PRODES Promotion of Renewable Energies for Water Production through Desalination

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Guidelines for the regulation of desalination

Deliverable 6.2

Intelligent Energy Europe

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Contents

Abbreviations

ADS: autonomous desalination system

BAT: best available technique/technology

BWRO: reverse osmosis of brackish water

DWD: Drinking Water Directive

ED/R: electrodialysis, reverse electrodialysis

EIA: Environmental Impact Assessment

IDA: International Desalination Association

MD: membrane distillation

MED: multi-effect distillation

MEH: multi-effect humidification

MF: microfiltration

MSF: multi stage flash

O&M: operation and maintenance

PV: photovoltaic

R&D: research and development

RE: renewable energy

RO: reverse osmosis

SDI: silt density index

SWRO: reverse osmosis of seawater

TDI: tolerable daily intake

UF: ultrafiltration

UN: United Nations Organization

UNEP: United Nations Environment Program

UV: ultra violet

WFD: Water Framework Directive

WHO: World Health Organization

Introduction

This report aims to develop guidelines for legislation addressing drinking water quality and environmental protection aspects related to desalination driven by renewable energy (RE-Desalination). At the same time ways to remove some of the barriers RE-Desalination is facing are recommended in order to assist a deployment of these facilities for an improved access to safe and sustainable drinking water in regions of water scarcity.

The report has been developed within the ProDes project which is promoting the market development of desalination driven by renewable energies in Southern Europe. ProDes is co-funded by the European Commission through the Intelligent Energy Programme and has been supporting RE-Desalination through various activities like training for professionals and students, seminars and technical publications. Extensive information about ProDes, the partners and the results is published on the project website: www.prodes-project.org.

The report includes an overview of currently existing guidance on desalination driven by renewable energies followed by an analysis of health, environmental and administrative aspects critical for the development of guidelines. General recommendations of elements to be included in guidelines are developed from a literature analysis. To what extent these qualify for application in various circumstances should be tested in additional country-specific studies.

1. Background on the development of guidelines for RE-Desalination

In this section, firstly, EU legislation will be examined for existing elements relevant to desalination driven by renewable energy sources. A comprehensive investigation of the EU legislation concerning water and renewable energy in general and the respective legislative and institutional issues in Greece, Italy, Spain and Portugal, is included in ProDes deliverable 6.1, which is available on the project website. Thereafter, existing guidance worldwide will be discussed.

1.1 EC Directive on renewable energy

Renewable energy sources (RES) have been officially promoted by the EU since 2001 and are widely regarded as one of the key factors towards sustainable development. In the newest edition of the Directive on renewable energy, the EU member countries committed to producing 20% of their energy requirements from RES by 2020. Although related to considerable energy consumption in Europe, water production is not addressed in the directive, thus RE-Desalination plants are not directly covered. The main focus of this directive are the energy segments electricity production, heating and transport fuels (European Council 2009).

1.2 EC Drinking Water Directive (Water quality aspects)

The EC Directive on Drinking Water Standards combines the Drinking Water Standards of the WHO (2008) with expert recommendations of a European Community Scientific Advisory Committee. The standards are designed to ensure safe consumption of the drinking water supplied over the consumer's entire life without affecting his or her health. No explicit reference is made to drinking water produced by desalination (EU Council 1998), thus the values apply to the same extent to RE-desalinated water as to conventional fresh water supply.

Gibbons and Papapetrou (2006) point out that most parameters listed in the Directive are microbial contaminants which will be automatically removed during the desalination process. Aspects specific to desalinated water, such as the very low mineral content are not addressed in the Drinking Water Directive. Small-scale water supplies providing on average less than 10 m^3 per day or to fewer than 50 people, are exempted from the water quality regulation of the Drinking Water Directive if the water is not intended for public or commercial use (EU Council 1998). It remains unclear if this exemption would still apply to small-scale privatised water providers or if those would be regarded commercial applications (Gibbons *et al.* 2008).

1.3 EC Water Framework Directive (Intake and discharge aspects)

The European Water Framework Directive (WFD) was implemented to attain a good qualitative and quantitative status of all water bodies including near-shore marine waters by 2015. It lists desalination as one of many supplementary measures to achieve the objectives of improved water management and protection (European Parliament and Council 2000, Article 11 (4), Annex VI). Moreover, abstraction for drinking water supply is part of this directive however, for volumes lower than 10 m³ per day on average, or less than 50 people are supplied, an exemption for water analysis and monitoring is given. For abstractions of 10-100m³ per day on average, exemption only for the monitoring is given (European Parliament and Council 2000, Gibbons *et al.* 2008). As with the Drinking Water Directive, a certain unclarity regarding the definitions for activities to be exempted exists. As Gibbons and Papapetrou (2006) point out, it needs to be addressed, how several exempt abstractions as well as supply amounts shall be dealt with: individually or cumulatively?

Regarding the discharge of the concentrate, salt or other pollutants from desalination processes are not explicitly listed in the Water Framework Directive. However, in view of the Riverbasin Management Plan new standards are expected to include salt concentration and activities, such as indirect discharge by percolation through ground or subsoil, which could cause saline intrusion into aquifers (Gibbons and Papapetrou 2006).

1.4 EIA Directive (Environmental Impact Assessment)

The EIA Directive regulates which project categories always have to conduct a formal EIA before development and for which projects countries decide themselves if an EIA is needed. The directive includes groundwater abstraction schemes, dams and activities to transfer water resources between river basins, above certain limits, in Annex I (mandatory EIA), however abstraction of seawater, and specifically desalination plants are not referred to. Annex II mentions the same water-related activities in cases of smaller scales and states energy projects, for instance wind farms. Impacts from the discharge of desalination plants are not addressed either, whereas other potentially polluting industries, such as the food and the paper industry, are listed (EU Council 1985).

Overall, EU legislation does not set a complete and transparent framework for desalination activities. A short investigation of the situation worldwide will be discussed in the following pages.

1.5 Relevant International Guidelines

On a global scale only a limited amount of country-specific legislation and guidance addressing desalination in particular was found. It was expected to find regulation issued by authorities in Middle Eastern countries due to their prolonged use of desalination. The fact that no guidelines could be found might be caused the lack of English translations on authorities' websites, however, in 2005 the status according to Hashim and Hajjaj was that "there exists NO strict and binding legislation on the quality control of fluid-effluents from desalination plants into the sea [Arabian Gulf]and NO treatments what-so-ever for these effluents." (p. 374).

A similar situation seems to be true to date for South Africa, given that a guidance document on desalination for municipal engineers, though referring to brine management and environmental protection in general, does not quote specific legislation (Swartz *et al.* 2006). Israel, on the other hand, has added environmental regulations for discharging brine from desalination into the sea to their Envrionmental Quality Standards for the Mediterranean Sea, including BAT guidance for outfall design, however, not setting general discharge quality standards (Safrai and Zask 2006).

The U.S. state of California's water authority's website lists six laws in connection with desalination, only one of which formulates concrete requirements (AB 314, Kehoe – 2003), namely that desalination projects are entitled to the same extent of state support as other water supply projects and that they have to comply with all applicable environmental protection requirements (Water California 2009). The United States Environmental Protection Agency is currently developing new rules regarding the direct discharge of residual products from drinking water production to surface water as well as the indirect discharge through wastewater treatment plants. These guidelines are likely to also apply to small plants and they will include concentrates from desalination processes as well as other residuals (US EPA 2010).

Similarly, regarding the health implications, the overall impression was that consideration of desalination-specific issues appears to be gaining ground at a slow rate. Neither the Australian Drinking Water Guidelines (ADWG), nor the English version of the Israeli drinking water regulations, include any reference to the quality specifics of desalinated water (NHMRC 2003, State of Israel-Ministry of Health 2000).

However, a dedicated working group of the Spanish Ministry for Health and Social Policy has initiated the development of a comprehensive guidance document on health and environmental implications of desalination for human consumption to guarantee adequate production procedures, which has been published in 2009. Renewable energy-driven desalination or renewable energy in general are not mentioned in this guidance document though (Ministerio de Sanidad y Política Social 2009).

From a regulatory point of view desalination as a source for potable water supply is relatively new in most countries except for a few states in the Middle East, which means that health and environmental policies, regulations, and guidelines are still underdeveloped. Existing policy and legislation generally do not address the unique issues resulting from desalination as a drinking water production process. Likewise, the implications of integrating desalination into the existing drinking water distribution system, such as different corrosion activity of desalinated water, bring about new aspects not yet included in the legislation (Carter 2009).

It appears that process performance and specifications for operation and water quality have evolved practically on a case-by-case basis depending on the respective source water and the intended product water use (WHO 2007). It is highly probable that this lack of guidance creates insecurity for investors and developers as well as for those authorities responsible for issuing permits for desalination projects. In view of the increasing desalination capacity worldwide and the growing awareness of, and concern about, environmental and health implications, initiatives are underway to discuss these issues on a global scale, for instance in the upcoming IDA Environmental Symposium (IDA 2010).

The recently published UNEP (2008) resource and guidance manual for Environmental Impact Assessments of desalination projects represents an important step towards the establishment of environmental regulations. Regarding the health implications, the WHO's initiative to publish a comprehensive guidance document supporting the Drinking Water Quality Guidelines, confirms the importance to address aspects specific to desalination (WHO 2010, WHO 2007).

Previous work regarding the legislative frameworks regarding RE-Desalination has dealt in detail with several countries under the ADIRA project: Turkey, Morocco, Jordan, Egypt (Mokhlisse *et al.* 2008), the ADU-RES project: Algeria, Greece, Jordan, Morocco, Spain, Tunisia (ADU-RES 7.2 2006), as well as currently the ProDes project (Greece, Portugal, Italy, Spain, (ProDes 6.1 2010). It is expected that their conclusions will contribute to the development of guidelines. However, for each case the legal and policy frameworks as well as the environmental and water supply situations will have to be analysed specifically, the various actors in the water and energy sectors identified and the respective legislation tailored to match these.

Besides updating their Guidelines on Drinking Water Quality regarding aspects of desalination, the WHO supports the International Network on Small Community Water Supply Management, which promotes the "achievement of substantive and sustainable improvements to the safety of small community water supplies around the world, particularly in rural areas" (WHO 2009b, p. 1). One of the Network's objectives ties in with this project, namely the development of internationally recognised general guidance on the management of small community water supply, at the same time the attempt to identify country-specific workable solutions.

To establish a base for guideline creation, in the following, health, environmental and administrative implications are analysed, which apply to RE-Desalination projects virtually regardless of the country-specific policy framework.

2. Health aspects related to the quality of desalinated drinking water

Producing and delivering potable water that meets health and safety quality specifications should be the priority of any drinking water system. To achieve this, the World Health Organization (WHO) has developed the Guidelines for Drinking Water Quality (GDWQ) (WHO, 2008) along with various related technical and guidance documents (Fawell *et al.* 2010). The WHO guidelines are recognised internationally and apply to both, traditional and unconventional drinking water production technologies, such as desalination. The characteristics of desalinated water and the issues arising from abstraction from non-typical water sources and utilisation of different production technologies, however, may not be covered entirely by the existing GDWQ and require a broader range of aspects to be addressed including potential chemical and microbial contamination (WHO 2007, Cotruvo and Abouzaid 2010, Cotruvo 2006, Fawell *et al.* 2010).

The WHO has included desalination as a topic in the rolling revision of the WHO Guidelines for Drinking-water Quality (WHO 2010) and gives direction on the application of the Guidelines in specific circumstances such as desalination (WHO 2008a). The need for providing more detailed guidance on the production and use of desalinated water for potable purposes in order to protect both, public health and the environment, had been identified. A specific guidance document supporting the GDWQ has been developed addressing the health and environmental aspects applicable to desalination for a safe drinking-water supply (WHO 2007).

Besides source water quality and unconventional treatment technologies, some aspects, which are specific to desalinated potable water are aesthetics and water stability, which are linked to the use of blending waters for stabilisation and replenishment with nutritionally desirable components. Furthermore, some chemicals and materials used in the desalination process are different from those used for conventional water production and distribution (WHO 2007, Cotruvo and Abouzaid 2010). Following a categorisation of drinking water production into the three sections source water, treatment technology and distribution system the respective impacts on the quality of the water delivered to the end-user will be analysed in the following.

2.1 Source water-related health aspects

When examining the potential impacts of source water for desalination processes on public health there are several factors to be considered. A key concern is the range of total dissolved solids (TDS) of saline water, which extends from about 5,000 mg/litre to 40,000 mg/litre, with high concentrations of particular ions, such as sodium, calcium, magnesium, bromide, iodide, sulphate and chloride. Furthermore, the type of total organic carbon (TOC), an often higher potential for petroleum contamination and finally, different microbial pollutants are present in seawater sources (WHO 2007, Cotruvo and Abouzaid 2010).

