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Environmental Technology & International Affairs

Desalination Technologies for Future Water Supply of Arid Zones under Emphasis on the Solar Thermal Potential

A Master's Thesis submitted for the degree of
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supervised by

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Affidavit

I, **OLIVER FISCHER**, hereby declare

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Abstract

The world is facing a massive water distribution problem which implicates that many areas on the globe cannot provide a sustainable livelihood for the people living over there. Anthropogenic global warming is expected to even aggravate the water scarcity in arid zones which is very likely to cause severe social and political problems for their people. To prepare arid zones to remain liveable or to again become so, political and technical solutions for their sustainable water supply under consideration of natural environment and traditions of residents have to be implemented.

Since the technical processing of water needs a considerable amount of energy, which in large-scale installations mainly comes from fossil fuels, the imperative of energy efficiency lead to the development of new generations of plants, which either combine energy generation with freshwater production or utilise renewable energy sources, especially solar power to run their processes.

The continually rising freshwater demand mainly concerns areas already suffering from aridity or zones which are threatened by gradually increasing drought, whereas most of exactly these regions are on the other hand blessed with abundance of solar radiation. This implicates the logic conclusion for such zones to utilise the potential power the sun provides as far as possible. And in the context with the processing of freshwater this conclusion then involves the idea to emphasize on solar powered water desalination technologies which in fact is a major focus of the present paper.

The state of the art of technical water treatment solutions to supply regions of water scarcity shall not just be presented here in regard to its future prospect, but moreover proven conventional technologies shall be compared with reasonable solar powered alternative solutions.

One major focus of this study is dedicated to the development of a solar thermal powered modular desalination system which was invented to provide a simple low-cost technology for freshwater production even capable for remote area installation. Still in the beginning of scientific research the outcomes and suggestions presented here shall facilitate further development and testing of the first prototypes of this system, presumably not just foreseen to operate in single module arrangement but also in interconnected combination allowing for performance increase and heat losses reduction.

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1 Introduction

There is a massive water distribution problem on earth, where some regions get far more water than they can use while other territories have much too little to provide a sustainable livelihood for their people. Anthropogenic global warming is expected to even aggravate the water scarcity in arid zones which is very likely to cause severe social and political problems for their people, or in the last resort starvation. All of these water scarcity problems anyway will result in mass emigration.

To prepare arid zones to remain liveable or to again become so, political and technical solutions for their sustainable water supply under consideration of natural environment and traditions of residents have to be implemented.

Since the technical processing of water needs a considerable amount of energy, which in large-scale installations mainly comes from fossil fuels, the price for treated water actually depends on energy cost and the efficiency of the plant. This lead to the development of new generations of plants, which either combine efficient energy generation with freshwater production or utilise renewable energy sources, especially solar energy to power their processes.

The continually rising freshwater demand mainly concerns areas already suffering from aridity or zones which are threatened by gradually increasing drought, whereas most of exactly these regions are on the other hand blessed with abundance of solar radiation. This implicates the logic conclusion for such zones to utilise the potential power the sun provides as far as possible. And in the context with the processing of freshwater this conclusion then involves the idea to emphasize on solar powered water desalination technologies which in fact is a major focus of the present paper.

In the following the state of the art of technical water treatment solutions to supply regions of water scarcity shall not just be presented without comparing proven conventional technologies with a reasonable solar powered alternative under providing a prospect for future solutions. But, when looking at the huge dimensions of present large-scale fossil powered desalination installations it shall also be analysed to which portion solar energy could replace such technologies. Whereas to cope with the gradually increasing demand for freshwater it can be assumed that like for future power production the conventional technologies will still have to supply a large principal share of the market. In this context earlier investigations by Johansen et al. (1996) pointed out that for satisfying the increasing water demand the technology of seawater desalination in combination with efficient power production probably would make most sense, under further arguing that especially in arid zones with rising population and therefore need for electricity the ‘fresh’ potable ground-water would be consumed faster than being replenished.

Coming back to the high energy input necessary to process water from seawater which is eased by the fact that in the poor countries most concerned by gradual increasing aridity the per capita water consumption makes just a small fraction of the consumption of an average industrialised country. This fact is illustrated in Figure 1.1 taken from the 2006 Human Development Report of the United Nations Development Program (2006), where the water demand of several countries is exemplarily compared. Roughly one could say that in average a developing country inhabitant actually consumes not more than a tenth of the water than a person in the industrialised world.

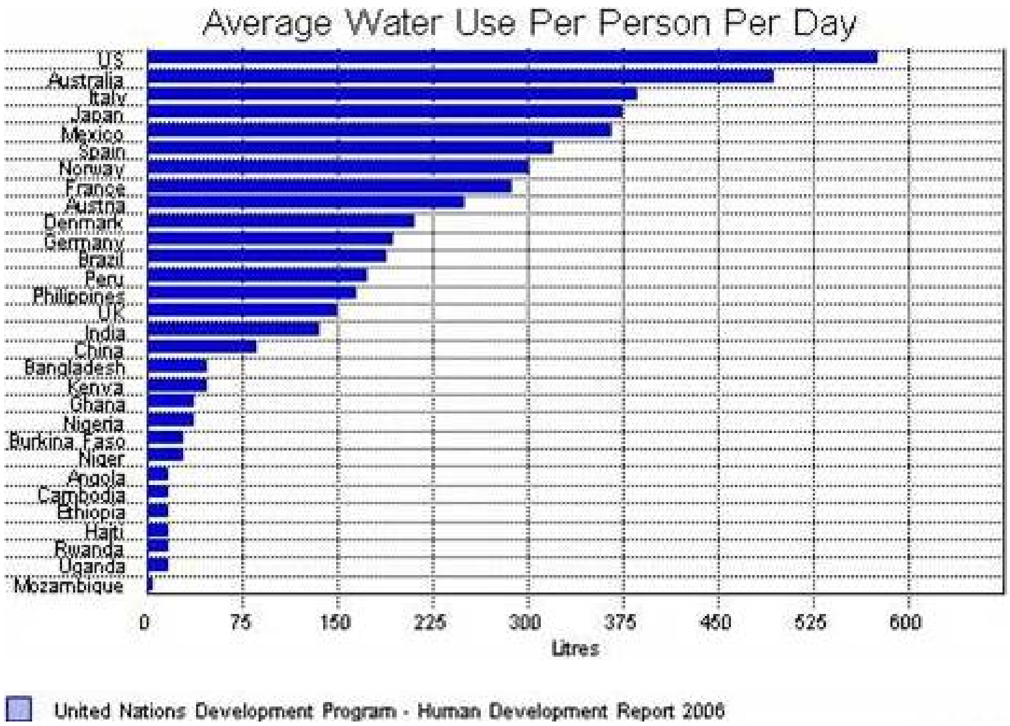

Figure 1.1 : Average daily world water use per person in 2006
(UNDP, 2006)

When hypothetically installing a seawater processing plant in a developing country, and even if it would be fired by fossil fuels, the small per capita water usage would therefore implicate just a small per capita carbon impact. Besides the carbon reduction mechanisms proposed by the Kyoto protocol (United Nations, 1998) to mitigate climate change could compensate such an impact for the benefit of all parties involved in such a potential investment project.

However as long term target power generating technologies based on renewable energy should be prioritised anyway, where as previously mentioned solar powered water processing solutions provide the most reasonable technologies for the future freshwater supply in arid zones.

2 Current Desalination Trends and the Role of Energy

2.1 The Need for Large-Scale Water Solutions

In the last 20 years the capacity of freshwater produced by desalination plants more than doubled each decade and cumulated to a daily production of around 40 million m³ in 2009. Correspondingly the number of installations rose dramatically in that period to more than 11000 units today, with individual capacities from less than one m³ per day to almost 1 million m³ per day. Figure 2.1 illustrates this tremendous increase from the very first installation in 1945 up to 2004 as recorded in the biennial report on the World's Water (Gleick et al., 2006). Due to the almost infinite availability of seawater the by far main portion of desalinated water is produced therefrom and nearly all huge-scale installations naturally are processing sea water.

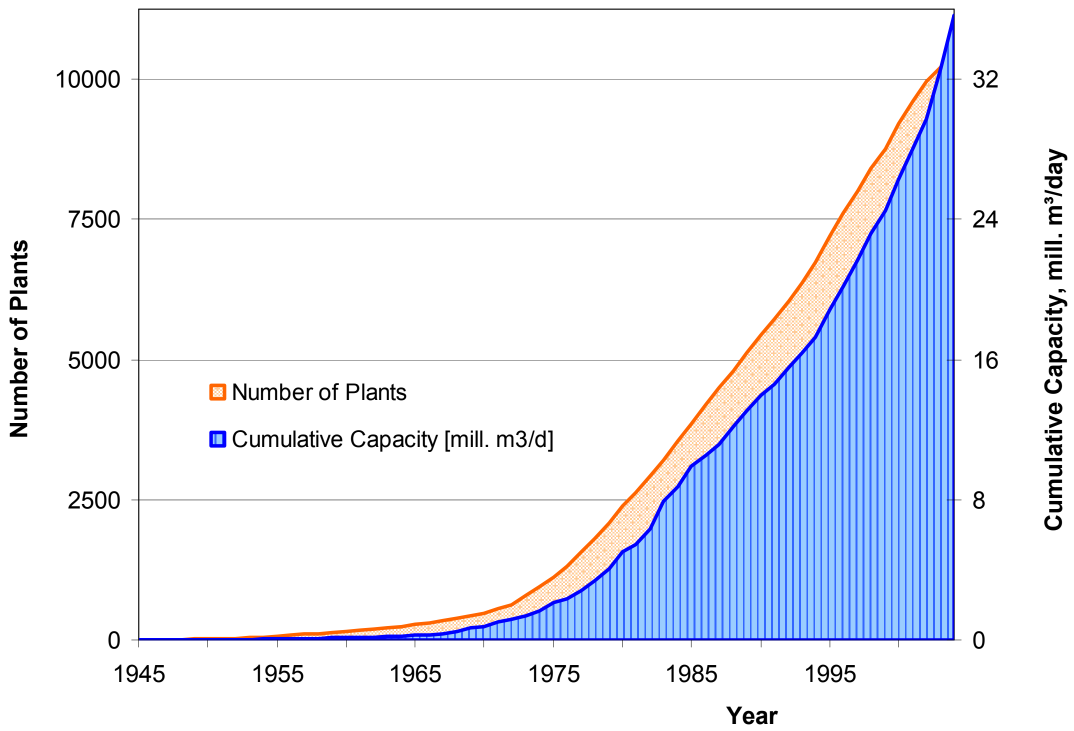

Figure 2.1 : Cumulative Installed Desalination Capacity, 1945 to 2004
(data from Gleick et al., 2006)

Currently the huge yearly increase in seawater desalination is primarily powered by the hugest large-scale plant projects of enormous capacity and their trend to steadily become bigger yet. Relying on data from 2005 (Gleick et al., 2006), the report on the World's Water analysed in this context that less than one percent of the desalination plants worldwide, in sum around 70 units out of over 10,000 installations in total, were responsible for almost half of the global desalination capacity, while the other more than 50 percent of all desalination capacity would come from around 99 percent of those plants individually producing less than 100,000 cubic meters of freshwater per day. Moreover, the vast majority of desalination installations that operated in 2005, namely more than 90 percent, belonged to the smallest capacity range of up to 5000m³ of daily water production.

Figure 2.2 illustrates the described uneven distribution of the global water production capacity on a wide scale range of desalination plants, which again massively differ in number.

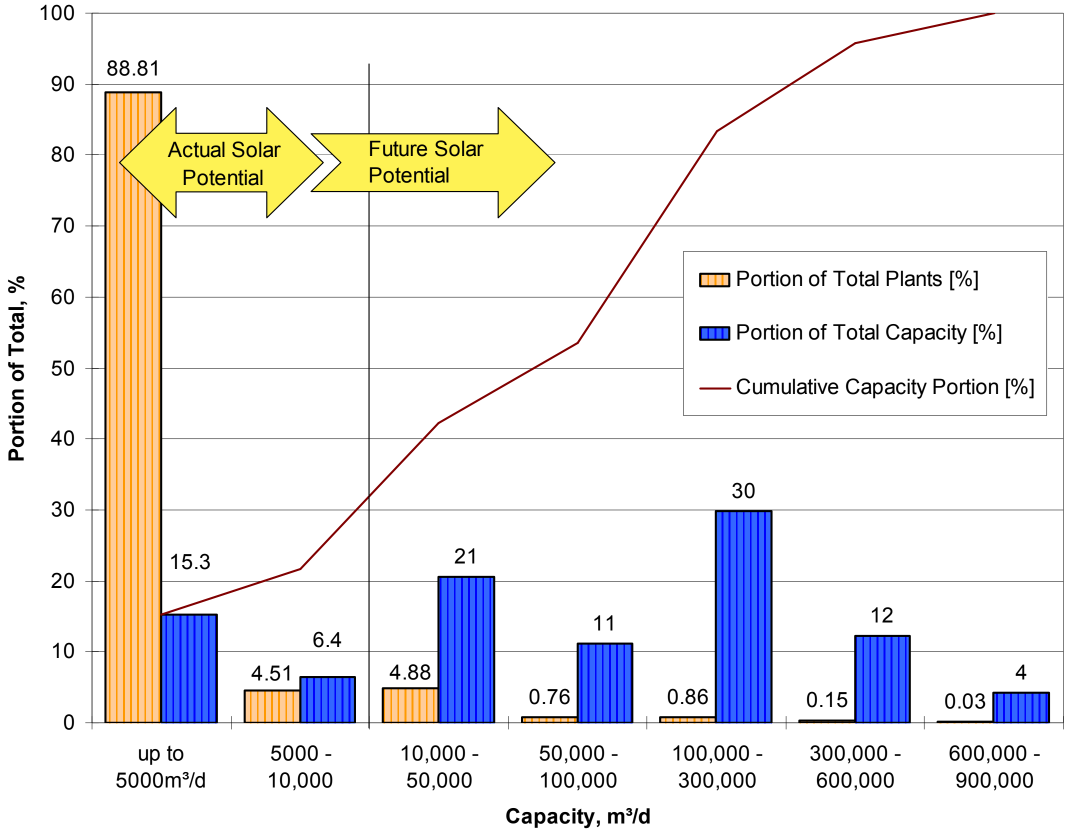

Figure 2.2 : Global Desalination Plants and Capacity (Status January 2005) (data from Gleick et al., 2006)

Huge in number but small in total capacity on the global scale the mentioned small-scale plants of up to around 5000m³ daily freshwater production nowadays provide the greatest potential for the implementation of solar desalination processes as illustrated by Garcia-Rodriguez (2007). In particular he mentions indirect solar desalination, the combination of solar collector technology with a desalination process, representing the most promising and most developed systems today. Currently such plants are already widespread for communal use in arid regions, especially in MENA[1] countries, while direct solar systems utilising direct solar evaporation with succeeding condensation, like solar stills are rather confined to smallest-scale individual applications (Ettouney and Rizzuti, 2007).

Although solar desalination is already widely-used in the small-scale plant sector and is, as Figure 2.2 shows potentially applicable for a diurnal water production up

[1] MENA: Middle East and North Africa

to 10000m³ per unit, it however makes only a small contribution to the global water production from seawater. In 2002 its portion was just 0.02% (Lindblom, 2003), and since then has rather decreased when considering the large number of huge-scale plants realised in the last years, as detailed next.

To cope with the mentioned steady rising water demand in regions of looming water shortage which usually result both from economic growth and from advancing aridisation due to climate change or mismanagement, the recent seawater desalination installations primarily are of the hugest dimension type with capacities far above 100,000 m³ per day. As reported by Gleick et al. (2006) most of these plants were recently installed in the Middle East and can produce up to almost a billion m³ of water each day. Naturally the huge energy demand of such plants accounting for some hundred megawatts can only be provided by fossil fuel input as analysed in the coming section.

Concluding for the next future with its prospected rising demand for water in arid zones one can in fact expect a boost in solar powered desalination solutions. However the main portion of rising production capacities will still have to come from conventional fossil fuel powered plants. Otherwise, for inland installations far from the sea, to process brackish or waste water, solutions of smaller magnitude will be usual and here the solar component will in turn significantly gain its share on the market.

Looking a little further into the future, new larger-scale high tech solutions utilising already known technologies like collector mirrors of parabolic, paraboloid or similar design (Trieb et al., 2007) to concentrate solar radiation certainly will establish in parallel to arrangements combining such solar design with wind power. With this rather realistic prospect in some years the renewable powered desalination sector will allow for single unit production capacities above 10,000 m³ of freshwater per day as outlined in Figure 2.2.

2.2 The Considerable Energy Effort for Desalination

Because of its high consumption of primary energy the preparation of water by desalination may be a controversial subject in the global energy debate. However its application is confined to arid zones, where in many cases without managed supply of water to feed communities and their agricultural production a sustainable life in these regions would not be possible. But when it comes to the energy debate one should distinguish the effort to process water by desalination simply essential to provide individual livelihood and potential use as luxury good in emerging or already rich economies.

The high power demand for desalination of water implicates a direct link between the applicable processing technology and its primary energy consumption. With it, in the context of fossil fuel consumption and its limitation targeted by global climate change policy also the source of energy to be provided gains in importance. As previously mentioned the majority of desalinated water is produced by large capacity plants of more than 10,000 m³ of daily water production which generally are powered by fossil fuels (2.1). But also for the smaller-scale applications today this fuel source is still dominant despite the numerous plants already operating by means of solar irradiation the potential for alternative energy usage is still enormous.

Depending on the processing technology the specific electric energy consumption of a large-scale state of the art seawater desalination plant varies between 2 and 5 kWh per m³ produced freshwater (Abu-Arabi, 2007). There the pure membrane desalination technology accounts for the higher value, while thermal processes indeed require less electric power but additional thermal energy of around 3 kWh/m³ for modern high efficient technologies (3.6). However it should be considered that small plants often cannot operate at efficiencies comparable with the huge high tech systems and therefore their specific power consumption may even exceed 15 kWh/m³ as Abu-Arabi (2007) reveals.

To get an impression for the huge overall power consumption for desalination and to estimate the potential for a solar powered alternative Ettouney and Rizzuti (2007) suggested following comparison. They exemplarily took the overall daily freshwater production of Kuwait amounting to around 1.92 million m³ per day and assumed that all water would be produced by thermal desalination with an average electric power consumption of 4 kWh/m³. Then under continuous 24 hours operation the electric energy to provide would result to

$$1.92 \cdot 10^6 \ \mathrm{m^3/d} \cdot 4 \cdot 10^{-3} \mathrm{MWh/m^3} \ / \ 24\mathrm{h/d} \ = \ 320\mathrm{MW} \ ,$$

an effort which is in the output range of an average modern natural gas fired combined cycle power plant. In addition thermal energy of a similar magnitude has to be provided as afore mentioned.

If the thermal energy alone would be generated by means of solar energy, a tremendous surface area of around 16 km² would be required. The estimated electrical power effort, if provided by photovoltaic technology then would take another around 6 km² of solar irradiation surface area. A detailed estimation of these area requirements is presented in section 3.1.

2.3 Introduction into the Current Desalination Technologies

In this section some of the major current desalination technologies shall be introduced including their practical field of application for commercial operating desalination plants. Providing the by far hugest share for the world freshwater production the branch for seawater desalination dominates as mentioned (2.1).

Looking at the conventional desalination technologies it can be summarised that today basically two major principles are implemented on a commercial scale, thermal distillation processes and membrane processes, where the most prominent processes in the first mentioned group are multi-stage flash distillation, multi-effect distillation and mechanical vapour compression, while in the second one reverse osmosis and electrodialysis dominate (Blanco et al., 2007). There the range of application is divided in that way that thermal processes are only economically feasible for the desalting seawater, whereas membrane technologies are practically applied for both brackish and seawater.

Currently only two processes, reverse osmosis and multi-stage flash distillation take up 80% of the market as figured out by Blanco et al (2007), where the first has extended its share on the market significantly in the last decade to slightly dominate it today showing that this emerging technology can come up with high efficiency desalination providing low cost in water production as compared later (Figure 3.7).

Additionally when comparing thermal and membranes desalination it can be argued in favour for the membrane technology that with these mechanical processes the freshwater production in relation to the raw water input, referred to as the freshwater conversion rate is in general significantly higher than for any current thermal processes. As compared next in the context with membrane processes characteristics these figures may even double when for example deciding for reverse osmosis instead of thermal technology. Besides others, this fact is an important argument when comparing the electrical pumping power required for transporting the raw water.

When looking at the total global water production the share of desalination installations using solar power is still small (2.1), despite the fact that numerous solar desalination plants are already in operation today, however those rather belong to the small-scale dimension of modest daily output, while the large-scale market is just served by conventional powered types. There are several solar water processing technologies both thermal powered ones and photovoltaic applications where the most important ones for commercial use are briefly presented in coming section 2.3.2.

