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SFERA-III 2nd Summer School
October 5th- 6th, 2021
Almería (Spain)

Lecture:
Fundamentals of water desalination

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- **Introduction**
- Desalination basics
- Industrial desalination technologies
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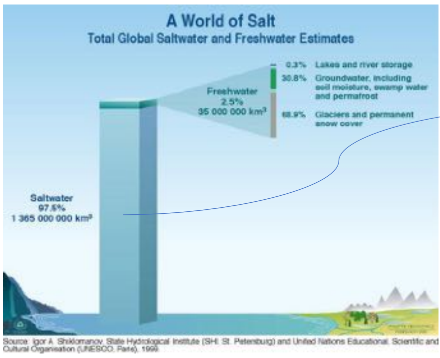
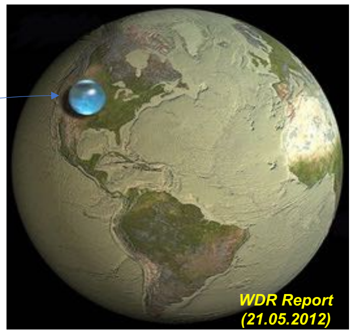
Water Resources





If all the Earth's water – including its rivers, lakes, groundwater, seawater and glacial icecaps – were contained in a bubble, that bubble would measure **1,385 km**. About **12,900 km³** of additional water, mostly in the form of water vapor, is contained in the atmosphere at any given time.

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Water Classification

- **Fresh water** or **tap water** may have salinity **up to 500 ppm**.
- **River water** or **low concentrated saline water** (**500 ppm – 3,000 ppm**)
- **Brackish** waters exhibit salinity in the range of **3,000-10,000 ppm**.
- **Seawater** salinity typically ranges from **10,000 ppm** up to **50,000 ppm**.
- **Brine or concentrated seawater** (> **50,000 ppm**)

1000 ppm = 1 g/L

The energy consumption of certain desalination processes depends on the salinity of the water, while in others, such consumption is independent. This must be considered when choosing the most suitable process according to the characteristics of the water to be treated.

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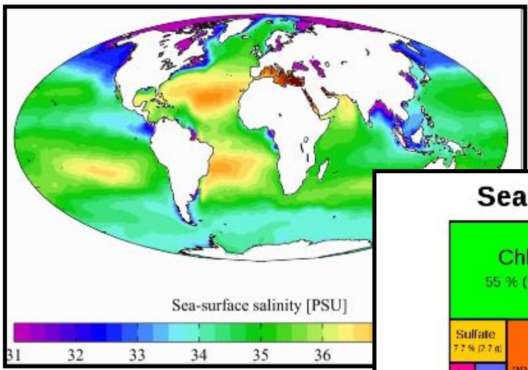
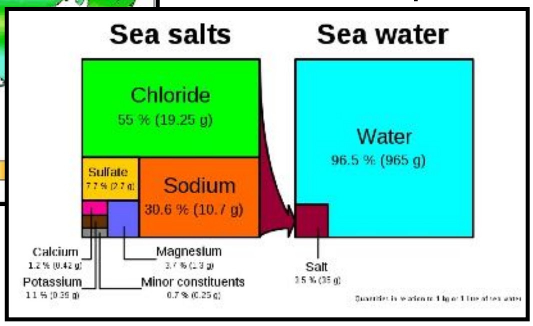
Seawater Chemistry

Variation of salinities in the seas



Seawater composition



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Seawater Chemistry

Seawater composition

Chemical Ion	concentration ppm, mg/kg	part of salinity %	mmol/ kg
Chloride Cl^-	19345	55.03	546
Sodium Na^+	10752	30.59	468
Sulfate SO_4^{2-}	2701	7.68	28.1
Magnesium Mg^{2+}	1295	3.68	53.3
Calcium Ca^{2+}	416	1.18	10.4
Potassium K^+	390	1.11	9.97
Bicarbonate HCO_3^-	145	0.41	2.34
Bromide Br^-	66	0.19	0.83
Borate BO_3^{3-}	27	0.08	0.46
Strontium Sr^{2+}	13	0.04	0.091
Fluoride F^-	1	0.003	0.068

It should be well observed that although salinity of seawater may well vary depending on the specific region of the world, **the percentage composition of seawater is essentially constant** throughout the world (i.e. the proportions of the major constituents are constant)

It is the minority salts (**divalent ions**) that will be the **main challenge** for the different desalination technologies.

