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DESALINATION:

Balancing the Socioeconomic Benefits and Environmental Costs

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GROUPE BPCE

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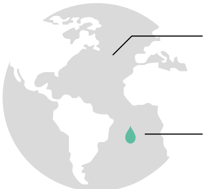
EXECUTIVE SUMMARY

DESALINATION

BALANCING THE SOCIOECONOMIC BENEFITS AND ENVIRONMENTAL COSTS



97% **OF WATER** available on earth is salty

1% **OF WORLD'S DRINKING WATER** comes from desalination

Desalination is the process of removing **SALTS AND OTHER IMPURITIES** from water to produce **DRINKING WATER**

TWO MAIN TECHNOLOGIES

THERMAL DESALINATION

Multiple Stage Flash (MSF) and Multi-Effect Distillation (MED)

Boils and evaporates salty water and condensates the resulting vapor into purified drinking water

- **HAS THE EDGE IN HOT SALINE WATER**

REVERSE OSMOSIS *(RO)*

Forces salty water through semi-permeable membranes

- **PERFORMS BETTER IN CLEANER, COOLER AND LESS SALINE WATERS**
- **ENJOYS DOMINANT POSITION IN THE MARKET WHILE STILL OFFERING POTENTIAL FOR FUTURE TECHNOLOGICAL IMPROVEMENT AND FALLING COSTS**

Desalination refers to the process of removing salts and other impurities from water to produce water that meets the quality and salinity requirements for different types of human use. The procedure consists of taking water out of seas, oceans, rivers or underground aquifers and running it through a desalination facility. Once there, intake water is either filtered through a series of membranes or evaporates and condensates while passing through a series of heating and cooling chambers. In both cases, the desalination procedure separates salty intake water into two distinct streams with very diverging characteristics: freshwater and brine. The freshwater is the very reason why people put effort and considerable amount of money into desalination assets. The desalinated freshwater is actually too pure to be drinkable straight away, it has to be remineralized first during a post treatment phase. Brine is a very different story, an unwelcome byproduct. It refers to a concentrated stream of hot, salty water containing numerous chemical products used during desalination. The common practice is to simply discharge brine back into water, which increases the temperature, salinity and chemical pollution of receiving water.

Commercially available desalination methods fall within two main categories: thermal and membrane desalination, which can be combined into hybrid with the aim of increasing operational flexibility and exploiting strengths of both technologies. Thermal desalination boils and evaporates salty water and condensates the resulting vapor into purified drinkable water. Membrane desalination methods separate salt and other impurities from drinkable water by forcing water passage through semi-permeable membranes. The two most widely used thermal-based technologies are Multiple Stage Flash (MSF) and Multi-effect Distillation (MED). The leading membrane separation desalination process is Reverse Osmosis (RO). The performance of desalination technologies is highly dependent upon local features such as water temperature and salinity, which means that comparison of desalination assets and the evaluation of their sustainability profile has to take into consideration local context. **While already advanced and scalable, desalination technologies still have potential for further improvement.** Further gains in operational efficiency are expected thanks to improving technologies. Such improvements will also bring down the production costs of desalinated water, hereby increasing its affordability and competitiveness relative to conventional water sources.

While thermal desalination technologies used to lead the market in the past, they have lost their dominant position to reverse osmosis over the past decades due to the faster technological improvement of the latter.

Thanks to rapidly falling costs, RO currently enjoys dominant position in desalination markets while still offering potential for ongoing technological improvement and further cost reductions. In terms of production costs, thermal technologies have the edge in hot saline water, while RO performs better in cleaner, cooler and less saline waters. This partially explains the persistent reliance of Gulf countries on thermal technologies, even though the current trends point to a progressive switch to RO even in this region particularly favorable to thermal-based desalination.

Designing, financing, building and operating a desalination facility is no easy task. The implied value chain is becoming increasingly complex with growing size of underlying assets, especially with RO facilities, and with the involvement of a multitude of specialized actors. As a result, the overall budgets for desalination facilities can often reach hundreds of millions of dollars. Apart from technical expertise, success of desalination projects also requires appropriate choice of financing, risk-sharing and contractual arrangements covering its operational lifetime, which usually spans two to three decades. Given the level of complexity involved in such large-scale projects, not every country in dire need of drinkable water can afford desalination. As such, desalination assets remain disproportionally concentrated in high-income water scarce countries. Over the past few decades, development of desalination assets has been achieved through PPPs (public-private partnerships) with varying degrees of risk allocation between public and private players.

The costs of desalinated water remain higher than conventional drinkable water sources due to high energy requirements of desalination and the complexity of designing, financing, building, and operating desalination assets. Consequently, desalination has to be used strategically when conventional solutions to water scarcity are not sufficient. The water production costs are influenced by a plethora of contractual, managerial and technological factors. Understanding the costs structure of desalination is a necessary condition for assessing where it is sensible to deploy such assets. The importance of consistent policies and integrated water management framework is illustrated in a case study of Singapore, which relies on desalination as one of the pillars for its water security, in conjunction with conventional water sources. The possible role of governments in bringing down costs of capital is illustrated in a case study of Israel, which has achieved some of the lowest costs of desalinated water thanks to governmental guarantees and innovative financing schemes.

From the perspective of sustainable finance, further development of desalination assets only makes sense if the associated benefits demonstrably outweigh drawbacks. For this purpose, we use the United Nations' framework of Sustainable Development Goals (SDGs) framework to highlight both the positive and negative impacts of desalination. By providing reliable source of drinkable water, desalination directly contributes to SDG 6 (Access to clean water and sanitation services) and enables socioeconomic development. Unlike conventional water sources, desalination is only marginally impacted by changing weather patterns and extreme weather events. Since climate change increases both frequency and severity of such events, desalination can serve as a source of climate change mitigation, hereby contributing to SDG 13 (Climate action). On the other hand, life below water (SDG 14) can suffer from discharge of brine of appropriate brine mitigation techniques are not put in place. Depending on project specific choices, several other SDGs can be impacted by desalination assets, either positively or negatively. Nevertheless, desalination should not be perceived as a free ticket to use water wastefully. For this reason, the local context, available alternatives and end-use of desalinated water are of an essential importance while weighting the benefits and costs of desalination. A case study of sustainable financing for desalination assets illustrates these considerations.

IN MANY WATER-SCARCE COUNTRIES,
DESALINATION IS OFTEN THE ONLY VIABLE SOLUTION
for securing a safe water supply. But the process is:

COSTLY

WATER PRODUCTION COSTS
between $0.50 to $3
per cubic meter

BUT COSTS ARE FALLING

ENERGY-INTENSIVE

between 3 and 7 kWh per cubic meter **FOR RO**,
between 6.5 and 12.5 kWh FOR MSF AND MED
(total equivalent electrical energy)

BUT ENERGY INTENSITY DECREASES

ENVIRONMENTAL IMPACTS

BUT THEY CAN BE MITIGATED
with desalination powered
by **RENEWABLES** and with **BRINE MITIGATION**

SUSTAINABLE DEVELOPMENT GOALS (SDGS)

SUSTAINABLE DEVELOPMENT GOALS

Sustainable development goals (SDGs) framework can be used to assess **socioeconomic benefits** and **environmental cost** of desalination assets

SOCIOECONOMIC BENEFITS

DIRECT

SDG 6 - Reliable source of drinking water

SDG 13 - Climate change adaptation: desalination processes are much less vulnerable to impacts of climate change than conventional water sources

INDIRECT

SDG2 - Agricultural production: produced water can be used for agricultural production in water-scarce countries

SDG7 - Clean energy: desalination plants can contain adjacent clean power plants

SDG8 - Economic growth

SDG9 - Industry, innovation & infrastructure

SDG11 - Sustainable cities and communities, especially in coastal areas in water-scarce countries

ENVIRONMENTAL COSTS

SDG3 - Air pollution related to combustion of fossil fuel, since numerous countries using desalination still rely heavily upon fossil fuels

SDG13 - Carbon intensity of fossil fuel-powered desalination

SDG14 - Environmental damage: discharged brine increases the temperature, salinity and chemical pollution of receiving water

IT OPENS WAYS FOR FINANCING DESALINATION ASSETS WITH EITHER **"SOCIAL"** OR **"SUSTAINABLE" FINANCIAL INSTRUMENTS**.

Whilst the benefits of desalination are socioeconomic, its drawbacks are mainly of environmental nature. The direct environmental impacts result from the discharge of brine back into water. Brine tends to be hot, salty and contains chemicals, which entails a variety of negative impacts upon marine life and aquatic ecosystems. Nevertheless, there are means to mitigate these impacts. Several technologies can be readily used to make brine less harmful. Computer modelling can be used to determine the optimal structure of brine discharge infrastructure, taking into consideration elements such as characteristics of underwater currents and distribution of marine life to find the optimal spots for brine discharge and the use of diffusers in some cases. Furthermore, brine can also be made less harmful before discharge, for instance through neutralization of some chemicals used during desalination processes. Finally, brine itself can be used as a source of minerals or salt. Moreover, there are also indirect environmental impacts related to high energy intensity of desalination. Since numerous countries using desalination still rely heavily upon fossil fuels for power generation purposes, desalinated water is indirectly responsible for air pollution and greenhouse gas emissions. However, since desalination plants are often collocated with power plants, these drawbacks can be remediated by replacing the adjacent power plant with a clean energy source.

This study proposes a framework for evaluating the sustainability credentials of desalination assets using both quantitative and qualitative indicators as well as several context-specific aspects. We identify four main categories related to socioeconomic benefits & environmental costs of desalination and four main key performance indicators (KPIs) focusing on the environmental performance of desalination assets. These KPIs can be used to assess the efficiency and performance of desalination assets relative to their peers and available alternative means of obtaining drinkable water. The key caveat with benchmarking is that the performance of desalination technologies is highly dependent on regional parameters such as water temperature and salinity. Consequently, the assessment of **the environmental sustainability performance of desalination facilities must be context-based, with regional benchmarks subject to data availability.**

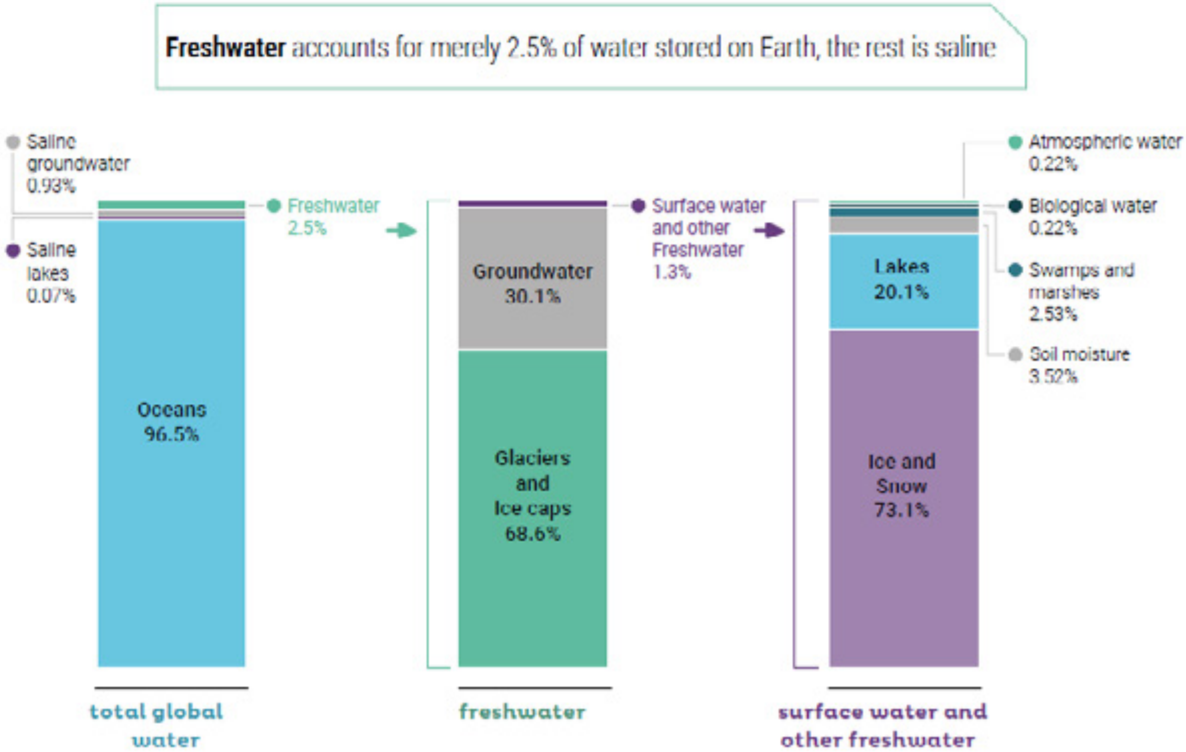
Desalination technologies can enhance prospects for sustainable development in certain regions in dire need for reliable drinkable water source. Nonetheless, such advanced technology cannot substitute for neither the institutional capacity and political will to implement water efficiency measures nor the social willingness to use water sensibly. While there are clear socio-economic benefits from a reliable and climate resilient water source such as desalination, efficient water use should be a pre-requisite for construction of desalination facilities. **Without first tackling the structural problems related to wasteful water use practices and inefficient water management institutions, desalination risks to amplify existing inefficiencies by simply providing an additional water source to fuel unsustainable growth rather than sustainable development.**

CHAPTER 1

Making sense of desalination: technological, financial and economic aspects of desalination assets

A. MAKING SENSE OF DESALINATION: TECHNOLOGICAL, FINANCIAL AND ECONOMIC ASPECTS OF DESALINATION ASSETS

Figure: Almost 97% of global water endowment can potentially be used as an input for desalination



Source: United Nations

Desalination refers to production of drinkable water from seawater[1] (typical salinity ranging from 30,000 to 44,000 milligrams per liter) **and from brackish water**[2] (salt content below 10,000 milligrams per liter). While desalination of brackish water is less expensive, but the source itself remains limited and already almost fully used in arid regions (World Bank, 2019). Oceans, however, seem like an unlimited desalination source as they contain almost 97% of the global water endowment, as illustrated by the figure above.

A recent global study surveying the state of desalination by Jones et al. (2019) found that there were 15, 906 desalination plants located in 177 countries in 2019. Combined, they produce 95 million cubic meters of desalinated water every day and their operations

1. Seawater salt content ranges between 30,000 milligrams per liter and 50,000 milligrams per liter.
2. Brackish water has salt content of less than 10,000 milligrams per liter.

result in a by-production of 141.5m cubic meters a day of brine, a hot salty sludge containing chemicals. **While a growing source of water supply, desalination still only accounts for around one per cent of the world's drinkable water** (World Bank, 2019). These figures also highlight the main challenge of desalination from the environmental perspective: the amount of brine (an unwanted and environmentally harmful by-product) exceeds the production of drinkable desalinated water by up to 50%. Out of the 95 million cubic meters of desalinated water produced every day, 62% is used for human consumption and another 30.2% is used for industrial purposes.

Desalination is a rapidly expanding field undergoing swift technological evolution. The main purpose of this study is to propose a framework for the evaluation of the sustainability of desalination assets. Any credible proposition in this direction has to be based on a detailed understanding of different desalination technologies currently available at a commercial scale: their performance, expected future development and environmental impact. Therefore, this part starts with a comparative review of commercially available desalination technologies.

1. DESALINATION TECHNOLOGIES

This section presents the main commercially available desalination technologies. The mechanisms of each technology are explained, and a particular attention is paid to the set of external factors influencing the performance of the desalination process. This understanding is crucial for a proper benchmarking of the performance and impacts of different desalination plants. By doing so, we lay the foundation of our framework for evaluating the economic, environmental and social aspects of desalination assets.

Generally speaking, desalination plants combine two key components: a desalination unit producing the desalinated water and an adjacent power plant supplying the necessary energy for the process. Water intake facility, usually located in the open sea, ensures a continuous supply of salty water. Before the desalination process itself takes place, seawater has to be pre-treated to avoid damage to the desalination facility. The pre-treatment consists of filtration to prevent mechanical damage to the facility and of addition of various chemicals to ensure that water is in an appropriate state to be treated. Once the seawater is in a suitable state, it can enter the desalination process itself, which is discussed in detail in the following section. This is however not all. The desalinated water is so pure that making it useful for human use requires a post-treatment procedure. The post-treatment of desalinated water includes re-mineralization, disinfection and neutralization or stabilization. Depending on the end use of desalinated water (drinkable, industrial or irrigation uses), more emphasis can be put on the remineralisation, pH adjustment or disinfection (Cohen et al., 2017). The permissible levels[3] of different contaminants present in desalinated water are specified in the World Health Organization (WHO) *Guidelines for Drinkable Water Quality.*

1. AN OVERVIEW OF DESALINATION TECHNOLOGIES

Desalination technologies can be divided between commercially available and those in the R&D phase. There are currently two[4] main desalination technologies: thermal and membrane technologies. Thermal desalination refers mainly to **Multiple Stage Flash (MSF)** and **Multiple Effect Desalination (MED)** technologies. The membrane separation processes refer to **Reverse Osmosis (RO),** which is the technology currently dominating the desalination market. Due to the widespread use of RO with seawater as input, the expression **Seawater RO (SWRO)** is frequently used in relevant literature and project documentation.

THERMAL DESALINATION: MULTISTAGE FLASH DISTILLATION AND MULTIEFFECT DISTILLATION

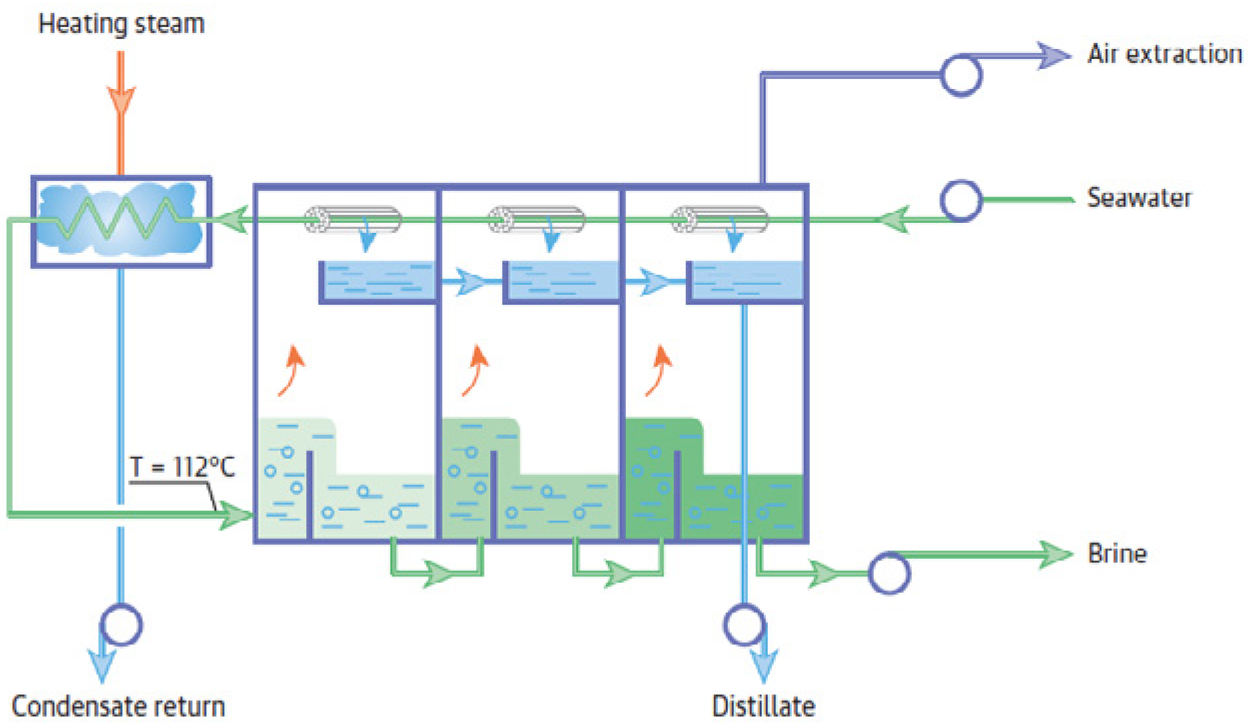
Thermal technologies apply heat to boil and vaporise water, which is then cooled and condensates into pure water. The repeated process of boiling, evaporating and condensing removes most salts and impurities. Two most commonly commercially used thermal technologies are Multiple Stage Flash (MSF) and Multiple Effect Desalination (MED) technologies, described in detail below.

Multiple Stage Flash (MSF) desalination is based upon a succession of stages. As the figure below (World Bank, 2019) illustrates, seawater passes through a series of chambers, each with decreasing pressure and temperature (from hot to cold). Seawater is brought in tubes (upper right side of the schema) where it gets warmed up by water vapour (vapour forms at each stage of this process). This

3. For illustration, the most important contaminant in terms of health and environmental impact is boron, with WHO guideline value at 2.4 mg/l (WHO, 2011). Bromide is largely present in seawater and not completely removed by the desalination procedures. WHO (2011) estimates allowable value in the range of 6 mg/l.

4. For completeness, there also other available desalination technologies. For instance, EDR and vapor-compression distillation. However, they only account for a very small share of the desalination market (World Bank, 2019). Consequently, these are left outside the scope of this study.

