

State of the Art and Future Applications of Desalination Technologies in the Middle East

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Abstract Traditionally desalination has been associated to the Middle East and North Africa economies. However the availability and security of water supplies is today a growing concern and policy priority, both in the traditionally supply-constrained market of the Middle East and, increasingly, in other regions of the world. Water shortage is not only a phenomenon limited to the Middle East, and several large scale desalination projects have been awarded in other areas of the world.

Desalination volumes have nearly doubled since 2000 and it is expected to triple by 2020. Desalinated water supply has grown from 9.8 billion m³/year in 2000 to 18.1 billion m³/year in 2008, reflecting an 8% compound annual growth rate (CAGR). As water stress increases and desalination use expands outside of early-adopting areas like the Middle East, it is forecast that desalinated water volumes will reach 54 billion m³/year in 2020.

Desalination is now used in more than 120 countries around the world. Several large scale projects demonstrated during the last 30 years that it is now technically and economically feasible to generate large volumes of water of suitable purity through the process of desalination of seawater, brackish water, and water reuse. In the past the cost for seawater desalination was below US\$ 0.50/m³ in many projects, however due to material cost increase the cost of desalination has subsequently increased to US\$ 1–1.5/m³. The present chapter aims at illustrating various state of the art desalination technologies adopted for main industrial projects as well as new emerging technologies aiming at a more sustainable generation of water.

The present chapter also makes a comparison among different technologies based on energy consumption and association with power generation.

Keywords Desalination technologies • Reverse osmosis • Brackish water

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Introduction

Desalination is defined as a water treatment process that removes salts from water. Desalination processes can be used in various applications including:

- Municipal desalting of brackish or seawater for drinking water production.
- Industrial and commercial applications for production of high-purity boiler feed water, process water, bottled water, and for zero discharge applications; and production of water for industries including the pharmaceutical, electronics, bio/medical, mining, power, petroleum, beverage, tourism, and pulp/paper industries.
- Treatment of wastewater for reuse applications.

Historically, large scale desalination has mainly been built in the Gulf region where there is no alternative for public water supply. Nearly half the world's desalinated water is produced in the Gulf.

Desalination has provided a reliable source of fresh water to the growing population and economies in the Arabian Gulf region for nearly half a century and it is the main method of supplying the region with potable water.

In the Middle East, desalination of seawater is the only new and economically sustainable source of fresh water. No real development in society or industry in the area would have been possible without the parallel development and implementation of desalination.

Today, desalination is a critical component of sustaining life and economy in the Middle East and Gulf region. Some economies in the Gulf rely on desalination to produce 90% or more of their drinking water, and the overall capacity installed in this region amounts to about 40% of the world's desalinated water capacity.

Today, desalination has become a solution to water problems well beyond the traditional arid areas of the Middle East and North Africa (MENA) and has now become an accepted water treatment process around the world as a price-competitive option for more communities.

This trend continues as the cost of desalination is decreasing with respect to the level of new supplies using conventional means. With the emergence of desalination as part of mainstream water resource management in many parts of the world, the industry has paid increasing attention to reducing energy consumption and increasing environmental responsibility in its practice.

Desalination Installed Capacity and Market

According to the 25th IDA/GWI Worldwide Desalting Plant Inventory, the total global contracted capacity reached 80.47 million cubic meters per day (m^3/d) as of August 2012, with 632 new plants added during the period from mid-2011 to August 2012. Global online desalination capacity was computed accordingly as of 74.8 million m^3/d , compared to 47.6 million m^3/day at the end of 2008.

There are more than 16,000 desalination plants around the world, and the period between 2010 and 2015 has seen a 57% increase in the capacity of desalination plants online.

The growth of the market for desalination reflects the fact that coastal communities are increasingly turning to the sea to meet their drinking water needs, while inland there is a tendency for groundwater to become increasingly brackish over time. Around 60% of desalination capacity treats seawater; the remainder treats brackish and less saline feedwater.

The largest thermal desalination plant in the world the 1,025,000 m³/d Ras Al Khair project in Saudi Arabia, which uses both membrane and thermal technology.

The combination of lower cost desalination technologies and increased water scarcity has pushed for the establishment of big desalination plants outside the Gulf. The largest membrane desalination plant in the world – the 444,000 m³/d Victoria Desalination Plant in Melbourne Australia – came online in 2012, but it will be soon surpassed by the 500,000 m³/d Magtaa plant in Algeria, and the 510,000 m³/d Soreq plant in Israel.

