Solar-Assisted Membrane Distillation for Water Production

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WInnER
Water Innovation:
Education & Research

Water-Related Challenges

SUSTAINABLE DEVELOPMENT GOALS

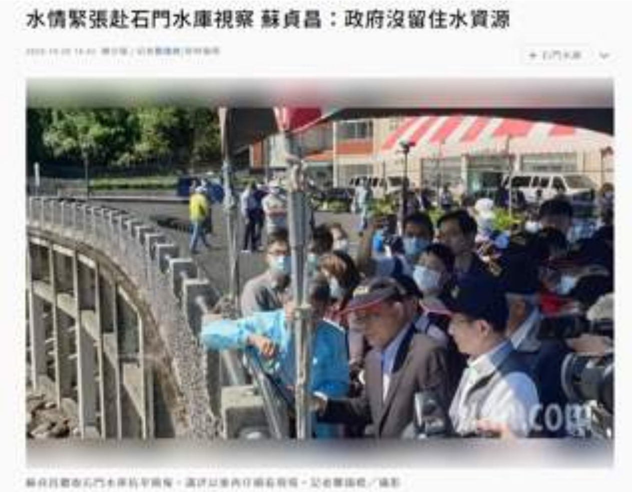
6 CLEAN WATER AND SANITATION

Clean, accessible water for all is an essential part of the world we want to live in and there is sufficient fresh water on the planet to achieve this. However, due to bad economics or poor infrastructure, millions of people including children die every year from diseases associated with inadequate water supply, sanitation and hygiene.

Water scarcity, poor water quality and inadequate sanitation negatively impact food security, livelihood choices and educational opportunities for poor families across the world. At the current time, more than 2 billion people are living with the risk of reduced access to freshwater resources and by 2050, at least one in four people is likely to live in a country affected by chronic or recurring shortages of fresh water. Drought in specific afflicts some of the world's poorest countries, worsening hunger and malnutrition. Fortunately, there has been great progress made in the past decade regarding drinking sources and sanitation, whereby over 90% of the world's population now has access to improved sources of drinking water.

To improve sanitation and access to drinking water, there needs to be increased investment in management of freshwater ecosystems and sanitation facilities on a local level in several developing countries within Sub-Saharan Africa, Central Asia, Southern Asia, Eastern Asia and South-Eastern Asia.

Facts and figures | Goal 6 targets | Links



Alternative Water Resources: Water-Energy Nexus

Water-Energy Nexus

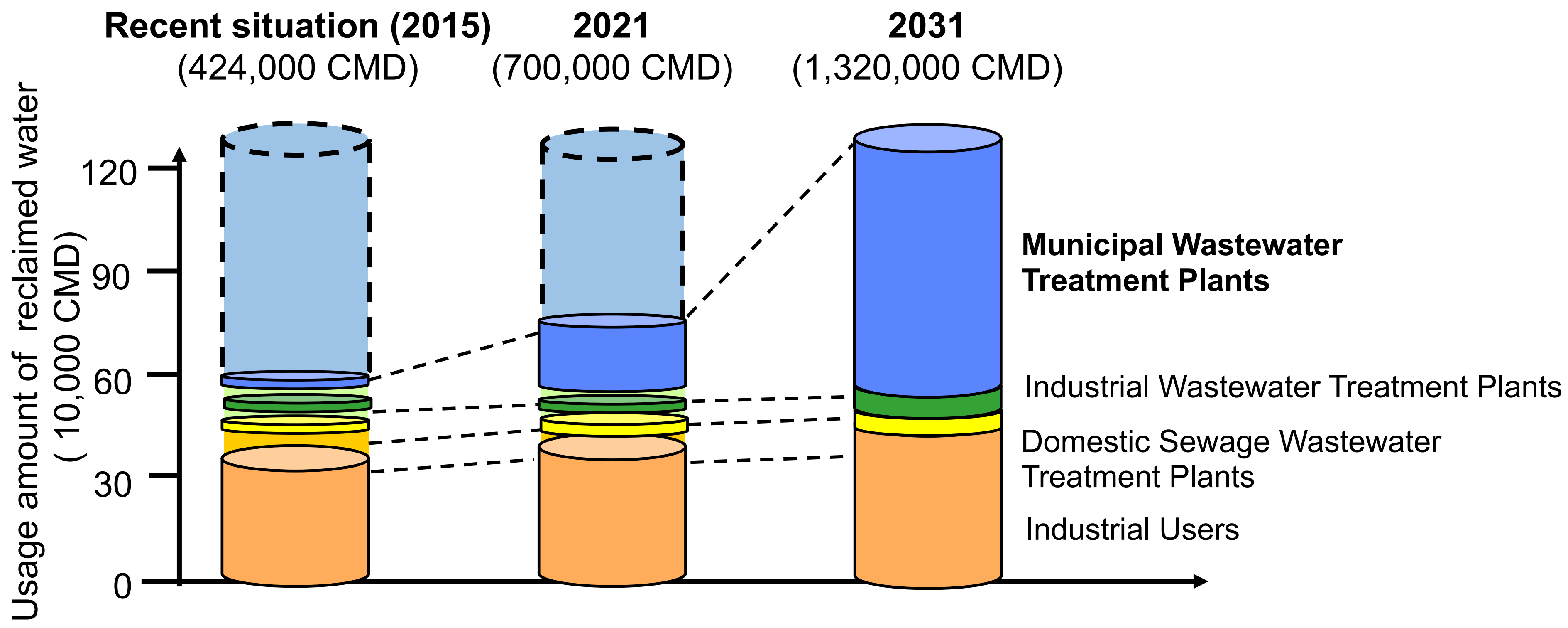
"If we could ever competitively, at a cheap rate, get fresh water from salt water, that it would be in the long-range interests of humanity which would really dwarf any other scientific compliments."

