Department Northern Africa "Policy Dialogue and Knowledge Managment on
Low Emission Strategies, in particular Renewable Energies in the MENA Region“

SolarDesalMENA
Overview of Solar Seawater Desalination in the MENA Region

Deutsche Gesellschaft
für Internationale
Zusammenarbeit (GIZ) GmbH

On behalf of:

Federal Ministry for the
Environment, Nature Conservation,
Building and Nuclear Safety

Content

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Background

Many countries in the MENA region are highly dependent on fossil fuels and energy imports, while energy demand grows steadily. In these countries an enormous solar energy potential is existing and the expansion of renewable energy is becoming increasingly important. But in most of the MENA countries there is also a great water shortage. The development and use of seawater desalination allows sustainable strategies for the long-term secure water supply. Many countries in the region are investing heavily in the construction of huge plants and in research to improve the technologies and applications.

This study shall give an overview on the current level of experience and on the possibilities of solar seawater desalination in the MENA region. The GIZ project "Policy Dialogue and Knowledge Management to Low Emission Strategies, in particular Renewable Energies, in the MENA region" moderates this issue and assists to make recommendations for possible cooperation.

Abbreviations

BW	Brackish water
CAPEX	Capital expenditure
CCGT	Combined-cycle gas turbine
CSP	Concentrating solar power
CSP-MED	Concentrating solar power – multiple effect distillation
CSP-RO	Concentrating solar power – reverse osmosis
DNI	Direct normal irradiance
EC	European Commission
ED	Electrodialysis
EDR	Electrodialysis reversal
EIA	Environmental impact assessment
GDP	Gross domestic product
GHG	Greenhouse gas
GIS	Geographic information system
GOR	Gain Output Ratio
HD	Humification - Dehumification
KSA	Kingdom of Saudi Arabia
LEC	Levelized electricity cost
LWC	Levelized water cost
MD	Membrane distillation
MED	Multiple effect distillation
MED-TVC	Multiple effect distillation – Thermal vapor compression
MEH	Multi-effect humidification
MENA	Middle East and North Africa Region
MSF	Multi-stage (or Multiple-stage) flash distillation
MVC	Mechanical vapor compression
OPEX	Operating expenditure
PPA	Power purchase agreements
PV	Photovoltaic
RE	Renewable Energy
RO	Reverse osmosis
SM	Solar multiple
SWRO	Seawater reverse osmosis
TES	Thermal energy storage
TVC	thermal vapour compression
UAE	United Arabian Emirates
VC	Vapor compression

Overview of Solar Technologies for Seawater Desalination in the MENA Region and State-of-the-Art of Technology

The first part of this study describes in a short overview the solar technologies that can be used for the desalination of seawater.

A-1. Overview of solar desalination technologies

Several concepts for the utilization of solar energy for desalination have been proposed (*Figure A1*). However, desalination powered by renewable energy is still not widely applied. Its development is limited to pilot plants and small units, mainly located in remote areas.

There are different types of barriers which hamper the introduction of solar desalination (economical, institutional and social), which will be shortly discussed in Chapter A-3. Markets and applications of renewable desalination can be best identified by the division of such plants in representative capacity ranges. The required desalination capacity and the eventual availability of the electrical grid play a crucial role in the selection of the technologies to be applied. This chapter briefly describes some of the existing concepts, with focus on CSP- and PV-based applications for medium and large scale applications.

Renewable and esp. Solar Power Technologies

The MENA Region (Middle East and North Africa) disposes over huge renewable energy potentials. In particular, solar and wind energy will play an even

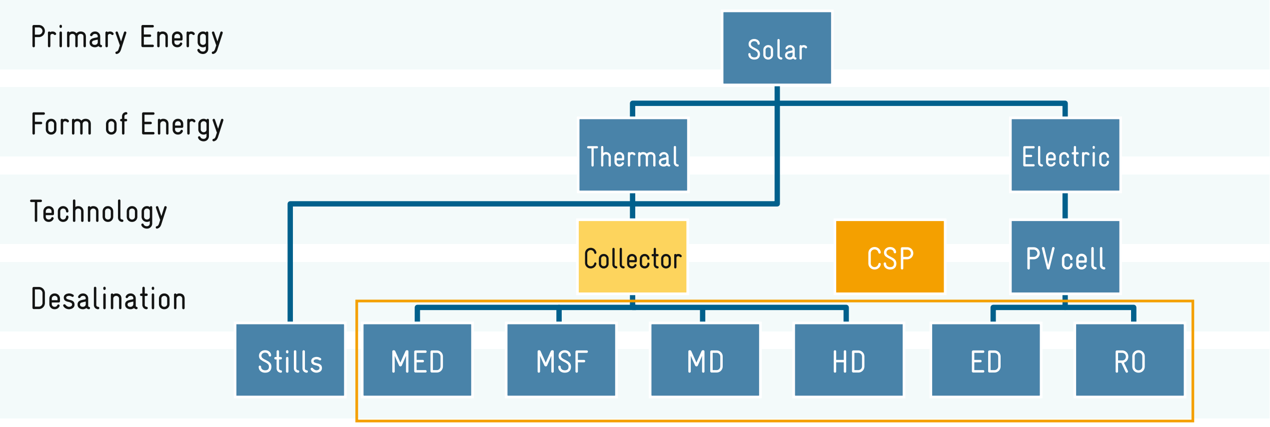

Figure A1: Solar energy desalination matching/own illustration
MED: Multi-Effect Distillation / MSF: Multi-Stage Flash / MD: Membrane Distillation / HD: Humification- Dehumification / RO: Reserve Osmosis / ED: Electrodialysis

important role in the future energy supply of these countries. With this regard, the most cost-competitive technologies will be CSP, PV and Wind power. Such technologies can be also used to reduce the dependence of energy-consuming desalination plants from fossil fuels.

Concentrating solar thermal power plants have the capability for thermal energy storage and alternative hybrid operation with fossil or bio-fuels, allowing them to provide firm power capacity on demand.

PV is a highly modular technology, which directly transforms incoming solar irradiation into electricity. PV can be used for on-grid and off-grid applications, starting from few watts and up to several megawatt plants. The largest market share is currently taken by crystalline silicon technologies. In the last years, the average electricity production costs have achieved an important reduction due to an elevated decrease in the module investment cost.