Schematic representation of Multiple Stage Flash (MSF) desalination



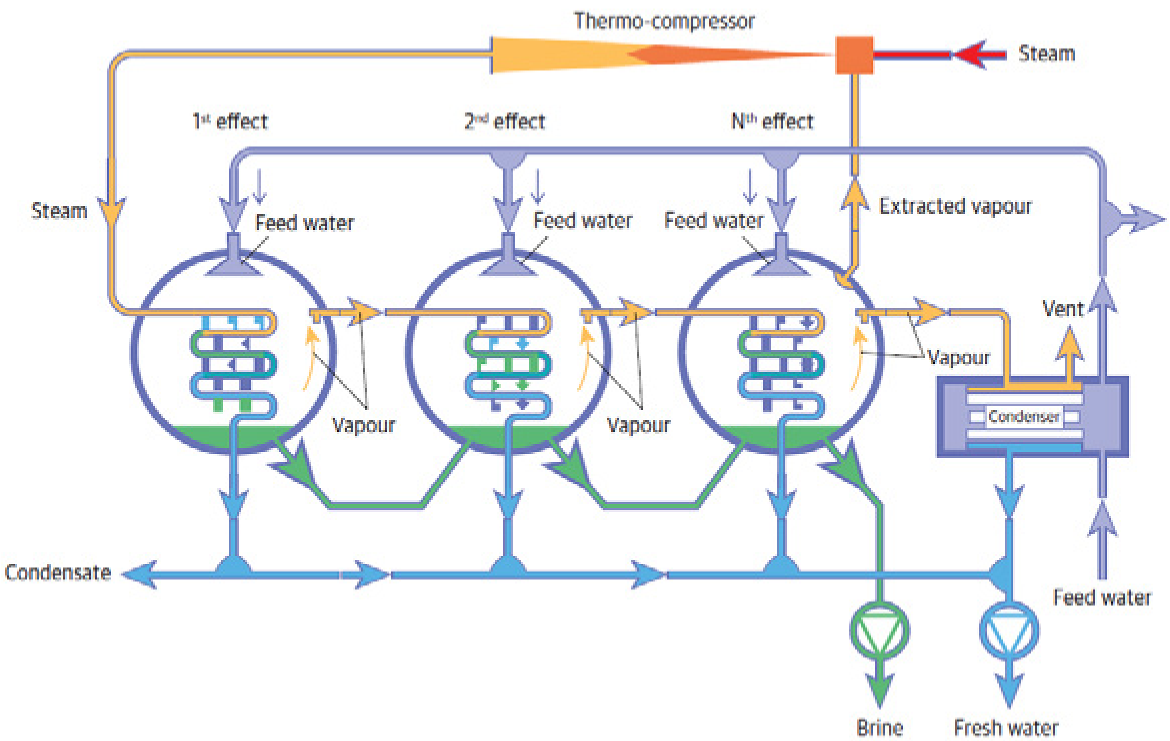
Source: World Bank (2019)

passage from each chamber to another increases seawater temperature from ambient sea temperature levels towards that of the heater (upper left corner of the schema). When seawater flows through the heater, it receives additional heat. After passing through heater, seawater is brought to the bottom of the hottest chamber (the one most to the left in schema). This is the first stage of the multistage flash distillation. Due to its recent passage through the heater, seawater is overheated relative to temperature and pressure condition in the chamber. To reach an equilibrium with the conditions in the chamber, water will immediately release heat and vapor. This process is known as "flashing", hence the name of this desalination technique. The vapour condensates into fresh water (this happens on the water tubes situated in the upper part of the chamber). This process takes place again and again until the last, coldest stage (represented by the chamber on the right end of the schema). The efficiency of heat use and reuse in this procedure depends on the number of stages involved. At the last stage, the freshwater which has build-up at each stage is finally extracted as schematized by the blue downward sloping flow in the right chamber (with a blue flash saying *"distillate"*). However, **fresh water is not the only product that builds up from one chamber to another and has to be extracted from the last chamber: this is also true for brine.** The manner in which brine is treated and disposed of is crucial for the overall sustainability profile of desalination assets, as we extensively discuss in the last section of this study.

The Multieffect distillation technology (MED), also uses the evaporation process. Just like with MSF, MED brings seawater through a succession of chambers, each with a lower pressure. However, **unlike MSF which only extracts freshwater at the very last stage, MED extracts freshwater out of each chamber.**

The process starts with the instruction of feedwater and hot steam into the first chamber (represented as first from the left in the figure below). As the feedwater (represented in dark blue in the figure below) sprayed into the chamber absorbs the heath from the steam, it evaporates. This vapor enters the next chamber through a tube (represented by a yellow flash in the middle of the figure) and the whole process repeats itself: vapor from the previous chamber condensates in the next chamber, this releases heath and results in a (partial) evaporation of the seawater sprayed there from the top. **Each time, the fresh water obtained in pumped out of the chamber** (represented by light blue color in the figure below). The brine, however, passes from one chamber to another (as indicated by green tubes and flashes indicating the direction) **and is only extracted in the last chamber** at the very end of the process.

Schematic representation of Multieffect distillation (MED) desalination



Source: World Bank (2019)

Furthermore, the efficiency of the MED desalination can be enhanced by installing a thermal vapor compressor (TVC). A TVC unit can be connected to the last chamber to extract some of its steam (schematized by an upward sloping yellow flash ***"extracted vapour"***) for reuse: this steam is mixed with the externally-sourced steam (red and yellow flashes on the top of the figure above) and serves as a source of heating for the first MED chamber (the one in the left corner of figure above). Since this efficiency enhancement reduces energy costs, MED technology is frequently used with TVC according to the World Bank (2019) data.

While the two thermal desalination technologies described above used to be the main players in the earlier history of desalination, the position of market leader has been taken over the past few decades by a competing technology: Reverse Osmosis based upon membrane rather than thermal desalination.

MEMBRANE DESALINATION: REVERSE OSMOSIS

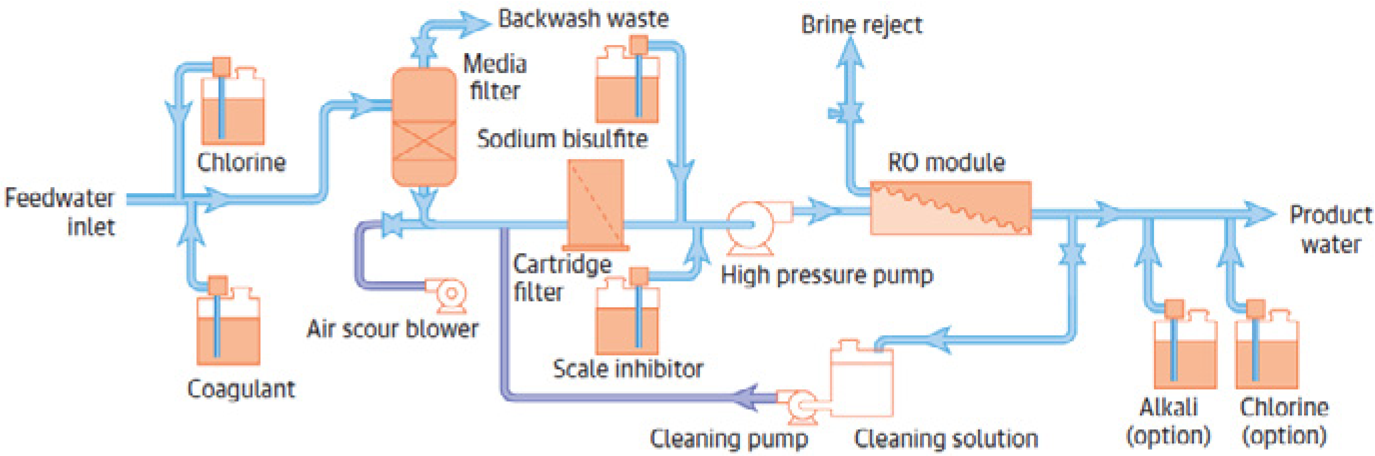
Membrane-based technologies refer mainly to RO.[5] Due to the widespread use of RO with seawater as input, the expression Seawater RO (SWRO) is frequently used.

RO process is based on overcoming the osmotic pressure of salty water. As the name suggests, this process is the opposite of what happens naturally in osmosis[6]: saline water is put under a pressure superior to osmotic pressure and forced to flow through a membrane which holds back salts and other impurities. Reverse osmosis is widely used both for the production of potable water and in other industrial processes since it can remove various types of dissolved entities from water, chemical and biological alike.

A schematic representation of RO technology is provided in the figure below (World Bank, 2019). The process of reverse osmosis takes place in separate RO modules (represented in the center of the figure below). **A high-pressure[7] pump is used to force saline water to**

5. Moreover, other membrane technologies apart from RO are also currently in use, though accounting only for a limiting market share. Those include Electro Dialysis (ED) and Electro Dialysis Reversal (EDR). These two techniques were demonstrated to work particularly well with brackish water. Both produce desalinated water by applying an electrical field across a set of cationic or anionic pairs of membranes. This causes the transfer of ions throughout the membrane, leaving desalinated water as a product.
6. Osmosis refers to the movement of water from one area to another, depending on the concentration of solute (that can be atoms, molecules, ions dissolved in the water)
7. Saline water is forced against the semipermeable membrane at 65 to 75 times the atmospheric pressure (World Bank, 2019).

Schematic representation of Reverse Osmosis (RO) desalination



Source: World Bank (2019)

flow through the semipermeable membranes designed to retain dissolved salts and other impurities on the one side while allowing freshwater to pass on the other side. As such, the RO module produces two separate streams: fresh product water and brine. The produced drinkable water then passes through post-treatment phase, just like in the case of thermal desalination to meet local drinkable water quality standards set out by regulatory requirements[8] . Brine is extracted separately and should be treated and discharged in a manner which attenuates its environmental impacts, as we will discuss in the last part of this report.

A relative weakness of RO desalination relative to thermal processes is the vulnerability of membranes. The membranes used for reverse osmosis are very vulnerable to the presence of suspended solids, microorganisms and mineral scaling compounds (World Bank, 2019), which is why the figure above contains a long succession of special facilities (between feedwater intake in the left and the RO module in the middle) which are not required for thermal desalination. These facilities ensure a range of pre-treatment processes and technologies which are needed to make sure that the intake water does not damage the fragile RO membranes.

The main advantage of RO relative to thermal desalination lies in lower energy requirements. Another advantage is the flexibility of RO membranes in terms of where they can operate. When it comes to desalination, both seawater and brackish water can be turned into drinkable water with the use of RO membrane: we refer to SWRO and BWRO, respectively. Furthermore, RO membranes are also used in wastewater treatment due to their ability to remove not only salt but also various unwanted elements such as bacteria, viruses and organic contaminants (World Bank, 2019).

HYBRIDIZATION OF THERMAL AND MEMBRANE DESALINATION

Hybrid desalination facilities combine membrane RO and thermal (MSF or MED) desalination technologies, usually in conjunction with an adjacent power plant. Hybrid solutions are appropriate for regions with high inter-annual variability of demand for either water or power. Under such circumstances, a hybrid plant can switch between thermal and RO desalination according to energy prices, **choosing whichever technology able to meet required water demand in the cheapest way.** World Bank (2019) recalls that hybrids require careful planning in order to balance both water and power supply at the least cost at any given time: as a consequence, desalination hybrids are usually part of newly-build IWPPs ("independent water and power projects" – complexes combining both water and power production) but tend not to be used for retrofitting of existing power plants.

Having reviewed the leading commercially available desalination technologies, we now turn our attention to parameters allowing us to compare their relative performance in terms of efficiency, energy consumption and production costs.

8. For instance, the adjustment of pH or remineralisation

A SET OF PARAMETERS TO ASSESS THE PERFORMANCE AND EFFICIENCY OF DESALINATION ASSETS

Several parameters can be used to evaluate the performance and efficiency of desalination technologies. In each case, context-specific factors, such as temperature and salinity of feed water or the stringency of health regulations for drinkable water in given jurisdiction, **will have considerable influence upon the final value of these parameters**. For this reason, it is advisable to **benchmark parameters to local and regional peers rather than to global average, if data availability permits.**

Recovery ratio is a simple measure of efficiency of desalination processes which can be used for comparison of different technology choices. Nevertheless, there are several factors which make comparison difficult. Recovery ratio (RR) is the *"volumetric processing efficiency of the purification process which indicates the proportion of intake water that is converted into high quality (low salinity) water for sectoral use"* (Jones et al., 2019). As table below shows, amongst the commercially available technologies, RO has higher recovery ratios than thermal technologies (MSF, MED). Several technologies in the right part of table 8 have far higher recovery ratio but are currently not commercially viable options – these are nanofiltration, electrodialysis, electrodialysis-reversal and electrodeionization. Furthermore, RR also depends on the quality of feed water which serves as the input for desalination: the difficulty and expensiveness of desalinating with high RR increase with the salinity and temperature of feed water.

Estimation of recovery ratios for different combinations of desalination technologies and feed water types.

Recovery ratio of different feedwater-technology combinations producing desalinated water.

Feedwater type	Reverse Osmosis	Multiple Stage Flash	Multiple Effect Desalination	Nanofiltration (emerging technology)	Electrodialysis	Electrodeionization	Electrodialysis Reversal
Seawater (SW)	0.42	0.22	0.25	0.69	0.86	0.90	
Brackish (BW)	0.65	0.33	0.34	0.83	0.90	0.97	0.90
River (RW)	0.81		0.35	0.86	0.90	0.97	0.96
Pure (PW)	0.86	0.35		0.89	0.90	0.97	0.96
Brine (BR)	0.19	0.09	0.12		0.85		
Wastewater (WW)	0.65	0.33	0.34	0.83	0.90	0.97	

Source: Jones et al. (2019).

The efficiency and economic viability of different desalination technologies depend on what kind of water is used as an input. Consequently, few technology-feed water combinations are far more widely used than others: just eight combinations of technology-feed water account together for more than 90% of the global production of desalinated water (Jones et al., 2019). Those combinations are SW-RO, BW-RO, SW-MSF, SW-MED, RW-RO, WW-RO, BW-ED, RW-ED.

The advantage of RO is that the technology is economically viable with several types of feed water. In their recent survey of current desalination assets worldwide, Jones et al. (2019) found that 50% of desalinated water produced by RO desalination technologies originates from SW and another 27% from BW, accounting respectively for 34% and 19% of the global desalination capacity. **Conversely, thermal technologies are used almost exclusively to desalinate highly saline[9] types of feed water:** SW constitutes 99.9% and 92% of feed water used for MSF and MED desalination, respectively.

Energy consumption of desalination is another important aspect to consider when assessing the performance of different desalination technologies. Table below presents the energy consumed by different desalination methods with seawater as an input. When benchmarking different desalination technologies, it is crucial to keep in mind that RO uses only electrical energy both[10] MSF and MED desalination plants require electrical as well as thermal energy. Therefore, **the assessment of energy consumption of both technologies requires a common unit of comparison: total equivalent electrical energy (in kWh) per cubic meter of water produced.**

9. This is considered as 'low quality' type of feed water.
10. However, MED has lower energy requirements relative to MSF (Shahzad et al., 2017).

Estimation of energy consumption of the leading commercially available desalination methods with seawater as an input

Energy Consumption of Seawater Desalination Methods (World Bank, 2019)				
Desalination Method	Multistage Flash Distillation (MSF)	Multiple Effect Distillation (MED)	Multiple effect distillation with thermal vapor compression (MED-TVC)	Seawater Reverse Osmosis (SWRO)
Electrical energy (kWh/m3)	3.4–4.5	1.5–2.5	1.2–1.8	3–7
Electrical equivalent of thermal energy (kWh/m3)	5.6–8.0	5–8.5	4.0–5.5	None
Total equivalent electrical energy (kWh/m3)	9.0–12.5	6.5–11	5.2–7.3	3–7

Source: World Bank (2019)

The performance of desalination technologies is highly dependent upon local context due to the strong influence of factors such as water quality, temperature and salinity. Keeping this variability in mind, the following table presents a global overview of the usual range of the main operational and performance parameters of different desalination technologies, based on the data collected by Shahzad et al. (2017). **The range of parameter values in some cases reflects the high context-dependency.** One should keep in mind that even two identical desalination plants located in very different environments would perform differently. Moreover, the two last columns in red emphasize that these technologies are not commercially available.

Summary of operational and performance parameters of different desalination processes

Summary of operational and performance parameters of different desalination processes (Shahzad et al., 2017)						
Parameters	Multiple Effect Distillation (MED)	Multiple effect distillation with thermal vapor compression (MED-TVC)	Multistage Flash Distillation (MSF)	Seawater Reverse Osmosis (SWRO)	Membrane Distillation (MD)	Hybrid Multiple Effect Distillation (MED) + Adsorption Desalination (AD)
Typical plant size (×1000 m3/day)	5–15	50–100	50–70	Up to 128	24	50–100
Unit capital cost ($/m3/day)	2000	1860	1598	1313	1131	2200
Operating temperature (°C)	65–70	65–70	90–110	Ambient	60–90	65–70
Thermal energy (KWhther/m3)	40–65	50–80	53–70	NA	100	30–40
Electric energy (kWhelec/m3)	2.0–2.5	2.0–2.5	2.5–5.0	4.0–6.0	1.5–3.65	2.80
Cost of water ($/m3)	0.52–1.01	1.12–1.50	0.56–1.75	0.26–0.54	1.17–2.0	<0.48
Technology growth trend	High	High	Moderate	High	R&D	R&D
Environmental impact	Discharge is 10–15 °C hotter than ambient, TDS increase of 15–20%	Discharge is 10–15 °C hotter than ambient, TDS increase of 15–20%	Discharge is 10–15 °C hotter than ambient, TDS increase of 15–20%	Brine discharge at ambient temperature, TDS increase of 50–80%	Discharge is 10–15 °C hotter than ambient, TDS increase of 15–20%	Discharge is 10–15 °C hotter than ambient, TDS increase of 20–30%
CO2 emission (kg/m3)	7.0–17.6	7.0–17.6	15.6–25.0	1.7–2.8	7.0–17.6	5.0–10.0
Recovery rate (%)	15–50%	15–50%	15–50%	30–50%	60–80%	60–80%

Note: TDS = Total dissolved solids, a measure of water salinity.
MED + AD hybrid cycle values (last column) are estimated on the basis of 10 m3/day pilot installed in KAUST, Saudi Arabia

Source: Shahzad, M., Burhan, M., Ang, L. and Ng, K. (2017). Energy-water-environment nexus underpinning future desalination sustainability. Desalination, 413, pp.52-64.

Several important points can be made based on the information contained in table below. Both MD and hybrid MED+AD desalination technologies show significantly higher recovery ratios than commercially available technologies, but they remain in the R&D phase. Among all the commercially available technologies, **SWRO has the lowest carbon footprint and the highest electrical energy consumption yet it does not require any thermal energy input,** unlike thermal based competitors, which require both energies as an input. This point will be crucial for proper comparison of the performance of different technologies, which is the main concern of the final section of this study. One can also note the differences in plant sizes and in capital costs, these aspects are further developed in section 1.2.

Having seen the technologies currently present in the desalination market, let us have a closer look at their past evolution and current geographical distribution in order to elucidate the socioeconomic importance of desalinated water in certain regions.

2. A BRIEF HISTORY AND GEOGRAPHICAL DISTRIBUTION OF DESALINATION TECHNOLOGIES

While RO currently enjoys the position of the market leader, it has not always been the case. As the following section shows, desalination market is driven by technological innovation and economies of scale. Both factors can help improving the sustainability profile of desalination assets in the future.

THE MARKET SHARE OF DESALINATION TECHNOLOGIES: FROM THE PREEMINENCE OF THERMAL DESALINATION TO THE CURRENT LEADERSHIP OF REVERSE OSMOSIS

A closer look at the evolution of the desalination market reveals **a shift away from previously dominant thermal technologies in favor of the membrane-based RO desalination.** This shift has been made possible by the speed of recent technological improvements in RO technologies which outpaced the improvements of their thermal peers.

During the early years of desalination, thermal technologies reigned supreme: before the 1980s, two main thermal technologies – MSF and MED – accounted for 84% of desalinated water globally. At first, the industry leaders were MSF technologies. However, over time the MSF lost ground to both MED and RO methods thanks to their faster technological developments. MED used to require larger CAPEX and OPEX compared to MSF, but those limitations were eventually overcome, and MED got into a position where it can compete with MSF.

Over time, RO rose to its current prominence thanks to continued technology improvement. The technological **improvement of membrane technologies,** especially RO, shifted the balance. Since 2000, the quantity of RO plants and their production capacity have risen exponentially while the use of thermal technologies has enjoyed merely marginal growth (Jones et al., 2019). The advantage of RO is that it only requires electricity; no thermal energy is needed unlike for competing technologies. However, the costs of RO desalination can exceed those of thermally driven processes depending on the quality of input water: the high concentration of algae, as well as high water turbidity, require extensive pre-treatment, which raises costs (Shahzad et al., 2017). According to the data compiled by the World Bank (2019), **SWRO represented [11]around 63% of the global desalination capacity, far ahead of MSF (23%) and MED (8%),** the remaining 6% represents mainly hybrid desalination technologies described in section 1.1.1.

GLOBAL DISTRIBUTION OF DESALINATION ASSETS AND COMMON CHARACTERISTICS OF COUNTRIES USING DESALINATION

Given the relatively high costs of desalination relative to conventional water supply methods, the technology is used strategically in specific markets. Desalination is particularly interesting in regions where water supply and demand share certain characteristics. On the supply side, this means a lack of available freshwater and the need to bring it long distances and/or high elevations. On the demand side, desalination is a good match for markets requiring completely reliable water of high quality while having the ability to afford to pay for it.