President John F. Kennedy
1962

Water Security Challenge in Taiwan

Alternative Water Resource

- Policy made by Water Resource Agency

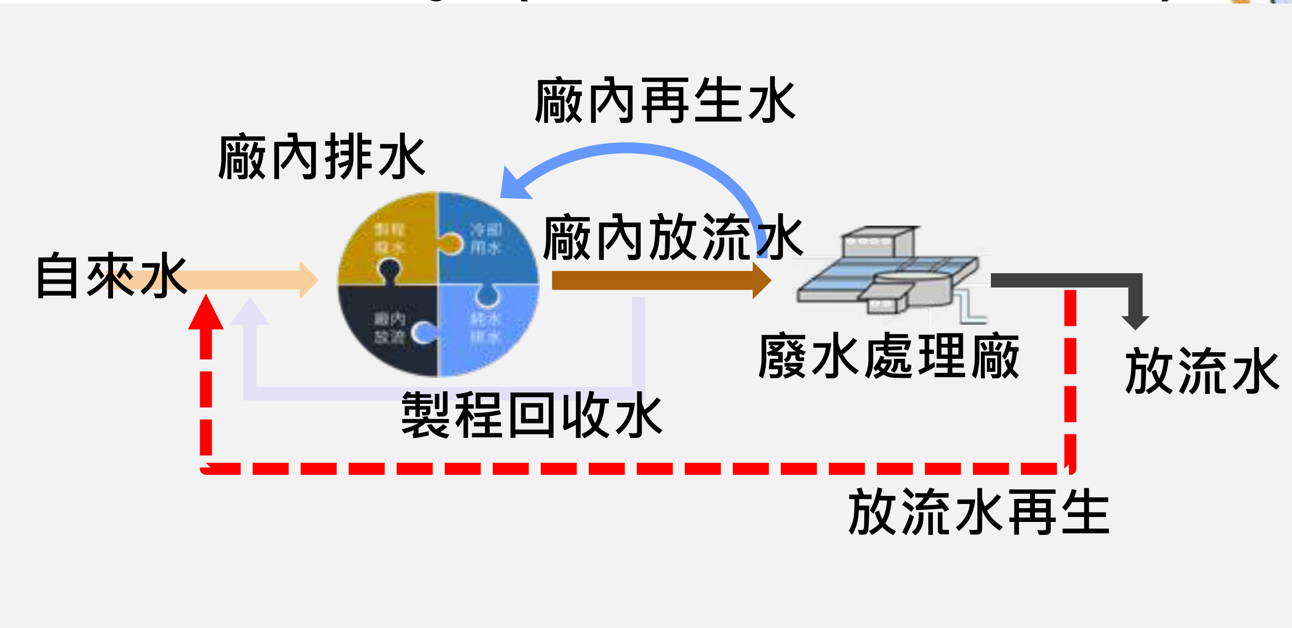


