Concentrating Solar Power for Seawater Desalination

Dr. Franz Trieb

Franz.Trieb@dlr.de, Phone: +49 711 6862 423, Fax: +49 711 6862 783

German Aerospace Center, Institute of Technical Thermodynamics,
Pfaffenwaldring 38-40, D-70569 Stuttgart, Germany

Abstract

All MENA countries have an outstanding potential for solar energy. Using concentrating solar thermal power (CSP) plants to power seawater desalination either by electricity or in combined generation with process steam to solve the water scarcity problem in MENA is a rather obvious approach. The AQUA-CSP project sponsored by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) quantifies the potential of this technology in MENA and the socio-economic and environmental impacts implied by a large scale dissemination in order to provide a reliable data base for decision and policy makers in the water sector and to facilitate the inclusion of this approach in national expansion plans. Some preliminary results of this project are presented here.

Growth of population and economy, increasing urbanization and industrialization, and the rather limited natural resources of potable water in MENA are leading to serious deficits of freshwater in many parts of MENA. Modern infrastructure for water distribution, enhanced efficiency of use and better water management are to be established as soon as possible. However, even the change to best practice would leave considerable deficits, which are poorly covered by over-exploiting groundwater resources. Increased use of desalted seawater is therefore unavoidable in order to maintain a reasonable level of water supply. The desalination of seawater based on fossil fuels is neither sustainable nor economically feasible in a long-term perspective, as fuels are increasingly becoming expensive and scarce. Concentrating solar power (CSP) offers a sustainable alternative to fossil fuels for large scale seawater desalination. CSP can help to solve the problem, but market introduction must start immediately in order to achieve the necessary freshwater production rates in time.

Keywords: water demand, seawater desalination, concentrating solar power, solar energy, long-term scenario, Middle East, North Africa

Introduction

Freshwater sources in the Middle East and North Africa are persistently over-used. This is partially due to a rather low efficiency of water distribution and use, which in many cases does not reach present state of the art. Another major driving force is the continuous growth of population and economy of this region, which requires more water for more people and for new cultural, economic and industrial activities. Since about a decade, the exploitation of freshwater in this region has surpassed the available renewable surface and groundwater sources, and the deficit is poorly covered by over-exploiting the groundwater resources [1]. Enhanced water management and more efficient distribution and use of water are the core of sustainable supply. However, a pre-requisite for water management is the existence of water to manage. Enhanced water management can delay and hopefully avoid the early depletion of groundwater resources, but it cannot supply new, growing demands.

New, unconventional sources of water must be found, and possible solutions range from the transport of freshwater to MENA by tanker ships to seawater desalination [2], [3]. It is common to all those solutions that they require significant amounts of energy. Moreover, sustainable supply of water requires a sustainable source of energy, sustainable meaning in this context affordable, compatible with society and the environment, and secure. With prices of fossil fuels like oil or gas having increased by 300 % since the year 2000, serious concerns on the stability of the global climate due to carbon emissions, and increasing conflicts about energy sources all over the globe, it is obvious that the conventional energy system does not fit to the requirements of a sustainable, secure and competitive supply of water. As a consequence, MENA governments are reluctant to invest in any of the new sources, but instead put increasing pressure on their groundwater, which is however a solution for only a very limited time span, with disastrous results once those resources are depleted.

Persisting in "least cost and proven technology", MENA governments in the past have favored energy solutions that at the end of the day have proven to be very expensive. Hoping that investments in off the shelf technologies would guarantee a low risk of supply, the contrary has happened. If such a situation is problematic in the energy sector, it is totally unacceptable in the water sector, as water is a vital commodity. Thus, building water supply on conventional energy sources could in fact lead to a critical situation in the medium and long term future. A change of paradigm is urgently needed, aiming at a sustainable supply of energy and water.

Concentrating Solar Power –Sustainable Energy and Water

Up to now, "least cost and proven technology" thinking has prevented MENA governments from using a clean, unlimited and very economic source of energy available at their door step: solar energy irradiated on the deserts and coasts (Figure 1).