Though seawater and feed water from deep brackish aquifers generally contain less pollutants than most surface waters (rivers, lakes or estuaries) in urban regions (WHO 2007), they do have unique hazards not encountered in freshwater systems. These include diverse harmful algal events associated with toxin-producing micro- and macro-algae and cyanobacteria; certain free-living bacteria; and some chemicals, such as boron and bromide that are more abundant in seawater (WHO 2008, Payment *et al.* 2010). In the same way as fresh water, saltwater can also be home to a variety of pathogens, such as bacteria, viruses and protozoa, of natural origin or from wastewater or waste discharges, which are to be addressed by adequate treatment including a sufficient extent of disinfection to be added to the desalination processes (WHO 2007, Cotruvo and Abouzaid 2010).

In areas where seawater desalination is practiced, water temperatures above 15°C occur frequently, thus, on the one hand, anthropogenic pathogens are likely to be reduced due to a higher activity of indigenous protozoa which use certain pathogens as a food source. Moreover, higher decay rates of most enteric bacteria in saline water are an advantage. However, on the other hand, currents and waves can carry pathogens over long distances. Health risks from natural bacterical pathogens and toxin-producing algae vary over the year due to increased productivity in warmer water during the summer months, which usually also contains more nutrients. Moreover, fluctuating discharges from wastewater plants lead to variable levels of nutrients (Payment *et al.* 2010).

Contamination of the product water can best be avoided by prevention of source water contamination. For that reason, an assessment of potential continuous or intermittent pollutant sources in the vicinity of intake locations (Fawell *et al.* 2010). as well as a complete source water analysis at potential intake sites is recommended to minimise contamination risks (WHO 2007). This should include a thorough examination of the raw water's physical, microbial and chemical characteristics, meteorological and oceanographic data, and marine biology, taking into consideration seasonal variations. It is critical that the analysis also considers factors that will impact the plant's operation, such as water temperature, total dissolved solids (TDS), total suspended solids (TSS), total organic carbon (TOC) and components with membrane scaling potential, which include calcium, magnesium and silica (Voutchkov *et al.* 2010, WHO 2007).

Raw water collected using brackish ground water wells is generally of better quality in terms of solids, oils and grease, as well as natural organic and pathogen contamination and marine microorganisms, as compared to open seawater intakes due to the effect of soil infiltration, provided the soil substrate is suitable and not too porous (Voutchkov *et al.* 2010, Payment *et al.* 2010). However, anthropogenic pollutants, such as dioxins, petroleum products, pesticides, pharmaceuticals, and leachates from industrial facilities could contaminate source water aquifers rendering them unacceptable for drinking water production if highly sophisticated treatment processes are not used (WHO 2007, Voutchkov *et al.* 2010).

In general, when tapping into subsurface water sources, hydro-geological assessments should be conducted to identify ways to avoid damage to freshwater aquifers (Voutchkov *et al.* 2010, WHO 2007). For well intakes, for instance, the sustainability of the aquifer with regards to the required volume of drinking water has to be considered, with a guideline for the appropriate daily intake being maximum 20,000 m³ (WHO 2007, Voutchkov *et al.* 2010). The capacities of RE-Desalination plants operational today stay significantly below this volume (mostly below 100 m³/d), with wind-driven RO with a capacity of 2,000 to 5,000 m^3/day being the largest plants currently available on the market (Käufler, J., Director of Synlift Systems, personal communication, 6 September 2010).

2.2 Process-related health aspects

Health issues from the desalination procedure could generally arise from pre-treatment actions, from the actual desalination process and from post-treatment, mainly due to formation of disinfection by-products and blending with source waters for remineralisation (WHO 2007).

2.2.1 Pre-treatment-related health aspects

The sources of concern for public health from pre-treatment options in desalination plants are the chemicals added and the by-products formed during the conditioning procedure, including biocides, coagulation and flocculation agents and scale inhibitors, with the potential that these are transmitted to the product water. Source water quality will determine the amount and type of pre-treatment as will the type of desalination process. In all cases, the chemicals used for pre-treatment should be food-grade and of high quality, i.e. have only the lowest levels of impurities (WHO 2007, Voutchkov *et al.* 2010).

2.2.1.1 Distillation process

Between distillation processes and membrane processes for desalination, the former is more robust, thus the extent of pre-treatment required is smaller. Scaling and corrosion reduce the efficiency of thermal processes, therefore, after removing oil, grease and grit from the source water, feed water to the distillation process is usually conditioned with scale inhibitor chemicals (Voutchkov 2010). As with every chemical used for drinking water production, adequate dosing control is important since these can be adversely affect human health if ingested in too high doses (Téllez *et al.* 2009). Corrosion is usually controlled by reducing corrosive gases through acidification (CO_2) or by addition of an oxygen scavenger (O_2) (National Research Council 2008), which are chemicals generally recognised as non-toxic that are even used for food production (sodium bisulphate) (US FDA 2009) and as fortifying supplements (ferrous sulphate) (WHO 2006).

2.2.1.2 Membrane processes

Given that membrane desalination, in particular reverse osmosis, is sensitive to fouling, pre-treatment is generally more extensive to ensure efficiency of the process. Continuous chlorination leads to high levels of disinfection by-products and is thus not advisable, in particular if the source water has high concentration of organic material. Intermittent chlorination is recommended instead

(Voutchkov *et al.* 2010). Another potential source of concern comes from using a chloramination process, which creates both chloramines and bromamines. Chloramines do not damage SWRO membranes, however, bromamines with their much higher oxidation potential are likely to cause a loss of membrane integrity, which impacts on the quality of the permeate water. Using chlorine or chlorine dioxide with subsequent dechlorination should therefore be the preferred means to manage bio-fouling in reverse osmosis systems (Voutchkov *et al.* 2010).

Chemicals used as coagulation and flocculation agents in the pre-treatment are the same as applied during conventional drinking water production and are generally considered as safe to use for drinking water production. In addition, the membrane treatment process will remove residual concentrations during the desalination process (Voutchkov 2010).

2.2.2 Desalination process-related health aspects

Desalination is fundamentally about removing impurities, namely inorganic salts, from a saline water source, thus efficient desalination processes will leave only trace quantities in distillation processes and low levels of some sodium chloride and bromide in reverse osmosis treatment, which are not harmful to consumers (Fawell *et al.* 2010). As those desalination processes, which are the most frequently employed, are so thorough at removing detrimental microorganisms and chemical compounds, they can technically be utilised in single-stage operations with merely a low level of residual disinfectant. However, health risks could arise from even short-term failures during operation. For this reason, greater assurance that finished water quality is at its highest levels can be achieved by using multiple barriers, on-line process monitoring and management as well as source water quality monitoring, especially for blending waters (WHO 2008, Payment *et al.* 2010).

2.2.2.1 Thermal/ distillation processes

Though the evaporation process in thermal desalination plants produces a distillate with a very high purity, a potential for health risks from these types of processes exists. If volatile organic compounds, such as some petroleum chemicals from to spills and other contamination, are present in the source water and no venting or pre-treatment is used, there is the possibility that they are distilled and thus transmitted to the product water. (WHO 2007, Voutchkov *et al.* 2010, Cotruvo and Abouzaid 2010, Kutty *et al.* 1995).

Another problem could be the inactivation of pathogenic organisms. Traditionally, thermal distillation took place at high enough temperatures (around the boiling point of water) to kill off most pathogens. However, a number of thermal desalination systems in use today, reduce the pressure in successive chambers to achieve lower boiling points, which in turn enables the exploitation of water temperatures as low as 50° to 60°C. Though a range of pathogens are still likely to be inactivated at temperatures in the 63°C (30 minutes) to 72°C (16 seconds) range, spores and a number of viruses will survive these temperatures, some of them posing a risk to the water consumers (WHO 2007).

A further possible source of health concern is from organic chemicals that naturally occur in source waters, such as humic and fulvic acids or algae and seaweeds. While some merely affect aesthetically the odour of the finished water, others , for instance cyanobacteria and dinoflagellates, can form a range of toxins. Overall, however, distillation processes are efficient in controlling these compounds, which are usually of sufficiently high molecular weight and low volatility to prevent a transmission into the distillate (Fawell *et al.* 2010). Source water analysis prior to development of a desalination plant is again the safest solution.

2.2.2.2 Membrane processes

Natural organic chemicals as well as toxic molecules from algal bloom and seaweed growth are generally of a size that is removed by reverse osmosis membranes as well (Fawell *et al.* 2010). Reverse osmosis is currently the most common membrane desalination system, therefore this section focuses on health issues arising in the RO membrane process. Electrodialysis systems, for instance, do not provide pathogen reduction (WHO 2007, Voutchkov *et al.* 2010).

Besides rejecting inorganic salts efficiently, reverse osmosis membranes are able to remove a range of undesirable microorganisms, for instance typically 4 logs of removal for Giardia and Cryptosporidium, other pathogens and larger viruses, as well as other organic molecules, such as most petroleum-related molecules, larger than about 0.027 nm. Most anthropogenic contaminants originating from pharmaceuticals or cosmetics are in fact more effectively removed by RO than by conventional water treatment trains (Voutchkov *et al.* 2010). Significant amounts of disinfection by-products are often formed during the pre-treatment process, most of which are rejected by RO membranes. However, some small solvent molecules such as trihalomethanes, which have demonstrated carcinogenic activity in certain mixtures (Pereira 2000, WHO 2004), may pass through (WHO 2007).

As long as the membranes retain their integrity, they will prevent the passage of practically all microorganisms. Nonetheless, there are still some bacteria that can grow through these membranes, which needs to be considered (Cotruvo and Abouzaid 2010, Payment *et al.* 2010). The membranes' ability to prevent salt and other particles from moving through to the product water is finite. Usually RO membranes are replaced every three to five years, however if fouling or scaling take place excessively, membrane integrity can be affected, and thus contamination of the permeate water may occur. Membrane life times are dependent on a range of source water characteristic, such as raw water pH, temperature, organic content, concentration of oxidants and oil and grease in the water, as well as solids content. Monitoring systems are therefore essential to ensure consistent permeate quality during a membrane's life span (WHO 2007, Voutchkov *et al.* 2010).

A health issue specific to reverse osmosis desalination is boron, which is not rejected as efficiently by RO membranes as most other inorganic contaminants (Fawell *et al.* 2010). Boron has been identified to be toxic to reproductive and developmental activities of animals and to cause irritation of the digestive system. Furthermore, accumulation in plants has been observed, which may impact on the suitability of high-boron water for irrigation purposes (Carter 2009). The current provisional WHO GDWQ value for boron in drinking water is 0.5 mg/litre (WHO 2008), however, a source re-allocation towards drinking water resulted in a guideline value of 2.4 mg/l proposed in the WHO's recent background document for the development of Guidelines for Drinking-water Quality (2009).

Since boron removal tends to be more problematic in seawater desalination processes, with either utilisation of specific membranes with higher boron rejection or an additional desalination step at a pH of 10 or above being typical procedures (Escobar 2010) required to achieve even this higher guideline value of 2,4 mg/, the WHO advises local regulators and health authorities to permit boron levels above 2,4 mg/l in desalinated water, in particular in regions with high natural boron levels. Microbiologically safe drinking water is set as the priority, in view that exposure to boron from food and other sources is less than the value allocated for TDI (tolerable daily intake), which is usually the case (WHO 2009a).

Independent from the question of desalination, elevated boron levels in drinking water have recently been closely investigated by the EU Scientific Committee on Health and Environmental Risks due to a request for derogation from the Drinking Water Directive by Italy, respectively for a value of 3 mg of boron per litre. The expert committee concluded that "notwithstanding the fact that drinking water concentrations exceed the EU standards and therefore potentially give cause for concern, SCHER is of the opinion that taking into account the toxicological and epidemiological evidence the risks for all age categories are tolerable in general." (SCHER 2010, p. 10).

Another issue to be taken into account is the utilisation of chemical agents for the cleaning of membranes. Even if they are safe for use in drinking water treatment systems in principle, care has to be taken that they do not remain in the system in high concentrations, which could affect the drinking water quality. Appropriate flushing procedures are necessary before the desalination process is restarted. Cleaning as well as flushing wastewaters require treatment and a way of disposal that does not pose a risk to contaminate the intake water for the desalination or blending process (Fawell *et al.* 2010).

2.2.3 Post-treatment-related health aspects

Managing the health impact of drinking water produced by desalination is accomplished through a variety of post-treatment measures. The most effective are stabilisation through additional carbonate alkalinity, corrosion inhibitors, mixing with source water for remineralisation and targeted removal of particular substances, such as boron or silica (WHO 2007, Voutchkov *et al.* 2010).

