Australian Government
National Water Commission

Emerging trends in desalination:
A review

UNESCO Centre for Membrane Science and Technology
University of New South Wales

Waterlines Occasional Paper No 9, October 2008

Waterlines

A SERIES OF WORKS COMMISSIONED BY THE
NATIONAL WATER COMMISSION ON KEY WATER ISSUES

Waterlines

This paper is part of a series of works commissioned by the National Water Commission on key water issues. This work has been undertaken by the UNESCO Centre for Membrane Science and Technology on behalf of the National Water Commission.

Online: ISBN: 978-1-921107-69-6

Emerging trends in sesalination: A review , October 2008

Published by the National Water Commission

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Canberra ACT 2600

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Date of publication: October 2008

Cover design by: AngelInk

An appropriate citation for this paper is:
UNESCO Centre for Membrane Science and Technology 2008, *Emerging trends in desalination:* A review, Waterlines report, National Water Commission, Canberra

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Overview

1. The desalination of seawater has become an important source of drinking water for Australia's coastal cities. By 2013 a total of approximately 460 gigalitres per annum (GL/yr) of drinking water will be produced from desalination plants operating in Melbourne, Sydney, Perth, Adelaide and parts of south-east Queensland.

2. Desalination systems have been used to supply potable water for coastal communities and urban centres in more than 40 countries. Desalination plants operate in almost all of the world's oceans and seas. However, most of this capacity is installed in the Arabian Gulf and the Mediterranean. Current installed desalination production capacity is approximately 3100 GL/yr in the Arabian Gulf and 800 GL/yr in the Mediterranean.

Technologies

3. Drinking water can be produced from seawater using membrane or thermal processes. Membrane desalination plants produce potable water by molecular separation, while thermal desalination plants work by breaking bonds between water molecules.

4. Thermal distillation is the oldest form of desalination and was first used to produce drinking water for large urban communities in the early 1950s. Thermal processes accounted for slightly more than 70% of the global desalted water capacity in operation by the year 2000, and are used in the majority of the desalination plants with a capacity of more than 100 megalitres a day (ML/d).

5. Membrane processes using Reverse Osmosis (RO) membranes were first used in the mid 1960s on small desalination systems (less than 10 ML/d). However, due to continuous improvement in RO, more than 70% of the desalination plants installed since 2000, including major facilities with capacities in excess of 100 ML/d, use RO.

6. The objective of the desalination process is to remove salts and other molecules that form the Total Dissolved Solids (TDS) content of the water source. For seawater desalination, it is necessary to reduce the TDS content from 35 000 to 45 000 mg/L down to less than 500 mg/L. In Australian applications, additional treatment is required to reduce TDS to less than 100 mg/L, to match the TDS level of the drinking water supply. Like any source of drinking water, desalinated seawater receives further treatment with disinfection, to:

    - remove microbial pathogens
    - achieve chemical stabilization, and
    - prevent corrosion of pipes, and in some cases fluoridation, to reduce the incidence of dental caries.

7. In Australia, desalination plants in operation or under construction use reverse osmosis membranes to produce drinking water. The reverse osmosis process is very versatile and can be used on other sources of water that contain levels of TDS in excess of 500 mg/L. These sources include brackish groundwater and wastewater. Brackish groundwater is mostly found in inland Australia. Communities with access to brackish groundwater use reverse osmosis membranes to reduce the TDS to drinking water levels (less than 500 mg/L). In the case of seawater or brackish water desalination, the product water is delivered directly to homes and businesses via the existing drinking water distribution system.

8. Desalination processes are also used to remove dissolved solids from municipal wastewater. The product water from the desalination of wastewater may be further treated to remove trace levels (<0.1 mg/L) of organic molecules, and to be disinfected. The desalted wastewater may be used directly for industrial applications by the chemical, steel and oil refinery industries. However, unlike desalinated seawater, this water may not be delivered directly to homes or business via the drinking water distribution system, even though the water is as clean as or cleaner than desalted seawater or groundwater. Nevertheless, in some cases, such as the south-east Queensland Western Corridor project, desalted wastewater is returned to the environment via a river or a groundwater basin, where it mixes with rain water and eventually forms part of the overall drinking water supply.

Cost

9. The cost of producing drinking water via seawater desalination has steadily declined since the first large-scale thermal plants were commissioned in the Arabian Gulf in the mid 1950s. Although little historical cost data is available in the public domain, the cost of production, or water tariff, for thermal plants has been estimated to decrease from close to US$9.0/m^3 in the later 1950s to US$0.7/m^3 reported in 2000 for the Taweelah A1 & A2 plants in Abu Dhabi. A similar cost trend can be gleaned from tariffs reported for reverse osmosis desalination plants, which range from US$1.55/m^3 in 1991 at Santa Barbara, California to US$0.8 in 2000 at Trinidad, down to US$0.63/m^3 in 2003 in Ashkelon, Israel.

Environmental Impact

10. The construction of a desalination plant will impact on the terrestrial, marine and atmospheric conditions of the local environment. Guidance documents developed by the California Coastal Commission (Seawater Desalination And the California Coastal Act, March 2004), the United Nations Environmental Programme [1] and the World Heath Organisation (WHO, 2008) describe how design and construction approaches can mitigate likely impacts. However, experience shows that best practice designs do not obviate the need for careful stewardship during the operating phase.

11. The environmental impacts that are unique to desalination plants are those associated with the intake of seawater and the discharge of concentrated salt stream. Other impacts such as the disposal of waste sludge from the chemical treatment process, and the physical impacts of establishing high voltage power supply and the pipeline to deliver water to the potable distribution system, depend on the location of the plant.

12. The impact of desalination plants on the marine environment can be mitigated with careful design and diligent operation. However, while the physical impact of desalination plants in industrialised precincts may be minimal, the plant and associated power and water distribution infrastructure will permanently mark the environment in a “greenfield” location. Therefore it is critical that the need for and capacity of a desalination plant as a means of creating addition potable water supplies be evaluated against the water savings that can be achieved in urban areas through recycling and conservation.

Energy Considerations

13. The efficient production of potable water by desalination of seawater is a global objective. Many countries including Singapore, China, Korea, Japan, the Arabian Gulf States, the United States and members of the European Union have active R&D programmes involving government, industry and academic institutions. The research is focused on reducing the energy requirements for seawater desalination from the current benchmark of 3.5 kWh/m^3 to the theoretical minimum of 0.8 kWh/m^3 (see Appendix 1 for an explanation of the theoretical minimum energy input for desalination). Options for reducing the energy requirements include alternative desalination processes (such as forward osmosis) and the development of new generation membrane materials for reverse osmosis systems. Some promising technologies, such as the nano-composite particle membranes and carbon nano-tube membranes are still in the developmental stage. Consequently, many R&D programmes include projects to improve the efficiency of established desalination processes such as distillation and reverse osmosis. The proceedings of the International Desalination Association (IDA) bi-annual conference contain information on the latest developments in both thermal and membrane desalination processes.

14. The management of energy consumption and the attendant greenhouse gas emissions are a significant factor in the development of desalination processes. The operation and maintenance costs for reverse osmosis based desalination processes are very sensitive to movements in the price of electricity. For example, in a two pass reverse osmosis system utilizing a medium efficiency energy recovery plant (4.0 kWh/m^3) designed to produce fresh water with less than 150 mg/L and less than 0.1 mg/L of boron, the water production costs would increase by 170% (\$0.34/m^3 to \$0.91/m^3) as the power costs increase from \$0.05/kWh to \$0.2/kWh (Section 3). Consequently, it is very important that water utilities investing in desalination develop effective strategies to manage the impact of increased power costs on the cost of producing and supplying potable water produced by desalination.

15. The operation and maintenance costs of desalination schemes will also be impacted by the introduction of a price for carbon. Consequently, offsetting the carbon emissions associated with desalination is an important part of managing potential increases in the cost of water as a result of the introduction of an emissions trading scheme or equivalent system that puts a price on carbon. For example, a desalination facility with a power consumption of 4.6kWh/m^3 that sources electricity produced by black coal will emit between 4.7 to 6.0 kg CO_2 /m^3 depending on the location of the plant. The introduction of an emissions trading scheme where carbon is priced at \$50 per tonne of CO_2 will add approximately 16% to the operation and maintenance cost of the facility.

1. Global Status of Desalination and Alternative Water Supply Projects

Desalination is the term broadly used to describe the production of potable water from various sources of raw water. The sources may include brackish water, river water, waste water, pure water, and seawater. In this sense, desalination is the process of reducing the concentration of dissolved solids in the raw water – ranging from 500-700mg/L for treated domestic waste water to 15,000-50,000 mg/L for sea water – to below the WHO target of 1000 mg/L for potable water (and in some cases less than 50 mg/L).

Desalination involves using one of a number of processes to separate salt from water. At a molecular level, this can be achieved by either breaking the hydrogen bonds between water molecules and the dissolved solids, or by separating free water molecules from the water molecules bound to solvated species. Desalination plants achieve this by exploiting differences between the water molecules and the salt ions, either in terms of size and charge, or in the energy required to break intermolecular bonds.

Membrane desalination plants produce potable water by molecular separation, while thermal desalination plants work by breaking bonds between water molecules. Both approaches require an energy input for seawater under standard atmospheric temperature and pressure conditions. The energy input for membrane processes reflects the pressure energy required to pump water molecules through a size/charge selective membrane and is expressed as kWh/m^3 of product water, while the energy input for thermal processes reflects a combination of the heat required to break the bonds between the water molecules (expressed as kJ/m^3) and the energy required to pump the seawater through the process (expressed as kWh/m^3).

This chapter provides an overview of alternative water supplies (including examples of existing projects), issues associated with gaining access to source water, and an outline of the different treatment processes. The chapter also canvasses the factors that must be considered in order to protect public health and safety, and provides guidelines for an assessment of environmental impacts (particularly those associated with the discharge of brine).

1.1 Geographical Distribution

Desalination systems have been used to supply potable water for coastal communities and urban centres in more than 40 countries. Plants operate on almost all of the world's oceans and seas. However, the bulk of the capacity is installed on the Arabian Gulf and the Mediterranean. In 2004, the installed desalination capacity was estimated at 3065 GLA in the Arabian Gulf and 711 GLA in the Mediterranean. Figure 1 illustrates the total size of the desalination market in each of the 4 key global markets.

1.2 Experience in the Use of Alternative Source Waters

Desalination techniques are applied to raw water of various qualities in addition to seawater. Brackish water, river water, waste water and even treated drinking water from municipal supply are subject to desalination. The definitions of different categories are as follows:

- Seawater: 15,000-50,000mg/L TDS
- Brackish water: 1,500-15,000mg/L TDS
- River water: 500-3,000mg/L TDS
- Pure water: less than 500mg/L TDS
- Waste water (untreated domestic): 250-1000mg/L TDS
- Waste water (treated domestic): 500-700mg/L TDS

Raw water quality is determined by geography and usage. The largest markets for brackish water desalination are in central Asia, Australia and the continental United States, where there is a greater prevalence of saline aquifers. Most river water and all pure water desalination are for industrial usage – typically where the user requires ultra pure water for an industrial process. The largest markets for river and pure water desalination are Japan, Korea and Taiwan.

Although brackish water desalination installations tend to be smaller than seawater desalination facilities, the number of brackish water reverse osmosis (BWRO) installations is growing at a faster rate.

Desalination techniques such as RO, nanofiltration (NF) and ultrafiltration (UF) are increasingly used in municipal water treatment plants around the world. This creates a definitional problem for anyone assessing the market for desalination. Most laymen would define desalination as the purification of seawater. Outside the USA, most water professionals define desalination as the purification of seawater or brackish water. They would not use the word “desalination” to refer to river water, wastewater and pure water filtration.

The breakdown of the utilized water sources for each of the 4 global markets is provided in Figure 1.

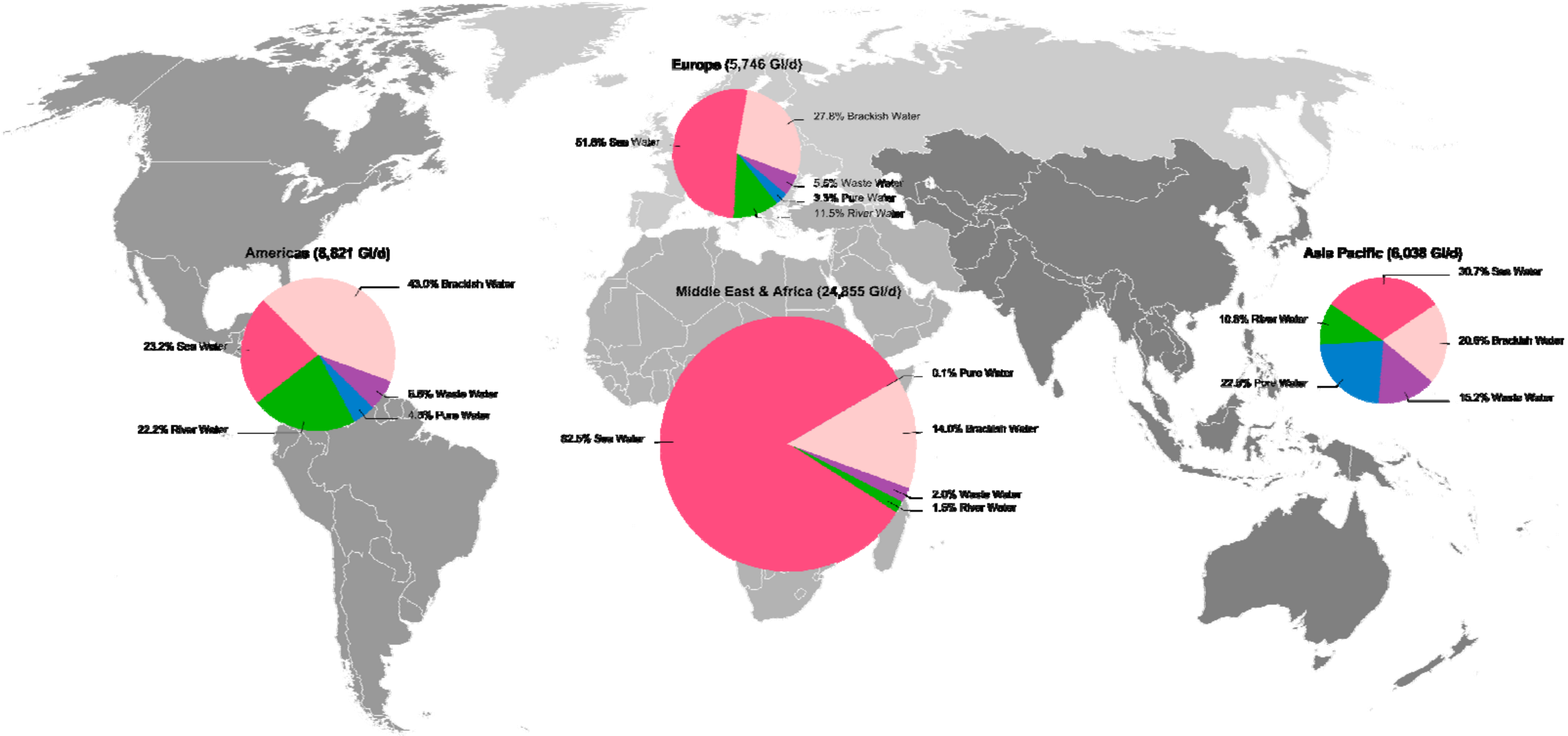

Figure 1: Relative usage of different source water types.

1.3 Current Desalination Technologies

Desalination technology can be broadly divided into two categories: Thermal and Membrane systems. Thermal processes are based on the concept of distillation, which is a phase separation process whereby two different molecules present in the same phase can be separated according to the latent heat of vaporization of each species. Thermal desalination processes exploit the lower heat of vaporization of water molecules compared to the dissolved salts present in seawater. Membrane processes work by forcing the water through a semi-permeable material using size and charge exclusion to purify the water. The membranes used in desalination processes are referred to as RO membranes, because water molecules move from the concentrated salt solution to a dilute salt solution against the osmotic pressure gradient.

1.3.1 Multi-stage Flash Distillation

Multi-stage Flash (MSF) Distillation is the most common form of thermal desalination in use today. The MSF process uses a series of chambers that operate at progressively lower pressures. Each chamber can be divided into three sections. The top section contains a bundle of tube heat exchangers, which carry the influent seawater. A distillate collection chamber is positioned immediately below these heat exchangers. Distillate condenses on the outer surface of the tubes, collects in the trough, and flows into the next stage in the opposite direction to the movement of seawater through the heat exchanger tubes.

Consequently, influent seawater enters the process through the heat exchanger tubes at the top of the last chamber, while distillate moves from the first chamber to the last chamber via the collection trough. Seawater temperature increases progressively through each chamber, until it reaches the first chamber, where steam for the boiler heats the seawater to the top brine temperature for the system – which occurs in the first chamber.

The top brine temperatures (TBT) for the MSF process typically range from 90^{o}C to 115^{o}C. The pressure in the boiler ensures that flashing does not occur until the seawater enters the low pressure environment in the first stage. The heated seawater enters the bottom section of the first chamber, where the combination of heating and low pressure forces the seawater to boil violently and instantly vaporize (or flash) into steam. The flash vapour rises rapidly to the top of the chamber and passes through demister pads to remove entrained brine, and it condenses on the outer surface of the tube heat exchanger, which also contributes to the initial heating of the influent seawater on the inside of the tube. Concentrated seawater (brine) and distillate flow in the same direction from first chamber to the second and so on until the last stage.

MSF plants can be designed as once through systems (MSF-OT), where the brine is discharged into the ocean or fitted with additional pumps to recirculate a portion of the brine (MSF-BR). Recycling brine can decrease the amount of steam and the volume of seawater required. It can also reduce the consumption of chemical conditioning agents such as anti-scalants and anti-foaming compounds,[1]

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[1] Antiscaling and antifoaming chemicals are discussed in more detail in Chapter 3.

which decreases operational costs. Brine recycling, however, increases the concentration of salts in the seawater, which will increase the boiling point of seawater and can increase the probability of corrosion and scale formation. Consequently, the brine concentration in the last stage must be maintained to avoid scaling, corrosion and the operational and maintenance consequences of elevated temperatures.

A rule of thumb is that use of MSF-OT plants are limited to small installations, typically less than 2500 m^3/d distillate production, while large scale applications (>2500 m^3/day) use the MSF-BR process with up to 50 to 60% of brine recycling. The energy requirements for MSF consist mostly of a heating and pumping component. Heating requirements can vary from 8 to 10 kWh/m^3 while pumping power requirements for MSF vary from 2.0 to 3.6 kWh/m^3.

Brine flow through the MSF process is turbulent as a result of the violent boiling in each stage. However, the use of progressively lower pressures from the first stage to the last stage minimizes heat losses, which allows multiple chambers to be linked together in a single unit. Consequently, MSF plants can have between 20 and 40 chambers in series. The relationship between the number of effects and gained output ratio (GOR) is influenced by a variety of variables, including the orientation of the heat exchanger tubes to the distillate collection duct. In general, with all other variables being equal, the GOR is approximately 1/2 to 1/3 of the number of effects for installations where the distillate collection ducts are perpendicular to the tube orientation, and 1/4 of the number effects in plants where the collection ducts are parallel.

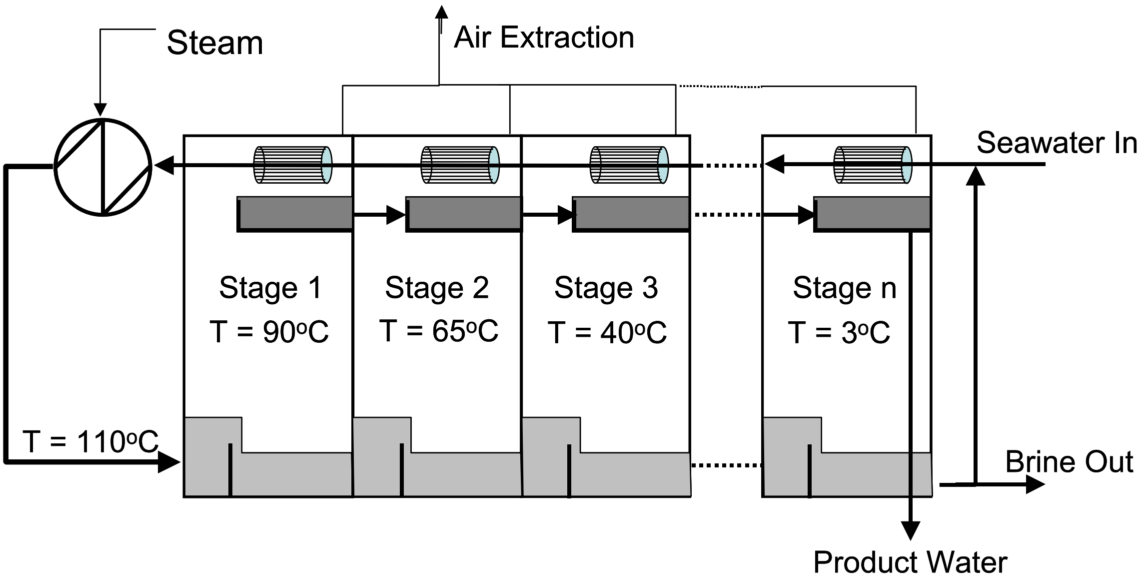


Figure 2: Multi-stage flash distillation

1.3.2 Mechanical Vapour Compression

Mechanical Vapour Compression (MVC) uses mechanical energy rather than steam as a source of thermal energy. MVC processes use a series of chambers each containing a set of heat exchanger tubes. Water vapour is drawn from the evaporation chamber by a compressor, and it is condensed on the outer surface of the heat exchanger tubes in all but the first chamber. The heat of condensation is used to evaporate a thin film of seawater that is recompressed on the inside of the tubes within the evaporation chambers. The smallest MVC systems are typically single effect units that operate slightly above atmospheric pressure at a temperature of 102°C.

1.3.3 Multiple Effect Distillation

The Multiple Effect Distillation (MED) process uses a series of chambers that operate at progressively lower pressures. The purpose of using multiple chambers at lower pressures is an attempt to maximize the recovery of energy in the vaporization condensation cycle and exploit the reduced heat requirements for vaporization at lower pressure. Each chamber is fitted with a bundle of tube heat exchangers. The orientation of the tubes in the chamber is a function of the mechanical and heat transfer properties of the tube material. Heat transfer per tube can be increased by increasing the velocity of the steam circulated on the inside of the tube. The efficiency of an individual chamber can be increased by increasing the surface area of the heat exchanger, which increases with small tube diameter (more tubes per bundle) and tube length. Heat exchanger design attempts to minimise the rate and number of tube supports required to prevent the deformation of the thin tubes that increases with tube length.

