

6. Environmental Impacts of CSP Desalination

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

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

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

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

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

The environmental impacts of seawater desalination will be discussed separately for each technology because of differences in nature and magnitude of impacts. The technologies regarded here are MSF, MED and RO as they are, at least at the moment, the predominant ones

of all desalination technologies and therefore these plants are responsible for almost all impacts on the environment caused by desalination. An excellent and highly recommendable compendium of environmental impact of MSF and RO desalination technologies is /Lattemann and Höpner 2003/. Much of the data used here has been taken from that source.

6.1 Multi-Stage Flash Desalination (MSF)

6.1.1 Seawater Intake

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

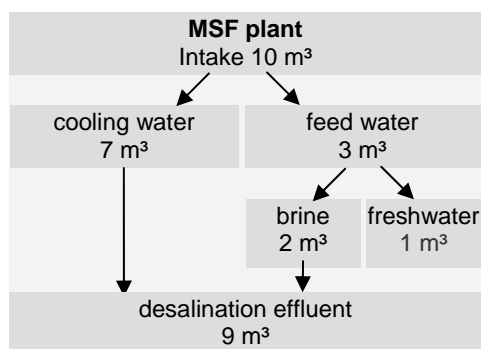


Figure 6-1: Flow chart of reference MSF process

6.1.2 Discharge of Brine Containing Additives

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

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

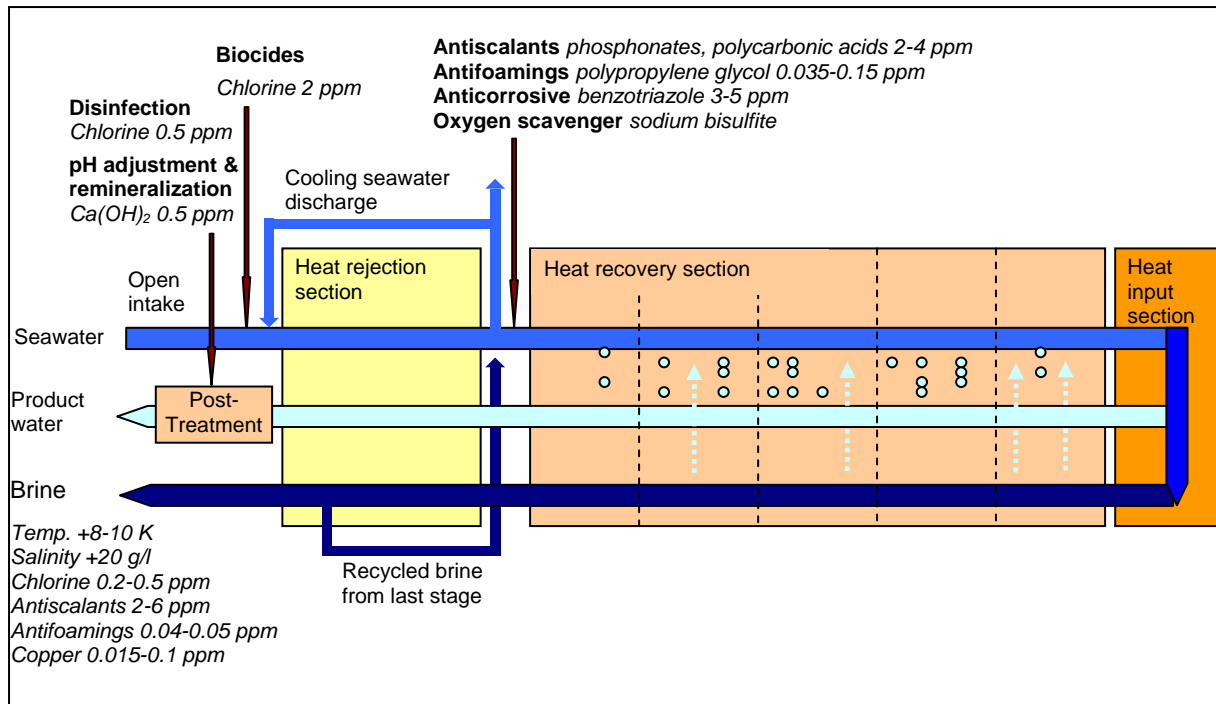


Figure 6-2: MSF process scheme with input and output concentrations of additives and brine characteristics, /Lattemann and Höpner 2003/, modified

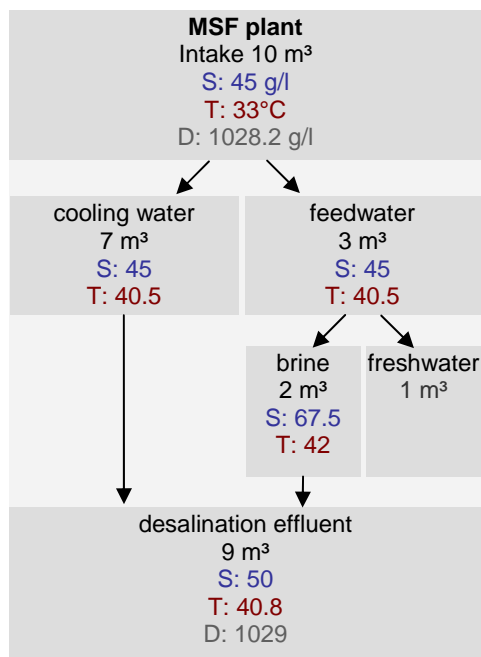


Figure 6-3: Flow chart of reference MSF process with salinity (S, in g/l), temperature (T, in °C) and density (D, in g/l), /Lattemann and Höpner 2003/, modified

Physical Properties of Brine

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

Biocides

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

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

distance of 1 km. The values are quoted in /Lattemann and Höpner 2003/ who took them from Hazardous Substance Databank (HSDB, <http://toxnet.nlm.nih.gov>).

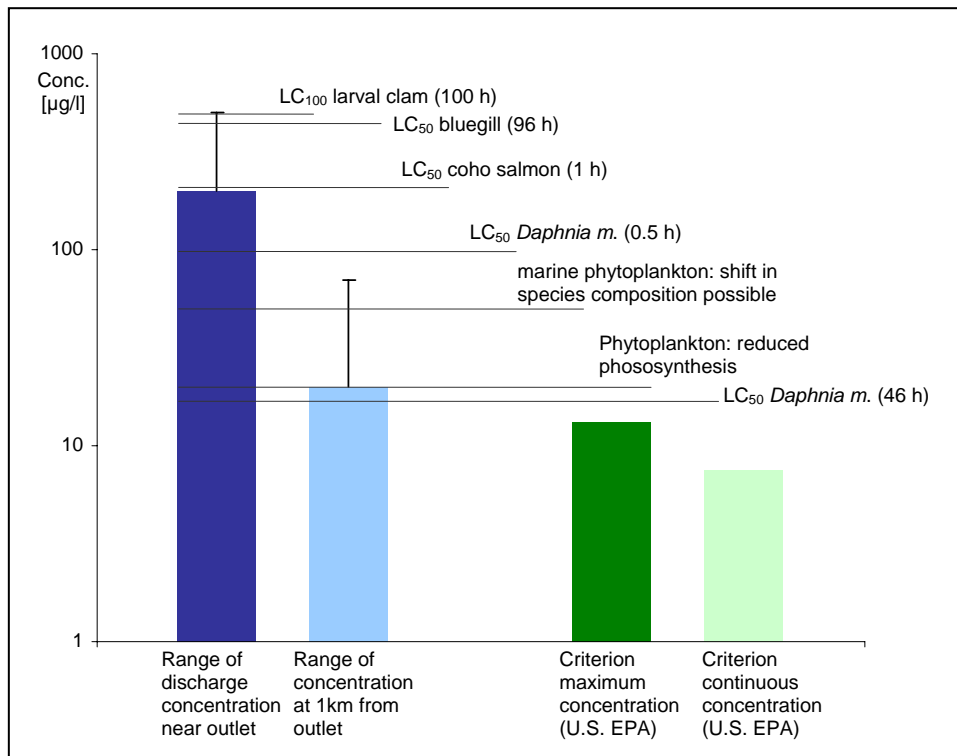


Figure 6-4: Chlorine: Ecotoxicity (LC50 = mean lethal concentration) compared to ranges of brine concentration and water quality criteria, /Lattemann and Höpner 2003/, modified

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

Antiscalants

A major problem of MSF plants is the scale formation on the heat exchanger surfaces which impairs heat transfer. The most common scale is formed by precipitating calcium carbonates due to increased temperatures and brine concentration. Other scale forming species are magnesium hydroxide calcium sulphate, the latter being very difficult to remove as it forms hard scales. Therefore sulphate scaling is avoided in the first place by regulating the operation parameters

temperature and concentration in such a way that the saturation point of calcium sulphate is not reached. Calcium carbonates and magnesium hydroxides, again, are chemically controlled by adding acids and/or antiscalants.

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

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

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

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

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

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

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

Antifoaming Agents

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

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

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

Corrosion Inhibitors and Corrosion Products

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

Corrosion inhibitors generally interact with the surfaces of the tubes. Ferrous sulphate, for example, adheres to the surface after having hydrolyzed and oxidized and hereby protects the alloy. Benzotriazole and its derivatives are special corrosion inhibitors required during acid cleaning. They possess elements like selenium, nitrogen, sulphur and oxygen with electron pairs which interact with metallic surfaces building a stable protective film. However, it is assumed that in the end the major amount is discharged with the brine. Due to the slow degradation of benzotriazole, it is persistent and might accumulate in sediments if the pH is low enough to allow adsorption to suspended material. Acutely toxic effects are improbable because the expected brine concentrations are well below the LC₅₀ values of trout and *Daphnia magna*. Still the substance is classified as harmful for marine organisms. The release of benzotriazole per cubic metre product water, corresponding to a continuous dosage of 3-5 ppm to the feed water, amounts to 9-15 g.