The advantage of CSP for providing constant base load capacity for seawater desalination can be appreciated in Figure A2 for a time-series modeling of one week of operation of equivalent wind, PV and CSP systems with 10 MW installed power capacity each at Hurghada, Egypt: while wind and photovoltaic power systems deliver fluctuating power and either allow only for intermitting solar operation or require considerable conventional backup, a concentrating solar power plant can deliver stable and constant power capacity, due to its thermal energy storage capability and to the possibility of hybrid operation with – typically – conventional / fossil fuel.

In our example the renewable share provided by CSP is about 90 %, that of PV is 25 % and that of wind power is about 35 – 40 %. Depending on varying conditions at different locations, these numbers can be also considered as typical for the average annual renewable share of such systems[1]. As a consequence, CSP plants can save more fossil fuel and replace more conventional power capacity compared to other renewable energy sources like PV and wind power.

To cover a constant load or to follow a changing load by wind or PV electricity would additionally require the electricity grid and conventional plants for ex-

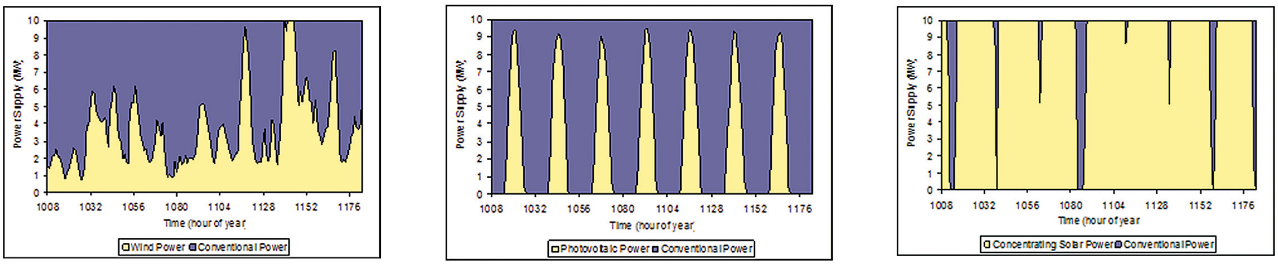

Figure A2: Power supplied by 10 MW CSP-plant with 16 hour storage (right), a 10 MW PV (mid) and 10 MW Wind (left) and conventional backup power from the grid needed to provide 10 MW base load supply.
Source: "Power supplied by 10 MW CSP, PV and Wind" / DLR REACESSS 2009 / www.DLR.de

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[1] For CSP a large range of renewable share can be delivered, depending on the plant design (mainly the ratio between turbine, solar field and storage). The 90 % value should be seen as the maximum under the consideration of technical and economic issues.

ternal backup. In both cases an additional backup capacity would have to be installed and operated for most of the time, generating a relatively small portion of electricity during daytime and wind periods, but full capacity during night and wind calms.

Desalination Technologies

The majority of the existing desalination plants belong to two groups of desalination technologies, i.e. thermal desalination technologies and membrane-based desalination technologies.

Thermal Desalination Processes

Thermal processes effectively treat seawater with high-saline content and low-quality (e.g. high turbidity, presence of algae or eventual oil spillages). For brackish water application, Reserved Osmosis (RO) is typically preferred. This is due to the fact that the energy consumption of RO plants is roughly proportional to the feed water salinity, while the energy consumption of thermal processes is almost independent of the salt content of the source water. In order to minimize the energy consumption per unit of produced drinking water, thermal desalination plants typically are designed as co-generation plants in combination with a steam turbine or a combined cycle. This means that the heating steam required for evaporation of the feed water is provided by the waste steam of the steam turbine at a temperature ranging between approx. 65°C and 115°C.

The operation of such desalination plants is relatively simple. The long track records on existing plants demonstrate their reliability and stability of operation. The quality of the product water is very high (approx. 10–20 ppm, i.e. almost pure distillate).

These characteristics made multi-flash stage (MSF) the favored desalination technology in the MENA region in previous decades. As the name suggests, MSF is based on the flashing of a share of the feed water in a number of chambers with different pressures. The gain output ratio (GOR), which is defined as the ratio between distillate mass flow and heating steam mass flow typically ranges between 8 and 10. MSF is typically operated as an utility scale desalination plant. Single units can reach 90,000 m^3/d. The main drawback of MSF is the high specific energy requirement (heat and electricity). In addition, investment cost and seawater consumption are higher than in Reserve Osmosis (RO) plants (*Table A1*).

Multi Effect Distillation (MED) also consists of a series of evaporation chambers. The main difference in comparison to MSF plants is the mechanism of vapor generation (evaporation, i.e. temperature-driven vapor generation instead of flashing, i.e. pressure-driven vapor generation). In MED plants the feed water is sprayed onto the external surface of a tube bundle. The heat required for the evaporation is provided by the condensation of steam flowing inside the tubes. The vapor is then used as heating steam (inside the tubes) in the successive stage. The heating steam in the first effect has to be provided externally (typically waste heat from a steam turbine).

The higher the number of stages, the lower is the specific thermal energy consumption (as the vapor is recycled several times) and the higher the GOR. However, the increment of the number of stages reduces the available net temperature difference between two consecutive stages, which leads to higher cost for the heat exchangers.

Finally, the optimal number of stages depends – among others – on the cost of the externally provided heating steam. MED plants can reach a gain output ratio of approx. 12, which means that 1 kg of waste steam is required for the production of 12 kg drinking water. Existing MED plants typically have a lower gain output ratio (approx. 4–6). MED plants have lower electricity requirement than MSF. The temperature required in the first MED-stage is also lower (< 70 °C). The main disadvantages of MED are the high investment cost and the high feed water requirements.

MED with thermal vapor compression (TVC) provides approx. 35 % higher GOR than the MED without TVC, which is obtained with the upgrade of a portion of the vapor produced in the last effects by means of a thermo-compressor. However, in this case, medium pressure steam is required (temperature higher than approx. 150 °C).

Membrane-Based Processes

Reverse Osmosis (RO) is widely used for seawater (SW) as well as for brackish water (BW) applications. RO currently is the preferred option of desalination for drinking water purposes. The market penetration of RO in the last decades is due to progresses in membrane technology (e. g. higher salt rejection, longer life time) and to increased system reliability. The basic idea in RO is the application of an external pressure (up to 80 bar) to a concentrated solution such as seawater, which makes possible obtaining a flow of almost salt-free permeate (150–500 ppm, depending on the system configuration) on the other side of a selective membrane. In particular cases, the removal of Boron from the product water represents a challenging issue.