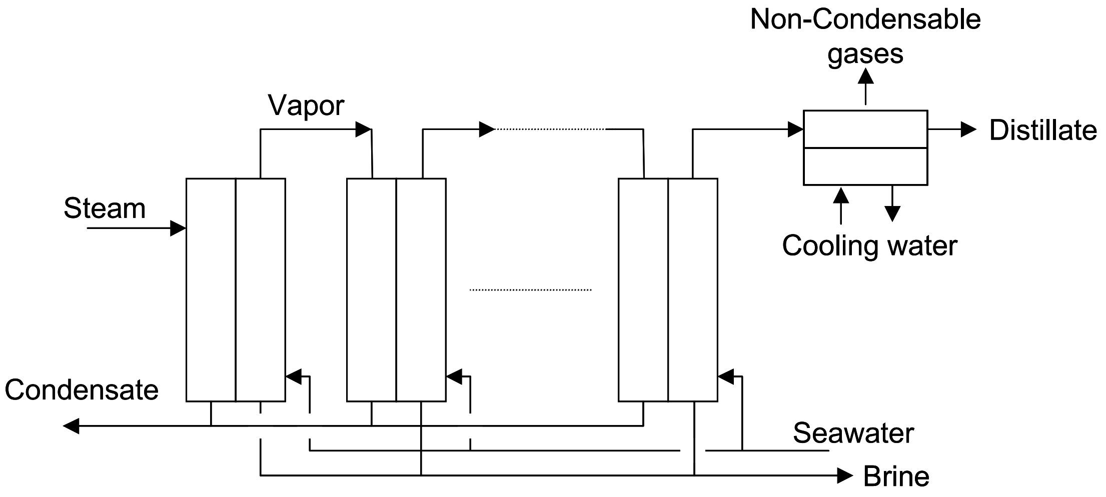


Figure 3: Multiple Stage Distillation with Thermal Vapour Compression

A comparison between currently operational thermal desalination facilities is shown in Table 1.

Table 1: Design and Performance Comparison of Recently Commissioned Thermal Desalination Plants

Parameter	**MED-TC**		**MSF - OT**	**MSF - BR**		**MVC**
Location	Abu Dhabi, UAE	Bahrain	Chile	Abu Dhabi, UAE	Balashi, Aruba	Lagos, Nigeria
Seawater Source	Arabian Gulf	Arabian Gulf	South Pacific	Arabian Gulf	Caribbean	Benin Bight
Seawater Temperature	16 to 38	33	23	18 to 32	27	25
Feed TDS (mg/L)	47,800	45,800	34,400	45,000	36,110	2,000 – 35,000
Product TDS (mg/L)			5	25	5	25
Commissioning Date	2002	2002	1996 & 2000	1995	1983 to 1998	2002
Production Capacity (m^3/day)	240,000	43,000	8,100	343,000	42,000	2,250
Seawater Feed Flow (m^3/day)	2,313,600	334,080	76,080	2,874,960	349,608	3000
Process Recovery	10%	12%	10%	12%	12%	50%
Number of Units	6	4	5	6	7	3
Capacity per Unit (m^3/day)	17,137	10,750	1,340 & 2,740[3]	57,254	6,000	750
Effects per unit	6	4	12	20	40	1
Top Brine Temperature (TBT) (^{o}C)	63	62	105	112	110	70
Gain Output Ratio (GOR)	8.0	7.51	3.6	7.6	11	-
Steam Requirements						
Low Pressure Steam (T/m^3 distillate)	0.124 (97%)	0.134[2]	0.266	0.102 (98%)	0.091 (96%)	-
Ejector Steam (T/m^3 distillate)	0.004 (3%)	-	-	0.002 (2%)	0.003 (4%)	-
Heat Consumption (kJ/m^3 distillate)	282.5	342	684.1	290.7	213	-
Power Consumption (kWh/m^3)	1.65	1.25	1.44	3.1	2.77	11

MED: Multiple Effect Distillation, MSF - OT: Multi Stage Flash Distillation Once Through, MSF-BR Multistage Flash Brine Recycling, MVC – Mechanical Vapour Compression

1.3.4 Reverse Osmosis

Membrane desalination processes rely on the ability of membranes to differentiate between and selectively separate water and salts. The most common application for membrane desalination used throughout the world is RO. Osmosis is a process which uses a semipermeable membrane to separate solutions of different concentration. The solvent flows at a faster rate than the dissolved solids from the side of low concentration to the side with higher concentration. RO relies on a difference in chemical potential between the solutions on either side of the membrane. The chemical potential is a function of concentration, pressure and temperature, and the solvent flows across the membrane in order to bring these factors in the two solutions into equilibrium. When in a system of finite volume, the liquid level on the low concentration side of the membrane decreases, resulting in a hydrostatic pressure difference between the two sides. Once the hydrostatic pressure difference is equal to the driving force for flow, the system has reached equilibrium, and the net flow of solvent stops. The equilibrium hydrostatic pressure level is known as the osmotic pressure.

RO operates by pressurising the saline feed solution to a pressure greater than osmotic pressure. This causes the chemical potential of the solution to fall below that of the pure solvent, driving solvent flow from the solution side to the pure solvent side of the membrane. The pressurisation process is the single greatest energy consumption process in the entire operation.

Aspects unique to the RO desalination process are the need for pre and post treatment of feed and product streams. Pre-treatment is required to prevent fouling, scaling and membrane degradation so as to increase the efficiency and operating life of the membrane being used for separation. Inert and reactive suspended materials are physically removed by coarse screens, while filtration is employed to rid the feed of fine colloidal matter or microorganisms. A chemical conditioning system is also employed to control pH and add anti-scaling compounds, which limit the build up of sparingly soluble salts and alkaline and non-alkaline scales on the membrane. Post-treatment meanwhile is implemented to remove any dissolved gases (CO_2) and to stabilise the pH (achieved with Ca^{2+} or Na^{+} salts) of the pure water being produced.

The efficiency of the membrane desalination process has the potential to be limited by several factors, including;

- High osmotic pressure
- Chemical composition of the feed
- Feed temperature

Increasing the recovery through the reverse osmosis system will lead to an increase in the concentration of dissolved salts on the membrane surface. This will limit the efficiency of the RO process by increasing the osmotic pressure that must be overcome by the feed pump, which in turn increases the energy requirement. Also, because the salt removal efficiency is a fixed property of the thin polymer film membrane, an increase in salt in the feed will lead to an increase in salt in the permeate. Similarly, increasing the recovery increases the concentration of salt on the membrane surface which creates conditions favouring the formation of alkaline scales such as calcium carbonate, non alkaline scales such as calcium sulfate, precipitating sparingly soluble salts such as barium sulfate or depositing silica complexes. The deposition of these scale forming compounds can be limited to an extent by pH control and the use of anti-scaling chemicals which interrupt crystal growth at the nucleation stage. Consequently, the combination of elevated osmotic pressure and scale formation limits the process recovery of RO systems to 40 to 60% depending on the nature of the seawater (see Table 2).

The viscosity of the seawater increases with decreasing temperature. Consequently the pressure driving force will be lower at higher temperatures for feeds to comparable water quality. However, the polymers used to fabricate the RO membrane elements become susceptible to damage and deformation at elevated temperatures. Therefore, although increasing the feed temperature can decrease the energy requirements, the safe upper operating temperature limit for RO membranes is between 35 and 40°C depending on the manufacturer.

Table 2: Definition of RO System Design Parameters and Typical Values

Parameter	**Description**	**Value**
Stages	The number of RO pressure vessels arranged in series. Increasing the number of stages will increase the recovery of the system	1 - 2
Passes	The number of times the permeate is processed in the desalination plant. Additional passes are required to achieve high quality (low TDS).	1 Pass (> 500 mg/L) 2 pass (< 300 mg/L)
Operating Pressure	Pressure at which the RO feed pumps operate to overcome osmotic pressure limitations and resistance due to membrane, feed viscosity and fouling. The operating pressure depends on the level of dissolved solids.	50 to 70 bar
Recovery	Percentage of water that is recovered from the feed as permeate. The recovery depends on the TDS of the seawater and the number of passes	35 – 60%
Energy Requirements	Specific Power Consumption per unit of water production. Power increases with increasing TDS and increasing temperature.	2.8 – 5 kWh/m^3

Location	Florida, USA	Grand Cayman
Seawater Source	Tampa Bay	Caribbean
Feed TDS (mg/L)	18,500 to 30,500	37,000
Feed Temperature (°C)	24°C to 35 °C	27 °C
Product TDS (mg/L)	TDS < 500: Cl < 100	TDS < 500: Cl < 100
Commissioning Date	2003	1989
Capacity (m^3/day)	94,625	2,270
No of Trains	7	2
No of stages per train	2	1
No of pasess	1	1
Recovery	60%	43%
Operating Pressure	60 to 68 bar	70
Energy Requirements	2.96 kWh/m^3	4.2 kWh/m^3

1.3.5 Electrodialysis and Electrodialysis Reversal

Electrodialysis is a membrane process which harnesses electrical rather than pressure energy for the separation of water from saline solution. ED functions by attracting ions with a DC current. Electrostatic forces attract positively charged ions (cations) to the negatively charged cathode, and negatively charged ions (anions) to the positively charged anode. EDR systems are comprised of a stack of ion exchange membranes, each either anion or cation selective. The selective membranes are arranged alternatively and allow like ions to pass, but reject unlike ions (i.e. anions are allowed to pass through anion selective membranes but cations are rejected). The membranes are thus able to remove the unwanted salts from the water to be purified.

The membrane stack itself is also comprised of alternating feed and concentrate channels. Thus for a feed channel in a vertical stack with cathode at the top and anode at the bottom, a cation selective membrane will be at the top of the feed channel to allow the cations attracted to the cathode to migrate through the membrane and up into the next concentration channel. The concentrate channel then has a cation selective membrane at the bottom and anion selective membrane at the top (at the anode), which works to keep the cations in the concentrate channel. The reverse applies to anions which travel down until they reach a cation selective membrane.

The presence of the cathode and anode at each end of the stack generates polarity. In electrodialysis reversal (EDR) the polarity of the electrodes is reversed periodically to prevent the accumulation of fouling and scaling material on the membrane surface. This makes EDR more tolerant to membrane degeneration and fouling than other membrane technologies such as reverse osmosis.

1.3.6 Hybrid Processes

A hybrid seawater desalination plant integrates the use of thermal and membrane processes with an electricity generating power plant. The design seeks to maximize flexibility by using two different forms of energy for desalination. The design also takes advantage of waste heat for the thermal process and higher feed temperatures for the membrane process. Finally, the design allows the use of RO on high TDS waters by making low cost power available during off peak periods for the operation of the second pass RO system. This would be required for RO to produce high grade water on high TDS seawater feeds.

1.3.7 Ion Exchange

Ion exchange (IE) is a process which uses chemical energy to desalinate water. Cations and anions are removed separately from saline water by very small resin beads in an exchange vessel. The process starts with the feed passing through a cation resin. Here the resin is initially highly charged with H^+ ions, but as the water flows past the resin, the cations in the solution (mostly Na^+) are absorbed onto the IE resin and replaced in the solution with the H^+ ions. The partially treated water is now rich in H^+ (thus has a low pH) and is fed to the anion exchanger. The anion resin is highly charged with OH^- and replaces any anions (mostly Cl^-) from the feed which will be attracted to the resin as before. The OH^- and H^+ ions in the stream combine to make water. This water leaving the stream is relatively free of ions and has a pH very close to neutral.

Over time the effectiveness of the exchange process decreases and the product water starts to incorporate unacceptably high levels of ions. This is due to the H^+ and OH^- ions in the cation and anion exchangers becoming used up. To restore the efficiency of the process, a strong acid (sulphuric or hydrochloric) is passed through the cation resin to regenerate its level of H^+. Caustic soda is similarly fed to the anion resin to replenish the OH^- concentration.

Due to the use of the very small resin beads in IE, it is essential to remove solids in pre-treatment. This will help to prevent excessive head loss development through the exchange bed.

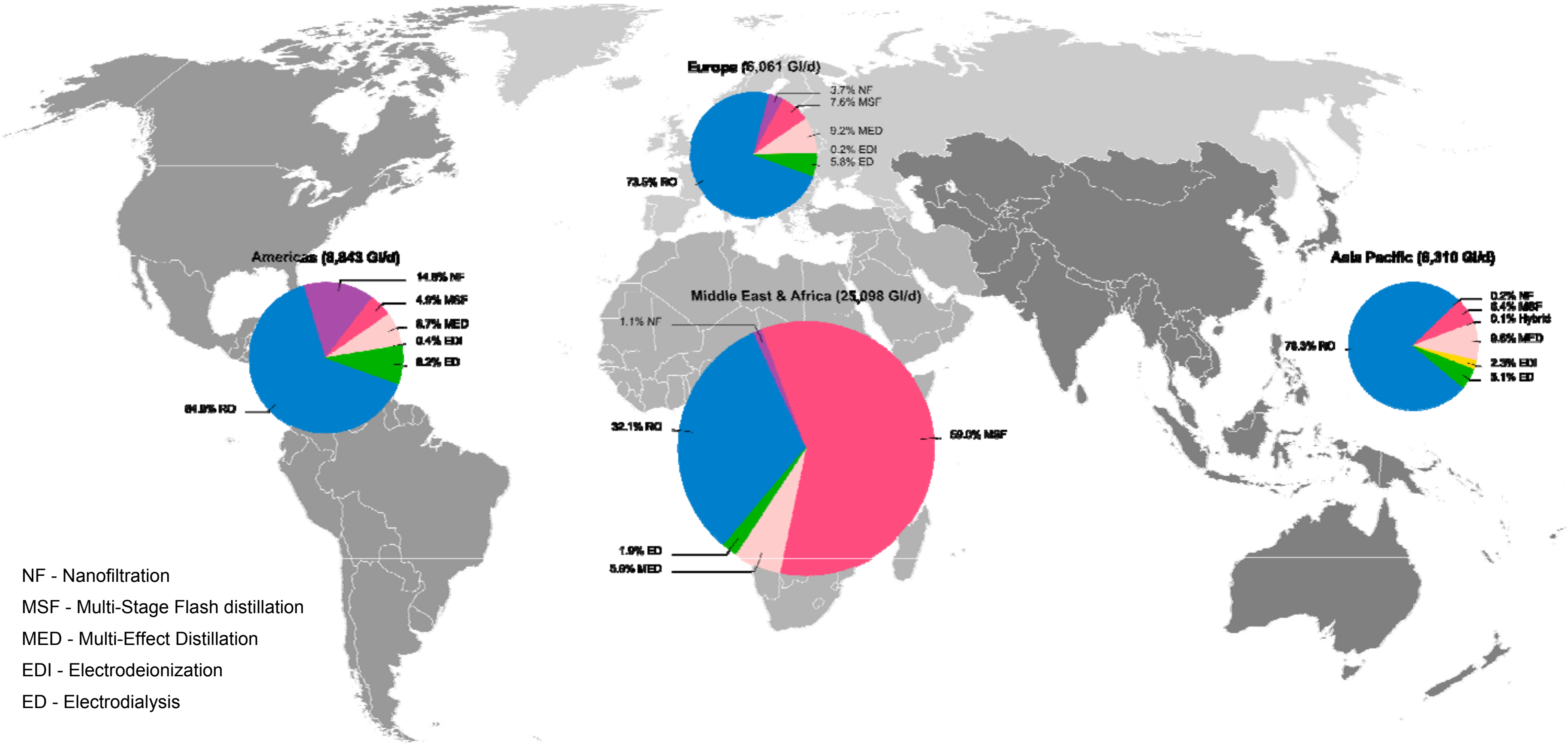


Figure 4: Global technology use for desalination

1.6 Health and Safety Considerations for Different Source Waters

Desalination feed water can be sourced from a range of locations including seawater, brackish or fresh ground or surface water, and waste water. The quality and consistency of the feed water is important, as it will affect the performance of the downstream treatment processes.

1.4.1 Seawater

In considering the health and safety impacts of different source waters, the World Health Organisation (WHO) noted that potential causes of concern for seawater sources include (WHO, 2008):

- Domestic waste water discharge containing microbial pathogens and/or persistent chemicals.
- Offshore dumping of hazardous wastes including chemicals, pathogens and radioactive materials
- Brine and other wastes from desalination plants
- Discharge from industrial complexes, including hydrocarbons and heavy metal –organic compound complexes
- Increased organic loadings associated with fish kills or decomposing marine life and
- The trapping or blocking of intake screens by aquatic organisms, or by the passage of these organisms through screens and into and potential colonisation of the process equipment.

1.4.2 Surface or ground-waters

Surface water can be drawn from sources such as lakes and estuaries whilst groundwater is drawn from aquifers. For open lakes and estuaries the similar sources of concern are applicable as for seawater. The use of groundwater is often more consistent in water quality than surface sources, however contamination of groundwater is a growing concern. Potential sources for groundwater contamination include discharge of domestic wastewater (contains a microbial risk), industrial discharge, hazardous waste dumping and fertilizer and pesticides from agriculture.

1.4.3 Wastewater

Municipal wastewater collected from domestic and some industrial sources can be treated and reused for a variety of agricultural, irrigation and industrial uses. In some applications municipal wastewater can be treated and used to augment raw drinking water supplies stored in aquifers or dams. In general the level of treatment required increase with the probability of public contact. The recently released Australian Water Recycling Guidelines use a risk management framework to determine the level of treatment and the preventative measures required to operate water recycling schemes. The treatment technologies used in recycling applications include filtration, UV irradiation or chlorination for the removal of microbial pathogens, reverse osmosis for the removal of salts and organic chemicals and advanced oxidation processes for the removal of trace levels of organic chemicals.

1.5 Operational Reliability of Different Source Waters

Desalination systems utilising seawater, ground water and waste water sources generally operate with high system reliability, maintaining constant water production and consistent product water quality. However, operational problems do occasionally occur, which may result in a loss of production capacity or a change in the water quality.

In the case of desalination systems that use the membrane process, the most common system reliability problem is loss of production capacity, rather than a change in the quality of the water produced. This is because operational problems that limit the ability to push water across the membrane are more common than those that damage the membrane and allow the passage of salts from the feed water to the product water side. Common operational problems, and their impact on system reliability in seawater, ground-water and waste water applications, include:

Table 3: Reliability of Water Sources

Application	Operational Problem	Impact on Reliability
Seawater (Membranes)	Clogging of intakes or pre-treatment	Decrease in plant production capacity. No loss of product quality
	Biological growth on membranes and process surfaces	Increase in energy requirements Possible loss of production. Negligible impact on quality
	Precipitation of calcium carbonates and sulphates on membrane surface	Marginal increase in energy. Decrease in product water quality
Seawater (Thermal)	Precipitation of salts and corrosion of heat exchanger surfaces	Loss of energy efficiency and decrease in equipment life. No loss of product quality
Groundwater (Membranes)	Precipitation of salts and silica on membrane surface	Marginal increase in energy requirements. Increase in salt transport across membrane and decrease in product water quality
Wastewater (Membranes)	Biological growth on membranes and process surfaces	Increase in energy requirements to drive water across the membrane. Possible loss of production capacity. Negligible impact on product quality

1.6 Environmental Impacts of Harvesting Alternative Water Sources

1.6.1 Site and Space Requirements

Sea water desalination plants are located in coastal environments. Factors to consider when selecting a site include:

- the availability of a power supply
- proximity of a main water distribution pipeline, and
- access to a predominantly marine coastline rather than an estuarine coastline, to provide consistent water quality at the plant intake and allow for rapid dispersion of the concentrated brine from the desalination process.

The desalination plant consists of:

- a network of seawater intakes
- a pretreatment process to remove suspended solids and other particles from the sea water
- the desalination process (either thermal distillation or reverse osmosis)
- a product water conditioning stage that includes a process that reintroduces mineral hardness to prevent corrosion of the potable water delivery system, and
- a final disinfection and possibly fluoridation.

The desalination site includes provisions for final product water storage and delivery to the potable supply system, and a series of balance tanks and pumps to return the concentrated brine to the marine environment.

Like any coastal development, the construction of a desalination plant will impact on the terrestrial, marine and atmospheric conditions of the local environment. Guidance documents developed by the *Seawater Desalination and the California Coastal Act, California Coastal Commission March 2004*, the United Nations Environment Programme [1] and the World Heath Organisation (WHO, 2008) describe how appropriate design and construction activities can mitigate likely impacts. However, experience demonstrates that even with the best practice designs, there is a continued obligation for careful stewardship during the operating phase to minimise the potential for adverse environmental impacts.

The key environmental impacts associated with desalination plants derive from the intake of seawater and the discharge of concentrated salt stream. Other impacts, such as the disposal of waste sludge from the chemical treatment process, the physical impacts of establishing high voltage power supply, and the construction and operation of the pipeline to deliver water to the potable distribution system, depend on the location of the plant. The desalination plants in Kwinana industrial precinct near Perth or around Tugun Airport on the Gold Coast are built in developed industrial areas, while the Melbourne's proposed desalination plant will be built on a Greenfield site near Wonthaggi. Consequently the likely impacts on the terrestrial environment, including noise, visual and traffic impacts, will be different for each location. Nevertheless, regardless of the location, each plant must mitigate the impact on the marine environment that is inevitably associated with the seawater intake and the brine stream outfall.

1.6.2 Brine Disposal

The desalination plants constructed in Australia use reverse osmosis membranes to separate seawater into a high quality product stream and a concentrated salt stream. The ratio of concentrate to product typically ranges from 1.2 to 1.9. Consequently, to produce 1 L of potable water it is necessary to draw 2.2 to 2.9 L of seawater from the ocean.

The environmental impact of brine discharge into marine environments is a key issue for coastal desalination plants [2] [3] [4]. However, the majority of current international knowledge relates specifically to a few heavily impacted and relatively enclosed water bodies, including:

- the Mediterranean Sea [5] [6] [7] [8]
- the Red Sea [9]
- the Persian Gulf [4] [10]

Many marine organisms are highly sensitive to variations in salinity [11]. For example:

- echinoderms appear to have been severely impacted in an area close to a Mediterranean SWRO discharge [6]
- seagrasses such as Mediterranean Posidonia and their associated ecosystems appear to have been impacted in some regions [5] [6] [7]

Because a dense, hypersaline plume will tend to sink and disperse slowly, biota likely to be affected are bottom-dwelling or non-mobile species that live on or are physically attached to the reef [12]. These include fan corals, sponges, stalked and sessile ascidians, anemones and attached algae.

At present, there is little information available on the salinity tolerances of these species or their responses to chemicals contained in the discharge plume. The impacted zone for a 500 ML/d plant under quiescent conditions is assumed to be about 0.5 hectares [13].

In some circumstances, brine plume density may lead to increased stratification reducing vertical mixing, which may reduce dissolved oxygen levels, with ecological implications [14]. This possibility was raised as a particular concern during the planning and assessment for the Perth Seawater Desalination Plant discharging into Cockburn Sound, a large semi-enclosed embayment.

However, detailed modelling and site investigation concluded that the anticipated brine discharge is unlikely to contribute to the exacerbation of low-oxygen conditions in this case [15]. Nonetheless, an on-going dissolved oxygen monitoring program has been installed since construction of the plant [3].