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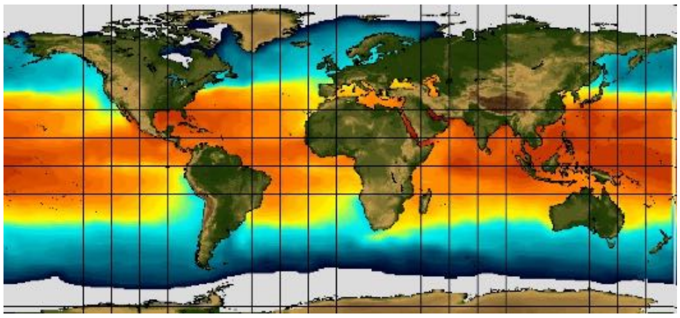
Seawater Temperatures

0 ºC<T<35-40 ºC



Seawater surface temperatures vary geographically and seasonally. When seawater is used as a **cooling source**, this can have an influence on **thermal efficiency**.

Increase of seawater surface temperature may also affect the biology growth, leading to more frequent occurrence of **red tides**, which are toxic and can cause serious damage in desalination plants

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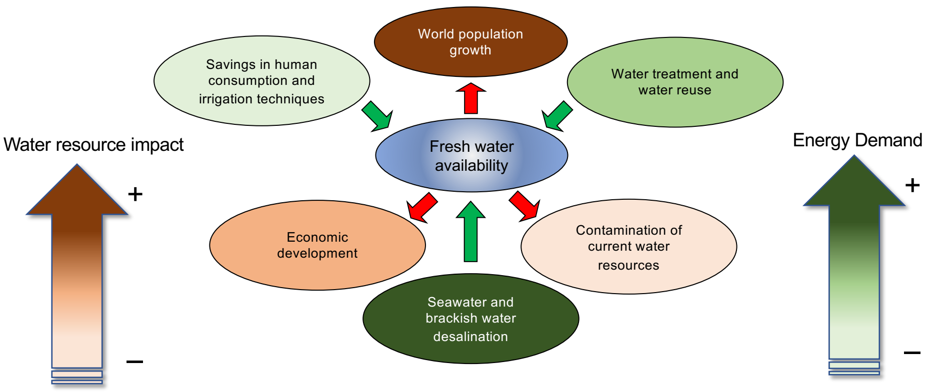
The Water Crisis



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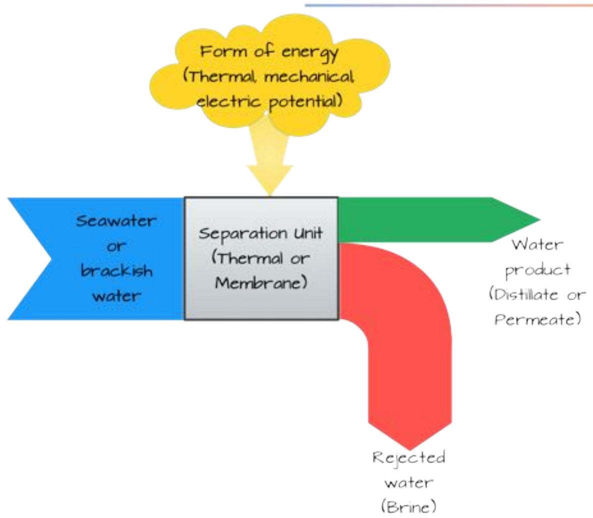
The Desalination Process



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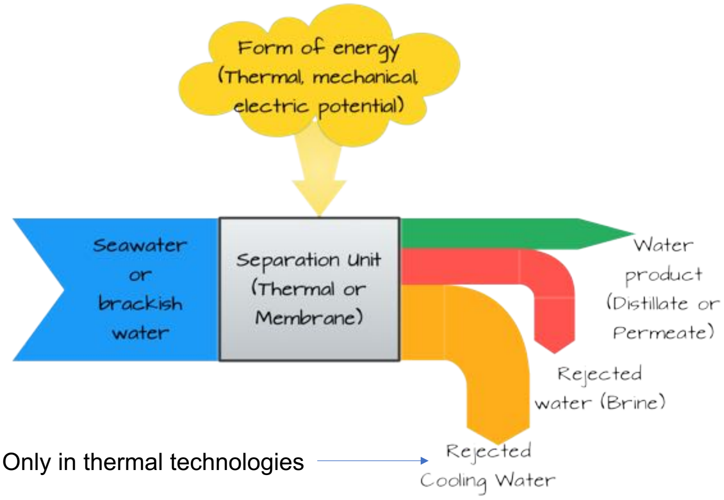
The Desalination Process



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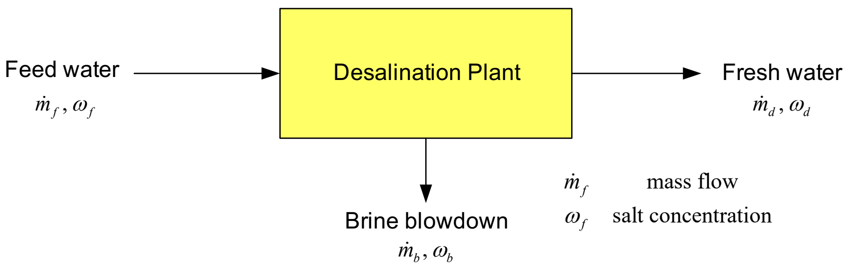
Basic Equations



