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How sustainable can desalination be?

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ABSTRACT

Population growth, climate change and urbanization are the main challenges to meet the water demand for the next decades. The global gap between sustainable water supply and water demand is expected to grow above 2,700 km^3 by 2030, equivalent to 40% of total water demand. Desalination is an established method to make fresh water—mostly as a last resort. Its contribution to water supply is minor on a global scale. In some regions, though, it is difficult to imagine a sufficient water supply without desalination. But is this technical fix sustainable? In its main part, this paper sheds light on the major issues that call the sustainability of desalination into question. Examination of a number of criteria indicates that the energy demand for desalination is by far the most important issue. Further relevant impacts are wastewater discharges, waste disposal and visual impact. In retrospect, it is noted that energy demand has already shaped today's desalination market, since energy-efficient membrane-based desalination technology has gained market share compared with the more energy-intensive thermal desalination technologies. This development has been supported by a substantial decrease in the specific energy demand of seawater reverse osmosis (SWRO) plants. As a result, state-of-the-art SWRO plants require approximately 3–5 kWh/m^3 compared to some 10 kWh/m^3 or more two or three decades ago. But almost all desalination plants are powered by fossil energy resources. Hence, using renewable energy (RE) resources instead would be a big step forward towards sustainability. Case studies prepared for three projects in the MENA region demonstrate that selecting RE sources for a desalination plant is economically feasible when compared to non-subsidized fossil fuel. This paper is based on our viewpoint as engineering consultants. It is a summary of studies, reports and surveys conducted on this issue by us in past years. It is intended to give an idea of the options that are available today to make seawater desalination sustainable.

Keywords: Sustainability; Energy demand; Carbon footprint; Renewable energy sources; MENA case studies; Water production costs

1. Desalination: an essential freshwater source in water scarce regions

Since the 1960s, desalination, the conversion of seawater or brackish water to freshwater, has been adopted to augment water supply. According to the 23rd desalting plant inventory [1], the seawater desalination capacity has reached close to 10 km^3 per year.

The following figure (Fig. 1) shows the breakdown of the desalination capacities on the membrane-based

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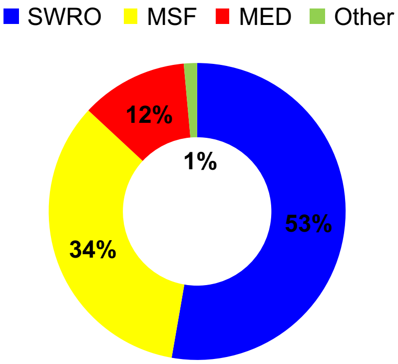

Fig. 1. Breakdown of total online seawater desalting capacity.

seawater reverse osmosis (SWRO) technology and the two thermal technologies, multistage flash (MSF) and multiple effect distillation (MED).

In relation to the global water use (approximately 4,000–4,500 km^3 per year [2,3]), desalination is a minor source of freshwater. Seawater desalination contributes a mere 0.22%; including the desalination of brackish water increases the percentage to at best 0.5%.

Things look different in water scarce regions. In the Kingdom of Saudi Arabia, for example, 60% of the potable water supplied for industry and domestic use are produced from seawater. Or, as another example, Sydney Water installed a seawater desalination plant which is capable to deliver 18% of Sydney's water demand. These percentages show that desalination is already today's vital importance for some regions. This applies in particular for the MENA region, but for certain regions in the Far East, in both Americas, in Australia and even in southern Europe as well.

2. Desalination: a potential mean to bridge future water gaps

Population growth, climate change and urbanization are expected to cause a global water gap of 2,700 km^3 per year by 2030. In other words, by 2030, only 60% of the water demand of 6,900 km^3 per year can be met by existing water sources on a sustainable basis.

Again, especially the MENA region is expected to severely suffer from above developments. Fig. 2 shows the relative changes of total renewable water resources expected by Future Water for the period between 2010 and 2050. Except Egypt, which is taking benefit from the river Nile, all countries will face a decrease in the availability of renewable water resources. For Jordan and Oman, the renewable water resources are expected to be depleted by more than 50%.

A number of options are available to overcome current and future water shortages. They can be summarized into three broad categories [4]:

- Increasing the productivity, e.g. by means of improved agricultural practice.
- Reducing industrial and domestic demand.
- Expanding water supply.