A comprehensive study on the effect of the disposal of seawater desalination brines on near shore communities in the Caribbean was completed by the Southwest Florida Water Management District and the University of South Florida [16]. This study involved a detailed analysis of the environmental impacts of the discharges from seven relatively small existing SWRO plants in the Caribbean with plant capacities between 170 kL/d and 6 ML/d, and discharge salinities between 45 and 56 g/L.

All of the plants had been in operation for at least 4 years prior to the completion of the study. The study found no statistically significant impact from discharges on local benthic marine life, seagrasses, microalgae or micro and macro-invertebrates.

Recently, a biological method was reported for the assessment of the salinity tolerance of marine organisms on seawater desalination plant discharges [17]. This method was used for the evaluation of the environmental impact of the discharge of the 200 ML/d Carlsbad and Huntington Beach seawater desalination plants located in Southern California.

The testing concluded that TDS discharge concentration of 40 g/L or less has no measurable effect on the marine environment in the vicinity of the discharge [17]. Chronic toxicity testing of the brine using topsmelt – a fish inhabiting the area of the discharge and used as a standard chronic toxicity-test organism – indicated that this species can withstand salinities of up to 50 g/L.

1.6.3 Inland environments

It is generally not feasible to discharge brines produced from inland brackish water desalination plants to the marine environment. In such cases, it is common to dispose of the brines via evaporation ponds managed by regular salt removal [18]. However, in circumstances where discharge to land or freshwater systems is proposed, a number of ecological factors should be considered.

Brines may be applied to land, either as an irrigation process or simply for disposal by infiltration or evaporation. In either case, over time, salts present in the water accumulate in the soil profile as exchangeable ions. This can affect the physical and mechanical properties of the soil, such as soil structure, the degree of dispersion of soil particles, permeability, and stability of aggregates.

Osmotic effects caused by salt concentration in soil water can have detrimental effects on plants [19]. Excellent drainage and maintaining a downward flow of dissolved salts through the root zone is the only practical way to manage this.

Irrigation water quality guidelines published by the Food and Agriculture Organization of the United Nations recommend maximum concentrations of trace elements in irrigation water [19]. Among these, selenium (0.02 mg/L) is likely to be a limiting element in some cases. Above this concentration, selenium is toxic to plants and may also be toxic to livestock if forage is grown in soils with relatively high levels of added selenium [19].

High sodium concentrations in soil can cause deterioration of the physical condition of the soil; for example, by waterlogging, the formation of crusts, and reduced soil permeability [20]. In severe cases, the infiltration rate can be greatly reduced, preventing plants or crops from accessing enough water for good growth [19]. Primarily because of the high levels of TDS, sodium, chlorides, and boron in the brine from seawater desalination plants, this brine is typically unsuitable for irrigating food crops. However, brackish water or surface water brines may be acceptable for irrigation of some halophytic plants.

The disposal (or run-off) of saline wastewaters into freshwater streams or wetlands poses risks to diverse biota including microbes, macrophytes and micro-algae, riparian vegetation, invertebrates, fish and amphibians [21]. Data suggest that direct adverse biological effects are likely to occur in Australian river, stream and wetland ecosystems if salinity is raised to around 1000 mg/L [21]. Furthermore, it is likely that salinity changes would disrupt broader ecosystem processes, such as nutrient spiralling/recycling and energy flow through trophic webs. Such processes underpin the health and integrity of entire ecosystems.

1.6.4 Current Status of Outfalls

Direct ocean discharge of brines is widely practiced in many countries employing seawater desalination. Examples include plants in:

- Saudi Arabia [9] [22]
- Malta [22]
- Cyprus [22]
- Oman [10] [23] [24]
- Palestine [25] [26]
- Spain [27] [28]
- Australia [3]

In fact, it has been reported that over 90 per cent of the large seawater desalination plants dispose of their brine through a new ocean outfall specifically designed and built for that purpose [29].

As a result of their high salinity, seawater brine plumes are denser than seawater. Therefore, they have negative buoyancy and sink towards the seabed, moving along the bathymetric contours [30]. This is in contrast to the more common wastewater plumes which are buoyant and rise to the surface. Accordingly, understanding and modelling desalination plumes involves different challenges to those posed by wastewater discharge plumes [30]. The dense plume has fewer immediate and far field mixing processes than more buoyant plumes [31].

A key challenge for dedicated ocean outfalls is to minimise the size of the zone in which the salinity is elevated, before adequate mixing with ambient waters [30]. In some cases, this can be achieved by reliance on the mixing capacity of the tidal (surf) zone. However, this approach may lead to high salt concentrations along the shoreline [32]. In other cases, where the discharge occurs beyond the tidal zone and in low energy environments, it is necessary to install diffusers to accelerate and facilitate mixing [33]. The salinity threshold, mixing/transport capacity of the tidal zone and/or necessary diffuser configuration, can be estimated with hydrodynamic modelling [3].

Two models used for salinity plume analysis are CORMIX and Visual Plumes [29]. Both allow depiction of brine plume dissipation under a number of outfall and diffuser designs and operational conditions. Other modelling techniques and criteria to enhance diffusion of discharged brine also exist [23] [30] [32]. However, it should be noted that the science of predicting near field dilution achieved by dense fields has not been greatly studied [31].

For the Perth Seawater Desalination Plant at Cockburn Sound, a series of tests and models – including a one dimensional box model and three dimensional hydrodynamic models – were used to ensure the plant would meet the required criteria at the edge of the mixing zone [3]. Increased certainty was achieved by running various scenarios and different models. Tank tests were also undertaken during the diffuser design, and an expert review of the design was undertaken prior to installation.

Pilot field measurements indicated that during calm periods, near-bed dissolved oxygen levels naturally decrease in Cockburn Sound [34]. As a result, and because of the semi-enclosed nature and topography of Cockburn Sound, a detailed study was undertaken to consider the extension (if any) of any natural stratification and associated dissolved oxygen issues that may result from brine discharge

[14]. This study concluded that any additional effect on dissolved oxygen levels would be infrequent and minor. However, it recommended that because of the uncertainty of predictions for long calm periods, a monitoring program should be implemented as part of an adaptive management plan [14].

The Perth desalination plant outlet measures 1.2 m in diameter and has a 160 m long, 40 port diffuser, where the ports are spaced at 5 m intervals – with a 0.22 m nominal port diameter, located 470 m offshore, at a depth of 10 m, adjacent to the plant in Cockburn Sound [33]. The diffuser is a bifurcated double-T-arrangement and incorporates a discharge angle of 60°.

This design was adopted with the expectation that the plume would rise to a height of 8.5 m before beginning to sink due to its elevated density. It was designed to achieve a plume thickness at the edge of the mixing zone of 2.5 m and, in the absence of ambient cross-flow, 40 m laterally from the diffuser to the edge of the mixing zone [35].

The operating licence for the Perth desalination plant requires that certain dissolved oxygen levels are met in order for the plant to operate [36]. Furthermore, a minimum of 45 dilutions must be achieved at the edge of the mixing zone, defined in terms of a 50 m distance from the diffuser.

Extensive real-time monitoring is currently being undertaken in Cockburn Sound for its first year of operations, to ensure that the model predictions are correct and that the marine habitat and fauna are protected [3]. This includes monitoring of dissolved oxygen levels via sensors on the bed of the Sound. Visual confirmation of the plume dispersion was achieved by the use of 52 L of Rhodamine dye added to the plant discharge [37]. The expulsion of the Rhodamine dye from one of the plant diffusers is shown in Figure 5 [38].

The dye was reported to have billowed to within about 3 m of the water surface, before falling to the seabed and spilling along a shallow sill of the Sound towards the ocean [37]. The experiment showed that the dye had dispersed beyond what could be visually detected within a distance of around 1.5 km – well short of a protected deeper region of Cockburn Sound about 5 km from the diffuser [37]. The environmentally benign dye experiment was first commissioned in December 2006 and repeated in April 2007, when conditions were calm.

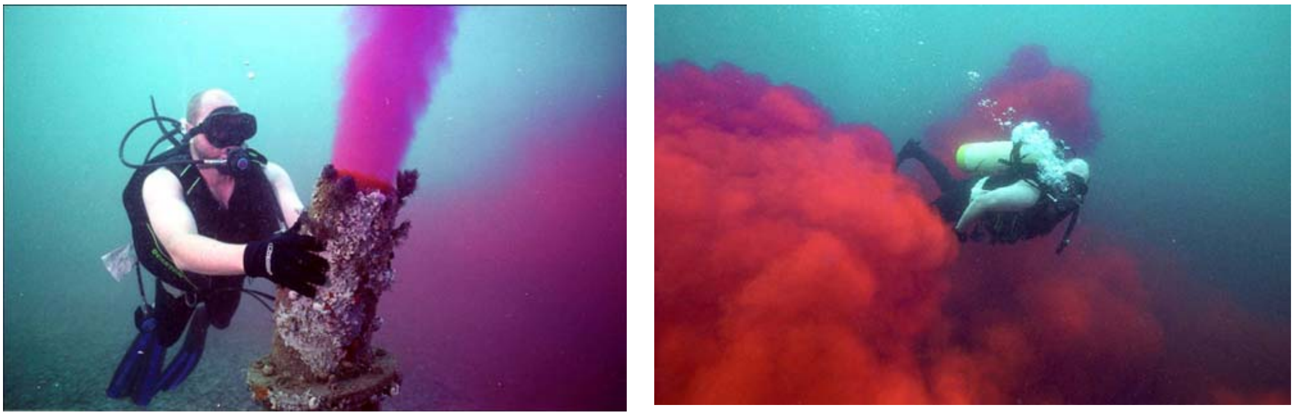


Figure 5: Rhodamine Dye Tests Undertaken at the Perth Seawater Desalination Plant .

An alternative approach for the marine disposal of desalination brines is by co-location with water-cooled power plants [39] [40] [41]. A key feature is the direct connection of the desalination plant intake and discharge facilities to the discharge outfall of the power plant. This allows for the use of power plant cooling water, both as a source of water for the seawater desalination plant and as blending water to reduce the salinity of the desalination brine prior to the discharge.

As an example, a 50 ML/d (permeate) capacity seawater desalination plant operating at 50% recovery and treating seawater at 35 g/L TDS draws 100 ML/d feed flow from the power plant cooling loop and discharges a brine stream of 50 ML/d at 70 g/L TDS. If the cooling water intake is 1500 ML/d, after the 100 ML/d desalination plant withdrawal and subsequent blending of 50 ML/d of brine, the ultimate ocean discharge consists of 1450 ML/d of seawater at about 36.2 g/L TDS, a salinity only 3.5% greater than ambient concentrations (as opposed to 100% greater without blending with cooling water discharge) [39].

1.6.5 Current Status of Intakes

The feed water intake for desalination facilities must supply a feed of reliable quality and quantity. The type of intake employed is important, as it will affect the plant capital cost and the pre-treatment options available to achieve the desired quality for the RO membranes. However, it must also meet environmental and ecological requirements, either onshore or offshore. The availability of types of intakes will also be influenced by the location of the desalination.

Desalination plants can draw seawater from open seawater intakes, below-ground beach wells and infiltration galleries, or from the cooling water discharge conduits of power plants. Potential impacts of intakes include:

- impingement of larger marine organisms such as fish, jellyfish or turtles in the intake structure
- entrainment of smaller marine organisms in the desalination plant
- disruption and re-suspension of sediments on the seafloor into the water column, and
- alteration of natural currents in the vicinity of the intake.

The extent of each impact differs for each intake structure.

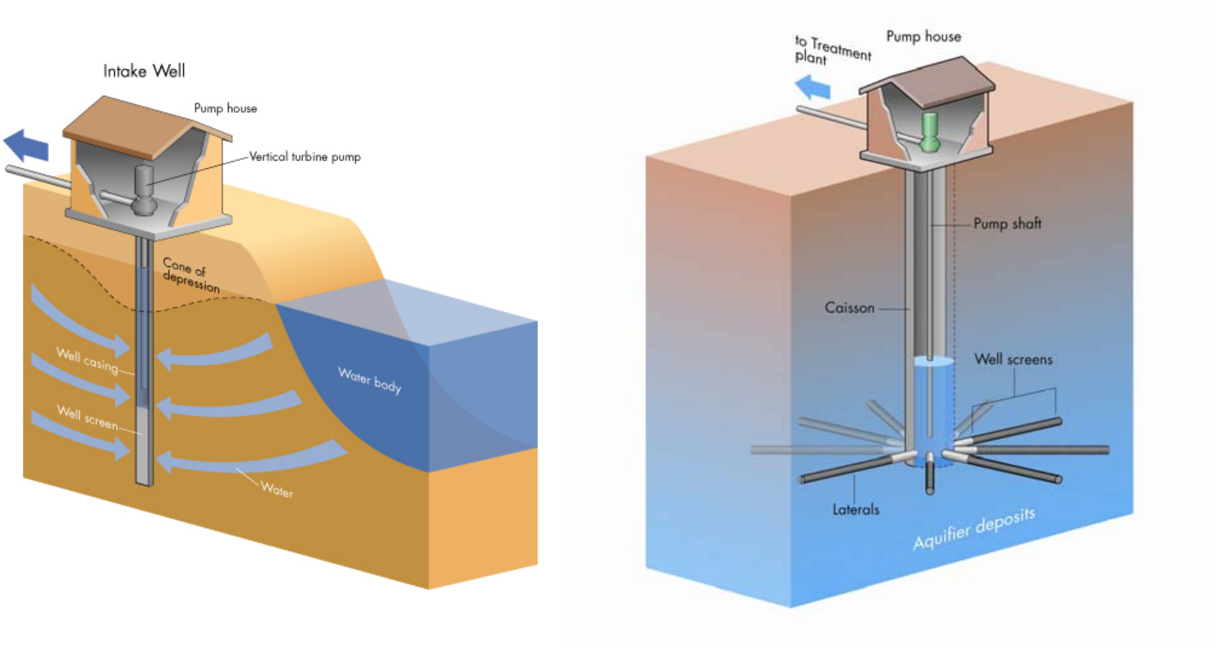
Open seawater intakes, either located on the seafloor or on a purpose built jetty, usually result in the loss of larger marine organisms when these collide with screens at the intake (impingement of fish, jellyfish, turtles, etc), or are drawn into the plant with the seawater (entrainment of phyto- and zooplankton, eggs or larvae).

The impact can be mitigated by creating a horizontal and vertical velocity gradient from the open ocean to the face of the intake, to give marine organisms time to swim away from the intake. Non-mobile organisms can be deflected by the use of mechanical screens.

For open intakes, fine-meshed screens should be placed in front of the intake structures to prevent the intake of larger marine organisms. While entrainment of smaller plankton, larvae or eggs cannot be avoided even by fine screens, it can be minimised by locating intakes away from highly productive areas, e.g. in deeper water layers or further offshore. This can also mitigate problems of biological fouling in the plant and intake of suspended material, thus reducing the need for chemical treatment.

The intake should be designed to lower the risk of impingement, which can be achieved by specially designed screens or limiting the intake flow velocity to values of week natural ocean flows (<5 cm/s).

Sub-surface intakes include horizontal or vertical wells or infiltration galleries and can be located either onshore (in either seawater or brackish water aquifers), or offshore under the seabed. The benefits of using an onshore location for an intake include a lowering of the conveyance costs by locating the desalination plant nearer the intake. However, these intakes do require a gravely or sandy substrate. Vertical intakes (Figure 6 (a)) are typically cheaper to construct than horizontal wells (Figure 6 (b)).



(a) (b)

Figure 6: (a) Vertical and (b) Horizontal Sub-Surface Intake Wells

Sub-surface intakes are often considered to be a better option environmentally than open ocean intakes, as intake wells use sand as a natural filter and can reduce the impingement and entrainment of marine organisms. This often results in a lowering of the chemical requirements in the pre-treatment stages of the process However, the use of sub-surface is limited due to the relatively low intake volumes of 0.1 to 15 MG/d, and it has therefore been favoured for small to medium size facilities.

2. Desalination Research and Development: past, present and future

The efficient production of potable water by desalination of seawater is a global objective. Many countries including Singapore, China, Korea, Japan, the Arabian Gulf States, the United States and members of the European Union have active R&D programmes involving government, industry and academic institutions.

The results from most of this R&D are available in the public domain, via the journal *Desalination* or the proceedings of the World Congress of the International Desalination Association. This chapter presents the desalination options, the historical developments, current R&D and trends and prospects for the future.

Table 4 outlines a range of desalination technologies and presents their current strengths and weaknesses, as well as potential future. These processes are discussed in more detail below, and a brief historical overview is provided in 2.1.

Phase change processes rely on the fact that boiling or freezing of salty water yields a salt-free phase, steam or ice respectively. In both cases energy is required, as latent heat exists, some of which may be recovered. Thermal evaporative processes are highly successful but freeze-thaw is not.

Voltage driven processes are based on the fact that salt ions (Na^+, Cl^-) can be moved by a voltage gradient allowing salt removal from the salty solution. Heuristically this is attractive ("remove the minor species first"), but to date none of these concepts has been adopted for large-scale seawater desalting.

Pressure driven membrane processes include RO and forward osmosis (FO). RO is the more mature and current preferred option for desalination, but FO is attracting significant attention. However FO is not yet commercial.

There is also significant R&D activity in RO membrane and process improvement. The thermally-driven membrane process, membrane distillation (MD) is also in active R&D, with modest demonstration plant in operation. The bio-enable option reflects the observation that cellular bioprocesses involve water channels and ion pump channels; and that it may be feasible to harness similar processes for desalting seawater. This is a long term prospect.

2.1 History of Desalination Development

Historically, the thermal distillation process was the first method of seawater desalination, dating back to antiquity [42]. A history of desalination before large-scale use is available [43]. The application of large-scale desalination only dates back to the 1950s, when thermal evaporative processes were installed in the Middle East. For example, in 1953 and again in 1955, Kuwait installed triple-effect evaporators of 4.5 ML/d capacity. This was followed by the first large-scale Multi-Stage Flash (MSF) desalination process of 10 ML/d capacity; an account of the early experiences with these plants can be found in the first issue of *Desalination* [44].

Over the years there have been steady advances in the development of thermal processes, which include Multi Effect Distillation (MED), Multi-Stage Flash (MSF) and Mechanical Vapour Compression (MVC), the latter usually for smaller units. Advances in thermal processes have included improved materials [45], pretreatment with Nanofiltration (NF) membranes to remove scale forming Calcium [46] and improved energy balancing, pretreatment and discharge by combining with power stations.

Table 4: Summary of Desalination Options

Process	Basic mechanism	Status	Strengths	Weakness	Future
Phase Change	**Salt-free phase produced**				
Thermal	Steam is salt-free, condenses to form pure water. Energy reused.	Major application	Well established	Energy demand	Strong in 'hybrid' systems **(a).**
Freeze-thaw	Ice is salt-free, thaws to pure water.	Not used	Limited	Energy demand	Unlikely.
Voltage Driven	***Salt ion transport***				
Electrodialysis	Ions move through anion & cation membranes.	Significant for low salt feeds	Well established	Possibly high salts Primary power	Strong, but SW desalination unlikely
Electro deionization	ED combined with ion exchange resin.	Possibly growing	Enhances ED	As above	As above
Capacitive deionization	Ions adsorb and /desorb on electrode due to DC voltage.	Developmental	Removes minor ions	Possibly high salts? Energy recovery	Possible
Pressure Driven	**Water transport through membrane**				
Reverse Osmosis	Pressure > osmotic pressure (OP), water through polymer film, salts retained.	Major application	Established Lower energy demand relative to thermal process	Energetic efficiency is low	Strong, with novel membranes
Forward Osmosis	Water passes to draw solute of high OP. Draw solute regenerated to give water.	Developmental	Lower energy Ambient pressure	Membrane type. Possibly draw solute	Potentially strong
Thermal -Membrane	***Water vapour transport***				
Membrane Distillation	Heated feed evaporates through hydrophobic microporous membrane.	Developmental, + demo plant	Ambient pressure. Low grade heat	Availability of low grade heat	Potentially strong
Bio-enabled	**Cellular ion transport**				
Biomimetic membranes	Cell wall transports/sorbs ions	Research	Biological Process	Development of industrial analogue to biological process	Possible, long-term

Note (a) Hybrid systems combine power plant and desalination processes.

A major stimulus for seawater desalting R&D occurred in the USA through the establishment of the Office of Saline Water in 1952. This activity had the goal of producing potable water from seawater and was citied by Presidents Eisenhower, Kennedy and Johnson as a key to enduring peace in a variety of regions of the world. It is fair to say that the state of the current desalination industry can be directly related to a grand US government R&D programme that spanned almost 30 years.

Most importantly, the Office of Saline Water (OSW) supported the development of Reverse Osmosis (RO) desalination. Funding provided by the OSW was used to develop the early formulations of cellulose acetate and thin film RO membranes. Industries, in partnership with research organizations funded by OSW, were entitled to develop commercial RO systems, by licensing the technology – protected by patents produced by the OSW programme.

This practice of holding patents in trust allowed companies to compete openly for the supply of similar membrane components. The resulting competition was instrumental in the standardization of Reverse Osmosis (RO) systems, which eliminated many of the barriers to the proliferation of the technology by simplifying the replacement of consumable items. An important example was the design and manufacture of the flat sheet spiral wound membrane element in 1968 [47].

The spiral wound membrane design was adopted by the four main suppliers of RO membranes affiliated with the Office of Saline Water: Fluid Systems, General Atomic (later purchased as Hydranautics by Nitto Denko), and Film-Tec (later a division of Dow Chemical). The spiral wound membrane element is now essentially a commodity item that can be used in a variety of RO systems.

Through competitive practice, manufacturers have improved production techniques and performance properties of the elements (such as flux and rejection), without altering the basic dimensions of the element. Consequently, consumers of RO technology could simply replace old elements with new generation elements – without replacing the RO plant infrastructure such as pumps, pipe work and pressure vessels.

Other notable achievements of this time included the development of the Thin-Film Composite (TFC) membrane by John Cadotte, through a project sponsored by Office of Saline Water [48]. The thin film membranes remove more salt from seawater than traditional cellulose acetate membranes, while producing an equivalent volume at lower operating pressures. Under the Office of Saline Water commercialization model, the thin film membrane technology was licensed to a variety of manufacturers and made available to the owners of RO equipment through the purchase of Spiral Wound Membrane (SWM) elements.

Today, the Thin-Film Composite Spiral Wound Membrane element is the standard component of municipal wastewater recycling, seawater desalination, brackish water desalting and groundwater softening plants around the world. The steady improvements in the Spiral Wound Membrane and RO membranes demonstrate the power of incremental change. The Figure of Merit has been defined by Birkett and Truby [49] to illustrate how, between 1978 and 2006, improvements in membrane permeability (2.25x) and membrane life (2.3x), and decreases in price per unit area (12x) and salt passage (7x), translate to a Figure of Merit increase from 1 to 480.