Concerning energy consumption, electricity requirements of RO depend of the source water salinity. The introduction of so-called energy recovery devices (ERD) allowed to dramatically reduce the overall energy consumption of RO plants by recycling a large share of the energy (i.e. pressure) still contained in the brine. RO systems are highly modular and therefore they are well suited for small-scale as well as for utility-scale applications. Investment costs are lower than for MED and MSF.

Water pre-treatment has been referred as the “Achilles heel” of RO. This is due to the fact that often this step may be very challenging /Sommariva/.

Process	Advantages	Disadvantages
RO	For BW or SW applications Relatively low energy consumption Modular layout Lower CAPEX than thermal systems Lower feed water consumption than MED/MSF	Dependency on pre-treatment effectiveness More complex operation than MED Lower product water quality (ca. 200 – 500 ppm for single pass units) Higher requirements for Boron removal
MED	Also for high saline/low-quality water High product water quality (< 20 ppm) Reliability / long operation periods without cleaning Higher efficiency than MSF Low spec. electrical consumption	High investment cost (dependency on metal price fluctuations) Higher feed water consumption than RO
MSF	Also for high saline/low-quality water High product water quality (< 20 ppm) Reliability / simplicity of operation Long operation experience Large units (up to 90,000 m3/day)	High investment cost (dependency on metal price fluctuations) Elevate feed water consumption High energy consumption

Table A1: Preliminary comparison of main desalination processes /DesalData 2011/

Pre-treatment is a functions of local water quality and its variations over time. Accordingly, the plant operation is more complex. Challenging feed water quality such as very high turbidity, eventual algae blooms or oil spillages requires particular pre-treatments such as dissolved air flotation (DAF). In this case, the investment costs are approx. 20 % higher than for conventional RO systems.

Table A1 summarizes the most relevant advantages and drawbacks of the considered desalination technologies /DesalData 2011/.

Environmental Impact of Desalination

Conventional desalination units present high carbon dioxide emissions, due to the fossil fuels utilized for the construction and the operation of the plants. The brine (i.e. the waste water from the process; typically between 50 % and 65 % of the feed water) contains hazardous chemical additives such as chlorine, coagulants, heavy metals and cleaning chemicals that are required to prevent the desalination units being damaged from biological matters as well as particulate. To avoid the impact of desalination plants on the development of coastal areas, such units should be integrated into management plans that regulate the use of water resources and desalination technology on a regional scale. As an example, a standard environmental impact assessment (EIA) procedure should be carried out, including the collection of information on environmental relevant impacts of desalination, monitoring activities, and the comparison of different water supply options / Lattemann 2008/.

The impacts of open intakes for the feed water supply can be minimized through a combination of screens and low intake velocity. Horizontal drains below the seabed should be taken into account whenever the geological and bathymetric conditions allow it /Peters 2008/, so that the impingement and entrainment of larger organisms can be dramatically reduced. Co-location of desalination and power plants should be considered where possible.

Pre-filtration with UF or MF membranes as alternative intake can significantly contribute to the reduction of chemical pretreatment needs.

Finally, the impacts from high salinity brine, which is typically discharged back into the sea, can be minimized by pre-diluting the waste stream with other waste sources (co-location). In addition, the impacts of high temperature in the brine (in MED and MSF) can be reduced by the optimization of heat dissipation to the atmosphere prior to the discharge into the sea (e.g. cooling towers) /Lattemann 2008/. Multi-port diffuser represent another effective measure to enhance the dilution /Bleninger 2008/.

Coupling Solar Energy and Desalination

Concentrating solar power (CSP) plants are technically suitable for the combination with both MED and RO desalination plants, while PV can be combined with RO (*Figure A 1*). Several studies on renewable desalination have been performed among others by DLR /AQUA-CSP 2007/, /MED-CSD 2010/, /MENAwater 2011/ as well as by other research centers such as CIEMAT /Palenzuela 2011/, MIT /Casimiro 2012/ and the Cyprus Institute / Georgiou 2013/.

One of the main advantages of such combinations is that CSP is able to nearly provide base load power supply due to the integration of relatively cheap (i. e. in comparison with electrical storages) and efficient thermal energy storage.

In the case of thermal desalination (MED), heat supply for water evaporation is provided by the waste steam from the CSP turbine, which is extracted at approx. 70 °C (or slightly lower) and is condensed in the first stage of the desalination plant. MED is preferred to MSF due to the higher efficiency (i.e. lower energy consumption, lower operation temperature), as it has been previously highlighted. Regarding MED with TVC, the capital cost can be reduced in comparison to the MED without TVC. However, this advantage has to be paid in terms of a higher heat cost. MED-TVC systems seem to be attractive whenever low-cost heat is available (e.g. waste heat, low fuel cost) or if the required water-to-power ratio is high. The eventual combination of a CSP collector for the exclusive heat supply of an MED plant is in principle feasible, but not economically (and thermodynamically) competitive.

Alternatively or in combination with this configuration, a portion of the generated electricity can be used to feed a RO plant. The main advantage of this combination is the fact that only electrical energy is needed. This means that if an electrical network is available, the CSP power plant -but also other renewable or conventional power plants- can be located independently from the desalination site. This means that the CSP plant could be located on a site with optimal DNI resources and best suited terrain.

On the contrary, in the case of CSP/MED, the steam turbine and the solar field have to be located in proximity (max. few kilometers distance) of the MED plant. In addition, reverse osmosis can be coupled with PV plants.

The combination between PV and RO is another interesting option for solar desalination. Such combination offers a series of advantages. The most important one is the high modularity of both PV plant and RO unit. This feature makes this combination an excellent choice for the supply of drinking water for small communities within insulated and water-scarce areas. Without proper backup for the power supply (i.e. battery, backup power plant and/or grid) the operation of the RO will be intermittent. Due to the fluctuating nature of solar resources, electricity generation needs to be stabilized by power conditioning equipment and energy storage devices (e. g. batteries) in order to guarantee proper operation of the desalination plant. Transient operation of the RO plant is related to lower efficiency (start-up procedures, stand-by cost) and shorter lifetime of the membranes (wear-and-tear).