Mass conservation (Overall mass balance):

$$\dot{m}_f = \dot{m}_b + \dot{m}_d$$

Salt conservation (Overall salt balance):

$$\dot{m}_f \omega_f = \dot{m}_b \omega_b + \dot{m}_d \omega_d$$

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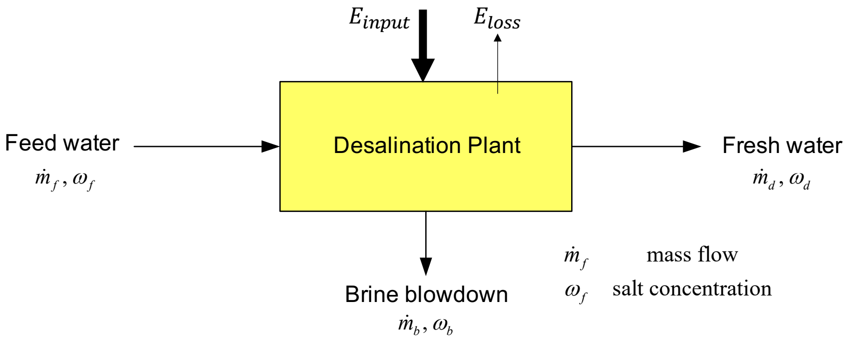
Basic Equations



Energy conservation:

$$\dot{m}_f h_f - \dot{m}_b h_b - \dot{m}_d h_d = E_{input} - E_{loss}$$

Relevant Parameters

- **Concentration factor**. Defined as the ratio between the brine and feed water concentration:

$$CF = \frac{\omega_b}{\omega_f} = \frac{\dot{m}_f}{\dot{m}_f - \dot{m}_d}$$

This parameter give us the number of times the brine is concentrated with respect to the feed water, and it is important from the point of view of possible salt precipitation if the concentration of any salt is above its solubility.

Combining the above definition and the mass flow and salt balance relationships:

$$\dot{m}_d = \dot{m}_f \left(1 - \frac{1}{CF}\right)$$

The higher the brine blowdown concentration the more the desalinated water that can be produced per unit of seawater

Relevant Parameters

- **Conversion or recovery ratio**. It represents the percentage of product that is obtained from a determined quantity of feed water:

$$RR(\%) = \frac{\dot{m}_d}{\dot{m}_f} \times 100$$

Typical values range between 35 y 50% for sea water and up to 70-80% for brackish water.

Low recovery ratios would be usually associated with high specific electricity consumption and higher use or chemicals for the pretreatments

Rearranging the terms, the concentration factor and recovery ratio can be related by the following expression:

$$CF = \frac{1}{1 - RR}$$

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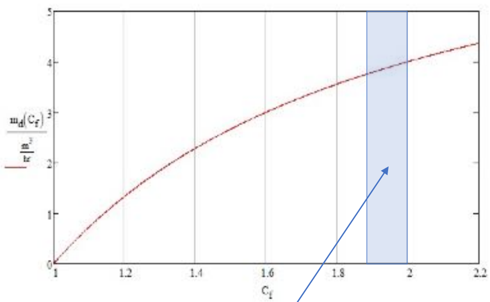
Relevant Parameters

- Seawater TDS = 35 g/L
- Distillate production = 3 m^3/h
- Feedwater = 8 m^3/h

$$CF = \frac{\omega_b}{\omega_f} = \frac{\dot{m}_f}{\dot{m}_f - \dot{m}_d} = \frac{8}{(8-3)} = 1.6$$

$$RR(\%) = \frac{\dot{m}_d}{\dot{m}_f} \times 100 = \frac{3}{8} \times 100 = 37.5\%$$



Technical limit due to scale precipitation

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Relevant Parameters

- **Capacity**. It is defined as the volume of freshwater produced by day. It is important to distinguish between plant capacity and unit capacity. Typical units are m^3/day (cubic meters per day), mgd (million of gallons per day) and migd (millions of imperial gallons per day).

$$1\ \text{mgd} = 3785.41\ \text{m}^3/\text{d}$$
$$1\ \text{migd} = 4546.09\ \text{m}^3/\text{d}$$

m3/d	mgd	migd
1.000	0,26	0,22
5.000	1,32	1,10
10.000	2,64	2,20
25.000	6,60	5,50
50.000	13,21	11,00
100.000	26,42	22,00

mgd	m3/d
0,1	379
1	3.785
10	37.854
20	75.708
50	189.271
100	378.541

migd	m3/d
0,1	455
1	4.546
10	45.461
20	90.922
50	227.305
100	454.609

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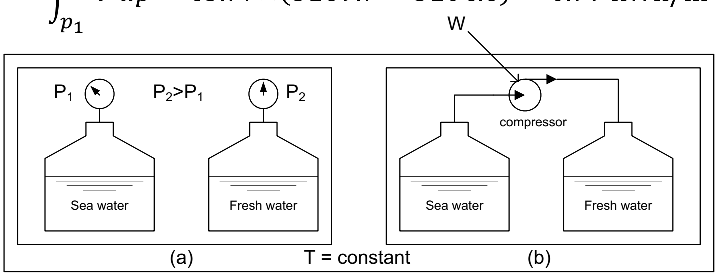
Minimum Energy Consumption