It is the outstanding feature of desalination, that it is broadly the only solution to battle water scarcity since it makes new sources accessible for water supply. In contrary, other sources are rather limited:

- The abstraction rate from groundwater or surface water cannot exceed the recharging rates of these water sources.
- Only municipal and industrial effluents are available for re-use. Water used for irrigation is lost in this regard.

Fig. 2. Total renewable water resources—relative changes from 2010 to 2050 [4].

Table 1
Key energy data

	Unit	MED	MSF	SWRO
Maximum Process Temperature of seawater/ concentrate	℃	<70	<115…120	<45
Pressure of heating steam	bar	≈2.5...3.0[a] ≈0.4...0.5[b]	≈2.5…3.0	–
Heat demand	MJ/m^3	≈233…258[c]	≈233…258[c]	–
Electricity demand	kWh/m^3	1.5–2.5	≈3.0…5.0	≈3.0…5.0

[a] MED with thermal vapour compression (MED-TVC).

[b] MED without vapour compression ("plain" MED).

[c] Corresponding to a performance ratio of 9–10 kg/2,326 kJ.

But is desalination sustainable? Or, following the definition set out in the Brundtland Report [5]: Does the use of desalination preserve the ability of future generations to meet their own needs?

To answer this question, at first the major issues that call the sustainability of desalination into question have to be explained. How these issues have been addressed in the past and what future options are available to further improve the sustainability of desalination is going to be discussed, subsequently.

3. Impacts of desalination

Alike other industrial activities, the construction and the operation of a desalination plant causes a variety of direct and indirect impacts on the environment. These effects are mainly related to:

- Energy demand satisfied by burning fossil fuel.
- Liquid discharges such as concentrate or process wastewater.
- Protection of marine biota.
- Waste disposal such as sludge generated in the pre-treatment section or used cartridge filters.
- Noise arising from plant equipment as well as from traffic, especially truck movements.
- Storage and handling of chemicals.
- Visual appearance of the plant.

This paper focuses on the single most important issue, the energy demand, as explained in the next two sections. Most of the other aspects are extensively discussed in expert literature (see, e.g. [6]) and are left out here. However, our recent experience in desalination projects shows that two impacts receive increasing attention: the disposal of pre-treatment residuals and visual appearance. Corresponding remarks are followed in the next but one section.

3.1. Energy demand of desalination

A decade ago, Bob Carr, the then New South Wales Premier Minister, called desalinated water as "bottled electricity". Although provocative, this statement is to a certain extend true: desalination is an energy intensive process. The extent of present day desalination plants energy demand is shown in Table 1.

The figures may be commented as follows:

- The SWRO process does not require any heat input. This is the single main reason, why the SWRO is the most energy efficient desalination process, in practice.[1]

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[1] It is correct, that the MED requires less electrical power. However, to get the full picture, you have to consider the electrical power that could have been generated when expanding the heating steam, which is required by the MED process, in a steam turbine. This "equivalent power" can be determined to be at minimum corresponding to 4.3 kWh/m^3. It is obvious, that he sum of the electrical power actually required and the equivalent electrical power exceeds the electrical power demand of a SWRO process.

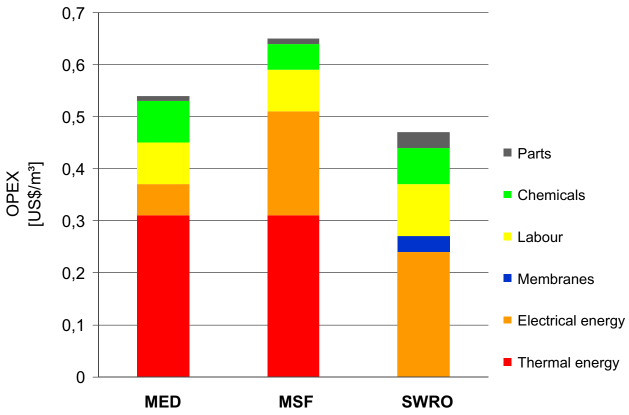

Fig. 3. OPEX for conventional desalination technologies (based on data from [11]).

- The typical heat demand of the established thermal desalination technologies MED and MSF has levelled out at around 230–260 MJ/m^3, corresponding to a performance ratio of about 9–10 kg/2,326 kJ.
- Compared to an MED process, an MSF process requires around double the electrical energy (3–5 kWh/m^3), because of the sheer length of the preheater pipes the concentrate has to be circulated through.

3.2. Significance of energy demand

A first impression regarding the significance of the energy demand shall be gained from a view on operational expenditures (OPEX) of desalination plants. As the OPEX can substantially vary depending on the project specifics, the more general set of data presented in Fig. 3 shall be used for the present discussion.