2.2.3.1 Stabilisation and remineralisation

Desalinated water from both common processes is highly corrosive and in case of distillation processes comes often with an unappealing taste. To alleviate these problems, calcium and magnesium are often added to the desalinated water for stabilisation either as a chemical product, for instance lime, or through blending with source water containing a higher level of these inorganic salts. Essentially, corrosion should be reduced to a level that water contact surfaces are left undamaged and metals are not released in concentrations exceeding standard drinking water guidelines or leading to discoloration of the water or the alteration of its taste (Fawell *et al.* 2010).

If chemical products are used, the usual certification and standards for food-safety should be applied (WHO 2008). The standard treatment of blending the product water with source water in order to improve hardness and ion balance presents more challenges considering health and safety due to the risks arising from the intake water. High quality source water for mixing is essential or suitable pre-treatment targeting microbial and chemical contaminants has to be conducted (Fawell *et al.* 2010, Payment *et al.* 2010). Blending water treatment requires at a minimum the use of cartridge filters. A more thorough treatment train employing granular activated carbon is advisable for raw waters that are likely to be contaminated by algae growth, surface runoff or other organic materials or elevated turbidity. Wherever seawater is used for stabilisation, only up to 1% can be blended in as it would affect taste otherwise (WHO 2007, Voutchkov *et al.* 2010).

Besides following general guidelines for drinking water under development by WHO (2007), country-specific regulation should be established stating the minimum requirements for particle removal and disinfection of blending waters (Payment *et al.* 2010).

A second reason for this remineralisation treatment is the consideration of health risks, which could arise from the continuous consumption of low-mineral water. Since desalination processes minimise all of the ions in drinking water including nutrients, such as magnesium and calcium, concern over a potential nutrient-deficiency has developed (Cotruvo and Abouzaid 2010, WHO 2007). Although this association is still debated and drinking water should generally not be relied on for daily mineral intake, nutrient replenishment with calcium and magnesium salts or by blending with source water is considered appropriate for cases when desalinated water supply displaces traditionally high-mineral drinking water (Fawell *et al.* 2010).

Residuals of sodium, chloride and potassium can be present in desalinated water after the treatment, but mainly due to blending with saline waters. There are currently no health-based guideline values for either of these three elements proposed in the WHO Drinking Water Quality Guidelines and issues arising from higher concentrations are largely related to taste considerations. A salty taste is detectable at about 200 mg/litre of sodium, and 250 mg/litre of chloride (WHO 2008). Sodium intake usually ranges from 2,000 mg to 10,000 mg per day and generally water does not play a noteworthy role, except for persons on extremely sodium-restricted diets of less than 400 mg per day (WHO 2007). Potassium residual levels after desalination do not pose a health risk either, since their contribution to recommended minimum daily intake of 3,000 mg per day is insignificant (Fawell *et al.* 2010, WHO 2007).

Spain has pioneered the development of guidance regarding health implications of desalination through its state-run organisation Acuamed. A scientific-technical document on the remineralisation of desalinated water to ensure its stability has been published recently. Furthermore, the document specifies standardised criteria and a clear set of methods for the characterisation of desalinated water, including testing procedures, to be used as a toolset for swift and simple on-line monitoring (Ministry of the Environment and Rural and Marine Affairs. 2010).

2.2.3.2 Product water disinfection

Because desalinated water is low in organic carbon content, low in microbial loads and has minimal oxidant demand, it is relatively easy to disinfect in comparison to fresh water produced from surface water sources. Though the desalination process itself has already purified the water considerably, remaining pathogens need to be inactivated, which can be achieved via the same disinfection process as for conventional water production. In order to sustain microbial safety during storage and distribution, it is recommended to maintain a residual level of a chlorine-based disinfectant (Payment *et al.* 2010), in particular in very warm climates where microbial growth may be of particular concern (WHO 2007).

Specific issues for the microbial safety of desalinated water that need to be taken into account are the passage of small viruses through RO membranes, the potential of a loss of membrane integrity which could allow pathogens through to the permeate and the practice of blending with source water for remineralisation. Except for blending water, for which the recommended treatment has been described earlier, these issues can be addressed by adding another barrier for water safety through post-desalination disinfection with a chlorine-based or alternative process, which will be explained in the following (Payment *et al.* 2010).

Chlorine, both as sodium hypochlorite or chlorine gas, is a widely recognised and effective disinfectant. Due to the low levels of disinfection by-product precursors in desalinated water, the formation of these does not pose a severe problem. If sodium hypochlorite is to be used, on-site generation by electrolysis of seawater is not recommended as in the process large amounts of harmful bromate and brominated disinfection by-products are also produced. (WHO 2007, Agus and Sedlak 2010).

Chloramination is also an effective means of disinfecting water with a longer residual nature and may be necessary if the desalinated water is planned to be blended with other water sources disinfected with chloramines due to undesirable decay reactions, which would take place if chlorinated and chloraminated water were mixed. It is essential to consider the compatibility of the different water sources prior to their blending.

Chlorine dioxide would be appropriate as its use does not lead to the formation of bromate even when the desalinated water is blended with water containing bromide ions. Moreover, because only small dosages are needed for the process, any level of chlorine dioxide by-products would be below WHO limits. (WHO 2007).

Ozonation can cause excessive amounts of the suspected carcinogen bromate due to the higher bromide content in seawater and is therefore not recommended for disinfection of water meant for consumption. (WHO 2007, Fawell *et al.* 2010, WHO 2008).

Ultraviolet Light Disinfection is effective and requires in fact lower levels of UV irradiation for desalinated water in comparison to surface water sources due to the minimal turbidity and lower pathogen concentrations. While the chemical-free disinfection has the advantage of no formation of by-products, due to the lack of residual disinfection it may still be necessary to use a chlorine-based product later to control microbial regrowth.

Overall, it was found that desalinated water usually contains lower levels of regulated chlorination by-products than conventional drinking water disinfected with chlorine. Moreover, a reduced amount of disinfection by-products in storage and distribution are expected to form in desalinated water due to the absence of high molecular weight organic DBP-precursors after the desalination process (Agus and Sedlak 2010).

2.3 Storage- and distribution-related issues

Construction materials of the desalination units and the storage and distribution systems can be a source of water contamination. Both, salt water as well as the finished, desalinated water, are more corrosive than usual fresh water used for drinking water. Metal pipes potentially release traces of copper, lead or cadmium from solder, whereas asbestos fibres stem from the inner walls of asbestos-cement pipes, coal-tar-based coatings in storage tanks or pipe linings can contribute polynuclear aromatic hydrocarbons, and chloride monomers from PVC pipes or polymerised coatings can release traces of unreacted vinyl organic chemicals (Rodrigo Sanchez and Betancort Rodríguez 2010).

Thus, the materials used in desalination plants such as piping and contact surfaces should be evaluated to ensure no leaching of chemicals or other contamination takes place (Fawell *et al.* 2010). For instance, if coatings applied to pipes or storage tanks to reduce corrosion were of a quality unsuitable for use with drinking water, chemicals transferred to the water could adversely affect the health of the consumers. Material approval schemes are important, which must also consider the high temperatures that the thermal desalination plants operate at and how that might induce for instance metal leaching of copper and iron into the distillate (Fawell *et al.* 2010).

The safest approach to prevent corrosion by-products to occur in the product water is the use of corrosion –free materials for all components of a desalination plant that come into contact with salt water. For thermal processes, the sections where condensing and evaporating takes place, could for example be made of polypropylene materials of food-proof standard (Papapetrou *et al.* 2009). The WHO (2007) refers to the common certification procedure, where governmental, public or specialised private organisations establish those quality standards. Guidelines should include a section on storage facilities, which must protect the stored drinking water, as well as provide for operation and maintenance procedures that guarantee the safety of the water (Epp and Papapetrou 2005).

Common EU standards and a positive list of authorised materials for desalination units including restrictions on their use would improve practicality for manufacturers as well as permitting authorities. One initiative to harmonise the existing national certification programmes is a European Acceptance Scheme (EAS) for testing procedures for construction materials in contact with water intended for human consumption, instigated by the European Commission. Besides harmonisation of regional regulations, the objective is to generally accept products, which comply with these common quality standards as safe to be used in contact with potable water (Rodrigo Sanchez and Betancort Rodríguez 2010).

Regarding the microbial safety during storage and distribution the same implications as for conventional fresh water distribution systems apply including the multiple barrier approach for disinfection, residual disinfectant levels and other guidelines addressing recontamination and the minimisation of microbial growth, in particular of Legionella in warm countries (Payment *et al.* 2010).

2.4 Other health-related issues

The concentration of fluoride, which is essential for the health of bones and teeth, is naturally low in sea water and desalination processes further reduce it. Whether to add fluoride to the product water for meeting the recommended GDWQ value and for tooth protection should be determined based on local climate and water consumption as well as the status of dental health in the population, as well as the diet and the dental care routine (Fawell *et al.* 2010).

Beyond the issues described in this chapter, the potential consumer groups that may be more at risk must also be considered. Bottle-fed infants, for instance, are one such group due to their comparatively high consumption of water. Their rapidly developing bodies are more vulnerable to elevated concentrations of some natural components, such as sodium (Fawell *et al.* 2010). Moreover, in arid regions, where desalination is most likely to be a measure of drinking water supply, water consumption is often higher than existing WHO guidelines set as the standard (2 litres per day for adults, 1 litre per day for a 10 kg child, and 0.75 litres per day for a 5 kg infant). It is essential that water intake rates and dietary habits are taken into account by health authorities when establishing local standards or guideline values (WHO 2008, Fawell *et al.* 2010).

2.5 Monitoring

In general, desalination processes are rather efficient at eliminating parameters of microbiological concern, thus rendering the product water usually safe. In-depth monitoring of source water quality for pathogens is therefore not practical. However, if post-treatment blending for remineralisation is practiced, indicator monitoring and pre-treatment of these waters is essential. For this purpose, Enterococci seem to be more suitable as an indicator parameter for pathogens than E.coli due to the high degradability of the latter in the marine environment (Payment *et al.* 2010).

According to the WHO (2007) the most successful way to ensure drinking water safety is to take a comprehensive risk evaluation and management approach of which monitoring is an essential element. Innovative or non-standard drinking water production or treatment processes typically require more extensive monitoring, which applies to desalination. Which specific monitoring and control measures should be employed depends on various factors, such as the scale of the desalination plant and the quality of the source water (Cunliffe *et al.* 2010)

In their guidance document for safe water supply by desalination the WHO published a summary of monitoring parameters with recommended monitoring frequencies for large-scale and small plants, "small" applying to plants producing less than 3,785 m^3 of fresh water per day (WHO 2007). It is proposed that in cases of limited financial resources operational parameters and monitoring frequencies should be derived from a risk assessment, prioritising potentially hazardous parameters based on their level of risk.

The guidelines lists the important elements of a comprehensive monitoring programme for desalination (p. 121):

- "pre-treatment residuals should be monitored for turbidity/suspended solids, coagulant chemicals, residual disinfectants and pH
- membrane cleaning solutions should be monitored for cleaning chemicals
- brine discharges should be monitored for TDS, salts, heavy metals, nutrients, temperature and dissolved oxygen (thermal processes) and additives such as antiscalants and antifoaming agents
- the temperature and dissolved oxygen of cooling water discharges should be monitored together with copper, nickel and iron as indicators of corrosion products."

Furthermore, quality control of additives and chemical and of the monitoring equipment procedures are discussed and guidance on surveillance requirements and regulation design is provided. For details on the WHO's guidance on monitoring, it is referred to section 5: Monitoring, Surveillance and Regulation starting on page 110 of the document. These guidelines are very clear and should be adopted by every country engaging in desalination. A full review of monitoring implications would go beyond the scope of this report.

A general research requirement regarding desalination process monitoring would be the improvement of existing analytical methods to test for metals, suspended solids, and organics in saline water for a more reliable source water quality characterisation. Those methods currently in use have been developed for the analysis of fresh water with inherently low salinity and using them may lead to erratic results due to the high concentrations of dissolved solids in brackish water and seawater (Voutchkov *et al.* 2010). Adapted standard analytical methods for waters of specific salinities should then be integrated into national quality assurance schemes.

2.6 Specific situation of RE-Desalination systems

"Small community water supplies are those most vulnerable to contamination and breakdown everywhere in the world. As such, even in developed countries these water supplies pose potential health risks." (WHO 2008b, p. 1) The majority of RE-Desalination currently in place and the largest potential in the nearer future are such small-scale community water supplies. RE-Desalination has the potential to improve the health situation in these areas if managed appropriately (ADU-RES 5.1 2006).