Desalination plants are generally long life assets. These plants are strategic assets requiring large investments. With an often abrupt industrial and demographic growth pattern in the GCC countries, desalination planning is very difficult (Sommariva et al. 2001a; Al Zahrani et al. 2004).

The planning of a desalination project is an extremely delicate process. Generally, the period between the inception of a project – the phase that includes a feasibility study, technical specifications, tendering process, etc. – and the first water production requires a minimum of three to a maximum of eight years. In this scenario, increasing capacity is a process that needs to be explored well in advance, and proper master planning is essential.

The investment in a desalination plant is generally amortised in the timeframe of 20–30 years, and therefore many technical parameters that may have an influence on today's decisions can drastically change during the asset's lifetime; these include the cost of energy, cost of chemicals, availability of steam and power, and level of O&M expenditures.

Continuing efforts to reduce the energy footprint is one of the most important aspects of the desalination technology. In particular, thermal desalination technologies have been traditionally less efficient from the energy footprint point of view than membrane processes, such as seawater reverse osmosis or “SWRO”. The two major thermal desalination processes are Multi-effect Distillation (MED) and Multi-stage Flash (MSF).

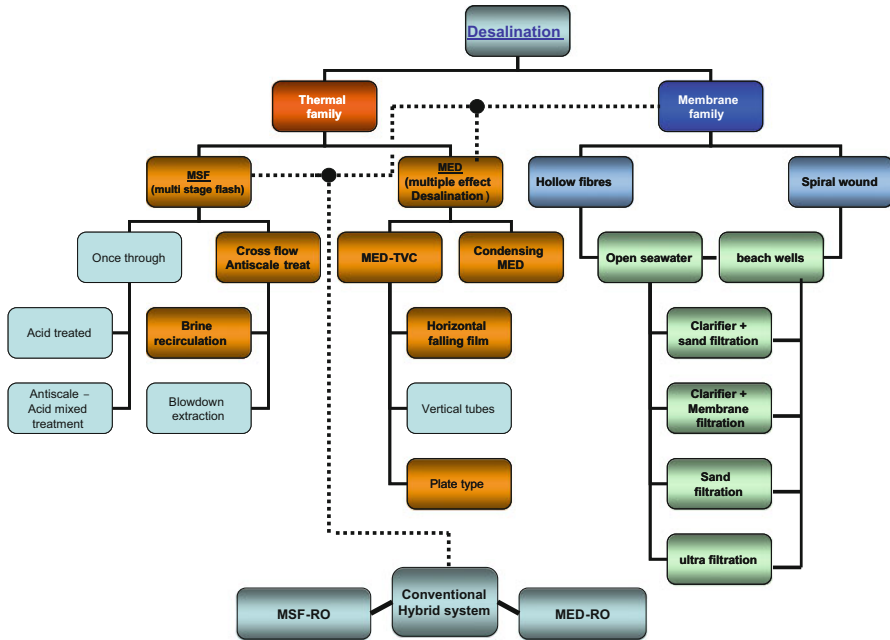


Fig. 1 Schematic illustration of desalination technology categories

Desalination State of the Art Technologies

The Family of Desalination Processes

The diagram shown in Fig. 1 illustrates schematically the family of desalination technologies that are adopted for large-scale production of water.

Commercially proven technologies include:

- Evaporative (distillation) processes
- Membrane (osmotic) processes

A combination of evaporative and membrane processes is the so-called

- Hybrid process (Sommariva and Awerbuch 2005)

Both evaporative and membrane technologies require a driving force (or driving potential) necessary for the separation process, hence they require the input of energy under various forms.

For evaporative processes the driving potential to achieve the separation of pure water from brine is the temperature difference between the hottest stage and the cooler stage, while for membrane processes pressure is the driving force.

The items in Fig. 1 marked with bold character and with colour effect are the so-called modern state of the art technologies. These technologies are available in the industry today and are operated commercially.

The remaining items indicate technologies and processes that have generally become obsolete and although still surviving in old installations not yet retired from operation, they are not specified for new projects tenders.

Thermal Family

The thermal desalination family is composed of evaporative processes.

These processes use thermal energy to produce distilled pure water from sea or brackish water. Evaporative processes rely on a phase change from liquid (in this case brine) to vapor. In this process only the water molecules pass to the vapour phase leaving the other constituents behind in the liquid. The two dominating systems that have evolved are Multi Stage Flash (MSF) and Multiple Effect Distillation (MED).

Multi Stage Flash Technology (MSF)

The MSF desalination plant is a process of compact modular construction and well-proven operational feedback in large scale industrial operation since the 1950s.