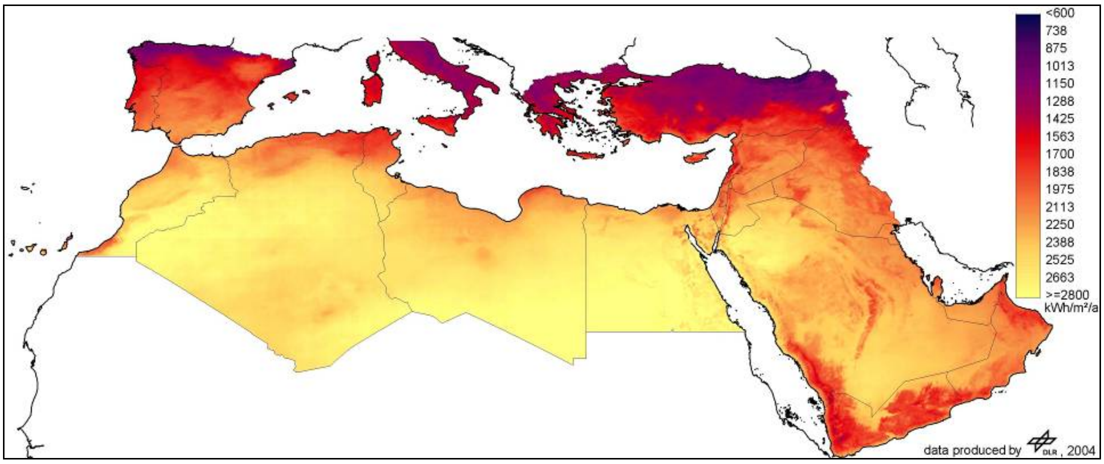

Figure 1: Annual direct normal solar irradiance in MENA and Southern Europe in kWh/m²/y.

Each square kilometre of land in MENA receives every year an amount of solar energy that is equivalent to 1.5 million barrels of crude oil[1]. The technology to harvest, store and convert it to useful energy is state of the art: concentrating solar power (Figure 2). A concentrating solar power plant of the size of Lake Nasser in Egypt (Aswan) would harvest an amount of energy

[1] reference solar irradiance 2400 kWh/m²/year, 1600 kWh heating value per barrel

equivalent to the present Middle East oil production[2]. Solar energy received on each square kilometre of desert land is sufficient to desalinate an amount of 165,000 cubic metres per day or 60 million cubic metres per year.