In general health implications from source water are the same for RE-Desalination plants as for conventional ones. Due to their usually very small intake volumes brackish water aquifers can be used for abstracting high-quality feed water. If contamination of the source water, sea or brackish, has occurred, however, small-scale plants might be more at risk due to their low water "turnover", and thus less opportunity for dilution. On the other hand, since desalination processes remove virtually all microbial and most chemical contaminants (WHO 2007), exemption from source water monitoring of these parameters was proposed for small-scale RE-Desalination, which would reduce operation costs considerably (Gibbons *et al.* 2008).

The recommendations to avoid situating open intakes for desalination plants close to discharges from water and wastewater treatment plants as well as from fresh waters, such as rivers (Voutchkov *et al.* 2010), are not particularly relevant for RE-Desalination, since this technology is not expected to be employed if the possibility of surface water abstraction or wastewater reclamation existed nearby. The same is probably true for locations near large industrial and municipal ports as these are generally connected to a water supply network.

Examining the health implications from RE-Desalination processes, the issue of chemical and microbial safety should be acknowledged. Desalination systems driven by renewable energies currently in use are relatively small-scale installations with daily produced drinking water volumes below 100 m^3 (Papapetrou *et al.* 2010). The market for RE-Desalination systems includes a large share of even smaller plants, which would provide less than 10 m^3 of drinking water per day. In the EU those installations would be exempted from meeting the water quality standards of the Drinking Water Directive if they were not used for public or commercial use (EU Council 1998). An issue that could arise in these cases, in particular if pre- and post-treatment are limited is that some RE-distillation processes might not reach temperatures at which all pathogens are eliminated, as for instance the MED process (Papapetrou *et al.* 2010). If the process is relied on to render the water microbial safe and no further disinfection is practiced this could pose a risk to the consumers of the water (Payment *et al.* 2010).

A number of commercial RE-Desalination systems appear to not employ chemical pre- or post-treatment on a regular basis (ProDes 4.2 2010, Käufler, J., Director of Synlift Systems, personal communication, 6 September 2010, FSW 2010), the trend rather going towards low-chemical operation. Sand filtration is regularly used, depending on the feed water quality. Reverse osmosis systems turn towards micro- or ultrafiltration pre-treatment. Richards and Schäfer (2002) stated that their tested system of photovoltaic-driven reverse osmosis with ultrafiltration pre-treatment removing suspended particulates, bacteria and viruses, produced safe drinking water without the necessity of adding chemicals for disinfection.

It is expected that often remineralisation of the product water will be practiced, to reduce corrosivity, enhance mineral content and to adapt the product water to the palate of the end users. In RE-Desalination this is usually done by blending with disinfected sea- or brackish water (ProDes 4.2 2010, Papapetrou *et al.* 2009). Here it is essential that the treatment of the blending water is sufficient since otherwise microbial contamination could become an issue (Payment *et al.* 2010).

Regarding material suitability, Epp and Papapetrou (2005) conducted an analysis of the three most used storage tank designs for remote RE-Desalination projects. The comparison of reinforced concrete, polyethylene and steel did not result in one singular optimal design but the conclusion that the best choice depends on the size of the project, the climate characteristics and other site-specific conditions. However, the essential recommendation given with regards to materials was that given that the desalinated water is intended for human consumption, quality has to be maintained to never imperil public health and safety, so that those materials in contact with the product water should be approved under a certification scheme. This is backed up by Rodrigo Sanchez and Betancort Rodríguez (2010) in their market study for food quality products for solar-driven membrane distillation system development. Since most RE-Desalination projects to date have been R&D or pilot installations, a number of them have not yet complied strictly with material standards for every element; for instance the membrane distillation modules developed under the MEDIRAS project will substitute one non-approved epoxy hardener currently in use (Rodrigo Sanchez and Betancort Rodríguez 2010).

Operation and monitoring are primary challenges for remote, small-scale desalination units. If capacity and funding lack, monitoring and quality management are particularly difficult (WHO 2009b). Several small-scale desalination plants had to be closed for reasons of operation and maintenance problems. Reliability of such systems can be enhanced by web-based or other remote monitoring applications, which has been practiced on some islands (Choi *et al.* 2009). Membrane technology, for instance, is susceptible to membrane fouling and therefore requires careful management, which can be a problem in remote locations (Werner and Schäfer 2007). Experts from the (RE-)desalination community recommend employing fully-automated control and management systems for stand-alone systems with automated shut-down functionality, if the efficiency of the pre-treatment or the membrane system is affected, in order to ensure reliable product water (Tzen 2009, Papapetrou *et al.* 2009, Voutchkov *et al.* 2010, Epp and Papapetrou 2005). The WHO's International Small Community Water Supply Network is currently developing a test procedure for the monitoring of small community water supply, which will be employing inexpensive technology, for instance mobile phones, for remote access (WHO 2009b).

Within the MEDIRAS project a water management protocol is under development including monitoring and operation procedures to ensure a high quality of the drinking water produced by membrane distillation. In the draft document, physiochemical parameters listed for water quality and system performance control are pH, conductivity, temperature, alkalinity, boron, calcium, magnesium, chloride, sodium, potassium, nickel, nitrate, sulphate, silver and copper. Microbiological parameters selected for analysis are aerobic microorganisms (at 22°C and 37°C), Escherichia coli and Intestinal enterococci. Standards for analytical methods, points of sampling and handling of samples are set and monitoring frequencies for the different parameters listed. A complete analysis of the entire set of EU drinking water quality parameters is recommended to be undertaken once per year. Furthermore, the protocol specifies operation and maintenance standards for the system, comprising of details on cleaning and disinfection of the water storage tanks and the membranes, as well as on inspection of equipment, such as the feed pump and the piping. Prior to publication of the protocol document, standards on remineralisation and disinfection will be added (MEDIRAS 6.1 2010).

It would be beneficial to include such standards in guidelines to smooth the progress of operation and testing while ensuring water safety.

2.7 Summary and recommendations

Countries adopting desalination plants of any size for drinking water production should introduce guidelines or amend existing guidelines to make sure that the specific health issues of desalinated drinking water are addressed. These should be applied to small units as well. The WHO guidelines under development would be a suitable base to build country-specific guidelines on. In each case, risk assessments should be conducted in order to identify which parameters are essential to be monitored in the particular plant, adapted to the local characteristics and potential risks (e.g. oil spill potential, algal bloom frequency, likelihood of source water contamination with wastewater). For some parameters, such as residual disinfectant concentration, water hardness and a pathogen indicator (like Intestine enterococci) monitoring should be made compulsory even for small-scale plants.

The main possible health implications of renewable energy-driven desalination are the microbial safety of the desalinated water and to a larger extent of the blending water used for post-treatment. Particular concern has been expressed regarding the presence of microbial contamination if the blending water is not of sufficient quality or pre-treated and disinfected. Guidelines should prescribe pre-treatment of blending water prior to mixing and recommend employing a series of disinfection and pathogen control measures rather than reliance solely on the desalination process for disinfection.

Decision-makers should consider establishing mandatory disinfection procedures for desalinated water in order to reduce the risk of the formation of bromates.

Standardised operation and monitoring procedures should therefore be included in guidelines, comprising test parameters and concentration values derived from a risk-based analysis. The actual guideline values need to be set in the context of local or national conditions, as drinking water standards that are overly stringent could threaten the availability of water supply able to comply, which could be for the worse in regions of water scarcity. Kutty *et al.* (1995) propose that countries, which are dependant on drinking water from desalination should establish sets of rules which allow particular levels of pollutants for specific short periods of time at which health impacts would not be expected to arise. The source water should always be analyzed before the system installation and before it starts operation. Based on a standard risk-analysis, the smaller systems can then be excluded from the obligation to monitor their source water.

Guidelines for RE-Desalination should include approval systems for quality standards and suitability of any chemical additive employed in desalination processes and any material coming into contact with drinking water, either by adopting existing recognised standards or by establishing specifications adapted to desalination conditions.

Should the reassessment of the toxicity of boron lead to stricter guideline values of the WHO GDWQ, guidelines for reverse osmosis desalination should include specific procedures on how to achieve these values (second stage or special membranes).

Regarding the mineral balance in the desalinated water, guidelines should state minimum levels for magnesium and calcium in order to prevent corrosion and thereby metal leaching, while at the same time providing adequate nutrient supply.

Since the health and the environment dimensions are not independent from each other some overlaps between this and the following chapter exist.

3. Environmental aspects

Consideration of environmental protection aspects is essential for a sustainable deployment of desalination projects. Most of the issues are not unique to renewable energy-driven desalination, and have been investigated and compiled for conventional, normally fossil-fuelled desalination plants (UNEP 2008, Latteman 2009, 2010b, Lomax 2009, Münk 2008, Dickie 2007, El-Fadel and Alameddine 2005). Only with clear legislation and environmental standards as well as measures to enforce these, adverse impacts from desalination plants can be prevented (Schenkeveld *et al.* 2004). The leading set of environmental rules and regulations for the implementation of desalination projects has been published by the United Nations Environment Programme (UNEP) in 2008 (Lattemann 2010) giving comprehensive guidance on environmental impact assessment embracing the abiotic and biotic environment, as well as public health, and the socioeconomic and cultural environment (UNEP 2008).

From a broader perspective desalination driven by fossil fuels will emit carbon dioxide and thus add to the climate change problem, potentially exacerbating the cycle of decreasing precipitation in water-scarce areas leading to more extended draughts. The concentrate discharge back to the seas, on the other hand, is unlikely to alter the salt concentration of larger water bodies, even if they are somewhat enclosed, such as the Mediterranean Sea or the Arabian Gulf, since natural evaporation rates far exceed the concentrating influence than brine disposal (Lattemann 2010). On a local scale, however, environmental impacts of desalination can be more problematic and can be attributed directly to a specific plant. The two major local environmental issues that arise from the desalination process typically originate from discharges of concentrate and chemicals as well as from considerable air pollution from nearby power plants, which are necessary to cover the high energy requirement of both, thermal and membrane desalination processes (Schenkeveld *et al.* 2004, Lattemann 2009). The latter issue can be minimised by employing renewable energy to drive desalination, nonetheless, the brine discharge remains a challenge.

3.1 Environmental impacts of RE-Desalination installations on land

All renewable energy installations bring with them certain environmental impacts. Wind turbines, for instance, may present hazards to birds and bats, larger solar photovoltaic fields can cover a significant area of land (UCS 2010) and geothermal energy exploitation has the potential to alter the soil structure or dry out hot springs (Arnórsson 2004).

With regards to the siting of a desalination project, the same considerations as for other coastal projects apply, comprising disturbance during construction and operation from noise and pollution, an increase in infrastructure and the general competition for land with both, human interests as well as animal habitats (Schenkeveld *et al.* 2004, Lattemann 2010).

3.2 Environmental impacts of desalination processes

The number of potential impacts of desalination plants on the environment is large and in many cases they are comparable to other construction projects. Intake and outfall structures can potentially cause damage to the marine environment by damaging or destroying coastal ecosystems, killing aquatic organisms by drawing them into intakes (impingement and entrainment), which may destabilise the population balance. Moreover, regular discharges of chemicals into the sea may impact on marine life, cause sedimentation and adversely affect water quality if they are not appropriately planned and managed. This chapter gives an overview of the main issues of desalination projects for the marine environment.

3.2.1 Water intake

Artificial structures in the marine environment, such as water intakes or discharge outfalls could interfere with commercial and leisure navigation as well as with water currents and transport of sediments and provide an attachment surface for marine organisms. Open intake of sea water can cause marine organisms to be killed when they collide with intake screens (impingement) or are drawn into the plant with the intake water (entrainment). Pre-treatment needs are generally higher for open intakes than for beach wells and infiltration galleries due to the less consistent water quality. It may be difficult to identify the optimal dosing of chemicals and overdosing may prove necessary to ensure safe operation for cases of inferior feed water quality. This, in turn, increases the number of events and concentration of chemical discharge into to the marine environment (Lattemann 2010)

Underground intake structures require minimal chemical pre-treatment and protect marine organisms from entrainment and impingement. The initial construction of such structures causes more acute disruption to marine environments by displacing sediments. Coastal wells can negatively affect water quality in shallow coastal aquifers, for example if overextraction causes saltwater intrusion or by changing patterns of groundwater flow. (Lattemann 2009, Lattemann 2010)

Feed water for sea water desalination plants can be sourced either through a surface water intake or a subsurface intake in the seafloor or in beach sediments.

Surface intakes

Submerged source water intakes located offshore and in deeper water where marine life is less abundant, typically at 10-15 m water depth and 2-5 m above the seafloor, generally produce higher quality feed water with lower amounts of suspended solids and microorganisms than intakes closer to the coast. Near-shore intakes are often located where they are protected by jetties or breakwaters for wave action reduction and some settlement of suspended solids. In order to reduce the debris and organisms taken in with the feed water, surface intakes are often equipped with screen systems similar to those in the power industry. New developments in intake systems have proven to protect marine organisms better from both, the impingement against screens and the entrainment into the plant (Pankratz 2004, Lattemann 2010).

