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The Use of Renewable Energies for Seawater Desalination - A Brief Assessment

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1. Problem Overview

About 97.5% of the world's water resources is accounted for by saline seawater, which has an average dissolved solids (salt) content of 35 g/liter (brackish water: 7.5 g/liter), while the WHO standard for drinking water sets the maximum allowable level of salinity at 0.25-0.50 g/liter.[1] Of the remaining 2.5% of the water resources, a large part is locked up in ice caps and glaciers. Less than 0.5% of the Earth's water is directly suitable for human consumption.

The shortage of potable water in many regions around the world has different reasons. Strategies for improving the availability of fresh water range from the sustainable management of water resources to long-distance water transport. Desalination is a comparatively expensive technique focusing on the supply-side.

Despite its high costs desalination of brackish water and seawater has gained momentum in the last 50 years, notably in water-short parts of the arid Middle East, North Africa and the Caribbean, but also in the USA (California, Florida) and on the Canarian Islands.[2] In 1998 about 12,450 desalination plants with a minimum capacity of 100 m^3/day were in operation. The total installed capacity was 22.7 million m^3/day, of which 13.3 million m^3/day were accounted for by seawater desalination. Two-thirds of the large-scale applications are based on condensation technologies, while one-third use the reverse osmosis process.

The existing desalination plants in general use process steam from combined cycle power plants or electricity generated in simple cycle units. So far, renewable energies (solar, wind, geothermal, tidal) have played only a minor part in seawater desalination. Besides an unknown number of small-scale applications (< 5 liter/day), little more than 100 solarthermal desalination plants with a daily output of 20 m^3 or less were registered in the early 1990s.[3]

The largest share of the existing desalination plants is in the Middle East and in North Africa, where conventional thermal distillation techniques abound. Approximately 27% of the worldwide desalination capacity is installed in Saudi Arabia. The USA, which mainly use

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[1] This standard applies to Europe, the USA and Japan. In other regions water with a salinity content of 1 g/liter is considered as drinkable.

[2] "Scarcity of water" prevails if the annual supply of fresh water from domestic sources is below 1.000 m^3 per capita. The case where the annual supply falls short of 500 m^3 per capita is referred to as an "absolute lack of water". The physiological minimum amount of fresh water (per capita) is 3-4 liter/day. Per-capita consumption of water by households ranges from 55 liter/day (India) or less to 630 liter/day (USA). If industrial and agricultural users are included, the per-capita consumption of water varies from1.5 m^3/day (India) to 7.3 m^3/day (USA).

[3] http://www.unep.or.jp/ietc/publications/techpublications/techpub-8d/desalination.html

reverse osmosis plants to desalt brackish water, account for 12% of the worldwide capacity. While in the past most of the plants were built in the public sector, the recent trend is for private sector participation and public-private partnerships based on BOO (build-own-operate) and DBOO (design-build-own-operate) arrangements.

2. Conventional Desalination Technologies

The most common desalination technologies are[4]

- distillation, notably *multistage flash evaporation* (MSF) and *multi-effekt-distillation* (MED), as well as
- *reverse osmosis* (RO).

Both techniques are energy-intensive and costly. Under favorable conditions (large-scale plants with modern technology), the costs of conventional, fossil fuel fired desalination plants currently amount to 0.5-2.5 US\$/m^3.[5] Fresh water from easily accessible sources (surface water, wells) is considerably cheaper.

In this connection it should be borne in mind that in supplying fresh or desalted water to final users additional costs are incurred by transport and distribution facilities. For instance, transporting desalted seawater to areas that are far off the coast may be as expensive as supplying coastal regions with freshwater from inland sources. Moreover, in many developing countries the water tariffs are kept at a level that falls short of the total costs of supply.

MSF- and MED-Plants

In MSF-plants, which have been built commercially since the 1960s, the feedwater is boiled repeatedly (at temperatures of 100 - 110°C) in up to 40 stages without adding more heat, each stage operating at a slightly lower pressure than the previous one, so that the water flashes into steam and is then condensed to produce an almost pure distillate. Since the amount of thermal energy needed for distillation does not increase with the salt concentration of the brine, the process is well suited for desalting seawater. Notwithstanding this efficiency gain, the technology tends to be energy-intensive (see Table 1). MSF-plants are available in units of 4,000 m^3/day to 45,000 m^3/day.