A-2 Overview of existing solar desalination plants in the MENA region

The application of renewable desalination is still limited to small capacities in remote locations. In addition, such plants are characterized by high capital and water cost. In most cases such applications have been realized within the framework of research or demonstration projects.

Following tables (*Table A2 – Table A4*) give an overview about the existing solar desalination plants in MENA.

Location	Year	Additional Power Supply	Production [m³/d]	Operator	Financing
Abu Dhabi, UAE	2008	Diesel	20	NEWRC	ADWEA
GECOL at Ras Ejdel, Libya	2005	Wind and grid	300	GECOL	GECOL
El Hamrawein, Egypt	1986	-	240		
Hassi-Khebi, Algeria	1988	-	22.8		
Sadous Riyadh Region, KSA	2001	-	14.4		
Maagan Michel, Israel	1997	Diesel	9.6		
Aqaba, Jordan	2004	-	81.6	NERC	
Ksar Ghilene, Tunisia,	2006	-	50.4	ITC	
Benhsaine, Morocco,	2007	-	24	ITC	
Msaim, Morocco	2007	-	24	ITC	
Jordan Valley, Jordan	2010	-	30		
Tasekra, Morocco	2008	-	24		

Table A2: Existing PV/RO plants in MENA /Li 2013/, /Cipollina 2014/ [2]

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[2] NEWRC: National Energy and Water Research Center, UAE
ADWEA: Abu Dhabi Water and Electricity Authority, UAE
GECOL: General Electricity Company Libya, Libya
NERC: National Energy Research Center, Jordan
ITC: Instituto Tecnológico de Canarias, Spain

Location	Year	Additional Power Supply	Production [l/d]	Operator	Financing
Morocco	2005	-	150	Fraunhofer ISE	
Aqaba, Jordan	2005	-	1000	Fraunhofer ISE	

Table A3: Existing solar MD plants in MENA /Cipollina 2014/

Location	Year	Additional Power Supply	Production [m³/d]	Operator	Financing
Qatar	2012	-	150	Fischer	
Alexandria, Egypt	201X	-		Fraunhofer ISE	EU

Table A4: Existing solar CSP/MED plants in MENA

The German company, fischer eco solutions has developed its own modular "Multiple Effect Distillation" system (MED) and has realized a small solar driven MED-TVC desalination system in Qatar. The system delivers a daily capacity of 10 m³. The unit is supplied by thermal energy from CSP-parabolic concentrating solar thermal collectors. The project shows extraordinary product water quality at high plant availability.

At least two new very large solar desalination plants have been recently announced. These are a SWRO plant in Ras Al Khaimah (UAE) with a capacity of 80,000 m³/d, which is powered by a 20 MWp PV plant and another SWRO plant in Al-Khafji (KSA), 30,000 m³/d, with a 10 MW CPV plant. /Zawya 2013/.

A-3. Barriers of the implementation of solar desalination

A number of barriers hamper the introduction of renewable and esp. solar desalination. Such barriers are of economic, institutional and social nature.

Economic barriers include for small and medium enterprises (SME) the lack of financial resources and/or missing know-how how to enter properly new markets. In addition, in-depth market analyses are not available. Furthermore, the subsidies in the water and power sector in many of the MENA countries are responsible for an unfair competition between conventional and renewable technologies. Concerning the installation of CSP plants, there are specific economic barriers which include the high initial investment due to the large scale of such installations (typically > 10 MWel) and eventually the uncertainty about the unknown revenues in the future.

Other barriers are related to the negative perception of desalination by the population and water authorities (i.e. preference for conventional technologies, centralized solutions) and to the fact that bureaucratic structures are not adapted for independent water producers.

B. Solar Seawater Desalination: Costs, Economics and Applications in the MENA-Region

The task of the second part of the study is to elaborate on possible applications of each technology to estimate the production cost of potable water from seawater or brackish water with desalination and compare the technologies in the most relevant configurations. Here also the influence of different sea-water salinities in the MENA region is shown. For solar desalination plants with PV or CSP a comparison of investment and operating cost is provided taking into account current prices. Finally, the trends of future development costs are shown particular taking into account the development of energy and water prices.

B-1. General Aspects

Water scarcity is a major problem in many parts of the world affecting quality of life, the environment, industry, and the economies of developing nations. The MENA region can be considered as the most water-scarce region of the world. Large-scale water management problems are already apparent in the region. Aquifers are over-pumped, water quality is deteriorating, and water supply and irrigation services are often rationed – with consequences for human health, agricultural productivity, and the environment.

As the MENA region's population continues to grow, and is projected to double over the next 40 years, per capita water availability is expected to fall by more than 50 percent by 2050. Moreover, climate change will affect weather and precipitation patterns with the consequence that the MENA region may see more frequent and severe droughts. To overcome current and future water shortage, countries have a range of options at their disposal to respond and adapt. These options can be summarized into three broad categories: (i) increasing the productivity, (ii) expanding supply, and (iii) reducing demand. Obviously, each of these options is associated with certain marginal unit costs, ranging from 0.02 € per m^3 for improving agricultural practices to more than 2.00 € per m^3 in case of reducing supply to domestic and industrial demand. /MENAwater 2011/

B-2. Applications: Countries and Sectors

The following tables and graphs are describing the regional and sectoral applications of desalination in the MENA region using data from BP Statistical Review of World Energy /BP 2015/ and the MENA Regional Water Outlook, Part II: Desalination Using Renewable Energy: Desalination Potential /MENA-water 2011/. The total lack between water resources and demand rises from 14 % (2000) to 20 % (2010) up to 58 % (2050).

In order to move in due time toward a sustainable water supply, several measures are possible. Among them are:

- increase of efficiency in irrigation (drip systems, precision sprinklers) and in municipal water distribution,
- use of water non-intensive crops,
- water re-use,
- creation of reservoir basins.

Such options are related with different investment as well as operation costs. In addition, they are limited by their own potential and other limitations such as time required for the planning and the realization of these measures, maximum reachable growth rates of efficiency improvements, political issues related to partial replacement of irrigation water by food imports (so-called “virtual water”). According to several water supply scenarios, such measures alone are not sufficient to satisfy the water demand. As a consequence, this remaining gap can only be closed by desalination, fossil as it is state-of the art today mainly in the MENA region but more and more with renewable energy sources.