- Pure water equilibrium pressure at 25ºC: 3169.7 Pa
- Volume occupied by 1 kg of water vapor: 43.34 m^3
- Sea water equilibrium pressure (35 g/L) at 25ºC: 3104.6 Pa
- Volumen occupied by 1 kg of water vapor: 44.25 m^3

$$\frac{43.34 + 44.25}{2} = 43.77$$

$$W = \int_{p_1}^{p_2} v\,dp = 43.77 \times (3169.7 - 3104.6) = 0.79\ \text{kWh/m}^3$$



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Minimum Energy Consumption

Temperature	Salinity	Pressure	Spec. Volume	Mean Vol.	Dif Press	Min. Work
ºC	g/kg	Pa	m3/kg	m3/kg	Pa	kWh
25	0	3169,7	43,34	-	-	-
25	5	3160,1	43,47	43,41	9,6	0,12
25	10	3151,0	43,60	43,47	18,7	0,23
25	15	3141,8	43,73	43,53	27,9	0,34
25	20	3132,5	43,86	43,60	37,2	0,45
25	25	3123,3	43,99	43,66	46,4	0,56
25	30	3114,0	44,12	43,73	55,7	0,68
25	35	3104,6	44,25	43,80	65,1	0,79
25	40	3095,2	44,39	43,86	74,5	0,91
25	45	3085,8	44,52	43,93	83,9	1,02
25	50	3076,3	44,66	44,00	93,4	1,14

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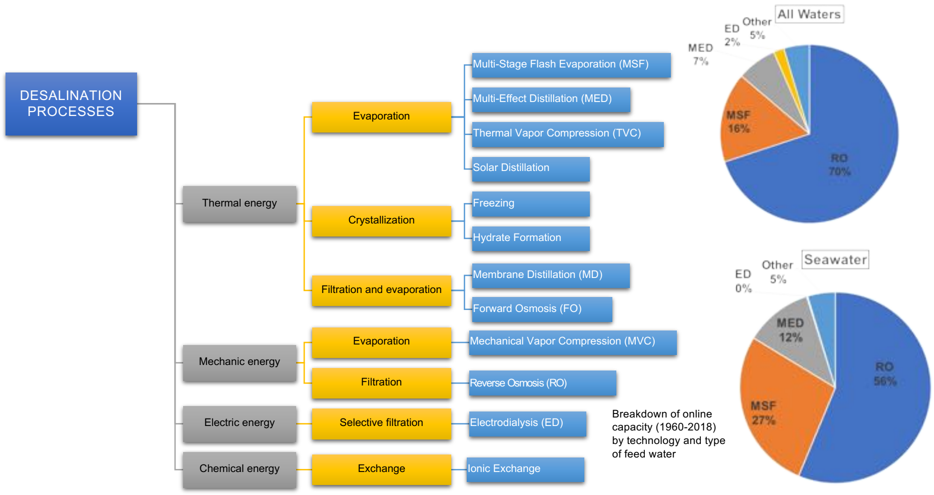
Classification



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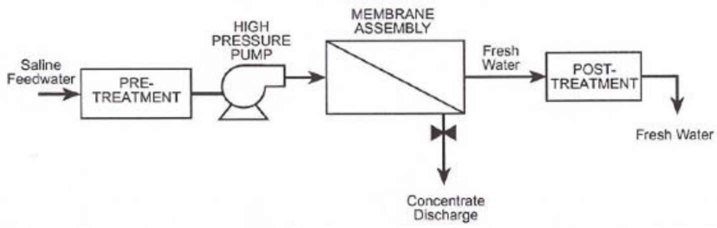
Reverse Osmosis (RO)

In practice, the saline feed water is pumped into a closed vessel where it is pressurized against the membrane. As a portion of the water passes through the membrane, the remaining feed water increases in salt content. At the same time, a portion of this feed water is discharged without passing through the membrane.



The high-pressure pump supplies the pressure needed to enable the water to pass through the membrane and have the salts rejected. This pressure ranges from 17 to 22 bar for brackish water and from 52 to 69 bar for sea water.