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

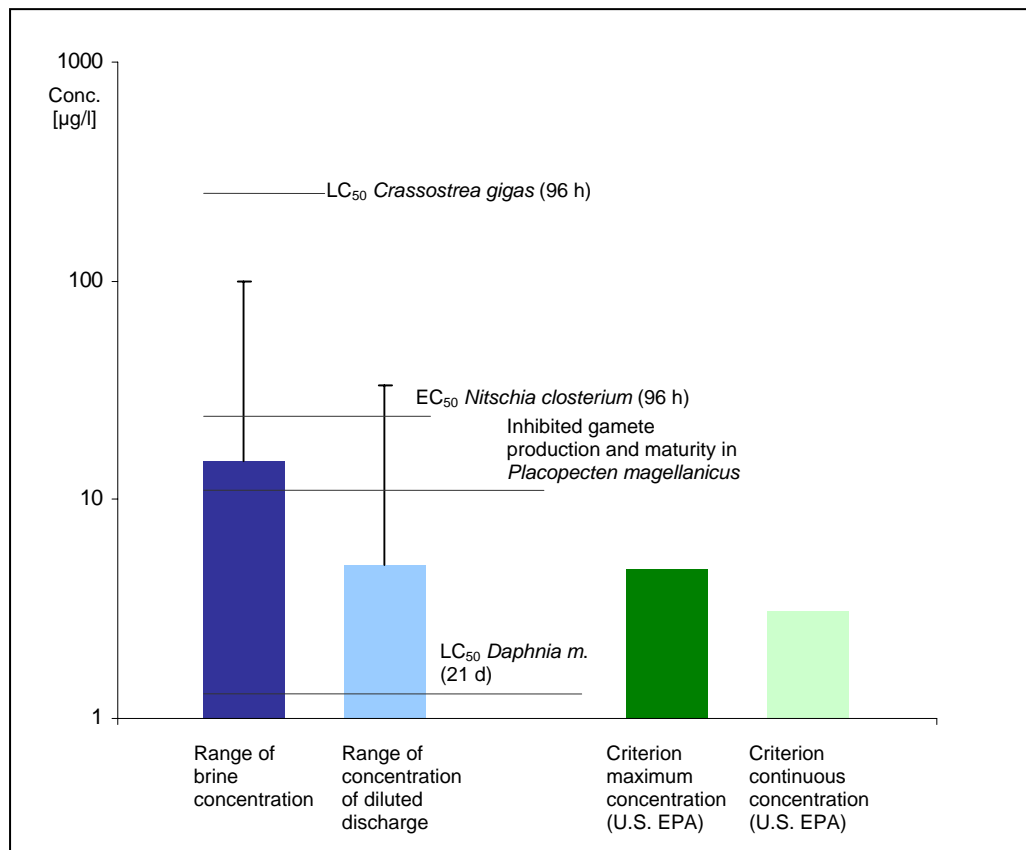


Figure 6-5: Copper: Eco-toxicity (LC₅₀ = mean lethal concentration, EC₅₀ = mean effective concentration) compared to ranges of brine concentration and water quality criteria, /Lattemann and Höpner 2003/, modified

6.2 Multi-Effect Distillation Desalination (MED)

6.2.1 Seawater Intake

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

6.2.2 Discharge of Brine Containing Additives

The discharge of brine represents a strong impact to the environment due to its changed physical properties and to the residues of chemical additives or corrosion products. In MED plants common chemical additives are biocides, antiscalants, antifoaming agents at some plants, and

corrosion inhibitors at some plants. The conditioning of permeate to gain palatable, stable drinking water requires the addition of chlorine for disinfection, calcium, e.g. in form of calcium hydroxide, for remineralization and pH adjustment /Raluy 2003/, /Delion et al. 2004/. Figure 6-7 shows where the chemicals are added and at which concentrations as well as the characteristics of the brine and its chemical load.

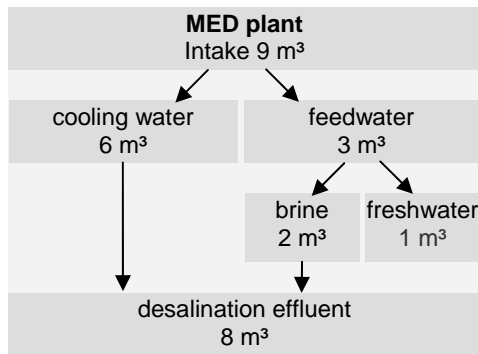


Figure 6-6: Flow chart of reference MED process

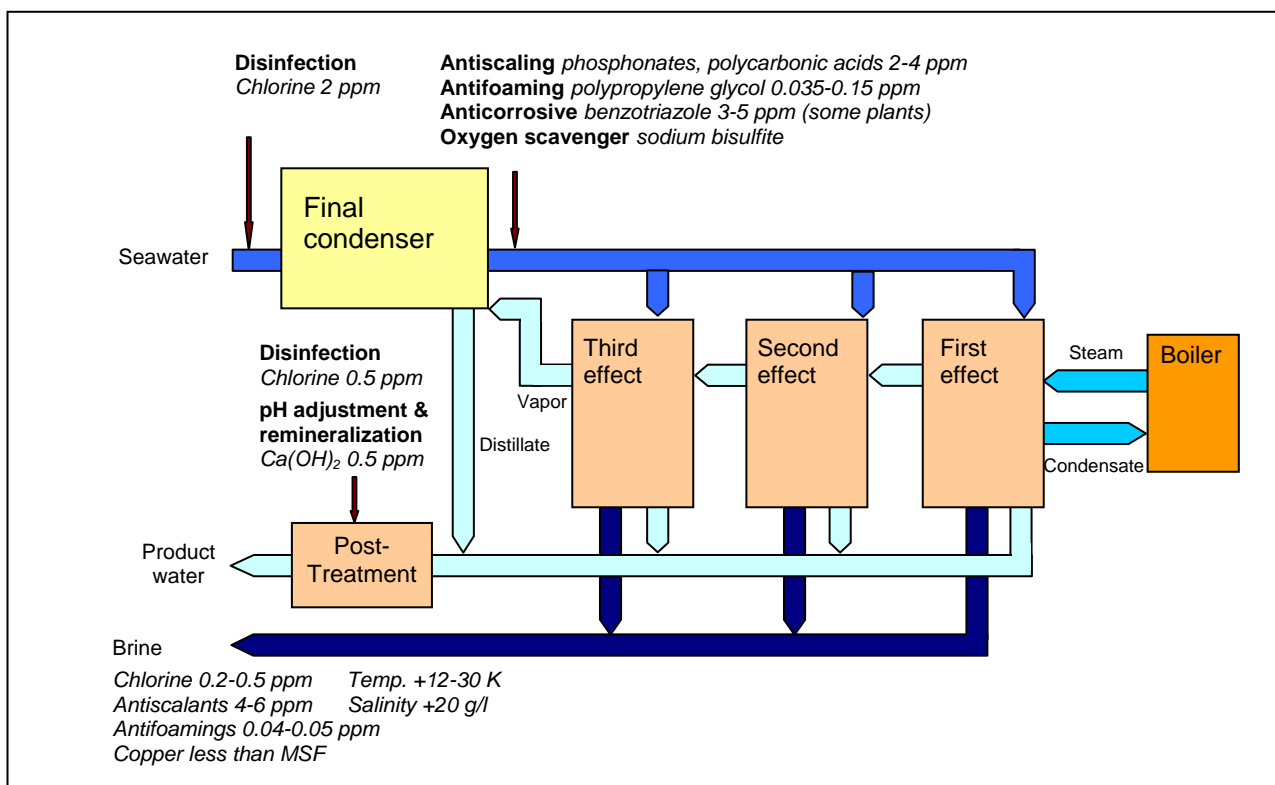


Figure 6-7: MED process scheme with input and output concentrations of additives and brine characteristics

Physical Properties of Brine

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

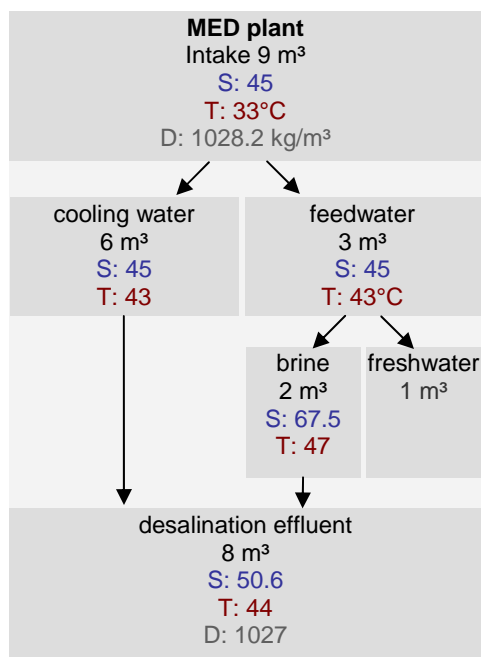


Figure 6-8: Flow chart of reference MED process with salinity (S, in g/l), temperature (T, in °C) and density (D, in g/l), /Lattemann and Höpner 2003/, modified

Biocides

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

Antiscalants

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

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

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

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

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

Antifoaming Agents

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

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

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

Corrosion Inhibitors and Corrosion Products

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

6.3 Reverse Osmosis (RO)

6.3.1 Seawater Intake

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

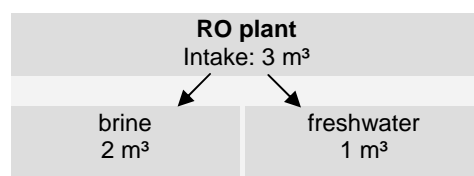


Figure 6-9: Flow chart of reference RO process

6.3.2 Discharge of Brine Containing Additives

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

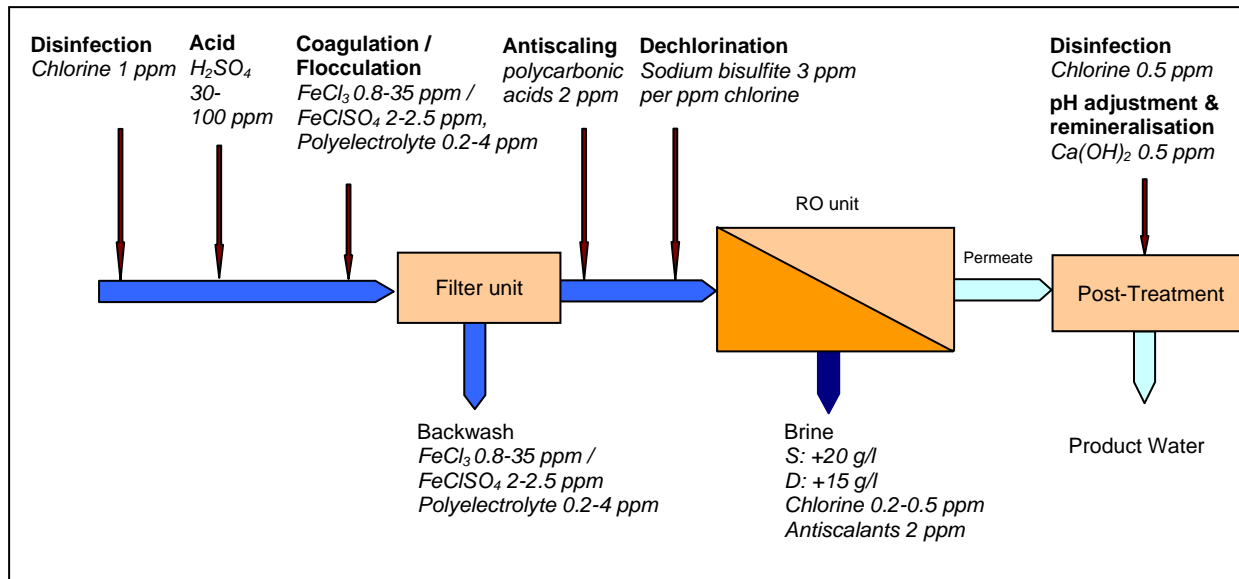


Figure 6-10: RO process scheme with input and output concentrations of additives and brine characteristics, /Lattemann and Höpner 2003/, modified

