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Desalination leaders in the global market – current trends and future perspectives

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ABSTRACT

Since the world's first land-based desalination plant was established in Australia in 1903, brackish groundwater and seawater desalination became a common water supply technology in many countries around the world. Desalination has proven as a reliable technology in times of drought and/or water scarcity, while in some countries it is an indispensable water supply source on a regular basis. This paper compares and evaluates major desalination leaders in the world (USA, Saudi Arabia, Israel, Australia, and China) with the aim of pointing out similarities and differences that made each of them successful. It also depicts a comprehensive picture of developments, trends and experiences in desalination at the global scale. Establishing desalination plants and ensuring their successful operation is a complex and multifaceted process dependent on capital and operational costs, production capacity, water salinity, geographical location, socio-economic and environmental conditions, and many other factors. The country specific comparison presented in this paper emphasizes the importance of regional planning for successful and sustainable desalination processes in the long term.

Key words | brackish groundwater, desalination, seawater, water management

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INTRODUCTION

In 2013, the total global desalination capacity amounted to 15.8 BGD (billion gallons per day) (60 million m^3/d) crowning a rapid growth in the desalination market and the global production capacity increase of 27 times since 1995 (GWI (Global Water Intelligence) 2013). The major leaders in the desalination market are Saudi Arabia, the USA, and UAE (United Arab Emirates), with their daily production capacity of 2.0 BGD (7.5 million m^3/d), 1.94 BGD (7.3 million m^3/d), and 1.89 BGD (7.1 million m^3/d), respectively. The USA is leading in terms of the number of operating plants with around 1,336 plants online in 2013, followed by Saudi Arabia with 1,324 plants and UAE with ~270 plants (GWI (Global Water Intelligence) 2013). The numbers indicate that desalination plants in Saudi Arabia and the UAE, even though fewer in numbers, operate at a higher production capacity. In some countries desalination may be the only option of water supply (e.g. Saudi Arabia, Israel). In other countries (e.g. USA, China, Australia) with a more diversified water portfolio and access to surface and groundwater resources, desalination represents a water supply source that is more reliable in certain locations than traditional water supply systems (rivers, aquifers, wastewater facilities), even though it is considerably more expensive at the same time.

Expanding interest and investments in desalination around the world have been accelerated by the growing population as well as frequent and unexpected droughts. Due to population growth, the global water demand is predicted to increase by 46% from 3 billion af (acre feet) in 2000 up to 4.4 billion af in 2050 (UN 2014; OECD (Organisation for Economic Co-operation and Development) 2012). At the same time, global water resources are shrinking, either as a result of human activities and aquifer depletion or due to extreme weather events like drought. Severe droughts have

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affected Australia in 1995–2012 (Millennium drought), the Southern USA (2010–2012), and North America (2012–2014), while they have also amplified the vulnerability of water resources and strained national economies. Rising industrial water use and unfavorably changing climate conditions exacerbate water shortage and create tradeoff constellations in water applications. In addition, the growing population can induce an increase in water use for agriculture, food production, industrial processes, and power generation. Desalination has been discussed for many years as one of the water supply sources that could mitigate water shortage in the mid and long term.

Many studies have addressed desalination in different countries of the world. Their main focus is on technological improvements and membrane efficiency in order to decrease desalination costs (Miller *et al.* 2015; Xu *et al.* 2015; Zhou *et al.* 2015). Other studies address the potential of renewable energies for desalination (Shatat *et al.* 2013; Reif & Alhalabi 2015), biochemical processes and biofouling treatment (Kim *et al.* 2015; Levi *et al.* 2016), as well as social acceptance of desalination by regional communities (Gibson *et al.* 2015). Environmental and sustainability issues related to desalination have not been evaluated enough yet (Tsiourtis 2001; Einav *et al.* 2003; Roberts *et al.* 2010; Alharbi *et al.* 2012; Haddad 2013; Liu *et al.* 2013).

This paper extends the literature in the field by depicting a comprehensive picture and a comparative analysis among the leading countries in the desalination sector. This topic has not been addressed extensively to date, mainly due to data paucity.

The paper analyzes and evaluates developments, trends and patterns in desalination in the major leading countries on the global scale, based on the following variables: GDP per capita, population, water resources, other socio-economic conditions, desalination capacity, applied desalination technology, feed water type, and the final consumer of desalinated water. The comparison analysis proves that socio-economic conditions have determined desalination developments in the analyzed countries.

The results and discussion presented in this paper are based on the literature review and the desalination database (Desaldata.com) provided by Global Water Intelligence. The database offers the most comprehensive dataset of desalination plants around the world so far. Different definitions of water salinity are available in the literature and used by scientists and practitioners. In order to avoid terminological misconceptions, new labels have been conceptualized and assigned to the salinity levels for the purpose of this research, as follows:

< 500	ppm TDS	water within the EPA drinking water quality standard
500–3,000	ppm TDS	brackish groundwater and most surface waters
3,000–20,000	ppm TDS	saline water, including some surface waters and groundwater
20,000–50,000	ppm TDS	brine waters
> 50,000	ppm TDS	deep brine groundwater sources (including seawater)

Accordingly, in this paper, the salinity levels (and the total dissolved solids – TDS, also expressed in ppm (parts per million) will be used interchangeably with the corresponding linguistic labels (seawater, brackish water, etc.).

The results of the study can be helpful to water authorities and communities to analyze available resources and regional water needs in the process of designing water portfolio strategies, including desalination. Moreover, successful examples and experiences from the leading countries in the desalination market can help to improve effectiveness and efficiency of desalination.

MAJOR LEADERS IN THE GLOBAL DESALINATION MARKET

In 2013, the USA, Saudi Arabia, UEA, China, Kuwait, India, Libya, Australia, Chile, and Qatar indicated the highest investments and the largest share in the desalination market. The US investments exceeded $7 billion, while Qatar was investing slightly below $2 billion (GWI (Global Water Intelligence) 2013).

This paper is focused on five countries: the USA, Saudi Arabia, Australia, Israel, and China, representing different continents and the major leaders in the desalination market. In 2013, the USA and Saudi Arabia each produced 2 BGD (7.5 million m^3/d) desalinated water, China was desalinating 970 MGD (million gallons per day) (3.7 million m^3/d), Australia provided 503 MGD (1.9 million m^3/d) of

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desalinated water, while Israel $\sim$487 MGD (1.8 million m^3/d) (GWI (Global Water Intelligence) 2013). Table 1 presents the top 10 desalination plants in each of the analyzed countries with corresponding detailed specifications.