		Water Unmet 2020 [MCM/y]	**Water Unmet 2050** [MCM/y]	**Oil & Gas Production 2014** [GWh_th]	**Fossil Desal. 2020 (red=stress)**	**Fossil Desal. 2050 (red=stress)**
North Africa	Morocco	6.761	17.243	9771	1%	1%
	Algeria	0	6.705	1.650.560	Low	246%
	Tunisia	0	3.776	29.075	Low	8%
	Libya	369	4.109	400.299	1086%	97%
	Egypt	25.745	40.847	919.781	36%	23%
Middle East	Jordan	1.041	2.367	11	0%	0%
	Palestine	476	1655	0	0%	0%
	Israel	3.431	5.503	67.595	20%	12%
	Lebanon	435	871	0	0%	0%
	Syria	2.948	8.312	65.248	22%	8%
	Iraq	23.703	43.911	1.878.069	79%	43%
Iran	Iran	22.730	60.123	3.724.087	164%	62%
GCC	**Saudi Arabia**	**16.593**	**31.538**	**7.466.662**	450%	237%
	Kuwait	136	962	1.927.644	Low	2004%
	Bahrain	290	400	179.140	618%	448%
	Qatar	418	515	2.849.425	6820%	5533%
	UAE	3.214	3.136	2.558.379	796%	816%
	Oman	39	2.612	844.706	Low	323%
	Yemen	2.920	19.827	178.518	61%	9%
MENA Region		**111.248**	**254.412**	**24.748.970**	222%	97%
World				**82.234.958**	739%	323%

Table B: Gap between fossil desalination and water demand in 2020 /2050

As one can see in *Table B1* there is and will be an increasing problem to feed the water gap between demand and sustainable water from ground water and precipitation of the MENA-region with domestic fossil fuel desalination. Especially the Middle East countries (Jordan, Palestine, Israel and Lebanon) with no or low own fossil fuel resources and also Egypt and Morocco are hardly suffering (red marked), but also huge oil & gas producing economies like Saudi-Arabia and Iran have to spent a large amount of their fossil resources on desalination and will loose a high value of their export capacities and income.

To feed the water demand of the MENA region with fossil desalination could be hardly achieved using all regional fossil energy sources because by the factor of 200 % in 2020, but in 2050 even all would not be enough, not yet considering the demand for electricity, mobility and the possibility to generate national income from the export of oil and gas.

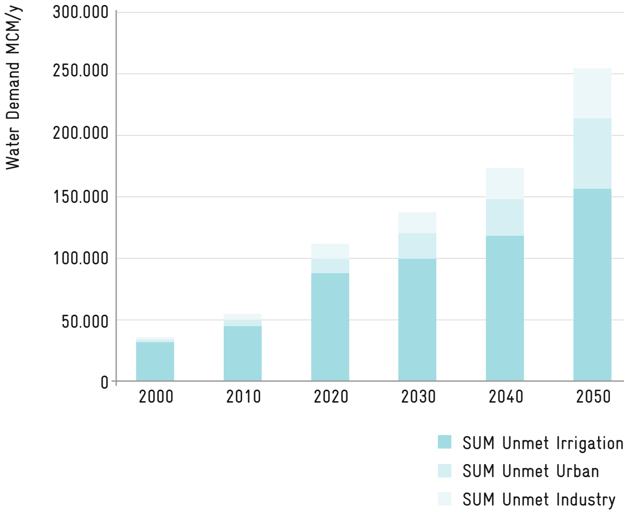

Figure B1: Unmet Demand divided into different sectors (cumulated values for the MENA Countries)

Looking at the different sectors of the water demand Figure B1 /MENAwater 2011/ we see today gap mainly comes from the unmet demand of irrigation but in 2050 the unmet urban water will have a share of 22 % and also unmet water for industrial demand rise to 16 %.

B-3. Investment and Operation costs

The comparison of desalination technologies is a rather complex issue. A number of technical and economic parameters should be considered, such as plant component susceptibility to water quality, chemical use, energy requirements, water product quality, reliability, and simplicity of operation, investment and maintenance costs, just to cite the most relevant of them.

Within the framework of this study, a simplified approach has been elaborated which allows a quick but relatively precise assessment of the investment as well as of the operational cost of solar desalination plants. In addition, the results will show the sensitivity of the levelized water cost (LWC) as a function of selected key parameters. Five representative utility scale (capacity 40,000 m^3/d) solar desalination configurations have been analyzed:

- **CSP/MED:** a high performance MED plant has been assumed (GOR of 12). The CSP plant as well as the MED plant is located in the proximity of the sea. The CSP plant (parabolic trough) supplies steam to the MED at a temperature of 70 °C. The large base load electricity generation from the CSP plant (which is much higher than the electricity requirement for the MED) is assumed to be fed into the local grid. The continuous operation of the plant is guaranteed by hybrid operation of the CSP steam turbine with fossil fuels.

- **CSP/RO:** in this second configuration the MED has been substituted by an RO plant. A once-through cooling has been assumed for the CSP turbine. For better comparability, the CSP plant is designed in order to generate the same net electricity amount as in the previous case. This means that the electricity generation as well as the water production in the first and in the second case is exactly the same.
- **CSP/RO inland:** similar to the second configuration, but considering that the CSP plant is located in an inland site. In this case, the CSP plant is equipped with a dry cooling.
- **PV+Diesel/RO:** The PV is designed in order to cover the electricity requirements of the RO under summer conditions at noon (considering the efficiency losses due to the high temperature). The continuous operation of the plant is guaranteed by the fossil backup (diesel motor). It is assumed that no electricity is fed into the local electricity network.
- **PV/RO Solar Only:** in this last case the PV is the only electricity source for the RO plant. Accordingly, the operation of the desalination plant is intermittent.
- **PV+Battery/RO Solar Only:** the RO operation time is extended by a LiIon batteries with 3 full load hour capacity. The RO operation is intermittent.
- **PV/RO grid:** similar to case 4 (PV+Diesel).The main difference is that the backup electricity is provided by the grid. This case includes two sub-cases with representative electricity prices for imports according to /AFEX EE 2015/. The assumed electricity prices are 4.4 ct$/kWh (3.8 ct€/kWh) (representative for Egypt Index 1) and 16.9 ct$/kWh (14.8 ct€/kWh) (representative for Morocco Index 2), respectively.

The first part of the comparison includes an overview of the main technical data, as presented in Table B2.

