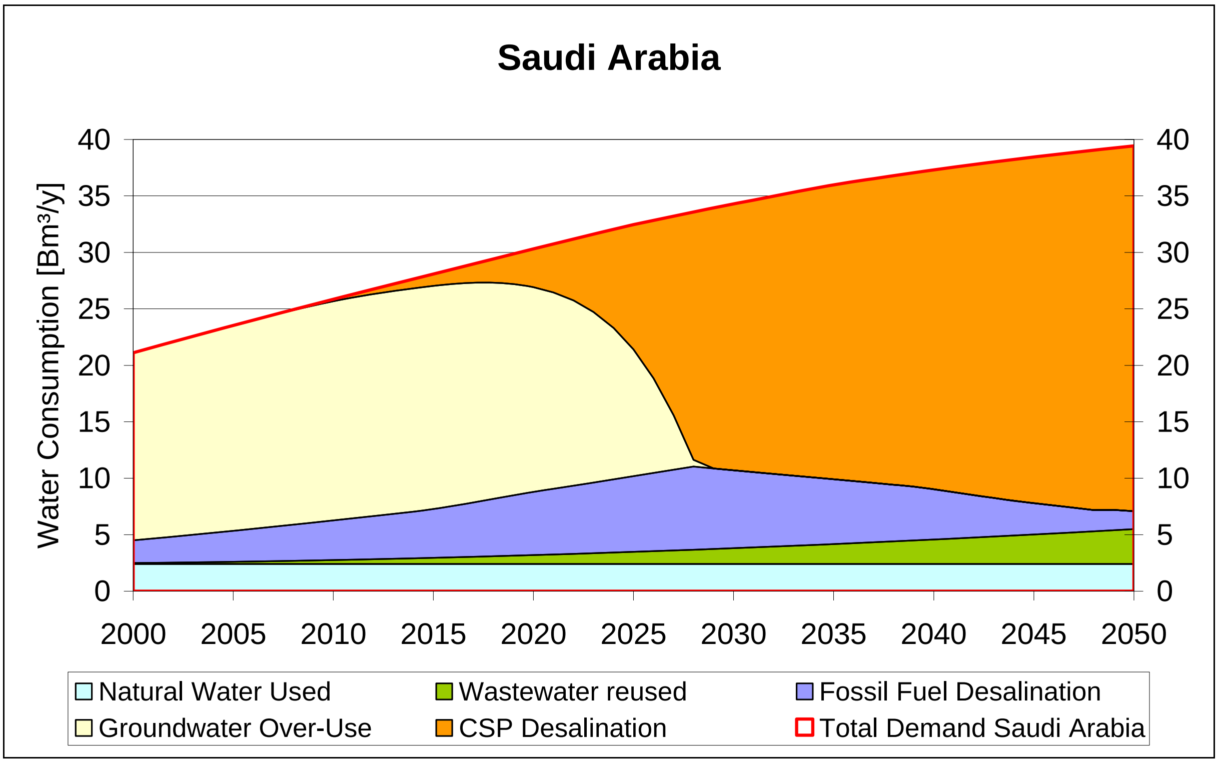

Figure A- 53: Water supply scenario until 2050 in Saudi Arabia

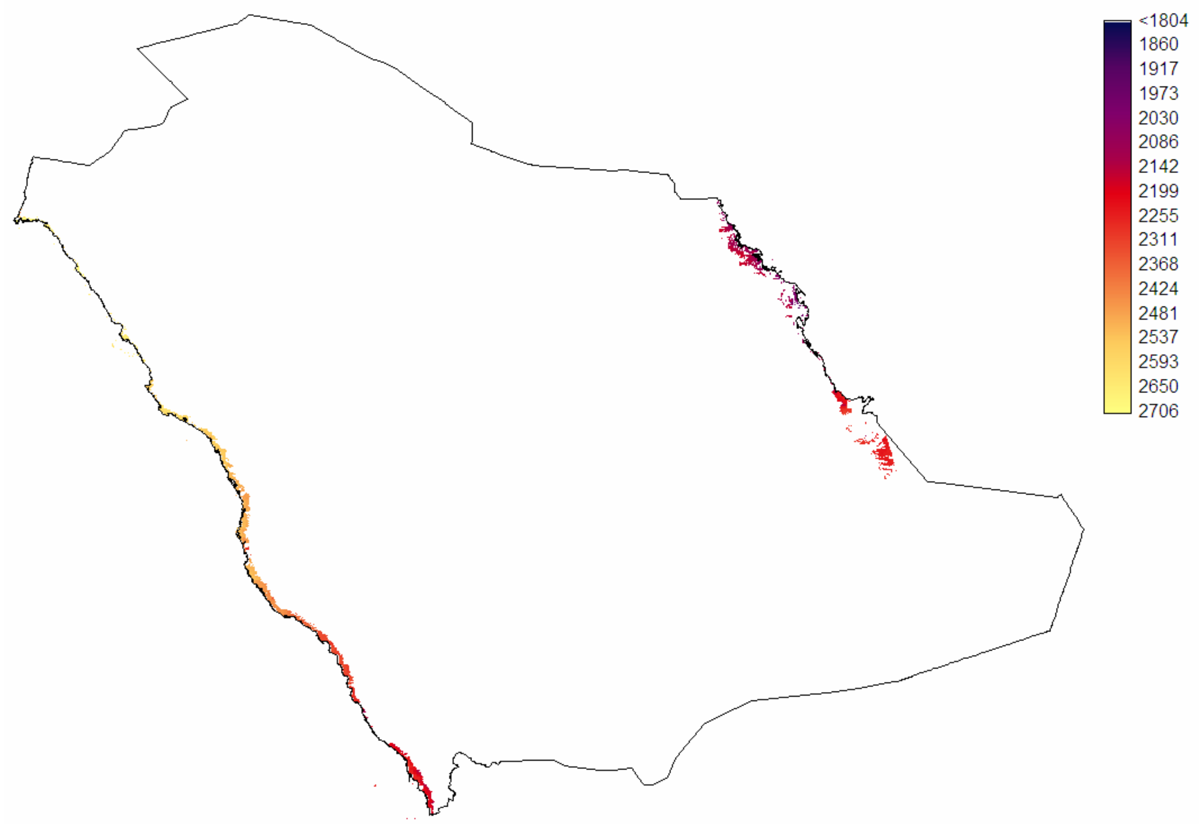

Figure A- 54: Direct normal irradiance in kWh/m²/y at potential coastal sites for CSP desalination in Saudi Arabia