Apparently, the costs related to energy demand play a predominant role. More in detail, the following conclusions may be drawn:

- The SWRO technology features the most economical OPEX (0.47 US$/m^3). The distance to MED (0.54 US$/m^3) is significant, but not immense. In consequence, it is quite realistic to assume that the MED technology is competitive with the SWRO technology under special circumstances. Compared to this, the substantially higher OPEX of the MSF technology (0.65 US$/m^3) has to be considered to be quite prohibitive.
- Both thermal desalination technologies are subdued to costs of thermal energy (0.31 US$/m^3), which amount to roughly half the total OPEX. Whereas this burden is to a certain extent compensated by a quite low demand of electrical energy in case of the MED technology, it causes the MSF to be the most expensive technology in terms of OPEX.
- The figures for further OPEX items reflect the differences between the various desalination technologies in several aspects (e.g. comparatively high labour costs due to the requirement of well-skilled personnel for the operation of an SWRO plant or low comparatively low chemical costs for the MSF technology). However, these differences are comparatively small and do thus not affect the broad picture set by the thermal and electrical energy demand.

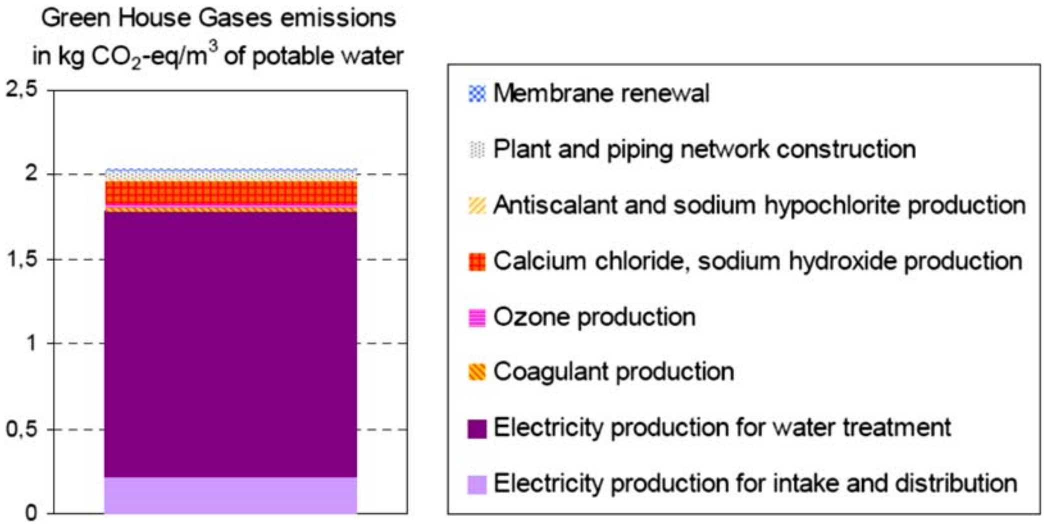

Fig. 4. Greenhouse gas emissions of a SWRO desalination plant in Spain [7].

As an engineering consultant, we use to assess and evaluate technical options based on costs. However, such considerations are sometimes biased, e.g. because energy resources are subsidized. That is why we propose to have a view on the greenhouse gas emissions, the so-called "carbon footprint", of a desalination plant. In their noteworthy publication, Jérôme Leparc and co-authors explain a methodology for the determination of a desalination plant's carbon footprint and present case studies [7]. For a Spanish SWRO desalination plant, they quantify the contribution of different sources as shown in Fig. 4.

Again, the energy demand is the single most important criteria. It is responsible for 90% of the greenhouse gas emissions; 80% can be attributed to the very desalination process, 10% to the intake and distribution pumping needs. In addition, Leparc and co-authors point out that the impact caused by the energy demand in other impact categories (damage to ecosystem, damage to human health and resource depletion) never falls below 70%.

In summary, the keys to sustainable desalination are the energy efficiency of the desalination plant and the sustainability of its energy source.

4. Impacts receiving growing attention

4.1. Pre-treatment residuals

When the 330,000 m^3/d SWRO plant in Ashkelon, Israel, commenced operation in late 2005, the situation shown in Fig. 5 gave reasons for concerns. Red-coloured wastewater is discharged into the sea. The red colour originates from ferric salts, which are used in the pre-treatment section for the separation of suspended solids.

