Solar thermal powered desalination: membrane versus distillation technologies

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Multiple Effect Distillation (MED) is generally considered to be the desalination technology most suited to integration with concentrating solar thermal collectors on a medium to large scale. However the cost and energy requirement of Reverse Osmosis (RO) have fallen significantly in recent years, so that solar thermal powered RO deserves consideration. We compare commercial desalination processes on the basis of their electrical and thermal energy consumptions, their recovery rate, and plant capital cost. Three experimental systems of potential interest are also identified. The daily desalinated water output per square metre of solar collector area is estimated for a number of system configurations. Depending on parameters such as feedwater salinity, the output from solar powered RO is much higher than that of solar powered MED. Performance metrics and units found in desalination literature are described.

1. INTRODUCTION

The global capacity of desalination plants has been increasing at a rate of nearly 12% since the early 1970's, and was over 25 gigalitres per day by the year 2000 (Rostek, 2003). Desalination processes consume large amounts of energy, so that there is an impetus towards developing renewable energy powered processes at the medium to large scale; Garcia-Rodriguez (2002) reviews the progress towards that goal. As part of a project investigating the possible use of solar energy in remediation of dryland salinity, a critical review of the literature on medium to large scale solar driven (or assisted) desalination has been conducted. Solar thermal driven Multiple Effect Distillation (MED) has been proposed in a number of studies (e.g. Garcia-Rodriguez et al, 1999; Sagie et al, 2001; Trieb et al 2003), and by manufacturers (Rotem, 2005; IDE, 2005), and has been trialled on a demonstration scale (Milow and Zarza, 1996; Blanco et al, 2002). Thermal (or distillation) desalination processes are generally regarded as most suited to integration with concentrating solar thermal concentrating collectors on a medium to large scale. However the cost of seawater desalination by Reverse Osmosis (RO) in large installations has fallen significantly in recent years, due to reductions in capital and operating costs, and optimisation of system performance (Wilf and Bartels, 2005). As a consequence RO is been chosen in an increasing share of new installations, such as the proposed Sydney desalination plant (GHD Fichtner & Sydney Water, 2005), and solar thermal powered RO deserves reconsideration.

2. DESALINATION PERFORMANCE METRICS

In reviewing the literature on desalination a lack of uniformity in units and terminology is apparent. Inconsistencies within a single report or paper are not uncommon, and often relate to the rating of desalination plant performance, in terms of the volume of water produced for the energy consumed. The two most commonly encountered performance metrics for desalination systems are the Gained Output Ratio (GOR) and the Performance Ratio (PR), which are discussed below.

2.1. Gained Output Ratio (GOR)

The GOR is a dimensionless ratio, used for thermal desalination processes, defined either as an energy ratio or a mass ratio. As an energy ratio it is usually defined as the ratio of the total latent heat of evaporation of the product water to the input thermal energy (e.g. Koschikowski et al, 2003):

$$GOR = \Delta h_{evap} \dot{m}_{product} \Big/ \dot{Q}_{input} \quad (1)$$

Koschikowski et al (2003) use the value for the latent heat corresponding to the inlet temperature to his system's evaporator (75 ºC, L = 2325 kJ/L). More commonly an approximate value, L = 2.3 MJ/kg is used; if the density of water is taken as ρ ≈ 1000 kg/m^3, then the GOR is related to the specific thermal input Q/V in kWh_{th}/kL by:

$$Q/V = 640/GOR \quad (2)$$

An alternative definition of the GOR, often used by manufacturers, is as the ratio of the mass of distillate to the mass of input steam (e.g. World Wide Water, 2005). This definition makes no allowance for the actual operating conditions (the steam temperature and pressure). It also effectively uses the total heat content of the input steam, rather than the heat transferred, as it ignores the heat content of the product and reject water flows.

Neither of the definitions of the GOR take into account the plant electrical energy consumption, which can be quite large (up to 4.5 kWh_e/kL for an MED system, see Table 2). The GOR also does not take into account any system efficiencies external to the desalination plant proper, such as boiler efficiency, or heat losses through piping from the heat source.