Physical Properties of Brine

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

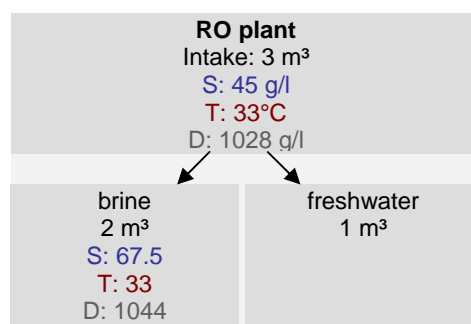


Figure 6-11: Flow chart of reference RO process with salinity (S, in g/l), temperature (T, in °C) and density (D, in g/l), /Lattemann and Höpner 2003/, modified

Biocides

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

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

Coagulants

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

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



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

Antiscalants

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

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

Membrane Cleaning Agents

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

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

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

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

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

Corrosion Products

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

Dechlorination

The removal of chlorine is performed with sodium bisulfite, which is continuously added to reach a concentration three to four times higher than the chlorine concentration, the former amounting to 1500-4000 $\mu\text{g/l}$. The corresponding amount per cubic metre of product water is 4.5-12 g/m^3 . As this substance is a biocide itself and harms marine life through depletion of oxygen, overdosing should be prevented. Alternatively sodium metabisulfite is used.

6.4 Life-Cycle Assessment of Materials and Emissions

6.4.1 Methodology of LCA and Material Flow Networks

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

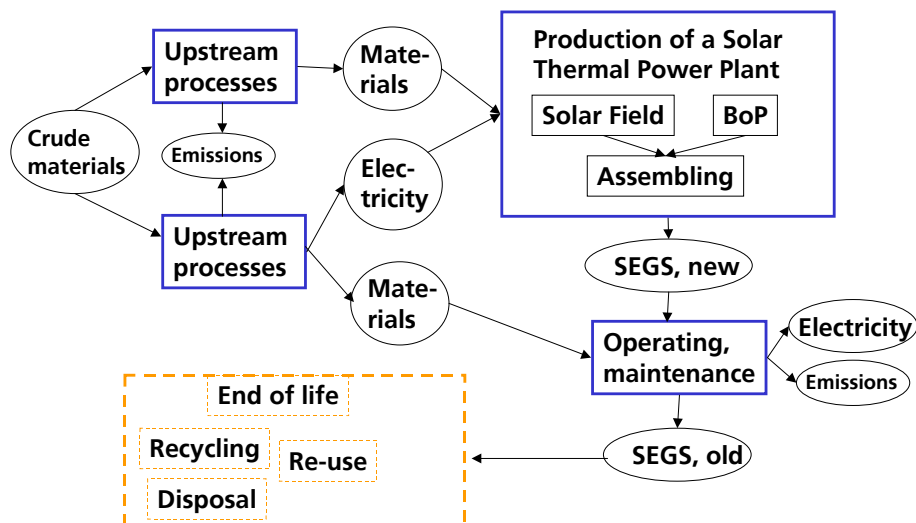


Figure 6-13: Life cycle of a solar thermal power plant (type SEGS)

After modelling the relevant material and energy flows in a material flow net the life cycle inventory is created. The input-output balance of the whole system is calculated using upstream processes taken from commercial LCA databases. Finally, the environmental impacts are

calculated by allocating the resulting emissions to different impact categories (global warming potential, acidification, or resource consumption, for example). By scaling the results to a functional unit (1 kWh electricity or 1 m³ water) different production processes can be compared and the best technology with regard to an impact category can be selected.

6.4.2 Frame conditions and data sources

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

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

The function studied in the LCA is that of cleaning seawater with a salinity of 45 g/l to produce freshwater with 200 ppm salt included. The *functional unit* has been defined as 1 m³ of freshwater delivered from the plant.

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

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

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

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

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

Solar thermal power plant

As CSP plant a direct steam based trough is chosen. As reference the pre-commercial 5 MW INDITEP power plant planned to be built in Spain is taken and scaled up to 20 MW. The data is taken from /NEEDS 2007/. Instead of using parabolic troughs as designed for INDITEP the solar field is exchanged by a linear Fresnel collector field. Data for one m² solar field provided by the company Novatec-Biosol who developed Fresnel mirrors with a very light design was implemented /Novatec 2007/. The solar field is linearly scaled up to the necessary extent.

Since for direct steam technology a latent heat storage medium is needed for evaporation, DLR provided data for a 6 hours 50 MW_{el} storage system using phase change materials (PCM) based on PCM developments in laboratory scale. The storage system is linearly scaled up to the necessary extent. It operates in three steps /Michels and Pitz-Paal 2007/: During the *preheating* step a conventional concrete storage is used which is heated up (sensible heat storage). This step is followed by the *evaporation* phase served by a (cascaded) latent heat storage. The increasing heat causes (several) phase changes (e.g. from solid to liquid) but does not increase the storage temperature by itself. In the last step, the *superheating* phase, a concrete storage is used again. For the applied storage system NaNO₃ is used, but in general different mixtures of NaNO₃, KNO₃ and KCL are possible. To increase the thermal conductivity aluminium plates are placed into the salt.

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

Desalination plants

The same desalination plants as described in the former chapters are modelled within the LCA. The inventory data is taken from /Raluy et al. 2006/. Table 6-1 shows the relevant energy consumptions of the desalting plants based on 46 000 m³/d capacity. The lifetime of the desalination plants is assumed to be 25 years, that of the building to be 50 years.

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

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

MENA electricity mix

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

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

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

Natural gas fired power plants

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

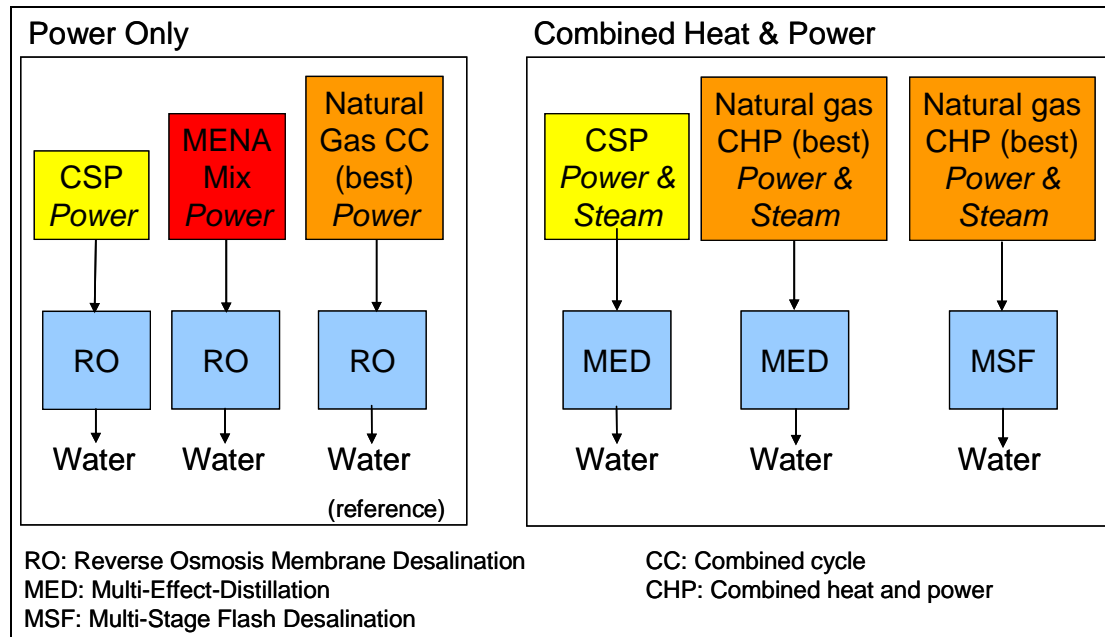


Figure 6-14: Considered seawater desalination technologies based on solar energy or fossil fuels

Impact category	Inventory parameter	Aggregated impact parameter	Ratio
Resource consumption	Cumulated Energy Demand (CED)	MJ (inventory parameter)	
Global warming ^a	CO ₂	g CO ₂ -Equivalents	1
	CH ₄		21
	N ₂ O		310
Acidification	SO ₂	mg SO ₂ -Equivalents	1
	NO _x		0.7
	NH ₃		1.88
	HCl		0.88
Eutrophication	NO _x	mg PO ₄ ³⁻ -Equivalents	0.13
	NH ₃		0.33
Summer Smog (Photochemical oxidant)	NMHC	mg Ethen-Equivalents	0.416
	CH ₄		0.007
Cancerogenic potential, human-toxicity	Particles and dust	mg (inventory parameter)	