The use of ferric salts is quite common in SWRO plants. However, the intensity of the colour is dependent on the actual dosing rate and the pre-treatment process design.

A new approach has been chosen for the 144,000 m^3/d SWRO Plant in Kwinana, Australia, which commenced operation in 2007. Here, the pre-treatment sludge is separated, dewatered by means of centrifuges and dumped.

Today, it is still disputable, which approach is more sustainable. The main disadvantage of the direct discharge is rather its aesthetical impression than its environmental impact. On the other hand, disposing of sludge calls for considerable capacities of high standard landfills:

- The sludge production rate of a 100,000 m^3/d plant can amount to as much as 30–40 tons per day.
- The sludge is of unfavourable consistence: it is at best semi-solid and comprises up to 85% saline sludge liquor.

Hence, we have to realize that a clear answer regarding the sustainable disposal of pre-treatment residuals is still pending.

4.2. Visual appearance

In recent years, we observe an increasing interest in the visual appearance of a desalination plant, a welcome development, since a good architectural concept can substantially improve the integration of desalination plants into their social and their natural environment.

Remarkable approaches have been published by Bitrián and Pfeiffer [8], Aquasure, the project company for the Victorian Desalination Plant in Australia, has prepared an impressive video presenting their architectural concept of the plant (accessible via the menu item "Artist Impressions" on http://www.aquasure.com.au/video_gallery.php).

5. Past developments towards sustainability

Making desalination sustainable is not only a future undertaking: past developments have already contributed significant steps towards its sustainability, chiefly in two regards:

- The market share of the most energy efficient desalination technology, SWRO, has been increased steadily and, in parallel,
- the energy efficiency of the SWRO technology has been improved.

5.1. Increase of SWRO market share

This aspect shall be discussed using Fig. 6. It shows the cumulative capacity of seawater desalination plant put online separated into the main desalination technologies as well as into two location categories: in GCC[2] Countries or in non-GCC Countries. The data have been generated from the 23rd inventory of desalination plants [1].

The graphs show that SWRO has become the dominant technology: Today, it represents the largest

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[2] GCC stands for Cooperation Council for the Arab States of the Gulf. The GCC Countries are: United Arab Emirates, The Kingdom of Bahrain, The Kingdom Of Saudi Arabia, The Sultanate of Oman, Qatar and Kuwait.

Fig. 5. Discharge of filter backwash water from the Ashkelon plant in Israel [6].

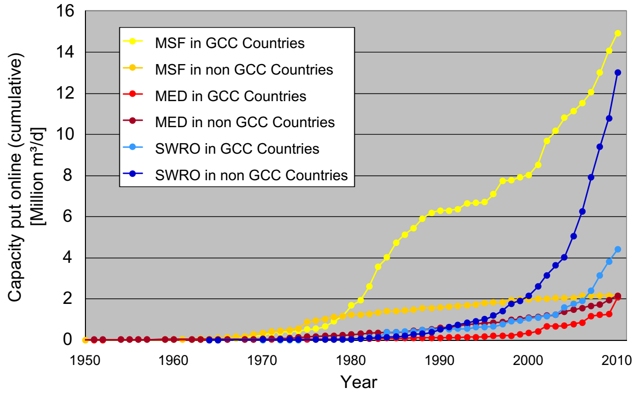

Fig. 6. Cumulative capacity of the main desalination technologies put online in and outside the GCC countries. (The graphs shown in this figure do not account for the reduction of online capacity due to decommissioning of plants.)

cumulative capacity in GCC Countries and has the highest growth rate of all categories.

It has to be acknowledged, that the MSF technology perfectly fitted to the rapid increase of in population and wealth in the 1970s ("oil boom") in the GCC countries. Firstly, for a long time it was the only technology with a proven track record especially regarding large scale plants. Secondly, it allowed for the simultaneous expansion of power generation capacity, because it is beneficial to combine an MSF plant with a power plant. Last not least, costs of fossil fuel were of minor importance in the GCC countries.

Irrespective of above, and although still today a certain level of reservation against SWRO can be observed in the GCC countries: the market share of SWRO technology is advancing in the GCC countries as well.

It is plausible, that energy efficiency has been one significant driver of above development, albeit presumably not the only one.

5.2. *Improving the energy efficiency of SWRO*

SWRO plants have not at all times been as energy efficient as today. The specific power demand of plants built in the 1980s could be as high as 10 kWh/m^3. Since then, substantial efficiency improvements have been achieved, chiefly by means of recovering the energy, which is released from the concentrate when it is depressurized after the permeate has been separated. For this purpose, different types of turbines or, more recently, the isobaric energy recovery method is used. Further efficiency gains result from improved membrane characteristics, improved pump efficiencies and the use of variable frequency drives for the control of pump heads.