2.3.1 The Established Thermal Desalination Processes

For large-scale desalination there are practically only two thermal processes in operations, the multi-stage flash desalination (MSF) and the multi-effect desalination (MED) as briefly presented next. Although the first pushed out the latter due to higher expectable efficiencies in the nineteen sixties (Blanco et al., 2007), today the established long-term operational experience of MSF is competed by the advantage of lower temperature operation provided by MED technology especially when such applications are used in combined applications with energy production (Mahbub et al., 2009). Such Combined Water and Power Plants are described in following chapter 3, where besides fossil powered technology even solutions driven by solar power are gradually emerging on the market (3.3, 3.4). The renewed interest in MED even caused that this technology is currently both technically and economically competitive with large-scale MSF processes Blanco et al. (2007).

The design principles of these two thermal desalination processes are briefly explained in the following not just for allowing their comparison, but to provide a widely studied and established technological base for potential application of the appropriate design ideas for the development of the modular desalination system being presented in chapter 4 of this document.

Multi-Stage Flash Desalination

In the multi-stage flash desalination (MSF) process the incoming seawater firstly runs inside a tubing passing through all increasingly warming desalination stages to be continually preheated prior to entering the proper heating chamber where it is superheated before it again moves back successively through the evaporation chambers of these stages, entering each under release of heat by evaporation, the so-called flashing. There the vapour condensates on the preheating tubes under releasing its latent heat of condensation which again heats up the seawater before the condensate is collected as produced freshwater. This heat recovery returns a huge amount of energy into the process as described later (3.2), an amount providing the essential argument to make this technology economical reasonable. Figure 2.3 shows a simplified scheme of the described MSF process.

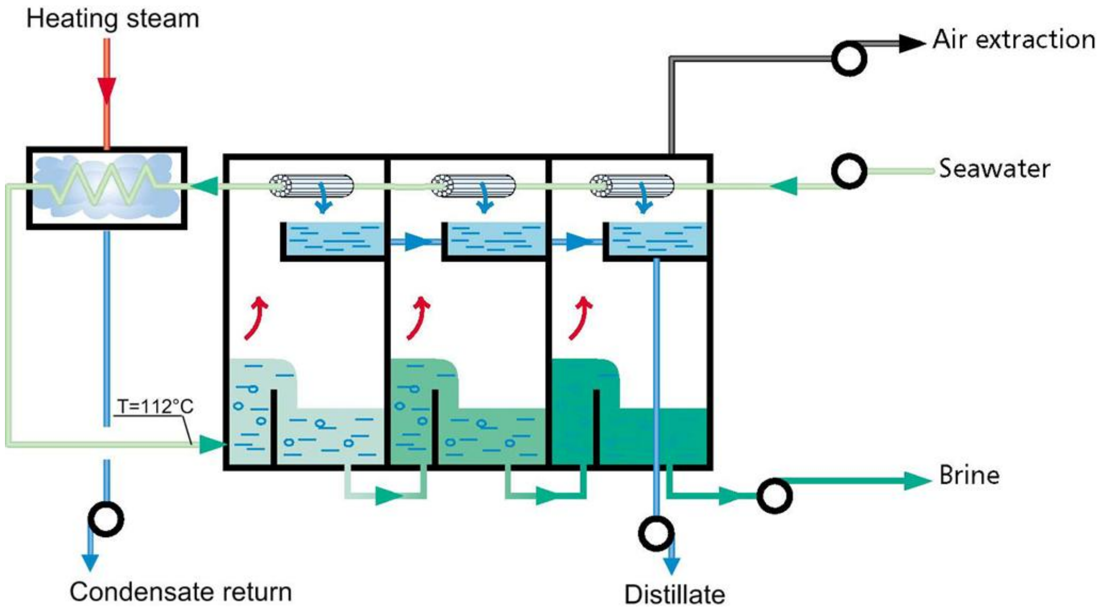

Figure 2.3 : Principle of a multi-stage flash distillation
"Once-through" desalination process (Sidem, 2010)[2]

During operation the consecutive stages are maintained not only on differing temperature levels, continually changing from one evaporation chamber to the next, but an air extraction additionally cares for evacuation to provide continually decreasing pressure from the hottest stage to the coldest, in order to promote evaporation even in moderate temperatures by lowering the water vapour pressure. Finally, the liquid water when passing each stage consecutively gains in salinity before being collected as resting brine in the last chamber of lowest temperature.

Multi-Effect Distillation

Desalination by use of multi-effect distillation (MED) is different to described MSF because of already sprinkling preheated seawater into each consecutive evaporation chamber and providing the hottest stage with external energy to promote evaporation of the introduced water. This vapour then leaves by piping to the next stage of slightly lower temperature and pressure to be condensed over there under supply of its released latent heat of condensation into the chamber to again promote vaporising of the water sprayed in here from the top. In detail on its way down this water creates a falling film on the condenser tubing where it partly evaporates and partly continues to the bottom with increased salt content to form the brine (Trostmann, 2009).

[2] http://www.sidem-desalination.com/en/process/MSF/

Both vapour and condensate leave the respective stage, the former to again condense in the neighbouring chamber, the latter to be collected as freshwater. Like in the MSF process also here the recovery of the huge potential of latent heat is the ultimate figure to run this process efficiently with regard to economic reasonability. Figure 2.4 shows the simplified scheme of the MED process.

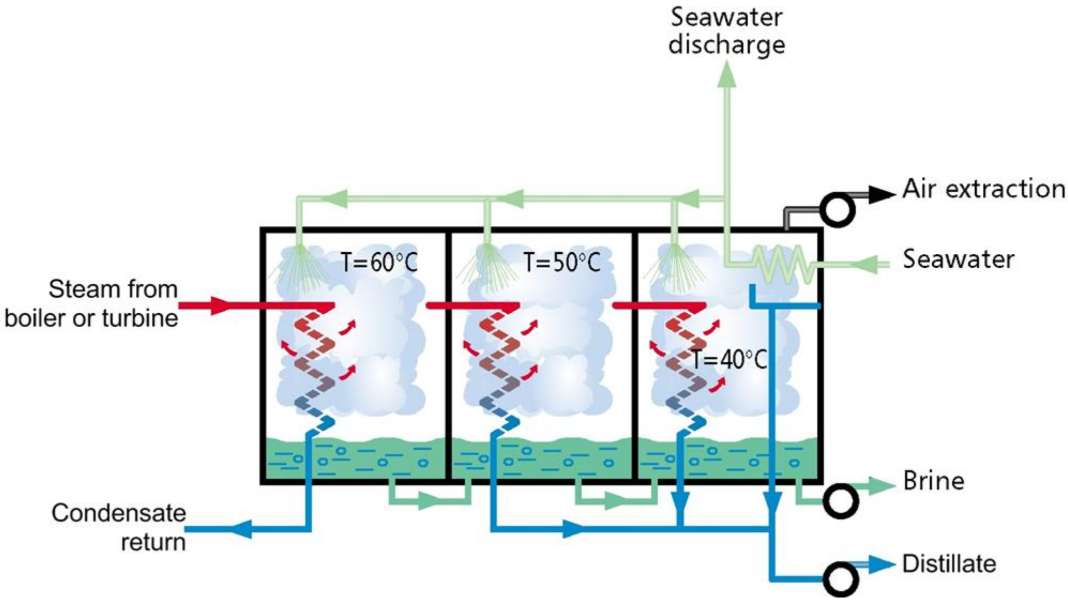

Figure 2.4 : Principle of a multi-effect distillation
The MED Evaporator (Sidem, 2010)[3]

Also in the MED process an air extraction cares for consecutive evacuation of the stages to provide decreasing pressure from the hottest stage to the coldest, in order to promote evaporation by reducing the water vapour pressure. The resting water of each chamber finally flows to the next stage under increasing its salinity before being again collected as brine when having passed the final stage of lowest temperature level.

The Rising Importance of Multi-Effect Distillation

Today the MED technologies on the thermal desalination market is rising, as previously mentioned mainly because this technology can operate at lower temperatures than MSF processes. This makes it attractive not only to operate in combined applications where process heat not usable elsewhere can be used to power the MED (Mahbub et al., 2009), it increasingly becomes more important when rethinking the application of renewable energy sources to run freshwater production plants.

As explained by Trieb et al. (2007) MED technologies can operate at process temperatures below 70°C, whereas MSF processes otherwise require a temperature

[3] http://www.sidem-desalination.com/en/process/MED/Process/

range between 90 and 120°. This low temperature application possibility provides a huge potential to run MED for example by solar thermal processes or in combination with them as presented in section 3.4. With such a prospect this technology is very likely to further gain importance for future water processing.

The Established Membrane Processes

In this section just reverse osmosis (RO) as being by far the most prominent membrane process for water desalination shall be briefly introduced. As mentioned the market share of RO has expanded in the last decades because of installations using this technology require less total energy input than the established thermal processes. However this energy has to be provided entirely by electricity, because electrical driven pumps of high power have to apply a considerable hydraulic pressure which allows the water to penetrate the appropriate filter membranes, which more or less is already the functional principle behind this technology. In the RO process namely the applied pressure is the driving force for mass transport through the membrane, where the operation pressure shall exceed both osmotic pressure and the filter pressure drop at the RO membrane (Cath et al., 2006).

The resulting product then is the separated freshwater with, worth to be mentioned in this context, a significant lower portion of rejected brine than with any thermal desalination process. Trieb et al. (2007) actually mention that freshwater conversion rates of RO plants can be between 20 and 50 %, depending on the technology. This means in the best case under high-tech applications only 50 % brine may be rejected. Otherwise thermal processes have a freshwater conversion rate between 10 and 25 % in case of MSF and between 23 and 33 % in case of MED. These figures, as previously mentioned are an important argument when comparing the electrical pumping power required for water transporting, which is one of the major electric efforts to be provided for thermal desalination processes.

And besides, this brine rejection may also be a source of massive energy loss when exemplarily taking up to 90 % accumulated brine amount being rejected by an MSF process at temperatures between 90 and 120°C (4.3.3).

In conclusion it can be argued that RO processes shall preferably be applied in cases where the amounts of rejected brine can not easily be discharged or where their discharge will cause environmental problems. This especially appears for brackish water treatment installations far away from any brine discharge possibility, whereas at plants close to the sea today this salinity enriched process water is sent back to the sea.

2.3.2 Current Solar Desalination Technologies

Commercial operating solar desalination plants often use the same processes as large-scale solutions like the above described ones, just the freshwater output of the installations then will generally be some magnitudes smaller. Actually both thermal and membrane technologies are applied for solar desalination, where the former are commonly of MSF and MED process type, while RO installations serve the latter. For the power supply of mentioned processes the solar energy input may either be transferred as heat to an operating medium for further conversion, be directly converted into electric energy by means of photovoltaic, or as simplest solution be directly used for local installations. Besides, thermal storages like solar ponds or storage tanks are used to balance diurnal lacks of solar energy, while simple modular thermal processes like solar stills provide for additional local solutions (Ettouney and Rizzuti, 2007).

When looking at the production rates of solar desalination systems one can find similar figures compared to large scale desalination if comparable technological refinement has been put into, which in case of thermal processes will be multiple stage operation or combination with heat storage systems. In comparing recent thermal desalination processes Ettouney and Rizzuti (2007) found a production rate range between 20 and even 50 % for some well engineered small-scale solar applications. Blanco and Alarcón (2007) present a good example of an actual solar water processing installation in southern Spain where a multistage MED process is powered by solar collectors to arrive at a production rate of almost 40 % under provision of 3 m³ fresh water per hour under design conditions. This example is further introduced in succeeding section 3.4.

Expectable freshwater amounts produced by solar thermal desalination systems lie between 10 litres and around 40 litres per m² of irradiated surface area and day (Ettouney and Rizzuti, 2007), whereas these figures logically depend on the solar irradiation itself which even sets the upper limit by the solar constant as explained later (3.2). A more detailed comparison of such performance data under different solar conditions is presented in section 4.3.2 in the context with the development of a solar desalination module.

Smaller-scale solar freshwater processing systems today are preferably installed in zones without sufficient power supply, often in remote areas and often far off the sea, which makes them rather attractive for brackish water preparation than for seawater. This independence from high voltage power supply appears here as one significant advantage.

Larger solar desalination solutions often base on the principle to collect the sun by means of mirror systems concentrating the irradiation by focussing to provide extreme local energy input for heating an operating medium. Such applications are already installed in sun abundant regions of the world and have huge potential for future use as discussed later (3.3.2, 3.4).

3 Analysis of Future Desalination and its Solar Potential

3.1 The Potential for Replacing Large-Scale Fossil Technology

As earlier mentioned seawater desalination is only possible by provision of huge amounts energy, which, depending on the technology will be electrical and shaft power or additional thermal energy, where thermal processes will also need the first mentioned, while for pure mechanic membrane processes the latter will not apply (2.2, 2.3). If thinking to gradually switch the conventional desalination technology to feed the current freshwater demand on a large-scale to solar powered systems not only the cost, but also the required surface area could be a limiting factor, which shall be shown in following estimation.

Taking the previous example (2.2) with the daily freshwater production of Kuwait and notionally change the desalination technology to solar powered energy supply as proposed by Ettouney and Rizzuti (2007) the irradiation surfaces to be provided would be impressively huge. In detail it shall be assumed that the daily desalinated water demand of Kuwait amounting to around 1.92 million m³ per day supplied by conventional fossil powered thermal desalination technology with an average electric power consumption of 4 kWh/m³. Then, as already estimated, the electric energy to provide would be $1.92 \cdot 10^6\ \mathrm{m^3/d} \cdot 4 \cdot 10^{-3}\,\mathrm{MWh/m^3}\ /\ 24\mathrm{h/d} = 320\mathrm{MW}$.

The switching of both electric power supply and thermal process energy to solar driven water desalination shall be based on following solar data and technology:

1. Average hot sunny day of vertical solar irradiation for around 9 hours with an averaged specific solar energy flow into the thermal desalination system of 0.7 kW/m². (This value is practical for following estimation since the absolute maximum under vertical irradiation defined by the solar constant is 1.4kW/m² as per 3.2)[4].
2. Photovoltaic monocrystalline silicium cells of proven commercial technology with an efficiency of 19% (National Renewable Energy Laboratory, 2010).
3. State of the art solar thermal collector producing around 45 liters of water per day at given solar irradiation (Ettouney and Rizzuti, 2007).

Then the needed surface area for photovoltaic electric energy production would result to

$$\frac{320 \cdot 10^3\,\mathrm{kW}}{0.7 \cdot 10^6\,\mathrm{kW/km^2}} \cdot \frac{1}{0.19} \cdot \frac{24\,\mathrm{h/d}}{9\,\mathrm{h/d}} = 6.4\,\mathrm{km^2}\,.$$

For the solar thermal desalination itself the required surface area than would be

$$\frac{1.92 \cdot 10^6\,\mathrm{m^3/d}}{45 \cdot 10^{-3}\,\mathrm{m^3/m^2h}} \cdot \frac{9\,\mathrm{h/d}}{24\,\mathrm{h/d}} \cdot \frac{1\mathrm{km^2}}{10^6\,\mathrm{m^2}} = 16.0\,\mathrm{km^2}\,.$$

4 given value without consideration of optical collector imperfections as per 4.3

This quite considerable area representing by far the major portion of land to be provided, however allows for an incredible solar thermal energy irradiation which on the assumed hot summer day then would be

$$0.7 \cdot 10^{-3}\,\text{MW/m}^2 \cdot 16 \cdot 10^6\,\text{m}^2 = 11200\,\text{MW} .$$

This notable magnitude for the energy needed is reasoned by the fact that the freshwater production process bases on full evaporation of the water amount to produce before again condensing it. And this evaporation of water requires a substantial energy amount for performing its aggregate phase change as the coming section highlights (3.2), an amount which though can be recovered to a large part in modern applications by utilising the succeeding release of heat of condensation. Here the freshwater output of the exemplary chosen solar thermal collector, on which the calculation was based, directly depends on the heat recovery efficiency of the system.

Returning to above estimated surface areas required for thermal solar water production, it can be summed up that the total surface area occupied by solar technology to produce 1.92 million m³ of freshwater per day would result in $6.4\,\text{km}^2 + 16.0\,\text{km}^2 = 22.4\,\text{km}^2$.

Concluding, if the exemplary taken state Kuwait notionally would meet its total desalinated water demand by hundred percent solar driven technologies, it would need to reserve around 22.4 km² of its land for this purpose. This seems quite a lot but when comparing it with its state territory of 20,000 km² in total[5], the portion to sacrifice for water production would then just be a little more than one per mille.

However the consideration of any state to gradually go for solar desalination on a large scale and therefore rededicate fractions of its land to harvest solar energy would have to be cautiously balanced with numerous counter-arguments of economic, environmental, socio-political and political nature. In any case one could argue that unused arid land or even deserts anyway would serve no better than for utilising the solar energy irradiated onto it. And then, if having acquired such potentially cheap territory, the energy provided by the sun would be for free.

If in future solar desalination will become suitable for large-scale freshwater production will mainly depend on costs-benefit analyses and political arguments. There the total investment costs for installation of solar technology and for land acquisition with the benefit of then having free energy supplied by the sun would have to be compared to conventional fossil fuel solutions with their burden of potentially increasing fuel costs in future.

3.2 The Thermal Limits for Solar Evaporation

While in previous section (3.1) the possible limits for solar desalination were approached by emphasising the immense areal requirements, besides briefly also the physical or technological limits were presented by showing the enormous thermal energy effort to cope with the considerable water production magnitudes needed for the supply of a whole region or even as state territory. Here the emphasis shall be placed on this thermal effort for water desalination by evaporation

[5] http://en.wikipedia.org/wiki/Kuwait

which provides limits and challenges for technical realisation of appropriate installations.

Radiation Constraint by the Solar Constant

The solar constant, a measure of the solar energy flux, is the amount of incoming solar electromagnetic radiation per unit area that would be incident on a plane perpendicular to the rays. It fluctuates between around 1.32 kW/m² and 1.41 kW/m² where the World Radiation Center adopted a value of 1.37 kW/m² (Duffie and Beckman, 2006). In the warm and arid regions to be concentrated on in this study the daytime solar radiation will remain high due to high percentage of intense sunlight periods and only rare, seasonal cloud formation. However it can never exceed the figures just mentioned, which provide the ultimate and inescapable natural limitation for mankind to utilise solar energy.

The coming estimation shall provide an idea for the order of magnitude of water that can realistically be produced under maximum expectable solar energy provision. Therefore the irradiation energy flow into the thermal desalination system shall be set to 1.0 kW/m² which is a feasible figure for intense vertically arriving sunbeams at noon under consideration of a well developed solar collector system effectively concentrating the solar energy as described later (4.3.1).

The Role of the Enthalpy of Evaporation

The evaporation of water is performed by the provision of significant amounts of heat energy. In practice this comprises firstly the increase of temperature up to the evaporating temperature and secondly the transformation from the liquid to the gaseous aggregate phase, the actual evaporation. There the phase change generally requires a multiple of the energy input which is necessary for the temperature increase only.

Summing up mentioned energy amount needed to heat up the water mass m_{water} of 1 kg by a temperature $\Delta\vartheta_{water}$ and then to fully evaporate it, can be formulated as the specific evaporation enthalpy of water

$$h_{evap,\,water} = c_{water} \cdot \Delta\vartheta_{water} + h_{latent,\,water} \qquad \text{(in kJ/kg)} . \qquad (3.1)$$

This energy effort to be provided for the evaporation can be evaluated with the specific capacity of water c_{water} and the latent heat of evaporation $h_{latent,water}$ as per Table 3.1.

Table 3.1 : Assumed averaged specific physical properties of water
(Averaged for operating conditions range: 20°C-100°C, 0.95bar-1.05bar)

Water Characteristics	Symbol	Value & Unit
Density, averaged	ρ_{water}	1.0 kg/litre
Latent Heat of evaporation at 100°C	$h_{latent,water}$	2260 kJ/kg
Specific heat capacity at 20°C	c_{water}	4.19 kJ/kgK

Based on described calculative approach it is finally possible to calculate the energy effort to exemplary heat 1 litre of water from 25°C to 100°C and to afterwards to evaporate it totally. By taking the density of water from Table 3.1 the water amounts to 1 kg. With the figures above the energy input per this kilogram of water to be provided splits into

- the minor portion to heat up the water by 75 K, which amounts to 4.19 kJ/kgK . 75 K = 314 kJ/kg, and
- the major portion of latent heat which is 2260 kJ/kg.

The total energy demand for this evaporation of one litre of water at 100°C then turns out to around 2574 kJ, where the effort necessary only for the phase change of the fluid dominates by almost one magnitude. And for this reason exactly this latent heat portion is the essential part to be taken care of by all thermal evaporative water production technologies, not just confined to solar applications.

Under concluding this outcome it can be argued that the only way to economically viable produce freshwater by thermal processes is to recover most of the latent heat of evaporation when it again is released during the processing by succeeding condensation of the produced freshwater!

Each appropriate thermal desalination installation mentioned in following sections makes use of this recovery potential as far as its technology allows for. Some processes not only utilise the released latent heat, but their design principle even depends on this provided heat exchange to run a thermal convection of associated fluids within the system. This is the case for the prototype desalination module comprehensively discussed later in this document (4), which is designed to run a thermal cycle within its tubular structure driving the process.

Solar Energy Effort for Evaporation

When the solar radiation of 1 kW/m² as assumed afore vertically irradiates a surface area of 1 m² for 1 hour the sun can supply 3600 kJ/m². When comparing with the above estimated energy demand of 2574 kJ/kg required for the evaporation of 1 kg water it shows that in one hour just around 1.4 litres of water can be evaporated per m² of surface area, however without consideration of any heat losses.