^a Time horizon 100 years

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

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

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

6.4.3 Results

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

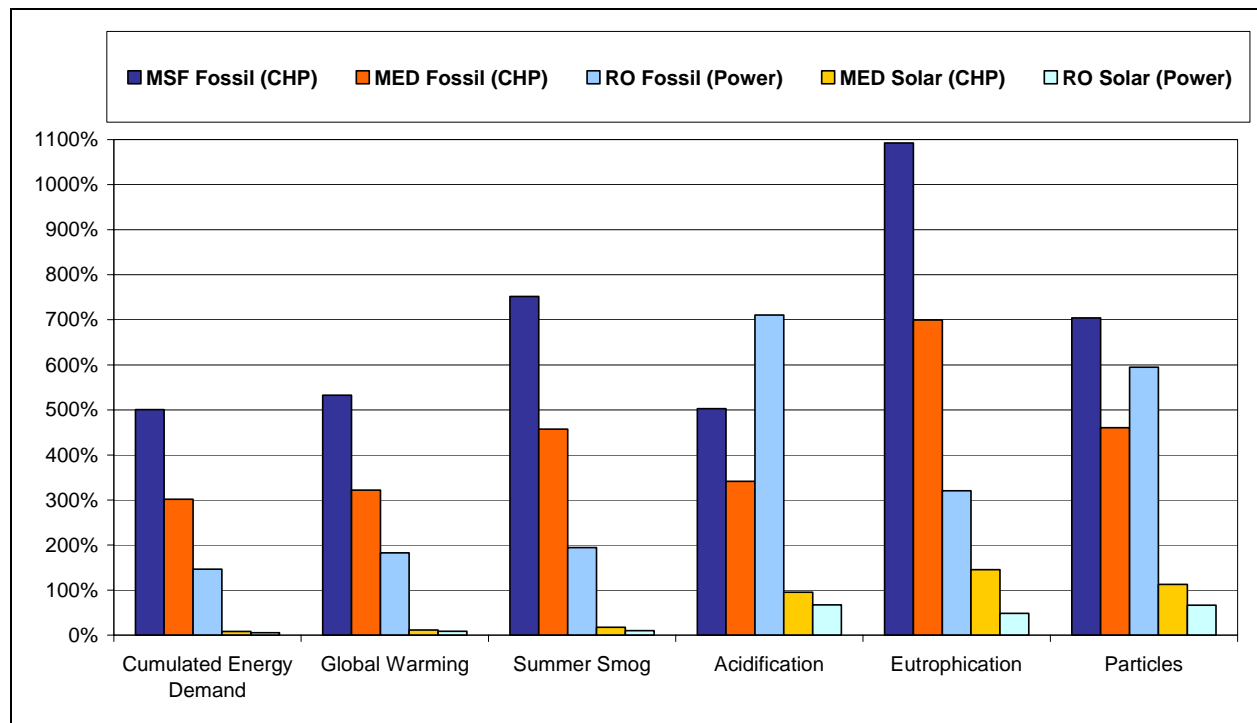


Figure 6-15: Life-cycle emissions of seawater desalination technologies in the MENA region based on fossil fuel and concentrating solar power compared to the best possible conventional solution based on a gas-fired combined cycle power plant providing electricity for reverse osmosis (100%). MSF Multi-Stage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

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

Impact Category	Unit	MED Solar (CHP)	RO Solar (Power)	RO Fossil (Power)	MED Fossil (CHP)	MSF Fossil (CHP)
Cumulated Energy Demand	kJ/m ³	3,579	2,298	63,790	131,767	218,417
Global Warming	kg CO ₂ /m ³	0.27	0.21	4.41	7.75	12.83
Summer Smog	kg Ethen / m ³	5.89E-05	3.30E-05	6.53E-04	1.54E-03	2.53E-03
Acidification	kg SO ₂ /m ³	4.48E-03	3.16E-03	3.35E-02	1.61E-02	2.37E-02
Eutrophication	kg PO ₄ / m ³	4.50E-04	1.49E-04	9.90E-04	2.16E-03	3.38E-03
Particles	kg PM ₁₀ / m ³	1.01E-03	5.97E-04	5.33E-03	4.13E-03	6.31E-03

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

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

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

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

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

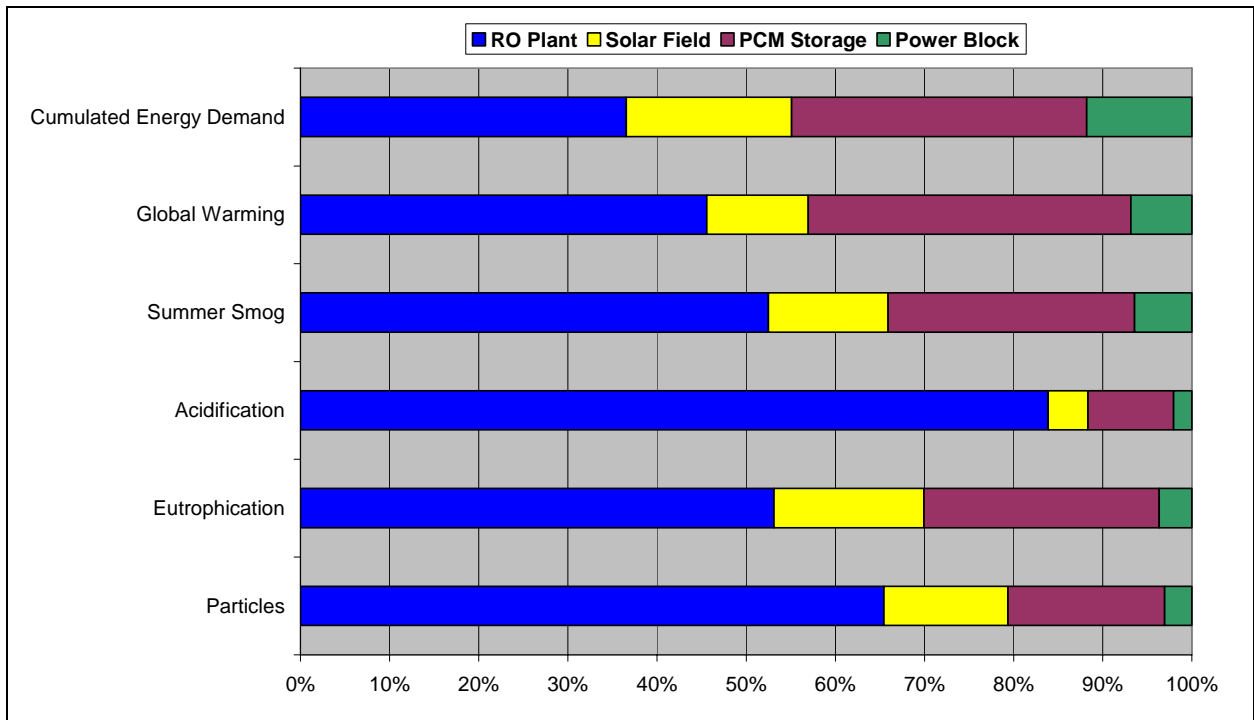


Figure 6-16: Contribution of the different components of a solar CSP/RO plant to life-cycle emissions.

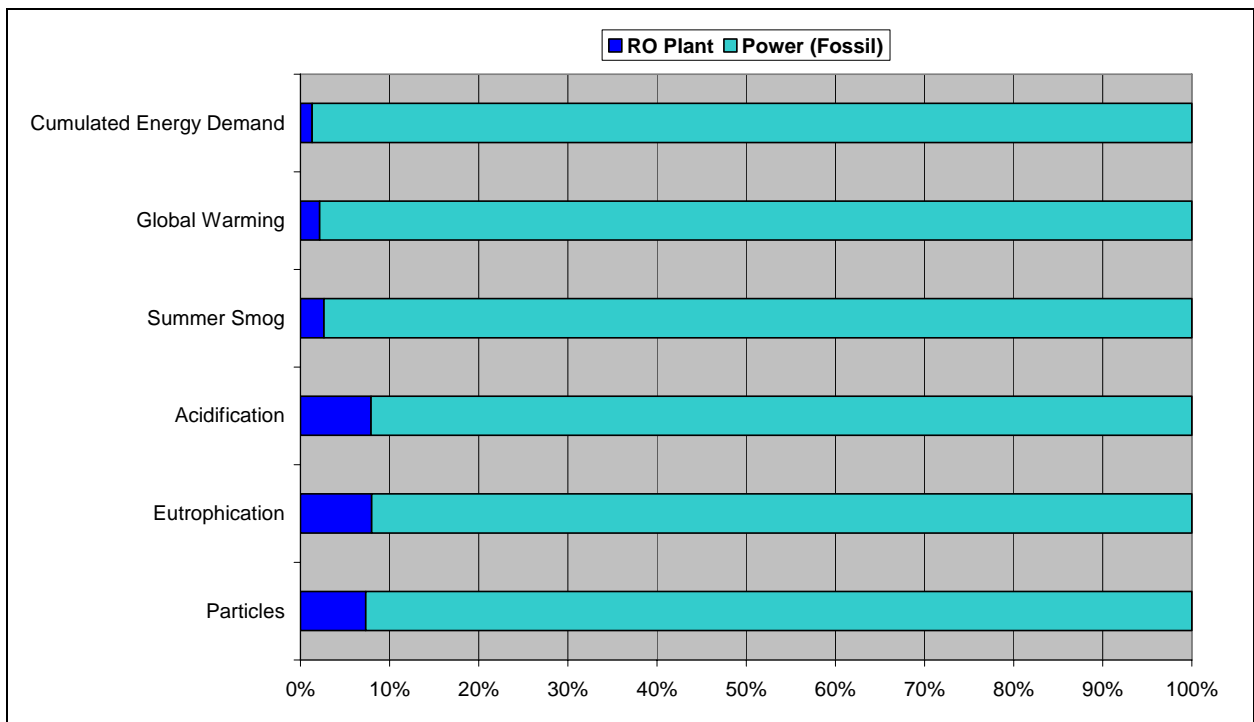


Figure 6-17: Contributions to the life-cycle emissions of a conventional RO plant receiving power from the MENA electricity grid.