To mitigate impingement and entrainment of larger marine life, a reduction of the intake velocity of feed water to 0.1 m/s, which is comparable to gentle ocean currents, may enable non-sedentary organisms to escape the intake area. Moreover, the entrainment of smaller plankton organisms, eggs and larvae can be minimised by locating intakes away from productive areas, for instance into waters of greater depths, offshore or underground (e.g. beach wells or horizontal drain intakes) (Lattemann 2010, Pankratz 2004).

Open seawater intakes are detrimental to the eggs and larvae of fish and invertebrate species, algal spores and sea weeds, phytoplankton and zooplankton, as well as smaller aquatic organisms which are drawn into the plant with the feed water. Moreover, larger aquatic organisms can die of suffocation, starvation, or exhaustion when they are pulled against the screens**.** Endangered and protected marine species such as sea turtles and sea snakes are particularly threatened by impingement. The cumulative effects of impingement and entrainment on marine ecosystems have not been extensively investigated and are therefore difficult to estimate (Lattemann 2010).

Subsurface intakes

Shallow coastal wells are only suitable for brackish water desalination plants and relatively small sea water desalination plants with capacities below 20,000 m^3/d due to their limited yields. Subsurface intakes make use of the surrounding sediments for pre-filtration, acting as biofilters. Highly transmissive geologic conditions are favourable for subsurface intakes, while less permeable sediments, particularly those containing large amounts of silt and clay, which impede water flow are only suboptimal natural treatment systems. Biofilter intakes generally produce better feed water quality than open intakes since they reduce organic carbon, suspended solids, nutrients and microorganisms, thus achieving a decreased potential for membrane fouling with the consequence of a considerably reduced pre-treatment requirement. Engineered pre-treatment can be limited to acid and/or anti-scalant addition and single-phase cartridge filtration. However, the occurrence of insoluble salts in the feed water is a risk of water extracted from beach wells and may require the use of additional granular media filtration if feed water conditions continue to deteriorate (Lattemann 2010).

The location of the well intake is essential. In wetland areas this procedure could lead to wetland drainage affecting the environmental significantly. Moreover, water from such sources may be of inconsistent quality, which in turn would necessitate a more elaborate treatment (WHO 2007, Voutchkov *et al.* 2010). In order to minimise the environmental impacts from desalination projects it should be avoided to locate the water intakes in ocean areas containing endangered or rare marine species (WHO 2007, Voutchkov *et al.* 2010).

The location, design, construction and capacity of intake structures must employ the best available technology for minimising adverse environmental impacts and should be considered as an integral part of any assessment of environmental impacts performed for a potential desalination plant.

3.2.2 Discharge of wastewaters

Wastewater streams from desalination processes include the concentrated brine, backwash liquids and sludges from pre-treatment and cleaning processes containing suspended solids and coagulant salts as well as anti-scaling, anti-fouling, anti-corrosion chemicals. As seawater is a highly corrosive liquid, wastewater may also include trace metals from corrosion processes in the desalination system (Miri and Chouikhi 2005). The brine from a desalination plant has the same properties as the intake seawater but in concentrated form. Dependent on the process used, environmental issues may be caused from the high concentration of inorganic salts or the increased temperature of the wastewater, which may, in turn, increase the ambient salinity and water temperature at the discharge site and consequently adversely affect the ecosystem. Moreover, chemical additives are utilised for pre-treatment of the feed water and they are discharged as part of the wastewater. In the following, the potential impacts from the different wastewater characteristics will be described separately, however, it is highly probable that synergistic effects of thermal and osmotic stress with residual chemicals, exacerbate the environmental impacts (Lattemann 2010, Lattemann and Höpner 2008).

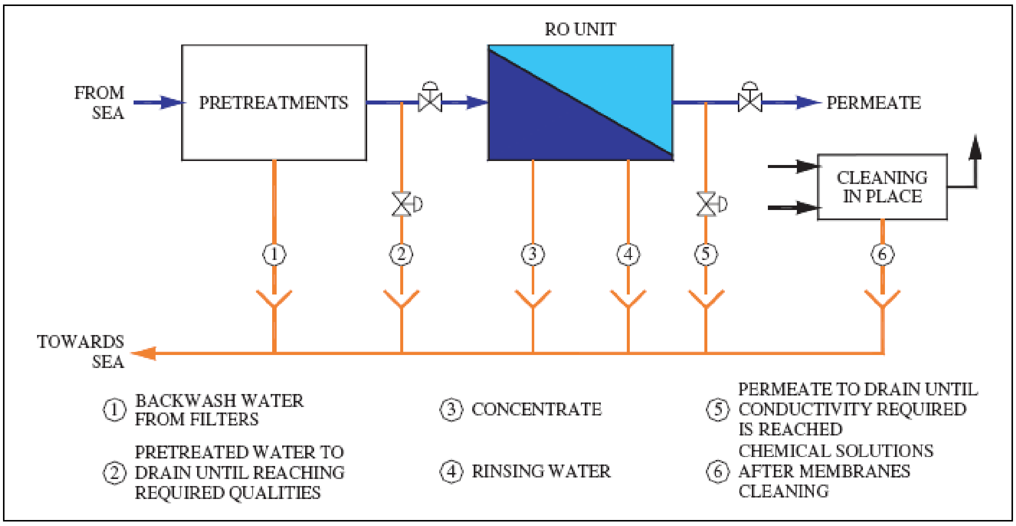


Figure 1: Illustration of various discharges from a reverse osmosis desalinatin plant (Maugin and Corsin 2005, p. 358)

3.2.2.1 Impacts from salinity, temperature and density

The salinity of the concentrate emerging as wastewater at the end of the desalination process depends on the plant recovery rate, which in turn is affected by the salinity of the source water and the applied desalination process. Reverse osmosis plants have higher recovery rates than distillation plants and will therefore produce wastewaters with higher salinities. As a consequence, wastewater discharges of desalination plants increase the salinity of outfall zones to different extents. On a broad perspective, desalination plants do not change the salinities of larger marine systems noticeably in comparison to natural evaporation rates and the subsequent increase in salinity. However, the impacts at and close to the point of discharge can be significant (Lattemann 2010).

Salinity in a specific range is essential for marine organisms, however, increased salt concentrations can be harmful and even lethal to aquatic life. In general, different species have different sensitivities to variations in salinity depending on standard variations in their natural habitats and their phase of development. Most marine organisms can adjust to minor variations in salinity, and, depending on their age and physical condition, may be able to recover from more severe, yet short term exposures to higher salinities. Few species are able to tolerate a pattern of extreme shifts or exposure to salinities significantly and continuously exceeding the concentrations to which they are adapted. The induced osmotic stress will cause these species to flee the discharge site, which, as a consequence, negatively affects and often kills sessile flora and fauna (Miri and Chouikhi 2005, Lattemann 2010).

The temperature of the wastewaters is another factor affecting the environment. The temperature of the brine emerging from reverse osmosis plants does not usually differ a lot from the ambient seawater temperature, whilst the concentrate discharges from thermal desalination plants are between 5°C and 15°C warmer than seawater. Elevated water temperatures may cause “thermal pollution” at the discharge site. The effects on species distribution from changing the annual temperature profiles in the discharge site are similar to those occurring from salinity changes. Marine organisms could be attracted or repelled by the warmer water, and species more adapted to the higher temperatures and seasonal pattern may eventually dominate the discharge site (Miri and Chouikhi 2005, Lattemann 2010). In extreme cases, thermal discharge may cause a higher mortality of sessile marine species (Pennington and Cech 2010). On a positive note, an elevated temperature could potentially enhance certain biological processes in winter, however this may come with thermal stress during summers when critical values are exceeded (Lattemann 2009).

The discharge streams from reverse osmosis and distillation plants affect different areas of the marine environment. Increases in salinity and temperature have contrary effects on the density of the discharge solution, the plume, with an increase in salinity leading to a higher density and an elevated temperature causing the opposite. Thus, discharge streams from distillation plants can either be positively, neutrally or negatively buoyant, depending on their salinity and temperature. Because concentrate from RO desalination plants is generally negatively buoyant due to its increased salinity at constant temperature, their plumes tend to sink to the seafloor if not sufficiently dissipated, forming a concentration of high salinity water which spreads across the seafloor in the vicinity of the outfall pipe and can enter pores between sediments. Thus, discharges from reverse osmosis plants generally impact on benthic (seafloor) communities, while discharges from distillation plants tends to reach and affect pelagic (open water) organisms. In addition, the difference in densities between discharge water and ambient seawater is a controlling factor for how the discharged solution mixes and spreads with the receiving water, which is important for engineered diffusion solutions (Lattemann 2010).

The salinity increase caused by desalination plant discharges can effectively be alleviated by pre-dilution with other wastewater streams such as cooling water, as well as by dissipation through suitable diffuser systems, or discharge into ocean zones with good mixing characteristics due to strong wave action and currents. This measure can also be used to control the temperature increase. However, it should be mentioned that these dispersal processes are subject to the unique oceanographic conditions at the discharge point and must be examined in a site-specific context (Mauguin and Corsin 2005, Lattemann 2010).

As a basis for the design of mitigating measures, environmentally sound salinity and temperature thresholds must be established for the specific discharge site, taking into account the sensitivity of species, natural salinity and temperature variations and other local conditions (UNEP 2008). The strict discharge thresholds for desalination plants that have been established in places such as Spain, Australia, and the USA confirm that even minor salinity increases may be harmful to local marine ecosystems, and should be prevented by using advanced discharge designs which effectively dilute the saline discharge (Lattemann 2010).

Adequate design of outfalls with diffusers, or the pre-dilution with additional wastewater have the potential to minimise most adverse environmental effects from elevated salinity and temperature. Multi-port diffusers increase the mixing efficiency of the brine and the seawater, achieving salinity levels of one unit above ambient levels at the edges of the mixing zone. Sub-surface discharge via beach wells or percolation galleries beneath the beach of seafloor enables slow dissipation of the concentrate plume into the surf zone and is suitable for smaller desalination plants (Meneses *et al.* 2010, Lattemann 2010).

Co-discharge with cooling water of power plants is not a likely option for RE-Desalination systems, however, co-discharge with wastewater treatment plant effluents is an option for effective dilution of concentrate salinity to ambient seawater salinity levels. Disposal via sewer discharge, evaporation ponds, application to land or zero liquid discharge (ZLD) are further options for dealing with the concentrate (Lattemann 2010). The promising option of using the brine in solar saltworks for salt production has been studied by Laspidou *et al.* (2009) for the existing and projected desalination plants in Greece, and by the developers of the desalination plant at Voorbaai, South Africa currently under construction (Mossel Bay Municipality 2010) with the result, however, that due to prohibitively high transportation efforts or land use this is not a sustainable and economical solution.

Regarding the mitigation of the elevated temperature of the wastewater, the outfall system could achieve an enhanced heat dissipation, from the concentrate stream to the atmosphere, prior to discharge to the water body, for instance by employing extended outfall channels, reservoirs or cooling towers (Lattemann 2010).

3.2.2.2 Impacts from residual biocides and disinfection by-products

The key to reducing the environmental impact of the brine discharge is to sufficiently dilute and disperse the salinity load until it corresponds with the ambient concentrations of the receiving water body (Miri and Chouikhi 2005). This same approach cannot be used in regard to chemicals, however, since the chemicals used in the various treatment processes do not naturally occur in the marine environments where they will subsequently be discharged. Chemicals exhibit different behaviours in marine environments and may accumulate or otherwise critically affect certain types of organisms (Hashim and Hajjaj 2005).

To reduce bio-fouling, many desalination plants add chlorine to the intake water. Once inside the plant, the oxidant demand of seawater quickly lowers the chlorine concentrations. In reverse osmosis plants, due to the sensitivity of the membranes, the water must be de-chlorinated before it enters the pressurized chamber. Therefore, chlorine concentrations will be almost undetectable in the reject streams of RO plants (Lattemann 2009).

On the other hand, distillation plants discharge residual chlorine to surface waters in varying concentration. Even though, chlorine levels rapidly decrease on discharge, the potential for adverse effects still exists in the mixing zone of the plume. Depending on the species present and their life cycle stage, chlorine may be toxic on its release into the environment. As the discharge from distillation plants may be harmful to the marine life in the plume mixing zones, it is necessary to establish effluent standards and mixing zone regulations for desalination plants (Lattemann 2010, Miri and Chouikhi 2005).

An additional concern for desalination plant effluent is the formation of halogenated organic by-products, primarily by-products of trihalomethanes (THMs) such as bromoform. It is expected that for outfall designs ensuring rapid dilution of the concentrate, chlorination by-products pose merely minimal risks to aquatic ecosystems (Agus and Sedlak 2010). However, studies on the long-term impact of chronic exposure to the concentrations encountered in desalination plant effluents have not yet been completed (Lattemann 2010).