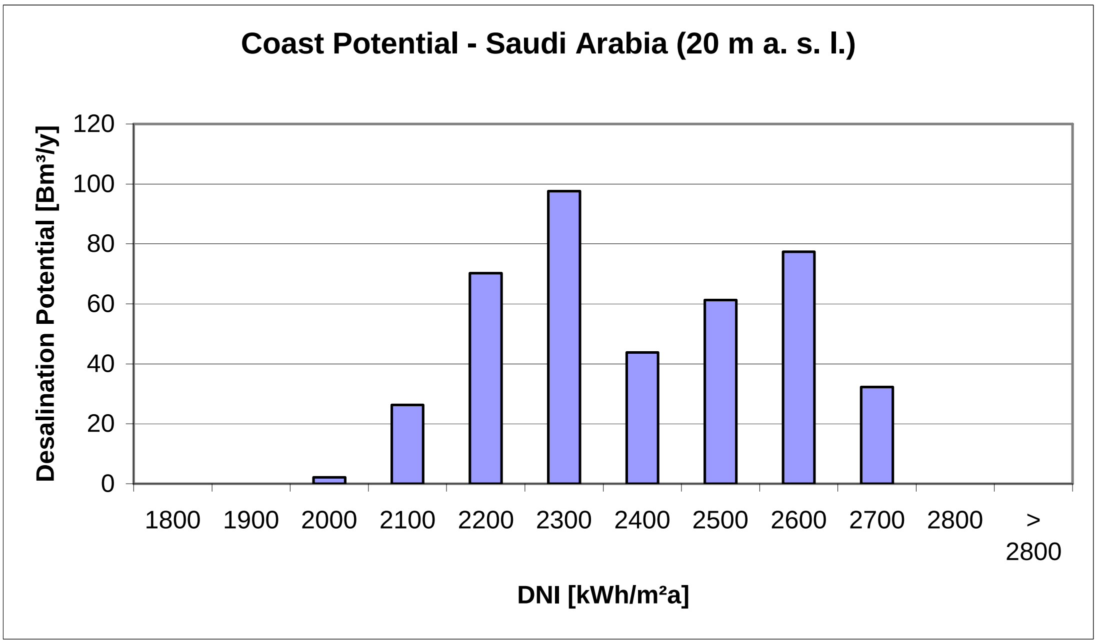

Figure A- 55: Statistical analysis of the DNI map for CSP-desalination in Saudi Arabia

Saudi Arabia		**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
Population MP	Mp	21.5	27.7	34.0	40.1	45.3	49.5
Exploitable Water	Bm³/y	2.4	2.4	2.4	2.4	2.4	2.4
Sustainable Water	Bm³/y	2.49	2.75	3.19	3.80	4.57	5.49
Irrigation Efficiency	%	0.43	0.46	0.49	0.51	0.54	0.57
Agricultural Use	Bm³/y	19.1	23.1	26.7	29.8	32.0	33.3
Municipal Efficiency	%	0.70	0.72	0.74	0.76	0.78	0.80
Municipal Use	Bm³/y	1.8	2.49	3.22	4.02	4.81	5.57
Industrial Use	Bm³/y	0.2	0.27	0.35	0.44	0.53	0.61
Total Demand Saudi Arabia	Bm³/y	21.1	25.9	30.3	34.3	37.3	39.4
per capita Consumption	m³/cap/y	982	933	891	855	824	797
Wastewater reused	Bm³/y	0.091	0.4	0.8	1.4	2.2	3.1
Non-sustainable Water	Bm³/y	18.6	22.9	23.7	6.9	4.4	1.6
CSP Desalination	Bm³/y	0.00	0.18	3.39	23.60	28.31	32.36
Fossil Fuel Desalination	Bm³/a	2.0	3.5	5.6	6.9	4.4	1.6
Groundwater Over-Use	Bm³/y	16.6	19.4	18.1	0.0	0.0	0.0

Table A- 19: Main scenario indicators until 2050 for Saudi Arabia

Annex 6: Concept of Multi-Purpose Plants for Agriculture

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AQUA-CSP-Project 2006, DLR

Project partner No. 7, IFEED (August 2007)