When utilising recovery of the latent heat as afore mentioned, this yield can be enhanced under same conditions to around 3 to 4 litres per hour depending on the technology. More details to the potential water production by solar desalination is provided later where the performance of the presented desalination module prototype is comprehensively discussed (4.3.2).

Concluding above-mentioned one has to consider that this natural limit for solar energy supply can never be enhanced by technology. Only the provision of additional surface area can increase the solar energy yield.

3.3 The Large-Scale Desalination Future

3.3.1 The Combined Water and Power Plant

To cope with the steadily rising demand for freshwater the currently rising capacities for large-scale fossil powered desalination will in next future still continue to rise as mentioned (2.1). Actually there is no proved alternative solution on the market to satisfy the huge water demand and the most promising technology to step into this market, namely the concentrated solar thermal desalination as introduced next (3.3.2) is still in emerging. And besides such expectable solar solutions would still be at least one magnitude smaller than the capacities which fossil technology can provide for.

In the following the ideas and advantages to combine large-scale water production with the generation of electric power by use of conventional, fossil fired technology shall be presented. Such solutions base on proven large-scale conventional installations of already optimised efficiency with the target to even increase the overall efficiency of the plant by reasoned operational combinations between power and water production aiming at maximising plant utilisation at optimum conditions (Mahbub et al., 2009). However to balance between water and power production it is inevitable to analyse the diurnal demand for electricity and water throughout the region to be supplied.

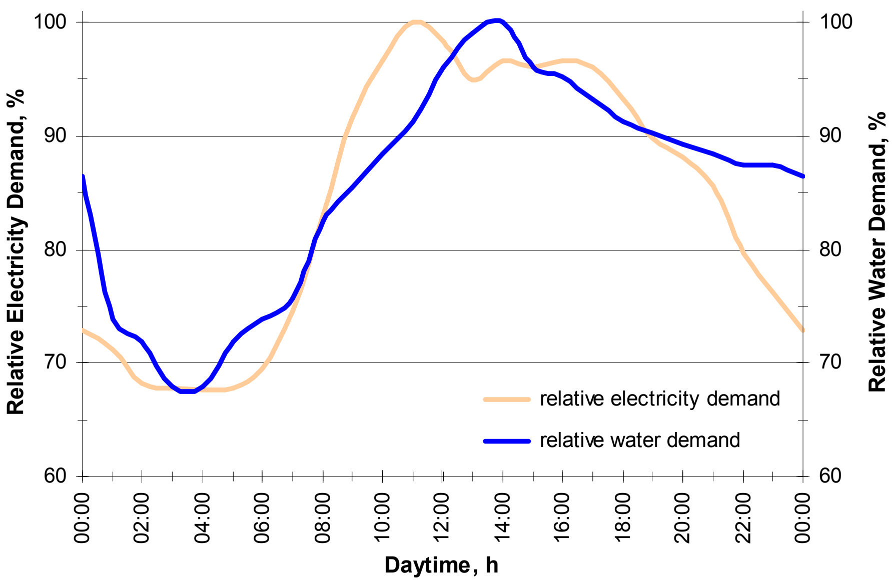

Figure 3.1 : Typical Daytime Electricity and Water Demand in the Middle East (Kamaluddin et al., 1993)

Looking at the daily usage the demand for water is different to the one of electric energy. As investigated by Kamaluddin et al. (2009) for arid zones of the Middle East the power demand is highly seasonal and is characterised by abrupt variation during each day compared to the water demand as to see in Figure 3.1.

Combining the technology of efficient power generation with the energy consuming freshwater processing from seawater which provides the primary water source in arid zones, the daily and seasonal demands for electric energy and water can be balanced under optimising the overall efficiency. This results in the so-called Combined Water and Power Plant (CWPP), a combination of a Combined Cycle Power Plant (CCPP) and a seawater desalination plant. A major advantage of such an installation is provided by the fact that the CCPP generates both power and steam anyway, both needed for current desalination methods. While electricity is generated by the appropriate gas turbine and steam turbine plants, the process steam from the heat recovery steam generator is needed to feed the steam turbine. So when the diurnal electricity demand is not peaking, both electrical and heat energy are disposable for water production.

For the latest generation of CWPP's the desalination plant preferably is of hybrid type, which means it consists of both a thermal operated distillation and an electrical powered membrane filtration stage. In this design the fluctuations in electric power demand can be even better balanced with water production to maximise the energy efficiency of the total plant. In particular the membrane process will work by reverse osmosis (RO) under utilising some of the generated electric power, while the distillation could be realised either by multi-stage flash (MSF) or by multi-effect distillation (MED), both running with thermal energy. Such a novel design installation is sketched in Figure 3.2. (The mentioned water processing technologies are explained earlier, 2.3).

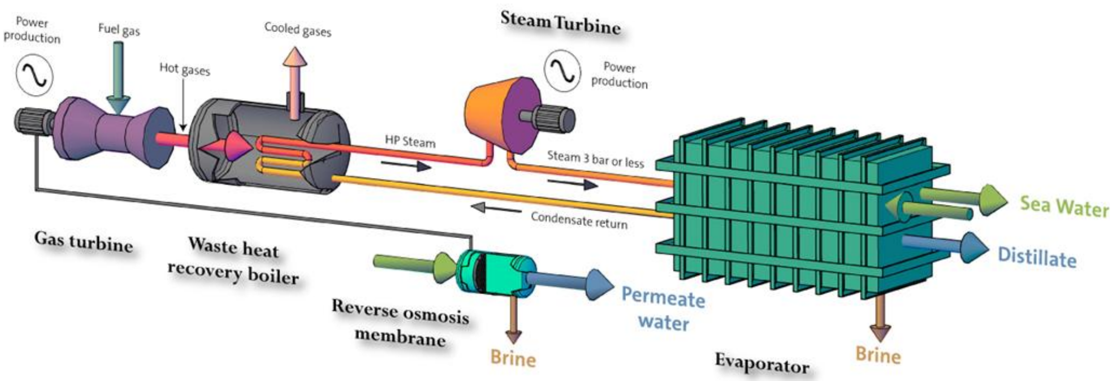

Figure 3.2 : Scheme of a Novel Combined Water and Power Plant
Coupling CC with thermal and RO desalination (Sidem, 2010)[6]

In their modelling of the afore described CWPP process Mahbub et al. (2009) could calculate overall thermal efficiencies of the installation as shown in Figure 3.3 for different operation cases and process combinations. There they figured out that combining of power and water production significantly raises the plant overall efficiencies because in such operational balancing the high efficient base load

[6] http://www.sidem-desalination.com/en/process/Hybrid/

operation of the CCPP can be utilised, even if the demand for power generation alone would not allow for. In such a case the processes then are balanced to produce more water under optimum base load efficiency conditions.

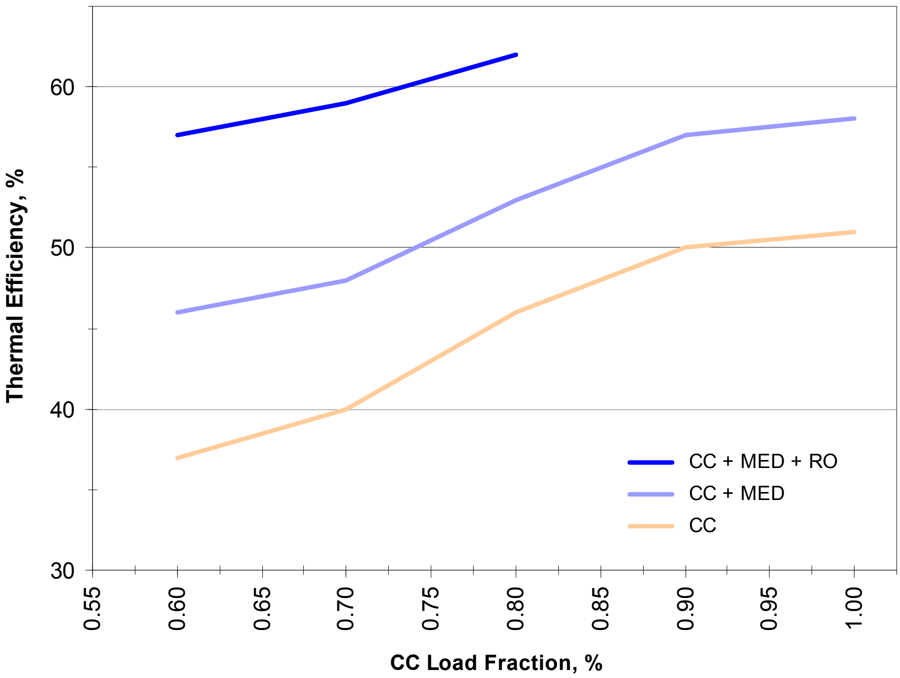

Figure 3.3 : Thermal Efficiency Potential of the CWPP in Combined Operation
Thermal Efficiency of the CWPP in Combined Water and Power Operation as function of the Combined Cycle (CC) load fraction (Mahbub et al., 2009).

Furthermore the calculations showed that by choosing a combination of both MED and RO the thermal efficiency of the total plant can be even further increased.

3.3.2 Concentrated Solar Power as Alternative

Solar Energy would be the most attractive alternative to power desalination plants in mentioned sun abundant arid regions. However the huge amounts of daily freshwater production provided by large-scale Desalination Plants and described CWPP's can hardly be achieved, because as detailed earlier the solar irradiation per surface area is limited (3.1, 3.2). Consequently for high solar energy yields immense collector surface areas would need to be installed.

When aiming at large-scale solar powered desalination solutions to help satisfying the increasing future water demand the most probable solution will combine with the technology of a concentrated solar power plant. There solar irradiation is collected by mirrors, concentrated into their focuses or focal planes in order to heat up a fluid that passes by in its circulating flow through the system (Duffie and Beckman, 2006).

This transformation of radiative energy by solar collectors is further detailed later (4.2.6) because of providing essential input into the performance calculation of the presented solar collecting desalination module prototype (4).

As concluding prospect for concentrated solar thermal power solutions one can argue that this technology will gain in importance because actually it provides the only potential large-scale solar power generation installation to reasonably match with fossil fired power generation.

3.4 Medium- and Small-Scale Gains for Solar Power

The previously introduced concentrated solar power desalination is an example showing that solar power has a potential to even serve large-scale freshwater production (3.3.2). Already today this technology is used for numerous medium- and small-scale solar desalination solutions as the example below shows.

As mentioned in the beginning water demand will further rise in the coming future, especially in regions suffering from aridity, whereas most of exactly these regions are on the other hand blessed with abundance of solar radiation. This leads to the logic conclusion to go for solar powered freshwater preparation technologies. And here solar desalination plants of small and medium size are expected to massively gain in importance because of providing an alternative to the large-scale solutions being only installable in areas of good infrastructure and high population density. The solar installations otherwise provide the best solution for remote areas lacking of infrastructure.

To illustrate the future potential of commercial operation of small- and medium-scale solar desalination possibilities an exemplary plant in Almeria, Southern Spain as briefly already introduced in section 2.3.2 shall be presented here. This desalination installation which evolved from a prototype of many years of investigations to a proven installations combines MED distillation with power supply from solar collectors. The plant was developed within the frame of a research program supported by the European Commission. Investigated and presented by Blanco and Alarcón (2007) it presents a good example where a multistage MED process which is powered by solar collectors ends up with a production rate of almost 40 % under provision of 3 m³ fresh water per hour under design conditions. In detail the solar thermal energy is provided in form of a heated fluid either running a low pressure boiler or producing high pressure steam, where the first directly provides heat to the MED while the latter can run a turbine to produce electricity and besides also feed the MED. For the 3 m³ daily water production the installation consumes 190kW solar power, but according to the water demand it also can also partly switch this input to cogenerate electricity. Important to mention is that the combination of water and power production is here applied even in a small scale application which makes the installation flexible and thus attractive. And additionally important is that the plant utilises a thermal storage tank to further balance energy supply and demand with the diurnal solar irradiation cycle and in this way allowing to target on maximising the solar power provided to increase the efficiency. Finally Figure 3.4 shows the principle of the presented solar desalination installation.

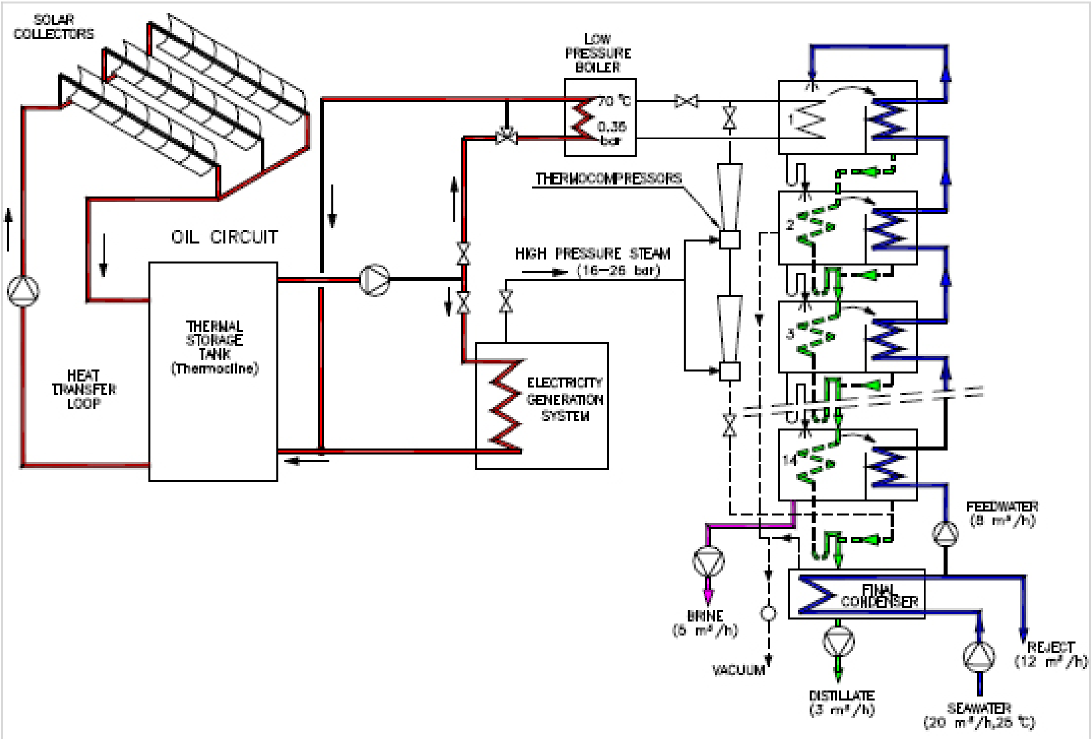

Figure 3.4 : Schematic diagram of the solar MED system
(Blanco and Alarcón, 2007)

Under again referring to the presented solar MED plant in Almeria the argument for thermal storage shall be briefly discussed. This plant optimises both efficiency and availability even in hours of weak or even no solar irradiation by means of a thermal storage tank, into which the solar heated fluid circuit may provide heat when passing by on its flow through the system. Most of the well investigated and optimised solar power solutions utilise such kind of energy storage for mentioned optimisation reasons.

There some applications have the additional argument not only to use the just produced energy for storage, which then could cause reduced base energy input into the process, but also to use the potential waste energy, here the one contained in the rejected brine. For a well engineered technology however this energy portion would be of little interest since anyway leaving the system not before having transferred most of its useable heat to the process. But for a single modular desalination system this possibility should be considered in the design. The topic of using waste heat flows is detailed here in order to provide possible ideas for the desalination system prototype being assessed in chapter 4.

Finally the possibility to combine a solar desalination system with a solar pond shall be presented here, because of being a simple technology to primarily provide the necessary heat for the processing. Secondarily such a pond can be used for mentioned storage of heat for periods of lacking solar irradiation, and thirdly, even more important in this context it can be used as final storage for the brine rejected from the process.

This argument shall not just suggest a cheap waste disposal but it is necessary for the functioning of the so called salinity-gradient solar pond technology, because the principle of such a system bases on the physical properties that the density of an aqueous solution increases with its salinity. Thus a pond containing different layers of water of different salinity with the highest concentrated one on the bottom therefore will not mix by natural convection. For this reason the highly saline bottom layer has the chance to heat up by transmitted solar radiation. This simple design yields temperatures up to 90°C as experienced by Lu et al. (2002) on a prototype plant in Texas. Actually solar ponds are already in operation for some desalination applications, whereas their simple design and the ideal combination possibility with freshwater preparation due to allowing for brine disposal provides for attractive future solutions primarily in the small-scale sector and for inland brackish water applications.

As last comment for the future of small- and medium-scale desalination systems powered by renewable energy it shall be mentioned that there is also huge potential for wind power installations due to the fact that some of the arid zones are not only sun abundant but also rich in wind. However this technology shall not be further discussed in the present paper emphasising on the solar thermal share of alternative solutions.

3.5 Research Still Ongoing: Forward Osmosis as an Example

The increasing pressure on the freshwater supply of arid zones has become a global problem to challenge scientist and engineers in the coming decades. Technological solutions to cope with this topic mostly base on proven technologies extracting already the most possible from the well developed processes. Additionally these processes may be adopted for alternative solutions to be supplied by renewable energy sources as previously discussed (3.4).

However the importance of future water supply on the global scale also provides for totally new research and development in hope to find processes even more efficient and sustainable in respect of resources use. As an example the phenomenon of osmosis has been extensively investigated, which once brought out the reverse osmosis process (RO) as most prominent outcome and today one of the leading technologies for water treatment and desalination. But within the field of osmosis there is another researched topic named forward osmosis (FO) which has a huge potential for water preparation processes as discussed in the following.

McGinnis and Elimelech (2007) presented a novel ammonia–carbon dioxide FO desalination process, on which they investigated in small laboratory scale, under concluding that this process could provide reasonable potential for use in field arrangements. Figure 3.5 shows a scheme of this process where a draw solution by containing ammonia (NH_3) and carbon dioxide (CO_2) is even more salty than the saline raw water to be processed that it allows drawing the pure water through the FO membrane by diffusion under leaving the salt within the concentrated brine on the other side of the membrane.

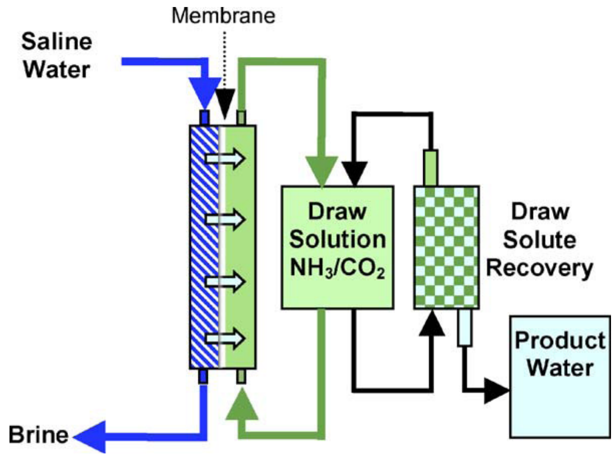

Figure 3.5 : Schematic of the novel ammonia-carbon dioxide FO process
(Cath et al., 2006)

However a second processing step is necessary to finally yield the processed water by separating NH_3 and CO_2 from the solution. But because of their low vapour pressure these substances easily evaporate at moderate heating to around 60°C to be recovered and again added to the process (Cath et al., 2006).

The principal advantage of the FO process is that the diffusion effect forced by the draw solution pulls the water though the membrane solely driven by the osmotic pressure difference between the two fluids, while the RO process follows the opposite principle which means it has to impose high pressure to push the water through the membrane because of having to cope not only with the filter pressure drop but also with the osmotic pressure acting in the opposite direction (Cath et al., 2006).

The comparison points out that the FO process provides for huge energy saving potential because it saves electrical power by allowing the water to penetrate the membrane without pumping effort, due to the fact that the water is pulled through the system by the force of osmosis. This enormous energy saving potential of the FO process was elaborated by McGinnis and Elimelech (2007) under comparing it with other proven desalination technologies as shown in Figure 3.7 next.

Also for this novel process the potential for solar energy application shall be analysed here. Especially the thermal energy provision shall be discussed in this context, because the electrical energy effort is anyway expected to be quite low due to explained osmotic phenomena.

Firstly the recovery of the draw solution substances from the freshwater operating as mentioned at low temperatures around 60°C which is enough to easily be powered by solar energy. Secondly laboratory observations showed that the FO water flux increases significantly with moderate rise of the operation temperature up to 50°C (Low, 2009). This moderate heat input again can be supplied by solar energy. The result for different tested water salt content is shown in Figure 3.6.