The environmental and health concerns about residual chlorine and disinfection by-products have led to the development of several alternative pre-treatment methods. For instance chlorine dioxide can be used instead of chlorine dosing. While it also is a strong oxidant, it has been found to give rise to less THMs when added in small doses. This reduces the environmental impact as compared to chlorine. Nonetheless, if discharged into surface waters without the appropriate care, non-target marine organisms may still be adversely affected by chlorine dioxide due to the biocidal effect (Lattemann and Höpner 2008, UNEP 2008).

Negative environmental impact from chemicals can be mitigated either by treatment before discharge, by replacing hazardous substances or by using alternative, non-chemical treatment options where feasible. Biocides, such as chlorine, may be detrimental for non-target organisms in the discharge site and should be substituted or treated prior to discharge. Chemical compounds, for instance sodium bisulfite as used at many RO plants, effectively removes chlorine from the water stream. Peracetic acid treatment products have been approved by environmental protection organizations for treating cooling waters from coastal power plants and ballast water from ships and represent a good alternative disinfectant (Lattemann 2009, UNEP 2003). Wherever feasible, alternative disinfection methods, such as UV-light for small, automated systems, should be applied (UNEP 2003).

3.2.2.3 Impacts from chemicals for removal of suspended matter in RO

Conventional pre-treatment in reverse osmosis plants uses chemical agents for coagulation and flocculation followed by a media filtration to remove suspended material from the intake water. Ferric chloride (FeCl3) and ferric sulphate (FeSO4) salts are the primary chemicals used for coagulation. To further enhance coagulation both, sulphuric acid for pH adjustment and polyelectrolytes are added. Filter beds remove particulate material before the seawater is fed to the RO membranes. The filter backwash water, containing natural suspended matter and the coagulation agents, is then discharged into the sea or dried and the sludge landfilled. The clarified backwash water with only about 1% of the residual material from the filter is usually discharged into the sea (UNEP 2008, Lattemann 2010).

Discharge of filter backwash may considerably increase the concentration of suspended material at the point of discharge (Voutchkov *et al.* 2010), which may cause aesthetic disturbance since ferric salts from the coagulants can colour the mixing zone of the backwash plume reddish-brown. Where this occurs, turbidity will increase and light penetration will be reduced. For its part, coagulant chemicals are often used in water treatment systems and are generally non toxic to marine life. Iron is not classified as a pollutant either, since it exists naturally in seawater. That being said, the discharge of large sludge volumes may cause physical effects that can have negative impacts on aquatic organisms. Lower light penetration can reduce the productivity of benthic macroalgae, seagrasses or corals, and slow settling of the suspended matter may eventually cover benthic communities (Lattemann 2010).

It is common practice to discharge filter backwash from desalination plants to surface waters without treatment. The lack of pre-disposal treatment is cost effective and under the condition that it takes place to large bodies with sufficient water flow, such as open oceans or large rivers, the environmental impact is considered to be minimal (Voutchkov *et al.* 2010). In places without substantial flushing, on-site treatment before discharge or recycling upstream are possible options if the filter backwash water does not meet surface body water standards. Gravity settling remains the most common granular media treatment method for backwash waters, removing over 90% of backwash materials (Voutchkov *et al.* 2010). Sludge dewatering and disposal to land is a recommended final option (Lattemann and Höpner 2008).

Alternative pre-treatment methods employing membranes, such as ultrafiltration (UF) or microfiltration (MF) have the potential to significantly reduce the need for chemical pre-treatment.

UF/MF pre-treatment in larger plants often utilises in-line coagulation and shock chlorination but at lower dosages than required for conventional treatment. (Voutchkov *et al.* 2010). Moreover, it does require a chemically enhanced backwash and periodic cleaning of the membranes, so it is not completely chemical free**.** UF/MF can be environmentally friendlier due to the option to collect and treat the comparatively low volumes of wastewater generated in the intermittent backwashing and cleaning processes (Voutchkov 2010).

An entirely chemical free treatment option is disinfection of the intake water by irradiation with UV-light. UV rays at a wavelength of 200–300 nm damage the DNA structure of microbial organisms and thus inactivate their productivity, leaving, however, no residual disinfectant in the water. While effective in smaller operations and conventional drinking water treatment, UV-light has not yet been successfully integrated into pre-treatment for larger desalination plants (Voutchkov *et al.* 2010).

3.2.2.4 Impacts from anti-scaling chemicals

Chemicals used for scale prevention in desalination processes are either acids or specific scale inhibiting agents. Though acids must be added in relatively high concentrations, a pH effect on the receiving water is unlikely as seawater has a sufficient buffering capacity that neutralises surplus acidity quickly following discharge (Lattemann 2009, Miri and Chouikhi 2005).

The three commonly used scaling inhibitors, organic polymers, phosphonates and polyphosphates, are not harmful to invertebrates and fish species at the concentrations employed in desalination processes (Altayaran and Madany 1992). Yet, algae may be affected by anti-scalants at higher levels of around 20 mg/l. Once discharged to the environment, anti-scaling chemicals are broken down by abiotic and biological degradation at a slow to medium rate. However, a reason for concern may be that anti-scalants potentially interfere with the natural processes of dissolved metals in seawater at the discharge site, particularly for areas with minor flushing. Field studies are needed to verify this conjecture (Lattemann and Höpner 2008). Concrete evidence has been found for eutrophication close to outfalls of desalination plants using polyphosphates. Since they are quickly hydrolysed to orthophosphates, which serve as essential nutrients, their use should be avoided (Lattemann 2010).

3.2.2.5 Impacts from corrosion products

Reverse osmosis plants usually employ non-metal equipment and corrosion-resistant stainless steels, hence only traces of metals are to be expected, which are generally below critical levels. However, corrosion of heat exchanger materials in thermal desalination plants can lead to a more significant contamination of the water with copper and nickel from the most commonly used alloys. Copper has been proven to accumulate in marine sediments at sites of point discharge, thus even if copper concentrations in the wastewater were uncritical, adverse impacts on the environment and potentially ultimately on human health could arise due to assimilation by benthic organisms living on the sediments, forming the bottom of the aquatic food chain (Lattemann 2010, Miri and Chouikhi 2005).

3.2.2.6 Impacts from cleaning processes

If adequate measures are not taken, accidental or even deliberate release of cleaning solutions has the potential to endanger aquatic life near the outfall due to elevated concentrations of harmful chemicals and the high alkalinity or acidity, depending on the cleaning agent in use. Some detergents, for instance, have been found to disrupt the intracellular membrane system of marine organisms. Moreover, typically applied biocides for membrane disinfection, both, oxidising and non-oxidising types, act in the same biocidal way on aquatic life if discharged into surface water untreated (Altayaran and Madany 1992).

Therefore, the membrane cleaning streams from acidic and alkaline cleaning should ideally be collected in one tank for treatment**.** This "scavenger tank" should ensure adequate mixing and employ a pH neutralisation system. Following this procedure, the solution should be mixed with the flush water streams, thus reducing the concentration of the cleaning chemicals markedly (Voutchkov *et al.* 2010, Lattemann and Höpner 2008). Chlorine should be removed before discharge, for instance with sodium bisulphite (Lattemann 2009).

3.2.3 Impacts of desalination on wastewater reuse possibilities

Several aspects have to be taken into consideration if desalination is to be added to an integrated water management system including wastewater reuse. With regards to its suitability for irrigation purposes Lahav *et al.* (2010) report that a considerable higher amount of sodium cations reaches the sewage if desalinated water is used in the water supply compared to conventional fresh waters, even if sodium levels for the drinking water are set very low. In combination with the low concentrations of calcium and magnesium ions, which are essential nutrients for agriculture, this may result in an elevated sodicity of the reclaimed effluent, thus rendering it unsuitable for irrigation as it would lead to soil deterioration. Remineralisation with at least magnesium can alleviate this problem.

Additional issues of the reclamation of desalinated water for irrigation can be the comparatively low buffering capacity, which can pose the risk of abrupt pH imbalance from interactions of certain fertilisers (Lew *et al.* 2009). Moreover, boron content after desalination, mostly as borate, and subsequent water use may be elevated to levels which would, although not harmful to humans, be herbicidal to some sensitive plants (Lahav *et al.* 2010, Fawell *et al.* 2010).

Even more problematic is the reclamation of wastewater effluent if disposal of the actual concentrate from the desalination process into the sewer system takes place. Total dissolved solids (TDS) levels, specifically sodium, boron and bromide concentrations are the parameters of most concern for irrigation suitability. Furthermore, if extensive discharge of brine into the wastewater system is practiced, the high concentration of TDS is likely to inhibit the wastewater plants' biological treatment stage (Voutchkov *et al.* 2010). Concentrate disposal into deep wells below fresh water aquifers is unlikely to be employed for small and medium-sized desalination plants due to the high costs. However, beach well disposal, which is sometimes practiced, comes with the potential for leakage from the well and contamination of the water supply, if the discharge aquifer is not sufficiently separated from groundwater aquifers (Gibbons and Papapetrou 2006, Voutchkov *et al.* 2010).

3.2.4 Positive environmental implications of desalination installations

Besides reliably providing high quality drinking water, desalination can have positive implications for the environment. In cases where the stress from overused freshwater aquifers is reduced due to the additional water supply by desalination, subterranean water resources can be preserved (Lattemann *et al.* 2010a) as proven in Murcia, Spain (Acuamed 2009b).

3.3 Specific situation of RE-Desalination systems

The major environmental burden of desalination in Life Cycle Assessment studies are typically allocated to the significant energy use that usually comes with all the challenges of extraction and burning of fossil fuels (Biswas 2009, Lyons *et al.* 2009, Muñoz *et al.* 2008, Raluy *et al.* 2006). While all renewable energy sources come with environmental impacts as well, these are considerably smaller than the extensive use of fossil fuels (Raluy *et al.* 2005, Micale *et al.* 2009). In view of large RE-Desalination projects being proposed or under development worldwide (KACST 2009, Acquasol 2010, TREC 2009), guidance regarding the environmental impacts should generally be applicable to desalination systems driven by renewable energy projects.

However, the RE-Desalination systems currently in use are mostly of small scale and environmental impacts are rather localised. The low intake volume for RE-Desalination plants make lower flow rates possible, thus low intake velocities are viable, which renders impingement unlikely to occur. In view of the fact that discharge volumes from RE-Desalination plants are very low compared to conventional installations, it appears acceptable to generally rely on natural dispersal of the concentrate, rather than requiring BAT for outfall design, including oceanographic characterisation, mathematic modelling of dispersion, setting minimum outfall pipe lengths etc. Concentrate discharge from these small systems to surface waters is not expected to pose a risk to the water body if it is not a very small one without a natural mixing regime (Gibbons *et al.* 2008, UNEP 2003).

Some even consider discharge of desalination waste effluents containing chemicals a minor problem for small-scale desalination with the assumption that no serious damage is caused to aquatic life (Semiat and Hasson 2010). The UNEP (2008) concurs with this opinion insofar as it proposes a simplification of the Environmental Impact Assessment (EIA) process for relatively small projects (e.g. for installations of less than 500 m³ output capacity per day) for reasons of their limited potential to significantly affect the environment. Nonetheless, residual biocides from feed water disinfection and from cleaning processes may have a detrimental impact on marine life even if discharged in small volumes and should therefore not be overlooked (Miri and Chouikhi 2005).

In her review on RE-Desalination García-Rodríguez (2003) states that all desalination systems need some measure of chemical pre-treament. However, a more recent analysis of RE-Desalination installations worldwide found that due to the use of beach wells, which is suitable for these relatively small plants, pre-treatment requirements were reduced considerably (Papapetrou *et al.* 2009). On the other hand, UF/MF membrane pre-treatment and UV-disinfection have been found to potentially have a higher environmental impact than conventional pre-treatment employing chemicals and a media filter. However, this conclusion was drawn from a life cycle analysis due to the increased energy requirement of the plant when these pre-treatments are applied. Since RE-Desalination units do not significantly contribute to global warming potential of an installation the alternative pre-treatment measures are environmentally preferable (Beery and Repke 2010).

Scaling in thermal processes can be avoided by low temperature operation, for instance practiced by the solar thermal-driven membrane distillation system MEMDIS (Papapetrou *et al.* 2009). Some of these systems operate entirely without anti-fouling and anti-scaling chemicals (Thiesen 2007). The wind-powered seawater desalination system SYNWATER for instance relies on ultrafiltration pre-treatment and a low recovery rate, thereby preventing membrane scaling (Käufler, J., Director of Synlift Systems, personal communication, 6 September 2010). In these cases the concentration of chemicals in the wastewater from RE-Desalination plants is low or nonexistent, thus it does not pose a risk if discharged back to sea.