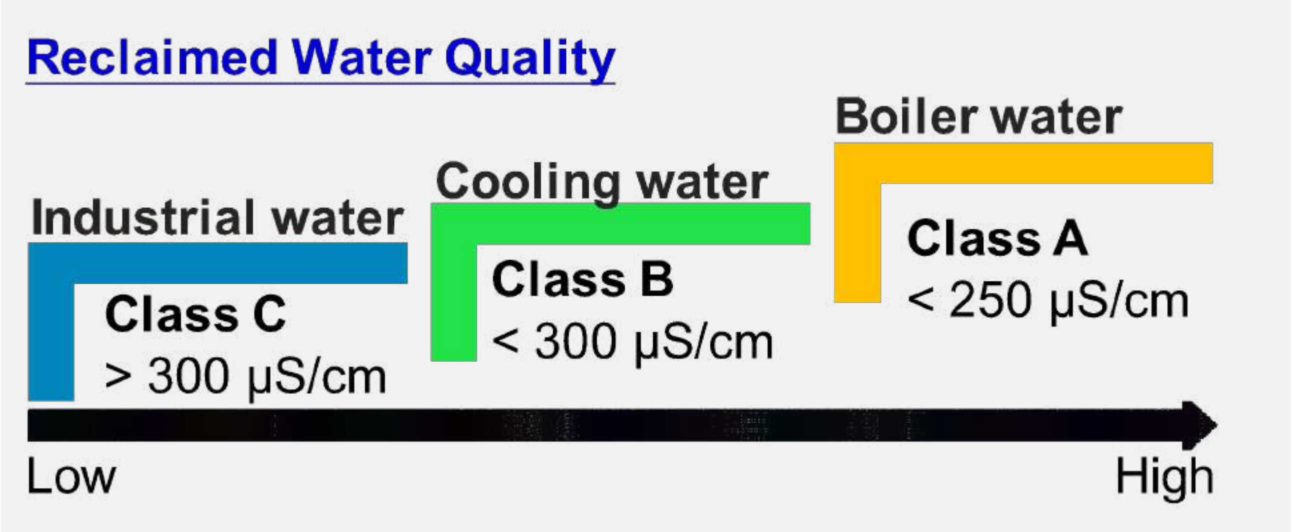
台南安平再生水廠

高雄鳳山溪再生水廠

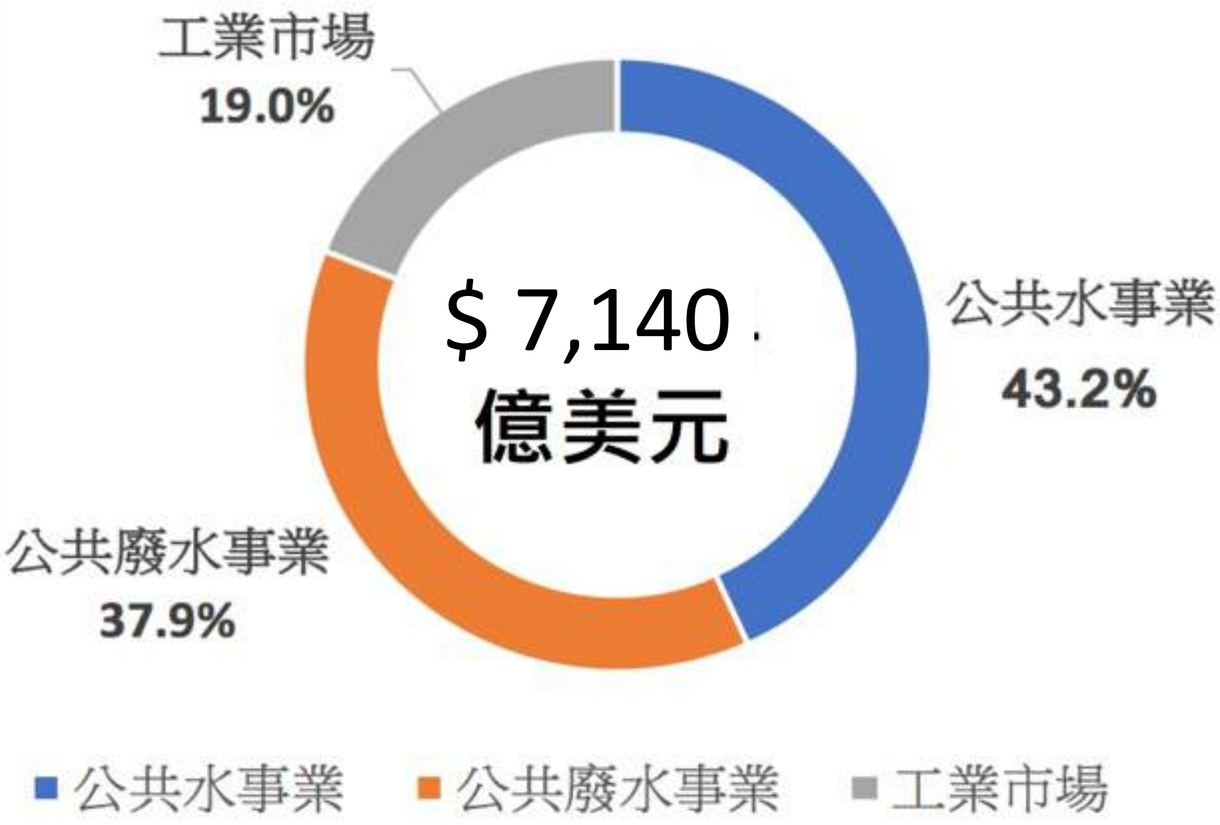
(資料來源：財團法人中興工程顧問社)

How Big is the Impact on the Industry (semiconductor)?