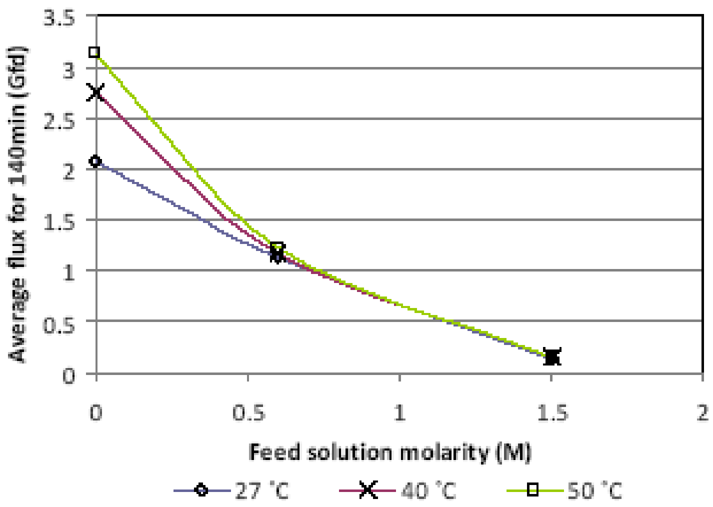

Figure 3.6 : FO flux variation with temperature and water salt content
Water flux over various molarities of Sodium Chloride feed and temperatures using fixed ammonium bicarbonate draw solution at 2.5 M and FO membrane (Low, 2009).

Finally it can be added as hypothetical idea for possible future application that even the salt enriched brine as waste product from desalination itself could theoretically be used as draw solution to potentially undergo a FO process in order to gain torque by additionally drawing incoming seawater though a turbine which it passes on its return to the sea. Similar principles have already been realised as emerging FO power plants (Cath et al., 2006), whereas in such installations the seawater acts as draw solution.

3.6 The Energy Impact as Incentive for Solar Solutions

As earlier mentioned the technical production of freshwater has a huge energy impact demanding that the currently dominating fossil fired large-scale solutions are installed with power generation equipment similar to power plants. Here is the major argument for solar powered systems, which although cannot produce water at the same cost as huge plants do but the application of this technology can save most or in ideal case all of the energy input because of being supplied by the sun. In the course of their investigations on the forward osmosis desalination (3.5) McGinnis and Elimelech (2007) compared by equivalent work modelling the energy inputs of different desalination technologies. There they distinguished between electrical an thermal energy effort. As expected the proven technologies (2.3) show high thermal energy requirement and moderate electric power effort if they are utilising thermal desalination processes like MSF and MED and otherwise high demand for electrical power in case of operating a membrane process like RO. As future prospect for the energy saving potential of the developing FO desalination process the calculated data include in comparison the expected energy demand for the FO process.

The calculated data for electrical and total energy demand of the different desalination processes arising from the modelling are displayed in Figure 3.7, where the thermal portion is shown as solar thermal potential added as difference between these two numbers.

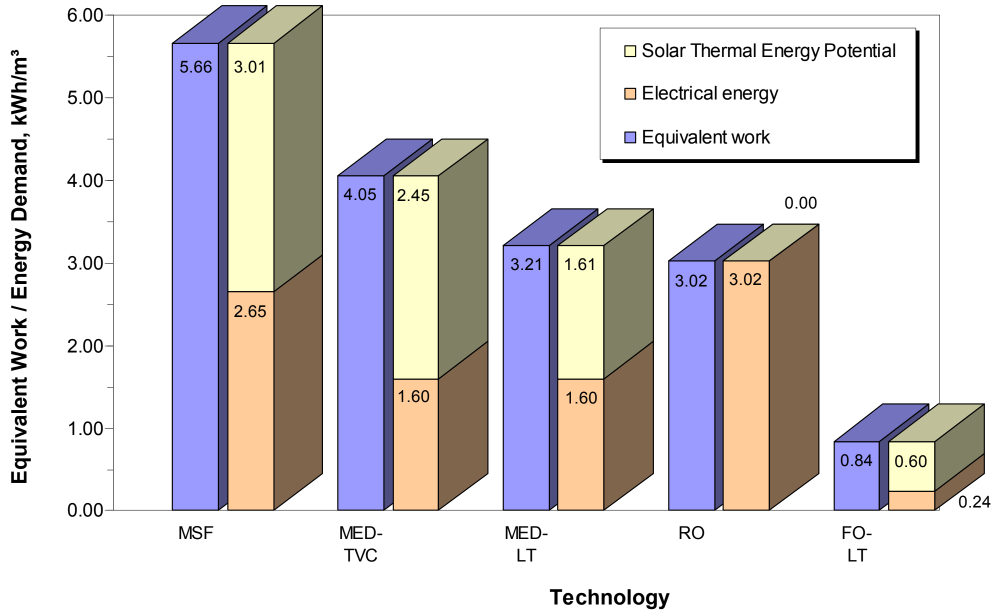

Figure 3.7 : Energy input comparison for different desalination technologies
Comparison of equivalent work, electrical energy demand and solar thermal potential for different seawater desalination technologies.
Data in kWh per m³ of produced water. MSF: multi-stage flash distillation, MED-TVC: multi-effect distillation with thermal vapour compression, MED-LT: low temperature multi-effect distillation, RO: reverse osmosis, FO-LT: single column low temperature forward osmosis.
(Equivalent work and electrical energy data by McGinnis & Elimelech, 2007)

Analysing the data shows that FO desalination actually would need just a fraction of the energy the other processes require, if it would be introduced as feasible alternative technology. Today just realised in laboratory prototype scale (3.5) this processing would very soon gain a considerable market share if proven as reliable and affordable investment. As earlier mentioned it shows further that FO actually needs just little electric power due to the FO principle, but also its thermal energy effort is moderate because of the low heating requirements.

Logic, but worth to mention is the zero solar thermal potential for membrane processes like RO, just photovoltaic or wind power could here provide for alternative energy sources. MED on the other hand is quite attractive to potentially be solar powered because of a high thermal energy portion, a just moderate electrical effort and by the way lower temperature requirements for the process than MSF (2.3).

4 Designing a Solar Thermal Desalination Module System

In this section the design of an innovative prototype for small- and potentially medium-scale solar desalination shall be comprehensively discussed with regard to its technical and economical feasibility for installation in the growing number of regions suffering from water scarcity but in exchange benefitting from solar irradiation abundance. Moreover, in the course of this investigation the most suitable modular arrangement targeting on high availability operation and low investment cost shall be found under considering overall efficiency maximisation and, at the same time, keeping the layout as simple as possible.

4.1 The Design Idea: Affordable and Simple Water Production

The modular solar desalination system to investigate on was invented to provide an alternative local implementable small-scale option for communal thermal freshwater production in zones of water scarcity to allow for sustainable agricultural production and in ideal case for potential preparation of potable water of suitable sanitation standard. The design idea was to go for an easy transportable modular system, although sophisticated in conception but simple in materials to use and thus low in cost.

These preconditions assumably will implicate compromises in overall efficiency and thus specific freshwater output compared to large-scale high tech desalination solutions, however as mentioned the superior priority of this prototype shall be aimed at low investment and short-term realisability. By means of this emerging technology local communities would have the chance of installing a practical alternative to produce freshwater without nameable operational cost for fuel and without any dependency of commercial water producers dictating the price of this valuable good. The only prerequisite for such a solar powered desalination system then would be that the resulting long term water price calculated from the investment effort should have to be below the one claimed by a local conventional water provider. But this actually could be possible when considering that the energy provision by the sun is for free and therefore the expenses for other fuels to run such a system could be reduced to a minimum.

4.2 Design Principle: Single Module Processing with Solar Collector

Under implementation of the mentioned ideas (4.1) the desalination system to develop shall be designed on base of following main principles:

1. Assembly of single modules to make it easy transportable and mountable,
2. Setup of low price standard materials to make it affordable and facilitate its maintenance,

3. Energy provision by solar power to be most suitable for the sun abundant but arid regions for foreseen utilisation and to enable energy independence in order to allow remote area installation and to minimize fuel cost,
4. Freshwater production by thermal evaporation and succeeding condensation both taking place in each module to recover the latent heat released by condensation and to reduce heat losses by maintaining moderate fluid temperatures,
5. Provision of the possibility to easily combine modules by simple piping and connector systems to allow for common supply and discharge lines as well to optimize the overall process under targeting on efficiency maximization,
6. Consideration of different solar irradiation conditions manageable by simple control mechanisms to follow the diurnal solar rhythm by sun tracking, as well as to maximise media heat transfer by controlling the water flow in order to optimize its evaporation and condensation with the ultimate aim to maximise water production.

These preconditions lead to a prototype design for each module of the desalination system as introduced next.

4.2.1 The Core Module – Simple Design for a Complex Process

The modular core of the emerging desalination system shall be constituted of a tubular framework which carries a characteristic wing-shaped solar collector on its outside while in its inside it contains the water to process. Figure 4.1 shows the principal design of such a single module which was applied for a patent (Kerschgens, 2008).

Figure 4.1 : Solar Desalination Module – Principal Design
(Kerschgens, 2008)

There the structure for the first module series was chosen to mainly consist of plastics, with the tubular frame as principal piping system made out of PVC. A possibly inflatable soft plastic collector wing as well as an inflatable heat exchanging surface in the condensing zone inside the frame to provide for preheating the inlet water with the latent condensation heat released from the produced freshwater as detailed later (4.2.3).

For sure the hot section of the tube located in the focal plane of the parabolic (or spherical) mirror surface shall be constituted of a metallic alloy, because in this zone temperatures above 200°C are to be expected. In this context Kalogirou (2004) provides practical data for the receiver of parabolic collectors. In detail when writing of optimum operation temperatures the author advices that for a system of a concentration ratio[7] of 50, operated at moderate ambient temperatures of 25°C, one can expect stagnation temperatures of even 565°C. Although maxima in this temperature range would solely occur without any fluid flow inside the pipe, but for designing the system such expectable extremes have to be considered. For normal operation Kalogirou (2004) then would expect optimum temperatures around 230°C for this system.

In described heating zone of the tube system also a specifically designed insertable structure shall be foreseen with the task to promote evaporation (4.2.3). Also for this structure the material has be chosen to sustain the temperature maxima just mentioned.

Finally, each of these modules has to be designed with piping terminations for raw water inlet, freshwater outlet and brine outlet at suitable locations (4.2.3).

4.2.2 The Parabolic Collector to Power the Process

In case of the present solar desalination module prototype a cylindrical collector of parabolic shape is planned to be foreseen which shall transfer the concentrated solar radiation to the receiver located in the central focal plane. Here the receiver shall be the bottom of the metallic tube surface which is part of the tubular framework that, as afore mentioned, constitutes the desalination module.

If it should appear that for the foreseen application a cylinder with the shape of a circular segmental would provide for similar performance as the parabolic shaped one, also such a surface could be contemplated to be used. But it shall be noted that only relatively flat shaped structures of small rim angle[8] manage to focus the incoming radiation to a central receiver. In other words this means that the so-called 'concentration ratio', defined by Duffie and Beckman (2006) as ratio of the area of aperture to the area of the receiver, dramatically decreases for circular cylinder surfaces at higher rim angles. Otherwise the concentration ratio of parabolic collectors not only is fine for types of larger rim angle with strong shaped parables, it even increases with the rim angle. This relation between concentration ratio and rim angle is shown later in the detailed design section (4.3.1), together with some more numbers and measures to optimise the optical efficiency are presented.

[7] Concentration ratio: definition see next (4.2.2, 4.2.6).

[8] Rim angle: The half opening angle of the collector surface curvature measured from the curvature centre at the structure rim. For parables this centre is identical with its focal point (Duffie and Beckman, 2006).

In this context also the optimal mounting under consideration of maximum exposure to solar radiation shall be mentioned. This major topic for efficient operation depends very much on the design itself, further on the geographic latitude of the foreseen placing location, and the annual operation regime to either prioritise high average or rather seasonal peak operation (Duffie and Beckman, 2006). A very useful feature to optimise the sun exposure for specifically adapted daily and seasonal operation is provided by solar tracking as suggested later in this section (4.2.6).

Not negligible for the energy intensity transferred to the receiver is for sure the optical quality of the collector surface, which shall feature high reflection and hence little absorption as well as limited diffuse dispersion of rays (Duffie and Beckman, 2006). Reciprocally the receiver surface shall be of low reflectance and high absorbance. In addition to optical features also thermal losses of the receiver should be considered, because at the anticipated focus temperature maxima of some hundred centigrade these losses can be respectable. However theses losses are hardly reducible by isolation measures because the concerned surfaces have to be transparent to the ambiance for receiving radiation (Duffie and Beckman, 2006). Just optimisation of the focussing, in other words increasing of the concentration ratio could reduce mentioned losses by spatial limitation of the receiver surface area to where the radiation is concentrated. And this would again depend on the optical quality of the collector to choose, sparing cost here would thus cost overall efficiency of the system twice twice, once optical and once thermal.

Kalogirou (2004) writes in this context that high performance solar collectors delivering high temperatures with good efficiency are required under mentioning that in practice systems with low cost technology are on the market where process heat up to 400°C could be obtained with parabolic through collectors. Thereby the range for effective heat production is at temperatures between 50 and 400°C. He further mentions that because of considerable experience with parabolic trough technology it is the most advanced for solar thermal energy production. These are additional good arguments when developing the solar desalination modules that choosing a parabolic cylindrical collector system not only is practical and efficient, but it also provides a huge archive of experience and development to get advice from.

Comparing the evolving module with concentrated solar power installations its solar collector design is in principle similar to a so-called ‘parabolic through collector’ (Kalogirou, 2004), which is formed as parabolic cylinder surface that usually has a tubular receiver located in its focal plane where the fluid to be heated flows. The major difference to those primarily power producing solar concentration plants however is that they target on heating up a fluid, usually special oil, without allowing it to evaporate. In the present case the aim of the solar concentrator is to already locally heat up water to temperatures just as high to enable evaporation but otherwise low enough to also allow for condensation in the succeeding section of the tubular frame. To achieve and maintain the suiting operating temperature range it could be advisable to do so by controlling the water flow within the system accordingly as described later (4.2.4).

A principle design difference between the present local solar desalination prototype and a large-scale parabolic through solar power station is that the former runs the total thermal process locally, which is called ‘local desalination’ (Ettouney and Rizzuti, 2007). The latter locally just heats the fluid in the collector focal plane to highest possible temperatures without processing it, but then transfers the contained heat to another process. There usually process steam is produced to feed a Rankine process, or to make use of its heat in another way, including its utilisation for large-scale thermal desalination (3.3). This kind of processing then is called ‘indirect desalination’ (Ettouney and Rizzuti, 2007).

4.2.3 The Fluid Cycle to Run the Desalination

Coming back to thermodynamics within the tubular frame of the present design, where not just the water fraction but also the aerial atmosphere will circle by natural convection due to heat gradients. This motion shall additionally be stimulated by the trapezoid design of the frame as shown in Figure 4.2. As previously argued to maximise the solar heat utilisation the basic thermodynamic design principle shall be to provide for conditions in the tubular framework which allow both evaporation and condensation. This means that the aerial atmosphere in the tube system which represents the major heat carrier throughout the system shall in general be below the boiling point of water with just slight local overriding of this limit above the heating zone in the focal plane where the steam emerges. If namely the air temperature would be too high especially in the condensation zone, it could not allow for condensation of the water on the cooler water inlet heat exchange surfaces by sufficiently supercooling itself at these surfaces and by additionally taking up a portion of the latent heat of condensation (3.2).

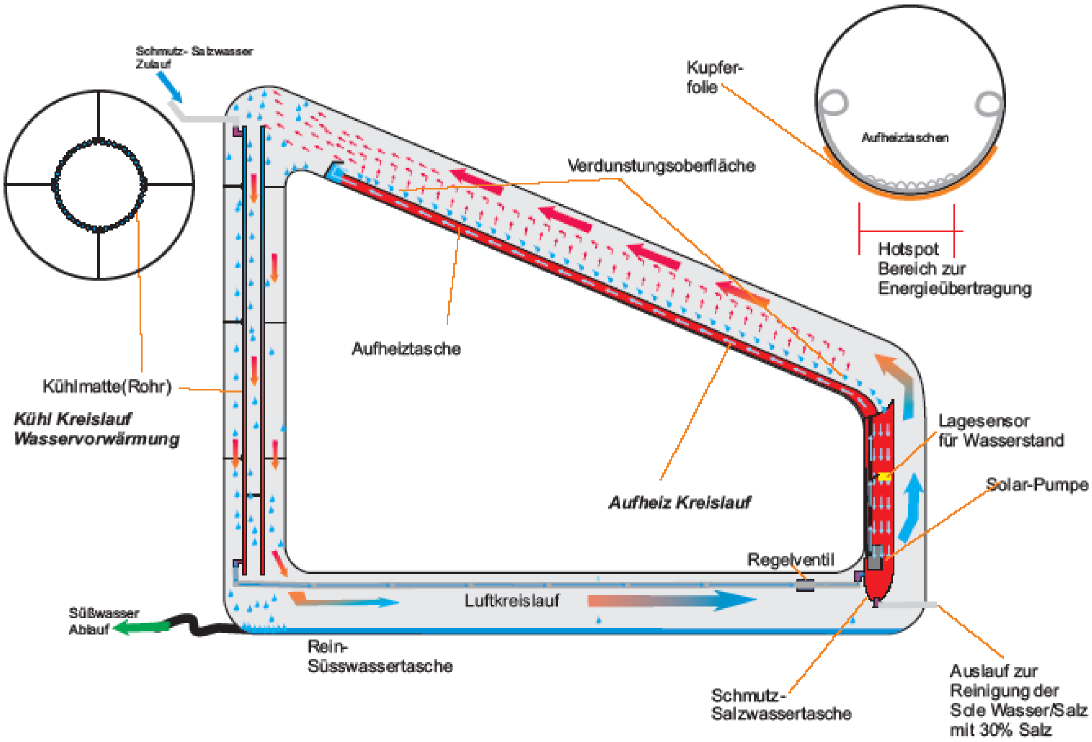

Figure 4.2 : Solar Desalination Module – The Fluid Cycle
(Kerschgens, 2008)

As shown in Figure 4.2 each module has its raw water inlet on top of the structure at the entrance of the condensation zone, its freshwater outlet on the bottom just after this zone and its brine outlet on the opposite bottom end of the trapeze where the rejected brine fraction passes by after running down along the heating zone.

So when raw water of a specific salinity enters the tube system it firstly will pass the mentioned heat exchanger to be heated up mainly by taking up a portion of the latent heat of condensation released by the produced freshwater, which after all is around 2260kJ per kilogram of this freshwater (Table 3.1). Besides, the incoming water will additionally gain some heat by supercooling both the surrounding air and the forming condensate, whereas this energy to potentially take up will be around one magnitude smaller than the latent heat (3.2).

During its passage through the temperate bottom zone of the structure the raw water separately flowing in a small pipe will gradually further warm up slightly by cooling the surrounding air mass. The heating gradient then will rise when this water passes the next heating stage in the brine collecting area because of the higher intensity of the liquid-to-liquid heat exchange between these two fluids.

The two ultimate processing stages for the water take place in the hot zone of the tubular framework where the parabolic mirror concentrates the solar energy along the piping which exposes its bottom edge into the focal plane of the parabolic structure to maximise the solar energy input into the system. There the passing water shall be heated up as far as possible to allow partial vaporisation of it. In detail the water to be vaporised firstly is superheated in a closed channel area when flowing along the rising bottom edge of the tube with its extremely heated surface. Secondly, when reaching the upper open end of this superheating channel the water enters the evaporation area where a certain portion of it already may rise up as steam close to the channel exit while the rest will flow downwards on top of the hot superheating channel to allow further heat ingestion and in consequence further evaporation. There, as mentioned (4.2.1) the evaporation surface shall be of specific design in order to promote the volatility of the processed water. Practically this could be achieved by micro-barriers to reduce the down flowing of the brine and at the same time to enlarge the vaporising surface atop of the brine.

Summing up all these single processes described one can distinguish three major zones within the tube frame where the introduced water in its continuous cycle will undergo six principal stages of phase or heat exchange as follows:

1. The condensation and primary preheating zone to run the condensation of already processed product and the preheating of entering raw water.
2. The secondary preheating zone for the inlet water, which is divided into two heat transfer stages, one providing for contact with the circulating air, the other to do similarly with the rejected brine.
3. The hot evaporation zone with the superheating channel area and the evaporation surface area, the first to superheat the water by direct wall contact with the hottest zone focussed on by the solar collector, the second to allow surface evaporation.

4.2.4 Process Optimisation Potential by Temperature Control

Coming back to afore explained optimum temperature range in which each module shall be operated to enable both evaporation and condensation in the same water cycle both solar intensity and inlet water flow play a prominent role. With increasing solar irradiation not only temperature and pressure of the superheated water in the heating channel will rise and with it its level of superheating. In succession this will cause higher steam production, higher brine temperature by surface heat exchange and finally higher air and overall inner tube system temperature driven by heat transfer and steam convection processes.

A higher live steam production would also mean higher freshwater output accordingly, if this steam would have its chance to condensate in the warmer ambiance prevailing in the tube system in supposed case of higher solar energy input. However if in the particular module total condensation of the produced steam could not proceed and hence a certain vapour fraction would persist, this vapour then would recycle with the air through the tube system. Consequently this would reduce the net water production and with it cause an efficiency decrease of the particular module despite higher solar energy input!

Such an idle operation as described reveals poor utilisation of energy sufficiently provided and has to be avoided. As previously noted in this section a corrective can be introduced by controlling the inlet water flow. As being adjustable in a theoretically far range by this probably only practical control option one could extensively manage the desired thermal conditions within the tube system and thus keep the inner temperature in that range to both promote evaporation and allow total condensation of the emerging vapour.