In summary, state-of-the-art SWRO plants require approximately 3–5 kWh/m^3. The exact value is depending on specific conditions and constrains such as seawater temperature and salinity as well as on the detailed process configuration, especially in regard to the pretreatment and the energy recovery system (see [9]).

Currently, there seems to be no technology in the pipeline, which has the potential to bring the energy efficiency of SWRO a big step forward. On top of that, almost all desalination plants are powered by fossil energy resources, today. That is why it stands to reason to examine the potential of renewable energy (RE) sources to improve the sustainability of desalination.

6. Desalination using RE resources

The technical and economical aspects of RE-powered desalination are explained on the basis of a case study carried out for a project in Yemen. This case study is a part of the "Regional Water Outlook in the MENA region", which is commissioned by the World Bank [10] and includes case studies for projects in Algeria and Egypt as well.

6.1. Methodology

The Yemen case study comprises five scenarios. SWRO and MED are the desalination technologies considered. The energy supply to the desalination plants is provided by the following RE technologies:

- concentrated solar power (CSP)
- photovoltaics (PV) and
- wind power (WP).

In general, other RE sources, such as geothermal or ocean energy can be applied to desalination projects as well. However, they are of minor significance in the MENA region, partly because the availability of their primary energy source is more restricted. Hence, the assessment focuses on CSP, PV and WP. Apparently, PV and WP can be combined with SWRO desalination plants, only.

The case study scenarios adopt the corresponding local conditions as well as already existing or planned infrastructure. The plant capacities are reflecting the local requirements.

The basic concepts for the RE generation are configured to ensure a good comparability between the different RE technologies:

- The CSP plant shall be operated in base load mode. The collectors are designed to satisfy the base load heat demand at maximum irradiation conditions. At times of lower or no radiation, the heat is either provided by thermal storages or by a fossil fuel fired boiler. Due to scale of economics, the rating of the CSP plant exceeds the demand of the desalination plant. The surplus power will be exported to the electrical grid. In other words, the CSP plant will supply power and, in case MED is selected as desalination technology, heat to the desalination plant and will export power to the grid on a steady state basis.
- The PV and WP generators are rated to produce the annual amount of electric energy required to operate the SWRO desalination plant. The fluctuations in instantaneous power generation are taken into account as follows: Surplus power is exported to the grid, a RE power supply gap is balanced by a fossil fuel fired power plant.

The technical analysis is based on the scenario modelling performed by a commercial software program called INSEL. The financial and economical analysis of the study looks at the water production cost of the different scenarios and compares the RE supplied desalination with fossil energy supplied desalination.

At first, the desalinated water production costs for both energy supply options—by RE and by fossil fuel fired power plants—as well as costs of RE generated electricity are determined. The corresponding calculations are based on a life cycle cost approach using the annuity method. Two significant assumptions have to be pointed out:

- Neither fossil fuel nor electricity generated from burning fossil fuel is subsidized.
- Compared to the base load power export of the CSP plant, the compensation for the power export of PV and WP generators is assumed to be lower by 12%, because the fluctuating export requires grid balancing measures.

In a final step, the water production costs, capital expenditures and OPEX, are compared on a net present value (NPV) basis.

6.2. The Yemen case study

The Yemen case study refers to Al Mokha, a port city on the Red Sea coast of Yemen. Al Mokha is currently considered for implementation of a larger desalination plant and a transmission pipeline to provide potable water to the city of Taiz, located about 100 km inland of Al Mokha. Taiz city is facing a serious water shortage since the mid-1980s; today Taiz has a daily water shortfall of 40,000 cubic metres.

Solar radiation and wind assessments show that CSP, PV and WP are feasible at the Al Mokha site. In addition to the general methodology outlined above, the five Yemenite scenarios assume:

- The desalination capacity is 100,000 m^3/d.
- The location of the desalination plant is either close to an existing small SWRO desalination plant or next to the existing thermal power plant, in order to benefit from existing or planned infrastructure.
- The energy requirements to be covered by the RE plants in some scenarios (Y-2, Y-4, Y-5) include the pumping needs for the potable water transfer to Taiz, too.

Resulting from the above conditions and constraints, in Al-Mokha four renewable "stand-alone" scenarios and one scenario using a mix of CSP and wind power have been selected for the analysis. Further scenario details are provided in Table 2.