For those reasons, desalination plants tend to be located in relatively affluent water scarce countries. The location of a desalination facility is itself crucially important for the economic feasibility of the project. Since transporting water is expensive (as illustrated by the table below), **a typical desalination plant is situated close to the water source and near the end-user market. In practical terms, this means in proximity to coastal cities or coastal industrial zones.**

An illustration of the influence of distance and elevation upon water transport costs for selected cities

Cost of Water Transport to Selected Cities (World Bank, 2019)

City, country	Distance (km)	Elevation (m)	Transport cost (US cents/m3)
Beijing, China	135	100	13
New Delhi, India	1,050	500	90
Bangkok, Thailand	30	100	7
Riyadh, Saudi Arabia	350	750	60
Harare, Zimbabwe	430	1,500	104
Crateus, Brazil	240	350	33
Ramallah, Palestine	40	1,000	54
Sana, Yemen	135	2,500	138
Zaragoza, Spain	163	500	36
Phoenix, U.S.	280	320	34

Source: World Bank. 2019. "The Role of Desalination in an Increasingly Water-Scarce World." World Bank, Washington, DC.

Water transportation costs depend significantly upon both distance and elevation separating the production and consumption locations. While the relatively short distance and small elevation difference between Bangkok and its water source results in low water transportation costs of 7 US cents per cubic meter of water, the situation is very different for some other major cities. For instance, water

11. In 2014

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used by New Delhi has to be transported over 1 050km, which results in transportation costs of 90 US cents per cubic meter. **High elevation can also increase costs significantly** as can be seen in the case of Sana, whose elevation of 2,5km results in water transportation costs of 138 US cents per cubic meter even though the transportation distance is only 135km. It should be noted that the costs provided in the table below are not static. Transport costs depend upon energy prices and the continuously falling desalination costs may[12] render local desalination the preferred option in the future for areas currently relying on water transports.

Another restriction for the potential list of countries that make a good match with desalination is the sheer scale of the projects themselves. Desalination plants are large since they benefit significantly from economies of scale (World Bank, 2019). Nevertheless, the optimal plant size differs for each desalination technology. For illustration, **MSF desalination facilities tend to have capacity in the range of 27.3 MLD to 32.7 MLD** yet the largest MSF plant Shuweihat in the United Arab Emirates has the capacity of 75.7 MLD. Commercially used **MED desalination facilities are composed of individual units with capacity between 3 MLD and 5 MLD** yet the plant Sharjah (again in the United Arab Emirates) has the largest per unit capacity of 23 MLD per unit. For illustration, the two largest operational MED-TVC plants are both located in the Middle East (World Bank, 2019). The Al Jubail facility (Saudi Arabia) and Az Zour North 1 plant (Kuwait) have capacities of 800-MLD and 486-MLD, respectively. **For SWRO, the optimal plant size was historically between 100 MLD** and 200 MLD. Beyond that capacity, the benefits of economies of scale decline for SWRO facilities due to additional complex requirements related to operations, treatment and flow distribution (World Bank, 2019). For this reason, largest SWRO desalination plants are usually build as several parallel desalination systems with the abovementioned optimal capacity[13] for each, sharing common water intake and brine discharge infrastructure.

Taking into consideration the sheer scale of desalination facilities, the country or municipality or other public authority which commissions the project must be able to handle the development, financing and management of large-scale infrastructure projects. Due to the complexity of such tasks, they tend to be carried out in conjunction with private companies. The exact distribution of tasks between public and private entities is determined by the choice of procurement method, which will be explored in detail in the following section (1.2.1). These requirements imply that countries wishing to use desalination as a source of drinkable water need to have a certain level of public sector expertise and financial means, which makes desalination assets beyond the means of lower middle & low income countries (as illustrated by the table below), several of whom are suffering from water scarcity. Considering these constraints, it logically follows that **most desalination assets are concentrated in high income coastal countries facing high levels of water scarcity. 67 % of all desalination facilities accounting for 70,5% of the global desalination capacity are situated in high-income countries while low-income countries possess so few facilities that they only account for 0.1% of the total desalination capacity** (Jones et al., 2019)

Breakdown of the global desalination capacity and the number of desalination plants by country income level

Number, capacity and global share of operational desalination plants by country income level			
	Number of desalination plants	Desalination capacity (million m3/day)	Desalination capacity (%)
Global	15,906	95.37	100
Income level			
High	10,684	67.24	70.5
Upper middle	3075	19.16	20.1
Lower middle	2056	8.88	9.3
Low	53	0.04	0.1

Source: Jones, E., Qadir, M., van Vliet, M., Smakhtin, V. and Kang, S. (2019). The state of desalination and brine production: A global outlook. Science of The Total Environment, 657, pp.1343-1356.

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Furthermore, a breakdown of global desalination capacity and the number of desalination plants by region (provided in the table below) reveals that **the main market for desalination is the rich and water scarce Middle East[14] , the leading players being Saudi Arabia and the United Arab Emirates,** accounting for 15.5% and 10.1% of global desalination capacity, respectively. Overall, 47,5% of global desalination capacity is located in Middle East and North Africa, followed from some distance by East Asia and Pacific region (18,4%), North

12. Assuming that desalination costs fall sharper than energy prices.
13. That is between 100 MLD to 200 MLD.
14. The prevailing choice in the Middle East is the set of thermal desalination technologies (MED, MSF) using sea water as feed water. Saudi Arabia is an exception as it operates a large quantity of inland RO desalination facilities using brackish water as feed water. Outside the Middle Eastern region, very few thermal plants operate, and RO dominates the market across various types of feed water.

America (11,9%) and Western Europe (9,2%). Conversely, **the water scarce Sub-Saharan Africa accounts for a strikingly low share of global desalination capacity: merely 1,9%** as the complexity and costs of desalination make this option infeasible.

Breakdown of the global desalination capacity and the number of desalination plants by region

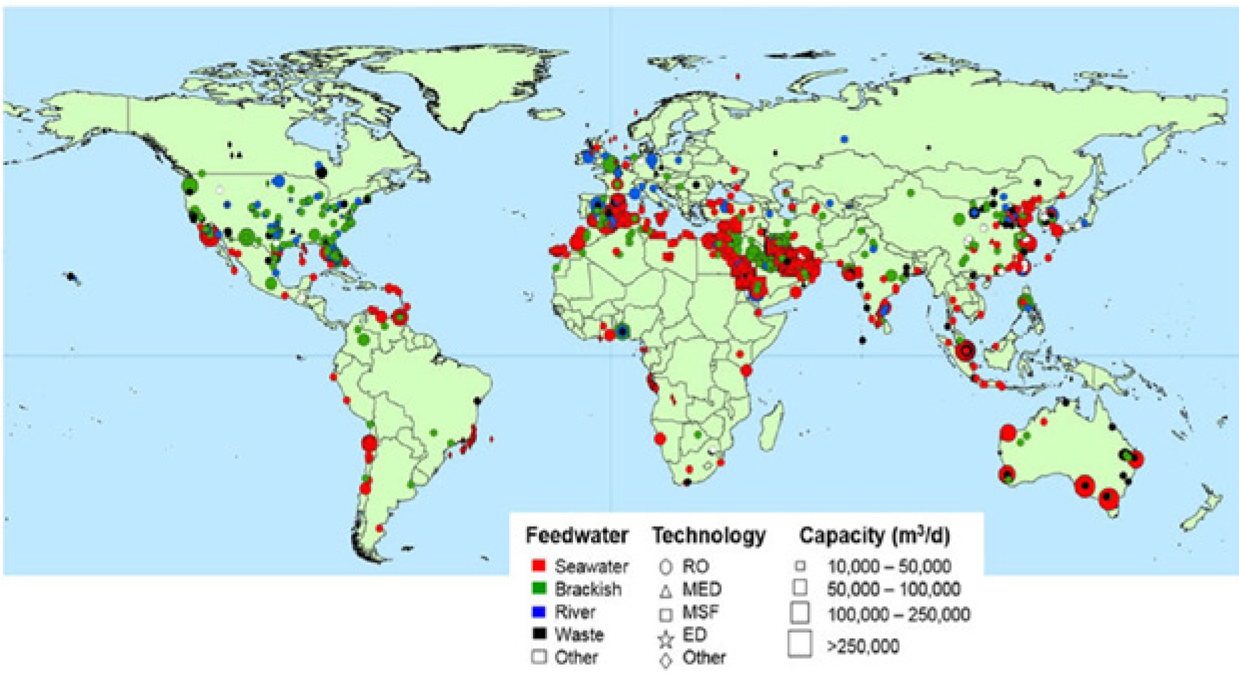
Number, capacity and global share of operational desalination plants by region

	Number of desalination plants	Desalination capacity (million m3/day)	Desalination capacity (%)
Global	15,906	95.37	100
Geographic region			
Middle East and North Africa	4826	45.32	47.5
East Asia and Pacific	3505	17.52	18.4
North America	2341	11.34	11.9
Western Europe	2337	8.75	9.2
Latin America and Caribbean	1373	5.46	5.7
Southern Asia	655	2.94	3.1
Eastern Europe and Central Asia	566	2.26	2.4
Sub-Saharan Africa	303	1.78	1.9

Source: Jones, E., Qadir, M., van Vliet, M., Smakhtin, V. and Kang, S. (2019). The state of desalination and brine production: A global outlook. Science of The Total Environment, 657, pp.1343-1356.

The figure below representing the distribution of large desalination plants across the globe illustrates the points made above: **desalination assets are overwhelmingly located in coastal areas of affluent water-scarce countries, seawater serves as the main input for desalination and reverse osmosis is the undisputed market leader.** It is noteworthy that both the USA and Saudi Arabia also use reverse osmosis with brackish water as an input and similar trend, although to a lesser extent, has been observed in China.

Global distribution of large desalination plants by capacity, feed water type and desalination technology



Source: Jones, E., Qadir, M., van Vliet, M., Smakhtin, V. and Kang, S. (2019). The state of desalination and brine production: A global outlook. Science of The Total Environment, 657, pp.1343-1356.

While it is clear that desalination is an essential component of water management policies in several countries, **this advanced technology producing drinkable water from seemingly unlimited sea resources is a double-edged sword. While some of the countries making use of desalination lead the world in terms of water use efficiency, others are amongst the least efficient water users.**

The following section provides a detailed overview of the financial and economic aspects of desalination. The influence of external factors upon the cost of desalinated water is considered in detail since water affordability is an important aspect to consider from the social standpoint and constitutes the main argument in favor of desalination assets. The key point about desalination is that it is a procedure using sophisticated technologies, usually in the setting of large-scale projects, which require considerable technical, managerial, legal and financial expertise as well as means to afford it.

2. FINANCIAL AND ECONOMIC ASPECTS OF DESALINATION ASSETS

The size and cost of desalination assets entail complex economic and financial aspects. The following section explores the structuring of desalination projects, providing an overview of the "typical" associated value chain and participants, then discussing the features and financing implications of the most widely followed development models.

However, **providing an accurate overview of the main project structuring models at work in the desalination sector is no easy task**. Such complexity comes from i/ the high local context-dependency of each project (both in terms of technology selection and structuring/financing given the dispersion of public/private players' involvement in each phase of the project), but also ii**/ the very "private" nature of the projects**[15] and the ensuing lack of truly industry-wide sources of comparable information.

Another **key differentiating factor among desalination projects in particular regarding projects' specific financials (IRR, etc.) is the degree of involvement of local public authorities as well as Multilateral development banks (MDBs), which can bring down cost of capital by their involvement.** Such involvement will be illustrated with the case study of Israel, which used innovative approaches to reach one of the lowest desalination costs worldwide. Singapore will serve as a case study illustrating the importance of long-term policy commitment for the development of domestic desalination industry.

THE DEVELOPMENT AND FINANCING OF DESALINATION ASSETS

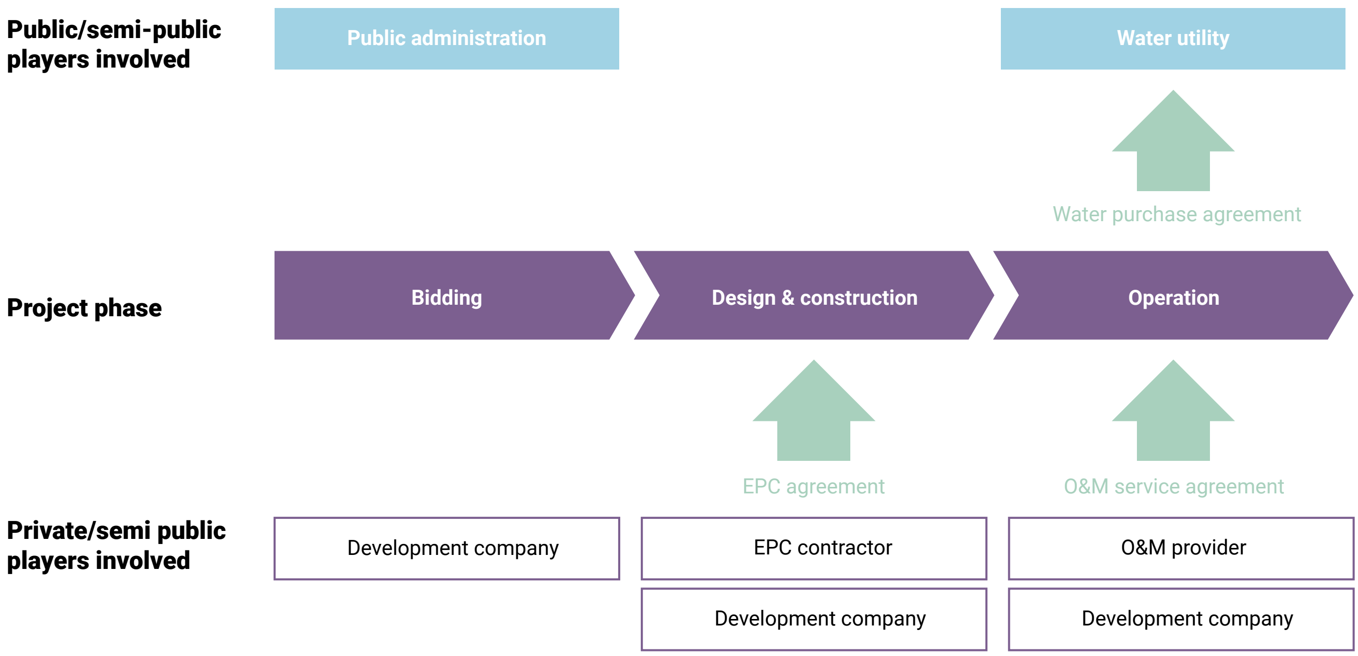
BUILDING AND OPERATING DESALINATION ASSETS: COMPLEX AND EVOLVING VALUE CHAIN

Development of desalination assets implies a fairly complex value chain. It not only involves a long [16] three-step process (bidding, design & construction, operation of the facility once it has been commissioned) and a set of diverse players involved, given the technicality of the facilities being developed.

The following figure summarizes the typical value chain of desalination assets mainly developed for municipal end-users and the types of players potentially involved under BOT/BOOT schemes.

15. As we elaborate in this section, desalination assets are embedded in special purpose vehicles (SPVs).
16. Construction of large-sized state-of-the-art plants current takes no less than 30 months (recent case of Suez's Barka 4 IWP project in Oman).

Value chain of municipal users-centered desalination assets



Source Natixis

There is a general trend towards increased specialization of the various players involved. This trend has to be put into the specific context of project sponsors increasingly seeking economies of scale through the development of bigger assets, in particular in the case of RO technology. It also has to do with the ever-increasing complexity of desalination projects and the ensuing rise of risks associated with each phase of the asset development:

i/ Permitting and licensing, entitlement, technology, construction, regulation and finance for the design and construction phase;

ii/ Quality of source water, power supply, operation and maintenance and demand for desalinated water for the operational phase

As a consequence, **the fully-integrated model where one player, be it public or private, tackles the various project development phases and takes all the associated risks** (both financial and operational[17]) **has been gradually abandoned over the past decades in favour of a more specialized one,** where each of the abovementioned phases is distinct and where the swift execution of the design & construction phase, hence the proper selection of the EPC (engineering-procurement-construction) contractor are key to project success. The current positioning of French market[18] leaders Suez and Veolia Environnement well illustrates this trend, with an involvement in desalination projects now mainly as EPC contractor. In such capacity, the two groups provide proprietary/in-house technologies (solely RO for Suez, MED, RO and sometimes hybrid MED-RO – see below - solutions for Veolia) and engineering services; they will subcontract with construction groups for the asset's structure and source equipment from specialist manufacturers. In this perspective, Suez tends to be a case apart, for the recent acquisition (2017) of US water engineering & equipment specialist GE Water has enabled the group to access proprietary membrane manufacturing technologies. In parallel, the desalination market structure has undergone major changes over the past two decades, **with the emergence of new players, on the project development side** (case of Saudi Arabia's ACWA Power and UAE's Metito) **as well as on the technology side** (case of Chinese solution specialist Beijing Origin Water).

PROJECT DEVELOPMENT MODELS: FINE-TUNING THE APPROPRIATE RISK-SHARING MODEL

While the private sector has an important part to play at numerous occasions along the supply chain, the high cost and long lifetime of desalination assets inevitably mean that **appropriate choice of procurement contracts with the local government/authority has a crucial role to play.**

17. Before and after the plant's commissioning
18. The desalination market is fragmented. Apart from Suez and Veolia Environnement, other important players offering proprietary technologies are IDE Technologies, Hyflux, Acciona Aqua, Aquatech, Fisia Italimpianti SpA, Nomura Micro Science, Doosan Heavy Industries, GS Inima Environment, RWL Water, B&P Water Technologies, Cadagua and Desalia.

In broad terms, when looking at the desalination market, one sees **three main project development models** also referred to as "project delivery methods": **BOT/BOOT** (build-operate-transfer/build- own-operate-transfer), **DBB** (design-bid-build) and DBO (design-build-operate), **each of them characterized by a specific degree of involvement and assumed risk on both public and private sides.**

The two following factors tend to greatly influence the choice of project delivery method:

i) **Asset's size:** the larger the desalination plant, the higher the potential involvement of private partners able to share with public authorities the burden of financial risk;

ii) **Asset's technical features and public authority's level of expertise** in the desalination asset under development. The latter issue accounts for RO projects generally calling for a higher level of private players involvement.

As the figure below summarizing main project development models shows, **the degree of involvement on each side varies a lot,** stretching from arrangements where private operators assume most of the project's risks (financing, construction and operation) as in the case of BOOTs, to arrangements where public authorities will only outsource the design and construction phase to an EPC contractor, as in the case of DBOs.

In the latter case, the EPC contractor will be taking no or minimal financing risk on the capital and will typically be paid a sum for the design-build of the plant, payable in installments on completion of construction milestones, and possibly an operating fee for all/a portion of the operating period. This operating fee is often seen upon completion of RO plants where the EPC contractor will be assigned O&M duties for a duration of two to five years and accordingly receive an operating fee.

This is because, unlike thermal desalination technologies, **it is difficult to assess the long-term performance of RO desalination facilities during the commissioning phase,** due to the sensitivity of membranes' performance to feed water quality variations and to the fact that some of the main O&M variable costs items, particularly projected membrane and cartridge filter replacement rates, can only be verified long after the plant is commissioned (World Bank, 2019).

Main project development models for desalination assets

	OWNERSHIP & FINANCING	DESIGN & CONSTRUCTION	OPERATION
BOT (build-operate-transfer)	Development company (sole financing responsibility)	EPC contractor	O&M contractor
BOOT (build-own-operate-transfer)	Development company (financing & ownership)	EPC contractor	O&M contractor
DBB (design-bid-build)	Municipality or utility company	EPC contractor	Municipality or utility company
DBO (design-build-operate)	Municipality or utility company	EPC contractor Single technology and operating service provider	Asset operator Single technology and operating service provider
DBOO (design-build-own-operate)	Municipality or utility company	EPC contractor	Municipality or utility company

Source Natixis

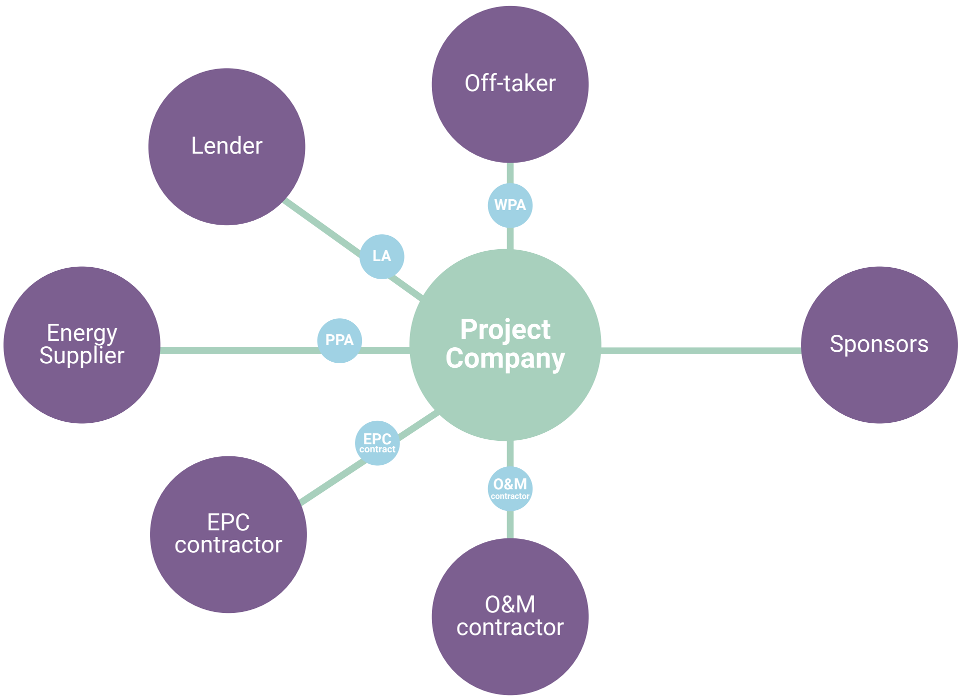
According to a recent report by World Bank citing a market analysis developed by Global Water Intelligence, **the popularity of BOOT schemes is such that 47% of desalination capital investments made in 2016 ($2.9bn) have been financed through this specific arrangement.** Better still, according to World Bank, this share is expected to increase to 50% by 2020. Given their essence lies in private partners assuming the bulk of the financial risk, **BOOTs imply a specific contractual set up where the initial investment as well as O&M costs are fully recovered during the project's lifespan.** Under such scheme, the asset owner/operator will enter into a long-term (typically 20-25 years) Water Purchase Agreement (WPA) with the local water authority/utility, such WTA establishing:

i/ **The conditions under which desalinated water will be delivered** (including the quantity, quality and the delivery pressure);

ii/ **The tariff at which the private owner/operator is remunerated.** As is generally seen with infrastructure assets in the electricity and gas sectors, this goes well beyond determining a unitary price for the m3 delivered as it entails setting an overall formula enabling recovery of the initial investment costs and variable O&M costs borne by the private owner/operator. The former cost item is generally recovered through fixed capacity payment either directly or indirectly.