These advances are also exemplified by the records for membrane replacement at the Orange County Water District, Water Factory 21, between 1976 and 1996. During this 20 year period four sets of Spiral Wound Membrane RO were purchased for the 20 ML/d plant. The first set cost US$1200 per element and had an energy requirement of 1.5 kWh/m^3 of permeate (in this case feed is secondary effluent), and the fourth set installed in 1996 cost US$650 per element and had an energy requirement of only 0.25 kWh/m^3.

This impressive record of process improvement, coupled with competitive cost reduction, was a sign of a maturing industry, with development underpinned by a targeted research and development programme. It is an interesting historical fact that a hollow fine fibre RO membrane was developed by Du Pont Chemicals at about the same time as the Spiral Wound Membrane development. This hollow fine fibre membrane element was developed independently of the activities of the Office of Saline Water and the patent was used exclusively by Du Pont.

However, in the early 2000s Du Pont ceased production for new plant and today Hollow Fine Fibre (HFF) are only produced to supply replacement membranes for a small number of seawater desalination plants. One reason the hollow fine fibre technology did not proliferate in the same way as the Spiral Wound Membrane (SWM) was due to the extra pre-treatment requirements. Other significant factors may have been the lack of price competition and the inability to use the HFF elements in plants configured for SWM.

An interesting 1994 report [50] claims that almost all significant breakthroughs in desalting technology occurred prior to 1980, and that the subsequent 15 years saw few advances. However this overlooks the impact of the above-mentioned incremental improvements in the Spiral Wound Membrane (SWM). Apart from some potentially interesting membrane developments the major recent breakthrough in desalination has been the development of highly efficient energy recovery devices [51] (see 4.3.1 for more detail). Nevertheless, it is fair to say that the desalination R&D programme in the US supported from 1952 to 1982 by the Office of Saline Water (OSW) and then the Office of Water Research and Technology, established the RO industry as well as effecting significant improvements in the design of thermal desalination systems and initiating nascent research on issues such as concentrate disposal, solar driven desalination and alternative desalination processes.

In 1985, three years after the cessation of government funding, the cumulative investment of the US government in R&D in desalination was estimated at US$900 million (about $2 billion in year 2008 terms).

2.2 Research and Development in Desalination Options

This section provides a brief overview of R&D activities entailed in the processes listed in Table 4. Some research activities are a response to the emerging need to reduce Greenhouse Gas emissions while other activities are driven by increasing water scarcity due, in part, to climate change.

2.2.1 Phase Change Processes

Thermal

The evaporative processes are mature technologies that nevertheless continue to be developed. Areas of innovation include materials development [45], control of scale formation and improved process design [52]. A significant development in the past decade has been in the application of so-called ‘hybrid’ desalination systems [53] [54], whereby thermal and membrane processes have been combined; most of these applications are in the Middle East.

The largest hybrid is the Fujairah plant in the Northern Emirates [55], with a capacity of 455 ML/d. This plant combines a power plant, Multi-Stage Flash (MSF) (63% of capacity) and RO (37%). The advantages of hybrid plant are the common intake and outfall, and the blending of water products that allow the RO to operate in a single stage with longer lifetimes [54].

Other large hybrid plants are found in Saudi Arabia. Research in the hybrid area has largely involved modelling studies to identify optimal arrangements [56] [57]. The other interesting thermal/membrane hybrid developed over the past decade involves pre-treatment of Multi-Stage Flash (MSF) feed by Nanofiltration (NF), to remove hardness ions (Ca^{2+}, Mg^{2+}, SO_4^{2-}, HCO_3^-) which cause scale formation on heat transfer surfaces (see [46] and papers in [54]). This pre-treatment brings significant benefit, as it allows higher Top Brine Temperatures (TBTs) in the MSF, reduces the need for anti-scalants and increases product recovery from 35 up to 70%.

Thermal processes also include the small-scale solar still (distillation) processes that can be used in remote locations. Although this is an old concept, research continues in system optimization [58]. These developments are relevant as water scarcity accelerates.

Freeze-thaw

The freeze desalination process was actively studied in the 1960s and 70s [59], and commercial small-scale systems were developed in the USA, Israel and UK. The Office of Saline Water (OSW) sponsored some of this work in the USA [50]. However, the concept appears to have been abandoned in favour of Multi-Stage Flash (MSF) and RO due to the technical challenge of efficient ice crystal handling and washing (to remove surface salinity), difficult energy recovery, and system costs.

2.2.2 Voltage Driven Processes

These processes desalinate by removing the salt ions from the bulk water.

Electrodialysis (ED)

ED uses dense flat sheet ion exchange membranes that allow passage of either cations (Na^+) or anions (Cl^-) when a voltage gradient is applied across a channel formed by a cation exchange membrane and an anion exchange membrane. One set of anion and cation exchanged membranes is referred to as a cell pair.

ED processes have multiple cell pairs operating in parallel between electrode chambers. ED is capable of seawater desalting, but has not been able to compete with RO due to its more complex arrangement and membrane costs. It has not been shown to provide any significant saving in energy demand and is more likely to be used for smaller scale brackish water applications. However, its application to sea water desalination is still a research topic [60] [61] and its potential role in boron removal from RO permeate is of particular interest [62] [63].

An extension of the Electrodialysis (ED) process is Electrodeionization (EDI) whereby ion exchange resins are placed in the feed channels [64]. It is claimed that the EDI process allows continuous electro-regeneration of the resins and improved removal efficiency. Optimization of the EDI process is also a current research topic [65]. Another hybrid concept that has been studied combines RO and ED, with hollow fine fibre RO located in the ED channels; the combined unit then operates under pressure [66]. ED and related processes continue to be of interest in desalination as they remove the salt from the bulk, rather than vice versa.

Capacitive Deionisation (CDI)

The principle of CDI is that ions can be transported from bulk solution to electrodes by an imposed voltage gradient and held in the electrical double layer on the electrode surface. The deionised bulk solution is removed and the salt ions released by polarity reversal to a concentrate stream. A key to CDI is the use of high surface area porous electrodes.

Research from the 1960s to the 1980s focused on porous carbon electrodes (for example [67]). However, the Capactive Deionization (CDI) approach to desalination was sidelined for over a decade due to problems with the carbon electrodes (degradation and high resistances for electrical flow, mass transfer and hydraulic flow). The CDI concept was revived when carbon aerogel electrodes were developed by the Lawrence Livermore National Laboratory USA. The aerogel electrodes have very high surface area and much lower resistances. Subsequent work by the Lawrence Livermore National Laboratory [68] and others [69] [70] have shown encouraging results for brackish water desalination using CDI Capacitive De-Ionisation with carbon aerogel electrodes. Carbon aerogels are a conducting material than with a high internal surface area. The aerogels are fashioned into electrodes that can attract either positive or negatively charged ions. The ions can be removed from solution and stored on the internal surface of the electrode. The stored ions can be discharged by reversing the polarity of the electrode on the same way that an electronic capacitor can discharge current.

In principle, this process could be used for Sea water desalination but, to quote Farmer *et al.* [68] from Lawrence Livermore National Laboratory "…this Sea water application will be much more difficult (than Brackish Water)… and will require electrochemical cells with low pressure drop and extremely tight, demanding tolerances [and]… an energy requirement less than that needed for RO can be envisioned through the use of potential-swing operation with energy recovery. However, practical constraints on cell geometry, aerogel properties and product concentration make this application of carbon aerogel Capactive Deionization (CDI) extremely challenging." There is no evidence of current R&D with CDI applied to Sea water desalination. However, the demand for low energy desalination could change that.

2.2.3 Pressure Driven Processes

These processes desalinate by removing the water from the bulk salty water.

Reverse Osmosis

RO is a mature technology, which nevertheless continues to be improved. Recent developments include novel membranes and Spiral Wound Membrane (SWM) design optimization. Significant R&D has gone into RO membranes with low Boron passage without loss of water permeability [71]. The overall energy efficiency of the reverse osmosis process has been improved by the development of energy recovery devices that capture the energy embodied in the waste brine solution (see 3.2). Other advanced in membrane systems have been achieved in the area of membrane materials, module design and pretreatment. Developments in membrane materials include high permeability membranes, mixed matrix membranes and the use of advanced materials such as carbon nano-tubes. The following text provides a brief summary of these activities.

High permeability membranes

The thin film composite (TFC) membrane introduced in the 1980s opened up the possibility of improved productivity and separation. Recently, step changes in performance have been achieved by new membrane chemistries and formulations . The performance of a typical 8 inch Sea water Reverse Osmosis (SWRO) element in the early 1990s was a permeate flow of 4000 gal/d (15.2 m^3/d) and a salt transmission of 0.6% (where transmission = [salt concentration in product/salt in feed)x100]. This is referred to as the “standard” 4000/0.6 element. By the mid 1990s the elements were 6000/0.4, and this was followed by 7500/0.25 and recently a 9000/0.3 element has been produced (this is double the flow at half the salt transmission) [72].

The advantages of these new high permeability membranes are that they can either operate at lower pressure to achieve a given recovery, or at higher recovery for a given feed pressure. It is also possible to mix standard and high permeability (HP) elements with standard at the feed end, and high permeability at the outlet where the driving force is lowest. It is important to note that, in a typical RO plant, the feed pressure is raised to overcome the osmotic pressure of the final concentrate plus an additional component of driving force.

Seawater typically has an osmotic pressure (OP) of about 25 bar and at 50% recovery the osmotic pressure of the concentrate is about 50 bar. Allowing for pressure losses through the plant and the need for driving force pressure, the feed could be about 60 bar. The use of high permeability membranes does not avoid the need to pressurize the feed above the final osmotic pressure of the concentrate, but slightly lower pressures are possible. For example , a comparison of a “standard” element and a high permeability (HP) element with almost double the permeability showed that feed pressure could be dropped by about 2.5 bar (58.3 to 55.8 bar), which corresponds to a 4-8% reduction in energy (kWh/m^3). The concept of low pressure RO overlooks the need to exceed the osmotic pressure of the final concentrate. Novel high permeability membranes give some benefit, but it is evident that doubling permeability does not halve the energy demand.

Mixed matrix Thin Film Nano-Composites

The mixed matrix Thin-Film Nano-Composite (TFNC) is an interesting recent development [73]. The approach is to prepare Thin-Film Composite (TFC) membranes with nano-particles incorporated into the thin film during manufacture. TFNC membranes with zeolite (about 100nm) have nearly double the permeability of standard TFC and are potentially less fouling. These membranes are claimed to be more hydrophilic, smoother and more negatively charged.

A major attraction of this concept is that it can easily be incorporated into existing membrane production facilities. It could be a breakthrough in RO membranes, as it introduces new parameters in membrane preparation. The Thin-Film Nano-Composite (TFNC) membrane is patent pending and being commercialized by a spin-off company, NanoH2O (www.nanoh2O.net). It should be noted that the comments above relating to energy requirements for high permeability membranes in RO also apply for the TFNC. However, if it is shown to be particularly low fouling it may be able to be driven at higher fluxes which would reduce capital costs.

Carbon nanotubes

Carbon Nanotube (CNT) membranes are another recent development from Lawrence Livermore National Laboratory that promises to provide improved desalination [74]. The CNT has 2 nm diameter pores and remarkable flow characteristics. The “fast mass transport” membranes show flow velocities 4 to 5 orders of magnitude greater than predicted from conventional fluid flow theory [75]. This almost frictionless flow provides interesting possibilities. However, claims of 75% reduction in energy for desalination [74] are clearly unrealistic as the Osmotic Pressure (OP) of the feed and concentrate determine the necessary pump delivery pressure. Even with a perfectly permeable membrane the energy savings are likely to be only about 35% [76], and this would require radical redesign of the membrane plant.

Another issue with the Carbon Nanotube (CNT) membrane is that if it is driven at the very high fluxes it is capable of, the fouling would dominate unless totally novel means of fouling control are developed. Finally, the CNT has to date only been produced in small samples and scale-up to large areas has yet to be developed. In spite of these challenges, there is growing interest in CNT membranes for desalination, including CNT/polymer blends [77]. One study has also used CNT in Capacitive Deionization (CDI) as a flow-through capacitor for desalination [78].

RO modules

As noted above, the Spiral Wound Membrane (SWM) element is the dominant concept in RO desalination. The SWM uses membranes, produced as flat sheets, but fabricated into membrane “leaves” that are connected to a permeate collection tube which it is wrapped around. Details of the design of the SWM and recent research developments have been reviewed [79]. The incremental changes that have seen the efficiency of RO modules increase 500-fold since the first modules were developed in the early 1960’s. These improvements continue to occur with the trend to larger modules (16 in vs. 8 in diameter), which appears to be of economic benefit [80]. Another focus of research is the feed-channel spacer, which defines the flow channel height but also improves fluid flow and fouling control [79]. Spacer geometry is now being actively studied by Computational Fluid Dynamics (CFD), which can simulate the complex flows, mass transfer and pressure drops in the flow channel. Novel means of fouling control being studied include the application of AC electrical fields to the membrane module.

The demise of the Hollow Fine Fibre (HFF) RO module and the dominance of the “standard” SWM have generally been welcomed. However, this has effectively curtailed research into alternative RO modules for desalination. The timing of the hollow fine fibre withdrawal is possibly unfortunate because there is a growing trend to improve feed pre-treatment, using low pressure membranes [81]. It is conceivable that a dual membrane process with submerged hollow fibre pretreatment and hollow fine fibre RO could be competitive for desalination. The hollow fine fibre module would be amenable to design improvements to improve fluid flow distribution.

Pre-treatment

Efficient pre-treatment for sea water RO desalination is vital. Conventional processes include coagulation, media filtration, and chlorination/dechlorination to remove colloids and bacteria. However, in the related application of waste water reclamation by RO the pre-treatment is almost universally by low pressure membranes . Membrane pre-treatment provides a better quality feed water and a smaller footprint. As a result, there is currently a trend towards low pressure membranes for sea water pre-treatment [82] [83] [84] [85], and active research in this area.

Forward Osmosis

The Forward Osmosis (FO) concept for desalination has become a popular topic for R&D because of the potential for lower energy desalination [86]. The FO process is strictly direct osmosis across a RO-type membrane. A draw solute of high Osmotic Pressure passes across one side of the membrane, and the seawater feed passes across the other side. Water transfers from the sea water to the Draw Solute side due to osmotic flow. It is then necessary to regenerate the Draw Solute and remove the water transferred by the FO process.

In principle, the FO process should be able to reduce energy for desalination towards the thermodynamic minimum.

However, there are two key obstacles to a viable Forward Osmosis process. Firstly, conventional RO membranes are not suitable. These membranes have a thin separating layer on top of a thicker porous support layer. Forward Osmosis (FO) differs from RO in having salty solutions on both sides of the membrane. If the porous support is presented to one of the salty solutions it will suffer internal polarization, which means that the concentration of salt ions inside the membrane will be very different from the bulk. This causes a loss of osmotic pressure driving force such that conventional RO membranes only achieve < 50% of their capability in Forward Osmosis [87].

There is one commercial supplier of Forward Osmosis membranes and these are more effective, but far from optimal. Accordingly, the development of better Forward Osmosis membranes requires further research. The other issue for Forward Osmosis is the Draw Solute, which must have a high Osmotic Pressure but also be able to release its water at a modest energy cost (< RO). This is a major challenge. Various Draw Solutes have been used, but the most attractive is probably ammonium carbonate [86], which can be regenerated by a thermal process (distillation) with energy recovery . Further work on Draw Solute options is required.

2.2.4 Membrane Distillation

Membrane distillation (MD) is by definition a thermal process but also involves features of membrane technology, such as polarization and fouling. The process uses membranes that are hydrophobic and microporous (typically < 0.2 microns). The membranes are internally unwetted, the feed is heated and the downstream side is cooled so that water passes through the membrane as vapour. In direct contact membrane distillation, the membrane has heated liquid on one side and cold permeate on the other. Variants include air-gap, sweep gas and vacuum membrane distillation [88], whereby the downstream side is not wetted but water vapour is condensed on a cool surface.

The concept has been around since the 1970s and has had steady interest from the academic community (with over 150 papers in the *Journal of Membrane Science* and a similar number in *Desalination* in the past 20 years). Although membrane distillation relies on thermal energy, it can operate effectively at about 60^{o}C with low grade heat, such as waste heat and solar. The amount of electrical energy required is minor and used for liquid circulation. Additional advantages of membrane distillation are its ambient pressure operation and its ability to process at very high salt concentrations [89] as it is not constrained by osmotic pressure.

The current interests in membrane distillation relate to its low use of primary (electrical) power and the ability to achieve very high recovery (>80%). One of the constraints to the technology has been the lack of a champion in the membrane industry, as the next stages are probably large-scale module development, process design and optimization and demonstration plants. This may be about to change.

In addition to the ongoing academic interest there are process developments such as Memstill [90], patented by the Netherlands Organisation for Applied Scientific Research Building and Construction Research (TNO), which has a multiple effect design (heat recovery) and uses waste heat. Another group, the Fraunhofer Institute for Solar Energy (ISE), has developed a spiral-wound membrane distillation module that also has integrated heat recovery giving it a Gained Output Ration (GOR) of about 4 to 6 [91].

It should be noted that membrane distillation system design involves a trade-off, as the multi-effect heat recovery feature reduces the available local driving force. For example, the ISE spiral module delivers a flux of 2.5 to 3.5 L/m^{2}hr through PTFE membranes at a temperature of 60 to 85°C [91]. In a once-through module, the flow rate per unit area would be about 20 L/m^{2}hr [89]. The ISE is developing systems driven by solar thermal energy with capacities of 0.2 to 20 m^3/d. These units are being tried in the Middle East. Globally there is strong R&D activity in membrane distillation, and module and system optimization are fertile areas for further work.

2.2.5 Bio-enabled

In cell membranes, lipids and proteins self-assemble to form water channels or ion channels. If these channels can be engineered into biomimetic membranes, they may offer a solution to low energy desalting, although the thermodynamic minimum energy of about 0.5 kWh/m^3 provides a lower range of possibility.

For example, there is interest in aquaporins that are very selective to water transport, although these may simply be another high permeability option for RO. Aquaporins have been inserted into polymer membranes by researchers at the University of Illinois [92], and there is also interest in Australia [93] through the CSIRO's Nanotechnology Centre.

The other approach is to develop synthetic analogues for biological membranes that selectively pump ions rather than water molecules. Pumping salt ions is energetically more favourable than moving water molecules because the number concentration of salt molecules is much lower than that of water molecules.

Researchers have developed molecular gates that mimic the action of biological membranes and allow the selective passage of ions [94]. There are many challenges for research into these *biomimetic* membranes, including proof of concept at high salt concentration levels, scale-up, module design, and the need for fouling control.

2.2.6 Energy issues

The need to address climate change by reducing greenhouse gas emissions is putting pressure on the desalination industry, which is perceived as energy intensive. The current generation of Sea Water Reverse Osmosis (SWRO) desalination processes use about 3 to 3.5 kWh/m^3, at a recovery rate of about 40%. This is about 20% of the energy used in the first generation RO desalination plant. However, it is still significantly higher than the thermodynamic ‘minimum energy’ of about 0.52 kWh/m^3 [72] to produce water of 300 mg/L from 35,000 mg/L seawater at 40% recovery.

The best RO performance to date has been achieved in a demonstration plant operated by the Affordable Desalination Collaboration (ADC) which has reported a value of about 1.6 kWh/m^3 [95]. Additional power is required for intake, pretreatment and discharge. The Affordable Desalination Collaboration demonstration used the best available highly permeable (HP) membranes and state-of-the-art energy recovery exchangers [82].

Indeed, the key to the significant drop in energy demand in RO desalination over the past 15 years has been the use of highly efficient energy recovery devices that transfer the pressure in the concentrate stream (typically 50 to 60% of the initial feed and at 50 to 60 bar) to the incoming feed stream. These devices, which have efficiencies up to 95%, are either turbines or pressure exchangers [82]. Industry-based development of these devices continues, including the use of ceramic materials. There may be opportunities for further energy reduction if the HP membranes are used optimally.

For example, although the osmotic pressure must be exceeded, it may be possible to minimize energy by using a multistage process, with inter-stage booster pumps and energy recovery devices. If the feed-side pressure profile is stepped up to match the rising osmotic pressure profile through the plant, and if highly permeable membranes are used it may be possible to save about 35% of the energy [76] (based on the ADC minimum, this could mean ~ 1.0 kWh/m^3).

This would involve a radical redesign of RO cascades and would probably come with higher capital cost. However, this example does illustrate the potential for further energy reduction. In order to approach the thermodynamic minimum of just over 0.5 kWh/m^3, it will be necessary to successfully develop one or more of the other desalination options described in this section. The most likely candidates are Membrane Distillation (MD) (in niche areas) and Forward Osmosis (FO). The energy issues around desalination have also prompted considerable R&D activity is desalination using renewable energy, including MD + solar, and RO+ solar, wind or wave energy.

The interest in desalination energy has prompted exergy studies of the options. Exergy (or available work) is used to describe the irreversible losses that occur in thermal or power cycles. Exergy analysis applied to desalination processes [96] [97] [98] suggests that significant losses occur across RO membranes and that MD is more favourable, provided waste heat is available. Information regarding exergy is given in 3.1.4.

2.3 Future Prospects

This section canvasses future prospects in desalination R&D, and the likelihood of a breakthrough emerging from current or future research. The history of desalination development (see 2.1) provides important lessons.

1) The major breakthroughs occurred in the 1960s when very significant funds were provided to investigate a broad range of concepts.

2) Industry and researchers subsequently achieved major improvements by incremental changes (e.g. the 500 fold increase in the Forward Osmosis membranes for the Spiral Wound Membrane).

Prospects for further incremental improvements are high, based on improved understanding of existing processes, powerful simulation techniques and market forces. The prospects for a major breakthrough are less evident. It would probably require adopting the Office of Saline Water (OSW) approach, in which the intellectual property from government funded R&D activities could be held in trust, and the technology commercialized by independent companies via a licensing agreement. This mechanism would allow several manufacturers to achieve the competition and economies of scale that have driven the desalting industry to date. If the technology is to be licensed on an exclusive basis, it must offer significant energy and cost savings if end users (water authorities/municipalities) are to tolerate a monopoly. Since the water industry is conservative and risk averse, demonstration scale plants are necessary before any new technology is used at the municipal scale. This is important when considering the potential of research into sustainable desalination systems that use renewable forms of energy. Any innovations will require developments in novel infrastructure to support the technology. Accordingly, the capacity of desalination systems that use renewable energy is typically less than 1000 m^3/d.

Table 5 summarizes the opportunities and the (arguable) probabilities of either incremental improvement or breakthrough in the various desalination options and related ancillaries.

Brief snapshots of different techniques and processes for the further development of desalination follow.

- Thermal Processes **-** These are very mature processes and a breakthrough would be very unlikely. However further improvements are anticipated and present R&D opportunities exist – in operations, materials and modelling of hybrid processes.
- Electrodialysis: ED/EDR **-** ED is a mature process and is unlikely to experience breakthrough, but there may be incremental changes in membranes and modules. EDI offers R&D opportunities for process optimization, rather than breakthrough.