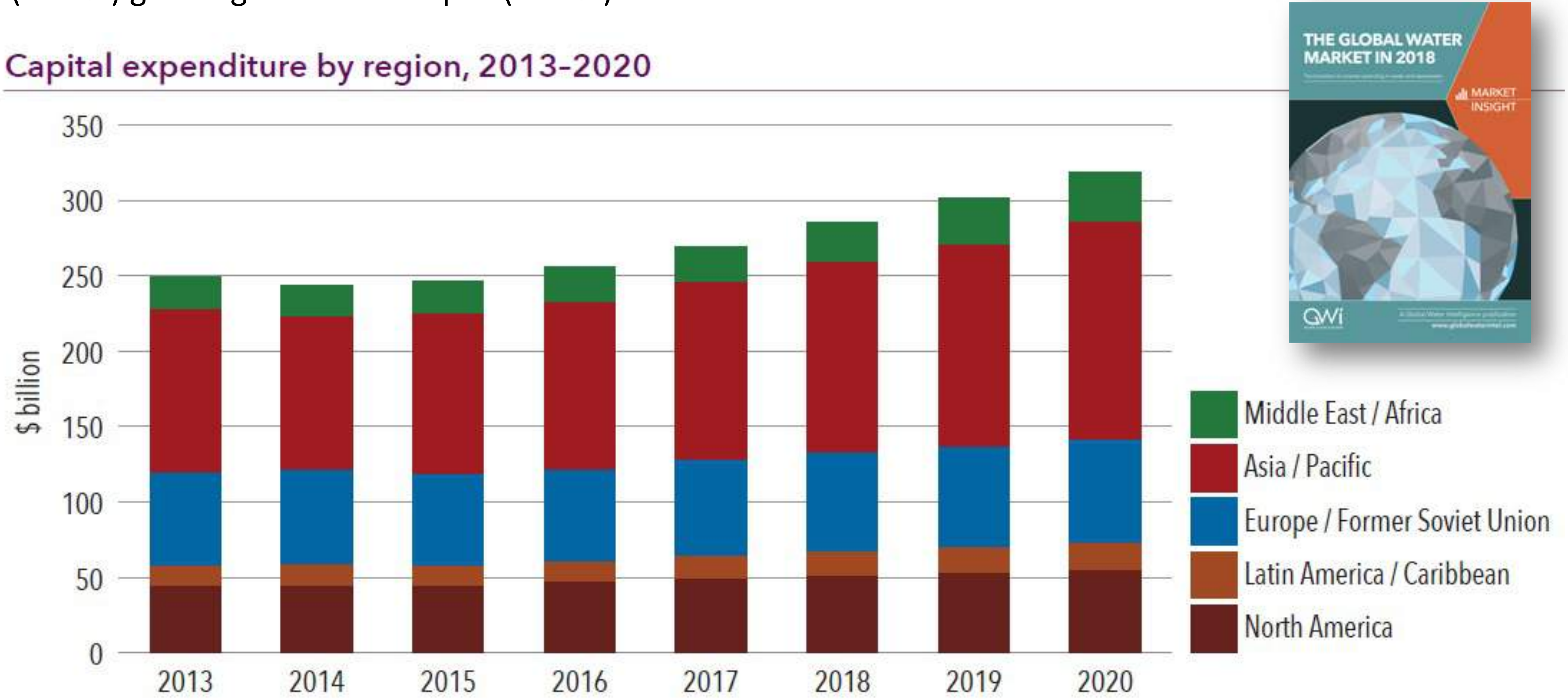


2016年水市場規模

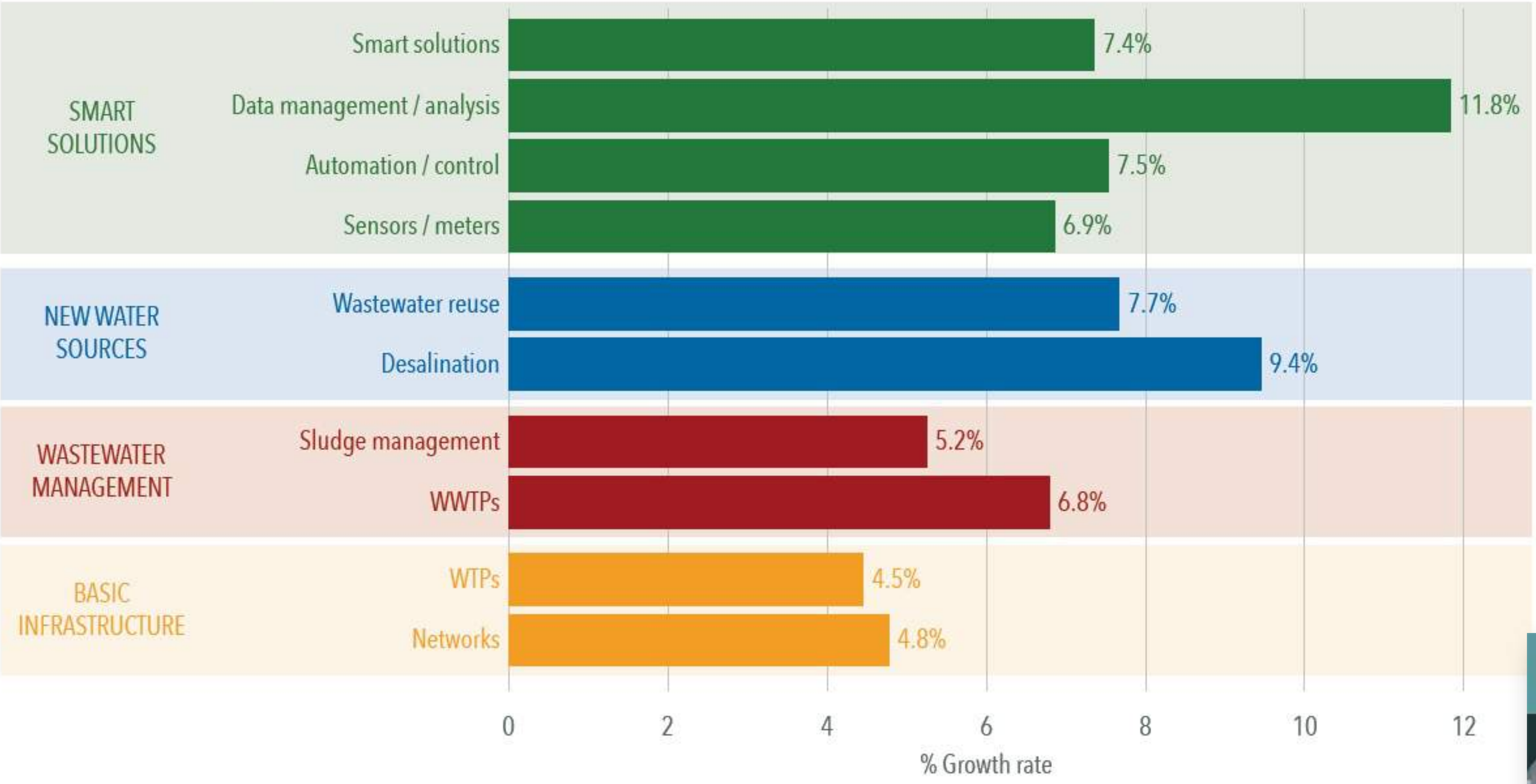


Source: GWI （Global Water Intelligence）

The global water market – that is to say the sum of both operating and capital expenditures by utilities and industrial water users on both water and wastewater – **is estimated to be worth around $714 billion in 2016***. It is expected to grow at **an average annual rate of 3.8% until 2020**, with capex (+5.3%) growing faster than opex (+2.8%).