MED-systems operate at temperatures of 63 - 80°C. The feedwater is sprayed onto the surface of evaporater tubes to promote rapid boiling and evaporation. This process takes place in a series of chambers, or effects (8-16), at progressively lower temperatures, using the vapor from one series to heat water in the next series. Compared with MSF, MED is less prone to operational problems with scaling and corrosion and has lower seawater intake requirements (50% of that of a similarly sized MSF). MED-plants are built in units of 2,000 m^3/day to 23,000 m^3/day. The investment costs of large MED-systems are 15-20% below the level of comparable MSF-plants. The advantages of MED explain that in the 1990s the installed MED capacity rose by 17%, while the increase in MSF was only 3%.[6]

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[4] Other known processes are: electrodialysis (a membrane process used in the USA to desalt brackish water), vapor compression distillation (occasionally used for small-to-medium-scale seawater desalination), and freezing (a process that has not been a commercial success).

[5] For brackish water the desalination costs of RO-plants with a capacity of 4.000 - 40.000 m^3/day lie in the range of 0,25 - 0,60 US\$/m^3 [3].

[6] IDA News, Volume 3, Issue 3-4 (March-April 2000), http://www.ida.bm/

⇒ *Both MSF and MED are rather energy-intensive distillation technologies, notwithstanding the recovery of process steam and the use of low grade heat from power plants. However, the technologies are fully developed, robust and commercially proven and are capable of producing a high-quality distillate from any kind of feedwater.*

RO-Plants

The RO-process, which was introduced in the 1970s, has developed to a technology representing the fastest growing segment of the desalination market. In RO, the feedwater is pumped at high pressure (55 - 80 bar for seawater) through permeable membranes, separating most of the dissolved solids (salt) from the water. Additional measures required by the process include the pretreatment of the feedwater (filtration, addition of chemicals) and, if need be, the removal of gases or bacteria from the product water. Comparative advantages of RO are the low energy requirements, the high share of recovered product water (up to 55%), the modularity of the systems, and the low unit investment costs.[7] Disadvantages are the sensitivity of the membranes to fouling, the high costs of maintenance and repair, the risk of disruptions in supply, and the lower product water quality (compared with thermal processes). However, advances in membrane and pretreatment technology have contributed to the increased use of RO.

⇒ *Compared with thermal distillation processes, RO consumes less energy and has lower investment costs. Even though the reputation of RO is still tainted by the risk of high operating and maintenance costs and concerns about the security of water supply, the market for RO-applications has been growing rapidly.*

Hybrid and Multi-Purpose Plants

Most of the desalination plants used in the Middle East and North Africa are integrated into multi-purpose projects with cogeneration facilities: Electricity is generated by a steam or gas turbine, while the desalination plant (MSF/MED) uses waste heat at the temperature level required for distillation. The advantage of this solution is that its energy efficiency is higher than would be the case if the heat and power were generated separately. A potential shortcoming, particularly with back-pressure turbines, is that the operation of the combined heat and power plant is constrained by the heat load (water demand) of the desalination process. Also, the power generated in combination with heat cannot be used efficiently by the MSF/MED unit.

Another option is to cogenerate steam for MSF/MED and electricity for RO; this would eliminate the reliance on a single desalination technology. It would also provide the opportunity to operate the MSF/MED-plant to meet base load water demand and to follow fluctuations in water demand with the RO-plant, while selling excess power to third parties or the grid [1].

Energy Consumption and Costs

Table 1 provides an overview of the specific energy consumption of different desalination technologies. Table 2 shows that the specific capital costs of large-scale desalination plants[8] (> 30,000 m^3/day) currently lie in the vicinity of 0.30 US$/$m^3$. On top of the capital costs, there will be fixed and variable expenses for operating and maintaining the plant (including replacement costs). Other costs

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[7] There are even small-scale units with an output of less than 10 m^3/day available.