The comparison of socio-economic conditions and available water resources as well as recent trends in desalination in those countries can provide valuable hints and perspectives for future developments of this market, including the country specific progress in this regard. Even though the selected countries are characterized by different socio-economic and environmental conditions (Table 2), water scarcity problems and the continuously growing demand for water are urgent and common in all of them.

Among the analyzed countries, China has the largest population and thus the highest water demand that directly translates to the highest water consumption. At the same time, it has the second highest level of total available water resources. The USA uses only 14% less water than China, even though the population in the USA is four times smaller than in China. Israel has the lowest population number and the smallest area. Thus, its water resources and water consumption are accordingly low compared to the other countries included in the analysis, although it is highly dependent on desalination (World Bank 2013a, 2013b, 2013c; FAO Aquastat 2014).

In regard to water needs in the specified countries, it is apparent that Saudi Arabia and Israel consume more water than their natural water reserves allow. Therefore, desalination has been developed extensively for many years and it has been used to close the gap between the domestic water demand and the water supply from the available inland water sources. On the contrary, water consumption in Australia, the USA, and China is lower than the available water resources in those countries. However, those numbers have not been adjusted to account for the effects of droughts in the past several years (World Bank 2013a, 2013b, 2013c; FAO Aquastat 2014). In the following sections, the countries included in this analysis will be discussed separately to point out their country specific characteristics and the background for the desalination markets.

Australia

In the last decade, the population growth rate in Australia has been less than 1% per year (UN (United Nations) 2006). Water resources in the country have been imperiled by the Millennium drought that exposed the country to a long-lasting water scarcity. Although Australia is considered the driest continent on Earth, the installed desalination capacity in the country makes only approximately 1% of the world's desalination capacity (El Saliby *et al.* 2009). Desalination in Australia has been promoted mainly through the National Centre of Excellence in Desalination (NCED) at Murdoch University, Rockingham, WA (NCED (National Centre of Excellence in Desalination) 2011) as a solution that can ameliorate or even eliminate the water crisis in the country. Australia's first desalination plant was constructed in 1903 to treat saline groundwater in Western Australia at Kalgoorlie (El Saliby *et al.* 2009). In 2013, a total of 219 plants were online, while the desalination facilities in Perth, Gold Coast, and Sydney are currently among the largest providers of municipal water in the country (GWI (Global Water Intelligence) 2013).

The Perth desalination plant provides approximately 17% of Perth's domestic water supply. It is owned and financed by the state and operated on behalf of the Water Corporation by Degrémont on a 25-year operation contract. The Gold Coast desalination plant was constructed to provide around 15% of South East Queensland's current water supply. The plant is publicly financed and was constructed by the Gold Coast Desalination Alliance, formed between Veolia, John Holland, Sinclair Knight Mertz, Cardno, Gold Coast Water, and the Queensland State Government. The Sydney desalination plant was built by Blue Water Consortium in 2010 to provide 15% of Sydney's current water demand. It is owned by the Sydney Water Corporation (the city utility). It was designed to operate constantly for 2 years and to be put in a standstill after that, with periodic time frames of operation if the dam levels fall below 70% (GWI (Global Water Intelligence) 2013).

China

According to the Ministry of Water Resources, China's population will reach 1.6 billion in 2030. At the same time available water resources are anticipated to amount to 1,750 m^3 (462.3 kgal) per inhabitant per year, which is considered as a threshold of severe water scarcity (Zhou & Tol 2004). Water withdrawals are estimated to amount to

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Table 1 | Top ten largest desalination plants in the analyzed countries by capacity

Country name	Location	MGD	Technology	Raw water type	Online date	User category
Australia	Wonthaggi	117.3	RO	Seawater	2012	Municipal
	Adelaide	72.4	RO	Seawater	2012	Municipal
	Kwinana	38.0	RO	Seawater	2006	Municipal
	Cape Preston	37.0	RO	Seawater	2012	Industry
	Perth	37.0	RO	Seawater	2011	Municipal
	Gold Coast	35.1	RO	Seawater	2008	Municipal
	Chinchilla	19.0	RO	Wastewater	2011	Industry
	Sydney	6.3	RO	Wastewater	2008	Industry
	New South Wales	5.6	RO	Wastewater	2013	Industry
	Wollongong	5.3	RO	Wastewater	2004	Industry
China	Hangzhou	40.0	RO	Brackish water	2008	Industry
	Tianjin	26.4	RO	Seawater	2009	Municipal
	Tianjin	26.4	MED	Seawater	2010	Power stations
	Qingdao	26.4	RO	Seawater	2013	Municipal
	Tianjin	26.4	MED	Seawater	2012	Power stations
	Mongolia	26.4	RO	River water	2011	Municipal
	Mayong	26.4	RO	Brackish water	2006	Industry
	Ningxia	19.9	RO	River water	2008	Industry
	Guangdong	13.2	RO	Wastewater	2007	Municipal
	Caofeidian	13.2	RO	Seawater	2012	Industry
Israel	Tel Aviv	142.7	RO	Seawater	2013	Municipal
	Hadera	97.2	RO	Seawater	2010	Municipal
	Ashkelon	86.2	RO	Seawater	2005	Municipal
	Palmachim	39.6	RO	Seawater	2013	Municipal
	Palmachim	21.7	RO	Seawater	2007	Municipal
	Hadera	19.6	RO	Seawater	2010	Municipal
	Ashkelon	10.8	RO	Seawater	2010	
	Palmachim	10.8	RO	Seawater	2010	Municipal
	Kefar Masaryk	6.3	RO	Brackish water	2012	Municipal
	Maagan Michael	6.1	RO	Seawater	2004	Municipal
Saudi Arabia	Shoaiba	232.5	MSF	Seawater	2009	Municipal
	Al Jubail	211.4	MED	Seawater	2010	Industry
	Shoaiba	120.0	MSF	Seawater	2002	Municipal
	Al Khobar	74.0	MSF	Seawater	1997	Municipal
	Jeddah	63.4	RO	Seawater	2013	Municipal
	Shuqaiq	56.0	RO	Seawater	2010	Municipal
	Rabigh	51.1	RO	Seawater	2008	Industry
	Riyadh	43.6	RO	Brackish water	2013	Municipal
	Al Wasia	40.4	RO	Brackish water	2004	Municipal
	Hail	39.6	NF	Brackish water	2010	Municipal
USA	Hillsboro, OR	53.3	RO	Brackish water	2011	Industry
	Boca Raton, FL	40.0	NF	River water	2003	Municipal
	Doral, FL	30.0	RO	Brackish water	2011	Municipal
	Tampa Bay, FL	28.8	RO	Seawater	2007	Municipal
	El Paso, TX	28.0	RO	Brackish water	2007	Municipal
	Palm Beach, FL	25.5	RO	River water	2005	Municipal
	Palm Beach, FL	25.0	RO	River water	2004	Municipal
	Collier County, FL	20.0	RO	Brackish water	1999	Municipal
	Granbury, TX	18.5	RO	Brackish water	2009	Municipal
	Sacramento, CA	16.6	RO	Brackish water	2012	Industry