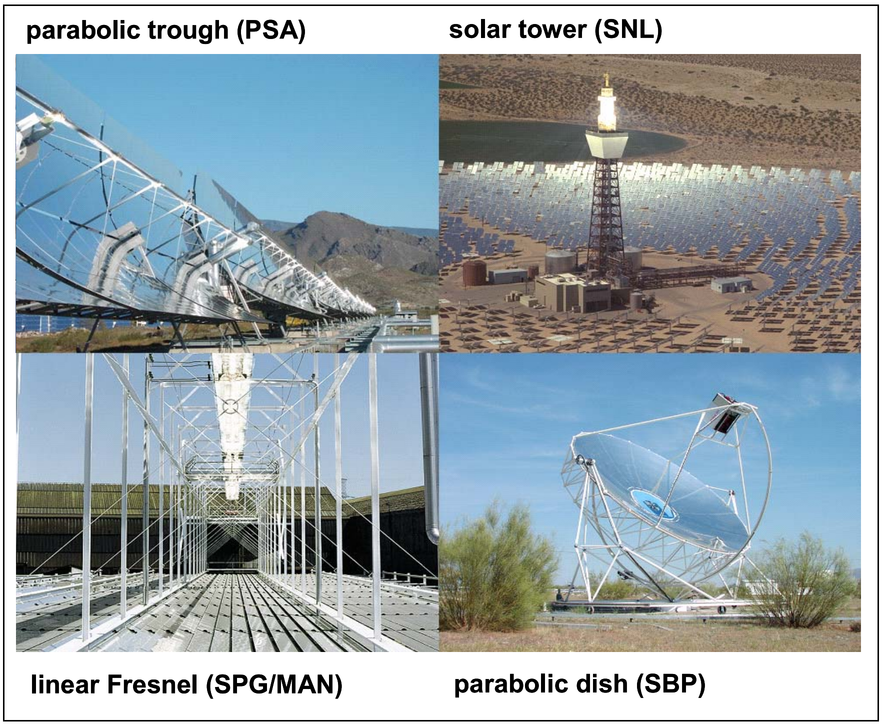

Figure 2: High temperature concentrating solar collector systems

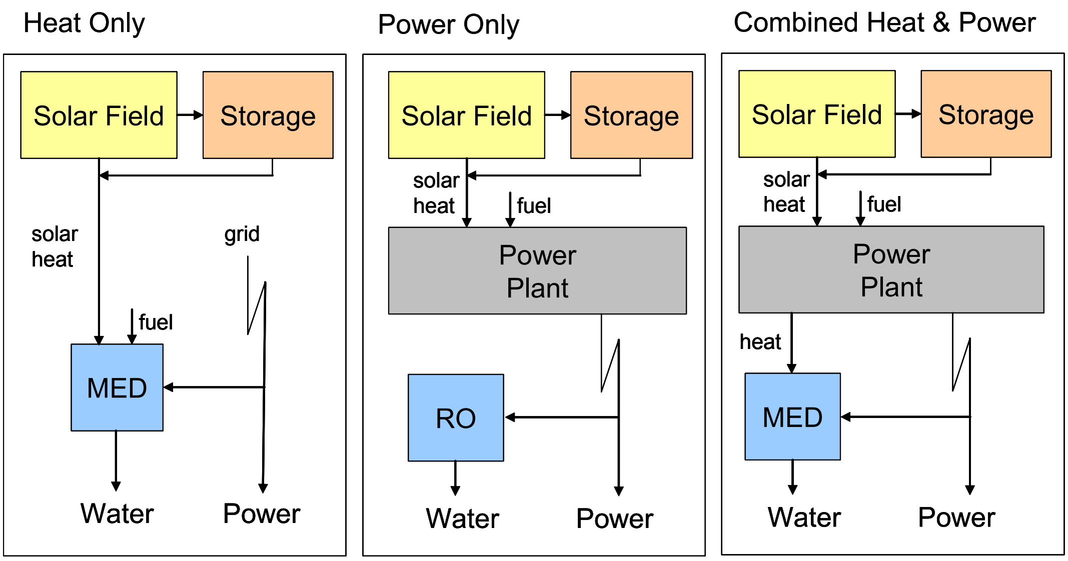

Figure 3: Left: Generation of heat for multi-effect desalination. Middle: Power generation for reverse osmosis and other uses. Right: Combined heat & power for multi-effect desalination and other uses.

Large mirror fields concentrate the sunlight to produce high temperature steam for power generation or for the combined generation of electricity and heat, that both may be used for

[2] Lake Nasser has a surface of 6000 km², Middle East oil production is currently $9 \cdot 10^9$ barrels/year

sea water desalination (Figure 3). Part of the harvested solar thermal energy can be stored for the night, and conventional fuel or biomass can be used as complement to guarantee round the clock operation. At the present state of the art, heat from concentrating solar collectors has a cost equivalent to about 50 $/barrel of fuel oil, with the perspective of a cost reduction of 50 % in the coming decade due to economies of scale, mass production and technological progress. The perspective of achieving a cost level of 25 $/barrel within 10 years and as low as 15 $/barrel by the middle of the century is a fundamental difference to fossil fuels, which do not seriously have this perspective any more [4].

Concentrating solar power plants with unit capacities of up to 80 MW are presently in operation in the USA and being built in Spain. The coastal CSP potential in MENA amounts to 5700 TWh/y, the total potential to 630000 TWh/y [4]. A total capacity of 410 MW will be operating world wide at the end of 2007. The engineering of a first plant for the combined generation of electricity, district cooling and desalted water has recently started in Aqaba, Jordan [5].

Growing Population, Economy and Water Demand

The number and growth rate of population is one of 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 [6]. According to that study, the population in the total MENA region will steadily grow from about 300 million today to about 600 million in 2050 (Figure 4). The population in North Africa will grow from today's 140 million to 240 million in 2050. Egypt is accounting for 50 % of the population of the total region. The population in the Western Asian countries will grow from 120 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, but Yemen's population will still be growing quickly by that time, becoming the most populated country in this region.