The figure below summarizes the contractual structure of BOOTs

Contractual structure of build- own-operate-transfer (BOOT) project development model



WPA: Water Purchase Agreement
PPA: Power Purchase Agreement
LA: Loan Agreement

Other agreements:
- Share holders Agreement
- Lease Agreements
- Security Agreements
- Direct Agreements
- Membrane Supply Agreement

Source Natixis

BRINGING CAPITAL TO DESALINATION ASSETS: AN INCREASINGLY STRATEGIC ISSUE

Given their high costs and capital intensiveness, desalination assets require optimized financing structures. In the abovementioned report, World Bank stresses that **the nontechnical factors such as the choice of project financing structures and delivery methods as well as institutional and business environments can influence project's overall costs in the range of 10% to 20%**, thus making viable a project that could have otherwise experienced difficulty reaching breakeven.

Furthermore, **financing costs for desalination projects can be important even in countries with developed financial markets such as Australia.** For illustration, the SWRO plant in Melbourne[19] construction costs were $3.5bn, yet the all-up capital cost equaled $4.8bn: the $1.3bn "extra" costs were related to project funding as the costs of equity and debt together accounted for 27% of the total capital cost.

19. The plant was commissioned in December 2012.

Looking specifically at the financing structures behind BOOT arrangements which involve high financial and ownership challenges, but also generally protective cash flow arrangements for private development companies (see above), **one sees debt-to-equity ratios in the range of 70:30 to 90:10.** Though relatively high in absolute terms, these ratios are consistent with those seen in other project -financed infrastructure asset classes, such as renewable energies, benefiting from PPA-like contractual arrangements[20] . The typical debt involved for the financing of BOOT arrangements will be non-recourse loans (also referred to as "project loans") from bank syndicates, amortized during the asset's operation.

Given the abovementioned weight of financing in the overall project's costs, it is worth highlighting **the factors influencing the project's overall cost financing,** in particular:

i) **The project's capital structure**, as measured by its debt-to-equity ratio, which itself is directly influenced by **the degree of visibility of the underlying asset's cash flows.** Debt being in essence cheaper than equity, **holding all else equal, the heavier the weight of debt in the capital structure, the lower the overall cost of funding;**

ii) **For both debt and equity, country-specific risks that account for the range of investors' expectations in each asset class** (from 3% to 8% for debt; from 10% to as much as 40% for equity): sovereign risk, local water market's degree of maturity in the form of a proven track record of asset development, reliable local subcontractors, etc.;

iii) **Accordingly, specific guarantees or subsidies provided by local authorities to improve project's risk and cost profile.** The case of Israel is particularly illustrative and is thoroughly analyzed in the following section;

iv) **Specific arrangements with creditors** allowing for a "grace period" on debt and equity payments (five-year deferral as in the case of Israel's Sorek project - see below);

v) **Last but not least, the project's features themselves.** For instance, in higher salinity environments, SWRO is perceived as riskier than thermal technologies, which translates into higher average discount rates and short repayment periods for SWRO in the Arabian gulf relative to competing technologies (MED, MSF) in the region, or similar assets in less saline environments (see table below).

Summary of key financing parameters for desalination projects in the Middle East

Summary of Key Financing Parameters for Desalination Projects in the Middle East (World Bank, 2019)

Desalination method	Discount rate (%)		Loan repayment period (years)		IRR	
	Range	Average	Range	Average	Range	Average
MSF	2.0–6.5	4.8	15–25	20	5.6–13.3	9.8
MED-TVC	4.8–8.0	5.7	10–20	15	6.8–12.0	11.2
SWRO Mediterranean Sea	5.4–7.6	6.4	15–20	18	7.8–16.8	14.9
SWRO Arabian Gulf	5.6–8.4	7.6	10–15	12	8.9–18.5	16.8
SWRO Red Sea	6.0–9.1	8.4	10–20	18	9.4–17.2	17.2
Hybrid (MSF/MED & SWRO)	5.6–8.4	6.1	10–25	20	8.4–15.3	13.8

Note: **IRR** = internal rate of return; **MED-TVC**= Multiple Effect Distillation with Thermal Vapor Compression; **MSF** = Multistage Flash Distillation; **SWRO** = Seawater Reverse Osmosis.

Source: World Bank. 2019. "The Role of Desalination in an Increasingly Water-Scarce World." World Bank, Washington, DC.

20. The notion of power price agreement (PPA) refers to a bilateral agreement for the sale of electricity generally entered into for the long term (typically over the lifetime of the generation asset) on the basis of a fixed price that is generally indexed to annual inflation levels.

Given the large influence of procurement method choices upon the overall project costs, it is clear that **successful desalination projects require not only specific technical but also financial and managerial expertise**. This point is well illustrated by the following case studies of Israel and Singapore since both States are leading players in the desalination field thanks to their homegrown private sector technical expertise and sound public policies. While Israel relies mainly on BOT procurement models, Singapore made a different choice: DBOO.

CASE STUDY OF DESALINATION IN ISRAEL: INNOVATIVE FINANCING SCHEMES ACHIEVING SOME OF THE LOWEST DESALINATED WATER COSTS WORLDWIDE

Israel's case is remarkable on two grounds for the **country's reliance on desalination assets for drinkable water has grown steadily over since 2000 to reach almost 80% and nearly all projects were executed by the private sector,** through typical PPP (public-private partnerships) arrangements (BOT or BOOT – see above) and international tenders.

Israel has achieved record low desalinated water prices thanks to a long- term strategy, carefully designed PPPs, government guarantees and technological innovation by the private sector. Over the last 15 years, Israel has constructed five large-scale desalination plants along the Mediterranean coast, four of which involved PPPs with private sector concessionaires and the BOT and BOOT schemes. A co-financier of Sorek's desalination plant, EIB highlights facility's low unitary cost ($0.55/m3)[21] which very favorably compares with average costs for SWRO desalination assets in the Mediterranean Sea ($0.98/m3).

Table below summarizes the main characteristics of the five currently operational desalination plants in Israel. Moreover, it also provides detail about the contract type and the concessionaire for each desalination plant. For the BOT projects, the plant will transfer back to the Government of Israel at the end of its lifetime.

Main characteristics of Israeli desalination plants

Desalination plants located on the Israeli Mediterranean seashore.						
Plant	Water production since	Yearly production (Mm3/year)	Brine discharge	Project type	Project lifetime	Name of Concessionaire
Ashkelon	August 2005	115	With power station cooling waters	BOT (Build Operate & Transfer)	25-year	**Vid desalination ltd** Owned by IDE Technologies Ltd and OakTree Investment Fund
Palmachim	May 2007	90	Outfall 1.98 km from shore (20 m depth)	BOO (Build, Owned & Operate)	25 years	**Via Maris Desalination Ltd** The company is fully owned by the Infrastructure Fund for Israel
Hadera	December 2009	127	With power station cooling waters	BOT (Build, Operate & Transfer)	25 years	**H2ID**, a consortium of IDE Technologies (IDE) and Shikun & Binui Housing and Construction.
Sorek	November 2013	150	Outfall 1.95 km from shore (20 m depth)	BOT (Build, Operate & Transfer)	25 years.	**Sorek Desalination Company (SDL)** SDL is a consortium established specially for the project, owned by IDE Technologies (51% share) and Hutchison Water (49%)
Ashdod	October 2015	100	Outfall 2.20 km from shore (22 m depth)	BOT (Build, Operate & Transfer)	26.5 years	**Ashdod Desalination Ltd.** Fully owned by Mekorot Initiation and Development Ltd.

Source: Adapted from Shemer, H. and Semiat, R. (2017). "*Sustainable RO desalination – Energy demand and environmental impact. Desalination, 424, pp.10-16.*"

In Israel, governmental guarantees contributed to record low bid prices for desalinated water. Israel uses the BOOT approach for desalination projects which entails financing and operational risks being assumed by the asset owner/operator. **An interesting feature of Israeli desalination PPPs is that they were designed to include special guarantees to reduce private party risks and hence achieved low bid prices,** with:

21. €0.5/m3, see https://www.eib.org/en/infocentre/stories/all/2015-january-01/sorek-alleviates-israels-water-shortage.htm

i) **The interest rate risk being borne by the government,** which provided concessionaires with full protection against changes in base interest rate. **This enabled concessionaires to use cheaper short-term debt** to pay for the construction and refinance later with long-term debt covering the operational period but also high debt-to-equity ratios in the region of 80:20, enabling projects to secure optimal capital structure and nearly lowest overall costs of capital possible (see above). Furthermore, each bidder was able to propose their own indexation formula based on their own selection of market indices instead of having imposed a pre-established indexation formula by the government;

ii) **Bidders being able to determine an optimal proportion of fixed and variable fees** given their own structure of costs and

iii) **The government bearing the cost of land,** which was a significant help given high land prices across Israeli coasts.

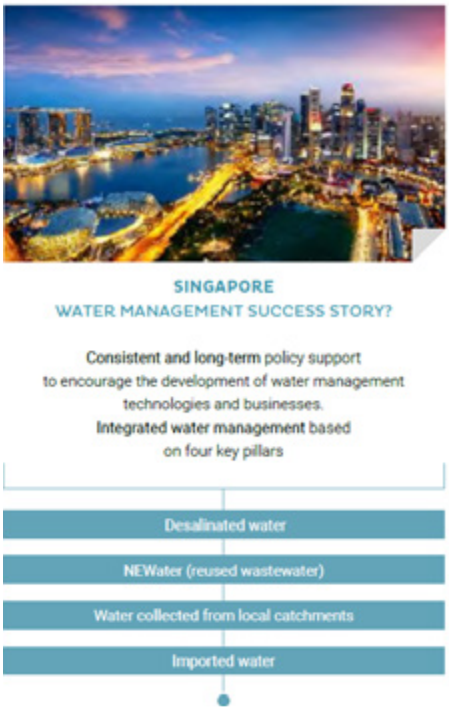
Furthermore, several interesting features about Israeli innovative approach to desalination can be revealed by a closer look at the Sorek desalination facility, co-financed by the European Investment Bank (EIB). At the time of its commissioning (November 2013), the Sorek desalination plant was the largest and the most advanced SWRO desalination facility in the world. A BOT project type developed by Israeli water specialist IDE, it provides clean, potable water for over 1.5 million people, comprising 20% of the municipal water demand in Israel, thus alleviating the country's potable water shortage. The plant has been used as an industry benchmark in terms of technology, environmental protection, financing structure and cost of produced water (World Bank, 2019). Several aspects are worth highlighting. Sorek uses a pressure center design which allows flexible increase and decrease of production. Moreover, it uses membranes with larger diameter (16-inches) to accommodate higher flow rates under the same operational conditions, thus reducing operational footprint. Furthermore, **the plant has two energy sources; a natural gas-fired power plant** serves as the primary source, but the plant can also **switch to grid energy during cheap off-peak times,** thereby reducing total energy costs.

Let us move now to another illustration of long-term county commitment to desalination. Similarly, to Israel, Singapore is also a developed country making use of desalination as part of its water policies for both geographical and geopolitical considerations.

CASE STUDY OF DESALINATION IN SINGAPORE: AN INDISPENSABLE PART OF AN INTEGRATED WATER MANAGEMENT POLICY

While Singapore has a long-term agreement for water importation from neighboring Malaysia, it actively seeks to reduce its dependency on these imports and relies upon advanced technologies to provide a reliable source of drinkable water. Up to 30% of Singaporean water demand is met by desalination, which is an integral part of Singaporean water management framework (as illustrated by the figure below) and benefits from committed long-term policy support.

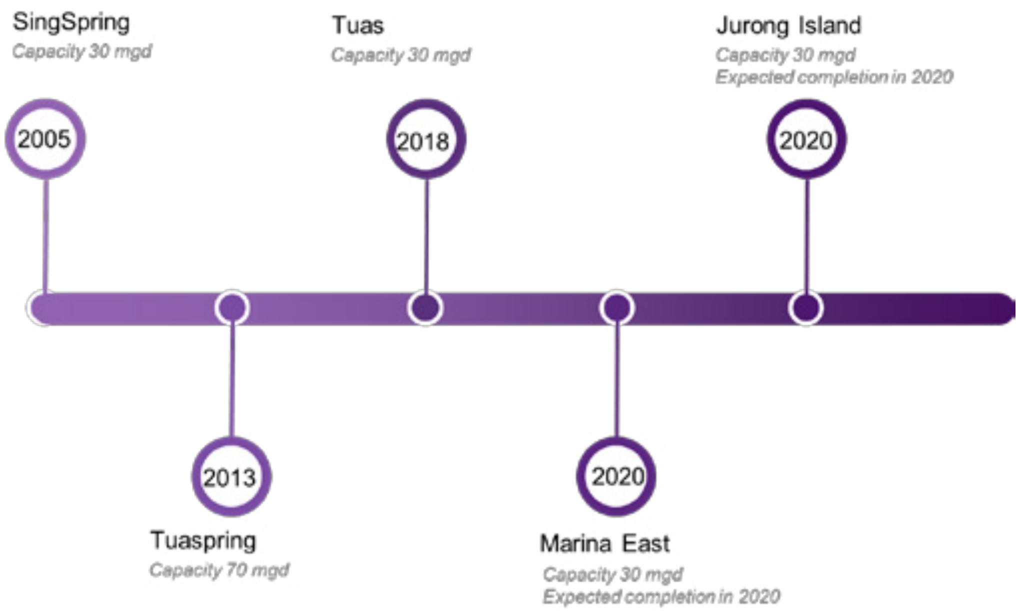
Summary of key financing parameters for desalination projects in the Middle East



Source: Natixis GSH 2019, Public Utilities Board

The country currently has three operational desalination plants and another two are under construction, to be commissioned in 2020. Desalination plays a key role in the national water policy and is expected to keep meeting up to 30 % of Singaporean water demand by 2060s, which is expected to double. Together with water reuse, **desalination is considered as a key technology to protect Singaporean water supply against weather uncertainties and other impacts of climate change.**

Timeline of Singaporean desalination journey



Source Natixis, Public Utilities Board - Note: mgd = million gallons per day, 1 million gallons = 3785 cubic meters

DBOO is the procurement instrument of choice for the Singaporean water authority, the Public Utilities Board (PUB). The operational desalination plants in Singapore are operated by Hyflux, the Singaporean desalination specialist. However, due to recent financial troubles of Hyflux, the now projects – Marina East and Jurong Island – were both given to other actors under the BDOO procurement, as shown by the table below.

Main characteristics of Singaporean desalination plants

Desalination plants located in Singapore					
Plant	**Status**	**Daily capacity (m3/day)**	**Contract Length**	**Project Type**	**Name of Concessionaire**
SingSpring	Operational	136,380	20-year period	DBOO (Design-Build-Own-Operate)	**SingSpring** Awholly owned subsidiary of Hyflux
Tuaspring	Operational	318,500	25-year period	DBOO (Design-Build-Own-Operate)	PUB has taken over in 2019 following financial problems of Huflux
Tuas	Operational	130,000	25-year period	DBOO (Design-Build-Own-Operate)	**SingSpring** Wholly owned subsidiary of Hyflu
Keppel Marina East	Under construction	137,000	25-year period	DBOO (Design-Build-Own-Operate)	**Keppel Infrastructure**
Jurong Island	Under construction	137,000	25-year period	DBOO (Design-Build-Own-Operate)	**Tuas Power-Singapore Technologies Marine** (TP-STM) consortium

Source: Adapted from the Public Utilities Board - Note: mgd = million gallons per day, 1 million gallons = 3785 cubic meters

The Singaporean national water agency PUB (Public Utilities Board) is responsible for water supply management and uses an integrated approach to water planning. Its water strategy is based upon water re-use (NEWater), collection of water (local catchment) and desalination. The PUB uses PPP approaches for constructing and operating both desalination and wastewater treatment facilities. This enables optimization of costs and innovation by the private sector but also places considerable requirements upon the PUB as it needs to deal with complex DBOO procurements. The recent bankruptcy of Hyflux, the EPC contractor for the two largest Singaporean desalination plants shows that even the most developed and innovative desalination markets have their inherent risks.

The PUB purchases the potable water (20- and 25-years long water purchase agreements) while the private sector designs, constructs, owns and operates the desalination facilities under the DBOO arrangements. The price of desalinated water reflects both capacity payments and output payments. **The capacity payments** are based on available capacity and reflect the capital costs (service of debt, equity, duties and taxes, distribution to shareholders), fixed operation & maintenance charges (insurances, salaries, administration) and fixed costs of procurement of energy. Conversely, **the output payments** are based on the actual water supply and therefore reflect the variable operation & maintenance charges (chemicals, consumables, spare parts) and variable charges for energy (variable energy cost components for power required for water production).

Hyflux used to be regarded as a Singaporean homegrown success story. Yet in May 2019, the PUB had to take over the flagship Tuaspring desalination facility after having terminated the water purchase agreement with the heavily indebted former posterchild. The reason for Hyflux's downfall can be tracked several years behind when it used an aggressive bidding strategy to win the tender **for Tuaspring plant.** Hyflux offered "an impossibly low bid" to supply desalinated water at a first-year price of S$0.45 per cubic meter. To put this number in perspective, competing offers were made at S$0.67 (Keppel Seghers) and S$1.42 (Sembcorp Utilities). The risky strategy of Hyflux was to **couple Tuaspring with power generation facility and sell the excessive electricity into the national grid.** However, electricity prices were not evolving as intended: when Tuaspring became operational, **electricity prices were brought low by excessive power generation oversupply. Instead of subsiding the operational losses from desalination, the power plant piled on extra debt** and sent Hyflux into troubles. Hyflux had to seek court protection for restructuration of almost S$3 billion of debt. Utility firm Utico (United Arab Emirates) appeared as would-be white-knight and the two companies signed a$400 million rescue deal in November 2019. The rescue deal has revised in July 2020 as Utico offered $485 million, comprising cash and stock. Hyflux now has time until the end of August 2020 to accept the offer. Concomitantly, an unsecured working group of bank lenders will file an application with the Singapore High Court with the aim of placing Hyflux under judicial management.

Costs of desalination, both in terms of upfront investment and water production, are clearly one of the key determinants whether desalination assets shall succeed or not. Let us now have a closer look at the cost structure

1. THE COST STRUCTURE OF DESALINATION

While desalination costs have fallen considerably[22] over past decades, it remains more expensive than obtaining drinkable water from rivers, groundwater reservoirs or from water recycling, when such options are on the menu (Caldera and Breyer, 2017). However, when demands for water cannot be met from the conventional sources, desalination is often the only choice, if the host country can afford it, as discussed in the previous section. In this section, we focus on the **variety of geographical, technological and regulatory factors influencing desalination costs.**

The main drivers of desalination costs are the interrelated factors relating to technology, plant size, location, project financing and delivery as well as stringency of environmental regulations. Apart from the factors related to technology and size, project capital costs as well as operation and maintenance costs also depend on several other factors such as energy use, plant location, quality of feed water, target quality for produced water and regulation. Combined, these factors determine the risk-return profile of a desalination project, thus driving investor's return expectations and overall costs.

THE EVOLUTION OF DESALINATION COSTS AND FUTURE PROJECTIONS

Both thermal and RO technologies have enjoyed significant cost decrease in the recent past. The trend has been particularly important for SWRO, which now under favorable physical and business condition reaches costs as low as 0.5 dollars per cubic meter of desalinated water (World Bank, 2019). Table below presents the capital costs as well as operation & maintenance and water production costs per main desalination technology. In the case of SWRO, a breakdown by region is provided to reflect the degree of influence that the characteristics of feed water have upon desalination by RO.

It should be noted that the above values are for the year 2016 and the estimates are based on a sample of 50 projects evaluated by the

22. The costs of desalinated water from MSF fell from around 10 $/m3 in early 1960s to below 2 $/m3 in 2010s. The costs of desalinated water from SWRO fell from around 3 $/m3 in mid-1970s to between 1.5 and 0.5 $/m3 in early 2010s.