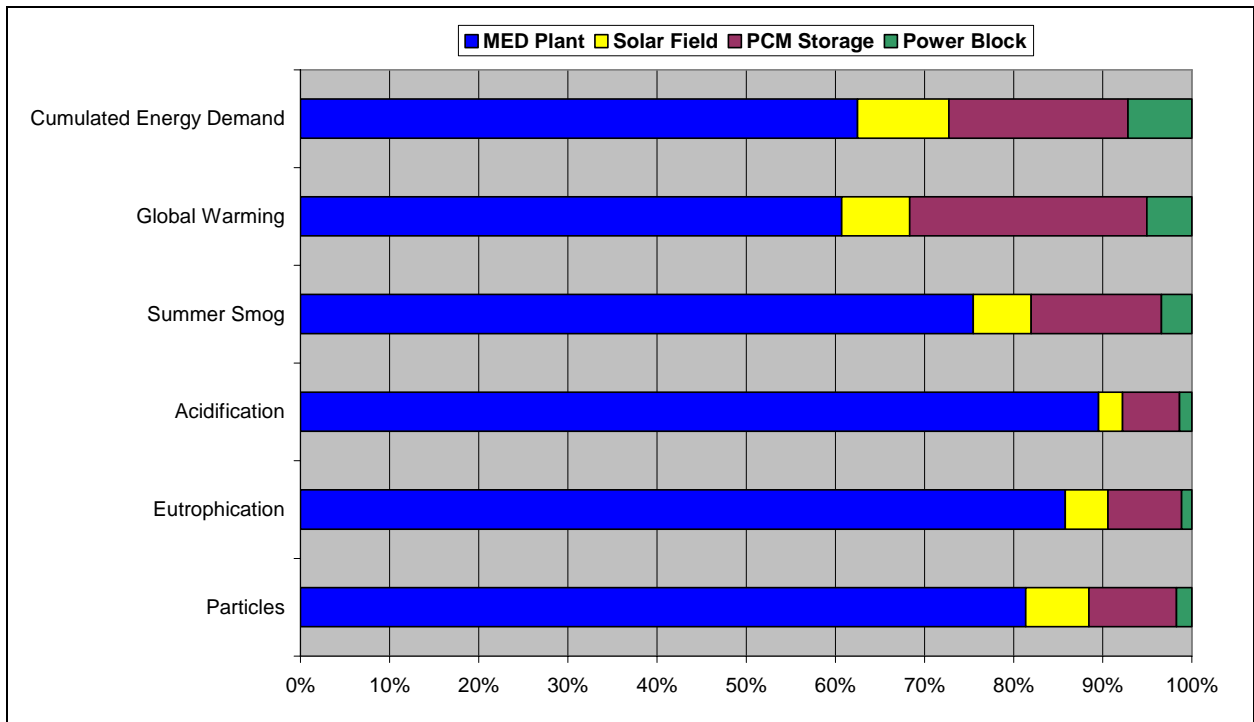


Figure 6-18: Contribution of the different components of a solar CSP/MED plant to the total life-cycle emissions.

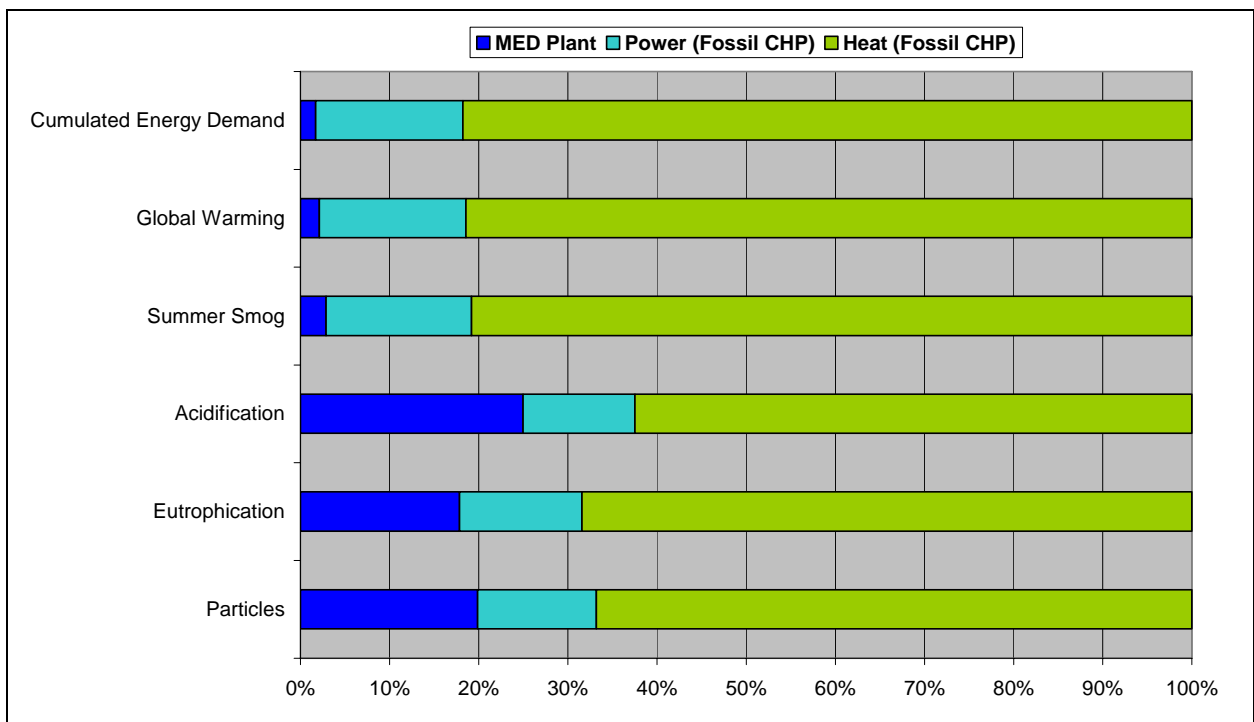


Figure 6-19: Contributions to the life-cycle emissions of a conventional MED plant receiving energy from a natural gas fired combined heat & power station (CHP).

6.5 Mitigation Measures

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

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

6.5.1 General Measures

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

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

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

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

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

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

6.5.2 Seawater Intake

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

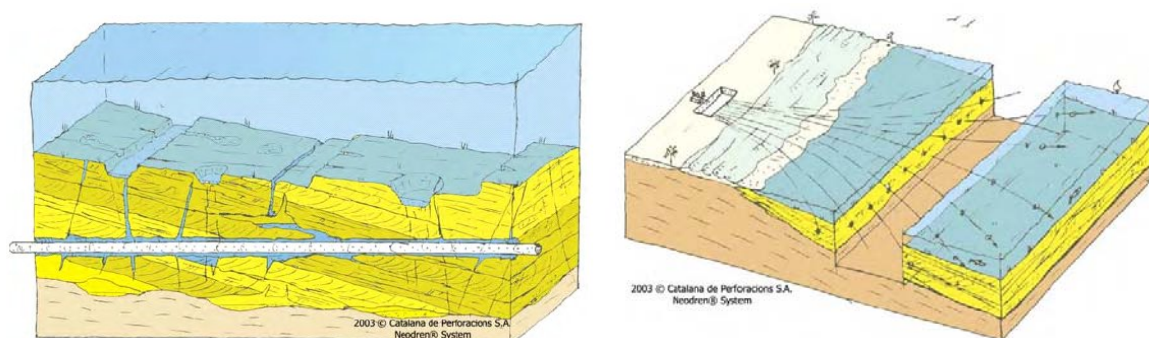


Figure 6-20: Single horizontal drain (left) and fan of horizontal drains in the sea bed /Peters et al. 2007/

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

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

6.5.3 Pre-treatment

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

Filtration Technologies

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

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

Ultrafiltration (UF) can be an effective pre-treatment against fouling of RO membranes as it retains colloids and dissolved organics. Depending on the operation scheme, a benefit for the environment is the reduction of RO membrane cleaning frequency and therefore the consumption of chemical /Vedavyasan 2007/. Another benefit can be the elimination of chlorine, sodium bisulfite for dechlorination and coagulants /Wilf and Klinko 1998/. No usage of chlorine means any formation of hazardous trihalomethanes, thus in this context, the impacts on marine organisms are significantly reduced. If the UF membrane is backwashed regularly and

thoroughly with permeate, the use of chemicals both in the UF and the RO step can be eliminated completely /Xu et al. 2007/. In the pilot plant tested here the UF shows excellent performance with a backwash executed every 40 minutes lasting for 30 seconds and a backwash flow rate of 1800 l/h. Apart from a sand filter upstream of the UF no further pre-treatment step was required.

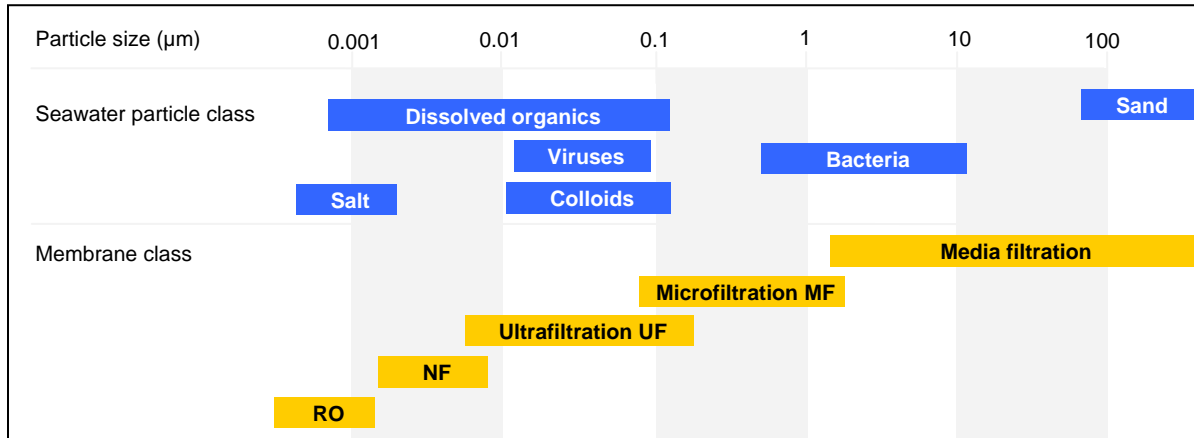


Figure 6-21: Typical seawater particles and filtration technologies compared in size (RO = reverse osmosis, NF = nanofiltration), /Goebel 2007/, modified.

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

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

Nanofiltration (NF) removes very fine suspended matter and residual bacteria, but above all it is a water softening treatment as it retains divalent ions. As these ions, e.g. Ca^{2+} and SO_4^{2-} , contribute significantly to scaling, nanofiltration prevents the formation of scales and replaces the conventional softening treatment /Hassan et al. 1998/. According to /Al-Shammiri et al. 2004/ nanofiltration can be considered as revolution in scale inhibition, as it prevents scale formation like no other treatment method. But NF does not only reduce hardness ions by up to 98 %, it also lowers the values of total dissolved solids by more than 50 % /Hassan et al. 1998./. Consequently, NF substitutes antiscalants, no matter which desalination process, and antifoamings in the case of thermal processes. Additionally it raises the performance of RO membranes as the RO feed water from nanofiltration contains less total dissolved solids.