As described previously, the Water Framework Directive does not specify brine discharge standards and, exempts very small plants from regulation regarding abstraction of source water. Moreover, the UNEP (2008) guidance on environmental impact assessment suggests a "class screening" for small-scale desalination projects, exempting them from EIA or making it easier with a standardised approach. Within the ProDes project (ProDes 6.1 2010) an approach was put forward to categorise RE-Desalination systems according to their drinking water output, thus making sure that only small-scale, environmentally benign projects would be exempted from EIA. Regardless if certain projects are exempted, in the longer term it is critical to keep track of installations in order to examine and control potential cumulative impacts, which could arise if many small-scale plants were concentrated at a (sensitive) location.

Analogous to all inland desalination facilities, RE-Desalination plants treating water from brackish wells far off the coast require different disposal options for the concentrate, such as local evaporation ponds, well injection or discharge into the sewerage system (UNEP 2003). The same problems apply as for conventional desalination plants, only that the comparatively small scale would probably make it easier to realise these environmentally soundly. If disposal to the soil is practiced, as is sometimes the case due to a lack of regulation of brine disposal, chemical contamination will affect soil fertility and the concentrate will potentially increase soil salinity causing desertification and loss of habitat (Rabi *et al.* 2006). The option of deep-well injection for the disposal of brine, which is usually conducted inland and at a safe distance from drinking water aquifers, is unlikely to be employed for small and medium desalination plants due to the high capital costs (National Research Council 2008).

The use of battery storage for remote RE-Desalination systems not connected to a grid, has negative environmental implications (Thiesen 2007, Rabi *et al.* 2006). Research efforts at several institutes go into developing RE-Desalination systems without batteries, where the drinking water essentially represents the energy storage (Infield 2009, De Munari *et al.* 2009, Gandhidasan and Al-Mojel 2009).

Besides alleviating the stress on local fresh water resources, RE-Desalination has a number of further positive environmental effects. Since drinking water is produced locally, environmental impacts from long-distance water transport via truck or an extensive distribution system are avoided. Moreover, improving access to safe drinking water and sanitation is likely to reduce unsustainable migration from remote communities towards urban centres (Rabi *et al.* 2006).

3.4 Summary and recommendations

Despite a large amount of literature on the potential adverse effects of desalination on the environment, few actual EIA studies or other evidence relating to environmental impacts are available to date. From what has been examined, the impacts of a small-scale RE-Desalination plant are expected to be close to negligible. The sizes of most of the currently available systems would stay below those capacities requiring EIA according to the UNEP manual (2008).

However, regardless of the necessity for an EIA and the size of the planned project, a guideline should preclude RE-Desalination installations for extremely sensitive habitats since some degree of environmental impact even comes with small-scale plants.

Guidance should recommend subsurface source water intake wherever possible. If this is not feasible, intake design has to provide for impingement protection by respecting a maximum intake velocity of 0.1 m/s.

The lack of clear concentrate disposal regulation has led to uncontrolled discharge or dumping. Guidelines should contain minimum levels of dilution required. An exemption of concentrate discharge for very small scale plants to sea is an option if no harmful chemicals are involved. For inland disposal of low volumes guidelines should recommend discharge to the sewage system. If this is not feasible evaporation ponds or well injection could be considered but must prove to be employed environmentally soundly. Uncontrolled disposal to land should be prohibited.

Guidelines should recommend the use of MF and UF pre-treatment systems as they do not require chemical conditioning of the source water to produce effluent suitable for SWRO desalination, thus backwash water from these systems is less harmful for the environment. If still utilisation of chemical agents remains necessary, the treatment of backwash water prior to discharge to the sea should be obligatory.

In order to reduce disinfection-related risks to the environment, guidelines should set standard procedures for disinfection pre-treatment in membrane (and if practiced in thermal) processes. Disinfection by UV-light should be the preferred process. If UV treatment is not feasible dechlorination of any wastewater discharged back to the environment should be made obligatory.

Guidelines should make clear which environmentally friendly chemicals are safe to use for corrosion inhibition and scaling control. Standards should be set which processes are permitted to utilise specific chemicals, for instance anti-scalants should be banned or restricted for low-recovery reverse osmosis systems, since their use is unnecessary unless a boron removal stage at a high pH is employed.

Guidelines should set standards of treatment procedures before discharge for chemical cleaning solutions from all membrane cleanings. No exemption for small-scale installations should be accepted due to the inherent hazards of these chemical cleaning agents.

Guidance should include standards regarding use and disposal of batteries.

Interrelated with the following chapter on administrative issues, legislation could set a minimum quota of renewable energy to cover the demand of newly established desalination installations.

4 Administrative issues

4.1 Issues from the structure of the water sector

4.1.1 Centralised organisation of the water sector

The water sector in most countries has traditionally been highly centralised, with water authorities being responsible for production, supply and monitoring of fresh water. Decentralised systems have been an option primarily in the more rural and remote areas, where the centralised systems were not feasible due to technical, economical environmental constraints (Cook *et al.* 2009).

Besides being considered an important step for attaining the Millennium Development Goals for developing and transition countries (Peter-Varbanets *et al.* 2009), proponents of decentralisation argue that it can lead to more efficient allocation and use of resources. Furthermore, decentralisation presents a better opportunity to include local people in the decision-making process and therefore has the potential to create a higher degree of transparency and ownership (OECD 2009). In order to facilitate future development of RE-Desalination, decentralisation of the water sector is suggested, with responsible administrative bodies represented on a local level (Stefopoulou *et al.* 2008).

Decentralisation of water and energy supplies addressing mainly small, remote communities and receiving financial and technical support from various national and international programmes is advantageous for the promotion and distribution of RE-Desalination technology. If water resources are managed and monitored on a local level, alternative water supplies are more likely to be integrated into water management systems, for instance by local authorities or NGOs (Mokhlisse *et al.* 2008) since awareness-raising within these organisations appears easier and more practical. Nonetheless, in order to maintain a safe drinking water supply in case of decentralisation or privatisation, systems design and operation need to follow a risk management approach taking into account the likelihood and consequences of system failure in terms of public health and environmental impacts (Cook *et al.* 2009) as analysed in chapters 2 and 3.

Water sectors are highly complex in most countries and decentralisation encompasses legal, institutional and financial elements. For a comprehensive analysis of water sector decentralisation, the OECD report "Dealing with post-decentralisation implications in the water sector – based on country experience cases" is proposed, presenting case studies of a number of European countries and evaluates the experience obtained with inter-municipal cooperation, which is a recommended policy option to overcome the issues arising from fragmentation of the water sector post-decentralisation (OECD 2009). Regardless if centralised organisation is maintained or decentralisation is practiced in the water and energy sector, transparency on the roles of the various institutions is essential (Schenkeveld *et al.* 2004).)

4.1.2 Complexity of the licensing process

Project development requirements and necessary permits for desalination plants differ from country to country and even within a country, often from one state to another. As an indicator for the timeline of recent projects, the development of the two Australian RO pants in Perth and Sydney from the initial concept, via EIA including public consultation, revision of proposals, through approval procedures until the final construction and commissioning took between 4 to 5 years (El Saliby *et al.* 2009). These two facilities, however, are large-scale desalination plants with capacities of 144,000 m^3/d and 250,000 m^3/d respectively, therefore a thorough EIA and licensing process is justified. Obviously, a timeline of this extent would be unfavourable for small-scale RE-Desalination projects.

For the implementation of desalination plants powered by renewable energy sources there has not yet been established any standard administrative procedure, neither EU-wide nor in any member state or elsewhere. The practice of obtaining the different licenses varies from country to country (Mokhlisse *et al.* 2008, Gibbons *et al.* 2008), for example the general practice in Greece is to adhere to the license procedures for water production in parallel to those for renewable energy production, effluents management and further related aspects (ProDes 6.1 2010).

In most countries a number of permits are required for the development of a desalination project. Clarity on the permitting procedure and contact with the competent authorities from an early stage is essential. Commonly, distinct licensing procedures for water supply and renewable energy projects apply, thus making separate applications for each element of a RE-desalination project necessary. Mokhlisse *et al.* (2008) describe the typical range of licenses required for RE-desalination in the countries examined during the ADIRA project, which are listed here for background information:

- Withdrawal/ utilisation of seawater or brackish water
- Brine disposal
- Construction in coastal zones
- Drinking water quality
- Renewable energy installations
- Import taxes and VAT (Value Added Tax)

When regulation is dispersed like this and possibly various addenda, exemptions and modifications exist but are not clearly published, it renders the identification of appropriate standards and rules for the implementation of new projects very time consuming and thus costly (Schenkeveld *et al.* 2004). This may remain a major impediment to the deployment of small-scale RE-Desalination projects. Furthermore, this process generally involves several public authorities (Lattemann *et al.* 2010a).

4.1.3 Suggested measures to facilitate the development process

RE-Desalination is not highly commercialised to date and a lack of real-world experience is still prevalent (Papapetrou *et al.* 2009). Guidelines for system standards and an accreditation programme for system installers could address authorities' and end-user's concerns about the reliability of RE-Desalination systems (Werner and Schäfer 2007).

A transparent and straightforward set of water laws and regulations is essential for a successful development, especially when actors from the private sector are involved. Schenkeveld *et al.* (2004) emphasise the importance of regulation to establish co-ordination mechanisms between authorities and other stakeholders. Lattemann *et al.* (2010a) propose to select one coordinating agency to guide through the process and integrate the relevant stakeholders and agencies with the project developer. In particular, the division of responsibilities makes a structured collection and management of data necessary, preferably by "a specialist, central body, created for this particular purpose" (p. 71).

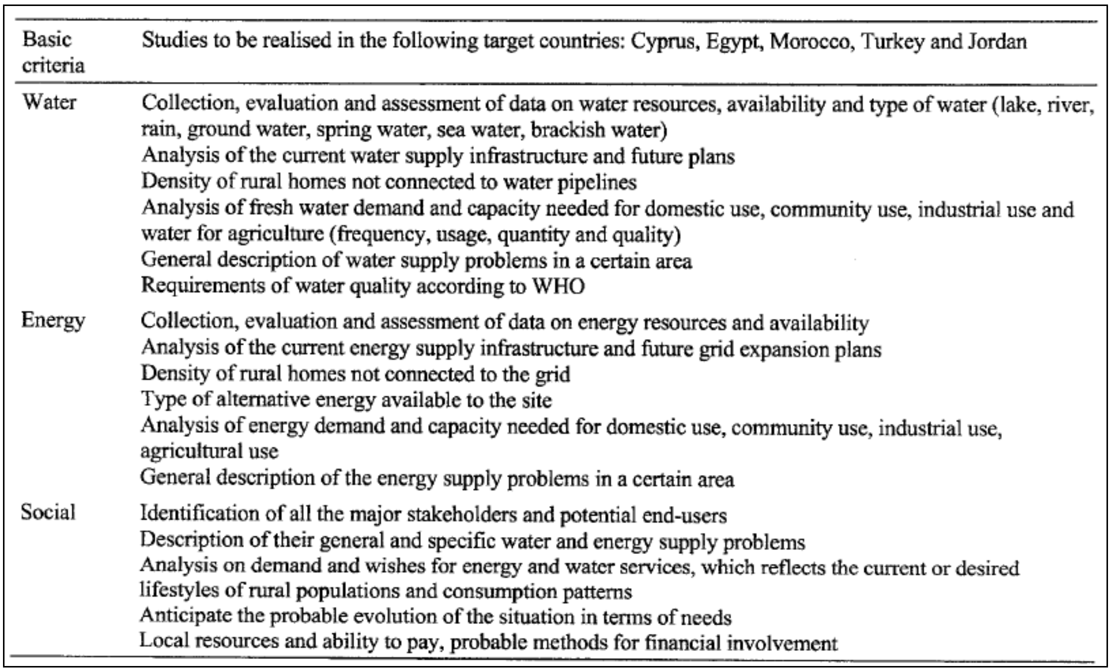
An additional idea could be to institute a centre for support and information for RE-developers, operators as well as public authorities within this organisation. This centre could also undertake documentation of projects implemented, for instance in a global database registering technology features, administrative procedures and experiences regarding health and environmental issues, in order to build an evidence base for future analysis. A guideline could be formulated that makes it compulsory to register new of RE-Desalination systems with this organisation, comparable to the obligatory listing of newly installed photovoltaic systems in Germany (Federal Network Agency 2009) could provide a complete database which could be used to determine cumulative effects as well as to control performance of the systems.