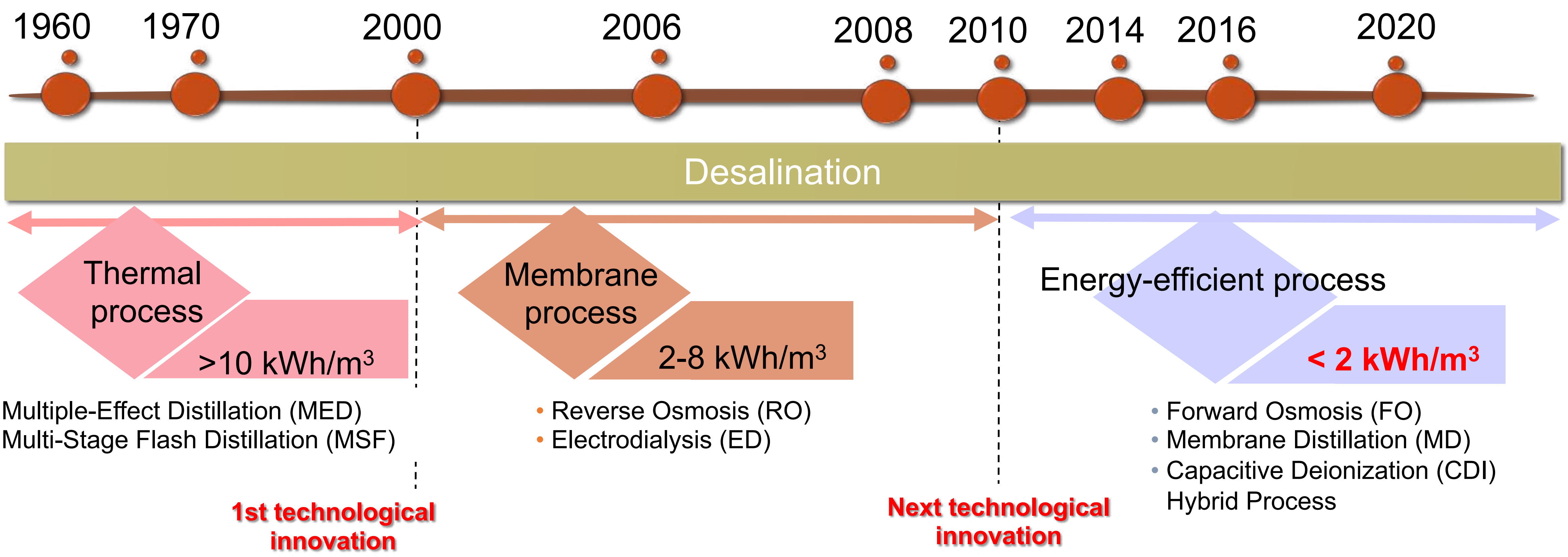


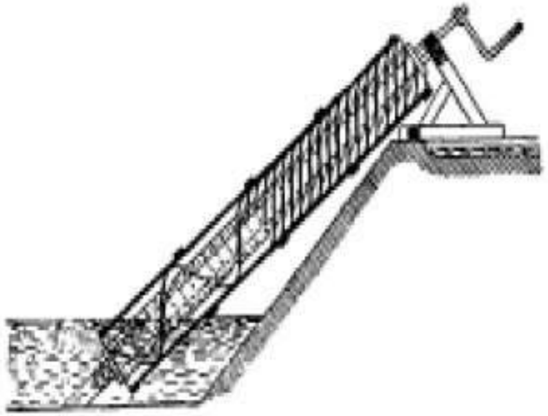
Growth in spending by market, 2017-2022

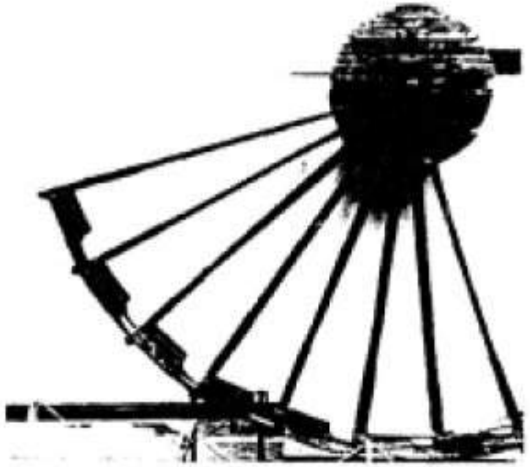