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

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

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

Green Additives

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

- Biodegradability: > 60 % in 28 days
Chemicals with a biodegradability of < 20 % in 28 days should be substituted.
- Toxicity: LC₅₀ or EC₅₀ > 1 mg/l for inorganic species, LC₅₀ or EC₅₀ > 10 mg/l for organic species
- Bioaccumulation: Log_{pow} < 3, pow = partition in octanol/water

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

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

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

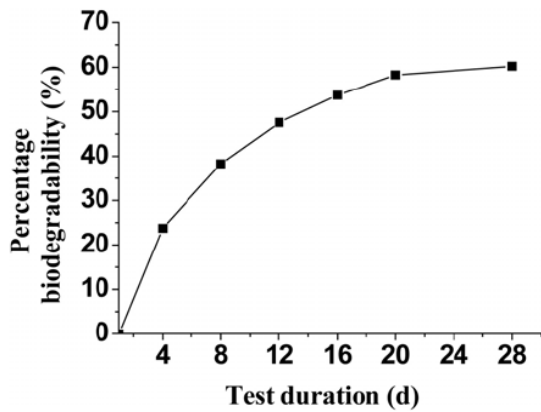


Figure 6-22: Biodegradability of PAP-1 as a function of time /Li et al. 2006/

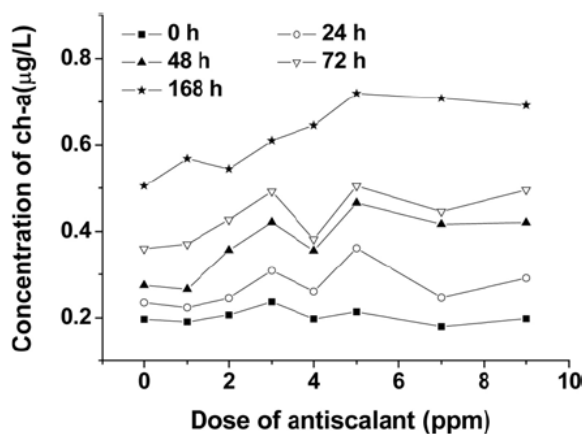


Figure 6-23: Concentration of chlorophyll-a ($\mu\text{g/L}$) as a function of antiscalant dosing concentration (ppm) with a varying test duration /Li et al. 2006/

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

6.5.4 Tubing Material

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

A high corrosion resistance of stainless steel is achieved by either a high grade of alloying, such as the 254SMO grade with 6 % of molybdenum, or by the austenitic-ferritic microstructure of duplex stainless steel (DSS). Due to its structure DSS possesses higher strength, at least twice as high as austenitic steel enabling gauge, weight and cost reductions /Olsson and Snis 2007/. With rising prices of alloying elements DSS is less costly than highly alloyed austenitic grades. Therefore DSS represents a real alternative to 254SMO for the replacement of corroding low alloyed stainless steel. In Table 6-5 some DSS grades and their possible locations in desalination plants are listed. In SWRO plants the high pressure parts require the most resistant grade S32750 with the highest grade of alloying. Where pressure and salinity is lower, e.g. in the second pass parts, the lower alloyed grades S32205, S32101, and S32304 are sufficient. In MSF evaporator shells a dual duplex design has been implemented consisting of the more resistant grade S32305 for hostile conditions and of less resistant grades (S32101, S32304) for less hostile conditions.

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

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

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

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

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

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

6.5.5 Treatment of Effluent before Discharge

Dechlorination

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

an oxidant like chlorine. Additionally residual chlorine can be depleted by activated carbon filters.

Removal of Metal Cations

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

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

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

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

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

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

The possibility of biosorption has been tested with *Streptomyces rimosus* biomass /Chergui et al. 2007/ obtained as waste from an antibiotic production plant. The biomass samples were prepared by washing with distilled water, drying at 50°C for 24 h, grinding, and sieving to receive the fraction between 50 and 160 µm of particle diameter. The biosorption of Cu²⁺ has been most efficient in the sodium form, i.e. after NaOH treatment of the biomass. Desorption and regeneration showed to be most efficient with sulphuric acid reducing the biosorption capacity by 17 % in the case of copper. This method needs further research concerning the influence of surface-active and complexing agents or other metal ions, which might be present in desalination effluents.

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

Natural evaporation and disposal as solid waste

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

6.5.6 Enhanced Practice of Discharge to the Water Body

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

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

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

6.5.7 Changing Operation Parameters

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

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

6.6 Options for Environmentally Enhanced Seawater Desalination

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

6.6.1 Enhanced CSP/MED plant

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

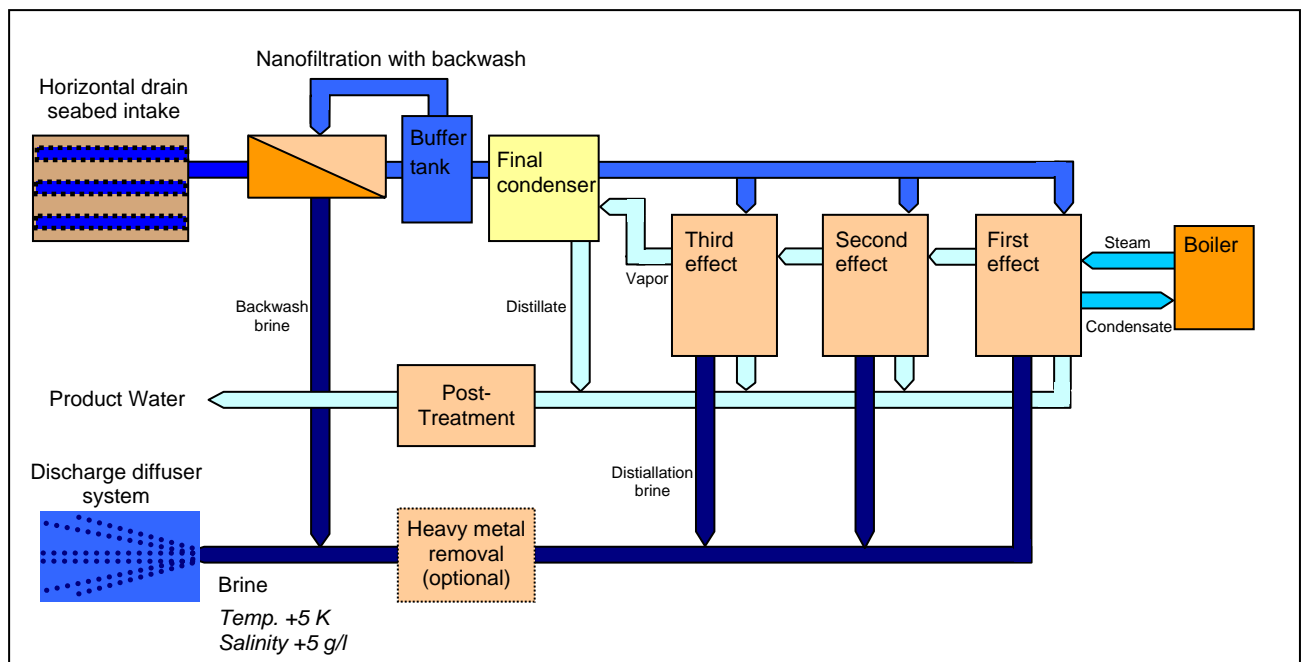


Figure 6-24: Scheme of A-MED process including horizontal drain seabed intake, nano-filtration unit, buffer tank for backwash of nano-filtration membranes and discharge diffuser system

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

Optimally, the pre-filtered seawater does not require chlorination due to the long passage through the subsoil. In that case the pre-treatment consists of a nano-filtration system to

eliminate colloids, viruses and hardness, i.e. divalent ions. As these ions are largely removed no antiscalants are necessary. Furthermore anti-foaming is dispensable as hardly any organic matter passes the nano-filtration membranes. The nano-filtration system comprises a permeate buffer tank where the NF permeate is stored for membrane backwashing. Backwashing is the essential measure to retain the performance of the NF membrane and has to be done regularly with a sufficient backwash flow rate. The backwash brine is blended with the distillation brine.

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

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

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

6.6.2 Enhanced CSP/RO Plant

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

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

Optimally, the pre-filtered seawater does not necessitate chlorination due to the long passage through the subsoil. In that case the pre-treatment consists of a nano-filtration system to

eliminate colloids, viruses and hardness, i.e. divalent ions. As these ions are largely removed no antiscalants are necessary. The nano-filtration system comprises a permeate buffer tank where the NF permeate is stored for membrane backwashing. Backwashing is the essential measure to retain the performance of the NF membrane and has to be done regularly with a sufficient backwash flow rate. The backwash brine is blended with the RO brine.

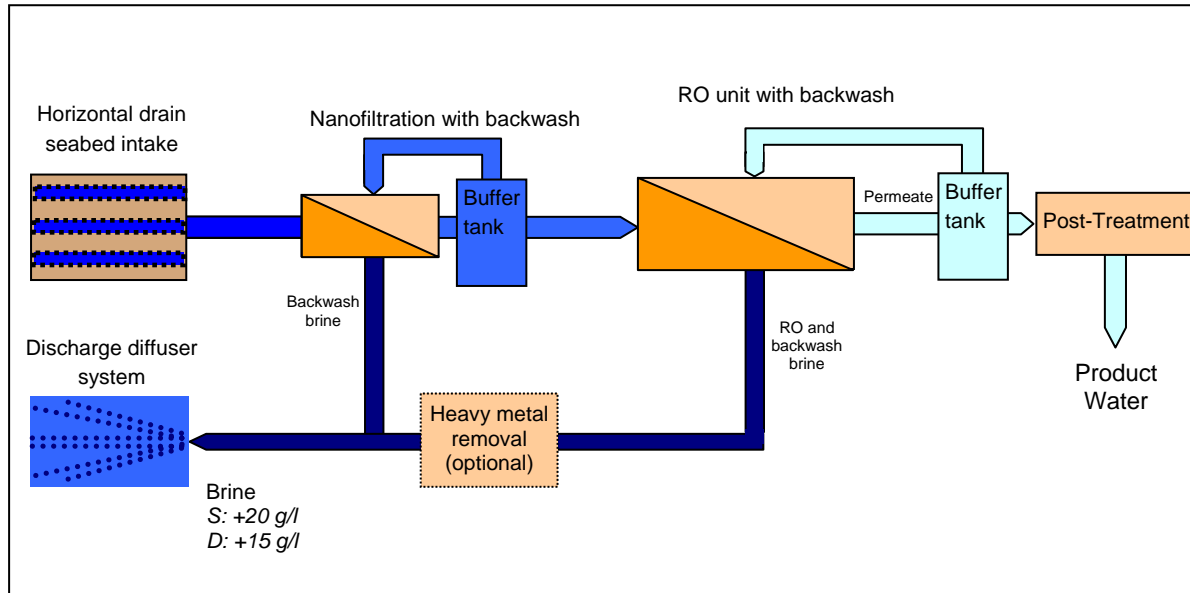


Figure 6-25: Scheme of A-RO process including horizontal drain seabed intake, nano-filtration unit, buffer tank for backwash of nano-filtration membranes and discharge diffuser system

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

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

In the future advanced CSP/RO plant, the use of chemicals and the concentration of brines will be avoided to a great extent by increased filtering and diffusion, and energy input will be

delivered by solar energy. For a first estimate, we will assume that the chemicals required per cubic metre of desalted water will be reduced to about 1 % of present amounts and that on the other hand an additional 20 % of electricity will be required for pumping.