[8] For smaller units (10 - 2,500 m^3/day) the specific investment costs may rise above 1,500 US$/$m^3$/day, with capital costs in excess of 0.5 US$/$m^3$.

not considered in Table 2 are the expenditures on feedwater supply, waste stream disposal (if relevant), and water transport and distribution.

Table 1: Specific Energy Consumption of Conventional Desalination Plants

Process	**Electricity (kWh/m^3)**	**Heat (MJ/m^3)**
RO	4.35 - 9.72	0
MSF	2.84 - 5.67	ca. 231
MED	2.03 - 4.05	ca. 197

Source: [2], [3], [8] , IDA News (http://www.ida.bm), and "World Water and Environmental Engineering" (May/June 2000)

Table 2: Specific Investment Costs for RO- and MSF-Plants (US$/m³/day)

Capacity (m^3/day)	**33,600**	**50,400**	**94,625**	**4 x 45,250**
RO Inv. Costs (US$/$m^3$/day) Saudi Arabia1) Tampa Bay2)	1222	1064	1005	
MSF-Inv. Costs (US$/$m^3$/day) Dubai3)				1250
Specific Capital Costs4) (US$/$m^3$)	0.32	0.28	0.26	0.31
Specific Desalination Costs5)	RO: 0.95 US$/$m^3$ (1.90 DM/m^3) MSF: 1.05 US$/$m^3$ (2.10 DM/m^3)			

1) lowest price offer April 2000 (IDA News, Volume 9, Issue 3-4; http://www.ida.bm)
2) http://www.wwinternational.com
3) mid-range price offer February 2000 (IDA News, Volume 9, Issue 1-2; http://www.ida.bm)
4) 5 % annual interest, 20 years lifetime, 90% (85%) plant factor for MSF (RO); not including capital costs of energy supply.
5) according to numerical example (see below).

Numerical Example: RO-Plant (30,000 m^3/day):

Assuming that the specific investment costs of RO amount to 2,500 DM/m^3/day, fixed annual expenditures on operation and maintenance (including replacement) are equivalent to 8% of the investment costs, energy consumption is 6 kWh/m^3 at 0.10 DM/kWh, the plant's useful life is 20 years (5% interest)[9] and the plant factor is 85%, then the specific distillation costs work out at 1.90 DM/m^3. The figure can be broken down as follows:[10]

Capital costs	0.65 DM/m^3	(34%)
Fixed O&M	0.65 DM/m^3	(34%)
Energy costs	0.60 DM/m^3	(32%)
Total costs	1.90 DM/m^3	(100%)

Numerical Example: MSF-Plant (45,000 m^3/Day):

Assuming that the specific investment costs of MSF amount to 2,700 DM/m^3/day, fixed annual expenditures on operation and maintenance (including replacement) are equivalent to 3% of the investment costs, energy consumption is 3 kWh/m^3 at 0.10 DM/kWh plus 230 MJ/m^3 at 3.80 DM/GJ (waste heat)[11], the plant's useful life is 20 years (5% interest), and the plant factor is 90%, then the specific distillation costs work out at 2.10 DM/m^3. The figure can be broken down as follows:[12]

Capital costs	0.66 DM/m^3	(31%)
Fixed O&M	0.25 DM/m^3	(12%)
Energy costs	1.19 DM/m^3	(57%)
Total costs	2.10 DM/m^3	(100%)

3. Seawater Desalination with Renewable Energies

Solarthermal Desalination

Simple *solar stills*, which operate in that the saline water is heated (70 - 90°C) by the sun's rays (humidification) with the condensate being collected as product water, produce 2.5-4.5 liter per m^2 of flat plate collector depending on the solar radiation and the plant's efficiency. The stills are available in modules for 5-8 liter/day and cost between US$ 490 and US$ 690.[13] Based on a collector price[14] of 700 DM/m^2 and a capacity of 4 liter/m^2/day, and assuming that the plant's useful life is 20 Years (annual O&M equivalent to 3% of the investment costs, 5% interest), the specific distillation costs work out at 52.86 DM/m^3.