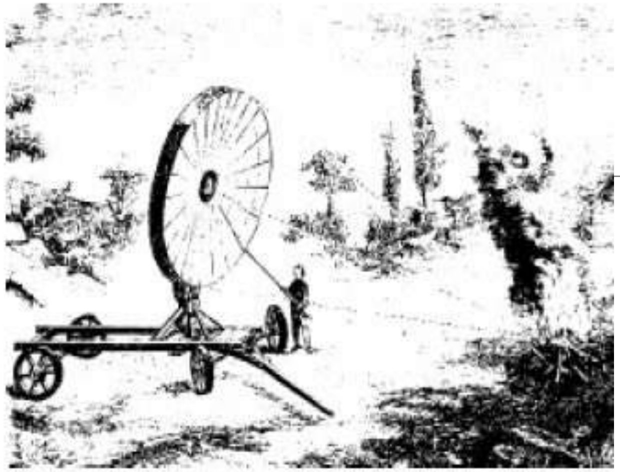
Source: GWI

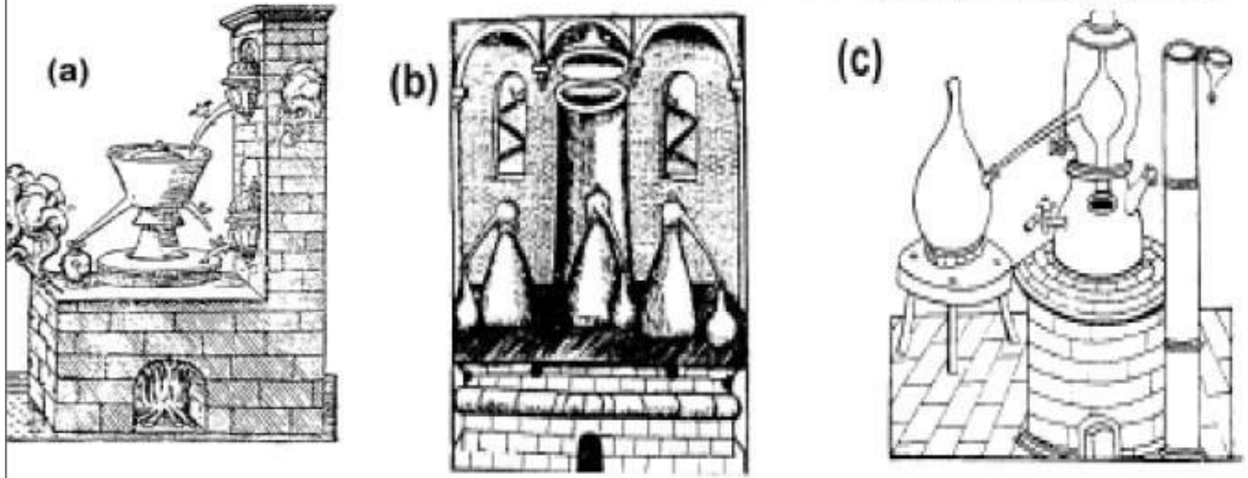
Timeline of Desalination Technologies

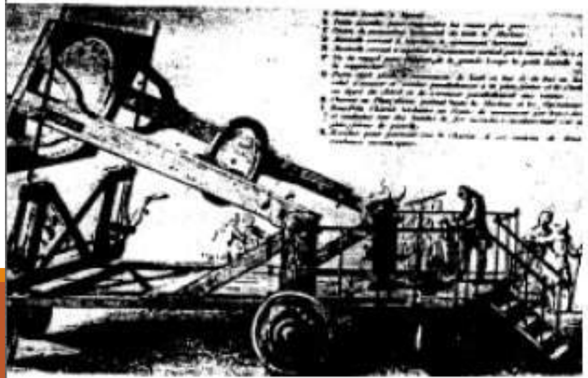