6.7 Impacts of Large-Scale Desalination in the MENA Region

In this chapter we will assess the total absolute emissions and impacts of seawater desalination in the Middle East and North Africa as for today and for the AQUA-CSP scenario until 2050. The world wide desalination capacity rising rapidly reached 24.5 million m³/d by the end of 2005 (IDA 2006, cited in /Lattemann and Höpner 2007a/). With 87 % of all plants the EUMENA region is by far the most important region in the context of desalination. “The largest number of desalination plants can be found in the Arabian Gulf with a total seawater desalination capacity of approximately 11 million m³/day (Figure 6-27) which means a little less than half (45 %) of the worldwide daily production. The main producers in the Gulf region are the United Arab Emirates (26 % of the worldwide seawater desalination capacity), Saudi Arabia (23 %, of which 9 % can be attributed to the Gulf region and 13 % to the Red Sea) and Kuwait (< 7 %)” (cited from /Lattemann and Höpner 2007a/). Regarding the emissions through the brine discharge, from all MSF plants the Arabian Gulf receives a daily load of copper of 292 kg, amounting to more than 100 t/y. The chlorine load emitted daily by MSF and MED plants reaches up to 23 t/d and more than 8000 t/y.

The Red Sea region shows the third highest concentration of desalination plants worldwide with an overall capacity of 3.4 million m³/day (Figure 6-28, /Lattemann and Höpner 2007a/). With a capacity share of 23 % RO plays a significant role compared to the Arabian Gulf, where this technology reaches only 5 %. Still enormous amounts of copper and chlorine are released yearly: 28 t of copper and 2100 t of chlorine from both MSF and MED plants.

In the Mediterranean, the total production from seawater is about 4.2 million m³/day, representing 17 % of the worldwide capacity /Lattemann and Höpner 2007a/. The largest producer of this region is Spain with 30 % of the capacity not including its RO plants on the Canary Islands with an additional capacity of 411,000 m³/d (Figure 6-29). While in the Gulf region thermal processes account for 90 % of the production, the predominant process in the Mediterranean is RO with almost 80 % of the capacity. The only exception to this trend is Libya where the dominating process is MSF. Consequently the release of copper and chlorine is less of concern compared to the Arabian Gulf.

According to /IDA 2006/ the MENA region had in 2005 a total desalination capacity of about 16.3 Mm³/day. If we consider the specific air pollutants from Table 6-4 for conventional MSF, MED and RO taking as reference background the MENA electricity mix according to Table 6-2, and the chemicals typically contained in the effluents of each desalination system as shown

before, we obtain the daily emissions of pollutants from desalination in the MENA region in the year 2005. For simplicity, MSF and MED plants have been calculated as if always coupled to power generation (Table 6-7). Therefore, estimates for 2005 are rather optimistic.

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

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

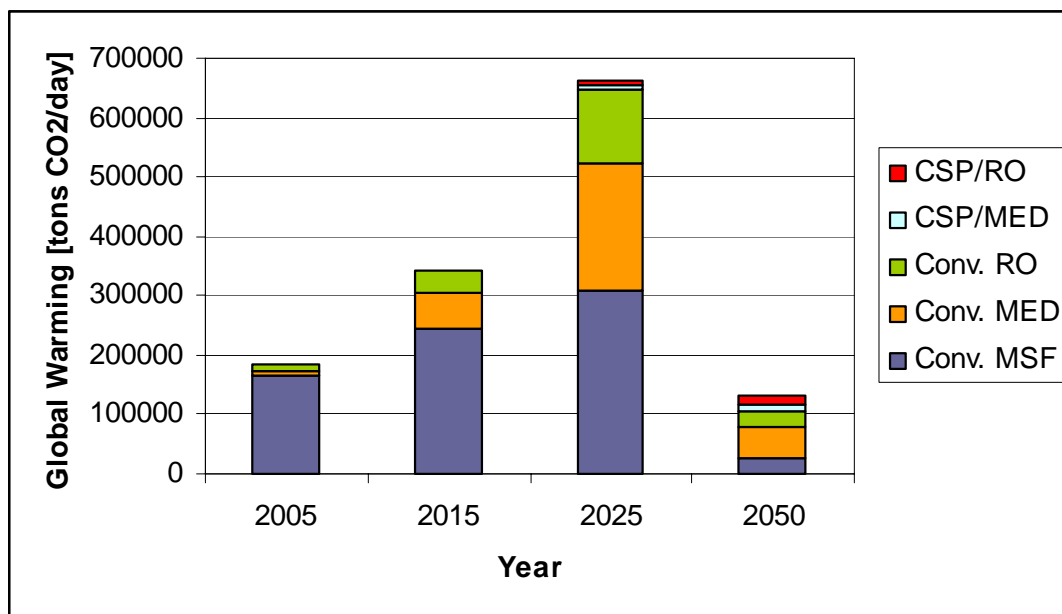


Figure 6-26: Greenhouse gas emissions from desalination in the AQUA-CSP scenario taking as basis the electricity mix of the MENA countries according to /MED-CSP 2005/. A similar pattern results for all pollutants, showing that the introduction and large scale implementation of advanced CSP/MED and CSP/RO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

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

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

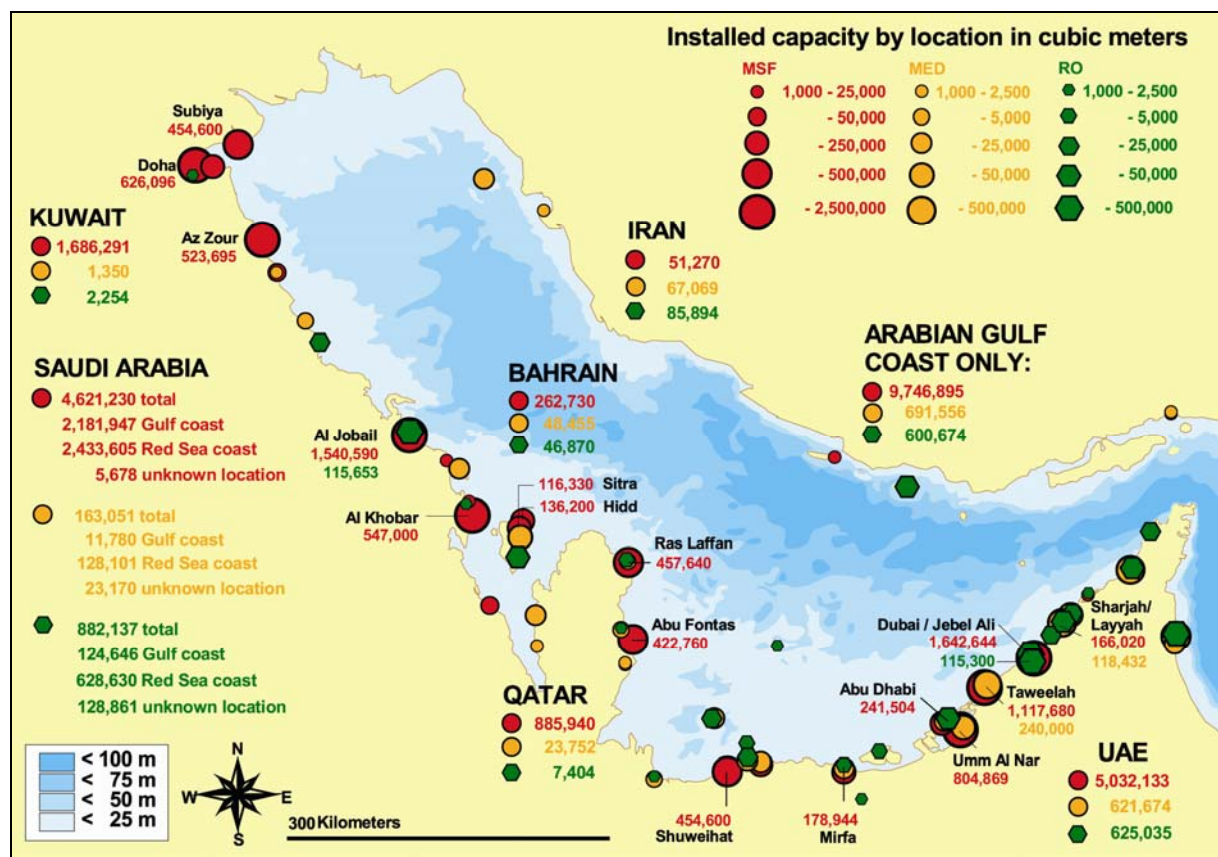


Figure 6-27: Capacity of seawater desalination in the Arabian Gulf in m³/d /Lattemann and Höpner 2007a/