RO – Reverse osmosis, NF – Nanofiltration, MED – Multi-effect distillation, MSF – Multi-stage flash distillation.
Municipalities (TDS 10 ppm < 1000 ppm), Power stations (TDS < 10 ppm), Industry (TDS < 10 ppm).
Source: Author's presentation based on GWI (Global Water Intelligence) (2013).

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Table 2 | GDP per capita, population, and water resources in the analyzed countries

Country	GDP per capita (US$) (2012)	Population (million) (2012)	Total water consumption (billion m^3/yr) [trillion gal/yr] (2011)	Total water resources (renewable, actual*) (billion m^3/yr) [trillion gal/yr] (2012)
Australia	67,442	22.7	22.6 [5.9]	492.0 [130.0]
China	6,091	1,350.7	554.1 [146.4]	2,840.0 [750.2]
Israel	32,567	7.9	2.0 [0.53]	1.8 [475.5]
Saudi Arabia	25,136	28.3	23.7 [6.3]	2.4 [634.0]
USA	51,749	313.9	478.4 [126.4]	3,069.0 [810.7]

Sources: World Bank (2013a, 2013b, 2013c); FAO Aquastat (2014).

*This may not be the total of surface and groundwater because of the overlap between those two water sources, non-exploitable water sources or irrigation water running back to rivers/aquifers and counted twice.

700–800 km^3/yr (185–211.3 trillion gal/yr), which significantly exceeds the available water resources. Even if water conservation measures were in place, an additional 130–230 km^3/yr (34.3–60.7 trillion gal/yr) would be necessary to satisfy the population's water needs. This translates to $146–292 billion of investments to fund new water supply systems like desalination or to promote other advanced water technologies (GWI (Global Water Intelligence) 2013).

China is exposed to water scarcity mainly due to the population growth, industrialization, and urbanization. Especially the Northern and Northwestern regions, coastal cities, and islands in the North of the country are affected (Zhang *et al.* 2005). Seawater desalination has been considered as one of the possible solutions to mitigate water scarcity; and its capacity increased from 10,000 m^3/d (2.6 MGD) in 2000 to around 660,000 m^3/d (174.3 MGD) in 2011 (Zheng *et al.* 2014). The first seawater desalination plant in China was constructed in 1982 on Woody Island in the Xisha Islands (Paracel Islands) with a capacity of 200 m^3/d (0.05 MGD). However, desalination has not been competitive compared to long distance water transfers that are subsidized by the government or compared to low water rates due to government price control. On the contrary, neither seawater desalination nor transfers of desalinated water over a long distance are subsidized. Therefore, seawater desalination in China is still inhibited compared to the desalination markets, for instance, in the USA and Japan (Shen 2008; GWI (Global Water Intelligence) 2013). Nowadays new cost-effective technologies in desalination as well as renewable energies are explored to improve efficiency and success of desalination in China (Zhang *et al.* 2005; Chen *et al.* 2012; Avrin *et al.* 2015; Jiang *et al.* 2015).

Israel

In recent years, Israel experienced a steady increase in domestic water consumption, triggered by a significant population growth (both natural and due to immigration) as well as improving living standards (Becker *et al.* 2010). The country is highly dependent on desalination due to extensive agricultural practices and recurring droughts that have contributed to contamination and depletion of groundwater aquifers (Muenk 2008). Water demand in the country is estimated to increase up to 2.8 billion m^3/yr (607 billion gal/yr) in 2020 (from previously 2.0 billion m^3/yr [508 billion gal/yr] in 2005). At the same time, seawater desalination in Israel is projected to increase from 2.1 billion m^3/yr (554.7 billion gal/yr) up to 2.9 billion m^3/yr (766.1 billion gal/yr) in the same time period (Dreizin 2006).

Israel's approach to managing water scarcity is based largely on the supply management (developing additional or alternative water supply sources, such as production of water from marginal sources – wastewater or seawater – or through imports of water from other countries) (Moatty 2001). At the same time, demand management measures (reducing demand for water through price adjustments, increase in price rates and/or trade of water allotments) are perceived as a second best option (Becker 2001; Hurlimann *et al.* 2009). Over the past decade, costs of seawater desalination in Israel have dropped significantly due to technological advances, which incentivized policy makers to invest in desalination as a way to cope with long-term water supply shortages (Becker *et al.* 2010). Currently, desalination is the primary water supply option pursued by Israel. However, despite positive developments, Becker *et al.* (2010) found that desalination is among the least cost-efficient alternatives included in Israel's water portfolio.

Saudi Arabia

Annual renewable freshwater resources in Saudi Arabia amount to 2.4 km^3/yr (634 billion gallons/yr), whereas

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abstraction of water to satisfy demand is about 24 km³/yr (6.3 trillion galons/yr). The remaining water demand is satisfied from non-renewable groundwater resources and desalination (GWI (Global Water Intelligence) 2013). The quality and quantity of groundwater resources in the country have been declining over the years and many desalination facilities are reaching the end of their production life. According to the National Water Company (overseeing water supply, wastewater collection, wastewater treatment, and water reuse) desalinated water accounts for 60% of the total annual urban water supply of 5.72 million m³/d (15.1 MGD) in the country (GWI (Global Water Intelligence) 2013).