- Capacitive Deionisation: CDI **-** This technique is not yet applicable to seawater desalination, and to be effective it will require incremental improvements in module design and scale-up. To be sufficiently energy efficient to out-compete RO, this technique would require a breakthrough in electrode materials and fabrication giving very high-energy recovery. This may be possible.
- Reverse Osmosis: RO **-** RO is a mature technology, but further incremental improvements in membranes and modules are probable. Breakthrough may come from novel nano-engineered membranes. However improved membranes will require improved (breakthrough) fouling control. Radical redesign of RO cascades may be required.
- Forward Osmosis: FO **-** The existing FO membranes need to be improved and this can be anticipated. The viability of FO will require a breakthrough in draw solute specification and regeneration. There is a strong probability that this will occur.
- Membrane Distillation: MD **-** While it is difficult to anticipate a breakthrough in MD, this process is in need of R&D – to provide the incremental improvement to modules and process needed to make it a commercially attractive option.
- Bio-enabled **-** This option is not yet proven for seawater desalination. It is intrinsically attractive but will need breakthroughs for successful fabrication and scale-up.
- Pretreatment **-** This is a major issue for any of the desalination options. Improved pretreatment by R&D can be anticipated; the major focus will probably involve low pressure membranes. It may be possible to exploit a novel phys-chem or biological process in a new approach.
- Energy - The strong incentive to reduce energy usage will ensure the continuation of R&D efforts directed towards that goal.

Table 5: Incremental & breakthrough opportunities for desalination options

Process	Incremental Improve	Breakthrough	Major Opportunity/Challenge Analysis
Thermal	High prob. -	- Negligible	Better scale control, materials, hybrid optimization. (No obvious opportunity for breakthrough.)
ED/EDI	High -	- Negligible	Lower cost membranes & EDI optimization. (No obvious opportunity for breakthrough.)
CDI	Possible -	- Possible	Practical modules and scale-up. Novel nano-structured (non carbon) electrodes with high energy recovery.
RO	High -	- Possible	Better membranes and module design (track record). High performance membranes from nanotechnology (mixed matrix, C nanotubes). High flux needs improved CP[1] control. Osmotic pressure is unavoidable.
FO	High -	- Probable	Improved membranes. Effective draw solute + efficient regeneration.
MD	High -	- Unlikely	Improved membranes and modules. (No obvious opportunity for breakthrough).
Bio-enabled	-	- Possible	(No established process to optimize as yet). Proof of concept, scale-up, CP[1] control.
Pretreat	High -	-Possible	More efficient removals at lower energy and cost. Exploit novel physico-chem-biological processes
Energy	High -	- Possible	Improved energy recovery, lower losses, modelling. Process specific opportunities

1. CP is concentration polarization, which occurs at the surface of separation (i.e. membrane) and is usually controlled by fluid mechanically induced mass transfer (fluid flow management in the module).

2.4 Current Research Support and Activities

An indicator of current R&D interests is the record of proceedings [99] of the recent International Desalination Association World Congress (Table 6). As this meeting has a strong commercial and industrial flavour, it tends to illustrate more of the “D” (Development) than the “R” (Research) activity. It is evident from the table that there is little reported R&D in thermal processes, and that most of the R&D is focused on membranes. The non-RO options receive only minor attention in Membrane Distillation (MD) papers (3 papers), Forward Osmosis (FO) (1), Electrodialysis (ED) (3) and Capacitive deionization (CDI) (1).

A major theme is pre-treatment, with at least 19 papers describing predominantly low pressure membranes. Energy issues are significant with energy recovery (6 papers) and solar energy (8) being important themes. At least 6 papers discuss R&D in spiral modules for RO. The conference confirms the strong incremental nature of desalination R&D and the fact that there is little evidence of breakthrough activity.

Table 6: Summary of Sessions at 2007 IDA world Congress

Topic	**Papers**	**Comment**
Economics	10	Hybrids (3 papers)
Operation of RO Desalination	15	Hollow fibre RO(1)
Operation of thermal	5	
Innovations in membranes	11	SWM(6), MD(2), ED(1)
Innovations in thermal	9	Analysis(4), Dynamics
Water reuse	16	MBR(7)
Non-traditional, Renewables	15	MD(1), CDI(1), Solar(8), Wind(2)
Energy recovery	9	R&D(6)
Scale control	6	Mechanisms, anti-scalants
Biofouling	9	Various R&D
Innovations in Pretreatment	19	Mainly membranes R&D
Monitoring	9	Indices(4)
Boron management	7	
Environment	10	R&D(2), FO(1)

The following summarizes known current activity in desalination research on a regional basis.

2.4.1 Australia

There are several desalination R&D activities in Australia. These include:

1) CSIRO Flagship Programme: Through CSIRO's Collaboration Fund, the Membrane Cluster brings together some of Australia's leading scientists and institutions from a range of disciplines with the goal of placing Australia at the forefront of novel membrane development. The research aims to improve membrane design to dramatically increase efficiency, and reduce the financial and environmental costs of producing desalinated and recycled water. Research outcomes will improve the capacity to progress water desalination and recycling as safe and alternative water supply options for Australia
2) DEST sponsored research as part of the European Union MEDINA programme (Membrane-Based Desalination: An Integrated Approach). The Australian activity is at the UNESCO Centre for Membrane Science & Technology at The University of New South Wales and University of Technology Sydney. The project involves optimization of RO pretreatment methods, novel fouling indices, and Computational Fluid Dynamic analysis of spacer filled channels.
3) Proposed National Centre of Excellence in Water Desalination, to be located in Perth, with Commonwealth funding of $20m over five years. The centre is planned to be structured around a national network with a central co-ordinating hub in WA.

2.4.2 Singapore

Singapore has an active membrane research community, with the Singapore Membrane Technology Centre at Nanyang Technological University and other activities at National University of Singapore For example, both universities are working on Forwar Osmosis (FO). The Singapore Government through the Environment & Water Industry Development Council has recently made a Challenge Call for Seawater Desalination. The challenge is to develop novel technologies that can desalinate seawater at an energy rate of no more that 1.5 kWh/m^3, including pre-treatment and post treatment. The chosen research teams will be announced in the second half of 2008, and will have access to up to S$10 million over 5 years.

2.4.3 China

China has made considerable progress in distillation and reverse osmosis technology for salt water desalination over more than 40 years of R&D. Sea water desalination capacity in China is about 200 ML/d today and will increase to 1000 ML/d by 2010. Over the next 5-15 years, China plans to construct 3-5 demonstration areas, cultivate 3-4 industrialization bases, establish 2-4 engineering research centres and test sites for seawater desalination. The Ministry of Science and Technology is sponsoring R&D in membrane distillation, with a 10m^3/d demonstration plant operating by 2010. Basic research into Forward Osmosis (FO) membranes and draw solutes is also being undertaken.

2.4.4 Korea

Korea has a very active membrane research community. There is a large national R&D program called SeaHERO (Seawater Engineering Architecture High Efficiency Reverse Osmosis) launched in August 2007 for 5 years. The total budget is approximately US$150 million (probably the largest desalination project in the world). The objective of this R&D program is to upgrade membrane-based desalination technology. The four main divisions of this program are comprised of:

1) Development of core basic technology
2) Technology upgrading for material localization
3) Design and construction technology for Scale-up of unit train of RO bank, and
4) Optimization of operation and maintenance technology.

2.4.5 Japan

(Information from Dr M Kurihara, former Research Director of Toray).

Although Japan has an active membrane research community, the current research on desalination in Japan tends to be limited to membrane manufacturers' R&D, which is aimed at improving membranes, boron removal and pretreatment. Japanese membrane manufacturers share about 60-70% of global seawater desalination membrane production. Japanese manufacturer, Toyobo, produces the only commercial hollow fibre RO membranes and continues to do R&D in this area.

2.4.6 USA

The USA has an active membrane research community. Notable research is being done on Forward Osmosis (FO) at Yale (Professor M Elimelech), and on the novel Thin-Film Nano-Composite (TFNC) RO membrane at University of California, Los Angeles (Dr E. Hoek). There has been considerable planning and discussion about the future needs for RO, which can be found in the 'Desalination and Water Purification Technology Roadmap' developed by the US Department of Interior, Bureau of Reclamation and Sandia National Laboratories [100]. The National Water Research Institute and the American Water Works Research Foundation also sponsor research activities at universities and partially fund demonstration or pilot studies at different water utilities.

2.4.7 European Union

A major research effort in desalination within the European Union is a 6th Framework STREP project entitled "Membrane-Based Desalination: An Integrated Approach" (MEDINA) aimed at boosting the sustainable development of desalination processes. The project spans a large number of teams in industry and academia and includes interactions with research groups in Australia.

The EU MEDINA project team developed nine work packages aimed at improving the overall performance of membrane-based water desalination processes. An innovative approach is proposed, based on the integration of different membrane operations in RO pre-treatment and post-treatment stages according to the strategy of Process Intensification.

The key focus of the EU research will be:

1) Development of advanced analytical methods for feedwater characterization, appropriate fouling indicators and prediction tools, procedures and protocols for full-scale desalination facilities
2) Identification of optimal seawater pre-treatment strategies by designing advanced hybrid membrane processes (microfiltration: MF/ultrafiltration: UF, submerged hollow fibre bio-reactors) and comparison with conventional methods

3) Optimization of RO membrane module configuration, cleaning strategies, reduction of scaling potential by nanofiltration: NF
4) Development of strategies aiming to approach the concept of Zero Liquid Discharge (increasing the water recovery factor up to 95% by using Membrane Distillation, Membrane Crystallization or Wind Intensified Enhanced Evaporation), and to reduce the brine disposal environmental impact and cost, and
5) Increase the sustainability of desalination process by reducing the overall energy consumption and the use of renewable energy (wind and solar).

2.4.8 Middle East

As the location of most of the world's desalination plants, the Middle East has an active R&D scene. For example, Israel has programmes on Spiral Wound Membrane (SWM) optimization and fouling control (Technion), and novel membranes and pretreatment technologies (Ben Gurion University).

Oman hosts the Middle East Desalination Research Centre (MERDC) which is formed by a consortium of countries with interests in desalination in the Arabian Gulf and the Eastern Mediterranean. Its current research programme is based on targeted research projects in:

1) Thermal Desalination
2) Membrane Processes
3) Non-Traditional and Alternative Desalination
4) Operation and Maintenance
5) Intakes and Outfalls
6) Energy Issues
7) Environmental Issues, and
8) Hybridized Systems.

2.5 Analysis

In contrast to the grand research and development scheme of the US Government in the 1960s and 70s, research into the desalination of seawater is now conducted with modest resources and in a less coordinated way. Exceptions to this might include Korea's SeaHERO programme, the EU MEDINA and MEDSOL projects and Singapore's Desalination Challenge.

Established RO manufactures independently continue to develop new formulations of membranes that are essentially variations on the original Thin-Film Composite (TFC) technology and make incremental improvements to the Spiral Wound Module.

The near future for seawater desalination is likely to be membrane-based and one of incremental change and optimization, which has been very effective in the past. On the other hand if the target for a cut in greenhouse gas emissions is to be 60% (or even 90%) by 2050, it will not be “business as usual” for desalination.

Therefore, in the medium to long term desalination will require step change breakthroughs (Table 5 suggests potential routes, as does the Desalination Road Map developed by the US Bureau of Reclamation and Sandia National Laboratories [100]). To make these required breakthroughs, substantial governmental R&D funding will be required. The model provided by the original OSW programme in the USA where intellectual property is held in trust and licensed to industry, would be the most appropriate. The chances of success would be increased if a coordinated global R&D effort could be established to develop the next generation of desalination technologies.

3. Water from Electricity: Energy Minimisation

Energy requirements are an important consideration in any alternative water supply option, particularly for desalination.

This chapter considers the minimum energy requirements to produce potable water from various raw water sources, and provides current estimates for the energy consumption associated with current water production technologies that require the removal of salt. This includes:

- recent advances in energy recovery devices
- the energy efficiency of renewables, and
- programmes to optimize and reduce energy consumption.

In addition to examining energy usage, techniques to estimate greenhouse gas emissions are considered, along with the various options available to offset these emissions and the effectiveness of such schemes.

3.1 Estimates of Energy Consumption

3.1.1 Salt content in seawater

Precipitation flowing over soil and rocks or infiltrating into the ground dissolves minerals and other materials that increases the salt content as the water eventually enters the sea. The evaporation of seawater over billions of years has resulted in the retention and concentration of these salts. The salt concentration of the world's oceans ranges from 31,000 to 46,000 mg/L depending on location; in areas closer to the shoreline, this figure will vary due to the evaporation and dilution phenomena [101] (Figure 7).

The highest salinity levels are recorded around the Mediterranean and Red Sea, where relatively high temperatures increase the rate of evaporation, while near the North Pole the salinity is lower due to the low evaporation rate and the occurrence of ice melting. The World Health Organization recommends that the dissolved solids concentration, or salinity, of drinking water should be less than 500 mg/L

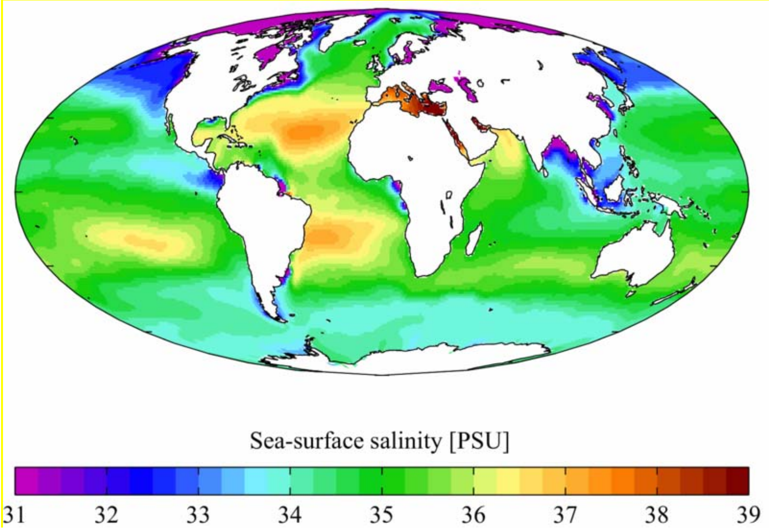


Figure 7: Sea Surface Salinity, g/L [101]

3.1.2 Ideal energy requirements

The mixing process between salt and water occurs spontaneously, during which entropy is generated and exergy is destructed. Therefore, the separation process of the mixed constituents is not possible without supplying some energy. This energy is called the ideal separation work, to overcome the entropy generation associated with the mixing process. Though desalination processes may have different technologies and configurations, the minimum power requirement is the same regardless of the process used, because the minimum separation work depends only on the properties of the incoming saline water and outgoing pure water and brine.

3.1.3 Determination of minimum separation work

This work is an activity involving a force and movement in the direction of the force. The rate at which work is done is called power, and it is expressed as kilowatt-hours (kWh). The minimum work is the amount of power required to transfer from state one to state two without generating any entropy. The second law of thermodynamics is used to derive the minimum separation work required in desalination processes. The detailed derivation of the minimum separation work is presented in appendix 6. The minimum work required to produce one cubic metre of water with TDS of 100mg/L, from sources of water with different salinities and with a recovery ratio of 40%, is shown in Figure 8.

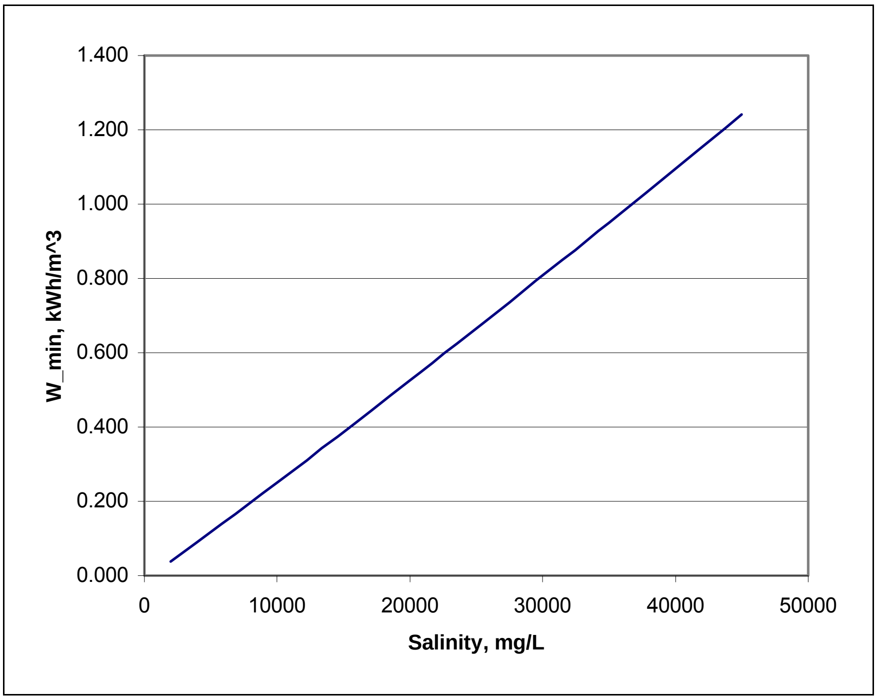


Figure 8: Variation of minimum work with the salinity of feed water

3.1.4 Exergy

The second law of thermodynamics introduces the entropy balance equation in addition to the energy and momentum equations. The resulting formula is a general potential work function called the exergy function. This formula measures the total losses that obliterate the input energy. The exergy also measures the lost work by calculating the difference between the minimum and actual work. The exergy analysis of any process is very useful, because it can be used to quantify and trace the locations where a significant amount of entropy generation (exergy destruction) takes place.

3.1.5 Efficiency of desalination plant

The second law of thermodynamic analysis can be used to measure the efficiency of the desalination process (η_{II}), by comparing the actual work (W_{act}) required with the minimum work (W_{min}) required for the same inlet and outlets stream conditions, as shown in equation (1).

$$\eta_{II} = \frac{W_{\min}}{W_{act}} \tag{1}$$

The efficiency of desalination plants is influenced by different variables, including:

- salinity and temperature of feed water
- product water recovery ratio, and
- actual power consumed.

Generally, the power required to desalinate water using reverse osmosis is governed by the osmotic pressure of the feedwater, and is directly proportional to the feedwater salinity; the higher the salinity, the higher the osmotic pressure and the more the energy that will be required.

For example, the SWRO desalination plant in Kwinana, Perth [102] consumes around 3.56 kWh/m^3 to produce water with TDS of 200 mg/L from seawater with TDS of 35000 mg/L. Using the same feed and outlet conditions, the minimum work consumed is around 0.951 kWh/m^3. Therefore, based on equation (1), the second law efficiency of the plant is around 26.7 %.

Table 7: Variation of Second Law Efficiency with Feedwater Source

Feed water (TDS, mg/L)	**Permeate (mg/L)**	**W_{min} (kWh/m^3)**	**Process**	**Energy source**	**W_{act}^{b} (kWh/m^3)**	***Effic-iency* η_{II} (%)**
Arabian Gulf (45,000)^a	200	1.24	RO	Electricity	4.0	31.00
	50	1.26	MSF	Thermal	12^C	10.50
	50	1.26	MED	Thermal	8^{C,e}	15.75
	50	1.26	MVC	Electricity	11^{C,e}	11.45
Average Seawater (35,000)^a	200	0.95	RO	Electricity	3.6^d	26.39
	50	0.97	MSF	Thermal	12	8.08
	50	0.97	MED	Thermal	8^{C,e}	12.13
	50	0.97	MVC	Electricity	11^{C,e}	8.82
Brackish water (5400)	200	0.16	RO	Electricity	0.82^f	19.51

$^{(a)}$ [103], $^{(b)}$ [104], $^{(c)}$ [105], $^{(d)}$ [102], $^{(e)}$*Average value*, $^{(f)}$ [106]

The efficiency of most desalination plants is between 8 and 30%[2]. This is very low when compared with the efficiency of other major industrial operations such as power generating plants, for which the second law efficiency is well above 50% .

In order to increase the efficiency of the desalination plant, and to facilitate the reduction of greenhouse gas emissions, the wasting of energy in the plant (exergy destruction) must be minimized. One way is to maximize the energy recovery rate from the outgoing streams (i.e., brine solution in SWRO plants). There are different types of energy recovery devices used for recovery, depending on the technology used in the desalination plant. For instance, in MSF distillation technology, in which thermal exergy is supplied as heat, heat exchangers are used to recover the exergy from the outlet steams. Meanwhile in RO processes, pressure exchanger devices are used to recover the

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[2] This value is higher than the one reported in the literature because the minimum separation work calculation in this report is based on the UMST 2nd law efficiency (Kempt, 2005) model, which takes into account the dissociation constant of the *NaCl* salt.

pressure exergy of the outgoing streams. The effectiveness of the different types of energy recovery devices is discussed in the following section.

3.2 Energy Recovery Options

The energy requirement of an RO system rises almost proportionally with increasing operating pressure. Brackish water systems have specific energy consumptions that typically range from 1.0 to 3.0 kWh/m^3, whereas SWRO system energy requirements range from 3.5 to 4.5 kWh/m^3 due to their higher operating pressures and lower product water recoveries. Most SWRO systems are therefore equipped with energy recovery devices to reduce energy requirements to more cost-effective levels.

After passing through the membrane, permeate is reduced to near atmospheric pressure while the concentrate retains most of the pressure energy from the feedwater pump. An energy recovery device can recover most of the energy from pressurized concentrate and reduce overall system energy requirements by more than 50%.

Turbine-type energy recovery devices convert the concentrate’s hydraulic energy into mechanical power to assist the high-pressure pump motor. Turbines were the first energy recovery devices deployed in sea water reverse osmosis plants. Initially, Francis-type turbines were applied, but they were replaced in 1980s by Pelton turbines that operated at higher efficiency in high-head applications like sea water reverse osmosis plants. Pelton turbines are widely accepted in sea water reverse osmosis plants due to their familiarity and proven reliability. These devices have energy recovery efficiencies of between 60% and 85%.

A “work exchanger” or “pressure exchanger” energy recovery device transfers hydraulic energy directly from the concentrate stream to the incoming seawater across a piston, using positive displacement technology. These devices can have energy recovery efficiencies of up to 96%.

While the natural inclination is to use the most efficient device possible (i.e. a pressure exchanger rather than a Pelton wheel), it is necessary to evaluate the system as a whole for each specific application. Each device has its own merits: some offer a greater degree of operating flexibility, while others offer a lower capital cost or higher efficiency.

3.3 Current Use of Renewables

Desalination is the most energy-intensive water treatment process when compared to other pure water supply options. However, in many locations, it may be the only available option able to deliver a reliable quantity and quality of fresh water. To mitigate the impact of its increased energy consumption, and in light of the increasing number and size of desalination plants, it is necessary to consider alternative energy sources.