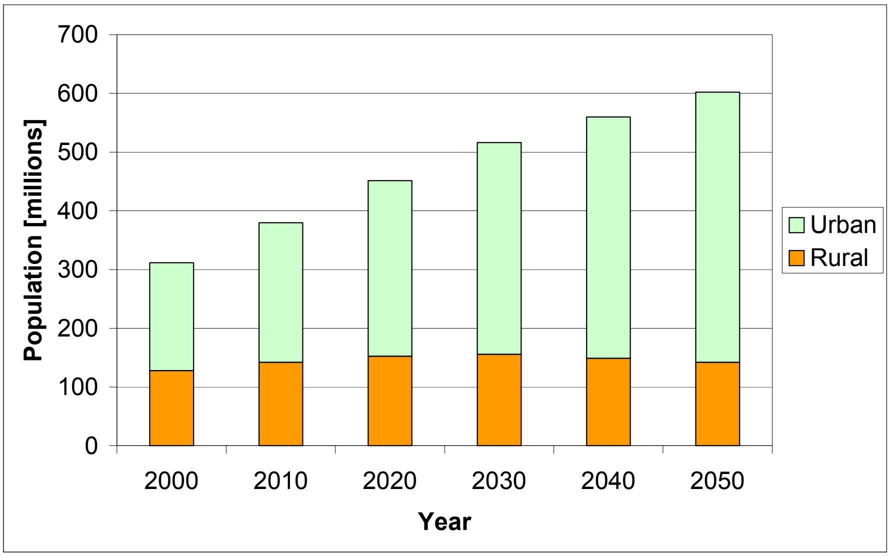

Figure 4: Population of the analysed countries in MENA according to the United Nations medium growth scenario revised in 2004.

The second driving force for electricity demand is economic growth, here represented by the change of the gross domestic product in time (GDP). Long-term average growth rates for the different countries have been selected in a range of reasonable values, most countries achieving a per capita income similar to that of present Central European countries by 2050 [4].

For the calculation of the water demand for irrigation, the population growth rate of each country 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 food production in each country. Efficiency gains lead to a closing of 65 % of the gap between present and best practice irrigation efficiency (70%) for all MENA countries until 2050.

The model also assumes that 65 % of the gap of present water distribution efficiency and best practice (85 %) is closed until 2050. The general end use efficiency is assumed to increase by 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 [8].

The resulting model of the development of freshwater demand in each country is shown in Figure 5. All in all, the MENA freshwater demand will grow more or less proportional to the population, which could be interpreted as if 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 over-using the natural freshwater resources.

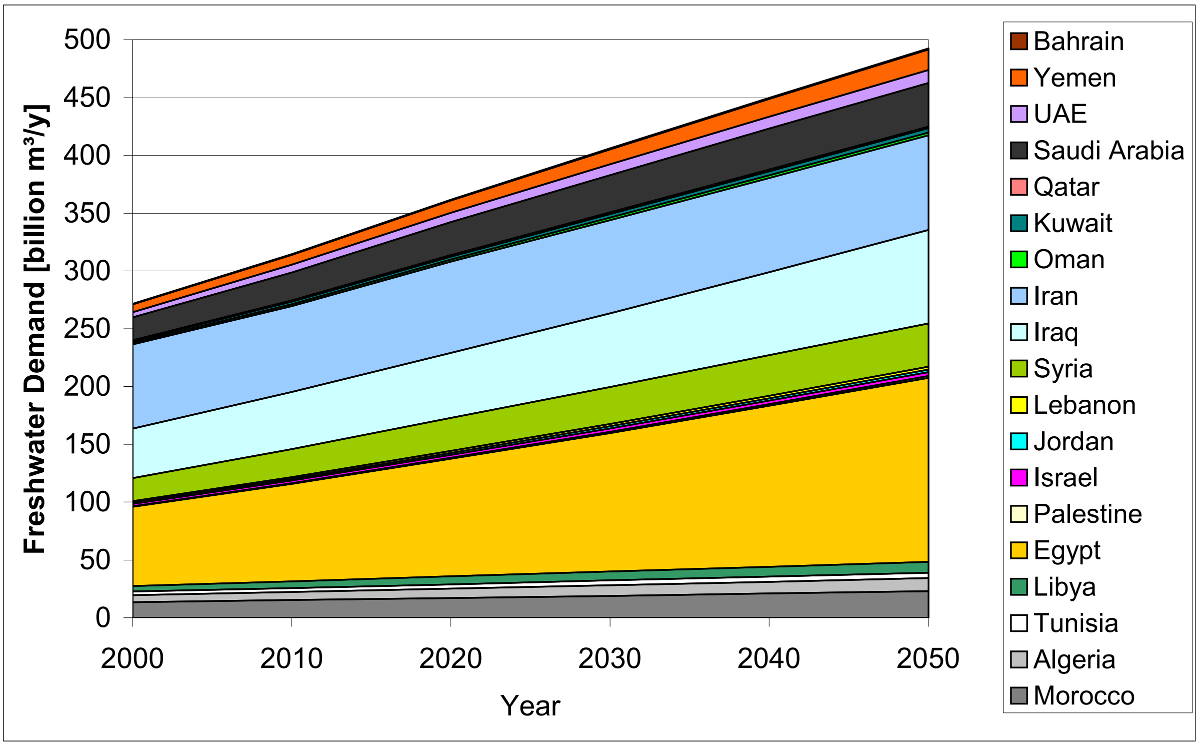

Figure 5: Freshwater demand derived from growth of population and economy considering increasing efficiency gains as described in the text.