In 2013, Saudi Arabia produced 2 BGD (570 million m^3/d) of desalinated water with 18% share in the global desalination market water output (Alarifi 2013). Due to its geographical location, solar desalination has expanded in recent years (Mokheimer *et al.* 2013; Chafidz *et al.* 2014). Desalination in Saudi Arabia is heavily subsided by the government, starting from water production (and including energy subsidies) to transportation and distribution (GWI (Global Water Intelligence) 2013). Therefore, the prices for desalinated water in the country are very low compared to the other analyzed countries, while the production and distribution costs are the highest worldwide. According to WWF (World Wildlife Fund) (2007), high subsidies favor inefficient desalination technologies in the country (thermal desalination with higher energy requirements compared to membrane technologies). In addition, water allocation policies in the country have been criticized by WWF (World Wildlife Fund) (2007) and Muenk (2008). The studies found that unproductive agricultural farms in the desert areas are irrigated with groundwater, while desalinated water for municipal purposes has to be transferred over long distances to the middle of the country. Improving technological efficiency and optimizing water policies are the main challenges that will affect the developments of desalination in Saudi Arabia in the mid- and long-term.

United States

The US water sector is facing the challenge of falling supply and increasing demand occurring simultaneously. In addition, recent droughts have caused significant depletion of aquifers, which occurs considerably faster than the replenishment process. Thus, desalination could extend current water portfolios in the country, and provide a buffer to water scarcity.

In terms of the annual desalination capacity, the USA has the second largest desalination market in the world after Saudi Arabia, but it is leading with regard to the number of operating plants. Almost 80% of the US desalination market is concentrated in California, Florida, and Texas. Florida and California have been suffering from severe water shortages and have the highest installed desalination capacity in the country: 230.8 MGD (0.8 million m^3/d) and 94.7 MGD (0.3 million m^3/d), respectively (GWI (Global Water Intelligence) 2013). While Texas has been affected by extreme drought in 2011–2015, desalination makes only 3% of the water portfolio approved in the 2012 Texas State Water Plan (TWDB (Texas Water Development Board) 2012). As of fall 2015 the El Paso Texas desalination plant is the largest plant in the USA with its optimal capacity of 25 MGD (0.1 million m^3/d). While brackish groundwater desalination has been acknowledged as a prospective option, most seawater desalination projects in Texas (and other US regions) have been rejected by the city and water authorities. The main reason for this trend is high construction costs and high prices of desalinated seawater, which would not be competitive with traditional (though scarce) water resources (Voutchkov 2010a, 2010b). Also, environmental concerns related to seawater desalination have caused resistance and skepticism towards seawater desalination (Einav *et al.* 2003; Roberts *et al.* 2010; Alharbi *et al.* 2012). Currently, due to the prevalent exceptional drought in California since 2011, and depleted aquifers, the state is considering seawater desalination more than ever before. The desalination plant in Carlsbad California is expected to open by the end of 2015, while also several projects have been initiated on the East Coast (Vedachalam & Riha 2012).

All of the analyzed countries demonstrate a distinctive need for new water technologies, and all have taken different paths and approaches to promote and foster desalination. The following sections will underscore similarities and differences among those countries for a set of different variables related to desalination.

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GLOBAL AND REGIONAL TRENDS AND DEVELOPMENTS IN WATER DESALINATION

This section provides an overview of global and national trends on the desalination market based on several desalination characteristics. The comparison analysis for Australia, China, Israel, Saudi Arabia, and the USA allows for addressing relevant issues of water scarcity and ways to apply desalination as a supplementary and integrated water management system rather than an exclusive water management strategy.

Feed water sources for desalination

Based on the production capacity reported by GWI (Global Water Intelligence) (2013), globally 60% of feed water for desalination constitutes seawater, 20% brackish groundwater, 10% surface water, while only 10% constitutes wastewater and fresh water combined. Almost all analyzed countries use primarily water sources with TDS in the range of 20,000–50,000 ppm, which represents highly concentrated brine water (mainly seawater). Israel is leading among the analyzed countries with 93% of seawater desalination, followed by Australia (75%), Saudi Arabia (69%), and China (40%). In the USA, brackish groundwater, saline surface water, and river water account for 84% of the total desalination capacity, while only 5% of the operating desalination plants process highly concentrated water (including seawater) (Figure 1).

The distribution of desalination plants in the analyzed countries in terms of their capacity based on the feed water sources is uneven. In terms of the absolute number of plants, brackish groundwater (TDS 3,000–20,000 ppm) and seawater (TDS 20,000–50,000 ppm) facilities are dominating worldwide. Globally, around 3,467 desalination plants use brackish groundwater and saline water, while approximately 3,550 plants rely on seawater and other highly concentrated water sources. The same trend can be found in Israel with ~20 brackish groundwater and ~23 seawater plants. In the USA, Australia, and Saudi Arabia, brackish groundwater desalination plants are dominating, while in China most of the plants desalinate seawater and highly concentrated saline waters (Table 3).

Feed water source for desalination is one of the main determinants of the final water price. Desalination of brackish groundwater is least expensive due to lower salinity levels and the relatively low energy costs associated with the desalination process. Desalination of seawater and other highly concentrated saline waters requires denser and more accurate membranes as well as higher energy inputs to push water through the membranes under a

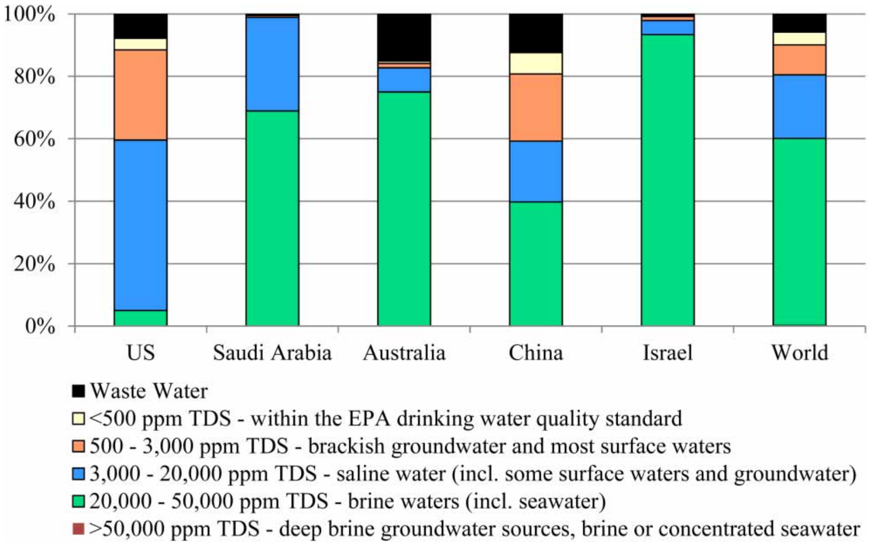

Figure 1 | Feed water sources for desalination in the analyzed countries in 2013. *Source:* Author's calculations based on GWI (Global Water Intelligence) (2013) data. *Note:* Wastewater originates from industrial, agricultural or other anthropogenic processes, such as municipal wastewater. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/ws.2015.184.