1. Introduction

Various human societies have also been established in deserts throughout history. And today deserts are important part of the world's natural and cultural heritage. Among the greatest contribution of desert cultures to the world are the three "religions of the Book": Judaism, Christianity and Islam which have had tremendous impact far beyond their areas of origin.
Deserts represent unique ecosystems which support significant plant and animal biodiversity, particularly with respect to adaptation for survival in arid conditions. With summer ground temperatures, near 80°C, and only very ephemeral pulses of rain, species in deserts have evolved remarkable adaptations to severe conditions, ranging from plant adapted to the fast use ephemerally abundant water or extraordinarily efficient use of scarce water, to behavioral, anatomical and physiological adaptations in animals. Due to their warm climate, deserts also export agricultural products, produced under irrigation to non-desert areas. Agriculture and horticulture are already profitable in many deserts and have great further potential. A new non-conventional desert export is derived from aquaculture , which is paradoxically, can be more efficient in water use than desert plants, and can take advantage of deserts´ mild winter temperatures and low cost of land.
Biologically-derived valuable chemicals, produced by micro-algae as well as medicinal plants, are also manufactured in deserts, capitalizing on their high year-round solar radiation, and exported to global market. Besides the ongoing export of wild plant products from deserts to non-deserts, there is pharmaceutical potential in desert plants which is yet to be exploited.
Within the agriculture sector, one possibility to improve water efficiency is to restrict irrigation to high-value crops (i.e. dates), intensive greenhouse farming or aquaculture.
Groundwater often extracted in excess of meager recharge, rates currently provide 60-100 percent of fresh water needs in most deserts lacking of a large river. The water in rivers that cross deserts is already thoroughly stabilized, if not over used. Useful technologies that can play an important role in future water supply include: drip irrigation and micro-sprinklers; desalination of brackish and saline water; fog harvesting in coastal deserts; and small sediments-holding dams and terraces.
Although deserts do not have much water, they do have other valuable natural resources that benefit people, such as biological and cultural diversity, oil, gas and other minerals. 40-60 % of minerals and fossil energy used globally is extracted from deserts (Oil and gas Belt).
Deserts in general have the highest levels of solar input in terrestrial world. They also have cheap, plentiful space and the potential to generate solar power for electricity, heat and water desalination. Continuously high solar radiation makes deserts ideal locations for solar installations, the potential reach of which is limited to deserts. Renewables might supply one-third to one-half of global energy by 2050 (Shell International 2001). The sun is supplying

deserts (solar belt) with energy equivalent to 250 liters of oil per square meter every year (2500 l oe/1oo m2). In less than 6 hours, deserts receive more energy than humankind uses in a whole year.
The scientific knowledge and engineering skills needed to generate sustainable incomes from desert resources (solar radiation) already exist; appropriate actions and equitable sharing of the proceeds need to be determined. Resource use and management in deserts for their developments focuses and depends heavily on water and energy, tow key resources. Desert development is going to be large determined by largely our common visions and collective actions taken to fulfill them. The challenge remains to harness not only local, but also global policy mechanisms and market incentives to develop future for deserts, where viable future environmental conservation and economic development are achieved.

Apart from technological feasibility, the adoption of solar energy as alternative to fissile fuels depends on global as well as national policy environments and concrete implementation strategies. The AQUA-CSP Project could be considered as a milestone towards achieving the goals of sustainability regionally and globally.

1. Objectives of the Subtask

The main objective of the subtask is to integrate agriculture in the system in order to protect the CSP installations, to improve the living and working conditions, stabilize the soils under and around collectors, creation a favorable micro-climate, combat desertification and to produce food, fiber and firewood.
Integration the AQUA-CSP system with agriculture needs the verification and analysis of the following essential determinants:

- Determination of the physiological constrains of water use efficiencies, drought and salt tolerance.
- Identification of desert adapted plant species (crops, flowers, horticulture and forest trees and shrubs).
- Verification of adequate cultivation systems adapted to desert environments (land preparation, sawing, harvesting, and weed and pest control).
- Identification efficient irrigation technologies and schemes for improving the water use efficiency (more crops for drops).
- Greenhouse technologies and facilities.
- Implementation procedures

The results the study of this task will have positive impacts on:

- Protection of the CSP Installations from sand and dust
- Contribution towards combating desertification
- Improving the soil fertility and soil conservation of the site
- Creating of a favorable micro climate for man and equipments
- Implementation of food processing and conservation as well as marketing pathways
- Reducing rural depopulation through job creation for some of the desert population and technicians of different disciplines and offering the possibility for the young people to be trained and improving their skills.
- Availability of vegetables, fruits, meat, fibers, flowers etc.

This study may contribute in formulating the anticipated project proposal “AGRO-CSP”

3. Background and Procedure

The FAO of the United Nations in support of the Sustainable Rural Environment and Energy Network (SREN) has authorized IFEED 2002 to develop the concept of the “Integrated Energy Farms, IEF”. The IEF concept includes a decentralized living area from which the daily necessities, economic and social activities can be produced and practiced directly on-site. The IEF based on

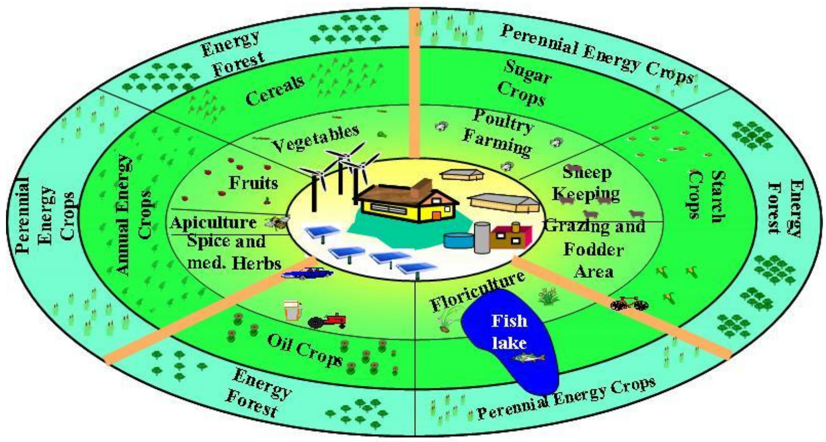

Fig. 1 Layout of the Integrated Energy Farms (IEF)

renewable energy sources would seek to optimize energetic autonomy and ecologically semi-closed system while also providing socio-economic viability (food, water, waste management and employment) and it should consider aspects of landscape and bio-diversity management. Ideally, it has to promote the integration of different renewable energies; contribute to sustainable rural development and to the reduction of greenhouse gas emission as well as improving the environment.