MSF technology is now considered a mature technology and its thermodynamic design continues to benefit from the operational feedback of installations that have been in operation for a long time and its performance was beyond the expectations that were projected at design stage.

The first MSF design was based on a long tube configuration with an acid dosing scale control method.

Figure 2 shows schematically the main difference between a long tube and a cross flow MSF plant. In the long tube configuration, flashing brine indicated as green arrows in the drawing flows parallel to the tube bundle which crosses each stage partition wall but in the opposite direction to the recirculating brine.

In the cross flow arrangement the tube bundle is generally located in the middle of the flash chamber and each stage tube bundle is connected by water boxes external to the vessel.

Whilst long tube arrangements present the advantage of having a large number of stages with relatively low additional costs, the expansion in size of this pattern is limited by the tube length and by the stage width.

However several long tubes MSF are still surviving in some plants in Europe and the Middle East. The scale control has been changed to mixed acid and antiscaling dosing.

On the other hand, particularly with the increase of plant capacity and unit size, the cross flow design proved not to be competitive with respect to the cross flow

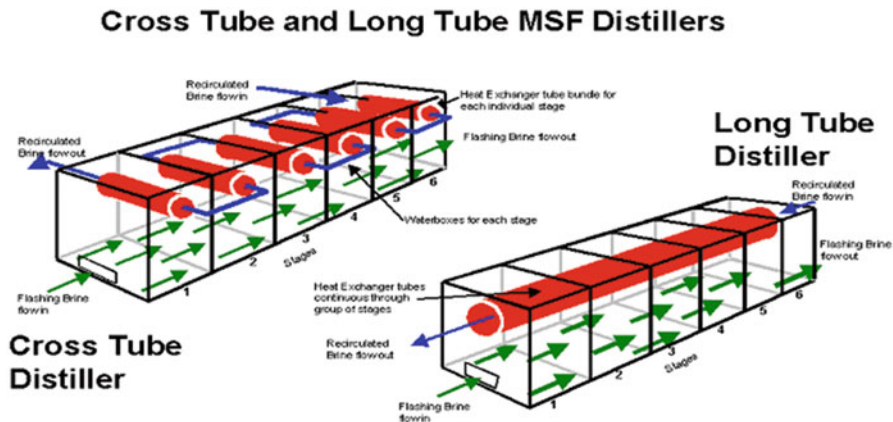


Fig. 2 MSF long tube and cross flow configuration

design and this configuration was abandoned since 1990 despite the lower specific power and heat consumption that the long tube design could offer compared to MSF (25th IDA/GWI Worldwide Desalting Plant Inventory; Sommariva 2010).

With the cross flow design the unit size has steadily increased over the years up to today's maximum of around 20 MIGD (3788 t/h) though larger units shall be considered for new projects as long as the tube length will not compromise the cross tube configuration.

The clear advantage offered by this configuration is the long life of the assets that has shown to reach 30 years and above using carbon steel material but will definitely exceed 40 years with modern material selections. Service and chemical costs are also relatively low.

Cross flow MSF distillers can be designed for a range of performance ratio (between water production and steam consumption), with a practical limit of about 11:1 (Wade et al. 1999).

Capital cost increases with performance ratio, due to the larger heat transfer surface area needed, and greater number of stages. The optimum value is usually in the range 7–9, depending on energy cost.

The operating temperature of the MSF technology is quite high and generally reaches a 110–112 °C top brine temperature. Steam is supplied from a steam turbine plant (at around 2.5 to 3.0 bar) and heat recovery boilers or a dedicated boiler plant (at around 15 to 20 bar) (Al Zahrani et al. 2004).

From the energy consumption and capital cost view point, MSF is the least efficient among the desalination processes. However in its present form of the multi stage/brine recirculation/cross tube arrangement, the technology has proven itself in long term practice to have solved the problems of reliability, scaling, chemical consumption, and unit size progression which severely limited earlier MED designs.

Until the early 2000s, MSF desalination was the main desalination technology in the GCC for plant unit size of 15 MIGD and greater and was generally combined with power generation plants. However, from the year 2010 onwards this technology became obsolete owing to high energy and CAPEX requirements.

Multiple Effect Technology (MED)

MED technology has been one of the first technologies adopted for seawater desalination.

This technology was initially very successful because of its ability to generate water with high performance ratio and the low operating temperature allowed moderate scale formation.

The first generation of MSF plant encountered severe scaling problems related to the high operating temperature and acid base scale control has always posed problems of handling and safety.

The scaling problem in MSF plants was gradually overcome by the development of sponge ball cleaning systems and specific anti-scale chemical products. Consequently, large capacity MSF plants were replaced by smaller installations using MED technology, capable of being installed in remote areas. Nowadays MED technology is the principal distillation alternative to MSF.