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Table 3 | Desalination plants by feed water source in the analyzed countries in 2013

Number of plants by water source for desalination in 2013	**USA**	**Saudi Arabia**	**Australia**	**China**	**Israel**	**World**
3,000–20,000 ppm TDS – saline water (incl. some surface waters and groundwater)	635	854	80	60	23	3,467
>50,000 ppm TDS – deep brine groundwater sources, brine or concentrated seawater	0	1	1	1	0	25
<500 ppm TDS – within the EPA drinking water quality standard	180	18	17	45	1	986
500–3,000 ppm TDS – brackish groundwater and most surface waters	301	19	22	73	5	1,140
20,000–50,000 ppm TDS – brine waters (incl. seawater)	98	424	71	166	20	3,550
Wastewater	117	8	28	42	2	572

Source: Author's calculations based on GWI (Global Water Intelligence) (2013) data.

higher pressure, mainly in the reverse osmosis process. Therefore, both capital and operational costs of seawater desalination plants are considerably higher compared to the costs of desalinating water from other feed water sources. Distillation processes are principally more expensive due to higher thermal energy costs compared with electrical energy (Table 4).

While many studies provide varying final costs of desalination, all of them substantiate a direct impact of energy costs on the final desalination price (Zhou & Tol 2005; Sauvet-Goichon 2007; Mezher *et al.* 2011). Other authors emphasize a very strong correlation between the energy prices and the final water prices (Ziolkowska 2015), but no significant impact of crude oil prices on overall desalination developments in terms of production and numbers of plants (Ziolkowska & Reyes 2016).

It is intuitive that low petroleum prices (as experienced, for instance, in 2015) will induce low energy prices and thus further reduce the final desalination costs boosting desalination developments. Accordingly, in the current state of the global oil market, desalination plants using the reverse osmosis technology have an economic advantage compared to distillation processes. However, economic benefits are derived from the technological application itself, while there is no proven correlation between low energy prices (and the resulting desalination costs) and the geographical location of the plants (countries applying desalination). Surprisingly, desalination plants in the Middle Eastern countries (with abundance of cheap oil) use distillation processes for 50% of their total desalination production capacity, and thus cannot take full economic advantage of low energy prices for desalination per se. The reason for the reliance on distillation (rather than filtration – RO) is a technological limitation of the RO membranes that need to be customized for the extremely high salinity of the Red Sea and the Gulf Sea. Moreover, hot climate and high humidity in the region negatively impact the production capacity of RO membranes.

Table 4 | Energy consumption and average water cost of large scale commercial desalination processes

Process	**Thermal energy (kWh/m^3) [kWh/kgal]**	**Electrical energy (kWh/m^3) [kWh/kgal]**	**Total energy (kWh/m^3) [kWh/kgal]**	**Investment cost ($\$/m^3$) [$/gal]**	**Total water cost ($\$/m^3$) [$/kgal]**
MSF (Multi-Stage Flash Distillation)	7.5–12 [28–45]	2.5–4 [9.5–15.1]	10–16 [37.8–60.5]	1,200–2,500 [4.5–9.5]	0.8–1.5* [3–5.6]
MED (Multi-Effect Distillation)	4–7 [15.1–26.5]	1.5–2 [5.6–7.5]	5.5–9 [20.8–34]	900–2,000 [3.4–7.6]	0.7–1.2 [2.6–4.5]
SWRO (Seawater Reverse Osmosis)	-	3–4 [11.3–15.1]	3–4 [11.3–15.1]	900–2,500 [3.4–9.5]	0.5–1.2 [1.9–4.5]
BWRO (Brackish Water Reverse Osmosis)	-	0.5–2.5 [1.9–9.5]	0.5–2.5 [1.9–9.5]	300–1,200 [1.1–4.5]	0.2–0.4 [0.7–1.5]

Sources: Quteishat (2009); Reddy & Ghaffour (2007); Pankratz (2008); Borsani & Rebagliati (2005); Sommariva *et al.* (2003); Maurel (2006); Australian Government (2008).

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Thus, energy costs determined by feed water and its salinity levels vary across the globe, from country to country, from region to region, and from one desalination plant to another.

Another aspect directly related to feed water and impacting the final price of desalinated water is the cost of brine disposal. Brine is a highly concentrated saline byproduct of desalination (not to be confused with highly saline aquifer waters that are also described by the same term). Due to missing universal and international/national environmental standards for brine disposal as of today (2015), many desalination facilities dispose of brine to surface water or sewer that are further treated by the conventional water treatment plants. Because no additional brine treatment is involved, disposing of brine to surface water or sewer creates the lowest costs to the desalination process in the range of \$0.03–0.66/m^3 [\$0.1–2.5/kgal]. Alternatively, deep injection wells (\$0.33–2.64/m^3) [\$1.2–10.0/kgal] and evaporation ponds (\$1.18–10.04/m^3) [\$4.4–38.0/kgal] are also used (Koyuncu *et al.* 2001; Miller 2003; Sethi 2007; Greenlee *et al.* 2009). Also in this case, a regional and country specific analysis is rather impossible, as brine disposal is determined by each single plant based on their production factors, geographical location, geological formations in the region, and a multitude of other operational variables.

Final users of desalinated water

Approximately 63% of desalinated water worldwide is used for municipal purposes as drinking water, 26% for industry purposes, and 6% in power stations for electricity generation. Also in all the analyzed countries (except China), municipalities are the main recipients of desalinated water, with around 60% of the final water use falling into this category in the USA, Saudi Arabia, and Australia, respectively. The industry sector is the second largest user of desalinated water (~20% of the total desalinated water consumption). In Israel, 98% of desalinated water is used to satisfy municipal needs and only 1% is directed for industry and irrigation purposes, respectively. In China, the pattern is the opposite: 53% of desalinated water is used in the industrial sector, 27% for power generation, and only 19% for municipal purposes (Figure 2). The pattern in the application of desalinated water in the USA is very similar to the global pattern.