Multi-effect-stills, which consist of collectors, a storage module and a desalination component, pass the feedwater through a number of evaporators an series without supplying additional heat after the first effect and, thus, have a higher gained output ratio than simple solar stills. A unit tested by the Bavarian ZAE on the Canarian Islands on average purified 12 liter/m^2/day.[15] ZAE reckons that mass production will reduce the costs of the desalination module from 30,000 DM/m^3/day to 15,000 DM/m^3/day. This would bring the total distillation costs down to 22.15 DM/m^3 (20 years lifetime, 5% interest, annual O&M equivalent to 3% of the investment costs).

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[9] Here and elsewhere it is assumed that the annual interest rate (opportunity costs) is 5% , reflecting the lending terms of the German financial cooperation. For market-based, commercial loans, however, the rate may lie significantly above 5% , thus resulting in higher capital costs.

[10] The figure does not include the costs of feedwater supply and waste disposal.

[11] If the heat is generated in a boiler, the costs would be 10 DM/GJ.

[12] Excluding the costs of feedwater supply and waste disposal.

[13] http://www.sunlightworks.com and http://www.primenet.com/~evsolar/prives.html

[14] Currently, flat plate collectors sell at 600 - 1,000 DM/m^2.

[15] http://zae4router.zae.physik.tu-muenchen.de/projekte/mwe/mwe.html

The German Fraunhofer Institute expects that the use of non-corroding polymer absorbers and the inclusion of thermal storage facilities for a 24-hour operation will further increase the still's output. The target is a daily production rate of 20 liter per m^2 of collector.[16] This would cut the total distillation costs below 20 DM/m^3.

The use *solar troughs* for desalination was tested mainly in the USA. Commercially available are small-scale units that combine the MSF process with steam-generating parabolic troughs: A typical plant uses 48 kW to produce 450 liter/day in three stages.[17] The collectors (about 45 m^2) currently cost about US$ 10,000, which translates into production costs of 7.90 US$/$m^3$ or 15.80 DM/m^3 (5% interest, 20 years lifetime, annual O&M equivalent to 3% of the investment costs, 85% plant factor). To this one has to add the costs of the distillation module.

Another disadvantage of solar-driven desalters is the huge collection area required for larger-scale outputs. For example, in order to supply 4,000 m3/day, a land area of 20 hectares (20 liter/m2) to 100 hectares (4 liter/m^2) would be needed. Where land is scarce, particularly in the vicinity of cities, the solar collection area requirements may considerably increase the desalting costs.

⇒ *In sum it can be concluded that the solarthermal desalination of seawater is a comparatively costly option that may take up large collection areas. Even under the most favorable conditions the distillation costs come near 20 DM/m^3. All units that are currently offered on commercial terms tend to have considerably higher costs. An advantage over conventional thermal desalting solutions is, however, that solar stills can be operated in small sizes to provide minimal amounts of water.*

Geothermal Desalination

At sites where drinking water is scarce and geothermal resources with temperatures of 80-100°C can be developed at acceptable costs (< 15 DM/GJ and < 3,45 DM/m^3, respectively), it may be appropriate to consider the option of geothermal desalination. However, such applications are in short supply. For reservoirs with higher temperatures there is also the option to generate geothermal power for use in a desalination plant (see below). But this does not alter the conclusion that the role of geothermal energy for seawater desalination is limited.

Power Generation with Renewable Energies

Another option that has recently caught attention is the use of renewable sources of energy for power generation to operate an RO-plant. The most promising candidates are wind and solar energy. Geothermal power projects, on the other hand, are limited to sites with developed or easily accessible reservoirs. And the worldwide potential tidal power generation is negligible; it roughly matches the annual power consumption in Germany.[18]

Power generation from renewable energies to operate desalination plants encounters two major problems:

- Power generation on the basis of renewable energy sources is comparatively expensive. Only wind turbines that benefit from favorable wind regimes and geothermal power plants supplied by low-cost reservoirs

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[16] http://www.ise.fhg.de/

[17] http://www.chatlink.com/~soltherm/desal.htm

[18] There is only one tidal power plant in operation (French Atlantic coast), and it is unlikely that additional units will be built in the near-to-medium term.