Another option to manage superheated desalination modules could be realised in case of serial arrangement of some of them. The control mechanism then could occur automatically if single modules of different thermal conditions would be connected by excess steam outlet pipes. However more information in this context shall be provided by comprehensive modelling calculations of serial module arrangements (4.3.4).

4.2.5 Efficiency Optimisation & Thermal Loss Reduction

As afore argued one important benefit to run the desalination process in each module at relatively low temperatures is to increase the overall thermal efficiency by optimally utilising the heat recovery potential and by reducing the heat losses. In particular, at the planned operation temperature the latent energy input for evaporation can be recovered by condensation of the produced freshwater directly within the module by preheating the inlet water. Since the temperature difference between the operating fluids within the tubular system and the ambience is the driving gradient for heat dissipation to the environment, this thermal flow can be reduced by running the overall process at moderate temperatures. Suitable insulation will also be a topic to consider.

However the rejected brine is expected to be up to 90% of the inlet water amount and to have an expected exit temperature clearly above 60°C as coming evaluations indicate (4.3.3). This provides for a potential heat loss exported with the wasted saline solution, a serious point of concern to be further investigated on, where a profitable solution to cope with this issue would be to consider its heat exchange with the incoming water or to feed it into a thermal storage (4.3.4).

4.2.6 Sun Tracking to Maximise the Irradiated Energy

Possibilities for Solar Tracking

Introduced earlier an advisable feature to optimise the sun exposure for specific daily and seasonal operation is the consideration to track the sun in order to minimise the angle of incidence between the actual mean solar beam direction and the normal to the irradiated surface (4.2.2). This so-called solar tracking can be achieved by adjusting the hour angle varying day-to-day with the earth rotation or the seasonal varying declination or by both as detailed by Duffie and Beckman (2006). According to their tracking characteristics solar energy collectors are basically distinguished into stationary ones, single-axis tracking types as well as types that allow two-axes tracking of the sun. Kalogirou (2004) compared theses types under listing the solar energy absorbed by each tracking alternative and concluded, as expectable that tracking in two axes direction has the best overall performance. However single-axis polar tracking from east to west to follow the daily sun irradiation is not far-off in performance. In detail at equinoxes its absorbance logically is the same as for the two-axis moving version. And from this twice-seasonal position the potential performance just slightly decreases when deciding for the single-axis east-west tracking variant in comparison to the two-axis variant to be in the maximum only 8% off at summer and winter solstice.

In practice two-axis tracking makes only sense if the collector is of circular geometry, like paraboloid surfaces where the solar energy is concentrated to a focal point, which causes a dramatic increase of the concentration ratio, compared to linear concentrating systems like parabolic cylinders as shown below in the calculation of the virtual maximum concentration ratio.

Here, supported by afore shown absorption capability comparisons, diurnal single-axis solar tracking from east to west is foreseen to be realised. This variant is quite usual for parabolic cylindrical systems and it also contributes to the design philosophy of developing a simple and easy-to-handle device. Furthermore, since the tubular frame is inclined by its design anyway it shall be positioned with its main axis orientated in north-south direction and its sloped collector surface facing the dominant annual orientation of the solar rays defined by the geographic latitude foreseen for placement of the system. This would mean that on the northern hemisphere each solar module would then be mounted with its collector facing southwards and vice versa on the southern hemisphere. A final assessment to find the optimum positioning for installation shall be supported by coming test runs, which possibly could reveal that reducing the designed tube frame slope for installation in zones within the solar turning circle would be beneficial for maximising annual solar irradiation onto the collector without compromising the convective motion of the fluids within the piping system.

Performance Potential of Sun Tracking Collectors

To estimate the potential performance of a single-axis solar tracking parabolic cylindrical collector surface, the concentration ratio briefly addressed earlier (4.2.2) provides a measure for. Defined by Duffie and Beckman (2006) as area concentration ratio C it results from the relation between the aperture area[9] A_c of the solar collector and the receiver area A_r onto which the solar energy is concentrated. Expressed as equation the area concentration ratio is

$$C = \frac{A_c}{A_r} \; . \tag{4.1}$$

When a collector surface is orthogonally orientated to the sun it can receive the incident beam of solar radiation which is a cone of 32' (= 0.533°) angular width. If this collector is equipped with a linear concentrator like the present parabolic cylinder, it can concentrate this beam in just one spatial direction. Therefrom Duffie and Beckman (2006) figured out that in this case the maximum possible area concentration ratio C_{max} is inversely proportional to the half incident angle θ_s of the sunbeam (while for circular concentrators it would be inversely proportional to its square).

Coming back to the single-axis tracking linear parabolic collector which tracks solar beams in that way to have them orthogonally projected onto its surface, in ideal design case the maximum possible concentration ratio C_{max} then could be

$$C_{max} = \frac{1}{\sin\theta_s} = \frac{1}{\sin(0.267°)} = 215 \; . \tag{4.2}$$

There θ_s is the half incident angle of a sunbeam which is 16' (= 0.267°). (Comparing with the circular concentrator where the proportionality is by the second power C_{max} then would be $1/\sin^2(0.267°) > 4.6*10^4$).

Naturally it has to be considered that this calculated maximum concentration ratio is an ideal number figured up just from geometric proportions without consideration of the actual solar collector design and the optical quality of its reflecting surface. However this figure shall provide an idea which performance could theoretically be realised and how far off the actual concentration ratio to be expected would realistically lie. This comparison then would provide assistance in figuring out possibilities to raise this ratio. In practice for normal proven parabolic cylinder collector technology one can expect ratios far below the ones theoretical possible, values less than 50 are usual (Kalogirou, 2004). For simple linear collector systems concentration ratios even below 10 are expectable when the concentrators are of non-imaging type as Duffie and Beckman (2006) outline. In contrast to imaging collectors which use a kind of simple lenses on their surfaces, the non-imaging ones have just reflecting surfaces as for the present system in development this could probably be the case. The potential concentrating and reflecting performance of the parabolic mirror of the system in development is further estimated in the coming detailed design section (4.3.1).

[9] Aperture area: Here defined as the projected solar collector surface area viewed from the curve main axis direction (Duffie and Beckman, 2006).

Realising Solar Tracking

For the prototype solar desalination module the planned east-to-west solar tracking is foreseen to be technically realised with a system which automatically adjusts to the sun by a solar energy drive mechanism. In particular each module shall be loose jointed to the floor in order to have the possibility to rotate in east-west direction around its bottom tube axis, only supported left and right to be kept balanced in upright position under neutral conditions when the sun is in the zenith.

The most probable technical solution to support the tube is by installing elastic wedges, which would be filled with air or water pumped from one side to the other according to the solar position, Figure 4.3 illustrates this potential design solution. (Note: the present picture shall just demonstrate the support for solar tracking, while the reflector design is another prototype differently shaped to the description earlier in this section). Presently it is not clear if the wedges will be realised to operate pneumatically or hydraulically, but in both options they will be filled or emptied by solar pumps to distribute the working fluid between the two wedged structures. Solar detector cells located on each module take care for measuring the actual solar position and controlling the pump accordingly.

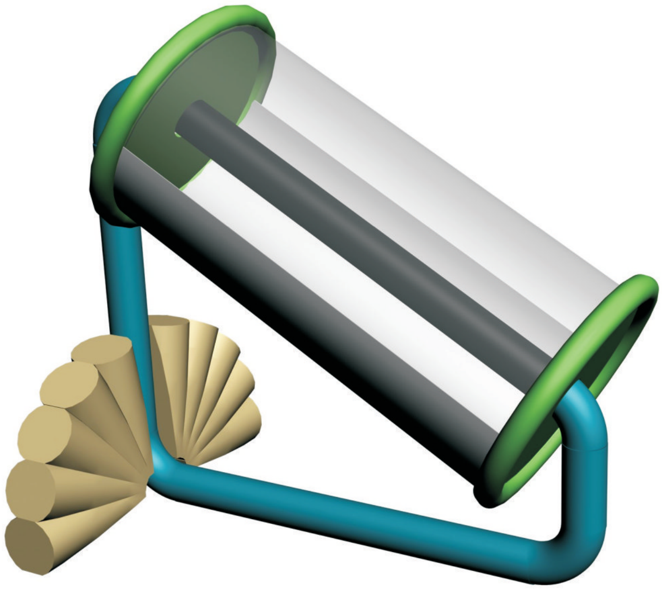

Figure 4.3 : Solar desalination module equipped with solar tracking facility
Solar tracking realised by inflatable wedge system (Kerschgens, 2008)

A further design option to be realised with hoses to rotate not the whole tube frame structure but only the paraboloid mirror is presently also in discussion. These hoses then could turn the mirror when differently inflated according to the solar position, again driven by the solar pump.

Further investigations and testing will show which design will be the final and best suitable one, where besides reliability in operation a significant argument for the design decision will be the shadowing effect of neighbour modules in the morning and evening hours of low angle solar radiation (Duffie and Beckman (2006).

4.3 Detailed Design – Some Features and Estimations to Consider

In this section the design of the emerging desalination module shall be discussed in detail with regard to its foreseen functioning and its performance in freshwater production. Additionally the efficiency of the process shall be analysed in order to detect weaknesses, potential heat losses and find suggestive measures optimise the potential performance of the present system, both for the single module and for reasonable arrangement combinations.

4.3.1 Performance Potential of the Parabolic Collector

The performance of each desalination module is very much dependent on the quality of the solar collector and its efficiency to concentrate the energy irradiated by the sun into the focal plane of the receiver to heat up the fluids circling in the tubular system for promoting evaporation of the introduced water. In the following the potential for optimising the solar collector system shall be estimated and discussed, including an assessment of possible optical and thermal losses, with the ultimate target to develop a design which though shall be simple but as fit as possible for efficient desalination of high availability.

As earlier mentioned the evolving solar desalination modules are in their collector basic design comparable with the parabolic cylinder structures of concentrated solar power installations (4.2.2), a fact which enables for present investigations the application of optical design considerations, efficiency estimations and figures from large-scale installation experiences.

Optical Performance Evaluation

From trigonometric considerations of the arriving sunbeam it is easy to deduct the expected size of its picture reflected onto the cylindrical receiver surface of a parabolic linear collecting system. For specular parabolic reflectors of perfect shape and alignment Duffie and Beckman (2006) calculate in this way the maximum image size displayed on a receiver, when representing all the reflector image of parabolic collector aperture size a_c and rim angle θ_r. For dimensioning the diameter D_r of a cylindrical receiver surface which shall display the total reflector image representing incoming sunbeams of incident angle $2.\theta_s$ the trigonometry leads to following relation:

$$D_r.\sin\theta_r = a_c.\sin\theta_s \ . \tag{4.3}$$

With the angular width of the sunbeam being 32' (= 0.533°) as introduced earlier (4.2.6) the half incident angle θ_s is 16' (= 0.267°) the minimum receiver cylinder diameter D_r necessary to image the whole reflector picture results in

$$D_r = \frac{a_c . \sin(0.267°)}{\sin\theta_r} = 0.0047 \cdot \frac{a_c}{\sin\theta_r} . \tag{4.4}$$

This means that the image size represented here by D_r becomes smaller when the rim angle θ_r of the parabolic shape increases and when the parabolic aperture dimension a decreases. When targeting to get an image as small as possible representing a reflector of dimension as big as possible the concentration would be maximal. Here the earlier introduced concentration ratio (section 4.2.6) comes into play again, where with above relation it can be shown that it increases with increasing rim angle θ_r. Transforming equation (4.4) accordingly as follows provides this concentration ratio.

Earlier defined as area concentration ratio A_c/A_r (section 4.2.6) here this ratio results in a_c/D_r , when considering same longitudinal extensions of reflector and receiver. Being more precise by subtracting the receiver dimension which covers the parabolic aperture in optical ideal case the maximum concentration ratio C_{max} then follows to

$$C_{max} = (a_c - D_r)/D_r = a_c/D_r - 1 . \tag{4.5}$$

Introducing this relation into equation (4.4) provides

$$C_{max} = \frac{\sin\theta_r}{\sin(0.267°)} - 1 = \frac{\sin\theta_r}{0.0047} - 1. \tag{4.6}$$

As mentioned the concentration ratio increases with increasing rim angle θ_r, which means for the design that one should try to consider in planning that the paraboloid is not shaped too flat. For constant aperture dimension a_c this again would mean that increasing the curvature of the parabolic shape increases the performance of the collector system. In practice this would then happen under decreasing the focal length, which results in decreasing the distance between the parabolic reflector and the receiver located in its focal plane.

Figure 4.4 illustrates discussed concentration ratio rise with increasing rim angle. In addition to the virtual ideal case a) as per equation (4.6) also the cases b) and c) considering optical losses as detailed next are displayed in this figure.

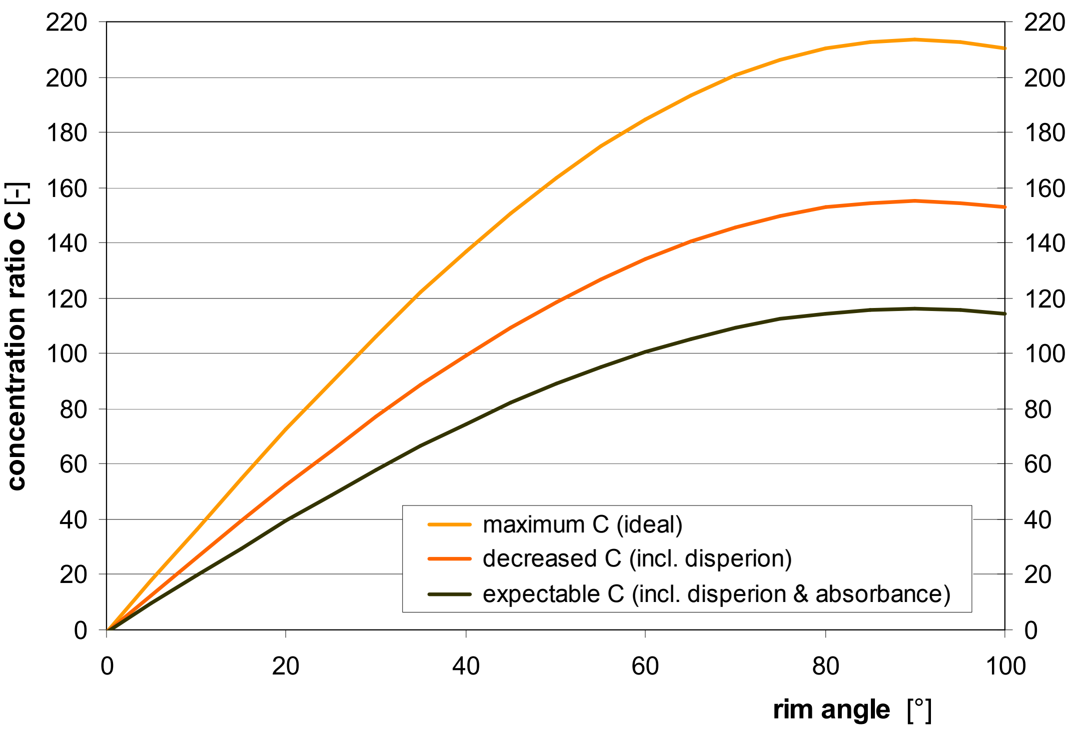

Figure 4.4 : Concentration Ratio variation with parabolic collector rim angle
Potential for raising performance by increasing rim angle, for parabolic linear collectors with cylindrical receiver. a) Maximum C curve: virtual ideal case, b) Decreased C curve: assumed dispersion angle = 0.2°, c) Expectable C curve: assumed dispersion angle = 0.2° and receiver absorbance = 0.75.

Surface imperfections and reflectance losses of the solar collector surface as well as absorption losses and diffuse reflexions of the receiver surface provide for the main optical losses in the course of transmission of solar radiation by the linear concentrator system. There these optical losses can be summed up to

- dispersion of the solar irradiation by surface imperfections, and
- absorption imperfections of the received radiation,

as suggested by Duffie and Beckman (2006). For quantitative estimations these losses are introduced into equation (4.6) by

- adding half of the dispersion angle δ to the half incident angle of the solar beam θ_s (= 0.267°),
- multiplying the absorbance α with the whole term.

Then the equation extends to the definition of the actual expectable concentration ratio

$$C_{actual} = \left(\frac{\sin\theta_r}{\sin(0.267° + \delta/2)} - 1 \right) \cdot \alpha \qquad (4.7)$$

which can be used for performance estimations under variation of the imperfection parameters δ and α as well as of the rim angle θ_r as figure to optimise the design.

For evaluation of the minimum receiver cylinder diameter D_r under considering the dispersion also equation (4.4) adapts analogously to

$$D_r = \frac{a_c . \sin(0.267° + \delta / 2)}{\sin\theta_r} \quad . \tag{4.8}$$

The graphs in Figure 4.4 reflecting the derived relationship show the influences of described imperfections on the concentration ratio varying with the rim angle. In present figure the dispersion angle is assumed with δ = 0.2 which would enlarge the incident angle $2.\theta_s$ = 0.533° by almost 40% which is plausible for non-perfect average quality mirror surfaces. The portion of radiation actually absorbed by the receiver is estimated as α = 0.75, a practical value as displayed by Kalogirou (2004).

For the solar collector of the present prototype the actual expectable optical performance can be estimated with above calculation after having chosen the surface qualities of reflector and receiving tube as well as the material for the receiver itself. This material information is important because it determines both the absorptivity and transmissivity of this pipe, which not only informs of optical losses but also of the overall transmittance of radiation to the fluid inside the tube system.

Optical Design Estimation for the Desalination Module

In the following a first estimation of design and optical performance for the present desalination module shall be conducted. For the module design the reflector dimensions shall be assumed to be 1.5 m x 1 m, which means parable aperture a_c = 1.5 m and cylindrical length b_c = 1 m being also the length b_r of the cylindrical receiver tube to dimension.

Choosing a rim angle θ_r for a reasonable parable shape to be 30°, the minimum cylinder diameter for the receiver to allow imaging of the whole solar radiation reflector picture then results with equation (4.4) for the ideal reflector of zero ray dispersion to

$$D_{r,min.0} = 1.5\,\text{m} \cdot \sin(0.267°) / \sin(30°) = 14.0\,\text{mm} \quad .$$

When assuming that the incoming rays of sunlight are dispersed on the parabolic surface by an angle δ = 0.2° the minimum receiver diameter as per equation (4.8) then would be

$$D_{r,min} = 1.5\,\text{m} \cdot \sin(0.267° + 0.2° / 2) / \sin(30°) = 19.2\,\text{mm} .$$

The actual design foresees to use a tube of 5 cm diameter in the minimum for the evaporator zone of the desalination module where just its bottom side shall serve as receiver to be directly heated up. However it has to be considered that for afore assumed design the superheating channel located in this zone as earlier described (4.2.3) on the bottom of the tubular structure has to have a suiting dimension of around 2 cm width.

Under chosen present design, in the virtual ideal case of 100% optical transmission the maximum concentration ratio would result with equation (4.6) to

$$C_{max,0} = \frac{\sin(30°)}{\sin(0.267°)} - 1 = 107.3 \quad .$$

Supposing again the realistic case with assumed 0.2° dispersion angle and an ultimate absorbance α of radiation transmitted to the receiver of realistically 0.75 (as afore mentioned) the concentration ratio for an imaging parabolic surface then would result with equation (4.7) to

$$C_{actual} = \left(\frac{\sin(30°)}{\sin(0.267° + 0.2°/2)} - 1 \right) \cdot 0.75 = 58.0 \ .$$

Comparing above results for the ideal maximum and the actual expectable concentration ratio, it shows that only by optical imperfections the efficiency of transmission can practically decrease by 46%. For coming estimations this resulting optical performance factor $\varepsilon_{actual} = 0.54$ shall be taken.

For a non-imaging reflector surface this value will be significantly smaller as noted earlier (4.2.6, Duffie and Beckman, 2006). Actual testing of material shall provide an optimum solution for the design of the emerging desalination module.

Taking now an average incoming solar energy flow of 0.7 kW/m² irradiated on a hot sunny day vertically towards the earth surface (3.1) and the fact that the present system is capable to track the annual solar radiation (4.2.6), which means that the radiation is coming orthogonally onto the reflector surface, then the energy potentially absorbable by the receiving tube can be estimated. This incoming energy namely will reduce by above mentioned transmission efficiency considering the optical imperfections. Thus by multiplication of the incoming solar energy flow with the relationship between actual and ideal concentration ratio, the actual absorbable specific energy to enter the receiver tube then follows as

$$q_r = 0.7\,\text{kW/m}^2 \cdot C_{actual}/C_{max,0} = 0.4\,\text{kW/m}^2 \ .$$

It shall be noted that this specific energy flow is related to one m² surface area exposed to solar radiation and not to the solar collector aperture area. The evaluated figure itself shall be used for the heat balances of the single desalination modules as presented in coming chapter 4.

The result again points out that in the course of collecting and concentrating solar irradiation the energy reduces by around 46% just by optical transmission imperfections. When choosing a larger parable rim angle to have an expectable higher concentration ratio this portion even increases as Figure 4.4 shows.