The presented picture is the opposite when considering the total number of desalination plants providing water for different final users. Only in Israel and China, does the number of plants producing water for municipal purposes correspond with the production capacity of those plants. In the USA, Saudi Arabia, and Australia, the number of plants producing for the industrial sector outranks the plants producing for municipal purposes (Table 5). This indicates

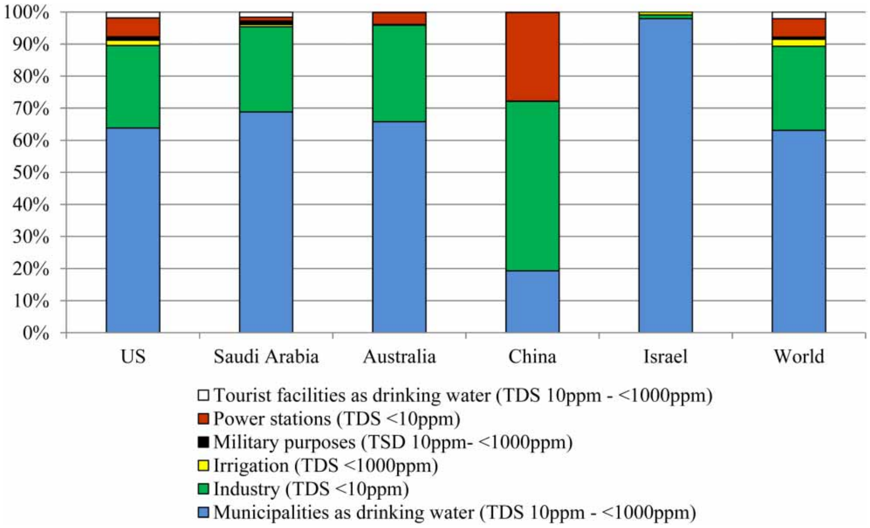

Figure 2 | Percentage of desalinated water for final users in the analyzed countries and the world based on production capacity (2013). *Source:* Author's calculations based on GWI (Global Water Intelligence) (2013) data. *Note:* The TDS ranges in the chart represent the salinity levels to which water is desalinated and treated. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/ws.2015.184.

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Table 5 | Number of plants by the final users by country in 2013

Number of plants by customer type in 2013	USA	Saudi Arabia	Australia	China	Israel
Industry (TDS <10 ppm)	690	417	134	189	15
Irrigation (TDS <1,000 ppm)	18	60	2	3	3
Military purposes (TSD 10ppm- < 1,000 ppm)	6	59	3	0	0
Municipalities as drinking water (TDS 10 ppm- < 1,000 ppm)	392	683	37	99	30
Power stations (TDS < 10 ppm)	174	31	29	88	1
Tourist facilities as drinking water (TDS 10 ppm - <1,000 ppm)	33	70	9	4	1

Source: Author's calculations based on GWI (Global Water Intelligence) (2013) data.

Note: The numbers in this table and the following section may not sum up to the total number of desalination plants provided in the previous section. Some plants using desalinated water for other (less relevant) purposes not listed here have not been included in this specification.

that in these countries desalination plants providing water for municipalities are operating at higher capacities compared to the plants providing water for industrial processes.

The percentage distribution of the plants producing desalinated water for different final users has not changed over time, since desalination was implemented for the first time in the analyzed countries. However, the total capacity of desalinated water provided to the final consumers increased considerably in each of those countries.

Desalination technology

Membrane technologies (Reverse Osmosis – RO) and distillation processes (Multi-Effect Distillation – MED and Multi-Stage Flash Distillation – MSF) are the most common desalination technologies nowadays.

Reverse Osmosis is predominant at the global scale. RO membrane filters separate out salt ions from the pressurized saline water solution, allowing only water to pass through the membrane. RO technology requires a post-treatment such as removing dissolved gasses (CO_2) and stabilizing the pH through the addition of Ca or Na salts. RO has proven to be efficient, especially for brackish groundwater desalination, which requires only low to intermediate pressure ranges (15–25 bar), while seawater RO requires higher pressure (54–80 bar) and thus is more energy intensive and more expensive (Buros 2000). As the pressure required for recovering additional water increases with the feed water salinity, the water recovery rate of RO systems tends to be low (Spiegler & El-Sayed 1994). Nowadays research is under way that would allow for an increased recovery rate up to 90% through the so-called Zero Liquid Discharge (ZLD) compared to the current average 50–60% recovery rate.

Thermal desalination processes – Multi-Stage Flash Distillation and Multi-Effect Distillation – have been applied widely in the Middle East (particularly in Saudi Arabia, United Arab Emirates, and Kuwait). MSF desalination accounts for around 18% of the world's desalination capacity (GWI (Global Water Intelligence) 2013). It relies on a distillation (thermal) process that involves evaporation and condensation of water. In order to maximize water recovery, each stage of the MSF unit operates at a successively lower pressure. In the Persian Gulf region, large MSF units are often coupled with steam or gas turbine power plants to utilize fuel energy more efficiently. Steam produced at a high temperature, and pressure generated by the fuel is expanded through the turbine to produce electricity. Low to moderate temperatures and pressure steam exiting the turbine are used to perform the desalination process (Darwish & Al-Najem 2000; Semiat, 2000).

MED units were applied for the very first time in 1950s. The process is closely linked to MSF and was outnumbering MSF mainly due to its better thermal performance. However, due to scaling problems on the heat transfer tubes, the MED technology was replaced with MSF (Al-Shammiri & Safar 1999). In the MED process, vapor from each stage is condensed in each successive stage, thus providing heat to drive more evaporation. To increase desalination performance, each stage is run at a successively lower pressure. This allows the plants to be configured both for high temperature (>90 °C) or low temperature (<90 °C) operations (Miller 2003).

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Over the past several decades, major changes in desalination technologies have impacted desalination costs and the final price of desalinated water. In the late 1970s, the RO technology gained momentum on the market, as it has been established as a less energy intensive and thus more cost-efficient alternative compared to distillation processes. While in the 1990s the main focus in desalination was on process improvements, the robustness of MED increased and it became more effective than MSF, which translated to increasing application rates of the MED technology. At the same time, progress in the reverse osmosis technology resulted in a growing market share for membrane desalination (Figure 3).