Renewable Sources of Freshwater are Scarce

Our analysis shows the resources of fresh water on country level. Most of the actual data on water resources and use has been obtained from the AQUASTAT Database of the Food and Agriculture Organisation of the United Nations [10]. The following definitions have been used for the water balances:

- Renewable Water = Renewable Surface Water + Renewable Groundwater - Overlap
- Exploitable Water = Renewable Water · Exploitable Share
- Sustainable Water = Exploitable Water + Reused Waste Water
- Water Demand = Agricultural + Municipal + Industrial Demand
- Deficit = Water Demand - Sustainable Water
- Unsustainable Water = Deficit - CSP Desalination

  = Fossil Fuelled Desalination + Excessive Groundwater Withdrawal

In our model the amount of reused waste water is increased continuously from the present statistical values of each country 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 6 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. The difference of sustainable sources and water demand leads to the water deficit.

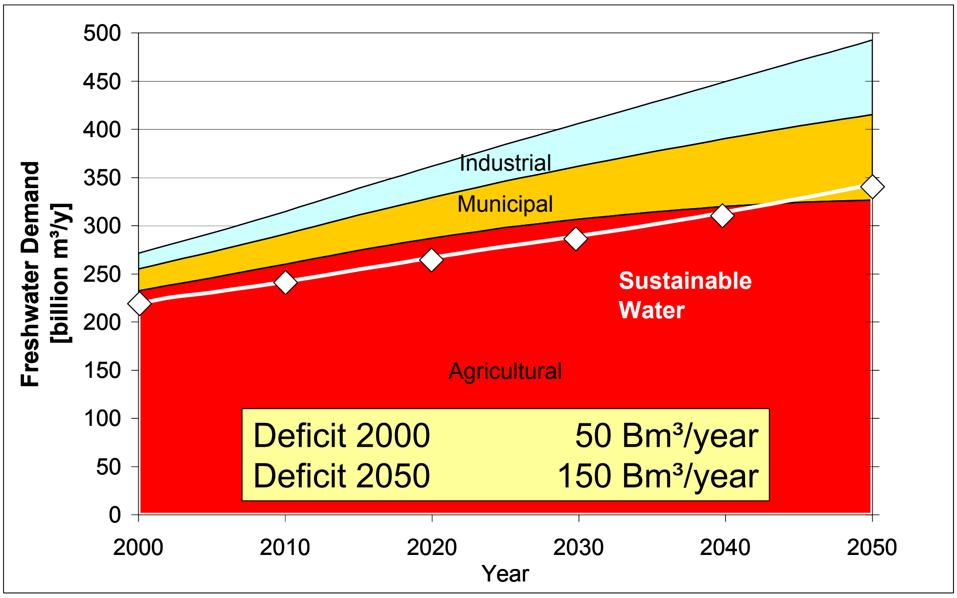

Figure 6: Industrial, municipal and agricultural freshwater demand in MENA in comparison to sustainable freshwater resources of the region (white line). The increase of sustainable water is due to enhanced re-use of water and to resources in some countries remaining untapped up to now.

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 falling groundwater levels, intrusion of salt water into the groundwater reservoirs and desertification in many regions in MENA. According to our analysis, this deficit tends to increase from presently 50 billion m³ per year, 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. Enhancement of efficiency of water distribution, use and management to best practice standards 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.

Such a possible additional measure can be concentrating solar power technology for seawater desalination. The following section will show in what time span solar energy could help to alleviate the water scarcity of the MENA region.

Concentrating Solar Power Potentials for Desalination

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. In the future, 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. However, we have not distinguished the individual potentials of the different renewable power technologies for desalination, but only their potential as a whole, and assumed that CSP would cover the whole, as it has the largest supply side potential for renewable energy in the region [4].