2.2. Performance Ratio (PR)

The Performance Ratio of a desalination system can be defined as the as the ratio of the mass of distillate to the energy input (Buros, 2000). As the ratio is not dimensionless the mass and energy units affect the numeric value of the PR, some of the different conventions are listed below.

a) The Performance Ratio in metric units is often defined as the number of kg of water per megajoule of heat input (e.g. Rostek, 2003)

b) The performance ratio can alternatively be defined as the number of kg of distillate per 2,300 kJ heat input (e.g. Milow and Zarza, 1996). This ratio will be 2.3 times larger than the performance ratio in kg/MJ, and is equivalent to the GOR. The electrical energy input is not included.

c) The performance ratio in British units is defined as the number of pounds of water per 1000 Btu energy input. This will be approximately 2.2 times the metric value in kg/MJ, and will approximately equal the (dimensionless) GOR, as the latent heat of evaporation of water is ~1000 Btu / lb.

d) Manufacturers commonly define the performance in terms of a mass or volume of product water per kg (or lb) of steam (e.g. IDE, 2005). As with the steam mass form of the GOR, this definition of the PR is only approximate as it does not take into account the operating conditions. Generally the steam input is relatively low pressure and temperature and the latent heat of vaporisation (~ 2.3 MJ/kg) can be used as the approximate energy input.

e) A dimensionless Performance Ratio is used by El-Nashar (2001). His (implicit) definition is actually that of the GOR, as a ratio of latent heat of product water to thermal energy input.

As a final comment, if heat recovery from the brine stream is employed, some authors consider that the performance ratio of the desalination plant proper is unchanged (e.g. Garcia-Rodriguez et al, 2002), whilst others use the net energy consumption to calculate the PR.

3. DESALINATION TECHNOLOGIES

The most commonly used desalination technologies are shown in Table 1, classified according to their operating principle. Reverse Osomosis can be further subdivided into Brackish Water RO (BWRO) and Seawater RO (SWRO); the distinction is useful as the operating parameters are quite different in the two cases. Vapour Compression can either be in the form of Mechanical Vapour Compression (MVC) or Thermal Vapour Compression (TVC), which is most often found as the final stage in a MED plant.

Table 1 Major desalination technologies (URS, 2002)

Distillation	Membrane
Multistage Flash (MSF)	Reverse Osmosis (RO)
Multiple Effect Distillation (MED)	Electrodialysis Reversal (EDR)
Vapour Compression (VC)	

Detailed discussions of the costs, advantages and applicability of the different technologies can be found in a number of reports (e.g. Rostek, 2003; URS, 2002; Buros, 2000). The following are some of the most important points of comparison:

- Distillation technologies have a higher total energy consumption than membrane (even when allowance is made for electricity generation efficiency)
- The performance of distillation technologies is relatively unaffected by feedwater salinity
- For low salinity feedwater, membrane technologies have a higher rate of recovery

Table 2 summarises some parameters for selected technologies. MSF is not included as although it still represents a major share of the worldwide desalination capacity, it is being supplanted by MED and VC in new thermal based systems (URS, 2002). Garcia-Rodriguez (2002) discusses the advantages of MED over MSF for solar thermal driven desalination.

Table 2 Operating parameter ranges for selected desalination systems

	BWRO	SWRO	EDR	MED	MVC
Electrical energy kWh_e/kL	0.5 - 2.0	≤3.0 - 4.5	≥0.6[1]	1.1 - 4.5	8 - 14
Thermal energy kWh_{th}/kL	Nil	Nil	Nil	25 – 165	Nil
Recovery rate %	75-85	30-60	≥80	20-65	40-50
Capital cost $A/(L/day)	0.65 - 1.05	1.30 - 2.13	0.60 – 1.10	2.80 - 5.67	3.47 - 4.00

Comparison tables of desalination technology parameters can be found in many reports, often with little referencing or explanation of the source data. The dangers of an uncritical use of tables of performance data are exemplified by GHD (2003, pii), where a table gives the range of capital and operating costs of different technologies. These implicitly cover a wide range of plant sizes, but are in fact based on a table and data in URS (2002) which relate to very specific examples. For instance the RO plants considered are only between 5 and 50 kL/day capacity and hardly likely to provide representative figures for > 1 ML/day installations.

Sources for the energy consumptions and recovery rates in Table 2 are: Rostek (2003), Milow and Zarza (1996), Blanco et al (2002), NSW Dept. of Commerce (2003), and URS (2002). The thermal energy consumption of MED is explicitly given in units of kWh_{th}/kL as some sources quote much lower values (e.g. GHD, 2003), which appear to represent an electrical energy equivalent of the thermal energy use. That is, for a dual purpose power generation and MED plant, the reduction in electrical energy generation compared to a power only plant is considered to be the MED energy consumption. The values given are indicative only as they depend strongly on factors such as the size, type and age of the plant, and the feedwater and site characteristics. They are also interdependent; for example the recovery rate can be optimised against energy consumption (Wilf, 2001, 2005), or can be improved by having extra stages, which increases capital cost.