Desalination technologies can serve either as stand-alone applications (RO, MSF, MED) or as process combinations (RO and MSF) called hybrid desalination. Also electrodialysis and nanofiltration reversal has been used in some countries as an alternative to the above mentioned technologies, however at a very low scale (Van der Bruggen 2003; Nair & Kumar 2013). In some cases, hybrid desalination – the combination of membrane applications and distillation processes (or any two kinds of desalination technologies) might provide a very efficient desalination system (Thampy *et al.* 2011; Altaee *et al.* 2014; Ang *et al.* 2015).

The beginnings of RO in the USA are dated from 1959 when Srinivasa Sourirajan and Sydney Loeb developed early stage reverse osmosis membranes at UCLA, with the earliest applications on brackish groundwater in Southern Florida (UIM (Water Utility Infrastructure Management) 2009). The world's first commercial brackish groundwater RO plant was built in Coalinga, California in 1965 with a capacity of 6,000 GPD (gallons per day) (22.7 m^3/d) (UCLA 2014). The applications in Saudi Arabia followed in 1979, in China in 1990, and in 1996 both in Australia and Israel. Over the years, the global cumulative RO desalination capacity increased from 6.1 MGD (23 thousand m^3/d) in 1979 to 11 BGD (41.6 million m^3/d) in 2013. In the USA, the capacity of water treated with RO has been increasing exponentially from 26 kgal/d (98.4 thousand m^3/d) in 1979 up to 1.7 BGD (6.4 million m^3/d) in 2013. The steep increase in RO occurred for all the analyzed countries, however, at different capacity levels for each of them (GWI (Global Water Intelligence) 2013). The main reason for the rapid growth of RO was a decrease in desalination costs due to the application of the membrane technology compared to distillation processes (MED, MSF) (Molina & Casanas 2010; Peñate & García-Rodríguez 2012).

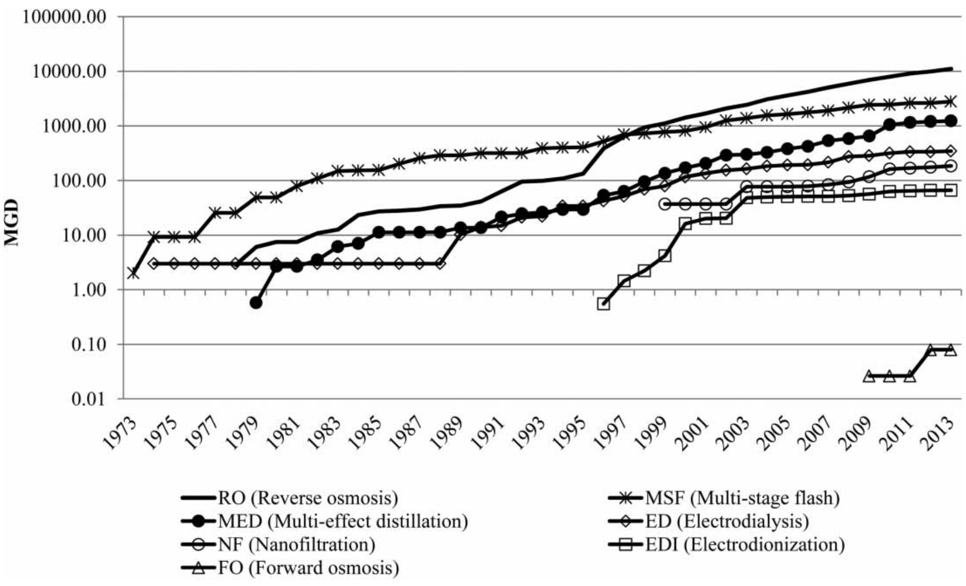

Figure 3 | Global changes in capacity of desalination plants subject to applied technology (1974–2013) (log scale). *Source:* Author's calculations based on GWI (Global Water Intelligence) (2013) data.

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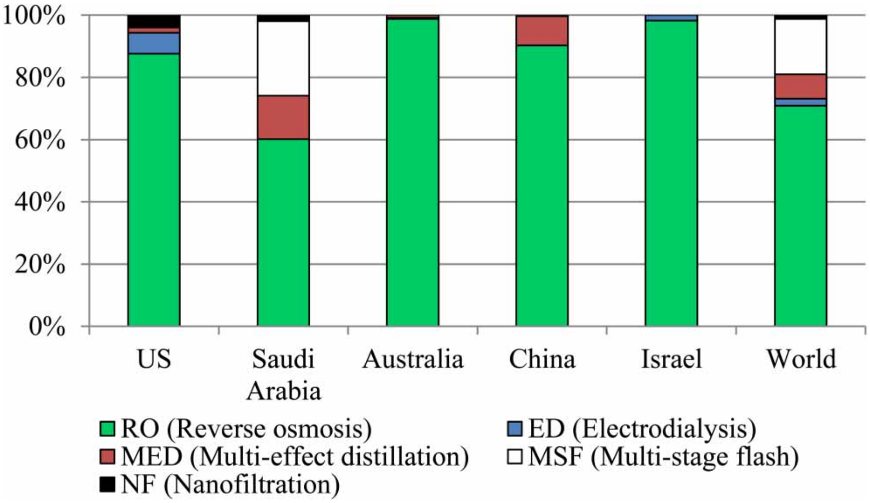

Figure 4 | Market shares of desalination technologies in the analyzed countries in 2013. *Source:* Author's calculations based on GWI (Global Water Intelligence) (2013) data. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/ws.2015.184.

As of 2013, 71% of desalinated water at a global scale was treated with RO (Figure 4). RO is predominant on the US market with its 87.6% share among all desalination technologies, 99% in Australia, 98% in Israel, and 60% in Saudi Arabia. MSF technology is still applied in Saudi Arabia (24%) due to high water salinity, which makes this technology more viable and efficient for large scale desalination in that region. MSF constitutes only 18% among desalination technologies on a global scale, while MED is applied in all analyzed countries except for Israel (Figure 4). As mentioned above, electrodialysis (ED) and nanofiltration (NF) make only a insignificant percentage among the applied desalination technologies at the global scale with 2% and 1%, respectively.