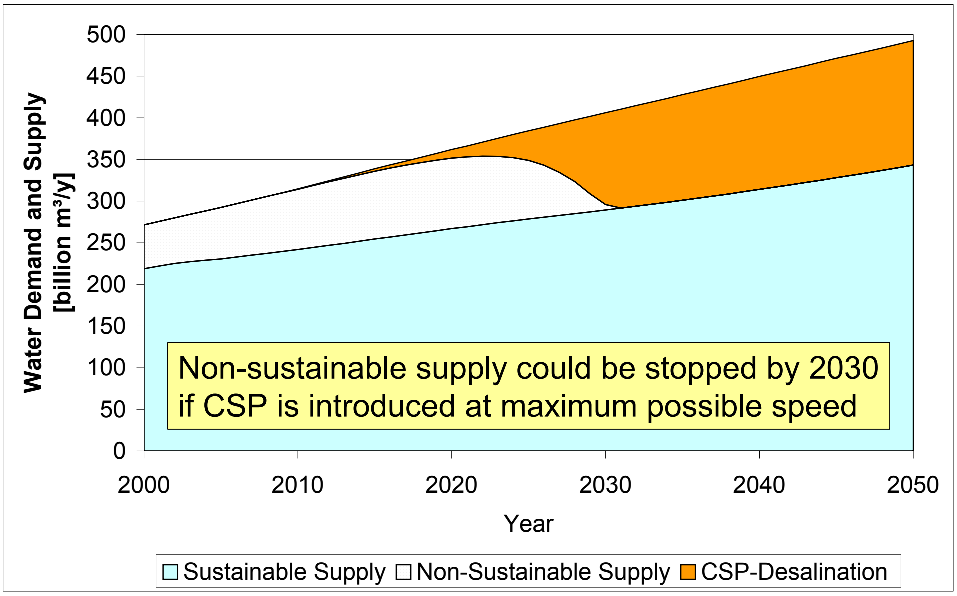

Figure 7: Water demand scenario for MENA until 2050 and coverage of demand by sustainable sources, by unsustainable sources and by solar energy.

In the time span from 2020 to 2030 the growing freshwater deficits could 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 (Figure 7). Until 2030, the increasing deficits will have to be bridged by fossil fuelled desalination and groundwater withdrawals, hoping that those resources will remain available and affordable until then. This may seem optimistic, but there are no sustainable and affordable alternatives. On the other side, 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 solution for the freshwater deficits in MENA that can be realized until 2030.

However, a considerable increase of non-sustainable use of water will occur in the meantime, with a maximum of 85 billion m³ per year between 2015 and 2025 (Figure 7). This calls for the intensive freshwater management and efficiency enhancement in urban and rural applications. Only a decisive employment and efficient combination of all possible measures will lead to a satisfactory and sustainable water supply in MENA. Seawater desalination with renewable energies is not an alternative, but only a complement to other measures to increase water efficiency as recommended by the United Nations and other organisations. The main factors for water sustainability are among others [11]:

- increase irrigation efficiency (from presently less than 40 % to 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.

Neglecting those measures would lead to a much higher deficit than shown in Figure 6. A sustainable supply can only be achieved in time if those measures are also realised with high priority [12], [13], [14]. To quantify the CSP potential for desalination, we have assumed in our model that all plants will be combined with multi-effect desalination, while the electricity generated is completely used for reverse osmosis. In view of the quick increase of water deficits in MENA, this may probably be necessary to avoid a severe overexploitation of unsustainable water sources. This model leads to a minimum installed (electric) capacity of CSP necessary to cover the future water deficits in MENA and to the maximum possible speed of expansion of this technology.

In MENA, the capacity of CSP plants until 2050 – if installed exclusively for seawater desalination – would amount to a total of 65 GW. North Africa (32 GW) has the largest potential for CSP desalination plants, followed by the Arabian Peninsula (25 GW) and the Western Asian countries (8 GW).

A CSP production of 115 TWh/y in 2025 and 550 TWh/y in 2050 may be used for desalination purposes. This will require 10 % of the existing coastal CSP potential. After 2030, the CSP desalination capacities will be large enough to cope with the freshwater demand and the solar desalination market will grow much slower.

Synergies of Water Desalination and Power Generation

Sustainable supply of water and energy are closely related challenges for the MENA region. If extended seawater desalination is a viable option to escape the threat of a water crisis, a sustainable source of energy will be required to power it. At the same time, the energy demand in MENA is growing with high rates, and a sustainable solution must be found for energy, too. In the past decades, fossil fuels from MENA have been the motor of the economic development of the industrialized countries of today. Just at the moment when MENA is starting to boost its economies, too, those resources are now found to be scarce, threatening climate stability and becoming increasingly unaffordable. Thus, MENA will probably be deprived from using those resources for its own economic development.