Variations of capital costs, operation & maintenance costs and water production costs of main desalination technologies

Summary of Worldwide Seawater Desalination Costs (World Bank, 2019)						
Desalination method	Capital costs (million US$/MLD)		O&M costs (US$/m3)		Cost of water production (US$m3)	
	Range	Average	Range	Average	Range	Average
Multistage Flash Distillation (MSF)	1.7–3.1	2.1	0.22–0.30	0.26	1.02–1.74	1.44
Multiple Effect Distillation With Thermal Vapor Compression	1.2–2.3	1.4	0.11–0.25	0.14	1.12–1.50	1.39
SWRO Mediterranean Sea	0.8–2.2	1.2	0.25–0.74	0.35	0.64–1.62	0.98
SWRO Arabian Gulf	1.2–1.8	1.5	0.36–1.01	0.64	0.96–1.92	1.35
SWRO Red Sea	1.2–2.3	1.5	0.41–0.96	0.51	1.14–1.70	1.38
SWRO Atlantic and Pacific oceans	1.3–7.6	4.1	0.17–0.41	0.21	0.88–2.86	1.82
Hybrid MSF/MED	1.5–2.2	1.8	0.14–0.25	0.23	0.95–1.37	1.15
Hybrid SWRO	1.2–2.4	1.3	0.29–0.44	0.35	0.85–1.12	1.03

Note: Costs are at 2016 values.; **MLD** = Million Liters Per Day; **MSF** = Multistage Flash Distillation; **MED**= Multiple Effect Distillation
O&M = Operation And Maintenance; **SWRO** = Seawater Reverse Osmosis.

Source: World Bank (2019)

World Bank (2019). It is not possible to have a broader view based on larger data sample due to the private and confidential nature of financial data presented in the table above.

Within the category of thermal desalination, MSF has until recently been more competitive for large-scale projects and MED for smaller-scale ones. However, MED is increasingly competitive for projects at all scales due to continuous technological improvement resulting in efficiency gains and further economies of scale. For MSF technology, water production costs are proportional to the size of the desalination plant.

RO enjoys the lowest average costs, but an overall comparison remains elusive since these costs are influenced by numerous site-specific factors. Consequently, depending on the asset location, SWRO water production costs vary from $0.50 to $2.86 per cubic meter. **Just as thermal technologies, RO also benefits from significant economies of scale. Optimal plant size for SWRO is between 100MLD and 200 MLD** (World Bank, 2019) and newest plants of that size produce water in the cost range between $0.50 and $0.80 per cubic meter.

Hybrid desalination plants combining thermal and membrane-based desalination can reduce costs further. Such hybrid projects usually produce around two-thirds of water with thermal desalination and the rest with SWRO. Hybrid production costs are often inferior to the costs of single technology desalination, especially when they can be periodically supplied by low-cost energy. This is thanks to the operational flexibility allowing SWRO part to be switched on when excessive cheap electricity is available, as discussed in part 1.1.1.

THE COSTS OF PRODUCTION OF DRINKABLE WATER DURING OPERATIONAL LIFETIME OF DESALINATION ASSETS

Table below provides a breakdown of total water production costs for SWRO desalination plant based on data from the World Bank (2019). While thermal technologies are more capital intensive than RO, **capital recovery costs still represent around 44% of the total costs of an SWRO plant,** as shown by table below (World Bank, 2019). This observation once again highlights just how important it is to select a suitable PPP arrangement for desalination infrastructure backed by an appropriate financing scheme. **The second largest cost item on the list is energy,** which relates directly to the choice of the on-site power source. **Energy costs remain the largest recurrent costs, accounting for between two-thirds and three-quarters of thermal desalination recurrent costs (OPEX) and for one-third to one-half of SWRO recurrent costs** (World Bank, 2019). **Desalination CAPEX and OPEX** depend on several context-specific parameters. Some technologies result in higher CAPEX due to expenses related to land & engineering as well as installation and transportation while other technologies are more expensive in terms of OPEX related to energy, labour and maintenance (Shahzad et al., 2017).

Breakdown of variable and fixed water production cost items for a typical SWRO desalination plant based on data available to the World Bank

Typical Breakdown of Total Water Production Costs for Seawater Reverse Osmosis Plants (World Bank, 2019)		
Cost item	**US$/m3**	**Percentage of total**
Variable costs	**0.30**	**42**
Energy	0.22	30
Chemicals	0.02	3
Replacement of RO membranes and cartridge filters	0.04	6
Waste stream disposal	0.02	3
Fixed costs	**0.42**	**58**
Capital recovery costs	0.32	44
Labor	0.02	3
Maintenance	0.03	4
Environmental and performance monitoring	0.01	1
Other O&M costs	0.04	6
Total costs	**0.72**	**100**

Source: World Bank (2019)

Geographical factors also play their part, bringing cost advantages to desalination plants in coastal regions and neighboring their target market. The quality of feed water is another important aspect since it determines the number and type of required pre-treatment steps ahead of the desalination procedure itself. Water salinity measures in total dissolved solids (TDS) as well as water temperature both influence desalination costs. Higher water salinity requires higher operating pressure and temperature and may also reduce the water recovery ratio. The temperature of feed water significantly impacts the performance of RO performance, while its impact is less important for thermal desalination. Generally speaking, **higher temperature and higher salinity mean higher desalination costs** since supplementary technologies and procedures are needed to make intake water suitable for desalination.

Table below presents salinity and temperature of seawater in several regions. These two factors have a considerable influence on the both the performance of desalination and the final costs of desalinated water. This complicates global comparison of the parameters selected for assessment of the performance of desalination assets and favors instead local and regional benchmarking.

In terms of production costs, thermal technologies have the edge in hot saline water while RO performs better in cleaner, cooler and less saline waters. The costs of RO desalination are lower in locations with lower salinity and less pronounced seasonal variation. The high[23] quality of seawater in the Mediterranean Sea makes RO the technology with the lowest costs in the region. However, **the hotter and more saline water in the Arabian Gulf increases the RO desalination capital costs by 16% and operation and maintenance cost by 14% relative to the Mediterranean,** as shown by the table below based on data from the World Bank (2019).

23. From the standpoint of desalination, high quality feed water means less saline and with less seasonal variations of temperature.

Average values of water salinity and water temperature in different regions

Salinity (Total Dissolved Solids) and Temperature of Various Seawater Sources (World Bank, 2019)		
Seawater source	**TDS (ppt)**	**Temperature (°C)**
Red Sea	42–46 (avg. 44)	24–33 (avg. 28)
Arabian Gulf	40–44 (avg. 42)	22–35 (avg. 26)
Mediterranean	38–41 (avg. 40)	16–28 (avg. 24)
Caribbean Sea	34–38 (avg. 36)	16–35 (avg. 26)
Indian Ocean	33–37 (avg. 35)	25–30 (avg. 28)
Pacific and Atlantic oceans	33–36 (avg. 34)	9–26 (avg. 18)
Note: **Avg.** = average; **ppt** = parts per thousand; **TDS** = total dissolved solids		

Source: World Bank (2019)

Comparison of SWRO construction and operation & maintenance costs using feed water from several seas relative to the Mediterranean Sea

Ratio of Costs with Source Waters from Different Seas (World Bank, 2019)		
Source	**Unit construction costs**	**Unit O&M costs**
Mediterranean Sea	1.00	1.00
Gulf of Oman	1.09	1.07
Red Sea	1.12	1.10
Arabian Gulf	1.16	1.14
Note: **O&M** = operation and maintenance.		

Source: World Bank (2019)

The targeted water quality level is another factor influencing the costs of desalination. The higher the quality requirements, the more significant the extra costs. The lower the concentration of total dissolved solids (TDS), chlorine, boron and bromide in desalinated water, the higher its quality. And costs. According to project data compiled by the World Bank (2019), costs of desalinated water from reverse osmosis can increase by up to 50% if the facility aims to meet the highest quality of output water. The construction, operation & maintenance and water production costs increase with the stringency of targets for the quality of produced water, as shown by the table below: **the more complex RO system** (resulting in lower concentration of dissolved solids, chloride, boron & bromide, hence in higher water quality), **the higher the associated costs.**

The production costs of desalinated water are expected to fall further due to ongoing technological improvements, hereby making this water source more affordable in water scarce regions which may not be able to pay current prices. In the following section, we consider the future possibilities for technological innovation aimed to reduce costs of desalinated water.

the impact of targeted quality of desalinated water upon the costs of desalination using RO, benchmarked to relatively simple RO system resulting in lower water quality

Effect of Target Product Water Quality on Costs (Ratio) (World Bank, 2019)			
Target product water quality	Construction costs	O&M costs	Cost of water
Single-Pass Reverse Osmosis System			
TDS = 500 mg/L Chloride = 250 mg/L Boron = 1 mg/L Bromide = 0.8 mg/L	1.00	1.00	1.00
Partial Second-Pass Reverse Osmosis System			
TDS = 250 mg/L Chloride = 100 mg/L Boron = 0.75 mg/L Bromide = 0.5 mg/L	1.15–1.25	1.05–1.10	1.10–1.18
Full Two-Pass Reverse Osmosis System			
TDS = 100 mg/L Chloride = 50 mg/L Boron = 0.5 mg/L Bromide = 0.2 mg/L	1.27–1.38	1.18–1.25	1.23–1.32
Full Two-Pass Reverse Osmosis System + Ion Exchange			
TDS = 30 mg/L Chloride = 10 mg/L Boron = 0.3 mg/L Bromide = 0.1 mg/L	1. 40–1.55	1.32–1.45	1.36–1.50
Note: The four levels of quality correspond to four levels of treatment: (1) single-pass RO; (2) partial second-pass RO; (3) full two-pass RO; and (4) full two-pass RO + IX. **O&M** = operation and maintenance; **TDS** = total dissolved solids;			

Source: World Bank (2019)

POSSIBLE AREAS FOR FUTURE COST IMPROVEMENTS OF DESALINATION TECHNOLOGIES

While desalination technologies have advanced significantly over the past decades, there is still enough space for further improvement.

Most likely areas for future advances are in the technology itself, in pretreatment procedures, in brine management and in energy efficiency. Thermal desalination technologies are expected to experience only limited improvements, whereas SWRO is expected to gain further competitiveness thanks to increasing efficiency for key cost components: SWRO costs are expected to fall by as much as two-thirds over the period of next two decades (World Bank, 2019). The past cost improvements of SWRO were due to increase in membrane productivity and durability. The membrane productivity refers to the amount of water that can be produced by one membrane – this has more than doubled for SWRO over the past two decades. Table below (World Bank, 2019) charts the expected developments of membrane technology which will drive further cost reductions.

The considerable space for future improvement of reverse osmosis desalination affordability and performance is expected to result in falling construction costs, higher energy efficiency and better membrane productivity, which will in turn result in lower costs of desalinated water. The table below outlines the expected improvements for medium-size and large-size RO desalination plants operating with seawater. It should be noted that these estimates are done for best in class desalination facilities, not the industry average. As such, these estimations could serve as reference for impact-based financing requirements as they reflect the most virtuous projects and practices.

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the impact of targeted quality of desalinated water upon the costs of desalination using RO, benchmarked to relatively simple RO system resulting in lower water quality

Areas for Further Reduction of the Cost of Reverse Osmosis Desalination Technologies (World Bank, 2019)
➢ Development of membranes of higher salt and pathogen rejection, higher productivity, and reduced transmembrane pressure and fouling potential
➢ Improvement of RO membrane resistance to oxidants, elevated temperature and compaction
➢ Extension of membrane useful life beyond 10 years
➢ Integration of membrane pretreatment, advanced energy recovery, and SWRO systems
➢ Integration of brackish and seawater desalination systems
➢ Development of a new generation of high-efficiency pumps and energy recovery systems for SWRO applications
➢ Replacement of key stainless steel desalination plant components with plastic components to increase plant longevity and decrease overall cost of water production
➢ Reduction of costs by complete automation of the entire production and testing process for membrane elements
➢ Development of methods for low-cost continuous membrane cleaning that allow reduction of downtime and chemical cleaning costs
➢ Development of methods for low-cost membrane concentrate treatment, in-plant and off-site reuse, and disposal

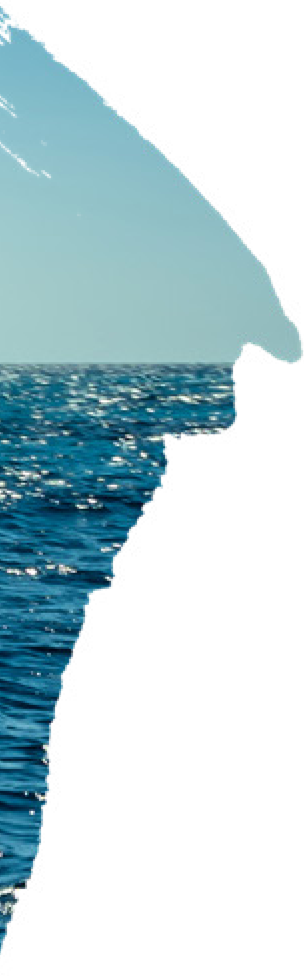
Source: World Bank (2019)

Furthermore, another potential improvement of reverse osmosis desalination could be achieved thanks to nanostructured membranes. Nanostructured membranes have up to 20% higher productivity relative to conventional RO membranes. Alternatively, they can operate at the same productivity levels as their conventional counterparts while using up to 15% less energy. If successful, the development of highly productive carbon nanotubes could bring desalination costs close to those of conventional water treatment.

Estimation of future value range for key parameters determining costs of desalination using SWRO

Forecast of Desalination Costs for Medium- and Large-Size Seawater Reverse Osmosis Projects (World Bank, 2019)			
Parameters	Year 2016	Within 5 years	Within 20 years
Cost of water (US$/m3)	0.8–1.2	0.6–1.0	0.3–0.5
Construction cost (US$/Million Liters Per Day)	1.2–2.2	1.0–1.8	0.5–0.9
Electrical energy use (kWh/m3)	3.5–4.0	2.8–3.2	2.1–2.4
Membrane productivity (m3/membrane/day)	28–47	35–55	95–120
Note: The figures are estimated for best-in-class desalination plants.			

Source: World Bank (2019)



CHAPTER 2

Sustainability assessment of desalination assets: recognizing the socioeconomic benefits and mitigating environmental costs of desalination

B. SUSTAINABILITY ASSESSMENT OF DESALINATION ASSETS: RECOGNIZING THE SOCIOECONOMIC BENEFITS AND MITIGATING ENVIRONMENTAL COSTS OF DESALINATION

Assessing the sustainability profile of desalination assets is no easy task. Desalination is not a universal solution to global water challenges and despite remarkable technological progress over the past decades, it still has considerable drawbacks in terms of energy intensity and environmental impacts. This being said, desalination is often essential for ensuring water supply security in water scarce countries, in which case there is a strong socioeconomic rationale in favor of desalination assets. Moreover, negative impacts of desalination can be attenuated, for instance by coupling desalination facilities with renewable power plants and by adopting techniques mitigating the damage inflicted by brine.

1. IDENTIFYING AND CONTEXTUALIZING THE SOCIO-ECONOMIC CONTRIBUTION OF DESALINATION

When both the geographical and socioeconomic factors favorable to desalination assets collide, desalinated water can serve as a reliable and long-term solution for the ever-increasing water demand. In this section, we shall use the framework of Sustainable Development Goals (SDGs) to identify the direct and indirect contributions of desalination to human develop development while also using the same framework to point out the potential tradeoffs between desalination and other development objectives, mainly of environmental nature.

Concerning the contribution of desalination, the emphasis is given on **the benefits of desalinated water for socioeconomic development and political stability,** while also considering **the potential role of desalination in enhancing resilience of water supply to climate change related fluctuations and shocks**. When it comes to the negative impacts and the potential trade-offs related to desalination, the key issue relates to environmental damage caused by brine.

1. THE CONTRIBUTION OF DESALINATION TOWARDS THE ACHIEVEMENT OF SEVERAL SOCIAL AND ECONOMIC SUSTAINABLE DEVELOPMENT GOALS (SDGS)

We will use the framework of Sustainable Development Goals (SDGs) to identify the various ways in which desalination can contribute towards human development. The SDGs can be divided into three thematic groups: environmental, social and economic. The environmental SDGs aim at stewardship of the biosphere. The social SDGs have the objective of ensuring social stability and progress while the economic SDGs aim to improve the economic performance of our societies. As we have shown in detail in our study[1] *"Water Economy: Deciphering the Challenges, Financing the Opportunities"*, water relates in a more or less direct manner to each of these goals: it can contribute towards their achievement, but it can also undermine them. As we show in this section, **water from desalination can indeed contribute towards local economic development while ensuring social and political stability and hedging from shocks to water supply, be they of geopolitical or climate change related nature. Nevertheless, the negative impacts of desalination – if not properly mitigated – can undermine several SDGs related to the environment, responsible use of resources and even human health.**

1. Available at https://gsh.cib.natixis.com/water-economy

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THE ESSENTIAL IMPORTANCE OF RELIABLE WATER SUPPLY FOR SOCIOECONOMIC DEVELOPMENT

There can be no life without water and no society can develop without a reliable source of water supply. While *water on Earth is an abundant supply, water suitable for human use is a scarce resource.* The concept of water scarcity refers to a lack of available water resources with the sufficient quality to meet the water use demands in a certain area. Scarce water availability results from physical unavailability or pollution of water resources while scarce water access results from mismanagement of available water or lacking water infrastructure. In both cases, social and economic consequences can be dire, as illustrated by the two figures bellow.

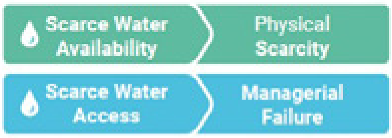
Key facts about water scarcity

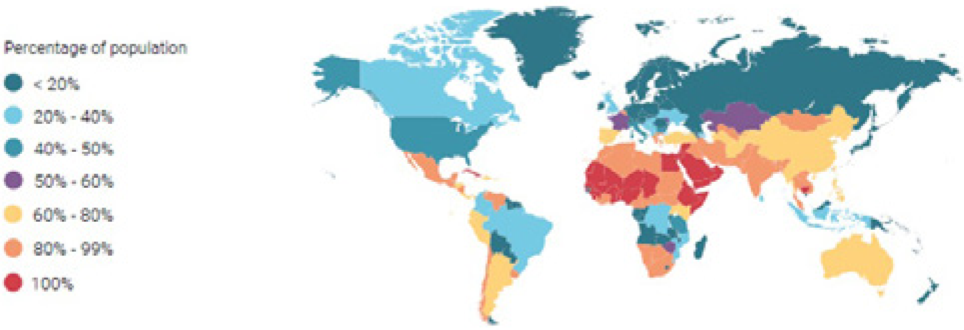
Water scarcity refers to a situation when water supply fails to match water demand

"Two-thirds of the global population live under conditions of severe water scarcity at least 1 month of the year. Nearly half of those people live in India and China. Half a billion people in the world face severe water scarcity all year round". (Mekonnen and Hoekstra, 2016)

WATER SCARCITY

Lack of sufficient available water resources to meet the water use demands in a certain area.





Source: World Bank (2019)

Inappropriate water supply can act as a drag on socio-economic development

Water can act as a drag on socio-economic development.

ECONOMIC DEVELOPMENT AND HUMAN WELFARE CAN BE UNDERMINED BY WATER SCARCITY.

→ The impacts of mismanaged water resources are felt disproportionately by the poor since they are more likely to rely on rain-fed agriculture for food and live on lands without adequate flood protection. The poor are also most at risk from contaminated or polluted water and inadequate sanitation services

→ Inclusive economic development and alleviation of poverty will require improved and reliable water supply for marginalized and poor people in developing countries.

"Some regions could see their growth rates decline by as much as 6 percent of GDP by 2050 as a result of water-related losses in agriculture, health, income, and property-sending them into sustained negative growth" (World Bank, 2016).

Source: Adapted from OECD (2017), World Bank (2016) and Sadoff et al. (2015).

While overcoming water scarcity by ensuring a reliable water supply is indeed of an utmost importance from the standpoint of human development, it should be highlighted that desalination is one of the possible solutions – a solution which has to be used strategically, under specific circumstances and when conventional sources are not a feasible option. The set of potential answers to global water challenges summarized in the figure below.

Desalination amongst the possible solutions to global water challenges

Source: Natixis

Desalination is one of many solutions for facing current and upcoming water-related challenges, as shown by the figure above. Given the complexity of desalination projects, the energy intensity of desalination techniques and the related environmental impacts, desalination should not be considered as a universal solution for any issue related to water. **While desalination assets can indeed provide a reliable source of abundant quantities of drinkable water, their use can only be justified from sustainability standpoint if other economic and technical solutions for water challenges are already in place and yet insufficient for achieving water security.** In concrete terms, this means that **desalination assets have a substantiated claim for sustainability credentials if constructed in places where public policies already promote efficient water use by the means of water pricing, provide support for water reuse and for wastewater treatment and already exploit conventional water sources when feasible**. The role of adequate institutional frameworks, consistent long-term policy support, incentives for the involvement of the private sector and public-private partnerships is discussed is discussed in detail in section 2 of our study *Water Economy: Deciphering the Challenges, Financing the Opportunities.* When reasonable policies, proven business models and efficient water management are not enough to provide water security, desalination can indeed be the reasonable choice. In opposite setting, it is merely an expensive excuse to waste even more water.

Desalination amongst the possible solutions to global water challenges

Number, capacity and global share of operational desalination plants by sector use			
	Number of desalination plants	Desalination capacity (million m3/day)	Desalination capacity (%)
Global	15,906	95.37	100
Income level			
Municipal	6055	59.39	62.3
Industry	7757	28.80	30.2
Power	1096	4.56	4.8
Irrigation	395	1.69	1.8
Military	412	0.59	0.6
Other	191	0.90	0.4

Source: Jones, E., Qadir, M., van Vliet, M., Smakhtin, V. and Kang, S. (2019). The state of desalination and brine production: A global outlook. Science of The Total Environment, 657, pp.1343-1356.