The main difference between MED and MSF is in the method of evaporation and heat transfer. In MED plants, evaporation occurs from a seawater film in contact with the heat transfer surface, whereas in MSF plants only convective heating of seawater occurs within the tubes and evaporation takes place from a flow of brine 'flashing' in each stage to produce vapour.

MED desalination plants are generally built in units of about 500 to 46,000 m³/d (0.1 to 10 MIGD). A dramatic increase in the unit size has been observed in the last 5 years and this has allowed MED technology to gradually take over the market shares belonging to MSF technology.

The configuration in the MSF process is unavoidably rigid due to the fact that each stage shares a partition wall and main structural elements with adjacent stages. Such a constraint would not apply in an MED process which offers the possibility of modifying basic flow configuration in many more patterns as opposed to MSF technology.

The performance ratio between water production and steam consumption of straight MED plants is approximately equal to the number of effects minus 1 to 2. For a modern project, a 10:1 performance ratio plant is typical. Accordingly, the number of effects expected would be around 12. This is much lower than in equivalent MSF plant. The smaller number of effects in MED plants results in capital cost savings.

The thermal compression of the vapour (TVC) from the low temperature stages to the first effect of the MED process offers the possibility of increasing the performance ratio of the unit by recovering the latent heat of the steam that is

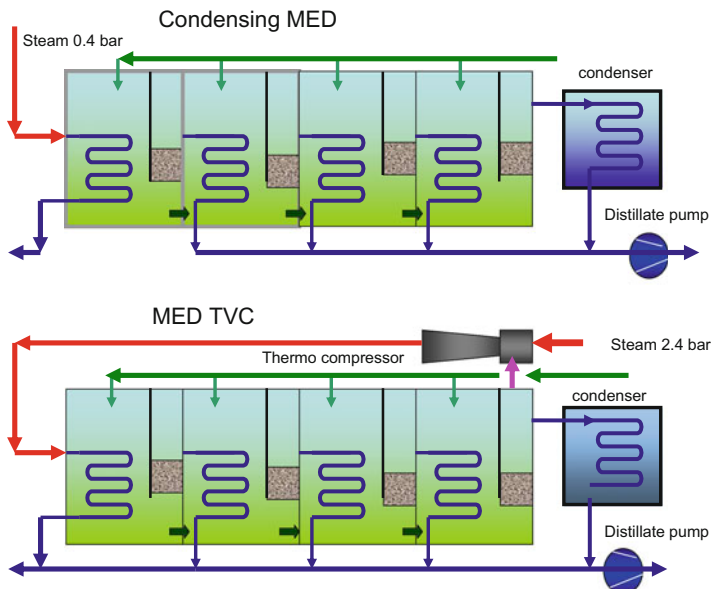


Fig. 3 Illustration of condensing MED unit and MED-TVC schematic process differences

thermo compressed to the first stage. On the other hand, this solution increases the steam extraction pressure and as the desalination unit is matched with a steam turbine the inherent power losses also increase.

The conceptual difference between a condensing MED process and a MED-TVC is illustrated schematically in the Fig. 3.

Internal power consumption of MED plants is lower than MSF, as there is no requirement to recirculate large quantities of brine. The combination of a higher performance ratio and lower power consumption results in lower overall energy costs.

Membrane Family

Membrane processes may be applied to a variety of raw water from brackish water to Gulf seawater and recently membrane processes have been successfully applied to the treatment of waste water.

The membrane acts a barrier between two phases that permits preferential and selective crossing of one or more kinds of fluid mixtures from one phase to the other (US Patent 3,133,132)

The driving forces for membrane separation may be different such as:

- difference in pressure,
- difference in concentration,
- difference in chemical potential.

Typically industrial reverse osmosis (RO) – ultrafiltration (UF) processes are pressure driven. In RO processes electric energy is used to pump seawater (or brackish water) through a series of semi permeable membranes to obtain a low salinity permeate as a product.

Thermal desalination membrane processes (with exception of membrane distillation currently applied only on small scale projects) do not rely on phase change but rather on the size and transport mobility of water molecules through a permeable membrane.

SWRO Technology

Reverse osmosis is used for the separation of fresh water from seawater or brackish water.

In 1963 Loeb and Sourirajan at the University of California, in Los Angeles (US Patent 3,133,132), developed the first synthetic RO membrane. In RO, permeate passes from the feed to the product side of the membrane when a pressure exceeding the osmotic pressure is applied. This ‘reverses’ the natural osmotic effect and concentrates salt ions into a waste concentrate stream. However, high pressure energy-intensive pumps (up to 60–70 bar) are required to drive the process.