Only recently, Saudi Arabia announced plans to establish a comparable organisation, namely the "National Center for Renewable Energy Applications in Desalination" (NACREAD), whose aim it is to support a large-scale deployment of RE-Desalination plants (Pankratz 2010a). Regardless if such an agency is established, guidelines should be issued specifying the procedures, required documents, fees, etc. for issuing the generation, installation and operation licenses required for renewable energy projects as well as water production projects. Integrated design should be supported by instituting legislation concerning the licensing for both, the installation and operation of RE-Desalination (Stefopoulou *et al.* 2008).

Tendering could be used to create predictable processes for all involved parties and calls/invitations to tender should give guidance to developers on standard and specific terms and conditions of contracts, thus on how to design the projects and what procedures to follow. The Greek Cyclade islands are currently undertaking a survey on how to formulate a RE-Desalination invitation to tender, by asking suppliers for their input (Käufler, J., Director of Synlift Systems, personal communication, 6 September 2010).

Water authorities should integrate RE-Desalination in their strategic water management plan (Mokhlisse *et al.* 2008). The concept of strategic search areas, which is for instance used for wind power deployment (Simão *et al.* 2009, Cowell 2010) could be identified and the permitting efforts reduced or even active promotion of RE-Desalination projects pursued for these areas. This would require a geographical supply and demand analysis regarding both, water and renewable energy to select the most suitable areas or communities for projects to be promoted. Seibert *et al.* (2004) identified a list of inter-related factors that should be considered in the selection process (Table 1).

Table 1: Basic indicators for the implementation and quantification of suitable regions



Basic criteria	Studies to be realised in the following target countries: Cyprus, Egypt, Morocco, Turkey and Jordan
Water	Collection, evaluation and assessment of data on water resources, availability and type of water (lake, river, rain, ground water, spring water, sea water, brackish water) Analysis of the current water supply infrastructure and future plans Density of rural homes not connected to water pipelines Analysis of fresh water demand and capacity needed for domestic use, community use, industrial use and water for agriculture (frequency, usage, quantity and quality) General description of water supply problems in a certain area Requirements of water quality according to WHO
Energy	Collection, evaluation and assessment of data on energy resources and availability Analysis of the current energy supply infrastructure and future grid expansion plans Density of rural homes not connected to the grid Type of alternative energy available to the site Analysis of energy demand and capacity needed for domestic use, community use, industrial use, agricultural use General description of the energy supply problems in a certain area
Social	Identification of all the major stakeholders and potential end-users Description of their general and specific water and energy supply problems Analysis on demand and wishes for energy and water services, which reflects the current or desired lifestyles of rural populations and consumption patterns Anticipate the probable evolution of the situation in terms of needs Local resources and ability to pay, probable methods for financial involvement

In order to employ the appropriate technology for RE-Desalination, awareness of the respective local resource should be precondition for a development process. Understanding of the renewable energy source's potential and its respective seasonal variation should be proven by utilising decision support tools such as average wind speed maps, solar plots etc. Proof of a good match of RE supply with the water demand pattern should also be requested (Richards and Schäfer 2010).

A defined and transparent procedure for the licensing of RE-desalination should be developed. Even more advantageous would be the reduction to a single license for specific project sizes and configurations (Mokhlisse *et al.* 2008).

4.2 Financial aspects

4.2.1 Pricing of water

The economics of renewable energy-powered desalination systems differ from conventional plant economics since the former are almost entirely determined by the fixed costs of the installation as they do not consume any fuel for operation (Gude *et al.* 2010). The costs of RE-desalinated water differ widely depending on process type, design and characteristics of the desalination site (Ettouney and Wilf 2009). Generally, costs of water desalinated by renewable energies are still higher than for conventional water supply despite steadily decreasing costs for equipment and improvements due to experience (Greenlee *et al.* 2009, Papapetrou *et al.* 2009). However, in some remote areas, which rely on water transported by trucks or ships, they are already competitive (Papapetrou *et al.* 2009).

RE-Desalination projects face serious financial obstacles compared to conventional desalination due to the large investment burden at the beginning of the project, the perceived uncertainty attributable to the lack of proven working systems, and the general cost disadvantage of small-scale developments. Moreover, many countries still support the water sector in general, and specifically the conventional, fossil-fuel-driven desalination industry with high subsidies (ProDes 6.3 2010), which enables these to maintain their often unrealisticly low water tariffs. This ties in with the centralised organisation of the water sector discussed previously. Combined, these factors generally render investment in RE-desalination unprofitable even in situations where they would be the most efficient solution for water supply.

To overcome this situation of unfair competition the water pricing framework and subsidy practices should be reconsidered. In general, pricing structures should lead to more efficiency in water use and an investment allocation towards the factually most economic water supply option. Concurrent, the EU Water Framework Directive states that water production costs should be reflected in the water pricing for all ways of production (European Parliament and Council 2000). An approach taking into account the negative externalities of conventional desalination proposed by ProDes (6.3 2010), involves a taxation rather than a subsidising of fossil-fuel-powered plants, which would inevitably lead to higher but fairer water prices.

Pricing structures that reflect the true value of drinking water, thus treating it like other commodities can improve water conservation (Schaefer 2008, ProDes 6.3 2010). At the same time, it is essential to differentiate between basic water requirements and water usage above those requirements. Implementation of new pricing structures could have a negative impact on the less wealthy, if affordability of this essential good is compromised. One method to balance profitable pricing systems and a basic right to water access is the use of lifeline rates. These low or even cost-free rates apply to a minimum water volume that would be considered non-discretionary (e.g. for consumption and sanitary requirements) with any usage above that being charged at a higher specified price (US EPA 2009). For lifeline rates to be applied successfully, the minimum water requirement has to be determined by country and area-specific studies, taking into consideration water availability, climate and traditional consumption rates (Zetland 2010, ProDes 6.3 2010).

4.2.2 Suggested financial support schemes

For both, renewable energy and conventional desalination, well-established support policies exist in a number of countries. Within the ProDes project a dedicated working group of experts identified appropriate elements of a financial support scheme for RE-desalination (ProDes 6.3 2010). A comprehensive value-based analysis of six support schemes identified feed-in-tariffs for produced water as the most favourable solution for financial promotion of RE-Desalination, followed by production and investment subsidies. A quota-scheme comparable to the ROC-system (Renewable Energy Obligation) in the UK for renewable energy, a 100%-renewable-energy-for-desalination-obligation and an inclusion of the RE component of RE-desalination have been assessed less effective. However, the latter would be the support scheme most easily integrated into functioning existing policies.

Hence, it is recommended to adapt the methodology developed in this publication for deriving the optimal scheme to every country individually as combinations may be beneficial and the respective desirability of effects from the subsidy varies in different circumstances. Moreover, the initial position differs widely with some countries having sophisticated water metering in place and others still lacking this system.

Regardless of which scheme is chosen it is essential that it is transparent and reliable so that investors can easily understand and use it. Furthermore, it is recommended to make a distinction of support for the various technologies, capacities and the respective source water quality (seawater vs. brackish water) since the energy requirements differ and long-term cost development is expected to vary between technologies.

An important factor of subsidy schemes is that they do not over-support since their aim should only be to implement RE-desalination in locations where water conservation or recycling programmes do not suffice.

In general, every support programme for small communities offers opportunities for RE-desalination. The ADIRA project described a number of countries where programmes supporting rural communities in setting up water and energy infrastructure have been initiated by the governments and found that these programmes can have a positive influence on dissemination of RE-Desalination (Mokhlisse *et al.* 2008, Sözen *et al.* 2008). Small-scale, private projects should be supported in addition to large government initiatives, and environmental, health, and social criteria should be included for all projects (Gibbons *et al.* 2008).

Compliance of the RE-desalinated water with quality standards should be the precondition for any measure of financial support. A streamlined and easy process for both, the license applications and the application for respective financial support could improve the development process for RE-Desalination.

Policy and financial support for research and development programmes and the dissemination of the developed pilot units is likely to produce improved systems and raise awareness of decision-makers regarding RE-desalination. The U.S. Department of the Interior Bureau of Reclamation for instance, is supporting a research programme on desalination and water purification, under which a fully functional pilot plant was developed employing a PV-driven feedback control module regulating the flow rate via a pressure stabiliser, the required system operating pressure can be maintained even for fluctuating the wind speeds between 3 and 9 m/s (Liu 2009).

Even more committed, the recent American Clean Energy Leadership Act (2009) directed the Department of the Interior to operate the Brackish Groundwater National Desalination Research Facility, and to take as one focus the integration of brackish water desalination and renewable energy technologies (Carter 2009).

4.3 Summary and recommendations

From this description of the administrative issues, it becomes obvious that the process for installing a RE-Desalination unit is long-winded and rather complicated, thus costly already. Furthermore, if following the recommendations for guidelines from the previous chapters, barriers to the implementation of RE-Desalination could even be exacerbated. Non-exemption from health aspects as well as a certain amount of EIA could prolong the licensing process and drive up the costs for both, the permitting as well as operation due to more stringent requirements.

Therefore, an effort should be made to create a clear institutional framework and water sector organisation and to establish a transparent legal framework also providing facilitation of a close cooperation between public authorities in energy and water sectors with private developers. Simplified, streamlined processes to obtain a license for independent water production by renewable energy should be designed and included in the legislative guidance.

Small drinking water supply plants generally have a comparative cost disadvantage since they should comply with all the health-related rules as well as a considerable amount of environmental regulations while not being able to realise economies of scale of larger plants. In order to overcome these financial disadvantages, support schemes should be developed, which should then be applied to those projects that improve the current supply situation in terms of health and environmental aspects (e.g. shift from brackish water consumption, change from over-abstraction from fresh water aquifers).

Appropriate financial support schemes should be designed and tested in order to include them in future guidelines. A feed-in tariff for the supplied water is the recommended solution if water metering is already in place. As a minimum, existing support schemes for renewable energy generation should applied to RE-Desalination.

A further important aspect for improving the water supply situation is clear guidance on access to and pricing of the desalinated water. Where consumers had been able to use free or inexpensive water from brackish wells, they should not be left worse off after a desalination plant is brought on line

Financial support for further RE-desalination research should be included in the budgets for water and energy R&D programmes.

5 Summary of recommendations for guidelines and conclusion

Summary

Desalination for fresh water supply can be a reliable option within an integrated water management plan but should generally only be adopted as a last resort due to the high energy use. The sustainability of desalination can be improved significantly by employing renewable energy sources to cover the energy needs. On the other hand, RE-Desalination can also improve the accommodation of intermittent electricity production of weaker grids with fresh water being effectively a means of energy storage.

This report on desalination driven by renewable energy sources encourages and supports decision-makers to establish a clear framework addressing drinking water produced by desalination in order to protect the health of the consumer and the environment, while removing unnecessary administrative barriers.

The most critical points identified are:

Relating to water quality:

- Guidelines should prescribe pre-treatment of blending water prior to mixing and recommend employing a series of disinfection and pathogen control measures rather than reliance solely on the desalination process for disinfection.
- Standardised operation and monitoring procedures should be included in the guideline.
- Guidelines for RE-Desalination should include approval systems for quality standards.
- Guidelines should outline mandatory disinfection procedures for desalinated water.
- Guidelines should state minimum levels for magnesium and calcium in order to prevent corrosion.

Relating to environmental protection:

- A guideline should preclude RE-Desalination installations for extremely sensitive ecosystems.
- Guidance should recommend subsurface source water intake wherever possible.
- Guidelines should contain regulation of concentrate discharge.
- Guidelines should recommend the use of MF and UF pre-treatment systems wherever possible.
- Guidelines should make clear which environmentally friendly chemicals are safe to use.
- Guidelines should set standards of treatment procedures before discharge for chemical cleaning solutions from all membrane cleanings.
- Environmental assessments as well as health issues should be linked to the permitting process as overlaps exist, in order to avoid duplicate reports. The assessment should take into account the "alternative" means of drinking water production, thus factoring in the potential positive effects of RE-desalination, for instance prevented overuse of aquifers or avoided consumption of brackish water or having to walk long distances to obtain drinking water.

Relating to administrative aspects:

- A clear institutional framework and water sector organisation and a transparent legal framework should be created, facilitating a close cooperation between public authorities in energy and water sectors and with private developers.
- Simplified, streamlined processes to obtain a license for independent water production by renewable energy should be designed and included in the legislative guidance.
- Financial support schemes should be developed and implemented.

The conclusions drawn from the analysis of health, environmental and administrative aspects regarding guideline development for RE-Desalination are general recommendations of elements to be included in the national frameworks. These have been derived from an extensive literature review. For application in country-specific circumstances of course further work, adaptation to the country specific conditions and update according to the latest scientific developments is required.

Further useful work in the future would be a comprehensive examination of the water quality of different systems currently working would be useful, preferably using consistent test methods and parameters. Interviews with end-users about their experience with RE-desalinated water could complete this evaluation. The health aspect is important for the promotion of RE-Desalination to both authorities and consumers.

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