Another aspect to consider when assessing the sustainability credentials of desalination assets is the end use of produced water. Desalination is not a free ticket to continue wasteful water use or an excuse to delay reforms of water policy reforms. Following table (Jones et al., 2019) presents he number, capacity and global share of operational desalination plants by sector use.

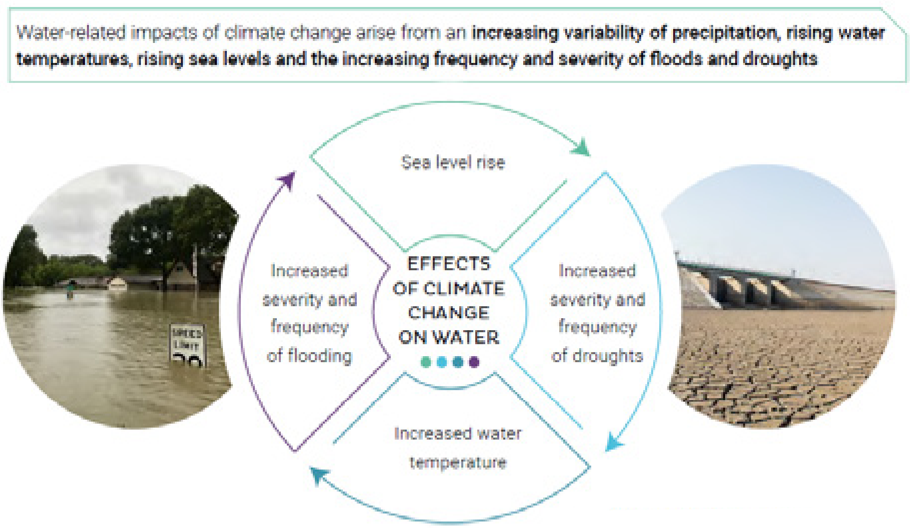
The municipal sector consumes 62.3% of the annual desalination capacity, followed by industry which accounts for 30,2%. This underlines the role of desalination as first and foremost a source of drinkable water for people in water scarce regions and, secondly, a source of water used as an input for industrial activity. In both cases, there is a strong contribution towards several SDGs, as we will discuss in detail below.

Having access to supply of drinkable water is an essential requirement for human development. But it is not only the quantity and quality of supplied water that counts – reliability is also crucial. **When it comes to reliability of water supply, desalination has a clear advantage relative to conventional water sources as it is far more resilient both to the impacts of climate change and to exogenous geopolitical shocks.**

DESALINATION AS A SOURCE OF CLIMATE CHANGE RESILIENCE

Since water production in desalination facilities is not vulnerable to changing rainfall patterns, fluctuating air temperature or droughts, desalination enhances resilience of drinkable water supply to climate change. This is a major advantage of desalination relative to conventional water sources, which are likely to be further impacted by climate change. As we discuss in our previous study *"Water Economy: Deciphering the Challenges, Financing the Opportunities"*, climate change is already threatening water security across the world and projected impacts of climate change are expected to make the water scarcity issue even more pressing (as illustrated by the figure below). **On the supply side**, water scarcity will be further exacerbated by increased evaporation resulting from higher temperatures, by more frequent and more pronounced occurrence of droughts and by less predictable rainfalls. **On the demand side**, water scarcity will be further reinforced by higher demand for water, which will itself by caused by higher temperatures. Agricultural water use is expected to experience the strongest increase in face of rising temperatures, which also brings the question of completion for water between municipal, agricultural and industrial use. Since the production of desalinated water is nearly immune to the abovementioned factors which will trouble conventional water sources, **desalination constitutes a good candidate to enhance climate change resilience of entire regions, hereby contributing towards SDG 13 related to climate change adaptation and mitigation.**

Water-related impacts of climate change.



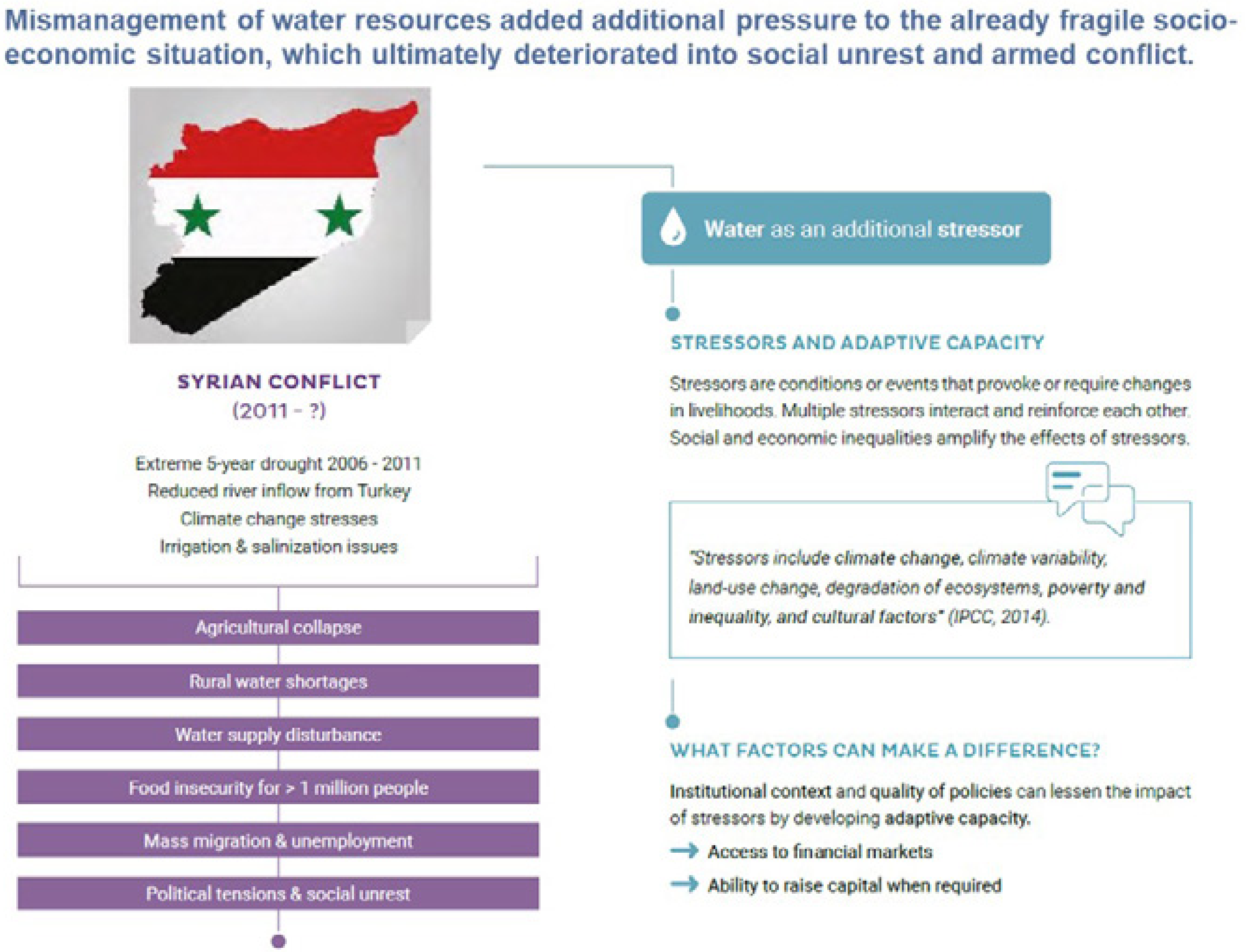
Source: Natixis (2019), Water Economy: Deciphering the Challenges, Financing the Opportunities

Apart from making water supply more resilient to the impacts of climate change, desalination can also provide protection against geopolitical risks.

DESALINATION AS A SOURCE OF POLITICAL STABILITY AND PROTECTION FROM EXOGENOUS RISKS

Climate change is not the only risk to water supply against which desalination can contribute to protect. In addition, having domestic desalination capacity makes countries much less vulnerable to exogenous risks by ensuring their self-reliance and independence of drinkable water supply. This benefit of desalination is crucially important for both Singapore and Israel, for example, two countries which made desalination an essential component of their policies aimed at reducing their exposure to exogenous water supply shocks. **Singaporean** national water strategy places emphasis on desalination combined with wastewater reuse in order to reduce dependency on water imports from neighboring Malaysia. Considering its difficult geopolitical situation and natural water scarcity resulting from its geographical position, **Israel** decided to ensure its water security through desalination. In both cases, the stability, reliability and efficiency of desalination as a source of water supply made desalination a political priority with the aim of ensuring economic development and social stability. Conversely, a water scarce country whose water supply does not have these characteristics is far more vulnerable to exogenous shocks, be they climate change related or of geopolitical nature. This is illustrated by the case of **Syria**, where failure to secure water supply led to socio-economic collapse, social unrest and political instability, a situation which ultimately escalated into an armed conflict. The role of water in the Syrian conflict is discussed in more detail in our study *"Water Economy: Deciphering the Challenges, Financing the Opportunities".*

How Syrian instability and conflict relate to water



Source: Adapted from Falkenmark et al. (2019) and from IPCC (2014). Image purchased from Shutterstock.

Reliable water supply is essential and yet its numerous roles and benefits are often difficult to disentangle in a clear manner. We will use the framework of SDGs to illustrate how desalination can contribute towards several socioeconomic development objectives, distinguishing between direct and indirect contribution.

CONTEXTUALIZATION OF THE DIRECT AND INDIRECT BENEFITS OF DESALINATION WITHIN THE FRAMEWORK OF SUSTAINABLE DEVELOPMENT GOALS (SDGS)

Desalination directly contributes to the achievement of **access to clean water (SDG 6)** and to **climate change adaptation (SDG 13)**. Reliable and predictable water supply from desalination provides safe drinking water in water scarce regions, which is an essential prerequisite for socioeconomic development, industrial activity and agricultural production. Moreover, construction of new desalination capacity can also alleviate pressure upon conventional water sources, for instance underground aquifers, lakes or rivers. Furthermore, desalination can also be considered as a climate change adaptation activity for the reasons presented above. As climate change further advances throughout this century, adaptation is likely to become increasingly important. In this perspective, a climate resilient source of drinkable water may become an essential component in water management policies in more and more countries.

Source: Natixis (2020).

Moreover, desalination can also bring several co-benefits, thus indirectly contribution to the achievement of several other SDGs. **While the two directly impacted SDGs benefit from construction of new desalination facilities almost everywhere, not every desalination project necessarily contributes towards the achievement of all the indirectly impacted SDGs listed below.** The exact scope of contribution will depend on local context and choices inherent to each specific project.

Desalination facilities can be designed with an adjacent solar power plant (or in some cases wind farm), hereby contributing to the uptake **of clean energy (SDG 7)**. As discussed in section 1.1.2., desalination is an especially good match for coastal cities. When powered by clean energy, reliable supply of drinkable water from desalination can contribute to more **sustainable cities and communities (SDG 11)** in such regions. Moreover, long-term policy support for desalination can foster innovation and contribute to the creation of domestic industrial players (for instance IDE technologies in Israel, ACWA Power in Saudi Arabia or Hyflux in Singapore), hereby contributing to **economic growth (SDG 8) and industrial development, technological innovation and construction of infrastructure (SDG 9).** When used as an input for agricultural production, desalinated water can contribution towards local production of food (SDG 2). As we discussed in our study *"Water Economy: Deciphering the Challenges, Financing the Opportunities "*, water scarcity disproportionately impacts women and children, which means that securing water supply for all contributes towards gender equality (SDG 5).

Having seen the benefits of desalination, let us now consider its drawbacks.

POTENTIAL TRADEOFFS BETWEEN DESALINATION AND SEVERAL SUSTAINABLE DEVELOPMENT GOALS (SDGS)

While desalination can indeed offer numerous benefits of socioeconomic character, there are also several drawbacks, mainly of environmental nature. The concept of SDGs can once again be used to identify and contextualize such negative impacts of desalination. Desalination remains an energy intensive process powered mainly by fossil fuels. Combustion of fossil fuels results in emissions of greenhouse gases as well as in air pollution. Greenhouse gases such as carbon dioxide (CO2) contribute to global warming, hereby undermining climate change mitigation efforts encompassed in **SDG 13 (climate action)**. Air pollution, for instance in the form of particulate matter (PM), can be harmful to human health, which means fossil fuel powered desalination also contributes to undermining **SDG 3 (human health)**. Moreover, the possibility of having a seemingly unlimited supply of water can result in a sort of "rebound effect": instead of being used responsibly where really, desalinated water can provide an excuse for continuation of wasteful water use, thereby undermining **SDG 12 (responsible production & consumption)**. Finally, the most severe setbacks of desalination can be felt **below water (SDG 14)**. Brine, the byproduct of desalination, harms marine life, changes the composition and behavior of aquatic ecosystems and alters the chemical properties of water around brine discharge points, unless appropriate mitigation measures are taken. Both the impacts and appropriate mitigation measures will be discussed in detail in section 2.2.

Source: Natixis (2020)

Overall, **considering the above summary of desalination's environmental & socio-economic net benefits and impacts, our conviction is that, from a sustainable financing perspective, it is challenging to consider desalination as a "green asset" per say, i.e. with environmental net (absolute) benefit, though some desalination plants will have clear environmental relative benefits (vs peers) and worth supporting through sustainable financing. Through this work and a live case study, NATIXIS Green & Sustainable Hub acquired the conviction that desalination assets is eligible for sustainable financing under the logic of its proven (or to be proven) socio-economic benefits if and only if most environmental externalities (carbon & brine essentially) are properly mitigated...** This is illustrated by the following case study.

2. CASE STUDY OF THE FIRST SUSTAINABLE LOAN QUALIFICATION FOR A WATER DESALINATION PROJECT

TAWEELAH IWP

The recent Taweelah IWP project illustrates that the socioeconomic benefits of desalination coupled with a set of measures to mitigate related environmental impacts **can justify financing of desalination assets with sustainable financial instruments, in this case with a sustainable loan.**

ACWA Power and **NATIXIS** announced that the **Taweelah IWP has obtained the first-ever "sustainable loan" qualification for a water desalination project globally.** Closed in September 2019, this USD758 million project finance loan, with a contractual tenor of 32.4 years, will finance what will become the largest reverse osmosis plant in the world when completed in 2022.

NATIXIS acted as **initial mandated lead arranger, documentation bank, hedge provider, global facility agent** and **sustainable loan coordinator**. **NATIXIS** also acted as **sole arranger** and **investment agent** under the Islamic Equity Bridge Loan for ACWA Power's equity portion.

This project finance loan is dedicated to the financing of the design, construction, operation and maintenance of a state-of-the-art, 200 million imperial gallons[2] per day reserve osmosis plant and associated infrastructure and facilities. The plant will be constructed in the existing Taweelah complex, in the Emirate of Abu Dhabi, United Arab Emirates. The project also includes a 68 MW peak photovoltaic power plant to complement the energy supply from the procurer's grid. **Thanks to the photovoltaic power plant integrated to the project,** renewable energy is expected to account for at least 30% of the project's electricity consumption within ten years, with a target of raising this figure to 55% by the end of the first quarter life of the project. The remaining electricity will come from regional power grid, which relies almost exclusively [3](99%) on natural gas. The project is expected to substitute two local thermal desalination plants of lower capacity to be decommissioned in the coming years, improving local air quality and reducing greenhouse gas emissions. The project, when constructed, will also set another world record by utilizing the lowest amount of energy per gallon of desalinated water produced. The tariff offered by ACWA Power for the Al Taweelah IWP was the lowest achieved to date[4] in the world for desalinated water.

The Second Party Opinion (SPO) on the sustainability credentials & management of the abovementioned sustainable loan issued by Taweelah RO Desalination Company LLC has been provided by Vigeo Eiris. Taweelah RO Desalination Company LLC is a project company, created by ACWA Power and other shareholders. **The SPO assessment only covers the project company, not its parent companies.** For the time being, *"Social Loan Principles"* do not exist. For this reason, **the SPO referred to both** *"Green Loan Principles[5]"* **(GLP) and** *"Social Bond Principles[6]"* **(SBP) to assess the loan's potential contribution to sustainable development** by evaluating its alignment with the four core components of GLP and SBP. These four core components are i/ Use of Proceeds, ii/ Process for Project Evaluation and Selection, iii/ Management of Proceeds and iv/ Reporting.

Net proceeds of the loan will be used exclusively to finance the construction of a new desalination plant and its solar PV energy generation unit, this construction project falls under one single Sustainable Project Category (also known as *"Eligible Category"* in the language of SPOs), namely ***"sustainable water management".*** This eligible category contributes to one main social objective and one main environmental objective. **The main social objective *"access to water"* is pertinent and backed by a relevant selection of expected**

2. Approximately 902 216 m^3 per day
3. Electricity generation by sources in the UAE can be found at https://www.iea.org/countries/united-arab-emirates
4. Offered tariffs have fallen even further since then, hereby increasing affordability of desalinated water. In February 2020, a consortium of Engie and Mowah have been named a preferred bidder for Yanbu 4 IWP, offering a tariff of $0.465227/m3. In March 2020, bids for the Hassyan plant (the first privately financed desalination plant procured in Dubai) came close to $0.30/$m^3$ as UEA's Utico offered a tariff of $0.306/m3, closely followed by Saudi Arabia's ACWA Power's bid of $0.316/m3.
5. GLP were developed by the Loan Market Association with the support of the International Capital Market Association (ICMA). The most recent 2018 version is available at https://www.lma.eu.com/application/files/9115/4452/5458/741_LM_Green_Loan_Principles_Booklet_V8.pdf
6. SBP were developed by the International Capital Market Association (ICMA). The most recent 2018 version is available at : https://www.icmagroup.org/green-social-and-sustainability-bonds/social-bond-principles-sbp/

social benefits and targeted population, both being clearly quantified: water supply of approximately 902 216 m3 per day benefitting around 350 000 households in UAE. The project anticipates the growing water demand in the UAE, which is expected to double in the next three decades. **The main environmental objective *"climate change mitigation"* is also clearly defined and relevant but expected environmental benefits would benefit from a clearer definition and quantification.** The project uses the most efficient commercially available technologies, includes an adjacent solar power plant and displaces two older desalination plants. As such, it can claim contribution towards climate change mitigation by production of renewable energy, improvement of energy efficiency and avoidance of GHG emissions thanks to displacement of older, less efficient plants. Nonetheless, SPO points out that these expected environmental benefits should be further clarified by: i/ quantifying the expected GHG avoidance, ii/ quantifying the net carbon footprint of the project and iii/ providing evidence of the net environmental impact of shutting down two thermal desalination plants replaced by the project. Moreover, **the SPO also suggests including benchmarking of environmental impact of the project relative to environmental impacts of other available water management alternatives** such as reuse of treated wastewater, groundwater recharge, water demand reduction & water use efficiency measures.

The United Nations Sustainable Development Goals (SDGs) framework can also be used to highlight the contribution of the project. By providing drinkable water mainly for residential end use Taweelah IWP directly contributes to **SDG 6 (Clean water and sanitation)** and **SDG 11 (Sustainable cities and communities)**. Since the project includes a solar power plant, it can claim contribution to **SDG 7 (Affordable and clean energy)** and **SDG 13 (Climate action).**

In terms of monitoring and reporting, the SPO assessment concluded that both reporting process and commitments were "good" as they cover fund allocations and the environmental & social benefits of the project. This selection is presented in the table below.

Allocation of proceeds, Environmental & Social benefits – the selection of reporting indicators

Allocation of proceeds: reporting indicators		
The financed expenditures		
The total amount of net proceeds allocated to the selected project		
The amount available of unallocated proceeds, if any		
The co-financing share of the total cost of the project, if any		
Eligible project	**Environmental benefits indicators**	
	Outputs and outcomes	**Impact indicators**
Taweelah Reverse Osmosis IWP	Installed water supply capacity (m3)	Avoided GHG emissions (tCO2.eq) Net GHG emissions (tCO2.eq)
	Water produced (million m3 / year)	
	Water losses at production process level (%)	
	Water effluents discharged (millions m3 /year)	
	Water effluents compliant with quality standards (%)	
	Installed solar energy production capacity (MW)	
	Renewable energy produced (MWh)	
	Electricity use from the grid (MWh)	
	Social benefits indicators	
	Outputs and outcomes	**Impact indicators**
	Water supply to the local network (million m3/year)	Number of beneficiaries per year
	Water supply compliant with drinking water standards (% per year)	

Source: Adapted from Vigeo Eiris (2020)

2. UNDERSTANDING AND MITIGATING THE ENVIRONMENTAL IMPACTS OF DESALINATION

While socioeconomic considerations often make a compelling case for desalination, the environmental perspective is almost always very different: desalination is energy-intensive, overwhelmingly powered by fossil fuels and responsible for discharge of brine which causes damage to ecosystems if not treated properly.

Nevertheless, there are several ways to attenuate the negative environmental impacts of desalination. The falling costs of renewable energy can displace fossil fuels as the power source of desalination, hereby dramatically improving the carbon footprint of desalinated water while also reducing related levels of air pollution. Moreover, several methods can be readily put in place to make discharged brine less harmful.

This section starts disentangling the various direct and indirect negative environmental impacts related to desalination. Understanding the key characteristics of each negative impact is essential for implementing appropriate mitigating measures. A set of feasible measures to do so are presented in detail, along with four simple Key Performance Indicators (KPIs) which can be used to evaluate the key aspects of the environmental performance of individual desalination assets relative to their peers.