Renewable energy sources are those that use natural resources such as sunlight, wind, tides or geothermal heat sources, which can be naturally replenished in a short period of time. The availability of renewable energy sources and the maturing of the technology make it possible to consider coupling desalination with renewable energy production processes.

There are examples of small desalination plants that operate directly from renewable energy supplies, but most large-scale (i.e. >20 ML/d) seawater desalination systems that employ—or propose to employ—renewable energy, purchase it from a grid. Perth's plant in Kwinana is one example of such an arrangement in which the plant pays for electricity generated at a wind farm and fed into the regional grid.

A recent report by the German Aerospace Centre entitled *Concentrating Solar Power for Seawater Desalination* [107] suggests that concentrating solar power (CSP) may soon be a cost-effective method of renewable energy for desalination plants.

Concentrating solar power technologies are based on the concept of concentrating solar radiation to provide heat for electricity generation in conventional power cycles. Systems can use parabolic troughs, glass mirrors or solar dishes that track the sun's position to concentrate solar energy to generate steam to drive a turbine and produce up to 200 MW of electric capacity. A CSP system could produce up to 50 MW of power on 1km^2 of arid land.

A 64 MW plant was recently constructed in Nevada, USA for US$266 million and produces electricity at US$0.15 to 0.17 per kWh, It is estimated that the cost will reduce by 10 to 15% each time the world's installed capacity doubles.

3.4 Energy Optimization

The fact that energy costs may represent up to 50% of the operating expenses of a seawater desalination plant usually provides sufficient incentive to implement energy conservation and efficiency measures wherever possible.

Frequently employed energy optimization methods include:

- high efficiency energy recovery devices
- variable frequency drives (VFD)
- premium high-efficiency pumps
- the use of rooftop solar photovoltaic cells to augment the external power supply, and
- incorporation of Leadership in Energy and Environmental Design (LEED) principles for plant offices and commercial buildings.

3.5 Estimating Greenhouse Gas Emissions

The carbon footprint of desalination systems is not made by any one factor in the process. Instead it results from a combination of the emissions associated with power used in the desalination process and the embodied emissions associated with chemicals used in production, treatment and disposal of solid waste and the manufacture and replacement of the membrane components.

Operators of desalination plants will attempt to offset the emissions by purchasing credits associated with clean or renewable energy. It is important to note that the desalination plant itself is not powered by green energy, but credits are purchased to offset the emissions. The cost of these credits will be established when the Australian Government to launches the proposed Emissions Trading Scheme.

The Gold Coast's 125,000 m^3/d SWRO plant which will open in November 2008 has committed to offsetting all of its carbon emissions and is currently seeking offers from the private sector. It is estimated that the green energy will increase the energy source cost from $10 million to $19 million per annum, with the extra costs to be passed onto consumers (estimated to increase annual water bills by $2). Along with the benefits gained from reducing environmental pollution, the plant will become eligible for $100 million of federal funding by the complete offset of its carbon emissions.

Table 8 presents an overview of the source and amount of equivalent CO_2 emissions for a typical 100 ML/d RO plant. All process emissions are included, but any resulting from transport relating to the plant or product water are not.

Table 8: Amount of equivalent CO_2 emissions for a typical RO plant

Process Input	**Purpose**	**Typical amount (mg/L)**	**Typical amount (kg/d)^(1)**	**Emission factor (kgCO$_2$-e/kg produced)^(2)**	**Tons of CO$_2$-e/d**
Power	Feed electrical pumps	4.5 (kWh/m^3)		1.467 kgCO$_2$-e/kWh	660.15
Cl_2	Pre-treatment	50	12345.67	1.2	14.81
$FeCl_3$	Pre-treatment	5	1234.56	3.23	3.98
Anti-scalant	Pre-treatment	3	740.7	7.4	5.48
HCl	Pre-treatment	20	4938.27	0.76	3.75
NaOH	Second pass pre-treatment	6.34	704.4	3.23	2.27
Nylon	Membranes	4595 elements	30.21(3)	84.4	2.55

[1] Based on a typical amount of 100 ML/d.
[2] Data sourced from Australian Greenhouse Office Factors and Methods Workbook, December 2005.
[3] Based on five years life time of the membrane element.

4. Economics of Desalination

The cost of desalination has fallen significantly since it was first introduced on a large scale in the 1950's. This can be attributed to reductions in the cost of energy and improvements in the available technology. However, desalination still remains an expensive water supply option, and the economic issues behind costing of new desalination infrastructure are important factors in determining its success.

The cost of desalination is influenced by many factors making it difficult to compare costs between projects that have been reported in the literature. The aim of this chapter is to outline a framework for the cost estimation of various water supply options including desalination, and report this cost in terms of the unit cost of water.

There are four major desalination technologies employed on a large scale worldwide; Multi-Stage Flash (MSF), Multi Effect Distillation (MED), Mechanical Vapour Compression (MVC) and RO. This chapter will briefly comment on the cost of each technology, however, most focus has been given to RO which is the technology of most interest in Australia.

4.1 Unit Cost of Water

A logic tree has been developed to illustrate the steps used to calculate the unit cost of water for a given water supply project (Figure 9). The unit cost of water is given by the quotient of the total annual cost ($/yr) and the annual water yield (ML/yr).

$$\$/\mathrm{ML} = \frac{\mathrm{TotalAnnualCost}(\$/\mathrm{yr})}{\mathrm{AnnualWaterYield}(\mathrm{ML/yr})} \qquad (2)$$

4.1.1 Annual Water Yield

The annual water yield is calculated by multiplying the maximum daily production rate (ML/d) by the annual plant utility.

$$\text{Annual Yield (ML/yr)} = \text{Daily Production Rate (ML/d)} \times \text{Utilisation (d/yr)} \qquad (3)$$

The maximum daily production rate is the volume of water that can be delivered from the new facility each day. The annual plant utility is the number of days that the plant operates each year. A key assumption in calculating plant utility is that the plant will operate at maximum capacity every day it is on line. The number of operating days per year is typically the number of calendar days less time lost due to maintenance or plant shut down. Consequently, the number of days that a plant is not operating during the year will decrease the annual yield and potentially increase the unit cost of water.

4.1.2 Total Annual Cost

The total annual cost of a project is the sum of the debt service payment on the new infrastructure and the operating and maintenance cost to produce and deliver water. The maximum daily production rate is the key design criteria which determines the capital cost of the treatment and transport components of the new infrastructure.

The debt service represents a fixed cost, or costs that are incurred each year as a result of simply building the new infrastructure. The annual operation and maintenance costs are variable costs, and to an extent are discretionary (e.g. operational costs are not incurred if the water supply infrastructure is shut down).

It is important to differentiate the total capital cost of the project from the annual debt service. The total capital cost is the contract value (capital expenditure) for the construction of the new infrastructure. Large-scale water supply projects such as desalination have two major capital components; a treatment plant and a water conveyance component.

The annual capital cost is calculated by multiplying the capital expenditure (CapEx) by a Capital Recovery Factor (CRF), where the CRF varies as a function of interest rate (%) and the debt service period (in years). Selecting an appropriate debt service period has a large impact on annual capital costs.

The annual operation and maintenance costs may be divided into three general areas:

- conveyance costs
- treatment costs
- institutional costs

Treatment costs include the cost of energy, chemicals, consumable items (such as membranes and filters), maintenance costs and labour costs (operational staff). The cost of treatment depends on the number of process stages and the operating conditions.

Conveyance costs cover the cost of pumping with minor costs associated with pipeline maintenance. The pumping costs are determined by the distance and elevation (or lift) that is required to deliver the water into a distribution system back to the environment.

Institutional costs can cover a suite of items associated with the project. Examples include;

- the lease cost for land or site access fees
- cost to access feedwater and dispose of some waste
- charges or fees associated with delivering or discharging the final water into the environment
- licensing or contractual fees that are required to cover the cost of taking water from one source in lieu of an existing contract to take water from another source

Comparing the merits of two water supply options requires that all institutional costs are transparent and levelled equitably. The concept of institutional costs will be expanded in 5.2 and used to explain the gap between simple treatment and conveyance costs, and the reported costs for some recently proposed desalination projects.

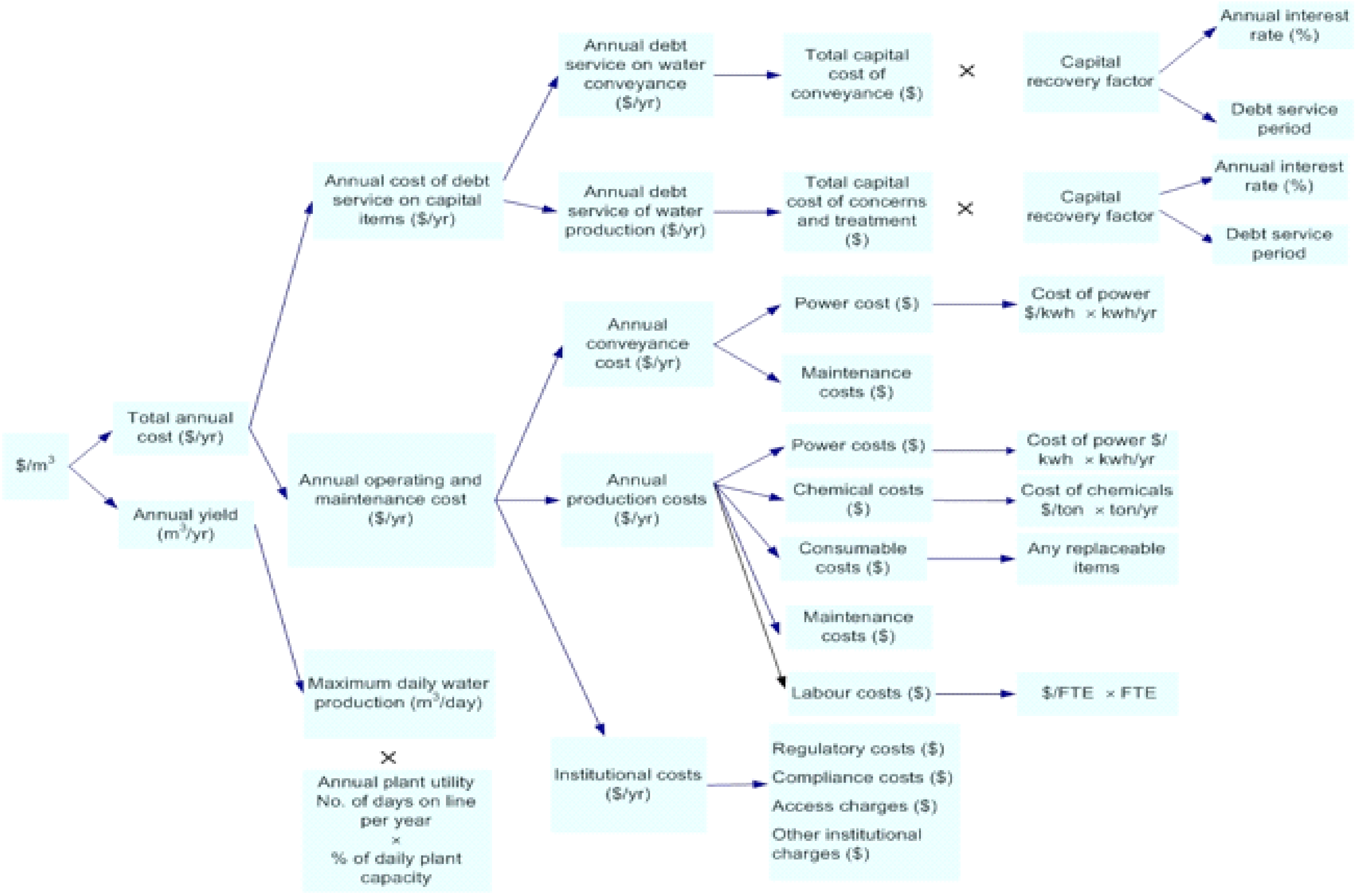

Figure 9: Logic tree for the unit cost of water

4.2 Capital Cost

The total CapEx for a water supply project is the contract cost paid by a water utility to a contactor to provide the infrastructure to produce and deliver water. The annual capital cost reflects the cost associated with servicing the capital used to build the new infrastructure. The annual capital cost of treatment and transport water is a fixed cost; that is the total annual capital costs may be calculated by multiplying the total capital cost of treatment and conveyance by an appropriate capital recovery factor.

4.2.1 Capital Recovery Factor (CRF)

The capital recovery factor is calculated using a Net Present Value (NPV) method. The net present value of the asset is defined for a given discount rate (r) and a series of future payments over a defined period of time (n).

$$\mathrm{CRF} = \frac{r(1+r)^n}{(1+r)^n - 1} \tag{4}$$

At the feasibility or assessment stage of most water supply projects, the debt on the assets is usually serviced over a period of 25 years at a discount rate of 6%. However, the selection of both the discount rate and the debt service period can have a significant effect on the unit cost of water. For example the capital recovery factor, a range of which is presented in Table 9, can vary from 0.0422 at 4% over 75 years to 0.1168 at 8% over 15 years, hence the annual debt service on the desalination plant valued at $500 million would range from $21.1 million per year (4% over 75 years) to $58.4 million (8% over 15 years).

Table 9: Capital Recovery Factors

Debt Service Period	**Interest Rate**		
	4%	**6%**	**8%**
15	0.0899	0.1030	0.1168
25	0.0640	0.0782	0.0937
50	0.0466	0.0634	0.0817
75	0.0422	0.0608	0.0802

4.2.2 Life of Capital Assets

The debt service period may be selected to reflect the life of the asset. For example permanent civil infrastructure such as major pipelines and the buildings for large pumping stations will be designed with an asset life of 75 or 100 years. The West Ryde pumping station in Sydney that delivers drinking water to over 60% of the Metropolitan service area is more than 100 years old. Large mechanical equipment such as the motors and pumps may have an asset life of 50 years, where as the mechanical equipment associated with membrane treatment plants (such as the pressure vessels, membrane racks and valves) is assumed to have an asset life of 25 years.

Finally, experience with seawater desalination plants and seawater intakes in power stations, teaches that the mechanical equipment such as screens and strainers in contact with seawater 24 hours per day has an asset life of 10 to 15 years. Given this broad range of serviceable (or useful life) for different components of a water treatment plant or pipeline it is not uncommon for all the debt associated with the new capital infrastructure to be retired over a nominal 25 year period. Notwithstanding this practice, it is important to note that the selection of the debt service period will impact on the annual capital cost which has a direct impact on the unit cost of water.

4.2.3 Capital Cost of Treatment

The capital cost estimate for various water schemes is divided into two parts:

1) The cost of the contract associated with the delivery of the treatment plant.
2) The cost of the Engineering, Legal and Administrative (ELA) tasks associated with developing the contract documentation and executing the contract.

In general the contract to deliver a desalination plant would consist of the following elements:

- General and Preliminaries – Cost for a contractor to establish the construction site and deliver the construction program. It is important to note that the cost of land is not included in the general contract price to build a water treatment plant. However, land purchase or lease costs may be absorbed in the unit cost of water as institutional costs.
- External Works – Cost to prepare the site prior to civil works and develop all access points for traffic and the intake and discharge of water
- Structural Works – Cost associated with developing foundations and structures for all the areas of the treatment facility
- Civil Works – Cost associated with the construction and installation of pipe networks, roads, drainage and other non-structural civil items.
- Architectural and Landscape – Cost to provide the fittings for the buildings and the layout of the ground and facilities
- Mechanical and Process Works – Cost to procure and install equipment such as screens, pumps, membranes, or tanks
- Electrical Works – Cost to connect the plant to the power grid and distribute power throughout the site to all buildings and processes
- Control and Instrumentation – Cost to install instruments to monitor the process and control and record the performance of the plant
- Testing and Commissioning – Cost to systematically test all components and verify plant is operating
- Maintenance and Spares – Cost to supply and replacement items required during early stages of operation while the plant is under warranty

A budget level capital cost for treatment may be estimated by assigning a percentage to each element of the contract to deliver the treatment plant. The percentages are established by analysing recently completed desalination plants.

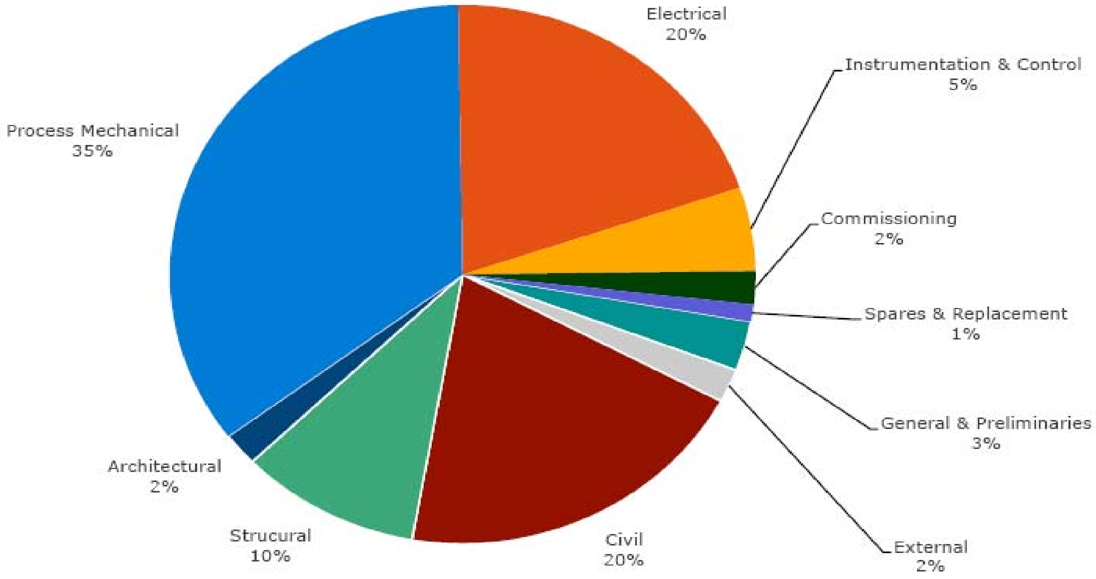

Figure 10: Percentage break-up of capital cost elements0

The Engineering, Legal and Administration (ELA) costs associated with the project represent a percentage of total contract value of these items. The percentage applied to calculate the ELA costs can vary from 10 to 15%. The value of the project contingencies is also expressed as a percentage of the contract cost estimate, which can vary from 40% at the budget stage through to 10% at the detailed design stage (the level of contingencies generally reflect the level of uncertainty in the contract cost element).

Comparing the report cost for various desalination projects is difficult, as the examples reported in literature were developed under significantly varying conditions. For example there is often a significant difference in the cost to purchase or lease land upon which the infrastructure is to be built. The review by Semiat [108] has reported the installation cost for a range of desalination technologies. Multi-Stage Flash (MSF) is reported to be the most capital intensive process, with RO requiring the small capital investment per unit production of water of between US$700-900/m^3. However, a review by Hafez and El-Manharawy [109] reported the unit cost of capital for a range of RO projects to be between US$1300-2200/m^3.

Table 10: Capital Cost Comparison for Various Desalination Technologies

Technology	Installation Cost (US$/m^3 2000)
Multi-Stage Flash (MSF)	$1200 - 2300
Multi Effect Distillation (MED)	$900 – 1000
Vapour Compression (VC)	$950 – 1000
Reverse Osmosis (RO)	$700 – 900

4.2.4 Capital Cost of Conveyance

The capital cost of conveyance or transport includes the cost of constructing pipelines and any appurtenances and turnout on the pipeline route. In the case of desalination it would also include the new treated water storage tanks or ties into the existing drinking water distribution system. There are several factors that affect the capital cost of the transportation system. These include;

- Pipe Length and Diameter – The total length of the pipeline as well as the required diameter of the pipe, which is a function of both the required flow rate and length of the pipeline, will influence the capital cost of the project.
- Pipeline Route – The factors considered include the ease of construction (i.e. river, road or rail crossings), passage through built-up areas and topographical obstacles, such as mountains or escarpments.
- Static Head and Friction Loses – The static head represents the net difference in elevation (gain or loss) along the pipeline route that must be overcome by pumping. The friction head is the additional energy required by the pump to overcome the losses due to friction in the pipe.

The contract elements for conveyance are the same as those for treatment. However, the total capital cost is heavily weighted in favour of civil works, including mechanical and commissioning work, which will contribute up to 90% of the capital cost. The installation costs will vary from site to site, and can be as much as $1M/km in some urban areas.

4.3 Operating and Maintenance Cost Contributions

The annual operating and maintenance (O&M) costs for treatment are incurred after plant commissioning and during plant operation. They include the cost of energy, chemicals, consumable items such as membranes and filter media, equipment maintenance, labour and water quality monitoring. The review by Semiat [108] compared the product costs for a range of desalination technologies. Multi-Stage Flash (MSF) is typically the most costly, whilst Multi Effect Distillation (MED), Mechanical Vapour Compression (MVC) and RO are all within a similar range.

Table 11: Operating and Maintenance Cost Comparison of Different Desalination Technologies

Technology	**Product Costs (US$/m^3 2000)**
Multi-Stage Flash (MSF)	$1.10 - $1.50
Multi Effect Distillation (MED)	$0.75 - $0.85
Vapour Compression (VC)	$0.87 - $0.95
Reverse Osmosis (RO)	$0.45 - $0.92

For a RO desalination facility, a typical breakdown of the O&M cost is provided in Figure 11. The energy component for desalination in a RO plant is primarily electrical power whereas in other desalination technologies such as Multi-Stage Flash (MSF), thermal energy is required. The typical electrical power usage in an RO desalination plant is between 3.5-5kWh/m^3 which represents between 50-75% of the total O&M cost – although it is typically closer to 60%, which makes it the most significant contributor to the production cost of desalted water. At these percentages an increase in the cost of electricity of 25% will increase the O&M costs by 12.5-18.75%.

The chemical requirements with a membrane desalination facility are moderate, contributing approximately 10-12% of the overall cost. The main chemicals used for desalination are:

- Chlorine - Used as a disinfectant, it is used to control biological growth and provide a residual disinfectant
- Acid - Used to dissolve carbonate scale that may precipitate on the surface of RO membranes. It is added continuously to the RO feedwater
- Anti-scaling agents – Used to prevent the precipitation of non-alkaline and sparingly soluble salts on the surface of RO. Anti-scalants are the most expensive chemical used in a RO system and are added continuously to the RO feedwater
- Coagulants – Used to flocculate suspended material in the pre-treatment system in desalination plants. Coagulants such as ferric chloride are added continuously to the plant feed stream.
- Caustic Soda – Used to raise the pH of the RO product water prior to distribution. The chemical is added on a continuous basis.