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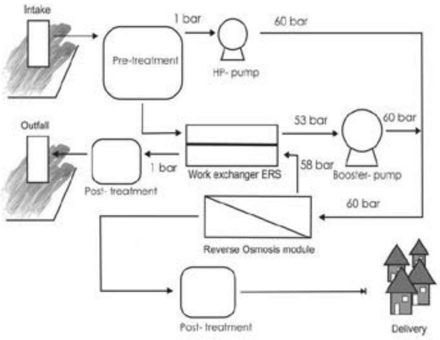
Reverse Osmosis (RO)

In seawater reverse osmosis process, about 40-45% of feed water is recovered as permeate. Remaining 55-60% is rejected to the sea at a pressure only slightly inferior to the pressure it had before entering into the module. Commercial plants have, in general, recovery systems that allow to recover part of the energy from the brine flow.



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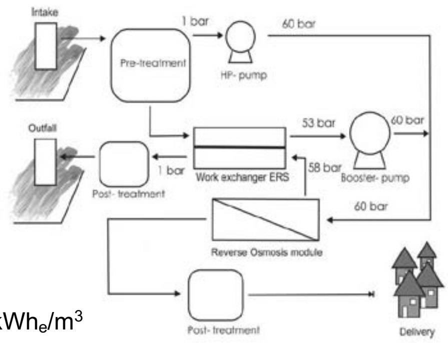
Reverse Osmosis (RO)

In Reverse Osmosis processes the high-pressure pump supplies the pressure needed to enable the water to pass through the membrane and have the salts rejected. This pressure ranges from 17 to 22 bar for brackish water and from 52 to 69 bar for sea water.



Energy consumption (sea water): ~3 kWh_e/m^3

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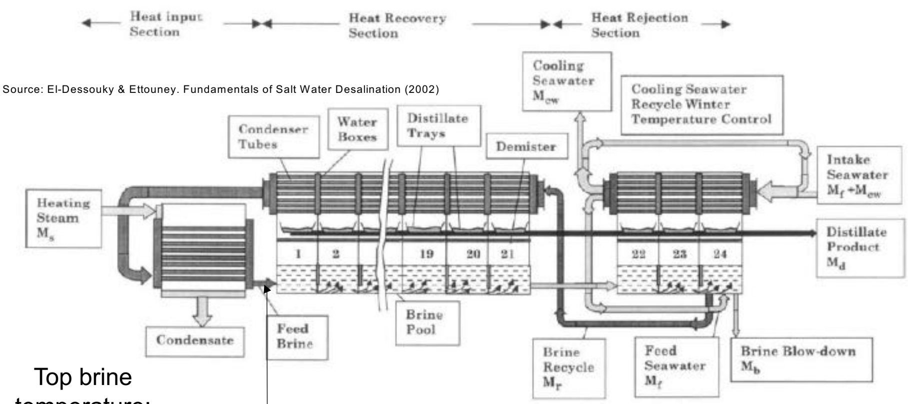
Multi-Stage Flash Evaporation (MSF)

Source: El-Dessouky & Ettouney. Fundamentals of Salt Water Desalination (2002)



Top brine temperature: 90-120 ºC

Energy consumption: 3.75 kWh_e/m^3
79.50 kWh_t/m^3

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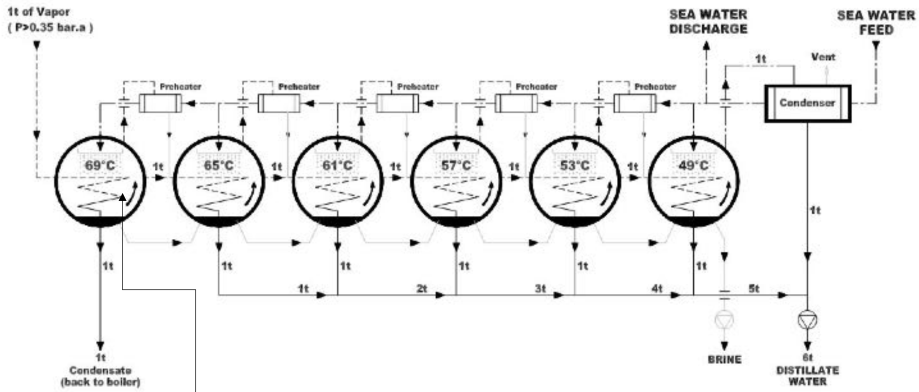
Multi-Effect Distillation (LT-MED)