By the 1970s larger scale commercial RO and ED/EDR systems began to be used more extensively. Initially, in brackish applications, RO had to compete against the now established electrodialysis (ED) technologies. Furthermore early RO was complicated and not always reliable.

The growth of RO was due to market standardization of the spiral wound membrane module, and the introduction of thin film composite (TFC) membranes to replace earlier cellulose acetate materials.

In the late 1970s and 1980s the development by Dow of the FilmTec TFC polyamide membrane brand resulted in process improvements including lower operating pressures, higher fluxes and higher salt rejection, which helped to reduce energy consumption and pumping pressures.

In the 1970s, the introduction of the isobaric energy recovery technology significantly reduced the operating costs of seawater RO.

By the 1980s, desalination technology had become a fully commercial enterprise and by the 1990s, the use of RO desalination technologies for municipal water supplies had become commonplace.

In this moment RO is used for:

- Desalination
- Industrial waste water treatment
- Food processing
- Production of ultra-pure water for electronic and food farms

The adoption of membranes for seawater desalination by reverse osmosis (SWRO) in the way the industry operates nowadays was put in practical use in the late 1970s. However the initial RO membrane modules were very expensive and they had very small capacity.

The membrane industry since then has continuously improved both in performance and cost, and RO became adopted in large sized plants.

SWRO membranes fall into two main categories, hollow fine fibre (HFF), and spiral wound (SW).

The use of HFF modules made from cellulose triacetate or aromatic polyamides is now limited exclusively to seawater desalination.

These modules incorporate the membrane around a central tube, and the feed solution is quite slow. As much as 40–50% of the feed may be removed as permeate in a single pass through the module.

Since then RO technology has made great progress in recent years, increasing in reliability and service factors and has become the technology of choice wherever there is a need for a stand alone desalination plant. The recent success of SWRO is derived by the lower sensible energy footprint compared to thermal desalination.

The application of this technology in the Middle East has been increasing lately and SWRO is recently taking over thermal desalination also in cogeneration plants.

In large scale SWRO plants, defined as those producing over 250,000 m³/d of fresh water, it is clear that technology will continue to see a further reduction in energy costs per unit of desalinated water, due to more efficient energy recovery devices, the introduction of new membrane types that are more resistant to fouling, larger membrane housings, and faster flows in RO plants (Sommariva 2004).

Energy Requirements

Desalination plants are energy intensive and the significant increase in fuel-energy and material costs that was experienced in the years 2006 and 2007 had a dramatic impact on the capital and operational costs of desalination and power plants.

All seawater desalting processes – multi-stage flash (MSF), multi-effect distillation (MED), and SWRO – consume significant amounts of energy.

The energy input for membrane processes is provided by electric power that is required for the major process pumps and equipment. For “thermal desalination” the energy input is both provided by the power required for the process pumps and by the heat that is the driving force of the distillation process (Sommariva 2008; Sommariva et al. 2001b).

The heat requirements of thermally-driven processes are usually met for large installations through the development of co-generation plants, where combined power and water production is achieved using the steam extracted from the turbine at a suitable pressure to produce distilled water through an evaporation process.

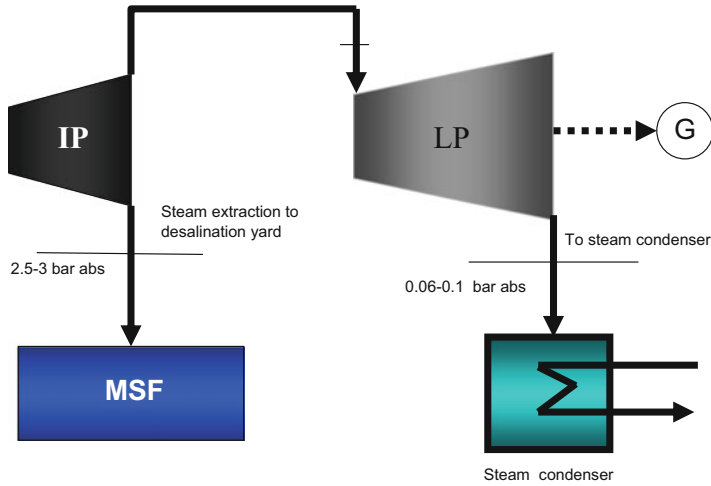


Fig. 4 Cogeneration of power and water: schematic diagram of condensing steam turbine with steam extraction feeding an MSF desalination system

The scheme that is applied is schematically indicated in Fig. 4 for a traditional condensing steam turbine configuration and in Fig. 5 for a combined cycle with back pressure steam turbine.