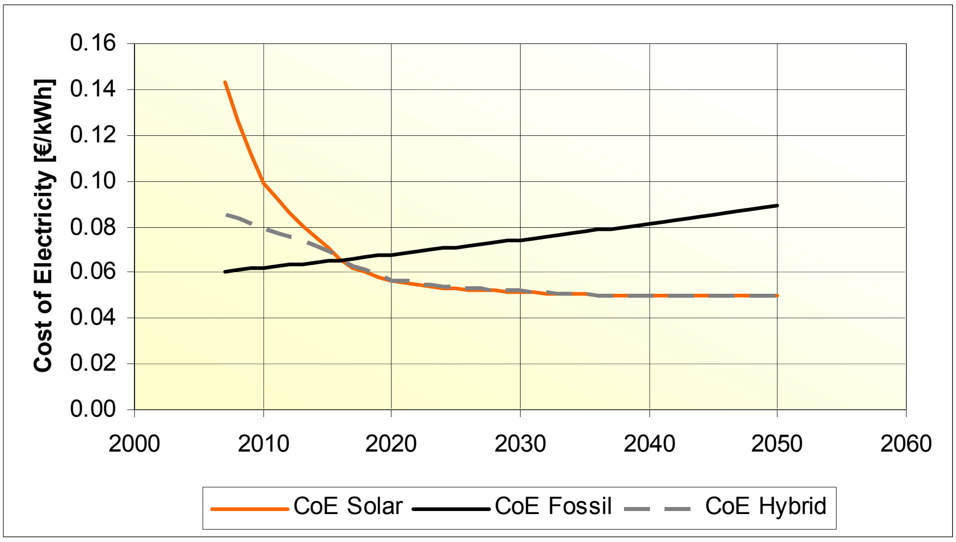

Figure 8: Cost of electricity from CSP plants versus gas-fired combined cycle power stations, 5 % project rate of return, 25 years life, 25 €/MWh fuel cost, 1 %/y escalation rate, irradiance 2400 kWh/m²/y [7]

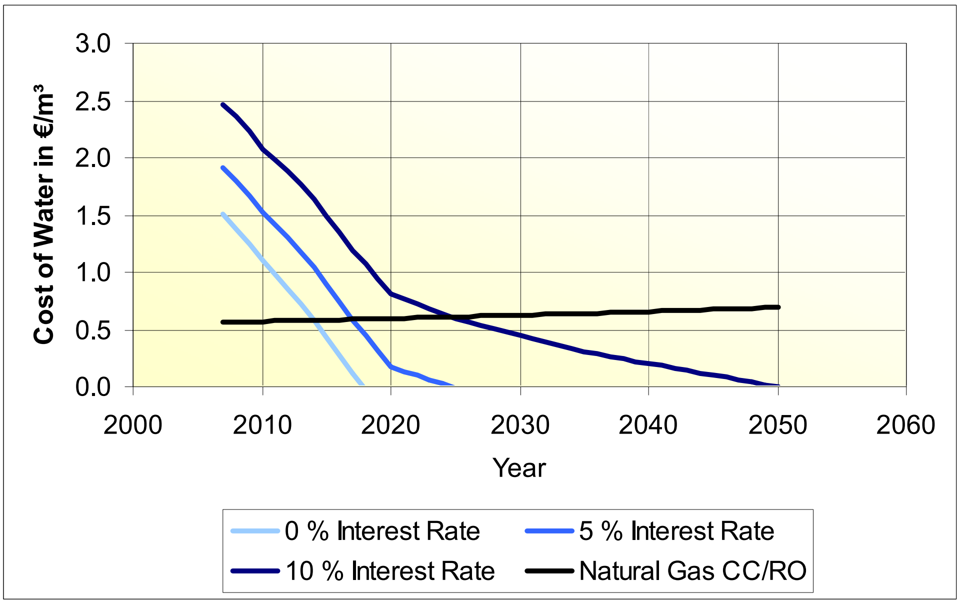

Figure 9: Cost of water desalted by concentrating solar power in cogeneration with multi-effect Seawater desalination according to Figure 3 (right) for 0%, 5% and 10% project rate of return, assumed revenue for electricity, 7500 full load hours per year, annual irradiance 2400 kWh/m²/y [7]

However, there are a number of different renewable sources in MENA like wind, hydropower, biomass and geothermal energy, and the solar energy potential alone has been found to exceed the total world energy demand by several orders of magnitude. Less than 1 % of the land area[3] would be required to power MENA in a sustainable way and in addition export solar electricity to Europe to supply 15 % of its demand by 2050 [15].

Underlying a scenario for the expansion of CSP technology in MENA (Figure 10), costs for concentrating solar collector technology will come down from presently around 300 $/m² turn key collector field cost to about 150 $/m² by 2015 and 100 – 120 $/m² by the middle of the century [4]. Considering also the introduction of thermal energy storage and the option of prolonging solar operation to base load, solar electricity costs from CSP will be in the long term as low as 0.04-0.06 $/kWh, depending on the solar irradiance of the respective site (Figure 8). This will compare very favourably with electricity from fossil fuels, namely combined cycle power stations using natural gas, that today have an unsubsidised cost around 0.06 €/kWh with increasing trend.