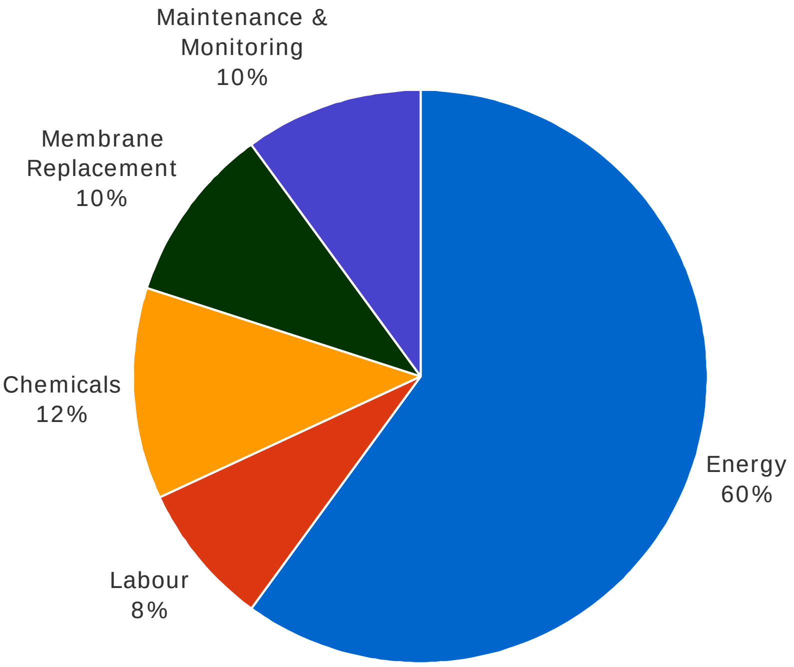

Figure 11: Typical Breakdown of Operating and Maintenance Costs

In addition, other chemicals including surfactants and cleaning agents are used intermittently to clean the membranes.

The membrane replacement cost covers the range of filtration media used in desalination plants. For RO desalination, this is mostly a combination of sand filtration, cartridge filters for pre-treatment followed by the membranes. The RO membranes are sold as individual modules and are typically replaced every five years. Approximately 20% of the sand is replenished in sand filtration annually, depending on the operating conditions, and the cartridge filters are also replaced annually. The total replacement cost for membranes and other consumable media is typically 8-10% of the annual O&M.

Maintenance costs cover all the activities and consumables associated with scheduled and emergency servicing of mechanical equipment, cleaning, calibrating and servicing instrumentation, data acquisition and electrical systems. Monitoring expenses include the costs associated with collecting, analysing and reporting on water quality data. For desalination this would be up to 10% of the O&M costs.

The operations of desalination facilities are not labour intensive, and therefore labour costs contribute only a small proportion to the overall O&M costs, typically about 8%.

4.4 Total Unit Cost of Desalted Water

The total annual cost of water is the sum of the annual debt service for the new infrastructure, often referred to as the fixed costs and the annual O&M costs. Table 12 summarises the total unit cost for the Perth and Sydney desalination projects.

Table 12: Comparison of the total unit cost for Perth and Sydney Desalination plants.

	Perth	**Sydney**
Type of Project	Desalination	Desalination
Plant Location	Kwinana	Kurnell
Plant Capacity (ML/d)	125	250
Distance from intake (km)	<1	< 1 km
Distance to delivery (km)	26	12 km
Total Cap-ex (\$M)	\$387	\$1833
Total Cap-ex Production (\$M)	\$335	\$1170[4]
Total Cap-ex Delivery (\$M)	\$52	\$663[4]
Annual Capital Cost[1]	\$30	\$143
Total Annual O&M (\$M)	\$20	\$55
Annual O&M Production	\$19	\$50
Annual O&M Delivery	\$1	\$5
Unit Cost (\$/m^{3}) Capital[2]	\$0.70	\$1.65
Unit Cost (\$/m^{3}) Production[2]	\$0.44	\$0.58
Unit Cost (\$/m^{3}) Delivery[2]	\$0.02	\$0.06
Unit Cost (\$/m^{3}) Total[3]	\$1.16	\$2.29

1. Assumes debt recovered at 6% over 25 years.
2. O&M costs based on 95% operating utility (i.e. full capacity 95% time).
3. Capital cost for Sydney Desalination includes \$257M Sydney Water project development costs

4.5 Cost Sensitivity

In establishing both the capital and the O&M cost of desalination facilities it is evident that asset life is important in terms of the fixed costs to service the debt for the new infrastructure. Additionally, the large amount of energy used in desalting seawater the greatest and hence most significant cost in terms of the annual operating expenses. The sensitivity of these variables to unit cost of capital and production (O&M) has been examined based on the cost outlined in Table 12 for the Kwinana desalination facility in Perth.

4.5.1 Impact of Asset life

It is assumed that the amortisation period for the infrastructure development is the same as the estimated asset life of the new infrastructure. On the basis of a 6% interest rate and a 25 year asset life (as is often assumed in preliminary cost estimates), the unit cost of capital for the Kwinana facility based on a total capital cost of \$387 million is \$0.70/m^{3}. A reduction in the asset life to 20 year would result in an 11.5% increase to \$0.78/m^{3}.

The influence of the asset life between 10 and 90 years is given in Figure 12 for a range of interest rates. From this figure is can be seen that there is significantly more impact on the unit cost of water as the asset life decreases. Despite preliminary calculations using a nominal asset life of 25 years, experience in desalination facilities informs us that for assets in direct contact with seawater, their asset life is between 10-15 years .

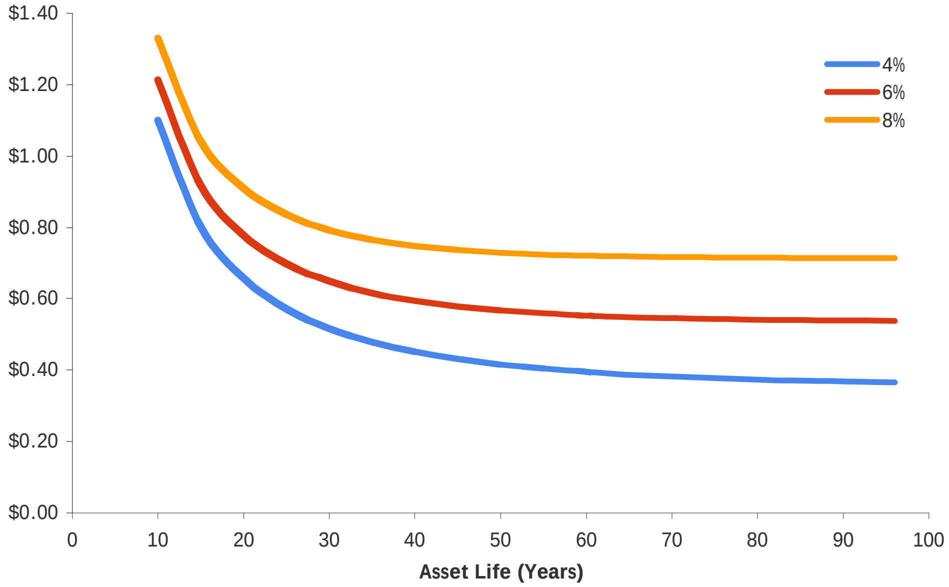

Figure 12: Sensitivity of Unit Cost($/m^3) to changes in life of capital components (assets)

4.5.2 Impact of Energy Cost

The energy cost in the form of electrical power represents the largest operating cost of running an RO desalination facility. As the energy requirements contribute approximately 60% of the total O&M costs, a doubling of the cost of electricity from 10c/kWh to 20c/kWh would correspond to an overall increase in the O&M cost by 70% - such that the total unit cost of production would increase from $0.66/m^3 to $1.12 /m^3 (Figure 13)

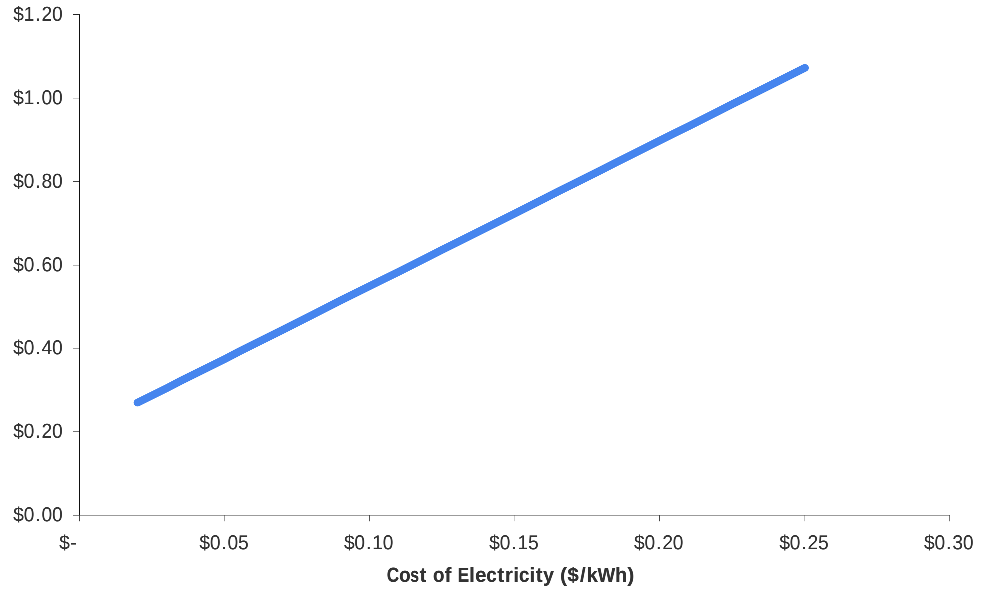

Figure 13: Sensitivity of unit cost of production to electricity prices

4.5.3 Impact of Cost of "Carbon"

It is likely that within the lifespan of any new major capital works, such as a desalination facility, the government will impose additional costs for carbon emissions. Accordingly, it is prudent to evaluate the impact or sensitivities this would have on a new desalination facility.

The amount of carbon emitted to produce a cubic meter of potable water by seawater desalination will depend on the source of energy used to generate electricity, the amount of chemicals used in the process and life of consumable items such as the membrane. Using estimates from the Australian Greenhouse Gas office (www.greenhouse.gov.au) it is possible to estimate the kgCO2/m^3 of desalinated water (Table 13). The largest component of the kgCO2/m^3 for desalination is power. Consequently, water utilities in Perth, Sydney and Melbourne have committed to buying renewable energy credits to offset the greenhouse gas emissions.

Table 13: Typical equivalent CO_2 emissions for a 100 ML/d single pass reverse osmosis plant

Process Input	Purpose	Typical amount (mg/L)	Typical amount (kg/d)(1)	Emission factor ($kgCO_2$-e/kg produced)(2)	Tons of CO_2-e/d
Power	Feed electrical pumps	4.5 (kWh/m^3)		1.467 kg CO_2-e/kWh	660.15
Cl_2	Pre-treatment process	50	12345	1.2	14.81
$FeCl_3$	Pre-treatment process	5	1234	3.23	3.98
Antiscalant	Pre-treatment process	3	740	7.4	5.48
HCl	Pre-treatment process	20	4938	0.76	3.75
NaOH	Second pass pr-treatment	6.34	704	3.23	2.27
Nylon	Membranes	4595 elements	30 (3)	84.4	2.55
Total carbon emitted in 100 ML/d single pass desalination plant ($kgCO^2/m_3$)					

[1] Based on a typical amount of 100ML/d.

[2] Data sourced from AGO Factors and Methods Workbook, December 2005.

[3] Based on five years life time of the membrane element.

Offsetting the carbon emissions associated with desalination is an important part of managing potential increases in the cost of water as a result of the introduction of an emissions trading scheme or equivalent system that puts a price on carbon. For example, based on the reported use of 24.1MW at the Kwinana facility the total energy used per unit of water is approximately 4.6kWh/m^3. The total carbon dioxide equivalent volume generated based on the average energy supply would be 4.7 kg to 6.0 CO_2-e/m^3. From this value the increase in the unit cost of production for a carbon tax of between $5 and $100/tonne C is given in Figure 14. The inclusion of a carbon tax at $50/tonne C would correspond to a 16% increase in the unit cost of production (Figure 14).

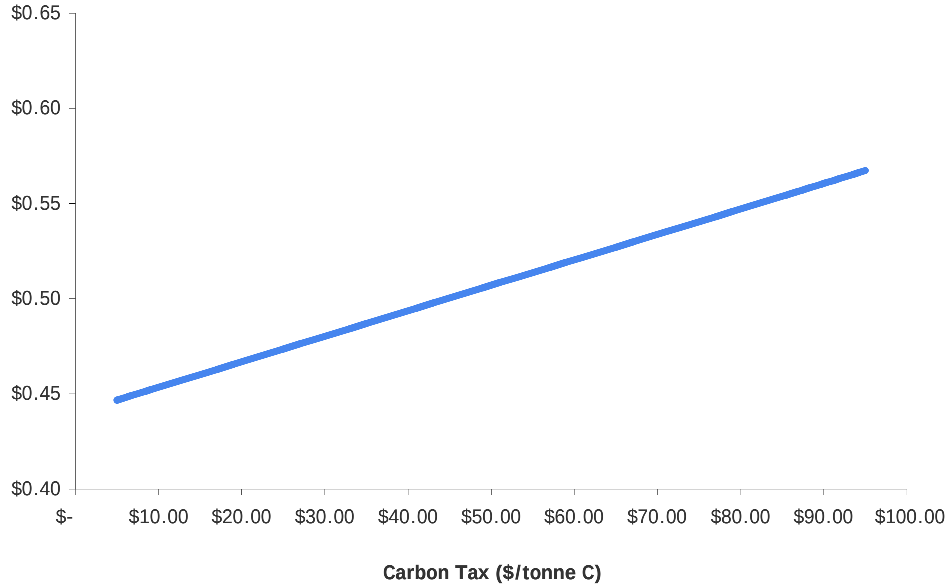

Figure 14: Sensitivity of Unit Cost of Production to a Carbon Tax

5. Urban Water Portfolio: Comparison of Alternative Water Supply Options

Australia's capital cities and major urban areas have traditionally relied on surface waters to meet the demand for potable water. In the past decade, however, the authorities responsible for water supply have turned to non-traditional sources of water, such as seawater, wastewater, brackish groundwater and in some cases stormwater, as alternative supplies to meet demands for potable water, and to provide increased reliability of supply of source water.

Developing alternatives to existing surface water and ground water supplies is necessary to match the increased demands of a growing population and the decreased reliability of existing supplies due to increasingly variable rain patterns and a decline in surface runoff.

Unlike the traditional supplies sourced from rivers, dams and freshwater aquifers, non-traditional water supplies require extensive treatment often involving the removal of dissolved salts. Consequently, water utilities serving Australia's urban population are investing in desalination equipment that produce water which is suitable for use in conjunction with, or as a substitute for, limited potable water supplies.

Building new desalination, groundwater treatment and wastewater recycling infrastructure diversifies the portfolio of water supply options. The type and scale of the projects included in the water supply portfolio is based on a variety of factors, including the geography and location, rainfall, cost, environmental issues and community attitudes.

Planning and development in the major capital cities in the last five years indicates that it is not possible to generalise as to what non traditional supply project is suitable for each city – and that local conditions, requirements and community attitudes ultimately determine the mix of options included in the water supply portfolio (Table 14).

It is clear that cities such as Perth, Brisbane and the Gold Coast, which are experiencing the highest population growth, coupled with the greatest decline in average run-off, are investing in a range of alternative water supply projects. In contrast, cities such as Melbourne are more selective in the development of alternative water supply options. This chapter considers how financial, regulatory, institutional, environmental and community issues are shaping the use of non-traditional water sources and consequently the use of desalination in Australia.

Table 14: Development of Alternative Water Supplies in Urban Australia. Response to population growth and variation in run-off

City	**Population Growth**[1]	**Change in Run-off**[2]	**Development of Non-Traditional Sources**					
			Completed/In Development			**Planned/Proposed**		
			Project	**Capacity ML/d**	**Delivery Date**	**Project**	**Capacity ML/d**	**Delivery Date**
Gold Coast & Brisbane[3]	66%	-9 to –5 %	Tugan Desalination	125	2008	Tugan Desalination	45	2009
			Western Corridor Recycling[3]	200	2008			
Perth[4]	51 %	-9 to –5 %	Kwinana Desal	144	2007	Groundwater Recharge[4]	80	2014
			Bunbury Desal	150	2010			
Sydney	33 %	-4 to 0 %	Kurnell I	250	2009			
			Western Sydney Replacement Flow	50	2009			
Melbourne	31 %	-9 to –5 %	Wonthaggi Desal	400	2011			
Canberra	25 %	-4 to 0 %				ACTEW Recycling	25	2012
Adelaide	5 %	-9 to –5 %				Adelaide Desal	150	2010

1. L. Beazley (PMSEIC, 2007)
2. CSIRO Median projected change in run-off based on 12 different climate models, three climate sensitivities and three emission scenarios (PMSEIC 2007)
3. Queensland Water Commission
4. Western Australian Water Corporation, Source Development Plan for Integrated Water Supply Scheme http://www.watercorporation.com.au/_files/publicationsregister/22/SourcePlan_2005.pdf

5.1 Regulatory and Financial Factors

5.1.1 Regulatory Issues

Regulations covering the development of alternative water supply projects fall into two broad categories:

1) Environmental regulations covering the location, construction and operation of the alternative water supply infrastructure,
2) Health regulations covering the application, entitlement and quality of the water.

Because the development of alternative water supply projects is critical, there have been significant developments in both regulatory areas that seek to achieve the correct environmental and health outcomes, while streamlining the development of water supply projects. Competition is another issue that requires consideration in a regulatory sense.

Environmental Regulations

Desalination projects in Australia are predominantly subject to state and territory regulation and approval requirements. The regulatory approvals process requires projects to meet, amongst other things, environmental, health, planning and water quality licensing requirements.

Alternative water supply projects must also comply with federal regulations and national guidelines covering the protection of the environment. The federal legislation is outlined in several documents including the *Environment Protection and Biodiversity Conservation Act (1999)*, the *Environment Protection and Biodiversity Conservation Regulations (2000)*, and the Australian and New Zealand Environment Conservation Council's (ANZECC) *Australian and New Zealand Guidelines for Fresh and Marine Water Quality (2000)*.

Water Quality and Health Regulations

Regulations and guidelines have been developed covering the use of alternative sources of water to augment drinking water supplies. The production and use of desalinated water is bound by the *Australian Drinking Water Guidelines (2004)*. The production of recycled water for use in reservoirs and dams is covered in Phase 2 of the *Australian Guidelines for Water Recycling (2008)*. These guidelines also outline the use of storm water harvesting and reuse, and managed aquifer recharge.

State health departments use these national guidelines as the basis for the formation of their own requirements for production of water from alternative sources. One such is example is found in Queensland, where the State Government passed the *Water Supply (Safety and Reliability) Act (2008)*. The legislation intends to further strengthen the safety and reliability of Queensland's water supplies by establishing new regulatory frameworks for drinking and recycled water.

5.1.2 Project Financing and Delivery

The involvement of the private sector in desalination projects has increased to the point where the majority of the large desalination plants slated for construction in the Arabian Gulf (Saudi Arabia and UAE) and the Mediterranean (Spain and Algeria) will be Build-Own/Operate-Transfer (BOOT) schemes. BOOT delivery methodology has become popular for a variety of traditional public sector projects. The perceived benefits of BOOT schemes include:

- fixed price at project inception with pre-arranged escalation over the life of the project
- minimal risk of stranded capital on the public books; and
- reduced project delivery time compared with traditional design-bid-build schemes.

While the merits of BOOT schemes over other forms of project delivery are debated, there are two aspects of desalination projects that are compatible with the BOOT approach to project delivery.

First, the BOOT contractor assumes the risk of selecting the appropriate technology (membrane or thermal) to deliver a specified water quality at a guaranteed rate. The advantage of this is that the public entity purchasing the water does not need to manage the risks associated with the technology. This can be an advantage because it is easy to be overly prescriptive on the requirements for process in the tender specifications. This often leads to over design and the exclusion, based on a lack of track record, of many of the incremental improvements associated with desalination systems. In the BOOT approach, the private entity has more flexibility to adopt processes or designs that may be more efficient but lack the track record.

Second, the useful life of the desalination infrastructure typically matches the duration of the BOOT contract. Unlike a dam or a water supply canal, which has a useful life of hundreds of years, a desalination plant is essentially a process equipment plant with a maximum useful life of 25 to 30 years. Therefore, the system can be implemented without including many of the design margins associated with traditional water supplies. To this end, more than 50% of the projected activity in the Arabian Gulf in the next 10 years is associated with replacing thermal desalination systems that were installed during the oil boom of the 1970s.

Table 15: Improvements in Reverse Osmosis Desalination Technology

	Pre - 1985	**1985 - 2000**	**Post - 2000**
Unit Cost, US$/m^3	> 1.50	1.25 – 0.8	< 0.6
Pre-treatment	Media filters	Membrane filtration	Membrane filtration
RO Feed Pressure	80 – 85 bar	65 – 70 bar	55 - 65 bar
NaCl Rejection	96 – 98%	99 – 99.5%	99 – 99.5%
Element Cost (US$/element)	US$ 2000	US$ 700	US$ 450
Train Capacity	3785	11 000	20 000
Energy Recovery[1]	0	10%	30-40%

1. Expressed as percentage of energy savings

The cost of producing water by thermal desalination has declined from approximately US$9/m^3 to US$0.7/m^3 since the first large scale desalination plants were introduced in the 1950s. The reduction in the cost of thermal desalination can mostly be attributed to improved performance of heat exchangers, an increase in the capacity of individual thermal desalination trains, improvements in anti-scaling and anti-foaming agents that can be used to maintain heat transfer efficiency, and a less conservative attitude overall to the problems of scale formation. Of these factors, the most significant in terms of cost reduction is the increase in the capacity of individual thermal desalination units.

The capacity of an individual Multi-Stage Flash (MSF) desalination plant increased from approximately 19,000 m^3/d in the early 1980s to 76,000 m^3/d in 2003. Increasing the capacity of individual MSF plants was made possible by improvements in the materials used to design heat exchanger tubes.

For example, heat exchanger tubes in modern Multi-Stage Flash (MSF) plants are up to 25 m long and 50 mm diameter, with a wall thickness of 0.7 mm. Not surprisingly, these tubes are very fragile and require extensive measure to handle, transport and install the tubes, so that damage is avoided.

The benefit of larger capacity desalination plants is that the complexity and number of components in large scale plants is significantly reduced. Consequently, it is possible to obtain a higher yield from a project using larger capacity components, based on the same capital and energy input. For example, the engineering firm Parsons Brinkerhoff has estimated that the capital cost for a 455,000 m^3/d facility can be reduced by US$25m through reducing the number of Multi-Stage Flash (MSF) units from 8 to 6, using larger capacity desalination trains.