As mentioned, all the desalination plants are assumed to have **the same design capacity of 40,000 m^3/d.** For the base scenario, a salinity of 40,000 ppm has been assumed. This value can be considered as a representative value of the Eastern Mediterranean Sea. The electricity consumption for the MED is significantly lower than the electricity consumption of RO (around one third). For the CSP plants, a common layout has been considered. The thermal energy storage with a capacity of approx. 11 hours allows a considerable extension of the operation time of the CSP turbine also during evening and even night time (at least during summer). **The annual water production is in all cases 13.3. Mio. m^3/y,** made exception for the case 5. In all three CSP scenarios, the largest share of the investment cost is represented by the CSP plant itself (approx. 300 Mio. €). The investments for the MED plant are around 100 Mio. €, while for the RO plants they are approx. 30 % lower. /Moser 2015/

This difference is also due to the high-efficient MED configuration (GOR of 12). A lower efficiency of the MED would lead to lower investment, but to higher heat supply cost. Therefore, the high-efficiency configuration has been preferred in this case.

In the two PV cases, the investment for the electricity supply is just 10 % of that of the RO plant. This is due to the small PV capacity, which is solely used for the supply of the desalination plant (as no electricity is fed into the electricity network in these cases).

	Unit	CSP/ MED Coast	CSP/RO Coast	CSP/ RO Inland	PV + Diesel/ RO	PV/ RO Solar Only	PV+ Grid$_1$ / RO	PV+ Grid$_2$ / RO	PV+ Batt./ RO
Investment Cost									
Solar field (CSP/PV)	Mio. €	169.1	160.5	185.2	14.7	14.7	14.7	14.7	14.7
Energy Storage	Mio. €	73.8	70.1	80.6	0.0	0.0	0.0	0.0	14.6
Power Block (CSP)/ Backup Plant (PV)	Mio. €	55.5	66.4	80.6	3.9	0.0	0.0	0.0	0.0
Desalination Plant	Mio. €	104.5	71.8	71.8	71.8	71.8	71.8	71.8	71.8
Specific Investment	M€/ m³/d	10	9,2	10,5	2	2	2	2	2.5
Operation Cost									
Power Plants									
Capital cost (CAPEX)	Mio. €/y	23.3	23.2	27.1	1.5	1.2	1.2	1.2	1.2
O&M and insurance cost	Mio. €/y	7.5	7.4	8.7	0.5	0.4	0.4	0.4	0.4
Fuel cost	Mio. €/y	24.7	23.4	27.3	3.9	0.0	0.0	0.0	0.0
Desalination Plants									
Capital cost (CAPEX)	Mio. €/y	8.2	5.6	5.6	5.6	5.6			
O&M cost (OPEX)	Mio. €/y	3.6	3.2	3.2	3.2	1.9	3.2	3.2	2.1
Electricity cost	Mio. €/y	3.5	8.6	10.1	5.1	0.8	1.5	3.4	2.8
Heat cost	Mio. €/y	5.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Water Production Cost									
Levelized water cost	**€/m³**	**1.66**	**1.42**	**1.54**	**0.96**	**1.75**	**0.84**	**1.00**	**1.94**

Table B2: Comparison of investment and operation cost and LWC [3]; assumptions fuel cost: base year 2014 with 80 US$/barrel (70 €/barrel), average escalation rate over plant life time: 2.5 %/y

The comparison of the LWC shows that – under the given assumptions – the PV with grid backup (assuming low electricity price of 4.4 ct$t/kWh /AFEX EE 2015/ configuration is the best performing one (0.84 €/m³).

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[3] In this comparison the CSP power plants are dimensioned to deliver enough (surplus) heat for MED at 70° C. The result is a huge electricity capacity and production from the CSP. For the PV / RO combination PV is only dimensioned to produce enough electricity for the RO only in summer around noon. There is no overcapacity for electricity production and no storage options. Therefore, a high investment is needed for the CSP cases on one hand which results is a high amount of electricity produced from solar energy. On the other hand the low investment for the fossil Diesel and PV option will result in very high fossil share (more than 75 %)

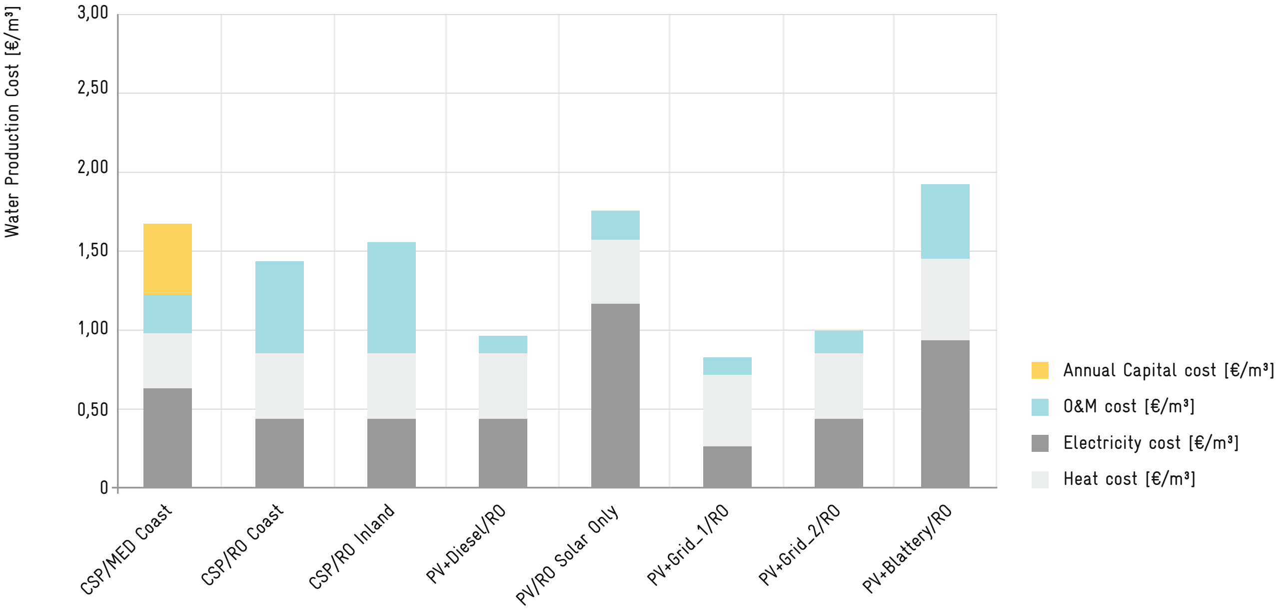

Figure B2: LWC comparison by configuration and by cost item

The comparison of the LWC shows that -under the given assumptions- the PV with grid backup (assuming low electricity price of 4.4 ct$t/kWh /AFEX EE 2015/ configuration is the best performing one (0.84 €/m³).