This concept aims at planning, optimizing, designing and building a first plant for solar electricity generation and seawater desalination based on concentrating solar thermal power (CSP) technology in a MENA coastal area with arid or semi-arid climate, and to prepare for the replication of this concept in the MENA region and world wide.

The overall task of IFEED in this project is the adaptation of the FAO concept of Integrated Energy Farming in AQUA- MED-CSP project for rural and agriculture development in Mediterranean desert regions as well as the identification of revenues and demand structures in agriculture and in desert regions.

4. Water availability, utilization and Water use efficiency (WUE)

Only 3% of the world water resources are freshwater, with 2, 31 being fixed in glacier sand permafrost in the poles and not available for consumption and about 0, 69% available in rivers, lakes, soil, swamps, groundwater and vegetation. Globally about 70% of water is being used in agriculture. Inefficiency in water use worldwide is huge. Losses in conventional irrigation systems are about 50 – 90%. Only 10-50% of irrigation water reaches the crops. The rest evaporates or seeps away.

Water use efficiency (WUE) is an important indicator for water demand of the crops to produce food. It also is used for meat productivity of various animals (beef, sheep meat and eggs). Productive WUE considers only the actual amount of water need in connection with the photosynthesis or transpiration rate which depends on the air temperature and humidity. Considerable water losses are resulted from surface evaporation, percolation and surface flows (1, 2, 8, and 10).

Huge differences exist in water requirements for different food production chains.
Fig.3 gives information on water consumption in different plant and animal production cycles and the amounts of water in liters required for producing one kilogram (kg) of food as dry matter. It shows clearly that lowest water demand is needed by vegetable crops. Meat production, especially of beef consumes the highest water rate.

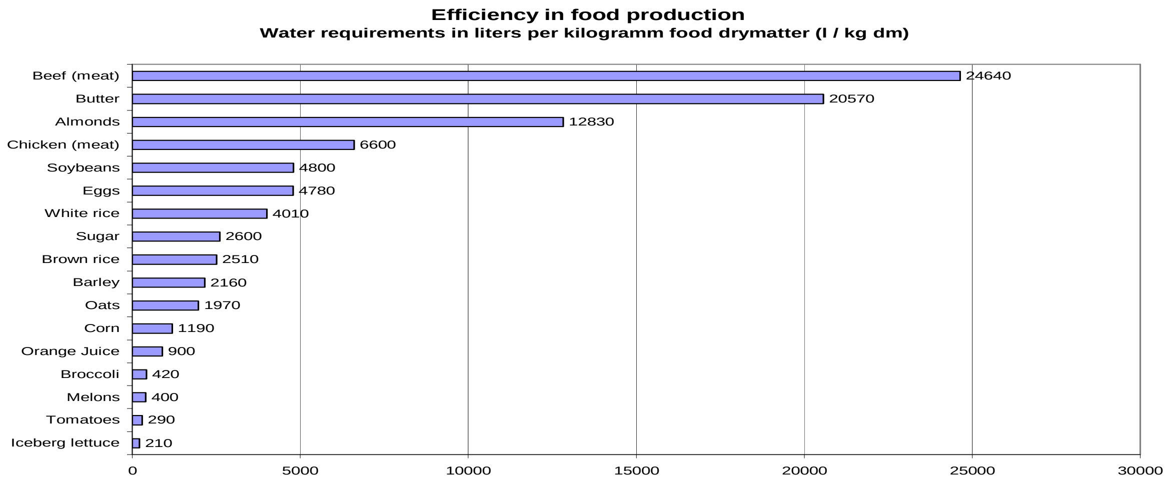

Fig. 2 Water requirements in food production

This project offers the possibility and chance to identify the most effective plant species in water use efficiency, the most effective irrigation system and suitable farming systems for CSP to reduce water demand, to combat desertification and ensure sustainable rural development.

5. Physiological background and the potential of plant productivity biomass

The potential growth of plant materials is the results of the interactions between the genotype (genetically fixed potential), environmental constrains (temperature, solar radiation, air humidity, wind velocity and precipitation) and the external inputs (fertilizers, water, chemicals, seeds etc.).

5.1 Environment and plant productivity

The tables 1-4 are essential for the interaction effects of genotypes, light, water and temperatures of the site on yield determination (6, 7).

Table 1: Photosynthesis (mg CO2 / s dw x h) of soil moistures and relative humidity

Field capacity	Relative humidity	
	70%	30%
30%	16,5	14,3
70%	8,8	6,6

Table 2: Light intensity under natural conditions

Quants / m² x s	
Day light, clear	800.000
Day light, cloudy	130.000
Day light under plant shade	17.000
Twilight	600
Moon light	0,2100
Star light	0,0009
Night sky, cloudy	0,0001

Table 3: Theoretical upper limit of crop production at 40° Latitude

Total energy radiation (TER)	1,47 x 10^{10}	kcal/ha
Upper limit of efficiency for TER	6,8	%
Average calorific value of biomass	4,00 x 10	kcal/ha
Maximum crop productivity	250	tons

Table 4: Photosynthetic efficiency of a standard crop

Total energy radiation (TER)	4,00 x 10^{10}
Photosynthetically active radiation (PAR))	1,47 x 10^{13}
Caloric value (4.000 cal / g)	6,32 x 10^{12}

The results of these interactions have been used to classify the major important plant species in 5 main groups I-V (table 6) according to their photosynthetic pathways

Table 5: Physiological characteristics and requirements of different plant species

Characteristics	Unit	Crop group				
Photosynthetic pathways		I	II	III	IV	V
Radiation intensity at max. photosynth.	cal / cm² x min	0,2 - 0,6	0,3 - 0,8	1,0 - 1,4	1,0 - 1,4	0,6 - 1,4
Operative temperature	°C	5 -30	10 - 35	15 - 45	10 - 35	10 - 45
Max. crop growth rate	g / m² x day	20 - 30	30 - 40	30 - 60	40 - 60	20 - 30