5.2 Institutional Factors

The development of alternative desalination water supplies is dependent on a variety of factors. These include:

- an Australian desalination industry in the context of a water industry skills shortage
- fragmentation of the water industry
- strategies to manage assets to extend useful life

An Australian desalination industry in the context of a water industry skills shortage

A pressing issue hindering the development of the desalination industry is the emerging skills shortage in the water industry in general, and in the fields of science and engineering in particular. A July 2008 study estimated that without corrective action, the water industry could face a shortage in 10 years time of up to 40,000 skilled personnel out of a total industry workforce of 100,000. The study noted in this context that some $40 billion of capital investment is planned over the next ten years (including desalination projects) to secure long term water supplies. Competition with the booming mining industry for civil engineers is also impacting on the water industry. In short, there is a substantial risk of ongoing shortages of skilled personnel to fill positions in operations, design, construction and regulation. This could lead to delays to proposed water infrastructure projects and higher labour costs.

The industry skills shortage has been recognised for some time by the Australian water industry, which has organised a number of conferences and studies to identify the scale of the problem and to seek solutions. To build on this momentum, the National Water Commission convened a National Water Industry Skills Forum in March 2008 jointly with the Australian Water Association and the Water Services Association of Australia. This Forum, which brought together more than 80 water sector leaders, led to the establishment of a Water Industry Skills Taskforce, through which the water industry is now promoting and overseeing a nationally coordinated effort to address the skills shortage in the water sector.

Also in March 2008, the Council of Australian Governments (COAG), in recognition of this critical issue, commissioned a skills audit of the water industry as well as the development of a national strategy to address the skills shortage. The skills audit was completed in July (as mentioned above), and a draft strategy was completed in September 2008. At this point (September 2008) it is expected that COAG will consider the recommendations arising from the skills strategy in December 2008.

Fragmentation of the water industry

The fragmentation of the process for alternative water supply implementation is another significant factor which must be addressed if the desalination industry is to reach its potential. As it stands, any new water supply option must be evaluated by authorities responsible for environmental, health, planning, pricing and service delivery considerations. However each institution may have different objectives, hence preventing the most beneficial development of a water supply option. Thus the coordination of water management and planning, and cross-portfolio engagement of all levels of government should be sought. This would support the introduction of efficient alternative water supply options while meeting regulations concerning public health, environmental management and urban planning.

Strategies to manage assets to extend useful life

Strategies must also be introduced to manage the assets used for alternative water supply options as they will be regularly exposed to corrosive substances, namely seawater used for desalination.

5.3 Community and Environmental Factors

The community factors that must be considered during the development of desalination projects are in most cases comparable to factors associated with more traditional water supply schemes. The recent popularity of desalination compared with traditional water supply projects can be gauged in terms of a lower or more acceptable cost to the community. A basis for comparison of the community costs of desalination with those of traditional water supply projects is to consider the project complexity, the project time frame and any external barriers to project implementation.

Traditional water supply projects that involve the impoundment and transfer of surface waters can be more complex than desalination systems. For example, implementing a traditional water supply project could encompass the construction of a dam, a multi-kilometre pipeline and in some cases a new surface water treatment plant. Similarly, the development of a ground-water scheme will involve the construction of multiple wells and distribution systems. In both cases the projects will involve negotiating right-of-way, implementing measures to mitigate environmental effects, and major infrastructure construction.

Often such projects are delivered using multiple contracts, which – because of the high contract value – can only be financed by the public sector or in developing countries by large international institutions, such as the World Bank or the Asian Development Bank. Moreover, because the quality of the water will be contingent upon conditions in the aquifer or native catchment, it will be necessary to implement an extensive water quality plan that encompasses either catchment management or groundwater monitoring.

In contrast, while desalination projects are more mechanically complex, the projects consist of a treatment plant, which can often be co-sited with existing infrastructure such as power stations and a relatively short connection to the distribution system. In addition, desalination plants typically produce very consistent water quality that is less affected by seasonal variations than traditional supplies, and that can be treated simply by disinfection, fluoridation and the stabilisation of chemicals prior to distribution.

Because desalinated water contains minimal amounts of divalent ions, it is often more suitable for industrial applications – such as low pressure and high pressure boiler make-up – than groundwater and some surface water supplies. Consequently, in terms of agreements, regulatory compliance, infrastructure needs and contractual complexity, the delivery of a desalination plant can be less complex than a traditional water supply project. Accordingly, it is possible that the project will be attended by a shorter delivery time. As a result desalination is often perceived as a solution in new residential and industrial developments, as a complementary process for power generation projects, and as emergency relief in times of drought.

In some places, external barriers to the implementation of traditional water supply projects favour the development of desalination schemes. The following are certain barriers that may be encountered:

- *Community and regulatory opposition to the effects of water transfers on ecosystems*

Some environmental groups support the proposed desalination projects in Southern California, in preference to increased transfers from northern California. These have caused seawater ingress into the less saline reaches of the Sacramento-San Joaquin Delta, thereby reducing the viability of this habitat for 22 species of fish and birds. Similarly, new desalination plants installed in the south of Spain were developed after the government in Madrid moved to limit additional transfers from the river Ebro, in order to restore some environmental flow in the river mouth near Barcelona. In such situations, environmentalists will advocate for the development of local supplies over increased water transfers.

- *Opposition by Agricultural Interests to Increased Water Transfers*

In many countries, the cost of water for agricultural use is often two orders of magnitude lower than the cost of water in urban communities. A consequence of subsidizing water for agriculture is the development of crops that are more profitable in terms of yield per area but also have higher water requirements. In such situations, it is politically difficult to alter the distribution of water between agricultural and urban interests, and the development of local supplies by desalination is the path of least resistance.

- *Community opposition to indirect potable reuse of wastewater*

Indirect potable reuse (IPR) is the term applied to the practice of using highly treated wastewater to augment surface water or groundwater supplies. IPR projects operate in the Netherlands, Belgium, Singapore, the United States and Southern Africa. Because treatment costs and energy requirements are typically lower for IPR than seawater desalination, IPR projects are often evaluated as an alternative water supply source by communities that are considering desalination. However, despite several successful public education campaigns, IPR is assumed to be unacceptable to the public. However, recently the Queensland Government and the Queensland Water commission have developed the Western Corridor project that will deploy the same technology used in desalination processes to recycle municipal wastewater (Table 16). The purified water will be used as an alternative to potable water supply in South East Queensland power stations and will be used to augment potable supplies stored in the Wivenhoe dam.

Raising community awareness of the similarities in the processes used to desalinate and recycle water and extensive nature of the treatment process is one way of gaining community acceptance for recycling. Similarly, by demonstrating that potable water produced using desalination will be recycled as part of an integrated water supply scheme is a prudent way of managing a valuable resource.

Table 16: Comparison of desalination and water recycling schemes.

Item	**Desalination**	**Water Recycling**
Example	Kwinana Desalination Plant, Perth, Western Australia	Western Corridor Recycling Project, Queensland
Plant location	Kwinana Industrial Precinct	Located at existing wastewater treatment plants (Luggage Point, Bundamba, Gibson Island, Oxley)
Intake structure	Sub-surface collector wells	Collection basin prior to discharge pump station
Intake structure capacity	2 – 2.5 x product water capacity	1.2 – 1.3 x product water capacity

Feed water	Seawater	Secondary treated municipal wastewater
Total dissolved solids, in feedwater (TDS)	26,000 – 40,000 mg/L	600 – 1500 mg/L
Treatment Process	Mechanical screening, chemical flocculation and filtration to remove microorganisms, suspended solids and particles Reverse osmosis to remove dissolved solids Chlorination, chemical stabilisation and fluoridation to prepare water for distribution system	Mechanical screening followed by chlorination and membrane filtration to control biological fouling and remove microorganisms and particles Reverse osmosis to remove dissolved solids Advanced oxidation (UV+H_2O_2 or Ozone) to disinfect parasites and remove small organic molecules Chlorination and chemical stabilisation to prepare water for discharge in the environment
Product distribution	Return to large node in drinking water distribution system	Supplied to power stations and used to recharge Wivenhoe dam

6. Appendix 1 – Minimum Separation work for the Desalination Process

6.1 Minimum Separation using 2^{nd} Law Thermodynamic Analysis

Given a mixture of two components (water and salts) with a mole fraction of xw and xs, the minimum separation work to separate the two components is the work required to overcome the entropy generated as a result of mixing process.

The entropy of mixing is given by equation A1;

$$\Delta S_{mixing} = -R \times \sum_i n_i \ln(x_i) \qquad \text{A1}$$

where R is the gas law constant, n_i is the number of moles, and xi is the mole fraction of component i. Thus, the exergy destroyed ($E_{destroyed}$) can be calculated from equation A2 as:

$$E_{destroyed} = T_0 S_{gen} \qquad \text{A2}$$

Therefore, the minimum separation work for complete separation of the two components is calculated as;

$$W_{\min} = T_0 S_{gen,ideal} = -RT_0 n_T \sum_i x_i \ln x_i \qquad \text{A3}$$

where, n_T is the total number of moles of the mixture.

The relationships derived above are used to calculate the minimum separation work to completely separate the two components into pure components. The same equation (A3) can be used to calculate the minimum separation work in a real desalination process, in which a complete separation of water and salts can not be achieved.

The minimum separation work for the desalination process is determined by first determining the minimum separation work for the incoming saline water and the minimum separation work for the outgoing streams (brine and permeate). The minimum separation work is then the difference between the two values:

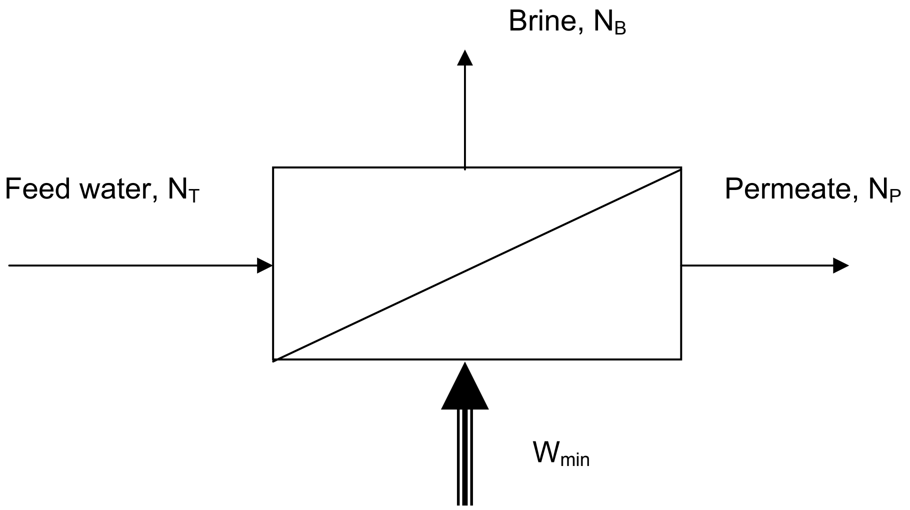

Figure A1 Schematic of ideal desalination process

The schematic diagram shows an ideal desalination process in which the feed water enters the process at T0 and P0, and the outgoing streams leave the process under the same conditions. By knowing the salinity of each stream, the minimum separation work of each stream can be calculated independently from equation (A3) as follows:

$$W_{\min,brine} = -N_{brine} R T_0 \left(x_{s,brine} \ln(x_{s,brine}) + x_{w,brine} \ln(x_{w,brine}) \right) \qquad \text{A4}$$

$$W_{\min,permeate} = -N_{permeate} R T_0 \left(x_{s,permeate} \ln(x_{s,permeate}) + x_{w,permeate} \ln(x_{w,permeate}) \right) \qquad \text{A5}$$

$$W_{\min,process} = W_{\min,Complete} - (W_{\min,brine} + W_{\min,permeate}) \qquad \text{A6}$$

where $W_{min,complete}$, is the minimum work for complete separation of incoming saline water, and is give by equation(A3). Therefore, combining the above equations of the minimum separation work for the brine and permeate streams with equation (A3) yields the minimum separation work required for desalination process as follows:

$$W_{\min} = RT_0 \left(N_{s,brine} \ln\left(\frac{x_{s,brine}}{x_{s,f}}\right) + N_{s,permeate} \ln\left(\frac{x_{s,permeate}}{x_{s,f}}\right) + N_{w,brine} \ln\left(\frac{x_{f,brine}}{x_{w,f}}\right) + N_{w,permeate} \ln\left(\frac{x_{w,permeate}}{x_{w,f}}\right)\right) \qquad \text{A7}$$

Equation A7 is a general formula for minimum separation work input for the separation of incoming saline water of known salinity x_s into two streams of know salinity $x_{s,brine}$ and $x_{s,permeate}$. It determines the minimum separation work for a range of 0 to 100 % recovery of fresh water, for any combination of salinities of the incoming saline water and the outgoing product water and brine.

6.2 Minimum Separation Work from Osmotic Pressure Theory

Minimum separation work can also be obtained using the osmotic pressure (π) calculated from the Van't Hoff equation as follows:

$$\pi = vN_s RT \qquad \text{A8}$$

where π is the osmotic pressure of the solution in kPa, vN_s is the molar concentration of solute in the solvent in kmol/m^3.

Once the osmotic pressure is determined, then the minimum separation work is calculated by multiplying the osmotic pressure by a unit volume of water, and dividing this by 3600 kJ/kWh to get the power consumption in kWh/m^3 as;

$$W_{\min}(kWh/m^3) = \pi(kPa) \times \frac{1}{3600}(kWh/kJ) \qquad \text{A9}$$

The minimum separation work obtained from equation A9 corresponds to the production of pure water, at a negligible recovery ratio ($r \approx 0$). This is because the osmotic pressure of a solution is defined as the applied pressure to maintain the solution in equilibrium with pure solvent when separated by a semi permeable membrane that only allows solvent to pass.

The Van't Hoff equation requires the concentration of solute in the solvent,\. Therefore, in the case of saline water, the salt (NaCl) is considered to be the solute and the solvent is water. The empirical dissociation constant for NaCl is 1.8, which means the concentration of solute in the saline water is almost twice the concentration of NaCl in the solution.

6.3 UMST 2nd Law efficiency model

There is a big difference in minimum separation work calculated by equation (7), at zero recovery ratio, and the minimum separation work calculated using equation (A9). The source of disagreement comes from the fact that in the Van't Hoff equation model the dissociation constant of NaCl was considered and included in the calculation of the osmotic pressure, whereas in the other model, the concentration of the solute was assumed to be equal to the concentration of NaCl in the solution. In order to adjust this error, it is necessary to assume the binary mixture is solute and water instead of NaCl and water, in which the solute is the dissociated NaCl. As a result, the concentration of the solute will be 1.8 times the concentration of NaCl in the water.

The aforesaid changes will affect the calculation of the number of moles of solute, and therefore will affect the mole fraction of both solute and solvent, as:

- salt concentration in the solution (m_{NaCl}) = (mass of NaCl)× 10-6 kg/(kg solution), and
- the molar concentration of NaCl [NaCl], mol/L = (m_{NaCl})×1000/58.44(g/gmol).

The molar concentration of solute is then calculated by multiplying the molar concentration of NaCl by the dissociation factor of 1.8.

[Solute], mole/L = 1.8× [NaCl]

Once the solute molar concentration is calculated, then the minimum separation work calculated from equation A3 will be approximately the same compared with the minimum separation work calculated based on the Van’t Hoff equation.

7. Appendix 2 – desalination timeline

The following tables show the major advances made in thermal and membrane desalination over time.

History of Thermal Desalination (Pre-1955)

320 BC - Greek Philosopher Aristotle writes of seawater distillation
70 AD - Rome's Pliny the Elder describes seawater distillation with condensation on fleece
200 AD - Greece's Alexander of Aphrodisias describes seawater distillation with condensation on sponges
975 AD - Persia's Muwaffaq and al-Harawi write that distillation is a suitable method of seawater conversion
1565 - French explorer Jean De Lery reports seawater was successfully distilled during voyage to Brazil
1616 - Spain's Pedro Fernandez de Quiros discovers Australia and makes successful use of a small copper still
1675 - Walcot files seawater distillation patent in England
1683 - Fitzgerald files conflicting seawater distillation patents, leading to protracted patent dispute with Walcot
1739 - Hales recommends limiting recovery in simple stills to 33% to improve quality and suggests aeration to improve taste
1753 - Watson and Appleby report on pretreating seawater with bone phosphate and quicklime
1756 - Lucas publishes article skeptical of many distillation designs and especially critical of recommended additives
1759 - Chapman reports on successful use of emergency seawater still on North Sea voyage
1761 - Lind experiments with parabolic mirrors for use with solar distillation
1772 - James Cook begins successful use of seawater still while circumnavigating the world
1791 - Thomas Jefferson publishes *Report on the Method of Obtaining Fresh Water from Salt*
1793 - Spain's Phillip II assembles a crude still producing 40 barrels/day of fresh water while fighting the Turks in Tunisia
1828 - Péclet hints at but does not build successful multi-effect evaporator

1840 - Swiss firm Escher Wyss installs vapour compression distiller in British Colombia, Canada
1843 - Rillieux patents, builds, sells successful multi-effect evaporators
1851 - France's Alphonse Normandy patents first of series of vertical tube single stage seawater stills in England
1862 - Three 27 m^3/d Normandy stills installed at Key West Florida, Fort Pulaski Georgia and Tortugas
1879 - Picard and Weibel describe, then patent first mechanical vapour recompression system
1881 - Seawater distiller installed on Malta
1885 - Wilson designs, installs 19 m^3/d solar distiller for mining application in Las Salinas, Chile
1886 - Yaryan introduces rising film vertical tube evaporators
1888 - Lillie introduces spray-film horizontal tube evaporator with provision for removing non-condensable gases
1895 - Mirlees-Watson installs two six-effect seawater distillers in Sudan
1899 - Kestner patents first of a series of rising and falling-film long tube vertical evaporators
1900 - Addison Waterhouse's US patent anticipates multistage flash distillation process
1907 - Two small land-based seawater plants known as ”The Kindasa” (the condenser), installed in Jeddah, Saudi Arabia
1908 - Prache designs, patents thermocompressor nozzle design and establishes TVC business
1910 - Frank Normandy publishes 244-page book entitled *Sea Water Distillation*
1912 - Weir installs six-effect evaporators on Red Sea in Safaga Bay, Egypt
1928 - UK's Aiton installs a Prache & Broullion TVC evaporator on Curaçao
1930s - Weir installs many submerged tube multi-effect evaporators on Curaçao and Aruba
1934 - SS Queen Mary launched, with triple effect cupronickel evaporators using ferric chloride as an anti-scalant
1940 - MECO manufactures diesel engine driven VC distillers for US military producing 12 lb water for 1 lb fuel
1941 - MECO introduces Model K diesel powered vacuum distiller with 260:1 water to fuel ratio
1946 - Kuwait Oil Company installs country's first evaporator using a unit from an old World War I destroyer
1954 - Cleaver Brooks (later Aqua Chem) provides four 190 m^3/d 5-stage MSFs for aircraft carrier *Independence*

History of Membrane Desalination

1748 - Abbe Noilett discovered the phenomenon of osmosis in natural membranes.
1855 - Adolph Fick created a cellulose nitrate (nitrocellulose) membrane as the first synthetic membrane.
1866 - Thomas Graham a British physical chemist first used the term dialysis.
1869 - The first synthetic polymer studied & produced commercially by Schoenbein.
1907 - Bechold first introduced the term ultrafiltration.
1927 - Sartorius Company first made membranes commercially available.
1934 - Research on electrodialysis done by G. R. Elder
1950 - Gerald Hassler introduces the first concept of membrane desalination
1958 - C. E. Reid and E. J. Breton showed that cellulose acetate was an effective membrane material for water desalination.
1960 - Sidney Loeb and Srinivasa Sourirajan developed the first practical membranes for a water desalting process called reverse osmosis.
1960 - H. K. Londsdale develops thin film composite type membranes.
1963 - H. I. Mahon developed the first capillary (Hollow Fibre) membranes.
1965 - The world's first commercial RO plant was built in Coalinga, CA
1977 - John Cadotte patents thin film composite membrane under government grant.

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9. Abbreviations and Acronyms

- **BW** – Brackish Water
- **BWRO** – Brackish Water Reverse Osmosis
- **CA** – Cellulose Acetate
- **CapEx** – Capital Expenditure
- **CRF** – Capital Recovery Factor
- **CDI** – Capacitive Deionisation
- **CNT** – Carbon Nanotube
- **ED** – Electrodialysis
- **EDR** – Electrodialysis Reversal
- **ELA** – Engineering, Legal and Administration
- **EU** – European Union
- **FO** – Forward Osmosis
- **GLA** – Gigalitres per Annum
- **GOR** – Gained output ratio
- **HFF** – Hollow Fine Fibre
- **IDA** – International Desalination Association
- **ISE** – Institute of Solar Energy
- **MVC** – Mechanical Vapour Compression
- **OP** – Osmotic Pressure
- **OSW** – Office of Saline Water
- **O&M** – Operating & Maintenance
- **MD** – Membrane Distillation
- **MED** – Multiple Effect Distillation
- **MF** – Microfiltration
- **MSF** – Multistage Flash Distillation
- **NF** – Nanofiltration
- **R&D** – Research & Design
- **RO** – Reverse Osmosis
- **SW** – Salt Water
- **SWM** – Spiral Wound Membrane
- **SWRO** – Seawater Reverse Osmosis
- **TDS** – Total Dissolved Solids
- **TFC** – Thin-Film Composite
- **TFNC** – Thin-Film Nano-composite
- **UF** – Ultrafiltration
- **WHO** – World Health Organisation

10. Terminology

- **Brine –** the term used to describe the concentrated salt stream produced during the desalination process
- **Total dissolved solids –** the amount of soluble material present in a water source
- **Direct reuse -** The beneficial use of reclaimed water with transfer from reclamation plant to the reuse site.
- **Indirect reuse -** The beneficial use of reclaimed water after releasing it for storage dilution into natural surface waters or groundwater.
- **Non-potable reuse -** The beneficial use of reclaimed water other than potable water supply augmentation.
- **Potable reuse -** The beneficial use of highly treated reclaimed water towards augmentation of drinking water supply.
- **Preliminary treatment -** Treatment steps including comminution, screening, grit removal, pre-aeration and/or flow equalization which prepare wastewater influent for further treatment.
- **Primary treatment -** Treatment steps including sedimentation and/or fine screening to produce an effluent suitable for biological treatment.
- **Reclaimed water -** Wastewater that has been treated to a level that allows for its reuse for a beneficial purpose.
- **Repurification -** The use of advanced technologies to treat secondary, tertiary and quaternary effluents to a very high quality, often exceeding potable water standards.
- **Secondary treatment -** The treatment of wastewater through biological oxidation after primary treatment.
- **Tertiary treatment -** The use of physical, chemical, or biological means to improve secondary wastewater effluent quality.
- **Quaternary treatment -** The use of a double membrane process in the repurification of water. This might involve micro filtration or ultrafiltration for pre-treatment before reverse osmosis or nanofiltration.
- **Water reclamation -** The restoration of wastewater to a state that will allow its beneficial reuse.
- **Water recycling -** Reclamation of effluent generated by a given user for on-site reuse by the same user.