Finally the energy input into the evaporator per unit receiver length $b_r = 1$m will be

$$Q_{r/m} = 0.4\,\text{kW/m}^2 \cdot 1\text{m} = 0.4\,\text{kW/m} \ .$$

Any shading by the receiver itself is already considered here by the concentration ratio definition as per equation (4.5). However when assuming that the considered module may be partly shaded by a neighbouring module as mentioned (4.2.6) especially in the morning and later afternoon hours then the estimated expectable energy can diminish by a factor.

With above figures the energy flux to potentially flow into the receiving tube will be

$$\Phi_r = e_r \cdot C_{actual} = 0.4\,\text{kW/m}^2 \cdot 58.0 = 22.0\,\text{kW/m}^2 \ ,$$

a figure useful for estimations of the energy transport estimations.

4.3.2 Performance Estimation for a Single Desalination Module

The following estimation shall give an idea of the possible daily water production quantity to expect for the operation of the emerging desalination module. It bases on a simple thermodynamic calculation adopting a similar approach as preceded earlier (3.2) to outline the limits for solar evaporation. Based on the fact that the solar energy input provides the energy effort to evaporate a specific amount of water, here it shall be presupposed that a major portion of the released latent heat of condensation is recovered by the system as stipulated by the module design principle (4.2).

Basic Formulations and Performance Arguments

For the evaluation itself the data already used or calculated in section 4.3.1 before shall provide the base, in particular the average solar irradiation on a hot sunny day shall account for 0.7 kW/m² orthogonally arriving on the collector system, where the optical performance of the collector shall be 0.54, which results in the expectable energy arriving in the receiving tube q_r of approximately 0.4 kW per m² irradiated surface area. However for reviewing the potential design performance of the desalination module and its design range of operation also higher irradiation energy data shall be used as calculation inputs.

Multiplied with the duration t_{irrad} of daily solar irradiation of given averaged intensity this given solar irradiation input provides the energy amount available to care for evaporation of the water processed within the desalination module.

Dividing described available energy amount per day by the effective heating enthalpy effort $h_{evap.eff}$ per kg of water which again shall consider heat recovery and thermal losses, the daily water production volume can be calculated as

$$\dot{V}_{prod,i}\left[\frac{\text{litre/m}^2}{\text{day}}\right] = \frac{q_r\left[\text{kW/m}^2\right]\cdot t_{irrad}\left[\text{h/day}\right]\cdot 3600\left[\text{s/h}\right]}{h_{evap.eff}\left[\text{kJ/kg}\right]}\cdot\frac{1}{\rho_{water}\left[\text{kg/litre}\right]} \tag{4.9}$$

with ρ_{water} being the water density as per Table 3.1.

From the total heat released during condensation of the product water the portion r, defined as recovery rate, can be provided to heat the incoming raw water. The remaining heating effort is afore introduced effective heating enthalpy, mathematically to formulate as portion (1 - r) of the available released heat. To consider the energy losses to the ambiance in the calculation model the heat loss factor λ shall be employed by multiplication. These heat losses to the surrounding atmosphere via heat transport through the pipe wall occur by the driving force of temperature difference between inside and ambiance. In the succeeding modelling presented in section 4.3.3 such losses will therefore be modelled as function of this temperature difference and thus be different for each operation case. However for the rough estimation presented here a suitable multiplier shall be sufficient.

Derived from the evaporation enthalpy of water defined in equation (3.1) earlier, the effective specific heating enthalpy then results with the formulations above in

$$h_{evap,\,eff} = \left(c_{water}\cdot\Delta\vartheta_{water.sup} + h_{latent,\,water}\right)\cdot(1-r)\cdot(1+\lambda) \tag{4.10}$$

Different to equation (3.1) is here that the heat term in parenthesis displays the released heat during condensation and supercooling of the product water which means that the temperature difference $\Delta\vartheta_{water.sup}$ is just the extent of supercooling below condensation temperature, which practically will just be some degrees centigrade. Since anyhow being much smaller than the latent heat as analysed in 3.2, the term for supercooling is almost negligible for this estimation (as experienced in the actual estimation below).

Practically the heat transfer from the condensing product to the inlet raw water will also take place via the air within the tube system, which not only is present there, but also dominates the circular convection. And therefore this air will also dominate the temperature adjustment throughout the whole system. Furthermore it can be assumed therefrom that in the condensing zone the temperature of the forming condensate and the air temperature will be quite in the same range because while the first will tend to release its latent heat, the second will tend to marginally heat up, which again would hinder the condensing progress. The practical solution then would be a heat balancing between these two fluids targeting on temperature equilibration and hence tending to mutually providing the latent heat to the cooler raw water inlet. These conclusions reflect some of the experiences of the model calculations for the single module as detailed next in section 4.3.3.

Thus it can be assumed that both the produced freshwater and the air will leave the condensing zone with the condensate supercooling temperature being just a few degrees below the condensing temperature of the product. And referring to afore-mentioned conclusions the resulting temperature difference will be almost negligible compared to the potential latent heat release.

Expected Performance of the Module

Finally, with the comprehensive formulations above and the data provided at the beginning the performance for one single desalination module can be evaluated as follows.

As mentioned before for reviewing the potential design performance of the desalination module and its design range of operation the radiation energy input data from 0.7 kW/m² to 1.4 kW/m² shall be taken, where the latter is reflecting the virtual absolute maximum for designing the system, since it describes the solar constant (3.2). Multiplied with the assumed optical performance of 0.54, the actual data for the solar input actually entering the receiver tube, referred to as specific solar energy flow q_r provides one parameter for the evaluation. It shall be reminded here that this specific energy is related to the irradiated surface area and does not reflect a flux into the system as argued earlier (4.3.1).

Further it shall be conservatively assumed that the recovery of heat released, mainly latent heat of condensation shall be 70 % of the heat input ($r = 0.7$) and the heat losses mainly by transport from the tubular desalination structure to the ambiance shall account for 20 % of the heat to provide ($\lambda = 0.2$). These values reflect practically expectable figures for the first generation design of the emerging module, which are supported by some test runs of a first prototype. However in the course of further development both heat recovery efficiency and heat losses will assumably reduce.

Besides, for coming estimations the condensate supercooling was properly chosen for the different calculation cases by choosing the temperature difference $\Delta\vartheta_{water.sup}$ between 6°C and 10°C. But anyhow, as afore mentioned, the belonging enthalpy portion term resulting therefrom practically did not influence the results of the evaluation.

Combining all these figures under application of the equations (4.9) and (4.10) the expected water production of the desalination module can be estimated by variation of the two input parameters, on the one hand the daily sun irradiation time and on the other the specific solar energy input. The whole performance area to expect for the module throughout its operation range up to the maximum limits is displayed in Figure 4.5.

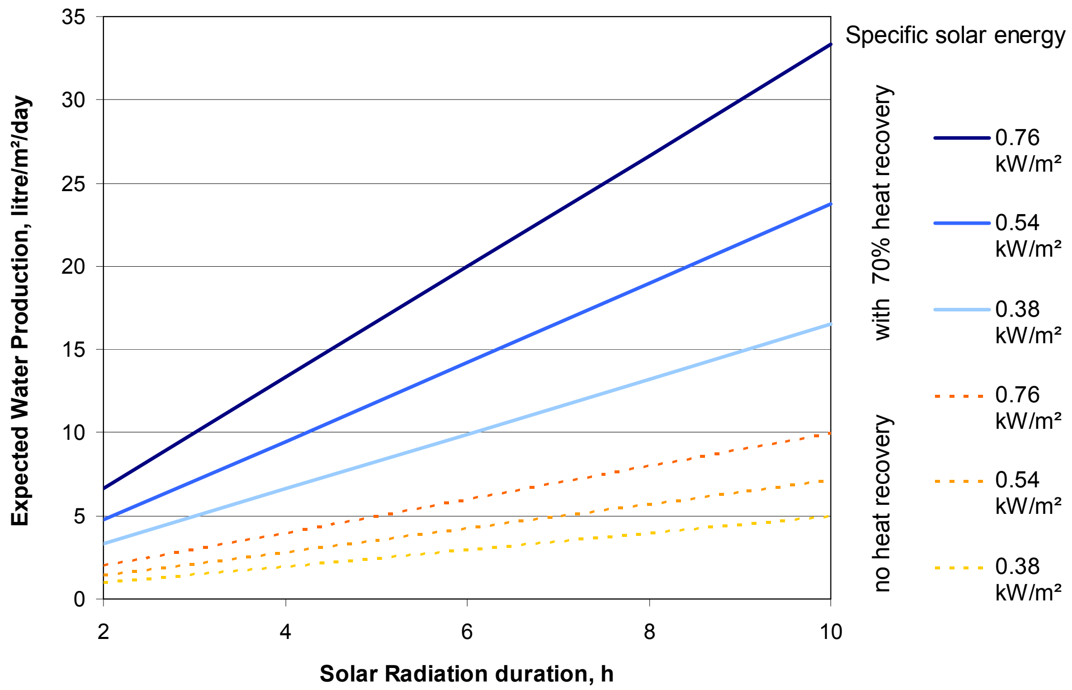

Figure 4.5 : Expected water production of a single desalination module
Distinction: Case 1: 70% heat recovery (mostly latent heat) – practical
Case 2: without any heat recovery – not practical
Comparison for 3 different solar energy inputs into the piping system:
a) Theoretical maximum (irradiation with 1.4kW/m², b) High peak average,
c) High average. Optical performance of collector system: 0.54.

The results of the evaluation provide expectable values for daily water production on a sunny day between 10 and 25 litres per m² of surface area for a single desalination module under the conservative assumption of 70 % heat recovery within the system and 20 % additional effort to cope with heat losses. These figures are quite reasonable because they fit to a first prototype test run and they are in a magnitude where practical small-scale solar thermal desalination systems operate, as comparisons of latest innovative installations by Ettouney and Rizzuti (2007) show. In their analysis of different so-called ‘novel cycles’ for thermal water processing they write of daily production rates per m² of surface area between 10 and 40 litres for single installations of adequate technology under sunny conditions. And in the same context they also mention that these figures even can rise to between 50 and 100 litres per m² in case of combination with a kind of thermal storage like a hot water storage tank as presented later (4.3.4).

Besides the taken case of 70% heat recovery also the fictive case if none of this released process heat would be used is shown in Figure 4.5. Then the performance would dramatically decrease to a level neither justifiable nor economic for operation. However the present design anyway excludes such an operation of zero recovery under the expected conditions. However, as argued earlier in the context with process optimisation (4.2.4), extreme heating cases which would hinder proper condensation of the product, could reveal similar performance losses despite the fact of raised evaporation. Then, because of excessively raised temperatures within the tube system, the condensate could not form which would result in superheated steam circulating within the system and finally diminishing freshwater production.

Finally, by analysing the evaluation results, it can be concluded that the calculation provides data which could be expected from the actual single module design, and that this system to investigate on is very likely to produce freshwater of an amount competitive with the other solar thermal desalination technologies as figured out above. However a certain uncertainty in present estimations is still provided by the figures for thermal losses of the system including the heat recovery rate. For further, more detailed calculations these terms have to be observed and continually improved by growing experience obtained on the one hand from testing prototypes and on the other hand from numerically modelling the system. Within this document additional evaluations shall further reveal present design, functioning and performance of the system as well as provide a base to verify optional operation in group installation and in combination with heat storage systems. These further investigations are discussed in succeeding sections (4.3.3, 4.3.4).

Potential for Performance Enhancement

In the previous performance assessment above the losses were assumed in a rather conservative way to probably approach the performance of the actual desalination module prototype as far as possible. And the relevant evaluation results also show reasonable performance figures comparable with practical data as mentioned.

Here the potential for further development of the desalination system shall be suggested under assuming that by increasing experience and further investigations the design of the single module is continually evolving in such a way that the next generation prototype is going to have improved performance in regard to water production as a direct cause of thermal losses reduction. Thus it is evident that further development of the system will focus on raising the heat recovery efficiency and reducing the heat losses through the system borders.

In this context it should not be forgotten that the mentioned heat losses would also include heat flows leaving the system with the leaving product and the rejected brine, where the second is expected to by far account for the major portion as shown later (4.3.3). Although these losses can be reduced by optimising the heat exchange within the system they can never be avoided. Such losses by leaving fluid flows are comprehensively discussed later (4.3.3, 4.3.4) where heat and mass balances of the system are conducted to survey the operation of the system.

Figure 4.6 shall provide an idea of the assumable potential for reasonable enhancement of the freshwater production performance in comparison to the figures previously calculated. There the heat recovery in the present upgraded evaluation case, named as Case 2 has been raised to 80 % (r = 0.8) compared to the 70 % in (r = 0.7) the previous case, displayed here as Case 1. Additionally the heat losses to be coped with by additional provision of solar energy were reduced for the revised Case 2 by 10 % from the original value $\lambda = 0.2$ to $\lambda = 0.1$.

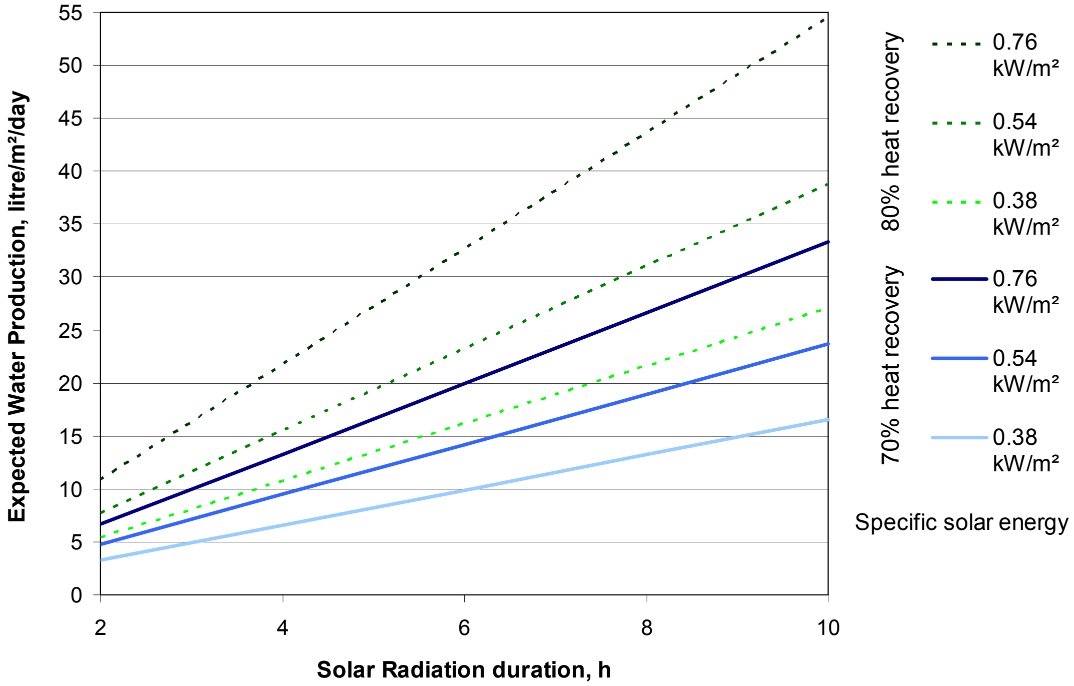

Figure 4.6 : Water production potential of a single desalination module
Distinction: Case 1: 70% heat recovery (mostly latent heat) – practical
Case 2: 80% heat recovery (mostly latent heat) – potential
Comparison for 3 different solar energy inputs into the piping system:
a) Theoretical maximum (irradiation with 1.4kW/m², b) High peak average,
c) High average. (p = 0.54, Case 1: λ = 20%, Case 2: λ = 10%)

The results displayed in Figure 4.6 show that the potential increase of performance by investigating on heat recovery enhancement and heat losses reduction the performance may increase significantly.

Thereby the major influence comes from the ameliorating effect of the heat recovery improvement which changes the necessary energy effort to introduce into the system by the number (1 - r) as per equation (4.10) with r being the recovery rate. Expressed in numbers the energy effort then reduces from 30% before to 20% in the enhanced case, which means a diminishing of the necessary effort itself by 50%. On the other hand the factor for the heat losses to be coped with by the described heating energy effort reduces this energy just by 10% as per equation (4.10) by changing its multiplicative contribution from 1.2 to 1.1. In total the contribution by this potential performance enhancement then accounts for (30/20*1.2/1.1 – 1) = 0.64 or 64%.

Finally Table 4.1 lists the evaluation results for days of persistent vertically arriving sunshine where the daily yields for the case of 70% heat recovery and the potential case to recover even 80% are compared (including mentioned heat losses consideration). It shows that the daily freshwater production of one module related to one m² of surface area can be quite considerable. There production rates around 20 litres per m² and day can be expected for single module arrangement at days of enduring sunshine at high incidence angle. These values then could potentially even more than double for optimising the system itself as presented above, by arranging the modules with each other in optimised combinations and finally by possibly combining the system with a heat storage system as discussed later (4.3.4).

Table 4.1 : Potential daily water yield per module at high solar radiation
Comparison for practical 70% and potential 80% heat recovery
(Case 1: $r = 0.7$, $\lambda = 20\%$, Case 2: $r = 0.8$, $\lambda = 10\%$)

Heat Recovery	Daily Solar Irradiation	Daily Water Production [litre / m² / day]		
70 %	6 hours	9.9	14.2	20.0
	8 hours	13.2	19.0	26.7
	10 hours	16.5	23.7	33.3
80 %	6 hours	16.2	23.3	32.7
	8 hours	21.6	31.0	43.6
	10 hours	27.1	38.8	54.5
Solar Irradiation Conditions		High average & vertical	High peak & vertical	Virtual absolute maximum
Solar irradiation energy		0.7 kW/m²	1.0 kW/m²	1.4 kW/m²
Utilisable solar heat		0.4 kW/m²	0.5 kW/m²	0.8 kW/m²

As conclusion for potentially improving the overall process it can be advised to firstly concentrate on optimising the heat recovery potential from the condensation effect, which also means to care for avoiding superheating the system, which would reduce the portion of product to condensate as discussed in previous section. The second emphasis naturally shall be to provide for appropriate insulation of the system to reduce any heat losses, a fact which is relatively straightforward to be realised. And then, the third issue to concentrate on is afore mentioned target on allowing as little energy as possible to leave the system primarily with the brine flow and secondarily with the product, without being utilised.

4.3.3 Operation Potential of a Single Desalination Module

In the coming evaluations the performance of a single desalination module shall be estimated and discussed, followed by an analysis of potential improvements to consider for the operation of the system. Therefore a comprehensive mass and energy balance for the whole module has to be conducted under taking actual design figures as inputs.

Mass and Energy Balance for the Single Module

Balancing the masses entering the system and leaving it seems simple, as its design principle suggests (4.2) that there is only one flow of water entering the system, and two flows leaving the system. And the overall balance for the module becomes even simpler with the design condition that all phase change shall be completed within this system, which practically means that although evaporation and condensation will take place inside the system, only water in the liquid aggregate state shall enter and leave each module.

In detail for the single module i these three mass flows are

- the inlet raw water flow as feed water flow $\dot{m}_{feed,i}$ to be desalinated,
- the freshwater flow providing the product flow $\dot{m}_{prod,i}$ of the processed condensate, and
- the brine flow $\dot{m}_{brine,i}$ of the rejected salinity-enriched water leaving the system.

Formed as an equation the relationship between theses three mass flows finally provides the mass balance for the single module i as

$$\dot{m}_{feed,i} - \dot{m}_{prod,i} - \dot{m}_{brine,i} = 0 \quad . \tag{4.11}$$

The second imperative for the following calculation is the energy balance of the module, where the most important input is provided by the irradiated solar energy as ultimate driver for the total process to run within the tubular desalination system. The other sources and sinks of heat crossing the system borders of the module originate from the mentioned three water mass flows. Considering heat losses with a further term, the heat flows balancing the energy content of each module i can be listed as

- the heat energy from solar radiation entering the tube system, in short the specific solar heat flow $q_{r,i}$,
- the energy content of the inlet water flow, expressed as feed water heat flow $q_{feed,i}$,
- the energy content of the leaving freshwater flow, expressed as product heat flow $q_{prod,i}$ of the processed condensate,
- the energy content of the leaving brine flow, expressed as brine heat flow $q_{brine,i}$, and
- the heat losses $q_{loss,i}$ leaving the tube system driven by the temperature gradient between the fluids flowing in the tube system and the ambience.