(see Table 3) are halfway competitive vis-à-vis fossil-fuel-fired power plants.

- Solar radiation and wind are intermittent, nondispatchable sources of energy. The operation of RO-plants, on the other hand, requires the supply of a constant load; fluctuating loads would wear out plant components; in particular, it would severely reduce the membrane life. Moreover, if wind and solar energy is used on a stand-alone basis, a constant power supply can only be maintained through energy storage or back-up systems, which would significantly increase the costs of this solution.

Table 3: RO-Plants Powered on the Basis of Renewable Energy

Energy Source	Power Generation Costs (DM/MWh)	Energy Costs of Desalination (DM/m^3)4)	Total Costs of Desalination (DM/m^3)7)
Wind1)			
4 m/s	240 - 530	1.45 - 3.12	3.00 - 4.67
6 m/s	100 - 130	0.60 - 0.78	2.15 - 2.33
8 m/s	60 - 70	0.36 - 0.42	1.91 - 1.97
Solar			
Photovoltaics2)	760 - 910	4.56 - 5.46	6.11 - 7.01
Solarthermal3)	410 - 570	2.46 - 3.42	4.01 - 4.97
Tidal5)	180 - 230	1.10 - 1.40	2.65 - 2.95
Geothermal6)	120 - 700	0.72 - 4.20	2.27 - 5.75
Conventional Power Plant	60 - 100	0.36 - 0.60	1.66 - 1.90

1) 1,900 DM/kW, 20 years, 5% interest, annual O&M equivalent to 4% of investment costs. The range of costs for a given average wind speed reflects different wind speed distributions.
2) 12,000-14,500 DM/kW, 20 years, 5% interest, annual O&M equivalent to 3% of investment costs.
3) Parabolic troughs; 6,500-9,000 DM/kW, 20 years, 5% interest, annual O&M equivalent to 3% of investment costs.
4) Excluding storage or back-up costs; the RO-plant consumes 6 kWh/m^3.
5) 3,500-4,600 DM/kW, 120 years, 5% interest, 25% plant factor, 5% interest, annual O&M equivalent to 6% of investment costs
6) 100-1,000 kW; 200-1,000 meter reservoir depth; 100°-140°C [7].
7) Energy- and fixed (capital) costs of RO. Fixed costs of large-scale RO with conventional power: 1.30 DM/m^3. Fixed costs of RO powered with renewable energy (< 2,500 m3/day): 1.55 DM/m^3 (3,000 DM/m^3/day, 20 years, 5% interest, annual O&M equivalent to 8% of investment costs, 85% plant factor).

Table 3 indicates that even in the absence of back-up and storage costs, power generated with renewable energies tends to be considerably more expensive than power supplied by a conventional, fossil-fuel-fired plant, thus resulting in comparatively high desalination costs.

⇒ *In sum it can be concluded that under current conditions power generation from renewable energies is not apt to reduce the costs of seawater desalination. Rather, technical design problems and high investment costs associated with power plants based on renewable energy sources will make RO-distillation more expensive.*

4. Conclusions

- Seawater desalination in itself is an expensive process, but the inclusion of renewable energy sources and the adaptation of desalination technologies to renewable energy supplies is in most cases a particularly costly and uneconomic way of providing water.

- The utilization of conventional energy sources and desalination technologies, notably in conjunction with cogeneration plants, is still more cost-effective than solutions based on renewable energies and, thus, is generally the first choice.

- The use of renewable energies for thermal desalination can be justified only in niches (e.g. in the presence of cheap geothermal reservoirs) or in decentralized applications focusing on small-scale water supply in coastal regions (e.g. village communities), provided the ability and willingness to pay for desalting is sufficiently large.

- Wind-powered desalination in small RO-plants (10 -2.500 m^3/Day) located at sites with an exceptionally good wind regime may be competitive vis-à-vis conventional solutions (e.g. diesel-based desalination) if cheap back-up or storage facilities are available. What may also prove a feasible option is the use geothermal power from cheap reservoirs in coastal areas to desalt seawater in RO-plants. Solar power, on the other hand, is currently too expensive to generate to be a viable alternative to conventional power generation for seawater desalination.

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