Top brine temperature: 60 - 70 ºC

Energy consumption: 2.6 kWh_e/m^3
64.0 – 78.0 kWh_t/m^3

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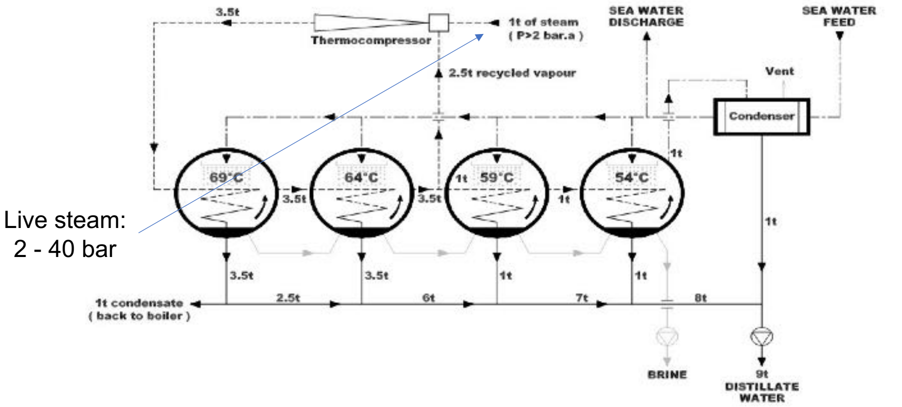
Multi-Effect Distillation (TVC-MED)



Energy consumption: 1.5 kWh_e/m^3
46.0 kWh_t/m^3 (15 bar, ~200 ºC live steam)

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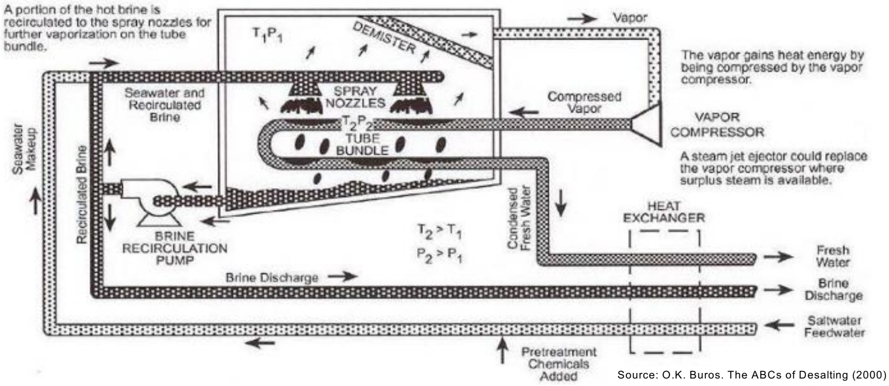
Mechanical Vapor Compression



Source: O.K. Buros. The ABCs of Desalting (2000)

The specific consumption of this type of units is around 8-10 kWh_e/m^3. They have the problem that there are not volumetric compressors that allow high water productions, being the typical capacity in the range from 20 to 3000 m^3/d.

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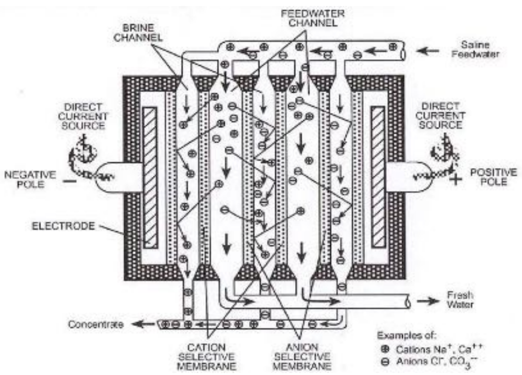
Electrodialysis



- Only brackish water applications in order to be competitive against RO for low capacity
- Based on the application of an electric potential (nice integration with PV)
- Better performance than RO when silica is present
- Less chemicals use than RO

Energy consumption: 0.4 – 2.5 kWh_e/m^3 (580 – 2500 ppm)

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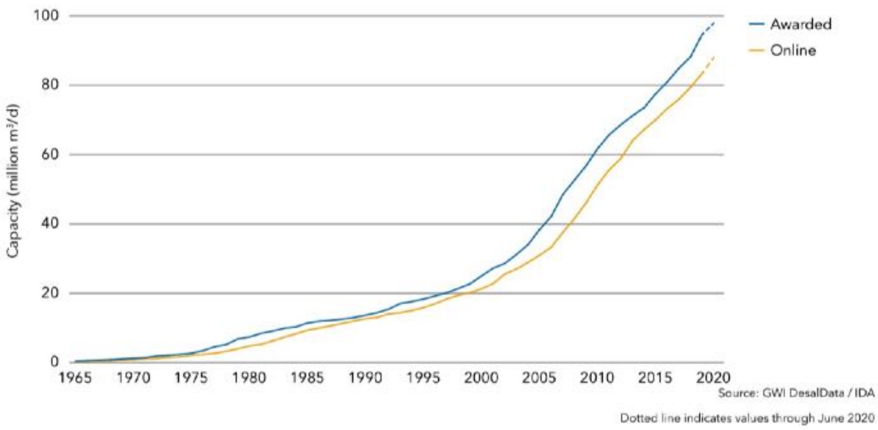
Desalination Market

Cumulative contracted and online desalination capacity (1960-2020*)