Water use efficiency	g / g	400-800	300-700	150-300	150-350	50-200

Representative Crops

- Group I C 3 pathway: Field mustard, potato, oat, tomato, rye, grape, rape, pyrethrum, sugar beet, bread wheat, chickpea, French bean, Arabic coffee, sunflower, olive, barley. Cabbage, lentil, linseed;

- Group II C 3 pathway: Groundnut, French bean, rice, fig, soybean, cowpea, sesame, tomato, hyacinth bean, roselle, tobacco, sunflower, grape, safflower, kenaf, castor bean, sweet potato, sweet orange, bananas, lemon, avocado pear, coconut, cotton, cassava, mango, Robusta coffee, white yam, olive, greater yam, Para rubber, oil palm, cocoa;

- Group III C 4 pathway: Japanese barnyard millet, foxtail millet, finger millet, common millet, pearl millet, hungry rice, sorghum, maize, sugarcane;

- Group IV C 4 pathway: Japanese barnyard millet, foxtail millet, common millet, sorghum, and maize;
- Group V CAM pathway: Sisal, pineapple

6. Identification and evaluation of plant species which meets the requirements of arid and semi-arid regions for food and biomass, under and around the STPD units

More than 450.000 plant species exist worldwide. Only small portion of it is being used at present. For this project, several plant species Tables 6-8 have been selected to meet the requirements of the anticipated sites (4).

The selection of proper plant species is essential to meet the requirements of the project. The main features of these crops should be:

- Drought and heat resistant
- Shadow tolerable
- Salt resistant
- Low input (Fertilizers, Chemicals and Water)
- High productivity

The plant breeding has achieved a great success in the last years in breeding of high yielding varieties and reduction of the inputs. Adapted varieties for different climatic regions produced and are also available. This is the reason why we are producing more food with less area, especially in OECD countries. The selection of the right seeds, beside water availability, is the key element for a successful farming system.
Priority should be given to introduce food and fodder crops and soil conservation. The people working in around the project sites needed to be supplied with vegetables, fruits, meat and other food to be produced locally.

The IEF can also provide an excess of energy resources in solid, liquid and gaseous states. Biomass such as wood and straw can directly used as solid energy for combustion for heat and power generation or for cooking. Oil and ethanol plants can be also cultivated for substitution for liquid fossil fuels. Wastes and other organic residues represent a suitable source to produce high quality organic fertilizers which are essential for soil improvement substitution of chemical fertilizers under and around the solar collectors.

More than 450.000 plant species exist worldwide. Only small portion of it is being used at present. For this project, several plant species Tables 6-8 have been selected to meet the requirements of the anticipated sites (4). Other wild desert plant species should be taken also in consideration.

Table 6: Food crops suitable for cultivation under the CSP installations

- Aubergine (*Solanum melongena L.*)
- Beans (*Vicia faba L.)*
- Chicory (*Cichorium itybus L.*)
- Cress (*Leoidium sativium L.*)
- Cucumber (*Cucmis sativus L.*)
- Herbs and spice plants
- Lady's finger (*Hibiscus esculentus L.*)
- Melons (*Cucumis melo L.*)
- Tomato (*Lycopericon lycopersicum L.*)
- Potato (*Solanum tuberosum L.*)
- Salad (Lactuca sativa L.)
- Peppers (*Capsicum annuum L.*)
- Spinach (*Spinacia oleracea L.*)

Table 7: Crops suitable for cultivation around CSP

- Alfalfa (*Medicago sativa L.*)
- Amaranth (*Amaranthus ssp.*)
- Annual ryegrass (*Lolium multiflorum Lam.*)
- Barley (*Hordeum vulgare L.*)
- Buckwheat (*Fagopyrum esculentum Moench*)
- Groundnut (*Arachis hypopgea*)
- Hemp (*Cannabis sativa L.*)
- Kenaf (Hibiscus cannabinus L.)
- Rape (*Brassica rapsus L.*)
- Lupines (*Lupinus ssp.*)
- Maize (*Zea mays L. ssp. Mays*)
- Meadow foxtail (*Alopecurus pratensis L.*)
- Quinoa (*Chenopodium quinoa Willd*).
- Reed canary grass (*Phalaris arundinaceae*)
- Rosin weed (*Silphium perfolatium L*)
- Safflower (*Carthamus tinctorius L.*)
- Salicornia (*Salicornia bigelovvi Torr.*)
- Sesame (*Sesamum indicum L*)
- Soybean (*Glycine max (L.) Merr.*)
- Sugar cane (*Saccharum officinarum L.*) *
- Sunflower (*Helianthus annus L.*)
- Sweet sorghum (*Sorghum bicolor L. Moench*)

- Switch grass (*Panicum virgatum L.*)
- Tall fescue (*Festuca arundinaceae Schreb.*)
- Timothy (*Phleum pratense L.*)
- Topinambur (*Helianthus tuberosus L.*) *
- Triticale (*Triticosecale*)
- Oats (*Avena sativa L.*)
- Rye (*Secale cereale L.*)
- Wheat (*Triticum aestivum L.*)

* = perennial crops (all others are annual)

Table 8: Trees and tall grasses for cultivation around CSP collectors fields

- Argan tree (*Argania spinosa*)*
- Bamboo (*Bambusoideae*) *
- Black locust (*Robinia pseudoacacia L*)*
- Broom (Ginestra) (*Spartium junceum*)*
- Cardoon (*Cynara cardunculus L.*)*
- Gigant knotwees (*Polygunum sachalinensis F. Schmidt*)*
- Common reed (*Phragmites communis Trin.*)*
- Cordgrass (*Spartina ssp.*)*
- Date palm (*Phoenix dactylifera*)*
- Eucalyptus (*Eucalyptus spp.*)*
- Fig-tree (*Ficus caraca L.*)
- Giant reed (*Arundo donax*)*
- Jojoba (*Simmondsia chinensis*)*
- Miscanthus (*Miscanthus ssp.*) *
- Olive (*Olea europaea.*)*
- Pomegrante (*Punica granatum L.*)
- Perennial ryegrass (*Lolium perenne L.*) *
- Poplar (*Populus spp.*)*
- Sesbania (*Sesbania spp.*)*