This process is largely energy intensive as the steam required to drive the desalination plant is extracted at a pressure of about 2–2.5 bars and could be utilised to produce substantial additional power in the steam turbine (Sommariva 2010).

The overall energy requirements according to the technology can be summarised in the Table 1. These values are based on the current state of art and include the energy requirement necessary not only for the desalination plant but also for its auxiliaries such as seawater intake, remineralization system, and potable water storage seawater chlorination.

Obviously, with reference to the second law of thermodynamic, it is impossible to compare precisely the heat and power on the same basis. Therefore the widely accepted method to align electric power and thermal energy input to the desalination plant is the reference cycle method.

Therefore the overall energy requirement has been compared with the reference cycle method. With this method, the energy associated to the steam extracted by the desalination plant is considered in terms of equivalent loss of electric power that would otherwise be rendered by the steam extracted in the power generation yard.

Table 1 summarizes overall electric energy consumption for the state of the art desalination technologies based on the current industrial configuration applicable.

As it can be seen from Table 1 after aligning the thermal and electric input to the desalination process, the difference in the energy input per unit of product water between thermal and membrane technologies is quite substantial.

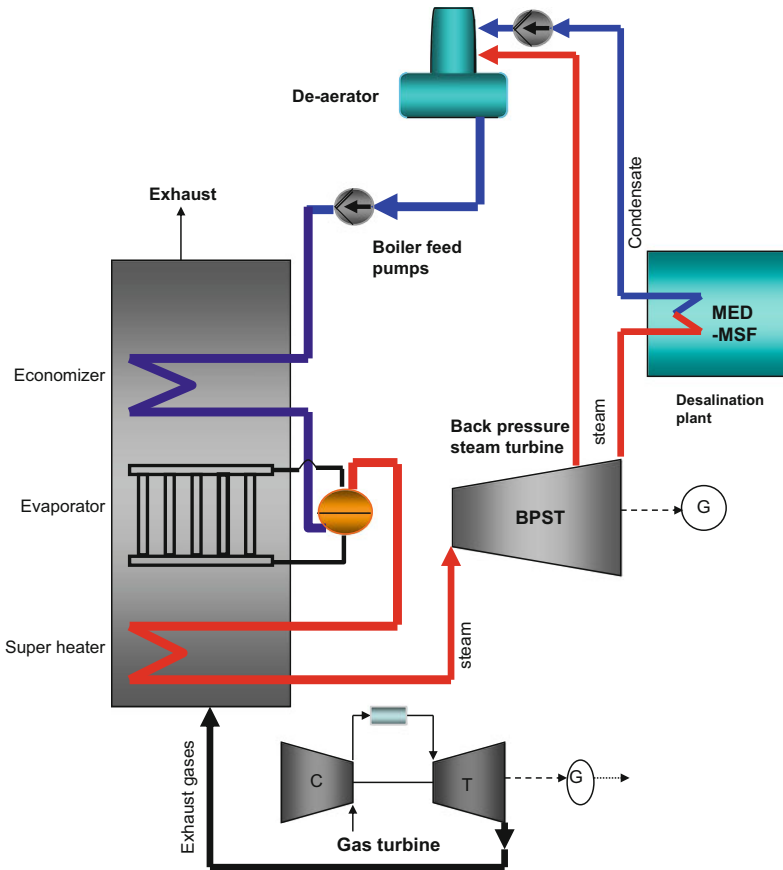


Fig. 5 Power generation combined cycle with bottoming MSF-MED schematic diagram

For general desalination projects the energy consumption of RO is considered to be lower than that for thermal processes such as MSF and MED. An exception to this is given by the low temperature condensing MED technology. This technology does not require steam for thermo-compressors and uses a 400 to 350 mbar(a) steam turbine exhaust to match the inlet temperature required for the MED units. With this configuration the thermodynamic losses are kept to a practical minimum. In this scenario MED provides a very similar equivalent power consumption to RO and MED power consumption improves. This concept was applied to relatively small plants and the main challenge is the large volume that is required for the high vapour specific volumes at low operating temperature.