The PV+battery/RO delivers much higher LWC (1.94 €/m³), which is due to the intermittent operation of the desalination plant and the still relatively high investment cost for the battery. This characteristic can also be appreciated in Figure B2, which shows the share of capital cost, operation cost as well as electricity and heat cost on the LWC in the different scenarios. The CSP configurations have a LWC ranging between 1.42 €/m³ and 1.66 €/m³.

Finally, a sensitivity analysis on selected key economic and technical parameters has been performed. The results are summarized in Figure B3. The parameters are seawater salinity, available solar irradiation

Water source	Salinity range (mg/L)	Temperature (°C)
Mediterranean and Atlantic	38,000–41,000	15–30
Red Sea and Indian Ocean	41,000–43,000	20–35
Gulf	45,000–47,000	25–38

Table B3: Seawater Characteristics in MENA

(DNI), specific investment cost for the CSP and for the PV solar field (CAPEX SF) as well as fuel price for backup. The sensitivity includes the base case scenario (100 %) as well as two variations, i.e. 75 % and 125 % of the base case, respectively.

The salinity has an extremely important impact of the performance of the reverse osmosis. In fact, a salinity increase not only increases the required feed pressure (and so the electricity consumption) at the entrance of the RO modules, but also is assumed to have an impact on the capital expenditures.

This is due to the fact that sites characterized by high salinity (e.g. Table B3) also typically have relatively poor water quality (e.g. high turbidity and/or eventual algae blooms). The challenging seawater quality requires increased capital expenditures for the pretreatment system (e.g. DAF). On the contrary, the performance of the MED is almost independent from the seawater quality and salinity (in reality there is some impact, but such an impact is assumed to be negligible in this simplified model).

As one could expect, an increase of the solar resources lowers the LWC (± 5 % within the considered variation range).

The costs of the solar field also have an important impact on the results. Such an impact is particularly relevant in the CSP/MED case, as in this case an eventual reduction of the CAPEX SF results in a reduction of both the electricity cost and the heat cost. The impact of such a cost variation is rather low in the PV+Diesel case due to the low solar share (25.1 %) of this configuration. Finally, the impact of the fuel price on the LWC is in the range of ± 6 % in all three considered configurations.

Finally, it can be concluded that PV/RO is a competitive option also for utility scale solar desalination as long as the price for fossil backup is relatively cheap. In the future, the solar share could be increased by the integration of batteries with storage capacities of several hours (and larger solar fields).

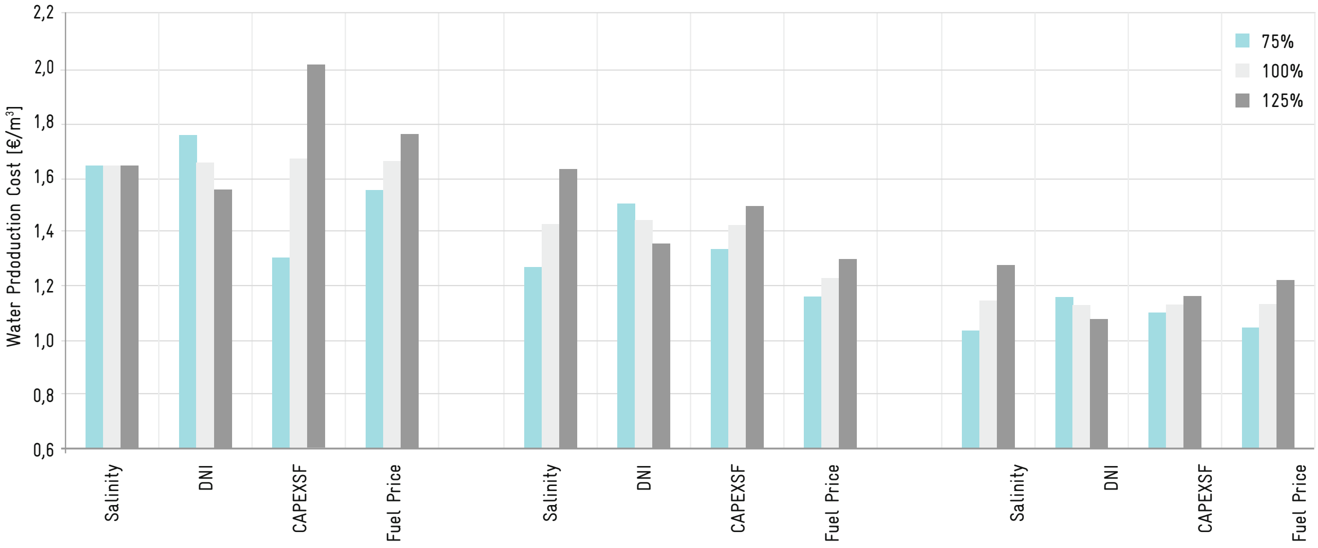

Figure B3: Sensitivity analysis of solar desalination on key technical and economic parameters

The disadvantage of such a configuration would be – similar to the analyzed CSP configurations – the high initial investment. In the case of smaller, off-grid applications, PV/RO is a competitive option due to its scalability, despite the LWC in this case are significantly higher. CSP remains an interesting option for utility scale desalination applications. The CSP/RO combination offers the advantage that the CSP can be almost freely located, as long an electrical network is available. The CSP/MED option is economically competitive under poor seawater quality and/or high seawater salinity (e.g. Gulf). In these particular cases, it has to further be checked if relative flat land is available near to the coast (for the installation of the solar field) and if the base-load electricity generation can be fed into the grid (e.g. for the electricity supply of the local community and eventually for industry purposes). The price developments of CSP and PV as well as of the thermal and electrical storages will significantly influence the preferred solar technologies for future desalination applications.

B-4. Development of Costs

Figure B4 and Figure B5 present two cost development scenarios for CSP and PV, respectively. The trend of the installed capacities worldwide as well as the political and economic frame conditions (e.g. setup of long-term feed-in tariffs) will significantly impact the real cost developments.