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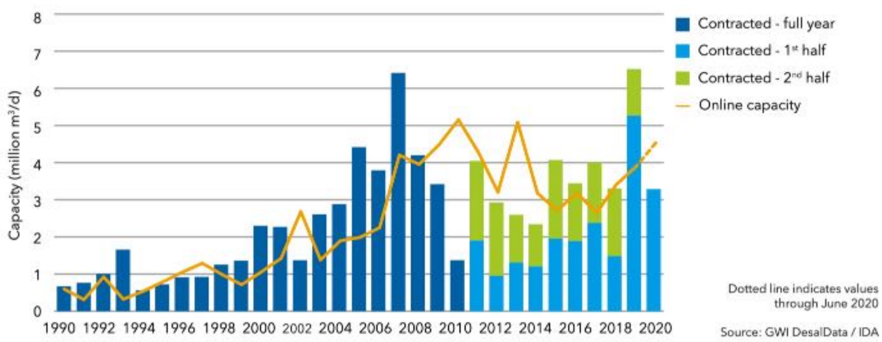
Desalination Market

Incremental contracted and online capacity by year (1990-2020*)



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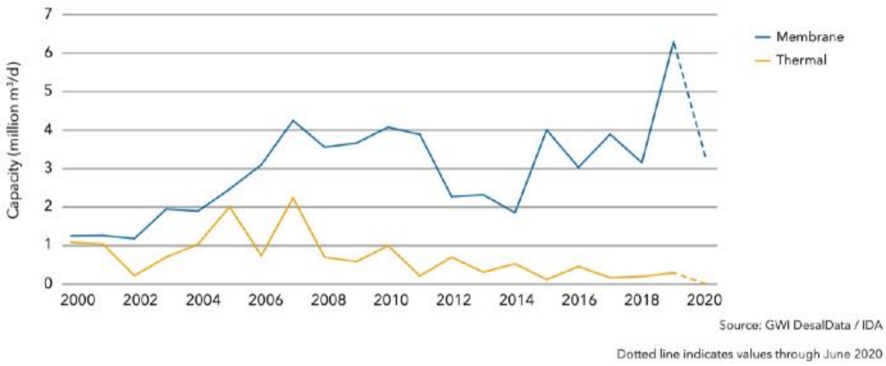
Desalination Market

Additional contracted desalination capacity by technology, 2000–2020*



- Transition of GCC to membrane technologies has reached maturity
- Is the thermal desalination market dead?

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Featured Plants

Featured Plants

Capacity (m^3/day)	136,380
Feedwater TDS (ppm)	47,800
Energy consumption (kWh/m^3)	3.55
RO Recovery (%)	38,8

Capacity (m^3/day)	281,000
Feedwater TDS (ppm)	42,000
Energy consumption (kWh/m^3)	<=3.15
RO Recovery (%)	46

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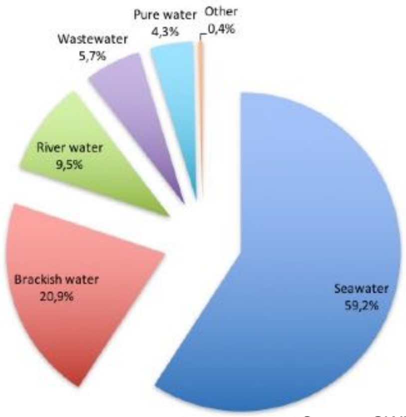
Feedwater Trends

Total worldwide installed capacity by feedwater type



Source: GWI DesalData / IDA

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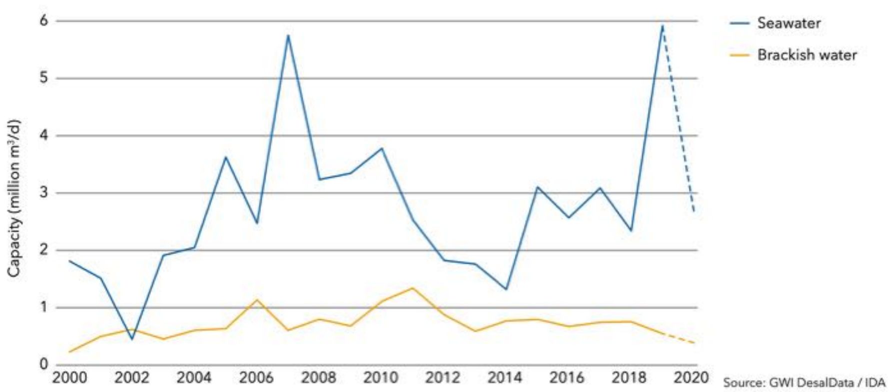
Feedwater Trends