However this project has particular circumstances whereby the energy consumption of MED is evaluated to be competitive with RO. These circumstances are:

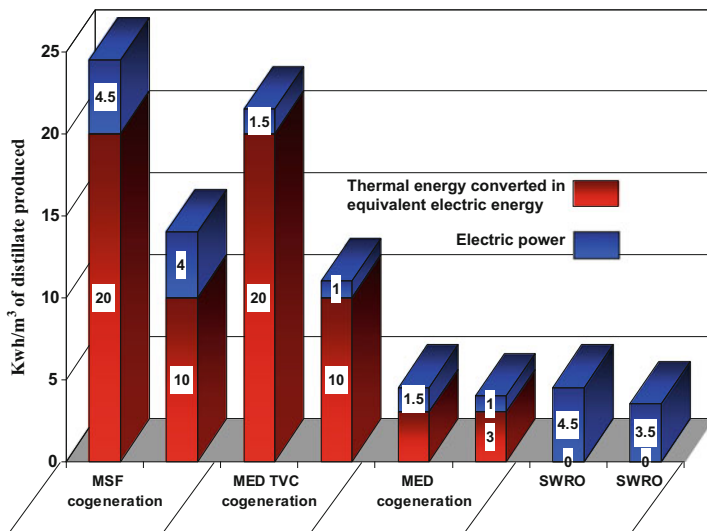


Fig. 6 Desalination technologies thermal and electric power specific energy consumption

This difference becomes even more significant as the efficiency of the power cycle decreases and the heat rate (i.e. how much fuel is burnt to produce a kW of power) decreases.

In addition to the values indicated above the difference in the power requirements can become even larger if the steam for the thermal desalination plant is generated through auxiliary boilers or with large supplementary firing that decrease the plant heat rate.

Nowadays this configuration is normally avoided at the planning and design stage. However there are still several “stand alone thermal desalination plants” – some of large capacity – still in operation.

Furthermore power plants are generally sized to meet the peak power requirement that occurs during the summer period. Steam requirements to desalination are designed to match this situation.

Unlike water demand, power demand drops dramatically in the winter season. This creates a mismatch between the steam available from the power cycle and steam actually necessary to produce the required water capacity. The additional steam needs therefore to be produced bypassing the power plant as schematically shown in Fig. 7.

The power loss for steam extraction in these operational scenarios is very high and can reach up to 40 kWh/m³ of product water.

This very high energy input is the reason why recently, even in cogeneration projects in the Middle East, SWRO has been preferred to thermal technology.

In particular it has often been proven to be more convenient taking full advantage of the steam available from the power cycle and condensing it in the power

Table 1 Desalination technologies energy consumption thermal and electric power cogeneration

	Specific electric power	Specific heat consumption	Steam Extraction pressure	Thermal energy	Equivalent power loss	Total Energy requirements
	Kwh/m ³	kJ/kg	Bar abs	Thermal kwh/m ³	Electric kwh/m ³	kwh/m ³
SWRO(Mediterranean Sea)	3.5	0	N.A.	0	0	3.5
SWRO (Gulf)	4.5	0	N.A.	0	0	4.5
MSF	4-5	287	2.5-2.2	78	10-20	14-25
MED-TVC	1.0-1.5	287	2.5-2.2	78	10-20	11-21.5
MED	1.0-1.5	250	0.35-0.5	69	3	4-4.5