Since all water flows enter or leave the system borders as afore mentioned in the liquid aggregate state, each of the fluid heat flow calculates just by multiplying its mass flow with the specific heat capacity for liquid water c_{water} and the temperature difference of the fluid in relation to given base conditions. The heat capacity variation with temperature and pressure shall be neglected for the following calculations because especially for liquid water within the given range of the expected thermodynamic conditions[10] the fluctuations are quite small and thus without potential influence on the result. Therefore the value for c_{water} from Table 3.1 can be used. Uniting above notes and definitions the heat energy balance for the module i can be formulated as

$$q_{r,i} + c_{water} \cdot \left(\dot{m}_{feed,i} \cdot \vartheta_{feed,i} - \dot{m}_{prod,i} \cdot \vartheta_{prod,i} - \dot{m}_{brine,i} \cdot \vartheta_{brine,i} \right) + q_{loss,i} = 0 \,. \qquad (4.12)$$

There the temperatures have to be related to base conditions, which here can be chosen to be the raw water inlet temperature, so that the temperature differences above this base provide the degree of energy content of the particular flows above the base state of the inlet water accounting for zero energy input into the system. In particular by introducing the appropriate temperature differences related to the inlet water into equation (4.12) the heat balance for the module i follows with $\Delta\vartheta_{feed,i} = 0$, $\Delta\vartheta_{prod,i}$, $\Delta\vartheta_{brine,i}$ as

$$q_{r,i} + c_{water} \cdot \left(\dot{m}_{prod,i} \cdot \Delta\vartheta_{prod,i} - \dot{m}_{brine,i} \cdot \Delta\vartheta_{brine,i} \right) + q_{loss,i} = 0 \,. \qquad (4.13)$$

For the modelling it shall be assumed that due to intense contact between condensing product and the circulating surrounding air the temperature difference between these two media shall be negligible in the condensing zone where the air presumably will take up a considerable portion of the released latent air and thus also participate in the heat transfer to the inlet raw water. This assumption is based on the explanations in section 4.3.2 in this context. To consider this heat transport to the inlet raw water the modelling shall approach this mechanism by iterative suitable choice of a supercooled condensate temperature to fit both into mass and heat balance and to allow heating up the incoming water with certain efficiency, here named as heat transfer efficiency ν_{feed}. This factor, suitably chosen shall be adjusted with modelling experience.

Finally the salinity of the brine leaving the module can be calculated easily from the inlet water salt content by mass balancing. Since the salinity of the produced freshwater has to be zero the brine salinity for the module i then results in

$$s_{brine,i} = \frac{\dot{m}_{feed,i} \cdot s_{feed,i}}{\dot{m}_{brine,i}} \,. \qquad (4.14)$$

Performance Evaluation for the Single Module

The evaluation shall again base on the data input used earlier (4.3.1, 4.3.2) which means an average incoming solar energy of 0.7 kW/m² orthogonally irradiating onto the collector on a hot sunny day, before being transferred to the desalination system

[10] Expected temperature and pressure range for entering and leaving water flows: 30°C - 90°C, 1 bar – 5 bar.

with an optical performance of 54 %, all of it again resulting in an expectable energy provided to the receiving tube q_r to be approximately 0.4 kW per m² irradiated surface area. Based on this figure, like in the previous evaluations the design of the desalination module shall be reviewed by also including operation cases of higher energy input up to the virtual maximum. Additionally the physical properties of water as per Table 3.1 shall apply here as well.

As only water input the inlet raw water flow shall have an inlet temperature $\vartheta_{feed,i}$ of 30°C and an inlet salt content $s_{feed,i}$ of 3.5 mass percent.

The heat recovery r in the coming approach shall be 70 % like in the previous evaluations (4.3.2), however here it shall mathematically not be applied on the total system like before but on an internal control volume within the condensation zone. The difference in present model consequently is that equation (4.10) to calculate the effective enthalpy as energy effort changes here by using the actual temperature difference to heat up the already preheated raw water to its boiling temperature. While the preheating temperature results with above introduced heat transfer efficiency ν_{feed}, the boiling temperature for the model has been chosen to be 100°C despite the fact that it probably will be slightly higher because of the inlet water salinity and the expectable operating pressure within the heating zone above atmospheric pressure. However for the first modelling choice is fine enough because the contribution of the temperature difference term to the resulting heating enthalpy is small compared to the added latent heat of evaporation as mentioned earlier (3.2, 4.3.2).

Also the heat losses in this calculation shall be dealt differently compared to previous calculation. Here they shall not be applied on the heating enthalpy effort as for the overall estimation according to equation (4.10), because in the present case they are part of the heat balancing as per equation (4.12). So while in equation (4.10) the losses contribution λ shall be zero the heat losses $q_{loss,i}$ instead are to be applied in the heat balance (4.12) to calculate the brine flow with the other inputs as afore described and the heat losses themselves to be a adopted as certain portion of the energy input $q_{r,i}$ into the system. As argued in section 4.3.2 the heat losses are expected to be mainly lost to the surrounding atmosphere via heat transport through the pipe wall by the driving force of temperature difference between inside and ambiance. For that reason these losses are modelled here as

$$q_{loss,i} = \frac{\vartheta_{inside,i} - \vartheta_{ambient}}{\Delta\vartheta_{max}} \cdot \lambda_{loss,i} \cdot q_{r,i} \ . \tag{4.15}$$

There the temperature inside the piping system $\vartheta_{inside,i}$ is approximated as the average air mass temperature inside the tube system, the ambient temperature is assumed $\vartheta_{ambient}$ while the loss factor $\lambda_{loss,i}$ is to be feasibly chosen by practical experience and by continual research in the course of modelling. Being a function of the temperature difference to the ambiance these heat losses are different for each operation case, with a virtual maximum value $\Delta\vartheta_{max}$ at virtual maximum solar irradiation. For that reason the case specific temperature difference is compared to this maximum in the formulated relationship, allowing that low performance cases of low tubing system temperature the losses will be lower than for high solar heating scenarios.

The results of present model calculations to evaluate the operation potential of a single desalination module finally were obtained by numerical iterative application of mass and heat balancing as described above under application of the relevant input figures as introduced and the choice of some essential parameters as follows.

There the heat transfer efficiency ν_{feed} describing the heating of the raw water input proved to provide realistic results for the simulation calculation at a value of 0.8, a value also reasonable when imaging the efficiency limits of heat exchangers. The heat losses $\lambda_{loss,i}$ on the other hand were chosen for the first modelling practically as to be 0.1, which would cause maximum theoretical heat losses of the total tube system at virtual maximum solar load to be 10 % of the solar energy input, while in cases of lower heat provision the losses shrink significantly as the results show.

Comparing the results of present evaluations in regard to freshwater output with the approximate performance estimation in 4.3.2 they appear to produce results not far-off the previous figures as presented in Table 4.2.

Concluding these first results it can be expected that on normal sunny days of intense orthogonal solar irradiation the desalination module could produce around 1.5 litres of water per hour and m² of surface area which again would reflect the earlier (4.3.2) estimated 15 or maybe a little more litres a day for the assumed case of 70 % recovery of latent heat and moderate heating losses. Improvements of the system as mentioned of course would raise the performance evaluable with this model in similar order as already discussed.

Taking the actual design of the module as introduced in section 4.3.1, which means an aperture surface of the solar collector of 1.5 m x 1m, or 1.5 m², then the single module actual output increases by 50 % to 2.3 litres of hourly water production per module, making on a whole day of sunshine up to around 20 to 25 litres.

Table 4.2 : Water yield modelling: comparison of different evaluation results
Comparison for 70% heat recovery, solar radiation orthogonal onto collector. Evaluation A: performance estimation as per 4.3.2: λ = 20%. Evaluation B: mass and energy balance modelling as per 4.3.3: ν_{feed} = 0.8, $\lambda_{loss,i}$ = 10%)

Evaluation	**Water Production per hour [litre / m² / hour]**		
A: Performance estimation	1.65	2.37	3.33
B: Balance modelling	1.55	2.29	3.34
Solar Irradiation Conditions	High average & vertical	High peak & vertical	Virtual absolute maximum
Solar irradiation energy	0.7 kW/m²	1.0 kW/m²	1.4 kW/m²
Utilisable solar heat	0.4 kW/m²	0.5 kW/m²	0.8 kW/m²

The water balance and the actual water production of a single desalination module resulting from present calculations are compared in Figure 4.7 for the three specified design loads. It shows that the freshwater conversion rates would be around 11 % for the single desalination module under normal intense solar radiation conditions. This is an expectable figure for thermal desalination by a just single module as earlier mentioned (2.3.1), especially in case of still not best developed technology and the consideration of the single module performance only. Proven thermal desalination technologies usually operate in serial combination of single desalination stages to in total allow for higher total conversion rates and besides increase the thermal efficiency by this measure. Further performance enhancement of the present desalination module shall be a matter of future investigations where possible system combinations by module interconnections or use of a thermal storage facility are expected to definitively raise this conversion rate. Approaches to such potential solutions are presented in section 4.3.4.

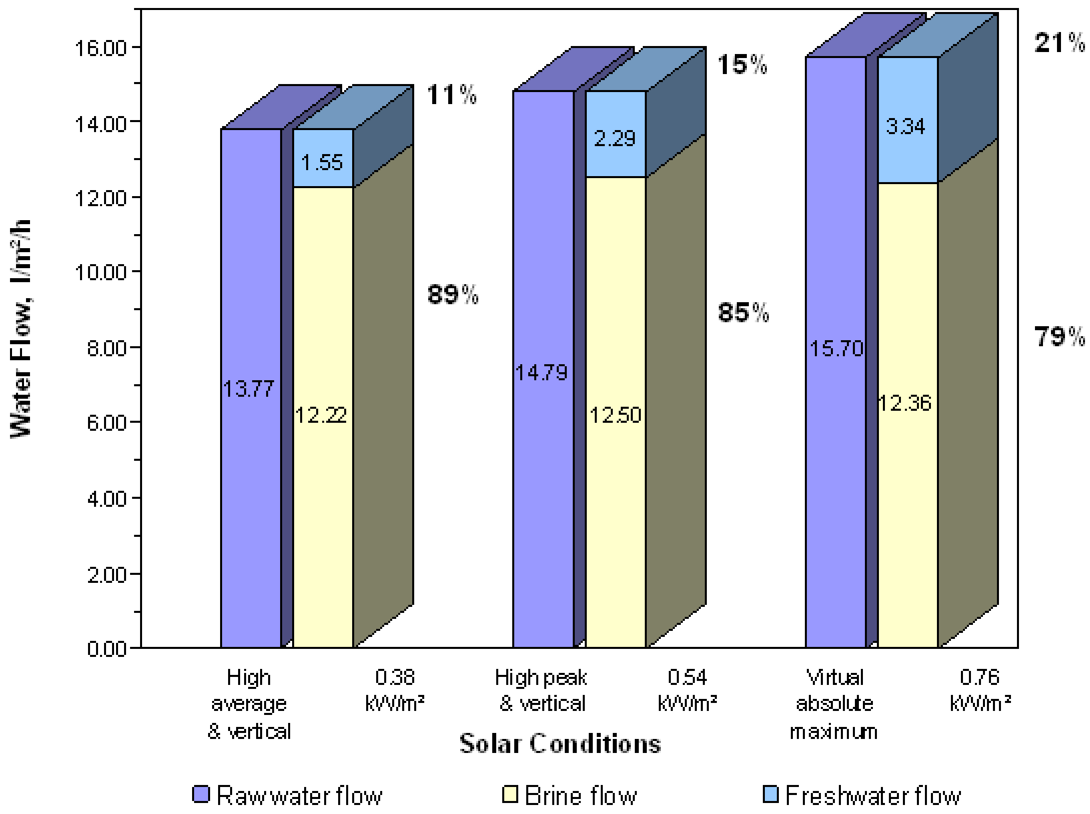

Figure 4.7 : Water Balance & Production for a single desalination module
70% heat recovery, 10% Total heat losses
Comparison for 3 different solar energy inputs into the piping system:
High average, High peak average & Theoretical maximum irradiation.

Comparing this result with the case of high peak solar irradiation or even with the virtual maximum case scenario Figure 4.7 shows different raw water input flows, because the calculation base is that mathematically the solar energy input directly relates to the freshwater production, while the other water amounts follow with mass and heat balancing. But anyway the amount of product and the percentage relations between the water flows are the essential results of this evaluation. However for the operation of the system it shall be noted that a water supply system either can provide for only a constant water amount or otherwise can control this amount under consideration of solar conditions. Which design ever will be realised one has to take care to never allow that the freshwater production may be confined to rates below the actual potential defined by the solar energy only because of raw water undersupply resulting from design fault.

Brine Rejection: Waste of Water and Energy or Recovery Potential

When having just moderate conversion rates of mentioned 11 % logically the amounts of brine rejection are considerable as shown in Figure 4.7. And with expectable 89 % salinity enriched rejected water for the average operation day of intensive sunshine this amounts to more than 12 litres per hour and m² of surface or for the assumed 10 hours of this average sunshine intensity this would then result in more than 120 litres per m².

Again multiplying this amount with the module aperture surface of 1.5 m², the figures for the single module then could even make more than 18 litres per hour or around 180 litres at each sunny day of operation. This considerable amount has to be thought about when planning to install the present solar desalination system, especially in remote areas where discharge may be problematic.

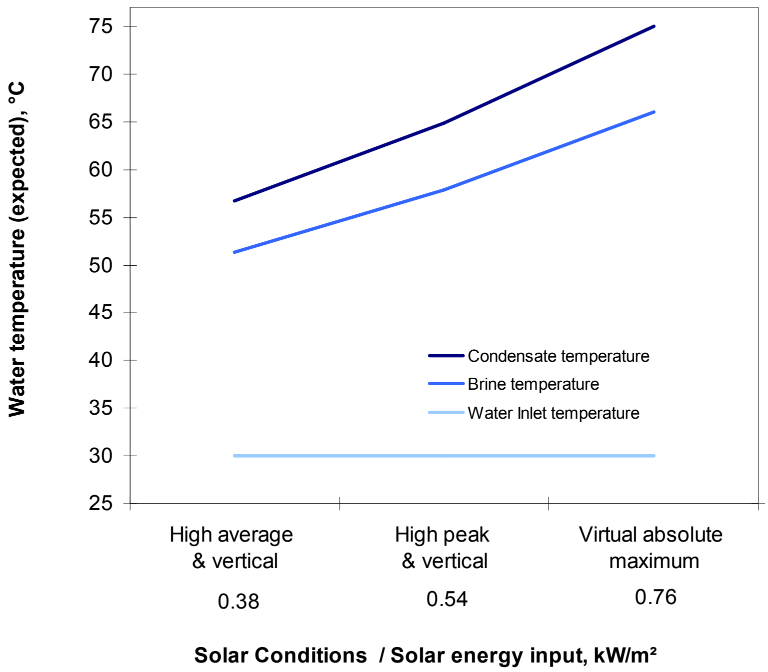

Figure 4.8 : Expected water temperatures for inlet and outlet water flows
70% heat recovery, 10% Total heat losses
Comparison for 3 different solar energy inputs into the piping system:
High average, High peak average & Theoretical maximum irradiation.

Continuing the thoughts concerning the brine as waste product under consideration of the energy potential contained in it being wasted, it can be assumed that this rejection water leaves the module with expectable temperatures of around 60°C and more under the given operating conditions. Temperatures within this range were identified in the course of present evaluation as displayed in Figure 4.8 in common with the expectable condensate temperatures, all based on the given raw water inlet temperature of 30°C. Due to the modelling and the lack of real data from measurements these results at the moment contain a certain uncertainty and therefore the exact numbers cannot be taken for granted, however they fit in their dimensions into the calculation model. This shows that the values cannot be far of the ones displayed in Figure 4.8 because else the iterative balancing could not provide for a reasonable result.

Although the temperature values of the condensate are expected to be also in the region of the brine temperature estimations, maybe even slightly higher, the energy to leave with the product flow is expected to amount to much less than the loss caused by brine because of afore discussed relatively small product flow portion.

With these estimated brine and product water temperatures the energy flows out of the module caused by the relevant two water outlets can be calculated with the appropriate energy terms taken from the heat balance defined by equation (4.13) as

$$\dot{m}_{prod,i} \cdot c_{water} \cdot \Delta\vartheta_{prod,i} \quad , \quad \dot{m}_{brine,i} \cdot c_{water} \cdot \Delta\vartheta_{brine,i} \quad . \tag{4.16}$$

Previous determination of the temperature base for to energy balancing to be set equal to the raw water inlet temperature of 30°C provides that the energy introduced into the system by the inlet water is by definition equal to zero. The only resting energy input then is the provided solar heat flow $q_{r,i}$.

Considering the energy losses as earlier defined (4.15) these energy flows resulting from the evaluation are displayed for the single desalination module and again compared for the three solar irradiation design cases in Figure 4.9.

As suspected the leaving brine is responsible for the by far major energy flow out of the desalination module. Figure 4.9 clearly depicts that in present single module design arrangement this heat loss accounts for almost all energy provided by solar irradiation, as displayed its loss contribution is considerable 80 %.

Consequently it can be deduced that utilising solar power for this kind of desalination without any energy recovery implicates that by far most of this energy is gone with the brine. And this argument can be derived for all thermal water processing technologies if the do not care to recover their leaving losses.

In comparison the expected heat losses by the leaving freshwater product accounts for around 13 % of the total while the heat losses via the piping system to the atmosphere defined per equation (4.15) make around 7 %. As previously argued these losses bear a certain uncertainty by the model assumptions used for this calculation and may differ slightly in reality, but the resulting figure allows for comparing the magnitudes of losses, which clearly are dominated by the leaving brine flow. And furthermore, the losses to the surrounding atmosphere can be coped with or practically limited by technical insulation solutions, whereas the potential brine losses are in no way avoidable in case of thermal desalination processes. But they can be significantly reduced by recovery solutions as presented later (4.3.4).

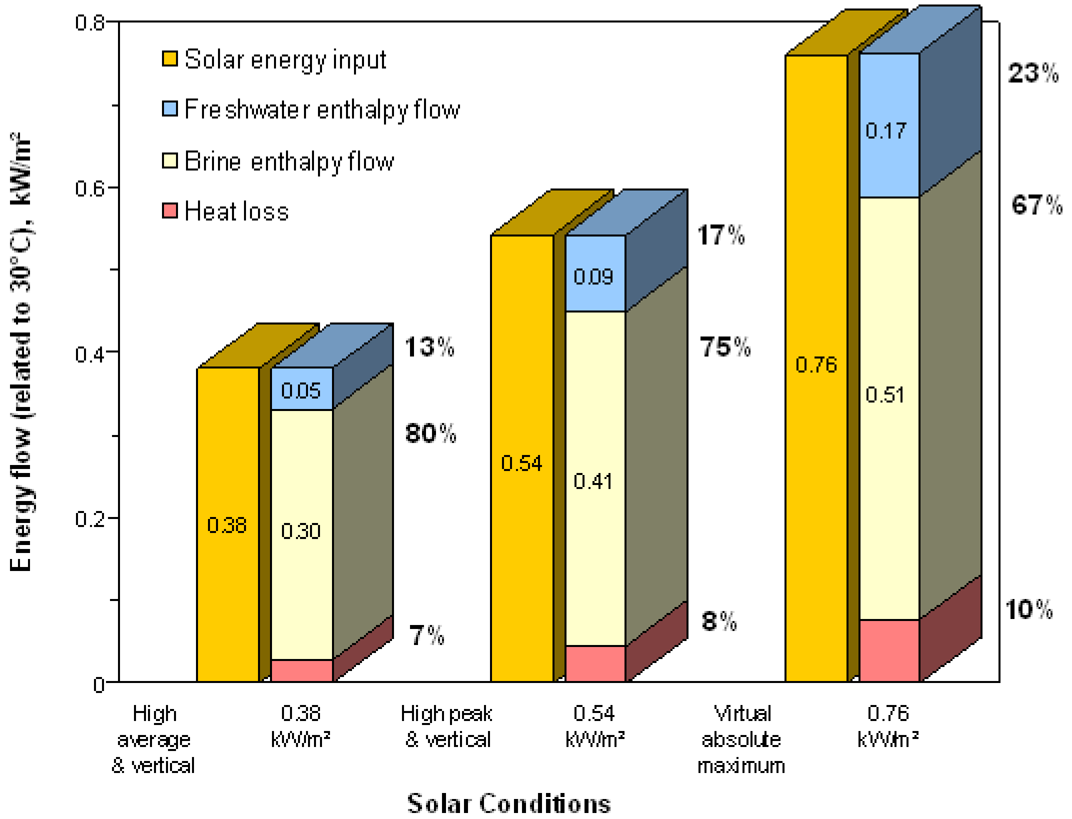

Figure 4.9 : Energy input & output flows for a single desalination module
70% heat recovery, 10% Total heat losses
Comparison for 3 different solar energy inputs into the piping system:
High average, High peak average & Theoretical maximum irradiation.

Conclusions for Successive Research

When concluding the arguments above it can be argued that further development of the desalination module itself will not be sufficient to design a proper system for efficient water preparation under consideration of both low cost and appropriate efficiency.

Furthermore one should pose following questions to be dealt with when continuing the development of present desalination system by practicable approaches in order to reduce any losses caused by the process itself:

- Would it make sense to arrange a kind of serial combination of the modules by reusing the brine in order to decrease its amount under further concentrating to higher salinity?
- Would it be feasible to utilise the wasted heat by storing it or providing for its transfer to the raw water inlet in order to again introduce this energy into system?

These possibilities for improving the present system by specified design arrangements are further discussed in the following section 4.3.4.

For further mathematical modelling of the desalination module it can be concluded that the present modelling of the losses to the ambiance with equation (4.15) seem to be reasonable for obtaining sound calculation results, however their dimensions still need to be proved by further calculations and future test runs of the desalination module.

Actual measurements in the field shall be used to directly update the calculations with series of proper data input finally targeting on the development of a comprehensive calculation model fit for simulation of a huge variety of operation conditions as realistic as possible.