6. Cultivation procedures

Special attention should be paid for the crop management which has to allow an efficient of the water. The combination of several measures is essential for water and soil conservation and optimum plant growth:

- Soil preparation
- Water supply
- Plant protection
- Crop management and crop rotation
- Harvesting, storage and conservation
- Ecological farming
- Desert cultivation system

7. Identification of water efficient irrigation systems

The identification and application of water saving irrigation technologies is one of the most effective measures to reduce the water required water rates for a proper plant growth. The technologies of irrigation are in the process of continues improvement and the water supply could be considerably reduced. Following advanced systems have to be considered in the project:

- Drip irrigation
- Micro sprinklers
- Advanced spray irrigation technologies (Centre Pivots)

Careful selection of the right systems for various applications; under the solar collectors, around the solar collectors and in the greenhouses has to considered.

8. Waste water management

Human activities within of the project produce and also animal husbandry produce considerable amounts of waste water which should be treated and recycled. The reuse of waste waters needs adequate treatment before its re-injection in the irrigation system.

- Micro filter systems for solid separation
- Solid densification > low volume and transportation
- Field irrigation of fluid residues (organic fertilizer)

9. Road map

Basic data of the specific sites of the implementation of CSP installations in desert regions are essential for the verification of the integration of agriculture in the whole system. These information are needed for a proper projection
Following specifications of the site are required:

- Climate data
- Soil and ground water characteristics
- Amount of water which could be used
- Market requirement for Food
- Type of CSP to be installed
- Infrastructure

These data should be collected from the site

10. Case Study: AQUA-CSP Project

In this study, the FRESNEL-CSP-System has been considered as an example for the verification the necessary input to achieve the integration of agriculture. We recommend creating greenhouse under the FRESNEL installation in order to optimize the crop production, mainly food and cash crops i.e. vegetables and flowers. Calculations and measurements have to be done in order to determine and to create the necessary and adequate production conditions.

10.1 Primary growth requirements for crops under CSP collectors

- Light: Light conditions under the collectors are inhomogeneous and of low intensities

Additional artificial light sources is necessary

- Temperatures

Temperatures under the collectors are too high for plant growth. Possible solutions are:
Solution:

- Aeration
- Cooling
- Plantations around the collectors

- Water Supply
  - Efficient irrigation systems i.e. drip, micro sprinkler etc
  - Enhancing the air humidity
  - Reducing the evapo-transpiration
  - Creation of closed system: Greenhouse

- Farming Mechanization

  - Adapted machinery for under and outside the collectors for plowing, weed control and harvesting is necessary

- Weed and Pest Control
  - Mechanical weed control
  - Biological herbicides, insecticides and pesticides

- Farming Systems
  - Organic farming offers the opportunity for healthy food of high economic value and better environmental protection

- Residues Treatment
  - Composting and recycling
  - Production of biofuels i.e. pellets and briquettes for cooking purposes

- Processing and Storage
  - Creating adequate short and midterm storage capacities i.e. cooling, drying etc
  - Introduction of special processing, packaging and preservation technologies

- Marketing Strategies
  - Verifying suitable marketing options
  - Implementation of adequate logistic systems for transport and distribution of the products

- Training of Technicians
  - Selection of technicians for the various activities
  - Training and education facilities

The integration and adaptation of the concept of Integrated Energy Farming in AQUA- MED-CSP project. The integration of agriculture around the CSP needs to combine advanced water supply devices such as drip irrigation and the selection of desert resistant plant species: date palms and olive trees as well as some shrubs using the three levels system:
Level 1: Date palm trees and olive trees
Level tow: citrus and fig trees
Level three: grasses and vegetable plants

Fig. 3 Projected layout of cultivation procedure (greenhouse system) under CSP insulations