According to Voutchkov (2010a, 2010b), the desalination market is expected to grow in the future. Due to improved membrane quality, doubled or tripled membrane productivity and longer membrane life span (10–15 years in 20 years compared to 5–7 years nowadays), the energy use for seawater RO plants is expected to decrease by around 40–50%. The final water cost is also anticipated to fall by ~20% in the next 5 years. Those developments could further incentivize investments in desalination (Ghaffour *et al.* 2013). Moreover, renewable energies (especially solar, wind, and geothermal), even though too expensive at the current price levels as of 2015, are a potential solution to boosting desalination developments in the long term (Hensel & Uhl 2004; Gude *et al.* 2011; Peñate & García-Rodríguez 2012; Sarbatly & Chiam 2013; Richards *et al.* 2014; Reif & Alhalabi 2015).

Current status of desalination plants at the global and regional scale

In 2013, the global capacity of the operating (online) desalination plants amounted to 14 BGD (23 million m^3/d). Both the USA and Saudi Arabia produced desalinated water at a similar capacity level (2,037 MGD [7.71 million m^3/d] and 2,060 MGD (7.79 million m^3/d), respectively) with 1,336 operating plants in the USA and 1,324 plants in Saudi Arabia. According to GWI (Global Water Intelligence) (2013), as of 2013, three plants were under construction both in the USA and Saudi Arabia, and four plants were being constructed in China with a total capacity of 20.3 MGD (76.8 million m^3/d), 21.4 MGD (81 million m^3/d), and 23.1 MGD (87.4 million m^3/d), respectively. The production capacity of the operating desalination plants in China amounted to 970 MGD (3.6 million m^3/d) in 2013, while both Australia and Israel produced around 500 MGD (1.9 million m^3/d) of desalinated water, respectively.

Many desalination plants have been constructed due to unexpected weather events, such as drought or due to shrinking water resources. In many cases, particularly in Australia, some plants have been mothballed once aquifers and rivers were replenished after the drought period. In

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2013, the total capacity of mothballed plants in the world amounted to 149.6 MGD (0.56 million m^3/d), with 113.4 MGD (0.43 million m^3/d) mothballed capacity in Australia and 6.9 MGD (26.1 thousand m^3/d) in the USA. This translates to six mothballed plants in Australia, while two additional plants were decommissioned, three on hold, and one cancelled. Both in China and Israel only one plant has been cancelled, respectively. In Israel, five plants were reported on hold, and only two plants in Saudi Arabia. In the USA, 22 plants were decommissioned, three were cancelled, and six are on hold (author's calculations based on GWI (Global Water Intelligence) (2013) data).

Mothballing desalination plants has raised controversies and questions about the feasibility of desalination projects. Despite positive feasibility studies for those desalination plants constructed specifically with the purpose of mitigating the negative effects of drought, the costs of providing desalinated water in the wet years following the drought are much higher than the costs for freshwater from aquifers or surface water. The main reason for decommissioning desalination plants lies in technical disturbances that result in a complete reestablishment of the plant or a closure rather than replacement of specific parts or membranes. The decommissioned plants in the analyzed countries have a much smaller capacity (0.05–24 MGD) [0.1–90 million m^3/d], which again indicates that the decommissioning process did not have significant impacts on the water supply. In most cases, decommissioned plants are replaced with new plants in the same location.

The characteristics used for the presented evaluation of the leading countries in the global desalination market can directly impact the final cost of water. The relation between water salinity and desalination technology, and their impact on water costs can be clearly explained. At the same time, the analysis shows also that the capacity of production (and thus water use by different sectors) as well as the current status of the plants (including capital, operational, maintenance or plant recovery costs) can significantly affect the final water prices. Thus, the prospects and future success of desalination depend on its current developments. Positive trends in the desalination market foster private and public investments in R&D, thereby creating a solid ground for more efficient and sustainable desalination technologies in the future.

CONCLUSIONS, PERSPECTIVES, AND OUTLOOK

Previous experiences in the leading countries in the desalination market and growing interest in this technology both from the private and public sector indicate the positive developments of desalination. Desalination has proven to be a viable and successful technology in many countries around the world. Desalination costs and the price of desalinated water constitute the most critical factor in economic feasibility analyses. Recent developments show constantly declining desalination costs, mainly due to technological and efficiency improvements of the membrane filters and low energy costs in recent years and months. Prospects for desalination in terms of costs are positive, especially with the future application of renewable energies, which are anticipated to become even cheaper than traditional energy sources. Thus, desalination has the potential to become an affordable technology in an increasing number of regions and countries.

Mothballing plants, which occurred at a larger scale in Australia might create fears and questions about the economic feasibility of large desalination plants as well as social acceptance. Based on the past developments, the process of mothballing plants is rare and case specific, and is not expected to be exacerbated in the future.

While the economics of desalination is one of the most pressing constraints for technological improvements, environmental concerns have not been studied extensively enough. If they are imposed through legal frameworks, laws, regulations and/or national or transnational agreements in the future, they could pose a considerable challenge for desalination and result in a spike in desalination costs. Environmental issues have also been raised by environmentalists due to the common practices of disposing brine to surface waters or directly to the sewer, which might create potential risks for biodiversity in the river ecosystems as well as to a proper functionality of wastewater plants. While environmental questions have been raised about seawater desalination and potential impacts on marine life and ocean water salinity after a regular disposal of highly saline brine, no significant scientific impact has been found to justify those concerns. However, a congruent set of environmental standards for desalination would be helpful to avoid any potential harm to ecosystems in the first place.

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Both at the global scale and in the respective analyzed countries, municipalities use the highest percentage of the total volume of desalinated water. In the face of recurring droughts, and also due to growing population, municipal water demand is expected to increase in the years to come. Accordingly, the need for an additional water supply source, like desalination, is anticipated to increase even more. In fact, several new plants are being built in California in response to drought and with the specific aim of supplying drinking water to local communities.

Clearly, concerted policy measures are needed to foster economic efficiency and process sustainability of desalination plants in order to maintain a long-term success in this sector. Desalination can be seen as a supplemental water supply source in water portfolios, once it becomes competitive with the traditional water sources in terms of the final water prices. Even though this statement is very optimistic and will require investments in R&D, it is possible technological breakthroughs (e.g. hybrid desalination) and affordable renewable energy application could help to achieve this goal.

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