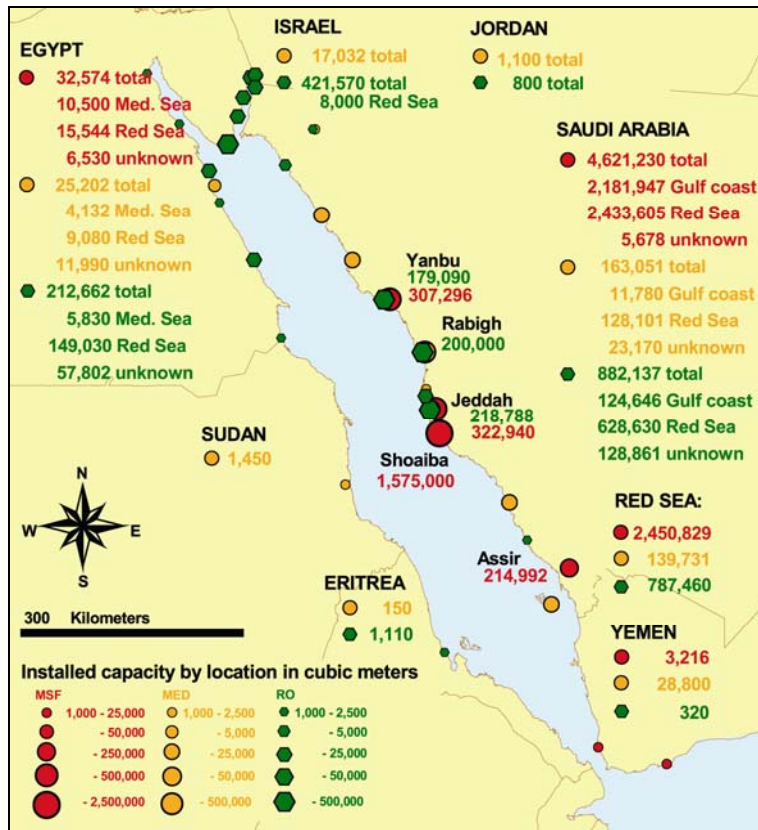


Figure 6-28: Capacity of seawater desalination in the Red Sea in m³/d, /Lattemann and Höpner 2007a/

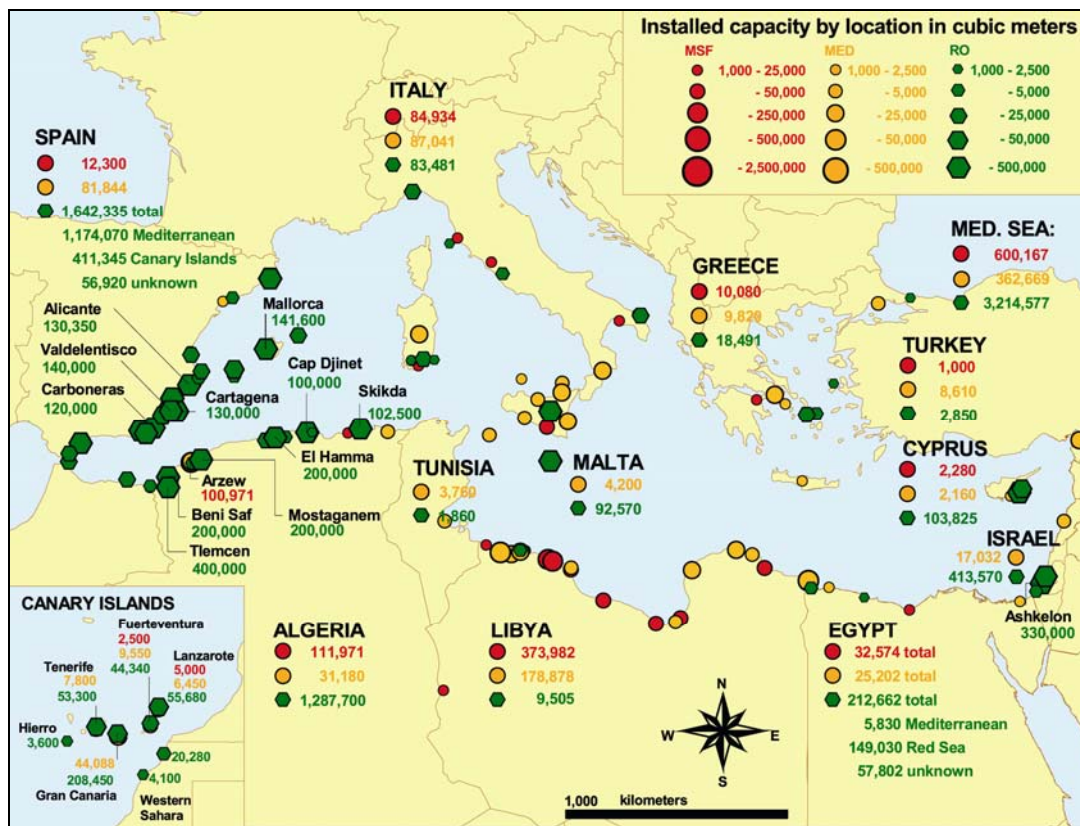


Figure 6-29: Capacity of seawater desalination in the Mediterranean in m³/d, /Lattemann and Höpner 2007a/

Specific	Unit	Conv. MSF	Conv. MED	CSP/MED	Conv. RO	CSP/RO
Desalting Capacity	m ³	1	1	1	1	1
Global Warming	kg CO ₂ / m ³	12.83	7.75	0.378	4.41	0.252
Summer Smog	kg Ethen / m ³	2.53E-03	1.54E-03	8.25E-05	6.53E-04	0.0000396
Acidification	kg SO ₂ / m ³	2.37E-02	1.61E-02	6.27E-03	3.35E-02	0.003792
Eutrophication	kg PO ₄ / m ³	3.38E-03	2.16E-03	6.30E-04	9.90E-04	0.0001788
Particles	kg PM ₁₀ / m ³	6.31E-03	4.13E-03	1.41E-03	5.33E-03	0.0007164
Chlorine	kg Cl / m ³	2.50E-03	2.30E-03	2.30E-05	5.00E-04	5.00E-06
Antiscalants	kg A / m ³	6.00E-03	6.00E-03	6.00E-05	6.00E-03	6.00E-05
Antifoamings	kg AF / m ³	1.00E-04	5.00E-05	5.00E-07	0	0
Metals	kg M / m ³	3.00E-05	1.80E-05	1.80E-07	0	0
Coagulants	kg Co / m ³	0	0	0	9.00E-02	9.00E-04

Status 2005	Unit	Conv. MSF	Conv. MED	CSP/MED	Conv. RO	CSP/RO	Total
Desalting Capacity	1000 m ³ /d	12886	1150	0	2313	0	16349
Global Warming	tons/day	165327	8913	0	10200	0	184440
Eutrophication	tons/day	32.6	1.8	0.0	1.5	0.0	35.9
Acidification	tons/day	305.4	18.5	0.0	77.5	0.0	401.4
Smog	tons/day	43.6	2.5	0.0	2.3	0.0	48.3
Particles	tons/day	81.3	4.7	0.0	12.3	0.0	98.4
Chlorine	tons/day	32.2	2.6	0.0	1.2	0.0	36.0
Antiscalants	tons/day	77.3	6.9	0.0	13.9	0.0	98.1
Antifoamings	tons/day	1.3	0.1	0.0	0.0	0.0	1.3
Metals	tons/day	0.4	0.0	0.0	0.0	0.0	0.4
Coagulants	tons/day	0	0	0	208.2	0.0	208.2

Status 2015	Unit	Conv. MSF	Conv. MED	CSP/MED	Conv. RO	CSP/RO	Total
Desalting Capacity	1000 m ³ /d	19000	8000	2500	8000	2500	40000
Global Warming	tons/day	243770	62000	737	35280	491	342279
Eutrophication	tons/day	48.1	12.3	0.2	5.2	0.1	65.9
Acidification	tons/day	450.3	128.8	12.2	268.0	7.4	866.7
Smog	tons/day	64.2	17.3	1.2	7.9	0.3	91.0
Particles	tons/day	119.9	33.0	2.8	42.6	1.4	199.7
Chlorine	tons/day	47.5	18.4	0.1	4.0	0.0	70.0
Antiscalants	tons/day	114.0	48.0	0.2	48.0	0.2	210.3
Antifoamings	tons/day	1.9	0.4	0.0	0.0	0.0	2.3
Metals	tons/day	0.6	0.1	0.0	0.0	0.0	0.7
Coagulants	tons/day	0	0	0	720.0	2.3	722.3

Status 2025	Unit	Conv. MSF	Conv. MED	CSP/MED	Conv. RO	CSP/RO	Total
Desalting Capacity	1000 m ³ /d	24000	28000	35000	28000	75000	190000
Global Warming	tons/day	307920	217000	6483	123480	9261	664144
Eutrophication	tons/day	60.7	43.1	1.4	18.3	1.5	125.0
Acidification	tons/day	568.8	450.8	107.6	938.0	139.4	2204.5
Smog	tons/day	81.1	60.5	10.8	27.7	6.6	186.7
Particles	tons/day	151.4	115.6	24.3	149.2	26.3	466.9
Chlorine	tons/day	60.0	64.4	0.8	14.0	0.4	139.6
Antiscalants	tons/day	144.0	168.0	2.1	168.0	4.5	486.6
Antifoamings	tons/day	2.4	1.4	0.0	0.0	0.0	3.8
Metals	tons/day	0.7	0.5	0.0	0.0	0.0	1.2
Coagulants	tons/day	0	0	0	2520.0	67.5	2587.5

Status 2050	Unit	Conv. MSF	Conv. MED	CSP/MED	Conv. RO	CSP/RO	Total
Desalting Capacity	1000 m ³ /d	2000	7000	155000	6000	310000	480000
Global Warming	tons/day	25660	54250	11132	26460	14843	132345
Eutrophication	tons/day	5.1	10.8	2.4	3.9	2.3	24.5
Acidification	tons/day	47.4	112.7	184.7	201.0	223.3	769.2
Smog	tons/day	6.8	15.1	18.6	5.9	10.5	56.9
Particles	tons/day	12.6	28.9	41.6	32.0	42.2	157.3
Chlorine	tons/day	5.0	16.1	3.6	3.0	1.6	29.2
Antiscalants	tons/day	12.0	42.0	9.3	36.0	18.6	117.9
Antifoamings	tons/day	0.2	0.4	0.1	0.0	0.0	0.6
Metals	tons/day	0.1	0.1	0.0	0.0	0.0	0.2
Coagulants	tons/day	0	0	0	540.0	279.0	819.0

Table 6-7: Daily load of pollutants at the Southern Mediterranean Coast, the Red Sea and the Arabian Sea in the year 2005, 2015, 2025 and 2050. The yellow shaded area shows air pollutants from energy consumption, while the orange shaded area shows water pollution from chemical additives. The blue area shows the installed desalination capacity according to the AQUA-CSP scenario. Life cycle assessment of emissions was calculated for each year on the basis of the subsequently changing electricity mix from /MED-CSP 2005/.