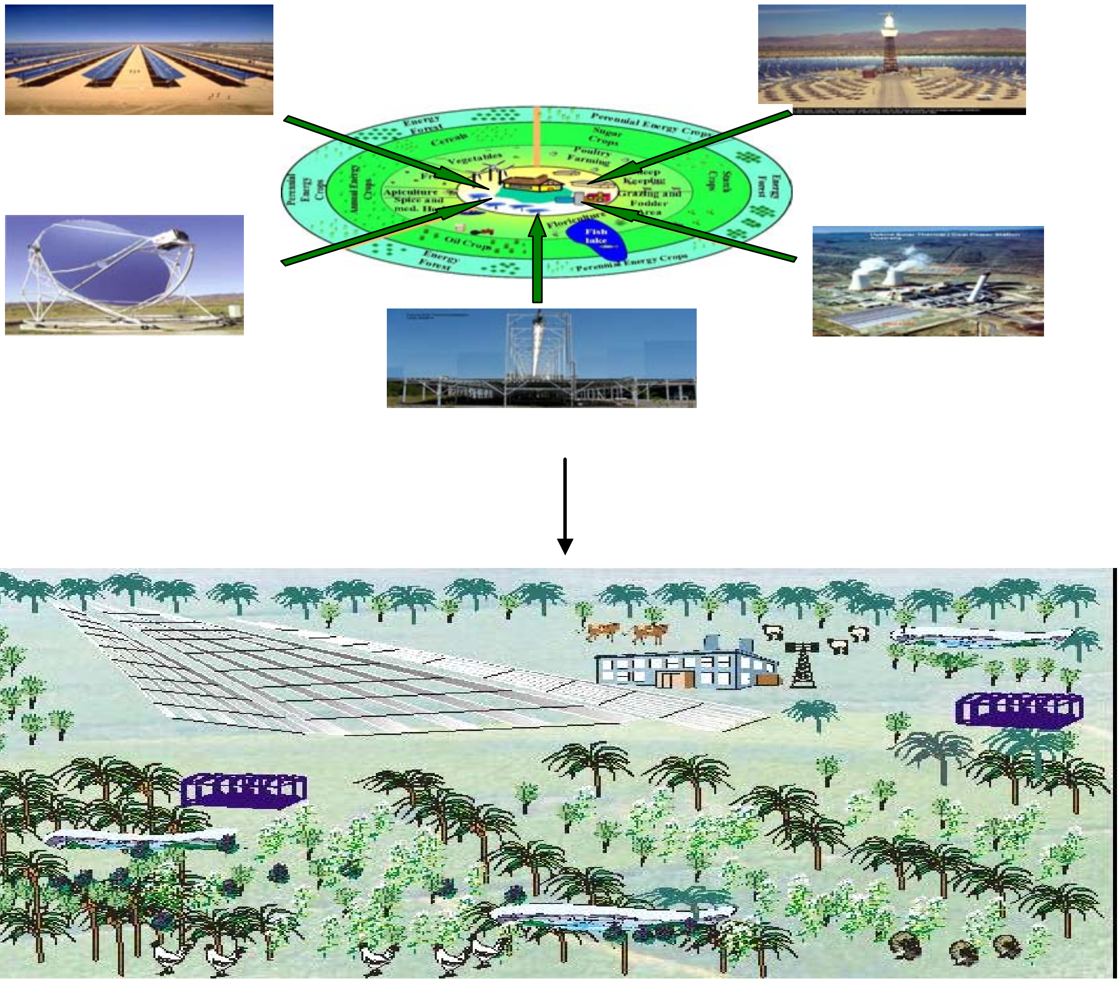

Fig. 4 Projected integration of agriculture around the CSP devices

11. Impact on climate, environment and desertification

The implementation of the IEF in the CSP project has several positives effects on the soils, climate and the environment:

- improving soil conservation
- increasing soil fertility
- water conservation
- creating of a favourable micro climate
- protection of the STPD Installations from sand and dust
- combating desertification

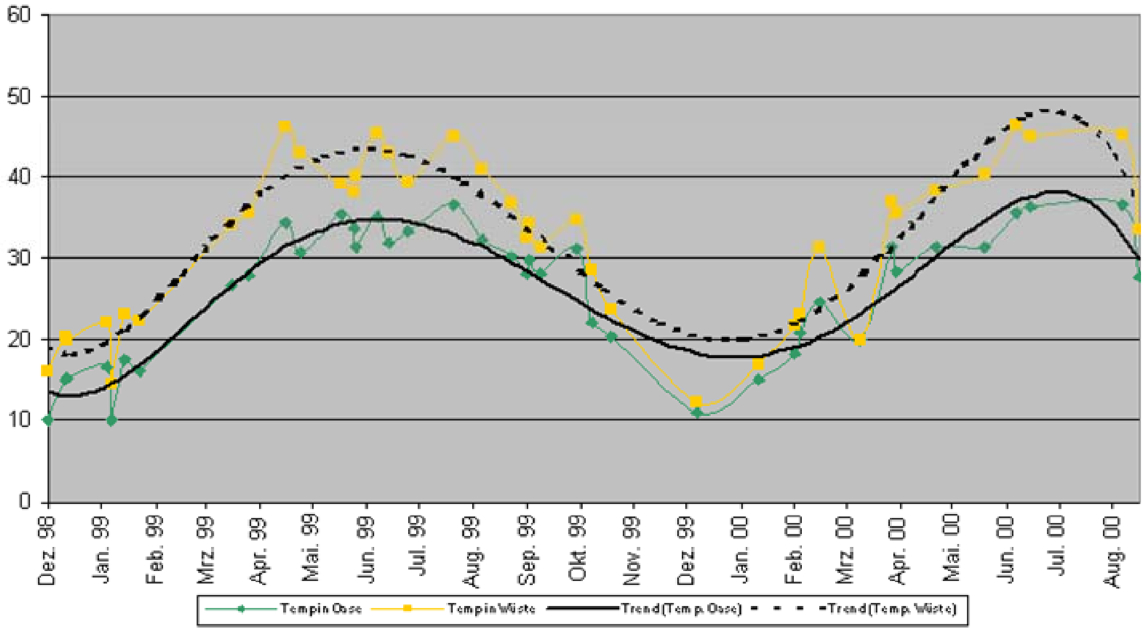

Fig. 6 Temperatures inside (green curve) and outside (yellow curve) and trends in a desert oasis

12. Social and economic impact

The concept includes social and economic elements which are of a great importance for the population in remote and areas:

- Job creation for farmers and technicians of different disciplines in farming, irrigation, landscape, animal husbandry, food conservation etc.
- The project opens chances for the young people to be trained and improving their skills.
- It will attract different groups from various disciplines and tourists.
- The processing and conservation of food could have positive economic effects.
- The production of solid fuels from biomass represents additional economic revenue.

13. Conclusions

Throughout history water has confronted humanity with some of its greatest challenges. Water is a source of life and a natural resource that sustains our environments and supports livelihoods – but it is also a source of risk and vulnerability. In the early 21st Century, prospects for human development are threatened by a deepening global water crisis. Water demand in Mediterranean countries has doubled in the second half of the last century and has now reached about 290 billion m³ per year. Water scarcity needs to be on the top of the priorities in bi- and multilateral relations among Mediterranean countries, as river basins often cross borders (12, 13 and 14). Efforts towards water savings and increased efficiency alone are essential but will not solve water scarcity problems in the Mediterranean. There is an urgent need to implement intelligent strategies an technologies to producing more water for ever growing demand. The AQUA- CSP project offers an unique opportunity to meet these challenges (8 and 9).