1. DIRECT ENVIRONMENTAL IMPACTS OF DESALINATION

The direct environmental impact of desalination relates to the water intake as an input for desalination and to the discharge of brine from the desalination plant as an unwanted byproduct of the procedure. While the risks and damages related to water intake are relatively easy to mitigate, the discharge of brine remains far greater challenge.

WATER INTAKE INTO DESALINATION FACILITIES

The intake of water can harm aquatic life by sucking organisms into the water intake pipelines. This can be mitigated relatively easily by use of appropriate filters to minimize the number of organisms and other matter into the desalination facility. The discharge of brine back into the sea after the desalination process is a more complicated challenge with several potentially negative environmental outcomes.

WHAT IS BRINE AND WHY IS IT POTENTIALLY DANGEROUS?

Brine refers to a hot, salty concentrate containing chemicals. It is an unwanted by-product of the desalination procedure. As the recent study by Jones et al. (2019) showed, **the volume of brine is superior by up to 50% to the volume of water produced by desalination facilities.** Previous estimates placed the produced volumes of brine at roughly the same levels as volumes of produced water. This recent study shows that the situation of brine is an even more concerning issue than previously thought. Brine resulting from the RO desalination is more saline than brine resulting from the use of thermal technologies, reaching up to 80 000 mg of salt per liter of discharged water. The exact composition of brine is highly dependent on the type of desalination technology and on the choice of chemicals used during the desalination procedure.

A closer look at what kinds of chemicals and pollutants are used during desalination is provided in table below. The table outlines the main types of pollutants resulting from desalination and provides their typical concentrations for both reverse osmosis and thermal (MED and MSF) desalination technologies.

At each stage of the desalination process, chemicals are added or further concentrated. Most of them are simply discharged at the very end of the desalination process. **Some chemicals are discharged continuously as part of the brine discharge while others in periodic intervals during clearing and maintenance of the facility** (Miller et al., 2015).

Key characteristics of main pollutants used in RO, MED and MSF desalination.

Potential environmental pollutants resulting from desalination process (Miller et al., 2015)		
Pollutant	**Reverse Osmosis technology**	**Multiple Effect Distillation (MED) and Multistage Flash Distillation (MSF) technologies**
Concentrate ("brine") salinity	Up to 65 000 – 80 000 mg/L	Around 50 000 mg/L
Temperature	Ambient seawater temperature.	Plus 5 to 15 degrees Celsius above ambient temperature.
Dissolved Oxygen (DO)	Typically below ambient seawater DO levels if well intakes are used. Approximately same as ambient seawater if open intakes used.	Could be bellow ambient seawater salinity due to physical de-aeration and use of oxygen scavengers.
Chlorine (biofouling control)	If chlorine or other oxidants are used to control biofouling to prevent membrane damage, they are typically neutralized before water enters membranes.	Approximately 10% to 25% of source water feed dosage if not neutralized.
Coagulants	May be present if source water is conditioned and if filtered backwash water is not treated. May cause effluent coloration if not equalized prior to discharge.	No pre-treatment required.
Anti-scalants (used for scale control)	Typically bellow toxic levels.	
Antifoaming agents (used for foam control)	Not present	Typically bellow toxic levels.
Heavy metals (contaminants due to corrosion)	Traces of iron, nickel and molybdenum if low-quality materials are used.	Traces of copper and nickel concentrations if low-quality materials are used for heat exchangers.
Chemicals used for clearing	Alkaline or acid solutions with additives, complexing agents, oxidants and biocides.	Acidic solutions containing corrosion inhibitors.

Source: Miller, S., Shemer, H. and Semiat, R. (2015). Energy and environmental issues in desalination. Desalination, 366, pp.2-8.

Breakdown of global brine discharge volumes by region, by country income level and by end use of desalinated water

Brine production of desalination plants by region, country income level and sector use		
	Brine production (million m3/day)	**Brine production (%)**
Global	141.5	100
Geographic region		
Middle East and North Africa	99.4	70.3
East Asia and Pacific	14.9	10.5
North America	5.6	3.9
Western Europe	8.4	5.9
Latin America and Caribbean	5.6	3.9
Southern Asia	3.7	2.6
Eastern Europe and Central Asia	2.5	1.8
Sub-Saharan Africa	1.5	1.0
Income level		
High	110.2	77.9
Upper middle	20.7	14.6
Lower middle	10.5	7.4
Low	0.03	0.0
Sector use		
Municipal	106.5	75.2
Industry	27.4	19.3
Power	5.8	4.1
Irrigation	1.1	0.8
Military	0.5	0.3
Other	0.3	0.2

Source: Jones et al. (2019)

GEOGRAPHICAL DISTRIBUTION OF BRINE DISCHARGE

The environmental impacts of brine are felt locally in areas making heavy use of desalination. Brine produced just by four countries – Saudi Arabia, UAE, Kuwait and Qatar – accounts for 55% of the global brine output (Jones et al., 2019). The main reason for this unwanted leading position is the combination of relatively challenging environmental conditions for desalination (hot and saline water of the Gulf) and significant presence of thermal desalination facilities in the region which produce higher volumes of less concentrated brine.

The Middle East and Northern Africa region leads the table terms of produced brine, accounting cumulatively for 70.3% of global brine production, which implies that these zones would be particularly interesting target for impact-based financing of brine mitigation strategies. The municipal sector is an end user responsible for 75.2% of brine production according to the data provided by Jones et al. (2019), which once again suggests a potential tradeoff between the socio-economic need for drinkable water and the environmental concerns related to brine.

THE DAMAGE CAUSED BY DISCHARGE OF BRINE INTO WATER

The exact scope and nature of damage caused by brine to the environment depends on the methods chosen for brine discharge from desalination plant. The choice of these methods in turn depends on the location of the plant itself. For desalination plants located in proximity to saline water surfaces, brine is discharged directly, often without any treatment. Inland desalination plants usually do not have saline water bodies nearby and therefore have to adopt alternative methods for brine disposal such as injection of brine into wells. This is a cheaper method for landlocked desalination plants relative to the transport of brine towards the sea. However, it can result in unwanted pollution and contamination of underground waters. Table below recapitulates the different methods of brine discharge options and presents the estimation of associated costs. The surface water discharge remains the most frequently used option as it has the lowest costs.

Key characteristics of main pollutants used in RO, MED and MSF desalination.

Brine Disposal Method and Construction Cost (World Bank, 2019)	
Disposal method	**Disposal construction cost (US$/m3/day)**
New surface discharge (new outfall with diffusion)	50–750
Colocation of desalination plant and power plant discharge	10–30
Codisposal with wastewater treatment plant discharge	30–150
Sanitary sewer discharge (low cost in small volumes)	5–150
Deep/ Beach well injection (limited by suitable geographical locations)	200–625
Evaporation ponds (used in warm, dry areas with flat terrain)	300–4,500
Spray irrigation	200–1,000
Zero liquid discharge (used for landfill disposal)	1,500–5,000

Source: World Bank (2019)

The environmental impacts caused by brine are strongest around the discharge point. Since brine tends to have elevated temperature and salinity and also contains several chemicals (antiscalants, coagulants, surfactants, acids and bases for pH control), **its discharge is hazardous for marine ecosystems.** For illustration, coagulants increase water turbidity and discharge of antiscalants adds organic phosphorus into ambient waters, hereby causing eutrophication (Petersen et al., 2018), which alters the levels of dissolved oxygen and leads oxygen depletion. Depending on the volumes of discharged brine, oxygen depletion can create so called "dead zones" where aquatic life cannot survive due to insufficient quantities of available oxygen dissolved in the water.

Other consequences of the discharge of brine into seawaters are the increased salinity of surrounding water and alteration of the levels of pH, nutrients and alkalinity of the water. Combined, these impacts can threaten marine life or change the composition and functioning of marine ecosystems (Roberts et al., 2010).

The indirect environmental impact of desalination refers to greenhouse gas emissions and other pollution required to keep the desalination facilities running. Most desalination plants are powered by fossil fuels, either in the form of on-site power plants or from the national grid, which remains carbon intensive many countries keen on desalination. Therefore, the produced water has a certain footprint in terms of carbon dioxide and other pollutants (such as SO_2, NO_x and particulate matter (PM)).

2. THE CARBON FOOTPRINT OF DESALINATION

The carbon footprint of desalination can be reduced via two principal channels: improvement of operational efficiency of the desalination procedure and decarbonization of the power supply used as an input in the desalination process. As far as power supply is concerned, the carbon footprint of desalination can be reduced either by nuclear or renewable energy. For the time being, both remain marginal. Nevertheless, there is a considerable commercial interest in exploring both possibilities.

The exact carbon footprint of desalinated water depends on the national grid composition and on the on-site power generation facility. Given the geographical distribution of desalination facilities, a considerable proportion of them use energy for highly carbon-intensive grids. While the expected progressive decarbonization of power supply could alleviate this issue over time, it is in itself not a convincing argument in favor of "green" credential of renewables. Arguments that are far more credible relate to efforts to combine desalination facilities with adjacent renewable power generation sources.

For the time being, a vast majority of on-site power generation adjacent to desalination facilities is based on the use of fossil fuel. Natural gas is less harmful than coal or oil in terms of GHG emissions with roughly half the CO_2 footprint (400g CO_2 / KWh). Nevertheless, it remains a fossil fuel and carbon capture and storage technologies are still far from being commercially viable. Some would argue that desalination powered by best-in-class gas power plant offers a compromise between the need for drinkable water and efforts to curb related environmental externalities. A counterargument would emphasize that gas could be replaced by renewables to strengthen the environmental credentials of desalination assets.

3. AIR POLLUTION

Apart from greenhouse gases, the combustion of fossil fuels results also in other negative externalities. The combustion of gas, oil or coal results in the emission of pollutants such as CO, SO_2, NO_x, particulate matter (PM) and volatile organic compounds, all of which pollute the air and cause harm to human health. While the estimation of economic costs of air pollution is outside the scope of this report, it is nevertheless pertinent to emphasize the magnitude of such costs. OECD (2016) estimations of the impact of air pollution on mortality, morbidity, and changes in crop yields come to the conclusion that *"outdoor air pollution could cause 6 to 9 million premature deaths a year by 2060 and cost 1% of global GDP – around USD 2.6 trillion annually – as a result of sick days, medical bills and reduced agricultural output"* (OECD, 2016).

The long list of negative impacts implies that desalination facilities have to take mitigation measures if they are serious about their claim for making a contribution to sustainable development. The social-economic argument in favor of desalination is strong, but insufficient on its own: **desalination assets aiming for financing with financial instruments used by sustainable finance have to show efforts in terms of environmental performance.** The following section maps the possible solutions to do that.

4. POTENTIAL SOLUTIONS MITIGATING THE ENVIRONMENTAL IMPACTS OF BRINE

While brine is by its very nature a harmful by-product of the desalination procedure, several mitigation measures can be put in place in order to reduce the impact of related negative externalities. The following *"checklist"* of mitigation measures does not necessarily have to be fully fulfilled by an asset seeking eligibility for sustainable financing, but the inclusion of some of the criteria enhances the environmental credentials for both the project and project developer.

The exact impact of brine upon marine ecosystems depends not only on the chemical composition of brine but also upon the proprieties of receiving water bodies. In order to account for the influence of water temperature, chemical composition and diverse characteristics such as strength and direction of water currents, **computer modelling can be used to determine the optimal location of brine discharge points.** Subject to local regulatory requirements for maximal allowable salinity change, such modelling exercise can determine whether to use one or multiple discharge points and whether diffusers should be used. As such, several technology choices and measures taken during project construction have been identified in the table below due to their potential to mitigate the negative impacts of brine when discharged into seas and oceans. Given the complex behavior of ecosystems and the large influence of underwater courants and other factors upon the final impact of discharge brine, not necessarily all the measures identified in table below need to be applied in every project. The exact choice of brine mitigation solutions should be a result of site-specific modelling by experts.

Let us now have a closer look at different options for mitigating the environmental damage caused by brine.

An overview of the possible set of measures that can be taken to mitigate the negative impacts related to the discharge of brine into ambient water

A set of possible measures to mitigate the direct environmental impacts of brine discharge
➢ Regulatory compliance with the maximal allowable levels of water salinity, temperature and other characteristics around discharge point(s)
➢ Continuous / frequent water quality monitoring around the brine discharge point(s)
➢ Use of computer modelling to determine the optimal brine discharge point(s) and brine discharge infrastructure characteristics such as the length of the outfall, the number of openings and the use of diffusers
➢ Mixing of brine with cooling water before discharge
➢ Neutralization of chemicals used during the desalination process before they are mixed with brine
➢ Use of brine minimization technologies to reduce the volume of produced brine
➢ Recovery of metals and / or salt from brine

Source: Natixis (2020)

The exact environmental impact of brine discharge depends on a set of factors related to the characteristics of the receiving ambient water. For this reason, it would be misleading to set up a list of indicators of water quality with maximal allowable thresholds for changes of values of such parameters. This is after all the task for local regulation of water & environmental quality, which differs from one jurisdiction to another. Of course, legal compliance with applicable regulatory frameworks is the first step in the right direction. This is indeed the first point to consider in terms of the direct environmental impacts of desalination. A necessary, but not a sufficient condition.

MONITORING OF WATER QUALITY AROUND DISCHARGE POINT(S)

Closely related to regulatory compliance is the aspect of regular monitoring. Claims of limited environmental impacts are laudable, yet actual empirical evidence compatible with such claims is even more commendable. Therefore, the next item on the sustainability "checklist" covers the monitoring requirements. Moreover, credible monitoring programs can help to increase public acceptance of desalination assets by increasing transparency of the project.

MIXING OF BRINE WITH COOLING WATER BEFORE DISCHARGE

One way to make brine less harmful is to make it less concentrated when discharged. Brine can be diluted by mixing with cooling water from power plants adjacent to the desalination plant. Since the water used for mixing is much less saline, the mixing reduces brine salinity via dilution (Giwa et al., 2017). Desalination plants often have adjacent power generation facilities. The cooling water from such power plants can be mixed with brine, diluting it before the discharge into ambient waters. This can partially mitigate the issues related to the high salinity, elevated temperature and chemical content of brine.

Depending on the volume of cooling water used for mixing, brine can be denser than the ambient seawater and sinks to the seabed where it flows as a concentrated stream. It should be noted that even though estimations and modelling can be done for the area impacted by brine, the location of where brine plunges to the seafloor can vary in locations with changing water currents (Petersen et al., 2018). This "bottom ponding" can, however, be restricted by mixing brine waters with receiving waters at the point of discharge, for instance by using pressurized dispersion nozzles (Roberts, 2015).

OPTIMAL BRINE DISCHARGE INFRASTRUCTURE

Computer modelling can then be used to determine the optimal length of brine discharge pipelines, the number of openings discharging brine into ambient water or the number and type of diffusers facilitating the mixing of brine with water. The exact impact of brine discharge upon the marine environment is context-specific, depending on a variety of factors related to the composition of water, strength and direction of underwater currents as well as behavior and migratory patterns of local organisms. Computer models can be used to account for the influence of a set of factors such as the chemical properties of receiving water or the strength and direction of underwater currents to determine the optimal structure of brine discharge infrastructure given the local conditions.

NEUTRALIZATION OF CHEMICALS USED DURING DESALINATION BEFORE THEY ARE MIXED WITH BRINE

Brine can be made less environmentally harmful before it is discharged. Various chemicals used during the successive stages of the desalination process can be neutralized before they are added into the brine. The exact modalities and related costs will depend on the type of chemicals used, but the point is generally applicable.

BRINE MINIMIZATION TECHNOLOGIES

Several technologies can be used at desalination facility to reduce the volume of produced brine. The exact choice of technology depends on the salinity of brine. Brine with relatively low salinity is best suited for membrane-based brine minimization technologies such as forward osmosis, vibratory shear enhanced processing (VSEP) and electrodialysis metathesis (EDM). For brines of higher salinity, thermal-based technologies can be used.

RECOVERY OF METALS AND SALT FROM BRINE

While usually considered as an unwanted byproduct of desalination, brine itself can also be used for other purposes. In this perspective, it is no longer an unsolicited environmental headache but a valuable resource for potential commercial exploitation. Several possibilities exist but are not yet used on an industrial scale. Investments in this direction would have the double benefit of turning "wasted" brine into an exploitable resource while avoiding the environmental impact of conventional ways of obtaining elements extracted from brine.

Adsorption is a process enabling the extraction of metals from brine. Depending on the exact composition of brine, recovered metals can include uranium, lithium, rubidium and cesium (Loganathan et al. 2017). While the recovered metals could provide a relatively high return on investment, the technology has not yet been demonstrated at a large scale. A co-benefit of metal recovery from brine would be a potential reduction of negative environmental impacts of mining.

Except from metals, brine can also provide another valuable resource: salt. Chemical precipitation, crystallization and evaporation all enable salt recovery from brine. For illustration, sodium phosphate and sodium carbonate are used around the Mediterranean and the Red Sea for this purpose.

USE OF BRINE FOR AQUACULTURE

Finally, brine can also be used as a resource for aquaculture since some organisms thrive in saline water. Two documented cases are "brine shrimp" used as a food for fish and shellfish and microalgae "Dunaliella salina" used in pharmaceutical and food industries. Brine can be used as a feedstock for such aquaculture activities, hereby also providing opportunities for local employment and economic activity.

Having seen a set of site-specific measures, let us now turn our attention towards holistic approach for assessing the sustainability credentials of desalination assets.

CHAPTER 3

Desalination sustainability performance scorecard

C. DESALINATION SUSTAINABILITY PERFORMANCE SCORECARD

KEY ELEMENTS TO CONSIDER WHEN EVALUATING THE SUSTAINABILITY PROFILE OF DESALINATION

An overall assessment of sustainability credentials of desalination assets requires evaluation of quantitative KPIs as well as consideration of several qualitative indicators. The following table summarizes the insights gained throughout this study by identifying four key categories relevant for the assessment of benefits & costs of desalination. Each identified category is further developed by the identification of several relevant indicators, both of quantitative and qualitative nature. Furthermore, several additional factors to consider are provided for each category, these account for the fact that both the performance of desalination assets and the severity of water challenges are highly context dependent.

Key elements to consider for the assessment of sustainability credentials of desalination assets.

Key elements to consider when evaluating the sustainability profile of desalination projects		
Type of benefit / cost of desalination	**Indicators**	**Additional factors to consider**
Socio-economic benefits	Water **access** Water **quality** Water **affordability** **Reliability** of water supply	Country / local levels of **water access** Applicable **water quality regulation** (WHO, national, local) **End use** of desalinated water **Water policies** (water pricing, water reuse, wastewater treatment, integrated water management framework, water use efficiency) Regional **vulnerability to future impacts of climate change** Geopolitical aspects of **water security**
Operational efficiency	**Recovery ratio** (%) **Energy intensity** (kWh/m3) **Membrane productivity** (m3/membrane/day; for reverse osmosis only)	Temperature, salinity and quality of **intake water** (and seasonal variations) **Total equivalent electric energy** for comparison across technologies
Energy-related externalities	**Carbon footprint** of desalinated water (CO_2 / m3) **Air pollution** from energy supply (NO_x, PMx, SO_2)	**Type of energy source** used in power plant adjacent to desalination facility **Carbon intensity** of the local grid **% of renewables** and /or other low-carbon energy in local grids Levels of **air pollution** in proximity of desalination plant
Brine management	Impact on **marine life** Impact on **water quality** Brine **mitigation** measures	**Volume, salinity** and **temperature** of brine **Chemical content** of brine **Biodiversity** hotspots / protected areas in proximity of brine discharge points

Source: Natixis.

WHAT ARE KEY PERFORMANCE INDICATORS (KPIS) AND HOW TO USE THEM?

In the context sustainable finance, the use of KPIs plays a dual role of a filter and a safeguard: assessing eligibility to "use of proceeds" green/social/sustainable financing both from an environmental and/or social benefit, transformative potential and ESG risks management perspectives. **As a general rule, KPIs should be meaningful, understandable, quantifiable and benchmarkable.** The KPIs can be used for an assessment of technology performance, economic feasibility, environmental impacts as well as social consequences and eventually applicability of relevant legal frameworks. Furthermore, apart from being useful for comparison of current performance, KPIs can also serve for identification of and incentives for margins for further improvements (Pramangioulis et al., 2019).

The strong context-dependency of desalination means that there is a need for benchmarking at local or regional rather than global scale. Both the operational performance and the water production costs are influenced by a set of external factors highly dependent on local conditions. For this reason, the KPI data used for benchmarking should be as granular level as possible: regional and local. For illustration, it is not pertinent to compare the KPIs for a RO facility in the Arabian Gulf with its Mediterranean peers since both regions differs significantly in terms of water temperature and salinity, which in turn influences the operational performance of desalination technology.

A prudent benchmarking would take into account both **the regional context and the other available alternatives for production of drinkable water.**

The following four Key Performance Indicators (KPIs) were selected to provide a picture of the operational performance of desalination facilities while allowing for relatively objective comparison and benchmarking. Given the context dependency of the performance of desalination technologies, these KPIs have to be used carefully, always taking into consideration the local context and regional data when available.

Key performance indicators (KPIs) for evaluation sustainability credentials of desalination assets. The table also contains intervals for the global average values of selected KPIs per desalination technology as well as a summary of possible brine mitigation measures.