Capital costs in Table 2 are derived from graphs in Rostek (2003), converting from US$ prices using an exchange rate of 1 AUD = US $0.75. The values for each technology represent the variation due to plant capacity, within the range 4-20 ML/day, as well as due to other possible differences in

[1] Rostek (2003) gives the electrical current requirement as 0.53 kWh/kL per 1000 ppm TDS reduction in salinity, for 21ºC feedwater. To this must be added the electrical energy for (low pressure) pumping.

configuration (e.g. the number of stages or efficiency of the plant). They are claimed to be accurate to ±30%, and are based on year 2000 data. The costs are higher than found in some other references (particularly for MED); this is mainly due to their (appropriate) inclusion of items such as pre and post-treatment facilities, buildings, intake system, and construction overheads. The MED basic "process construction cost" (desalination plant, interstage piping, pumps and controls, cleaning system and electrical distribution) is only around 50% of the total construction cost. With a dual purpose MED and power plant a fraction of the steam generation capital cost is sometimes allocated to the desalination facility (Rostek, 2003).

3.1. Experimental solar desalination systems

A number of experimental and prototype solar desalination systems have been constructed, where the desalination technology has been designed specifically for use in conjunction with solar thermal collectors, either static or tracking. To date such systems are either of very low capacity, and intended for applications such as small communities in remote regions, or else remain unproven on a larger scale. Three systems which are of some interest are discussed.

Desalination tower

Schwarzer et al (2001) describe a simple system which has flat plate collectors (using oil as a heat transfer fluid) coupled to desalination "towers" in which water evaporates in successive stages at different heights. The condensation of vapour in one stage occurs at the underside of the next stage, transferring heat and increasing the gain output ratio. The technique has the advantage that there is continuous water flow through the stages, which prevents a build up of salt. They estimate the system output using a theoretical model; based on their data the GOR is 3.3 if the incident solar radiation is used as the energy input. If the GOR was calculated using the heat input to the tower, i.e. making allowance for thermal inefficiencies in the collection system, (which is analogous to the normal practice for desalination plants) it would be ~ 4. The system has the advantage that intermittent operation does not cause maintenance problems or significant loss of efficiency. The concept could possibly be adapted for use with a high temperature steam solar power plant, functioning both as a cooling tower and a means of desalinating some water, although the volume would be quite small.

A very similar system (not mentioned by Schwarzer), called a "stacked plate still", is described by Fernandez (1990). It also consists of a series of vertically layered evaporation trays also coupled to flat plate collectors. More experimental detail (including operational problems) is given than in Schwarzer.

Vari-RO Solar Powered Reverse Osmosis

The Vari-Power Company, based in California, has developed an RO based desalination system which is specifically tailored to solar thermal input (Childs et al, 1995, 1999). A patented direct drive engine (DDE) converts heat to the hydraulic power required by RO. A projected overall solar to hydraulic energy efficiency of 25% was claimed in 1999, with the system having an energy input requirement of 2.1 kWh/kL. Desalinated water production using the DDE is projected to be more than 3 times greater (for an identical dish collector) than that which would be obtained by RO driven by a dish-Stirling electricity generation system or PV power. The project remains at the pilot stage with the DDE not commercially available: it has perhaps become less attractive due to the advances in conventional RO.

Aquadyne Solar Powered Vapour Compression

The Australian branch of the American company Aquadyne has formed a partnership with the CSIRO to develop a solar powered desalination unit, based on Aquadyne's "JetStream" Mechanical Vapour Compression Distillation process (Aquadyne, 2005). Little technical detail is available about the project; it is believed that the intention is to use solar steam to generate shaft power for MVC. An Aquadyne MVC unit is to be installed at the CSIRO QCAT facility in Brisbane for development and testing.

4. CONCENTRATING SOLAR THERMAL DRIVEN DESALINATION

The average daily product water output per square metre of collector area can be used to compare solar driven desalination processes. We estimate the output for different technologies driven by two-axis tracking concentrating collectors (dishes) with direct steam generation, located in the vicinity of Mildura, Victoria, Australia (lat -34.2º S, long 142.1º E). This site has a daily average direct beam radiation on a tracking surface of 22.1 MJ/m^2. As steam turbine thermal to electric efficiencies vary greatly with size (as little as 15% for turbines under 1 MW, and more than 40% for very large units), the output is calculated for two different values of turbine efficiencies for the electrically powered processes.