CSP plants producing both power and water can sell electricity at a competitive price and at the same time deliver water at the price shown in Figure 9. Shortly after 2015, water from CSP desalination will be considerably cheaper than water from conventional desalination powered by conventional fuels. In the medium term, it can achieve a price of less than 0.10 €/m³ that would be competitive even for irrigation. Until then, a series of pilot and demonstration plants of a total of 5000 MW capacity must be installed world wide to achieve the necessary economies of scale and cost reductions. The MENA region can participate significantly in this task with major benefits for the total region.

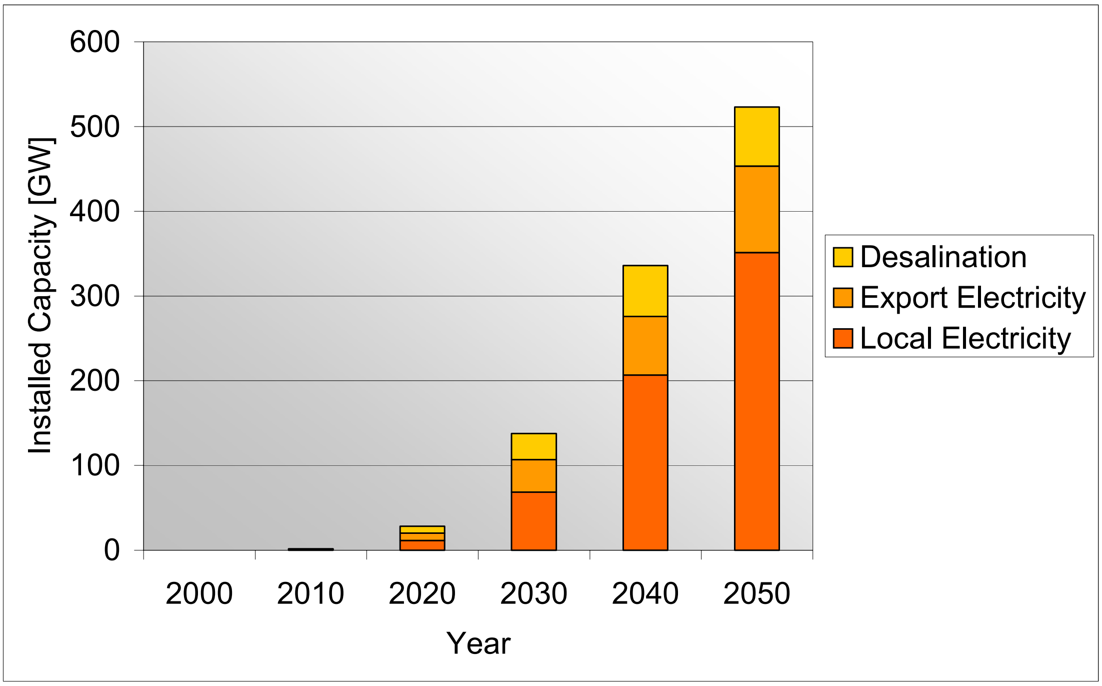

Figure 10: Scenario of market expansion of CSP resulting from different studies for local supply of electricity in Europe and MENA, for export of solar electricity from MENA to Europe and for seawater desalination in Europe [4],[7],[15].

[3] for comparison, Europe requires 1.2 % of its landscape for transport and mobility

Conclusions

Considering the severe consequences of a MENA wide water crisis that has never been faced before, and the long time that is necessary to build a sustainable alternative, the governments of MENA should immediately start to establish the necessary political and technological conditions for efficient water management and for a quick market introduction and expansion of CSP and other renewable energy sources for power and seawater desalination.

Seawater desalination based on concentrating solar power offers affordable, sustainable and secure freshwater potentials that are large enough to cope with the growing deficits in the MENA region. In fact, it is difficult to find any viable alternative to this concept.

However, starting with zero installed capacity in 2007, it will take at least 10-15 years until the CSP production capacities will be large enough to cope with the quickly growing water demand of the region. Even at maximum speed of market introduction of this concept and additional full implementation of efficiency measures, the unsustainable exploitation of groundwater cannot be ended before 2030. Even this is rather optimistic. However, a change to a sustainable supply is possible at least until the middle of the century if the necessary measures are decidedly initiated now.

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