The expected price reduction for CSP and PV will have an impact on the LWC, as energy cost represents one of the most important cost items in desalination plants (depending on the technologies and the economic assumptions, typically between 35 % and 50 %). Assuming for CSP a levelized electricity cost (LEC) in 2020 of 10 ct€/kWh, a decrease of the LWC of approx. 20 % in all considered CSP/desalination configurations can be expected. Another key factor will be the development of the fossil fuel price.

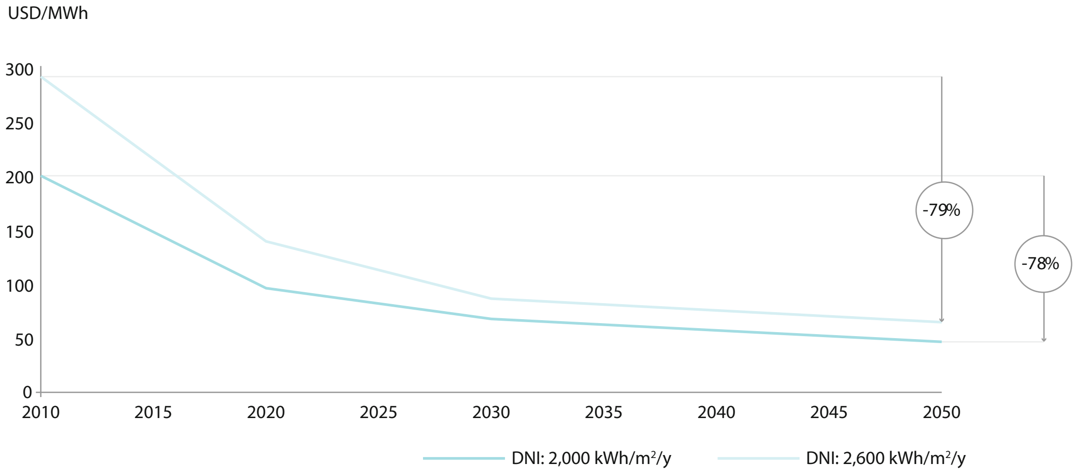

Figure B4: Development scenario for CSP levelized electricity cost /Schlumberger 2013/ (note: the legend should be emended: the dark line corresponds to the higher DNI value)

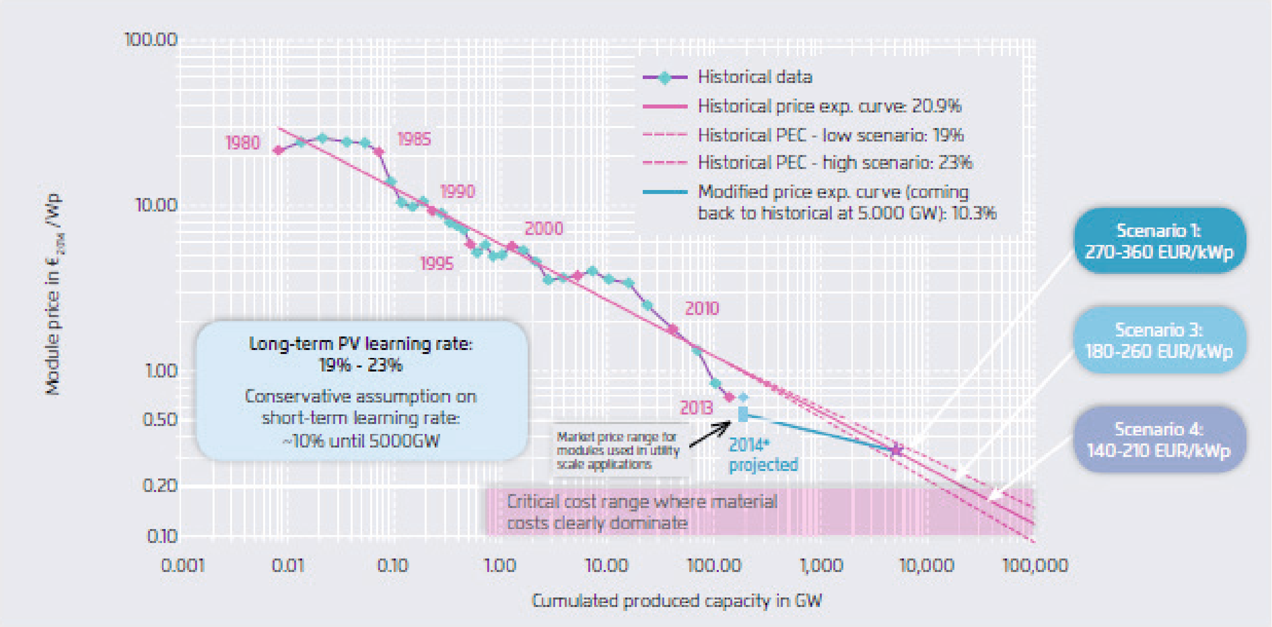

Figure B5: Extrapolation of the price experience curve for PV modules /AgoraEnergie 2015/
Concerning PV, the cost reduction strongly depends on the development of the fossil fuel price (PV+Diesel configuration) and so no general answer can be given. Regarding the PV solar only-configuration, a LWC reduction of approx. 4-5 % could be expected assuming a LEC of 3.5 ct€/kWh in the year 2020.
Source: "Extrapolation of the price experience curve for PV modules" /AgoraEnergie 2015/ Current and Future Cost of Photovoltaics-Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems http://www.agora-energiewende.de/fileadmin/Projekte/2014/Kosten-Photovoltaik-2050/AgoraEnergiewende_Current_and_Future_Cost_of_PV_Feb2015_web.pdf

B-5. Market Considerations

There is no worldwide standard for water pricing. In many countries of the MENA region as well as in many countries in sub-Saharan Africa tariff increases are determined by the state authorities. There are no objective criteria for tariff adjustments and they often lag behind those of inflation, so that a cost recovery is a long way off. Water prices have a significant impact on the water consumption behavior of people. It may be noted that water use patterns can change significantly if cost-covering water tariffs and metering are introduced in these countries.

In addition to the large price differences of water in different cities around the world we can see that the water prices are higher in colder regions than in warmer regions such as MENA although there is often a big water shortage.

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