The electrical output per unit area of solar collector, E_e/A, can be calculated from:

$$E_e / A = I_{dir,d} \eta_{optical} \eta_{receiver} \eta_{transport} F_A \eta_{t-e} \quad (3)$$

where $I_{dir,d}$ is the daily direct normal radiation in MJ/m^2/day; $\eta_{optical}$ is the dish optical efficiency, allowing for reflection and other optical losses; $\eta_{receiver}$ is the receiver efficiency, which allows for thermal losses in converting concentrated radiation to steam in the receiver; $\eta_{transport}$ allows for heat losses from the steam lines; F_A is the plant availability factor; and η_{t-e} is the turbine thermal to electrical efficiency. Values used are: $\eta_{optical}$ = 0.85, $\eta_{receiver}$ = 0.85, $\eta_{transport}$ = 0.96, F_A = 0.97. Steam turbine efficiency is usually quoted at full load; however a solar generation system will often be operating at part load, if the steam operating point is not maintained by an auxiliary fuel. Hourly weather data for Mildura for a complete year (1981) was convoluted with the load curve of a small steam turbine (data obtained from IPS Australia, 2005), using a linear relation between steam flow rate an insolation. Whilst this represents a rather crude model, it is preferable to applying the full load efficiency to part load conditions. The result was an average solar to electric conversion which was 80% of the full load value. Hence in applying Equation (3) for two scales of operation with full load efficiencies of η_{t-e} = 0.15 and η_{t-e} = 0.30, we use effective values of 0.12 and 0.24 respectively.

Table 3 Daily average electrical outputs versus turbine efficiency for Mildura, Australia.

Turbine full load efficiency	Electrical output kWh/m^2
0.15	0.50
0.30	0.99

Table 4 and Table 5 give the desalinated water obtained per unit area of solar collector, for different desalination systems, for the specified full load turbine efficiencies. Note that the outputs from EDR and BWRO are also strongly dependent on the feedwater salinity; the calculation has been done for brackish water with < 2,000 ppm TDS. The MED output is obtained by assuming a steam turbine configured for combined heat and power (CHP) operation, with total energy conversion of 90% relative to the steam input, and would represent an upper range estimate. The solar input for two-axis tracking is again used, even though single-axis tracking parabolic troughs may be a more economic arrangement for driving an MED plant.

Table 4 Desalinated water output per solar collector area, η_{t-e}=0.15 (except MED)

Process	Energy input kWh/kL	Output L/m^2/d
MED	30_{th} + 2.0_e	116
MVC	8.5	58
EDR	1.0	496
BWRO	1.0	496
SWRO	3.5	144

Table 5 Desalinated water output per solar collector area, η_{t-e}=0.30 (except MED)

Process	Energy input kWh/kL	Output L/m^2/d
MED	30_{th} + 2.0_e	116
MVC	8.5	117
EDR	1.0	991
BWRO	1.0	991
SWRO	3.5	283

For desalination on a medium to large scale (so that η_{t-e} = 0.30 would apply), solar Reverse Osmosis is more than twice as productive than either distillation technology for seawater desalination, and for low salinity feedwater the result is even more clearcut. BWRO is on a par with EDR, but the latter is usually only chosen in specific circumstances relating to feedwater impurities or the need for the highest possible recovery rate (Rostek, 2003). For small or demonstration scale solar desalination ($\eta_{t\text{-}e}$ = 0.15) the specific outputs for SWRO and MED are comparable, and a choice between them could not be made on the basis of this criterion alone.

The result for solar MED can be compared to Garcia-Rodriguez et al (2002), who considers a number of different solar collector configurations, driving an MED (or MSF) plants with intrinsic GOR of 10 (so Q/V = 64 kWh_{th}/kL) plus a heat pump with COP = 2. No mention is made of electrical energy consumption. For parabolic troughs with direct steam generation they calculate outputs of 100-190 $L/m^2/d$ for a site at Izana, Spain, and 50-80 $L/m^2/d$ at Madrid (the insolation levels are not stated). An experimental comparison is provided by the solar trough driven MED plant, using oil as the working fluid, at the Plataforma Solar de Almeria (PSA), which achieved only 27 $L/m^2/d$ (value derived from data in Milow and Zarza, 1996). A number of factors account for the low PSA specific output: the energy consumption of the MED plant was high (63 kWh_{th}/kL plus 3.3 kWh_e/kL; it was later reduced to 36 kWh_{th}/kL plus 2.9 kWh_e/kL due to system improvements); the collector field was oversized in relation to the MED plant; and there were energy losses in thermal storage and heat transfer.

Of the experimental solar desalination systems previously mentioned, the Vari-RO process is said to have an electrical energy consumption of 2.1 kWh/kL for seawater feed (Childs, 1999), which would place its specific output between that of BWRO and standard SWRO. Aquadyne (2005) claim a projected output of 500 L/m^2 in a media release, but no details of the design, insolation levels or operating conditions are given.