4.3.4 Combined Operation to Increase Efficiency and Output

Previous evaluations of the single desalination module operation could prove in numbers that the major output of this process is not the freshwater as product targeted on but the brine as rejected waste of the process. This certainly is not just the case for the present solar powered modular design but for thermal desalination in general. However technical sound design solutions as required for commercial operation always combine single modular stages with each other to systems which, if reasonable again may be combined with complementary technologies in trying to minimise energy consumption and heat losses.

In the following the operation of the module in serial and parallel operation shall be evaluated with regard to the arising potential to increase efficiency and output of the system. Besides the combinations with thermal storage systems shall be discussed.

The suggestions for the present desalination module are evaluated on base of proven technologies powered either by solar energy or by conventional fuel firing. For the considerations to optimise the design of thermal desalination systems with regard to energy use it is of little importance by which source of energy or fuel the process is supplied, because it is the thermal process itself to be looked at in pursuing the most energy efficient way to run a desalination installation.

Serial Operation to Raise Brine Salinity & Save Energy

The calculations for the single desalination module (4.3.3) showed that while the freshwater product accounts for just 11 % of the flows leaving the system, whereas the resting 89 % of the mass are rejected brine, rich in wasted heat energy but little enriched in salinity. This leads to the question why the brine should not be reused as input for the neighbouring desalination module in order to allow partial recovery of its heat by the succeeding desalination cycle and to further concentrate it before bringing it to its final storage, maybe under use of further electrical energy. The more stages the saline solution has to undergo the higher it will be concentrated at the end of the processing which means the lower will be the amount of waste to be disposed. Although expected to continually heat up during its path through the modules, its contribution to heat recovery will be significant. Besides, still not significantly higher concentrated than the original raw water inlet, the brine is not expected to change the evaporation conditions dramatically by its raised salinity.

By use of the presented calculation model (4.3.3) the scenario for the serial operation of just two modules can be evaluated by making the brine flow of one module the input flow to the next one. Then the succeeding module, named stage 2 is fed by water enriched in enthalpy and salinity, while the previous module, named stage 1 remains unchanged. Figure 4.10 shows the results from the evaluations of the serial module arrangement with regard to the energy flows into and out of the particular stages.

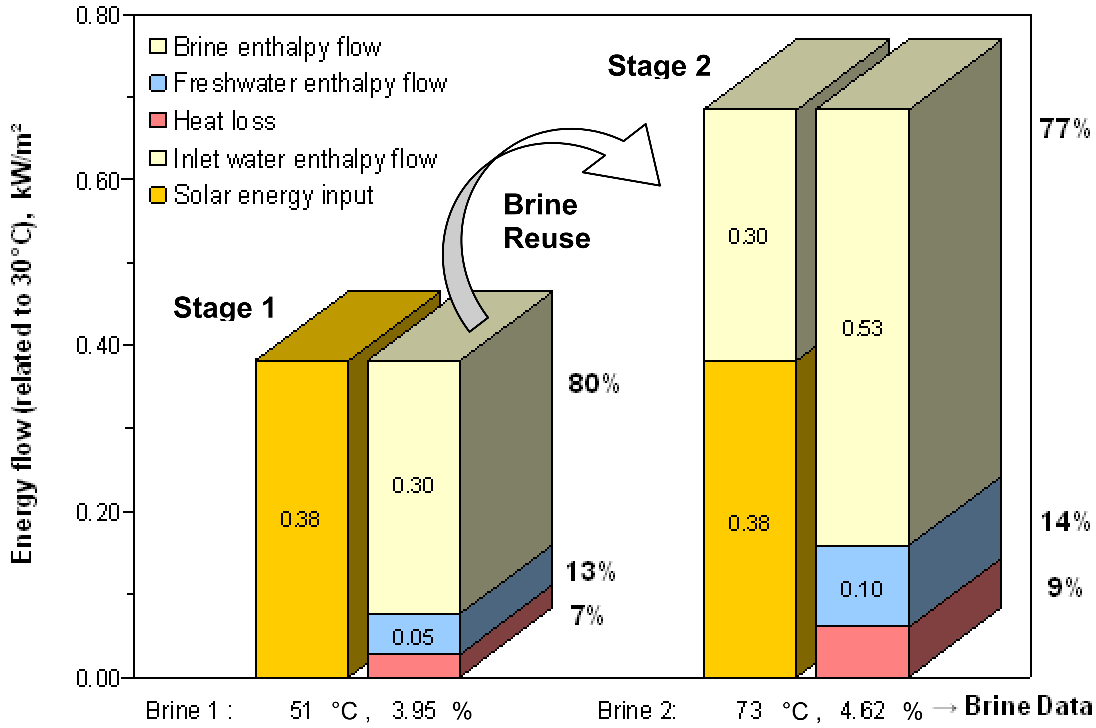

Figure 4.10 : Serial operation of 2 modules to utilise & concentrate the brine
Estimated energy input and outlet flows at the system border of each stage
Brine data: expected brine temperature [°C], expected brine salinity [%]
70% heat recovery, 10% Total heat losses

By the brine input into the second stage its energy input adds to the provided solar energy input causing that the heat flow into the system almost doubles, when again keeping the base for the enthalpy calculation at 30°C, the original raw water inlet temperature.

At the end of stage 2 the brine enthalpy has increased as expectable, however its contribution to the total energy losses leaving the system slightly decreased, mainly because of its mass reduction by further processing. The reduced energy loss again shows that the brine energy loss portion decreases with increasing number of processing stages. As to see in Figure 4.10 the heat losses to the ambient also increased at stage 2 because of increasing heat within the tube system. These losses however are to cope with thermal insulation and shall not be included in present discussion.

As conclusion for the arrangement it can be suggested for the case that the module system would be arranged in groups of just two serial connected modules as shown the expectable brine exit temperature would already be around 70°C which would make it reasonable to combine the system with a storage facility as discussed later in this section.

However it shall be noted that in the case of adding a third stage the brine inlet into this module could probably have a temperature around 90°C already, which would implicate that this inlet flow could not anymore allow for condensation of the produced freshwater vapour because the released latent heat of condensation could not be taken up any more. In such an idle operation case the vapour would continue to circulate through the system driven by air convection and thereby the efficiency of this module would dramatically decrease as earlier mentioned (4.2.4). But such an operation case could be avoided by foreseeing controlled raw water injection for cooling reasons or allowing the excessive steam by piping connections to migrate to the neighbouring stage of lower heat conditions. Similar design details are also used by the MED process (2.3) and in industrial steam generating installations for operating and control reasons.

In their development of earlier presented thermal solar desalination system project in Almeria, Spain Blanco J., Alarcón D. (2004) chose for their arrangement of a collector field of 252 single modules, grouped in rows, a serial combination of each time 3 modules to keep the expectable temperature within the structures below 80°C when fed with the design liquid flow. Although designed just for collecting solar energy to heat a successive MED system, but similar in design preconditions this installation allows for practical comparison with a plant already in successful operation.

Concluding the design analysis with the serial arrangement it is probably most suggestive to run a serial combination of just two modules for efficiency increasing reason and to avoid possible idle operation by adding a third module or the necessity to introduce a water injection control system at least in this stage of development. However further test runs of such an arrangement in different solar conditions are necessary to gain experience and to checkout the whole operation range.

Parallel Operation with Brine Heat Recovery

With the single desalination module operation expectable around 80 % of the solar energy input leave the structure with the rejected brine. To make use of this immense heat loss the potential to gain some of this energy by preheating the raw water input shall be evaluated and analysed in the following.

Utilising the presented calculation model (4.3.3) the scenario for the parallel operation of just two modules can be evaluated by providing for a modelled heat exchange between the leaving brine and the inlet water to take up the heat, where its heat exchange efficiency has to be chosen suitably. For the present calculations this figure was assumed to be 60 % as practical number based on the temperature difference between brine and water inlet.

The calculation results are displayed in Figure 4.11 where stage B is the naming of the module with its raw water inlet preheated by heat exchange with the brine from the earlier stage, named stage A. In this case the water inlet of stage B appears on the figure as energy input, since heated above the base conditions of 30°C, its original temperature, while the stage A water inlet logically does not. This results that the inlet flow into stage B by its gain in enthalpy contributes to around 30 % of the total energy input into the system dominated by the solar energy provision, with the figures basing on mentioned 30°C reference temperature.

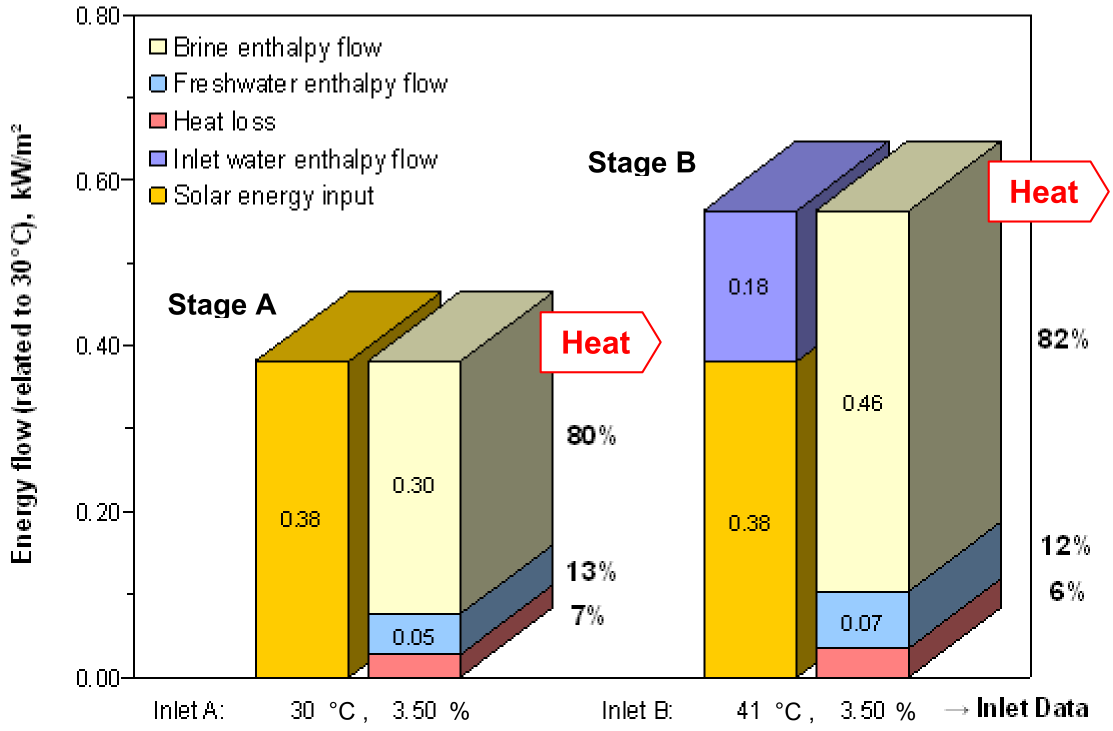

Figure 4.11 : Parallel operation of 2 modules to utilise brine heat
Estimated energy input and outlet flows at the system border of each stage
Inlet water data: expected inlet temperature [°C] , expected brine salinity [%]
70% heat recovery, 10% Total heat losses

At the end of stage B it again shows that the brine enthalpy has increased, here solely because of higher energy input into the system without any change of the mass input. The heat gain compared to the serial arrangement is slightly less because the saline solution does not significantly further concentrate just by the heat provision, which means that it leaves with similar salinity than in does from stage A.

For the evaluated parallel arrangement it can concluded that besides the additional heat input the process itself would not change significantly in a succeeding stage, since the salinity of the brine would just marginally change. But the parallel arrangement to just heat up the inlet causes slightly heating of the brine, which in total will be less dramatic compared to the serial operation due to the fact that each stage is fed with just moderately preheated raw water. Thus it can be expected that at least three parallel stages could be arranged without compromising the effective heat exchange between water inlet and condensing freshwater which could suppress condensation followed by idling of the vapour in extreme case (4.2.4). However since all preheating performance depends on the efficiency of the heat exchange itself, further detailed suggestions could be provided only after having chosen a suitable heat transfer pipe solution and after having conducted first field tests in described design arrangement.

Potential Field Operation of the Desalination Module System

Both serial and parallel arrangement of the desalination modules are supposed to provide for an increase in overall system efficiency and output accompanied by a reduction of wasted brine and thermal losses as above calculation results showed. To utilise both advantages a field arrangement could be foreseen for the actual installation of the emerging freshwater preparation system like schematically suggested in Figure 4.12 with serial brine reusing stages in on direction and parallel inlet preheating stages in the other.

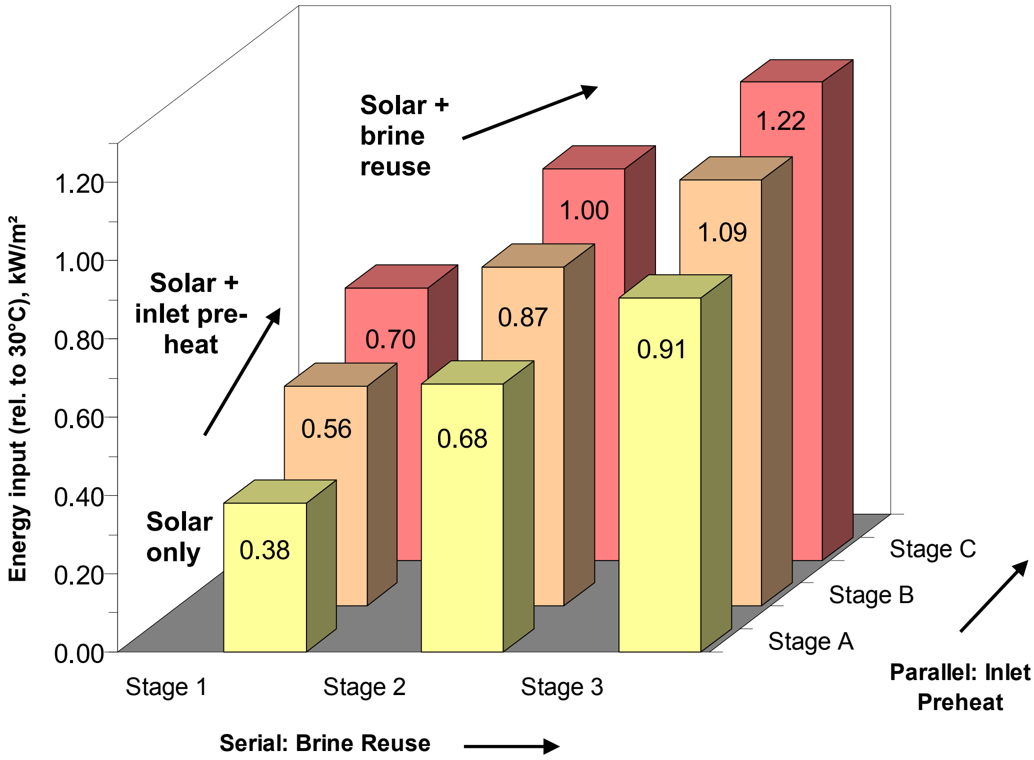

Figure 4.12 : Desalination system field arrangement for efficiency increase
Estimated energy input flow into each desalination stage
Stage 1 – Stage 3 : Serial operation to reuse and concentrate brine,
Stage A – Stage C : Parallel operation for inlet preheating with brine.
(Model assumptions: 70% heat recovery, 10% Total heat losses)

As conclusion for the system if it would be installed in suggested field arrangement some arguments still have to be balanced:

- Would the shadowing effect by neighbouring modules in the morning and evening hours be intensified by the arrangement to indeed result in higher thermal performance on the cost of optical performance?
- Would the combination of both serial and parallel operation not heat the single module that much to fear very soon compromising of the condensation efficiency?
- Would it make sense to combine serial and parallel operation to allow for intermediate cooling of the brine by heat exchange with inlet water before reusing it in the next stage?
- Would an excess vapour connection between the modules help to increase efficiency in high load operation due to shifting the not condensable steam to the next stage of lower heat conditions?
- Would the rising complexity caused by suggested arrangement not put the basic design idea into question to provide a simple low-cost system?
- Would it not be more advantageous to foresee a central thermal storage for the hot brine instead of the proposed module combinations, which then would allow for heat utilisation elsewhere or during hours without solar irradiation?
- Would the brine concentration by its serial reuse be sufficient to reasonably use it as heavy fraction in a solar pond (3.4)?

Potential Thermal Storage for the Brine

The last two questions posed above refer to a possible combination of the present system with a thermal storage to allow the accumulated heat to be utilised for the process itself or somewhere else on the site.

Thus for the system itself such a solution would only provide an efficiency increase if the stored heat would be used for centralised preheating of the raw water to be introduced into the process. And then, especially during periods of low solar irradiation there would be a reasonable potential to increase the performance of the system by preheating the module inlet flows. Then the high load operation periods could significantly be extended which would allow for proper freshwater production already in the morning as well as till sunset. The potential to operate the process by substantial support of the accumulated heat depends logically on the dimensioning of the storage facility.

If deciding to go for a solar pond to combine with the present system there would be the mentioned advantages to additionally profit from the considerable solar heat input into the pond and to dispose the brine rejection as pond input (3.4). In such a design the heat accumulation potential then would be far higher than just for a storage tank.

Finally it shall be referred to actual experiences which show that small solar single installations may even double their performance when utilising a well engineered thermal storage solution (Ettouney and Rizzuti, 2007).

5 Summarising the Desalination Module Evaluation

The prototype of the solar thermal desalination module investigated in this paper (4) is very likely to provide a simple low-cost solution for future freshwater production in arid zones, where its design would even include inland use for brackish water preparation. With conversion rates of the present design to be expected around 11 % the single module is in a performance range which indeed is moderate but reasonable for small-scale single desalination applications. In this context one should not forget that each module is capable to manage the whole desalination process, from collecting solar irradiation, heating up water and evaporating it to finally condensing freshwater as product. There each single process has an efficiency loss, all of which again multiply to confine the overall performance. Any improvement of the present design therefore requires analysis of these internal processes.

But the mentioned modest conversion rates of the single module also implicate that the by far dominating by-product is rejected brine, being responsible for massive energy flows out of the system. These losses can only be limited when reusing the brine itself or when recovering its heat energy by well elaborated combinations of the single modules to form a field arrangement, or even to combine the system with an additional heat storage facility. The latter could provide for extending high performance operation to even unfavourable solar conditions in order to again increase output and efficiency of the system. Comparisons with commercial operating desalination plants show that all of them combine multiple process stages in order to utilise the provided process heat as far as possible with the ultimate target to maximise the overall efficiency of the system. Alternative solar solutions usually include additional thermal storage for mentioned reasons. Only such an optimisation of the water processing makes both proven and novel technologies competitive on the market.

The evaluations of the solar desalination module prototype performed in this paper shall provide ideas how to improve the present design, continue its further development, and approach manufacturing. Additionally, with the concluded results possible arrangements of the modules to increase the overall system performance should be rethought under approving their feasibility by comprehensive test runs in the different combinations as suggested.

Finally the experiences from testing of the system should be complemented by further mathematical modelling of the system allowing for optimisation of the design with regard to maximising the product output under minimising the process losses to finally end up with a simple and competitive product solution of high reliability in its daily use to care for sustainable freshwater supply in arid zones of the world.

6 Concluding Outlook: The Solar Powered Water Supply

Freshwater is a valuable good, probably the most valuable for nature and mankind, especially for arid zones on earth where the lack of water is expected to even aggravate due to climate change, population growth and land mismanagement. But exactly these concerned zones already suffering from aridity or being threatened by advancing desertification, on the other hand are in the most cases blessed with abundance of solar radiation. This leads to the logic conclusion for these zones to go for solar powered freshwater preparation technologies.

However the technical processing of water implicates an immense energy effort and the continuous strong yearly increase of freshwater demand calls for large-scale desalination solutions, where fossil fuel fired installations will continue to dominate the market in the coming years because of currently being the only alternative to actually cope with the huge global capacities needed. In future also renewable, especially solar thermal powered solutions are supposed to gradually step into this market segment, however probably of dimensions expected to be at least one magnitude smaller than the fossil powered plants.

Solar desalination solutions, currently already widely distributed for local small-scale water processing will further gain importance in this share of the market. Their advantage of potential energy independence, moderate investment and individuality in design makes them unrivalled for installations in remote, rural areas, and for most brackish water applications. Continual performance improvements of solar desalination technology added by the ultimate advantage of zero energy cost for solar powered solutions are arguments to very likely attract investors.

The evaluations within his paper however showed that there are energetic limits of solar power and in particular solar powered thermal desalination, where the first is the limited solar irradiation itself which would implement immense surface areas to be covered with solar collectors if trying to replace fossil powered solutions. The second limit is provided by the process itself and the phenomena to require high heat input which can be recovered only to a certain percentage. This again calls for well-engineered solutions targeting on minimisation of heat losses by the process in order to maximise the freshwater output as decisive chance to make the system competitive on the global market.

Finally it can be concluded that global freshwater supply of arid regions will gradually become solar powered, whereas small-scale solutions are already on the right path, while the large-scale segment is still held back by economic decisions and political arguments. However when looking at expected increasing cost for fossil fuel in the coming future and the awaited investment impetus by climate change policy the chances for investment into large solar driven installations are promising.

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