Source: GWI DesalData / IDA
Dotted line indicates values through June 2020

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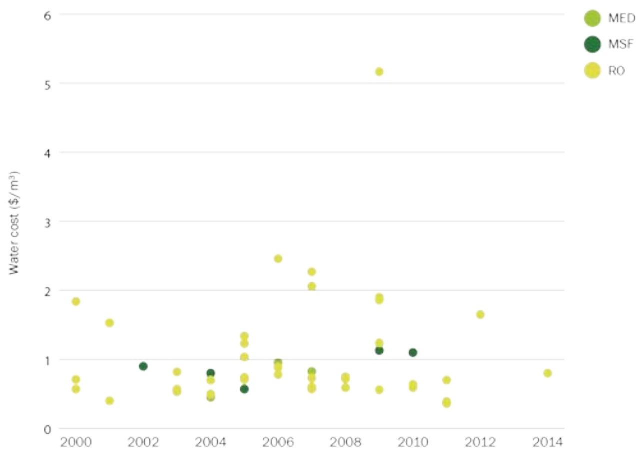
Desalination Costs



Source: DesalData

Water prices from desalination projects since 2000

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Desalination Costs - RO

Plant	Capacity (m³/d)	Contract year	Process	Water price ($/m³)	EPC cost (million $)	Capacity cost ($/m³/d)
Adelaide, Australia	274,000	2009	SWRO	1.86	900.0	3284.7
Ashdod, Israel	540,000	2010	SWRO	0.70	423.0	1321.9
Carlsbad SWRO, CA, USA	189,250	2012	SWRO	1.65	530.0	2800.5
Djerba, Tunisia	50,000	2014	SWRO	0.80	72.6	1452
Shuqaiq 3, Saudi Arabia	450,000	2019	SWRO	0.52	435.0	966.7
Taweelah RO IWP, UAE	909,000	2019	SWRO	0.47	870.0	957.1
Rabigh 3, Saudi Arabia	600,000	2019	SWRO	0.531	750.0	1250
Jubail 3a IWP, Saudi Arabia	600,000	2020	SWRO	0.413	649.87	1083.12
Soreq 2, Israel	670,000	2020	SWRO	0.405	600.0	895.5

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Desalination Costs - Thermal

Plant	Capacity (m^3/d)	Contract year	Process	Water price ($\$/m^3$)	EPC cost (million \$)	Capacity cost ($\$/m^3/d$)
Yantai City, China	160,000	2004	MED	0.45	252.7	1579.2
Shoaiba 3, Saudi Arabia	880,000	2005	MSF	0.57	2500.0	2840.9
Tianjin, China	100,000	2006	MED	0.95	119.0	1190.0
Al Jubail, Saudi Arabia	800,000	2007	MED	0.83	945.0	1181.3
Shuweihat 2, UAE	459,146	2009	MSF	1.13	800.0	1742.4
Ras Al-Khair, Saudi Arabia	1,034,700	2010	MSF	1.10	1760.0	1701.0
Zoushan Refinery, China	305,000	2017	MED	0.44	-	-

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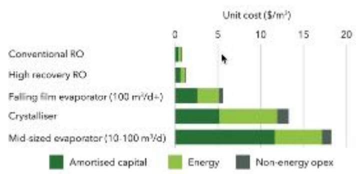
Brine concentration

The growing concern about the impact of brine discharges (high salt concentration and dissolved chemicals) on the environment has led to the proliferation of research activities in the field of zero liquid discharge (ZLD) and minimum liquid discharge (MLD) processes.

Technology	Typical feed (TDS, mg/L)	Typical product (TDS, mg/L)	Typical brine (TDS, mg/L)	Recovery	Electricity, (kWh/m^3)	Thermal (kWh/m^3)
Conventional RO	1,500-10,000	25-200	12,000-25,000	60-80%	0.75-2.0	0
High recovery RO	30,000-50,000	25-200	100,000-175,000	>70%	3-7	0
Small/mid-scale evaporators (10-100m^3/d)	50,000-80,000	<25	170,000-220,000	85%	0	30-80
Falling film evaporators (<100m^3/d)	50,000-80,000	<25	170,000-220,000	85%	20-25	0
Crystallisers	150,000-210,000	<25	250,000-600,000	90%	0	50-66

Source: GWI DesalData



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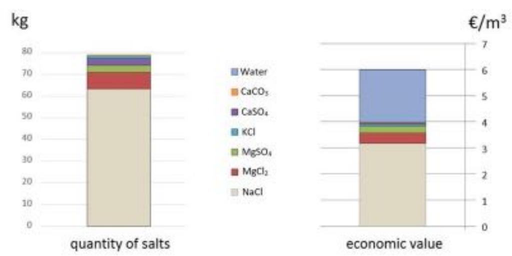
Water Mining

Research into minimal and zero discharge processes has had a synergistic effect on the promotion of a novel activity known as water mining.

This would consist of the **recovery/extraction** of **high added-value** compounds present in liquid effluents from both **industrial wastewater** and **brine** from desalination processes.



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End of Presentation

- Thank you for your attention
- Questions?

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