The output per collector area is not a definitive guide to the best technology, as it does not take into account reliability and maintenance needs and relative capital costs. Neither has any detailed consideration been given to how the desalination plant could be run at a steady operating point; for example if the desalination is electrically driven how to the solar plant generating capacity would be sized so as to optimise the overall economics. The choice of the RO desalination plant capacity depends on the daily and seasonal variations in solar radiation levels, on the buying and selling prices for electricity, and on the weight given to fossil fuel displacement. A conceptual layout for a solar dish based system with power generation and RO desalination is shown in Figure 1.

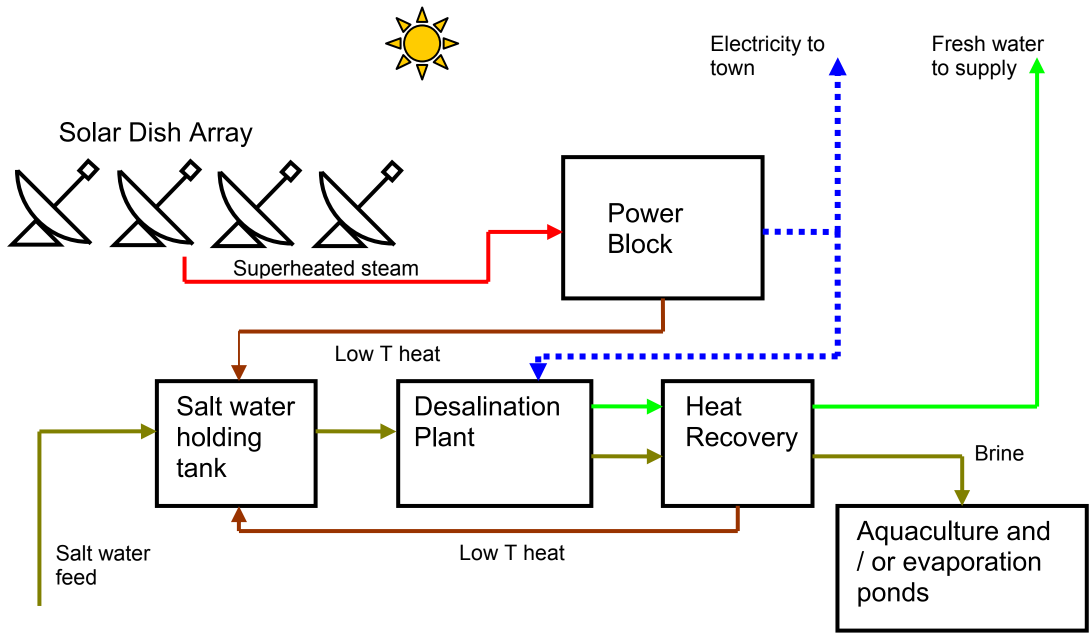

Figure 1 Combined dish based solar thermal power generation and RO desalination.

The low temperature waste heat is shown as an input to the feedwater as a reduction in RO energy consumption is achieved if the feedwater temperature is raised (but only up to a limit which is determined by the membrane characteristics and other operating parameters). A modification of this arrangement is described in Rostek (2003): steam is used primarily to power a steam turbine and generate electricity, but is also extracted from the turbine (at reduced pressure and temperature) and used to drive a booster pump, which provides part of the RO high pressure pumping demand.

Sagie et al (2001) compare three desalination options: (i) direct use of the heat from solar thermal collectors to power MED plants (possibly with fuel backup); (ii) using a solar thermal plant to produce electricity which powers Reverse Osmosis; (iii) RO driven by fossil fuel generated electricity. Although his comparisons are highly dependent on assumptions made about parameters such as the cost of thermal storage, fuel, and electricity, it is notable that for a small capacity plant (1 ML/day) solar-RO is found to be 20% cheaper than solar-MED.

5. DISCUSSION

A thermal desalination technology, such as Multiple Effect Distillation (MED), seems the most obvious choice for integration with solar thermal collectors. However the need for thermal storage and a backup heat source increases the cost and complexity of a complete system. Depending upon the scale of operation and the feedwater salinity, the specific output from solar-MED can be much lower than for membrane processes. Studies of solar thermal powered MED have generally concluded that such a configuration would only become cheaper than fossil fuelled desalination at quite large scale, or in special circumstances (such as remote locations where fuel is very expensive). A more detailed analysis of solar driven Reverse Osmosis is required to determine its costs and applicability.

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