Table 3 depicts the equivalent full load hours determined for the different scenarios. The most important aspects may be commented as follows:

- In Scenario Y-5, a CSP plant with large thermal energy storage provides the highest equivalent full load hour value of 5,122 h/a.
- In Scenario Y-1 and Y-2, a comparatively high equivalent full load hour value 3,670 h/a can be expected due to selection of large wind turbines (2 MW), high hub heights (94 m) and good wind conditions.

The calculation of the life cycle cost is chiefly based on below assumptions; further details are provided in [10]:

Table 2
Scenario configurations: installed capacities and desalination technology

	Unit	Y-1	Y-2	Y-3	Y-4	Y-5
CSP	MW	–	–	–	50.0	125.0
Solar multiple	–	–	–	–	2.0	3.5
PV	MW	–	–	70.0	–	–
WP	MW	34.0	100.0	–	60.0	
Back-up	–	Fossil fuel fired power plant	Fossil fuel fired power plant	Fossil fuel fired power plant	Fossil fuel fired power plant	Fossil fuel fired power boiler
Desalination technology		SWRO	SWRO	SWRO	SWRO	MED

Table 3
Scenario configurations: equivalent full load hours

	Unit	Y-1	Y-2	Y-3	Y-4	Y-5
CSP	h/a				3,766	5,122
PV	h/a			1,842		
WP	h/a	3,699	3,699		3,699	

Table 4
Analysis result: water production costs (NPV) in million US$ for different scenarios and different energy sources

Scenario	RE energy source (1)	Fossil energy source (2)	Difference (2) − (1)
Y-1	516	579	64
Y-2	513	579	66
Y-3	624	579	–45
Y-4	558	579	21
Y-5	908	955	47

- Annual rate of general indexation: 2.75%.
- Annual rate of fossil fuel escalation: 5%.
- Design life time of plant equipment: 25 a.
- Discount rate: 10%.
- Annuity factor: 0.110.
- Crude oil price: 110 US$/barrel.
- Deterioration rate CSP: 0.3%.
- Deterioration rate PV: 0.5%.
- Balancing power penalty rate 12%.
- HFO (fuel factor 0.8) 54.1 US $/ MWh,th (based on a crude oil price of 110 US$/barrel).

As a result of the analysis, Table 4 presents the water production costs of the different scenarios on a NPV basis.

For each scenario, two water production costs have been determined: one is based on powering the desalination plant with RE according to the configurations and assumptions explained above, the other assumes the power is generated by burning fossil fuel in an existing, already depreciated power plant.

At first, it has to be pointed out that the costs depend on site conditions and project assumptions relevant for the Yemen case study.

The cost advantages of the RE powered case is significant in scenarios Y-1, Y-2, Y-4 and Y-5.

Moreover, scenarios Y-1 and Y-2, which use WP, only, appear to be the most attractive and most economic solutions.

This means, that already today RE driven desalination is in most cases capable of competing with desalination powered by fossil energy sources, provided the fossil fuel is not subsidized and subject to an annual escalation rate of 5%.

Even for the Y3 scenario the picture changes significantly, if we increase the quite moderate escalation rate of 5–15%, which is the order of magnitude of the global fossil fuel price escalation rate in the past decade. In this case, the RE powered version of the Y3 scenario is competitive to the fossil energy source version already by today.

7. Conclusion

Nowadays, desalination plays a significant role in meeting the mounting water needs. But can this role be maintained on a sustainable basis? The explanations provided in this paper allow drawing the following conclusions:

- The keys to sustainable desalination are the energy efficiency of the desalination plant and the sustainability of its energy source.
- RE driven desalination is capable to produce desalinated water on lower cost than desalination plants supplied by conventional power stations fired with non-subsidized fossil fuels.
- RE driven desalination allows for substantial savings in fossil fuel consumption.
- The actual benefit is very sensitive to the presumed fossil fuel escalation rate.
- SWRO can be combined with any RE, which produces electricity.
- An MED desalination plant requires, in addition to electricity, uninterrupted thermal energy, which is preferably supplied from an associated power station. Hence, MED plants have to be powered by CSP plants comprising sufficient thermal storage capacity and a backup fuel boiler.
- It is favourable to employ the grid to balance differences between electricity generation and electricity demand.
- Certain aspects like, e.g. the disposal of residuals still require substantial improvements.

In summary, the use of energy efficient technologies and RE sources can turn desalination into a largely sustainable technique.

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