Main Key Performance Indicators (KPIs) for the evaluation of the eligibility of desalination assets for sustainable financing						
KPI	KPI interpretation	Project to be evaluated	Seawater Reverse Osmosis (SWRO)	Multistage Flash Distillation (MSF)	Multiple Effect Distillation (MED)	Multiple Effect Distillation with Thermal Vapor Compression (MED-TVC)
CO_2 emission (kg/m3)	Carbon footprint of desalinated water		1.7–2.8	15.6–25.0	7.0–17.6	7.0–17.6
Total equivalent electrical energy (kWh/m3)	Comparable measure of energy consumption per cubic meter of desalinated water		3–7	9.0–12.5	6.5–11	5.2–7.3
Recovery rate (%)	The proportion of intake water that is converted into high quality desalinated water		30–50% (Strong dependency on the temperature and salinity of intake water)	15–50%	15–50%	15–50%
Membrane productivity (m3/membrane/day):	Comparison of productivity amongst reverse osmosis plants		28–47 (Estimate for best-in-class SWRO plants in 2016 by the World Bank, 2019)	Not applicable	Not applicable	Not applicable
Measures taken to mitigate the direct environmental impacts of brine discharge	➢ Regulatory compliance with the maximal allowable levels of water salinity, temperature and other characteristics around discharge point(s) ➢ Continuous / frequent water quality monitoring around the brine discharge point(s) ➢ Use of computer modelling to determine the optimal brine discharge point(s) and brine discharge infrastructure characteristics such as the length of the outfall, the number of openings and the use of diffusers ➢ Mixing of brine with cooling water before discharge ➢ Neutralization of chemicals used during the desalination process before they are mixed with brine ➢ Use of brine minimization technologies to reduce the volume of produced brine ➢ Recovery of metals and / or salt from brine					

Note: **MED** = Multiple Effect Distillation; **MSF** = Multistage Flash Distillation; **SWRO** = Seawater Reverse Osmosis; **TVC** = Thermal Vapor Compression.
All the KPI data refer to the latest available global estimates. Regional estimates are more appropriate for benchmarking but may not be readily available.

Source: Natixis.

CARBON FOOTPRINT OF DESALINATED WATER

‹ KPI 1: CARBON FOOTPRINT - CO2 AND CO2-EQUIVALENT EMISSION (KG/M3)

The carbon footprint of desalinated water has the advantage of being easy to interpret: it is the amount of CO2 and CO2 -equivalent emissions per cubic meter of water produced by the desalination facility. The technical documentation of desalination facilities provides information about both the volume of water produced and the energy input to do so. The information about emission from the on-site power plant is usually available in the same documentation while the remaining carbon footprint related to the energy taken from the grid can be calculated using data about the carbon intensity of the grid in a given country.

The unit for this KPI, CO2 (and CO2 -equivalent) emission intensity (kg/m3), has the advantage of being readily comparable across all desalination technologies. This comparison usually favors reverse osmosis desalination, which is less energy intensive, hence lower carbon footprint than multiple effect distillation and especially multistage flash distillation. However, it should be noted that thermal technologies are better suited for hot and saline waters such as those in the Persian Gulf region, whereas RO is the preferable choice in colder and less saline waters. Hence the importance of benchmarking the performance of each technology under comparable conditions, preferably on a regional or local scale if data availability permits it.

The use of fossil fuels for desalination is problematic from several standpoints. Apart from the environmental perspective concerned with the emissions of greenhouse gases and discharge of brine, desalination powered by fossil fuels also exposes the user country to instability of fuel prices and depletion of fossil fuel reserves. This situation could be partially mitigated by an inclusion of renewables into the power sources for desalination. Several renewable technologies are suitable for this purpose. Solar PV and wind power plants generate electricity which can be used as an input for reverse osmosis. The heat and steam generated by solar thermal power plants is suitable for MED desalination. Nevertheless, the use of renewables to power desalination remains marginal. A study by Shahzad et al. (2017) identified 131 desalination plants powered by renewables worldwide in 2017, which only accounted for around 1% of global desalinated water production. The most used energy source for those plants is PV solar, followed by solar thermal and wind. **The major drawback for solar-powered desalination is the area required for the installation of solar panels, which may not always be available in the proximity of the desalination plant.** Existing examples of desalination powered by renewables include the Al-Khafji plant in Saudi Arabia combining SWRO and solar PV, the Australian RO plant in Kwinana powered by wind or the Hawaii thermal desalination plant operating with ocean thermocline energy (Shahzad et al., 2017).

ENERGY INTENSITY OF DESALINATED WATER

‹ KPI 2: TOTAL EQUIVALENT ELECTRICAL ENERGY - (KWH/M3)

Closely related to the carbon footprint is the second KPI measuring the total equivalent electrical energy needed by the desalination plant to produce a cubic meter of water. It is important to insist on the "equivalent" of electrical energy for the fairness of comparison. This is due to the fact that RO uses only electrical energy while thermal-based desalination technologies require both thermal and electrical energy. In absolute terms, thermal-based facilities require less electrical energy than RO facilities. However, since thermal-based technologies also require thermal energy, this has to be converted to an equivalent of electrical energy. Only after the appropriate conversion can we make a comparison between the total equivalents of electrical energy consumed by different technologies.

RECOVERY RATE: A MEASURE OF OPERATIONAL PERFORMANCE

‹ KPI 3: RECOVERY RATE (%)

Recovery rate selected as the third KPI refers to the processing efficiency of the desalination process. Recovery rate indicates the *"proportion of intake water that is converted into high quality (low salinity) water for sectoral use"* (Jones et al., 2019). This KPI is important both to evaluate the efficiency of the desalination process itself and to indicate how much water has to be taken from the water source. While the recovery rate is generally higher for RO desalination, it is highly dependent on local context such as the temperature and salinity of the intake water. For this reason, benchmarking the recovery rates of desalination facilities located in different regions could be misleading.

MEMBRANE PRODUCTIVITY (APPLICABLE ONLY FOR MEMBRANE-BASED DESALINATION)

‹ KPI 4: MEMBRANE PRODUCTIVITY - (M3/MEMBRANE/DAY)

This KPI concerns only the membrane-based desalination technologies, which in practice means reverse osmosis. Membrane productivity refers to the amount of water that can be produced by one membrane. The interest of this KPI is to track the technological progress of RO desalination plant since membrane productivity of RO has more than doubled of the past twenty years according to the most recent data from the World Bank (2019) and is set to continue to rise. Newer highly productive membranes lead to better yield of freshwater per membrane due to a larger area of the membrane surface and denser packing of membranes. This KPI also relates to KPIs 1 and 2 since productivity gains in the desalination process enable energy savings, which results in lower emissions per cubic meter of produced water.

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GREENING OF/GREENING BY DESALINATION IN SAUDI ARABIA

WHEN THE NASCENT GREEN TRANSITION OF A STRATEGIC SECTOR HAS THE POTENTIAL TO DRIVE STRUCTURAL CHANGE IN THE ECONOMY

When examining potential avenues to be explored to address the environmental externalities of desalination, Saudi Arabia's case is worth highlighting. Not only does the country heavily rely on desalination for the production of drinkable water (over 60%[1]) but it also runs a non-optimized power system both from an environmental and an economic standpoint. In 2019, Saudi Arabia generated 357TWh of electricity, 42% of which came from oil and 58% came from natural gas. It currently consumes nearly one-third of its oil production (consumption of 3,8 million barrels per day out of a total production of 11.8 million barrels per day in 2019[2]), of which around one-fifth is used for power generation purposes.

These issues are likely to further exacerbate in the coming years. The kingdom's population is indeed set to continue its growth from 4 million inhabitants in 1960 to 31.4 million in 2019 and 43.1 million in 2040, which means more desalinated water… and more electricity will be needed by then. Current forecasts estimate that Saudi Arabia will have to increase its installed generation capacity by as much as 80GWe (from 60GW in 2016 to 140GWe[3]) by 2040 to face incremental electricity demand. The bulk of the capacity needed to address such incremental demand is expected to be carbon-free, for the current government's energy infrastructure development plan provides for the commissioning of 50GW of renewable capacity (of which 41GW of solar CSP and PV assets) and 18GW of nuclear capacity.

In a threefold social, economic and environmental perspective, **Saudi Arabia's dependence on desalination and fossil fuels for the supply of drinkable water and electricity can be addressed by using the prisms of "greening of" / "greening by" desalination.** While the former concept refers to the use of new technologies/processes with the specific aim of reducing the environmental impact of desalination[4], the later emphasizes the potential role desalination could play in the transformation of Saudi Arabia's economic structures towards a more climate-friendly (and economically sustainable) business model.

"GREENING OF" DESALINATION THANKS TO LOW-CARBON ELECTRICITY GENERATION

In the desalination sector, the rationale for the targeted increased use of renewable (solar) and nuclear assets does not directly respond to environmental concerns but rather to mere economic considerations. Indeed, government's stated ambition is to bring down desalination costs[5], given the high share of electricity costs in desalination assets' overall costs, **while optimizing the use of hydrocarbon resources for the purpose of their exportation rather than domestic use.** It is also worth recalling that despite the recent development of various RO plants in the Kingdom, Saudi Arabia still mainly relies on thermal technologies (MSF and MED processes accounting for over 80% of desalination capacity) to produce desalinated water, these technologies being more energy-intensive than RO (see section 1.1.1.). To this end, the government has launched the King Abdullah Initiative for Solar Water Desalination which features the (now completed - see below) construction of the world's biggest solar-powered desalination plant (60,000 m3/day) in Al Khafji.

Saudi Arabia is actively considering the use of nuclear energy and has entered into discussions with Chinese, French, Korean and Russian engineering and equipment providers to design and later develop its own nuclear fleet. The 2010 Royal Decree laying the foundations for the future construction of nuclear reactors states that "the development of atomic energy is essential to meet the Kingdom's growing requirements for energy to generate electricity, produce desalinated water and reduce reliance on depleting hydrocarbon resources.» Development of nuclear energy could take two, not necessarily mutually exclusive directions, with the Saudi government considering:

i/ **The deployment of large reactors** (installed capacity higher than 1,000MW) to meet the country's overall electricity mix objectives but also

1. Hereby making up for roughly 18% of the world's production of desalinated water.
2. Source BP: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html
3. http://www.world-nuclear.org/information-library/country-profiles/countries-o-s/saudi-arabia.aspx
4. We leave aside the issue of brine rejection which is thoroughly discussed in the study to focus on the indirect climate externalities of Saudi Arabia's desalination industry taking the angle of the country's specific climate drinkable water-energy nexus.
5. As the abovementioned article from the World Nuclear Association highlights, "one of the main objectives of this initiative under King Abdullah City for Science & Technology (KACST) is to desalinate seawater at a cost of less than Riyal 1.5/m3 (US$ 0.40/m³) compared with the current cost of thermal desalination, which KACST says is in the range Riyal 2.0-5.5/m³ (US$ 0.53-1.47/m³), and desalination by RO, which is Riyal 2.5-5.5/m3 (US$ 0.67-1.47/m3) for a desalination plant producing 30,000 m3/d".

ii/ **The use of small units** (up to 100MW) aimed at directly powering desalination plants.

For what specifically concerns the deployment of the latter small units, discussions have been held with various providers, which eventually (2015-16) resulted in the signature of cooperation agreements with the Korea Atomic Energy Research (KAERI), Argentina's INVAP (Investigacion Aplicada) and China Nuclear Engineering Corporation (CNEC). Although there is little information available to shed further light onto these developing partnerships, it seems that KAERI's SMART reactors are well placed to address Saudi Arabia's specific needs in the desalination sector. Noteworthy is KAERI having designed an integrated desalination plant based on the SMART reactor to produce 40,000 m3/day of water and 90MWe of power at less than the cost of gas turbine.

All in all, **Saudi Arabia's case evidences a genuine albeit lengthy change in energy paradigm for the powering of desalination assets. In the next few years,** despite the difficulties experienced in the abovementioned Al Khafji project which is now completed, after having incurred a three-year delay, **change is most likely to come from renewable sources, in particular solar energy.** Two factors are likely to fuel the trend:

i/ **The continuing decline of solar (both solar PV and CSP) energy's LCOE** (Levelized Cost of Energy[6]) which has been particularly notable in the Arabian Peninsula in the recent past, as evidenced by the record-low price of the solar PV tender held in Abu Dhabi earlier this year[7] and

ii/ **Saudi government's intention to accelerate the involvement of private companies in the desalination sector through the IWPP (Independent water and power projects) framework initially set out in 2002.** This is a key factor to highlight for the expected continuing drop of solar PV and CSP technologies' LCOE will further improve the competitiveness of solar-powered desalination plants vis-à-vis fossil fuel-powered facilities. The expected landing of solar PV project costs across the Arabian Gulf should contribute to improving the economics of new desalination projects in Saudi Arabia. According to Global Water Intelligence, the price of electricity charged to desalination plant developers in Saudi Arabia currently stands on average at $48/MWh, a level substantial higher than the recent solar PV auction in Abu Dhabi ($13.5/MWh – see above).

"GREENING BY" DESALINATION THROUGH LARGE-SCALE GREEN HYDROGEN MANUFACTURING?

Taking a more forward-looking approach, the concept of "greening by" desalination is of particular relevance when applied to the Saudi economic context, for it illustrates how **the water-electricity nexus can be leveraged in such a way as to achieve both climate friendly and economically sustainable structural changes.**

Despite various economic diversification initiatives taken over the past 10 years (which are set to intensify in the wake of the recent - December 2019 - IPO of Saudi Aramco[8]), **the Saudi economy remains very dependent on oil rents,** as evidenced by the oil sector still accounting for roughly 87% of budget revenues, 42% of GDP, and 90% of export earnings[9].

This dependence raises the question of the sustainability of Saudi Arabia's economic model in the twofold context of mounting climate change awareness and gradual evolution of energy systems towards a lesser dependence on oil, particularly in the mobility sector. Observation of recent trends in this sector reveals a multiplication of technological and / or regulatory initiatives aimed at developing low carbon (or lesser carbon-intensive) energy substitutes for oil, hereby reducing the climate footprint of the various means of land, sea and air transport. In this field, let us cite the development of electric and fuel-cell vehicles[10] for land transport, regulatory incentives to switch to liquified natural gas (LNG) for marine transportation[11], exploratory developments by aeronautical companies for the propulsion of aircraft with hydrogen etc.

There is a growing consensus around the idea that **the share of oil in the means of transport (94% currently[12]) should reach a plateau in about 10 years before gradually declining thereafter** under the effect of the development of alternative vehicle fleets fueled by electricity, natural gas, biofuels and hydrogen.

6. LCOE is a concept developed to measure the average net present cost (expressed in $/MWh) of electricity generation for a generating plant over its lifetime.

7. As for solar PV, let us just mention the recent (2020) tender held in Abu Dhabi, with a record-low solar price of $13.5/MWh, which shows the considerable progress achieved by the technology in just ten years. By way of illustration, it is worth remembering that the LCOE of the solar PV sector stood at $360/MWh in 2010 (source: IRENA 2018 renewable cost database).

8. As the World Bank emphasizes, "the completion of Saudi Aramco's IPO in December 2019 reflects the government's drive to leverage oil wealth to finance diversification, transforming the Public Investment Fund (PIF) into an activist sovereign wealth fund". http://pubdocs.worldbank.org/en/223911554825481995/mpo-sau.pdf.

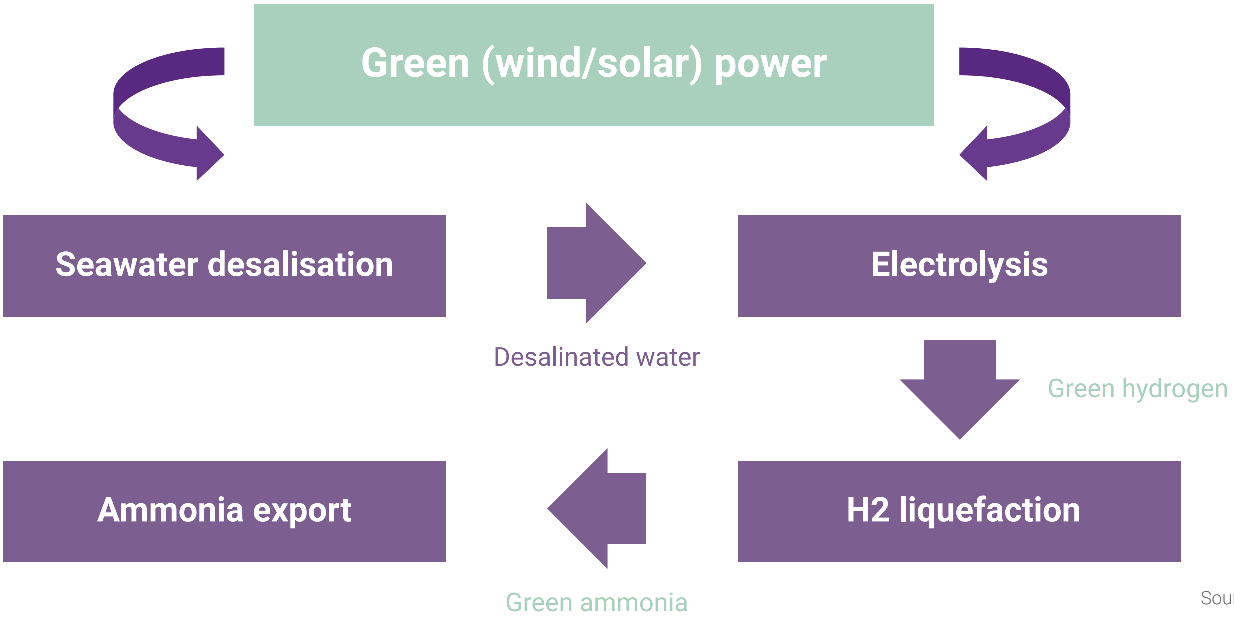
9. Source: https://theodora.com/wfbcurrent/saudi_arabia/saudi_arabia_economy.html

10. Fuel cell vehicles are electric vehicles that use a fuel cell, sometimes in combination with a small battery or supercapacitor, to power its onboard electric motor; instead of requiring recharging, however, the fuel cell can be refilled with hydrogen.

11. IMO 2020 regulation states that "from 1 January 2020, the limit for sulphur in fuel oil used on board ships operating outside designated emission control areas is reduced to 0.50% m/m (mass by mass). This will significantly reduce the amount of sulphur oxides emanating from ships and should have major health and environmental benefits for the world, particularly for populations living close to ports and coasts" (source: http://www.imo.org/en/mediacentre/hottopics/pages/sulphur-2020.aspx).

12. Source: BP (https://www.bp.com/en/global/corporate/energy-economics/energy-outlook/demand-by-sector/transport.html)

Considered value chain for green hydrogen in Saudi Arabia: From production to exports



Source Natixis

It is against such backdrop that the kingdom is currently exploring alternative strategies going beyond the mere diversification of Saudi economy, this with a clear "post-oil" perspective. The scheme being studied by the Saudi authorities considers the large-scale development of a value chain around the production of green hydrogen (namely hydrogen produced by green energy-powered electrolysis) taking advantage of the various seawater desalination and renewable energy production infrastructures (wind, solar PV) under development in the kingdom. In this scheme, the exponential fall in solar energy production costs (see above) seen over the past 10 years would be leveraged to lower the cost of desalination and electrolysis and ultimately to enter into the mass production of a molecule able to compete with fossil fuels (oil, coal, natural gas) as an energy carrier but also as a feedstock for specific manufacturing processes (production of steel, petrochemical products, etc.). Upon undergoing a liquefaction process similar to that used for the maritime transport of natural gas but requiring much lower temperatures than for the latter[13], such green hydrogen would be exported in the form of ammonia. In this context, **Saudi Arabia could eventually at some point find itself an exporter of a nearly perfect, carbon-free substitute for all fossil fuels across a wide range of sectors.** The underlying logic is to combine the different emerging water and power infrastructures so as to eventually develop a substitute for oil rent.

Although it is still under development and has not yet been the subject of any official statement by the Saudi authorities, **this national strategy is beginning to take institutional form. This is illustrated by the recent admission (January 2020) of the national oil company, Saudi Aramco, to the World Hydrogen Council,** a global initiative of leading energy, transport and industry companies with a vision and long-term goal for hydrogen to foster the energy transition.

In addition, this strategy is starting to take concrete shape, in the form of industrial projects, which are already very ambitious. As one part of "Vision 2030" laid out by Crown Prince Mohammed bin Salman, plans were announced in 2017 to create the Neom (which translates to New Future) smart city entailing a $500bn business and industrial zone covering 26,500km2 between the Red Sea and the border with Jordan. Neom has a stated aim of being "built and powered completely by renewable energy" as it strives to lead the world in commercializing clean energy intensive industries including green hydrogen, produced from renewable electricity.

The first stage in this process came in early July this year when Neom signed **a $5bn deal with Air Products, a US industrial gas and chemical company, and Acwa Power, a Saudi Arabian power and desalination utility, to build the world's largest hydrogen project.** The production facility will be powered through the integration of more than 4GW of renewable power from solar and wind. The completed facility will produce 650 tons of green hydrogen daily, enough to run around 20,000 hydrogen-fueled buses, Air Products said. The fuel will be shipped as ammonia to end markets globally then converted back to hydrogen. Ammonia production is expected to start in 2025.

The launch of this project is illustrative of Saudi Arabia's ambitions in the production and export of green hydrogen. It is however probable that **the implementation of a more systematic approach in the mass production and export of the H2 molecule should depend on technological developments in the sector** (improved cost competitiveness of electrolysers vis-à-vis established processes such as steam methane reforming – SMR – this through lower unitary capex and improved operational efficiency).

13. - 253 ° Celsius for hydrogen to compare with -161° Celsius for natural gas.

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