It can be concluded that the adaptation of the FAO Concept “Integrated Energy Farm” (IEF) could offer the possibilities to reduce the water requirements for irrigation through selection of draught and heat resistant adapted crops, using water saving irrigation technologies and introduction of combination between desert cultivation approaches, greenhouse facilities and ecological farming systems.

The planning of the IEF consists of 4 pathways: Food, energy, environmental and social-economic pathways. The outputs are, beside the power, heat and water, food, fodder, education, training and employment. Soil conservation, microclimate improvement are further positive effects on sustainable development of the site.

Several plant species have been identified to be cultivated under and around CSP installations. They include herbal crops, vegetables, grasses, grains, pulses, shrubs and trees. Emphasis will be put on drought tolerant, salt resistant and high productive genotypes with a harvest index (HI) higher than 50%.

The area which can be cultivated with the desalinated water ranges between 17 and 50 ha annually, depending on HI.

Agricultural activities are almost subsidised (OCED countries 1 billion dollars every day). Considering the global market, it could be estimated that the prices of the agricultural products produced under and around CSP stations could range between 0.12 and 1.20 Dollars per kilogram of food.

Greenhouse technologies offer the best possibilities for producing food and cash crops. They are very efficient in water use and water saving and could work all around the year.

The integration of agriculture around the CSP needs to combine advanced water supply devices such as drip irrigation and the selection of desert resistant plant species: date palms and olive trees as well as some shrubs using the three levels system:

Level 1: Date palm trees and olive trees

Level tow: citrus and fig trees

Level three: grasses and vegetable plants

The integration of agriculture in this chain does not represent only an additional services but it is an essential part for sustainable water desalination and power generation in desert regions, protection of the installations and combating further desertification.

All these assumption has to be verified in a demonstration project.

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Annex 7: List of Abbreviations

α	progress factor
AC	Alternating Current
β	best practice efficiency
bar	unit of pressure
bbl	barrel of crude oil
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
BMU	German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
Bm^3/y	one billion cubic metre per year = 1 km^3/y (one cubic kilometre per year)
c	cost variable
cap	per capita
CC	combined cycle (gas and steam turbine) power plant
CED	Cumulated Energy Demand
CSP	Concentrating Solar Thermal Power Stations
CSP/RO	advanced solar powered reverse osmosis
CSP/MED	advanced solar powered multi-effect desalination
CHP	Combined Heat and Power
CoE	Cost of Electricity
Conv.	Conventional
CO_2	Carbon Dioxide (greenhouse gas)
ct	Euro-cent
D	destillate
DC	Direct Current
DME	Deutsche Meerwasserentsalzung e.V.
DNI	Direct Normal Irradiance (solar beam radiation on ideal sun-tracking collectors)
€	Euro
η	efficiency
ED	Electrodialysis
EU	Europe
EUMENA	Europe, Middle East, North Africa
Flh/y	full load hours per year
Fresnel	Inventor of a facetted concentrating mirror assembly
γ	driving force variable
GCC	Gulf Cooperation Council
GDP	Gross Domestic Product
GHG	Greenhouse Gases (emissions responsible for climate change)
GIS	Geographic Information System (electronic geographic data base)
GJ	giga-Joule (million kilo-Joule, thermal energy unit)
GT	gas turbine
GW	Giga-watt, one million kilowatt (capacity unit)
GWh	1 million kWh (energy unit)
Hybrid	Mixture of solar and fossil primary energy in a concentrating solar power plant
IE	Ion Exchange
irr	irrigation
kg	kilogram
kJ	kilo-Joule (thermal energy unit)
kV	kilovolt = 1000 Volt (unit of tension)

kW	kilowatt (unit of power)
kWh	kilowatt-hour (unit of energy)
LC	lethal concentration
LCA	Life Cycle Assessment of Emissions, Materials and Energy Consumption (Eco-Balance)
LEC	Levelised Electricity Cost
MAN/SPG	MAN Ferrostahl Solar Power Group, Essen
ME	Middle East
Med	Mediterranean Region
MED	Multi-Effect-Desalination
MED-CSP	Study that can be found at www.dlr.de/tt/med-csp
MENA	Middle East & North Africa
Mm^3	million cubic metres
MVC	Mechanical Vapour Compression
m	meter
m^2	square metre
m^3	cubic metre
mm	millimetre
MSF	Multi-Stage-Flash Desalination
MW	million Watt
MWh	1000 kWh
NA	North Africa
O&M	Operation and Maintenance
RE	Renewable Energy
PPA	Power Purchase Agreement
ppm	part per million (concentration unit)
PPP	purchasing power parity
PSA	Test Centre Plataforma Solar de Almeria, Southern Spain
PV	photovoltaic
R&D	Research and Development
RD&D	Research, Development and Demonstration
REA	Renewable Energy Act
RES	Renewable Energy System
RO	Reverse Osmosis Membrane Desalination
S	Seawater
SD	Solar Distillation (usually small scale)
SEGS	Solar Electricity Generating System
ST	steam turbine
Stirling	Inventor of an external combustion piston engine
t	time variable
T	temperature
TREC	Trans-Mediterranean Renewable Energy Cooperation
TRANS-CSP	Study that can be found at www.dlr.de/tt/trans-csp
TVC	Thermal Vapour Compression
TWh	1 billion kWh
UAE	United Arab Emirates
$	US Dollar = USD
ω	water consumption
x	variable describing the abscissa
y	year, variable describing the ordinate