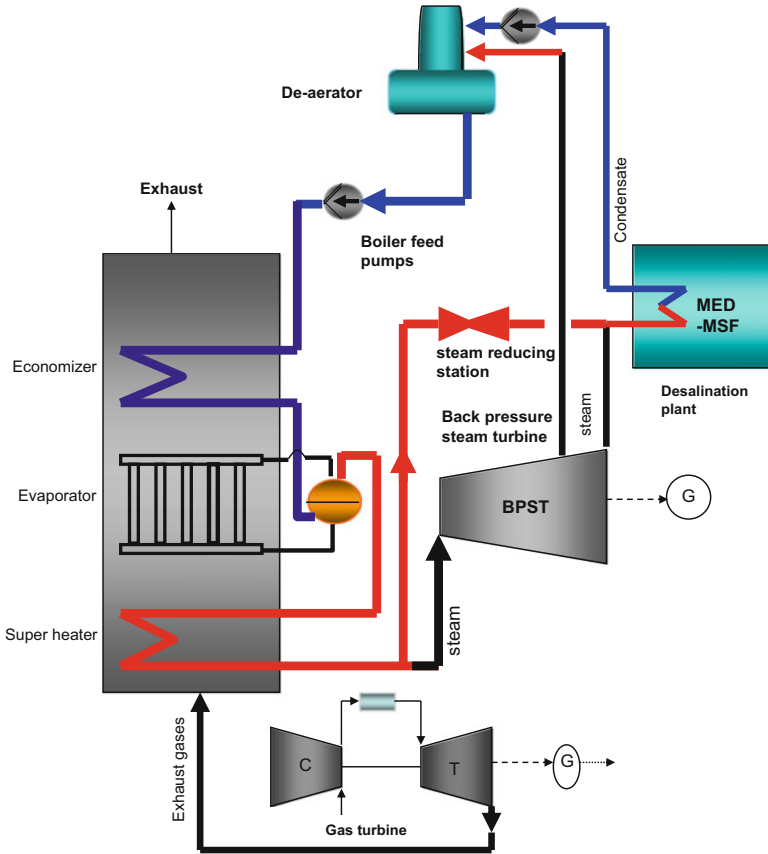


Fig. 7 Power generation combined cycle with bottoming MSF-MED schematic diagram with steam turbine isolation in winter conditions

plant condenser rather than extracting the steam to drive a thermal desalination process.

The additional power that is rendered by the steam turbine in this manner would be more than sufficient to drive a SWRO process and the electric output generated by the plant will be higher.

The viability of this solution that has been adopted in several cogeneration sites in the Middle East is generally subject to the seawater quality at the site and the extent of pre-treatment that are required for the SWRO process.

Although overall energy consumption of thermal desalination plants is greater than that of SWRO, a fair comparison would take into account that thermal desalination plants are generally installed in a co-generation scheme. That is because part of the energetic cost required to pump seawater to the thermal desalination plant would be saved by pumping seawater to the steam condenser which in turn condenses the steam coming from the back pressure of the condensing

steam turbine. In this system, the energy required to produce an equivalent amount of potable water as an SWRO could be estimated in the range of 0.3–0.5 kWh/m³ of product water. In a fair comparison of these technologies this energy amount could be credited to the electrical power demand of thermal technologies.

The energy consumption for membrane technologies is strictly related to the nature of the membranes that are employed for the desalination or purification system. New membranes are continuously developed with lower trans-membrane

Table 2 Innovative desalination technology development outlook

Thermal			
Process	Energy requirement		Energy optimisation Development outlook
	Thermal [kJ/kg]	Electric energy [kWh/m ³]	Notes
Low energy application to MED technology	200 Required at 70 °C in form of hot water or steam therefore at low exergy value	1.0–1.5	Relatively limited. However the thermal energy footprint could be reduced to 150 kJ/kg.
LTD desalination ^b	250 kJ/kg Required at 70 °C down to 50 °C in form of hot water or steam	0.8–3.0 ^a	Potentially very high. However the thermal energy footprint could be reduced to 100 kJ/kg.
Membrane distillation	300–400 kJ/kg Required at 70 °C down to 50 °C in form of hot water or steam	1–2.0 ^a	Potentially very high. However the thermal energy footprint could be reduced to 100 kJ/kg with multistage installation and proper development of MD membranes
Forward Osmosis With associated thermal energy for draw solution separation	80–100 kJ/kg Required at 90 °C in form of hot water or steam	2–3	Specific power consumption development outlook could decrease to 1–1.5 through the development of a dedicated FO membrane
Pressure retarded Osmosis	80–100 kJ/kg Required at 90 °C in form of hot water or steam	1–2	Tested in pilot application with waste water could potentially offer some substantial energy savings
Forward Osmosis	0	4–4.9	The values of 4–4.9 have been actually tested and verified in the semi industrial plant operation the development outlook suggests that a further reduction to 3 kWh/m ³ is feasible in the short term

^aThe specific electric consumption increases as the number of stages/effects increases

^bLTD low temperature distillation

pressures and therefore lower specific power consumption. Furthermore more sophisticated energy recovery devices are being introduced in the market.

Innovative Desalination Technologies and Renewable Energy

In the past 5 years, there has been a strong drive towards the development of solar desalination. This trend has been moved forward by a generally more environmental and energy conscious approach to the power and desalination market in the region. The successful application of renewable energy in the region will depend on several factors, and primarily on the capacity of creating a strong platform of interest that involves both researchers and investors as well as the governments and includes a set of policies that can seriously promote this application further.

At the present time, combinations between renewable energy sources and desalination are implemented as pilot plant size applications or are still in the R&D phase. Therefore implemented capacities -with few exceptions- are relatively small and typically range between a few m³ up to 100 m³ per day.

Table 2 summarizes the innovative desalination technology development outlook for some of the most promising developing technologies.

The desalination industry is committed to a program to reduce the energy consumption in all major seawater desalination processes. The objectives are the development and implementation of new desalination technologies characterized by lower energy footprints that could be easily combined with renewable energy sources, and the implementation of more energy efficient solutions, retrofitted into existing desalination plants.

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