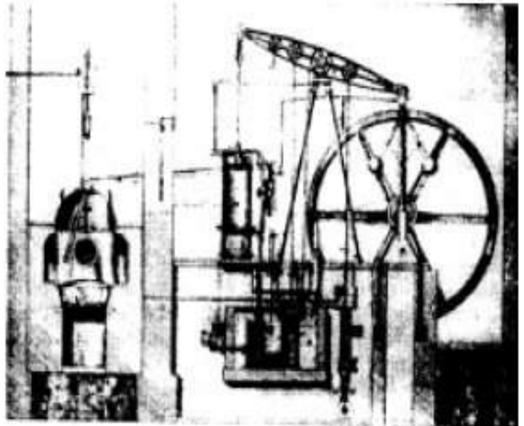




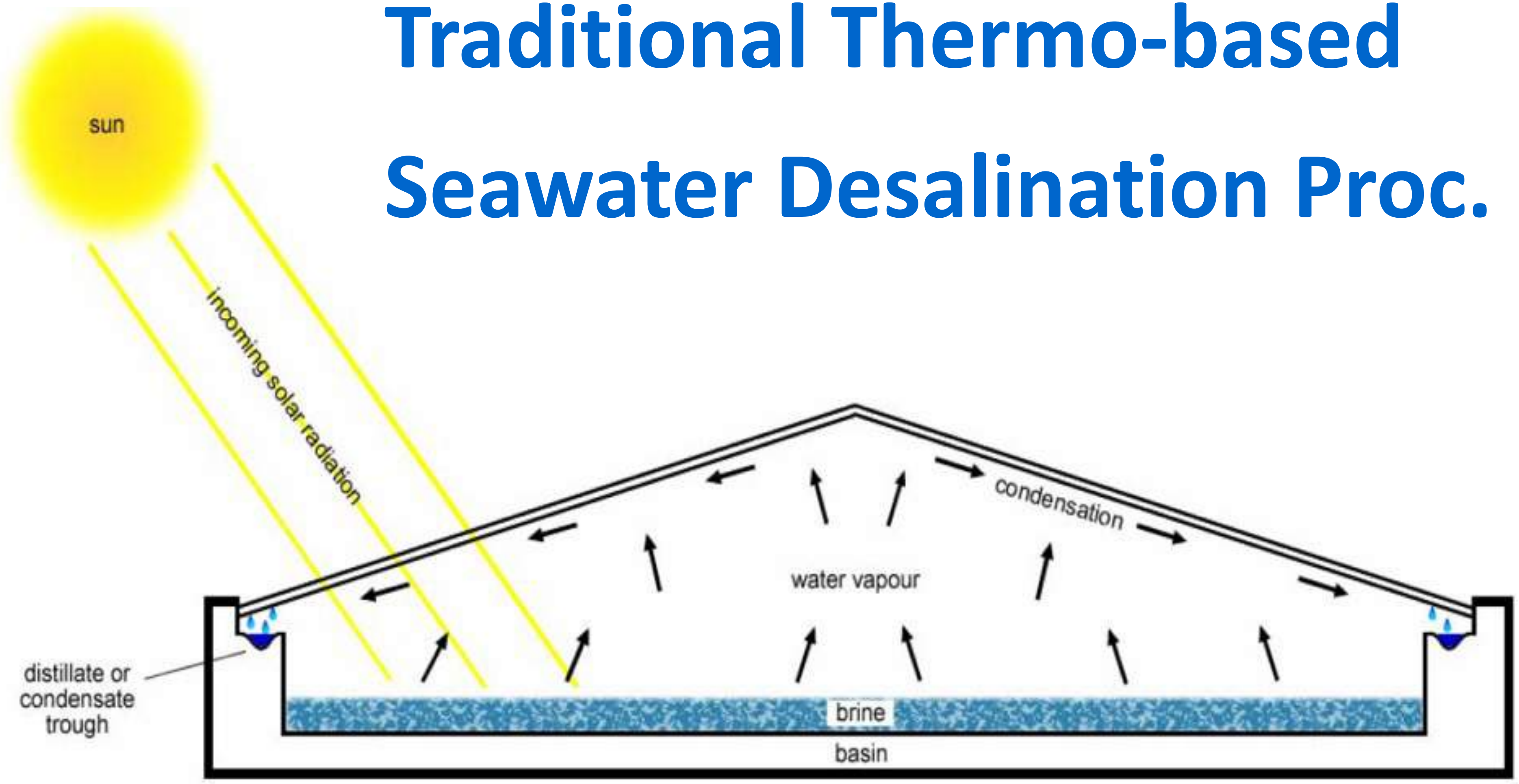


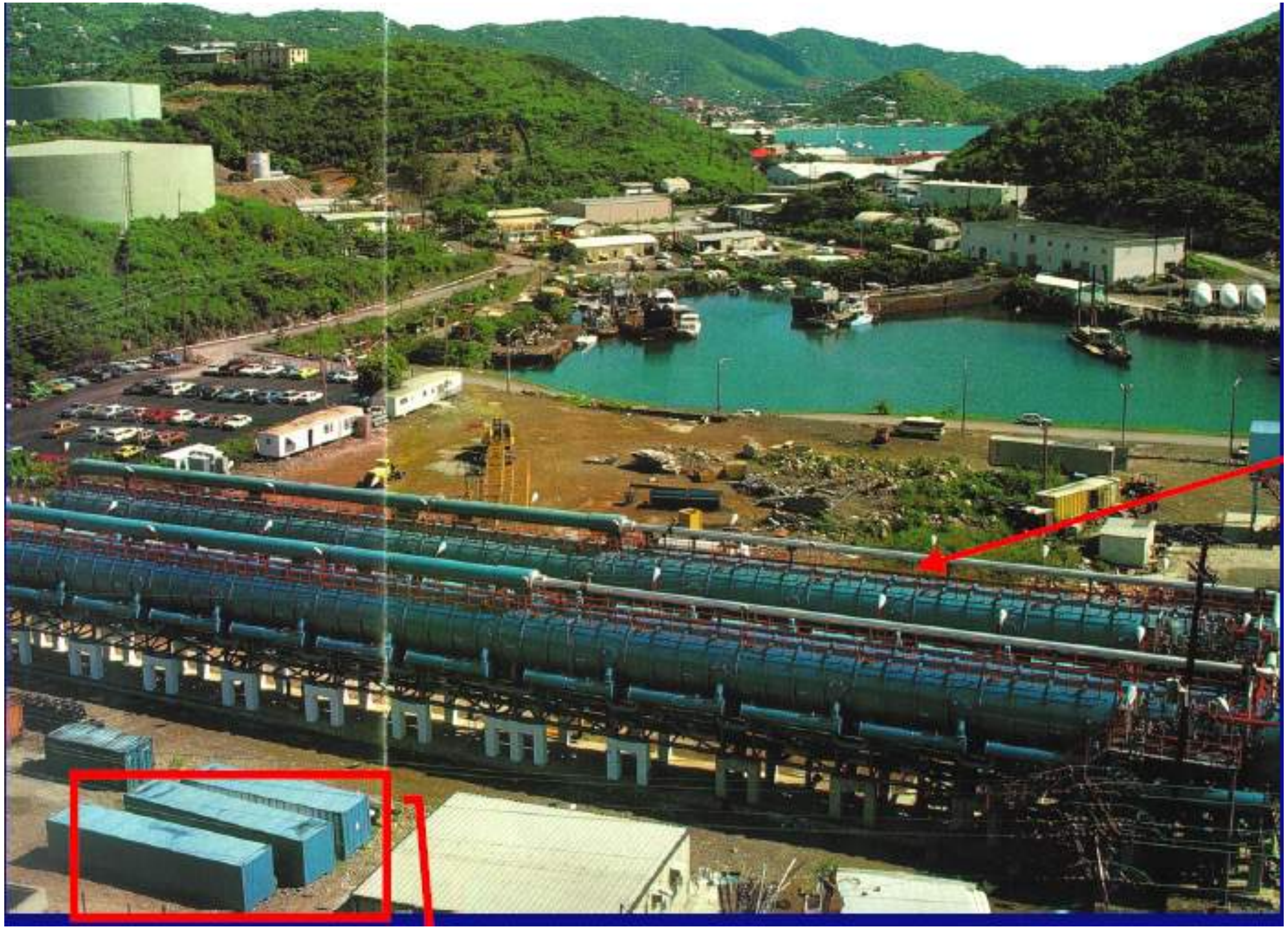

(a)
(b)
(c)





Traditional Thermo-based Seawater Desalination Proc.

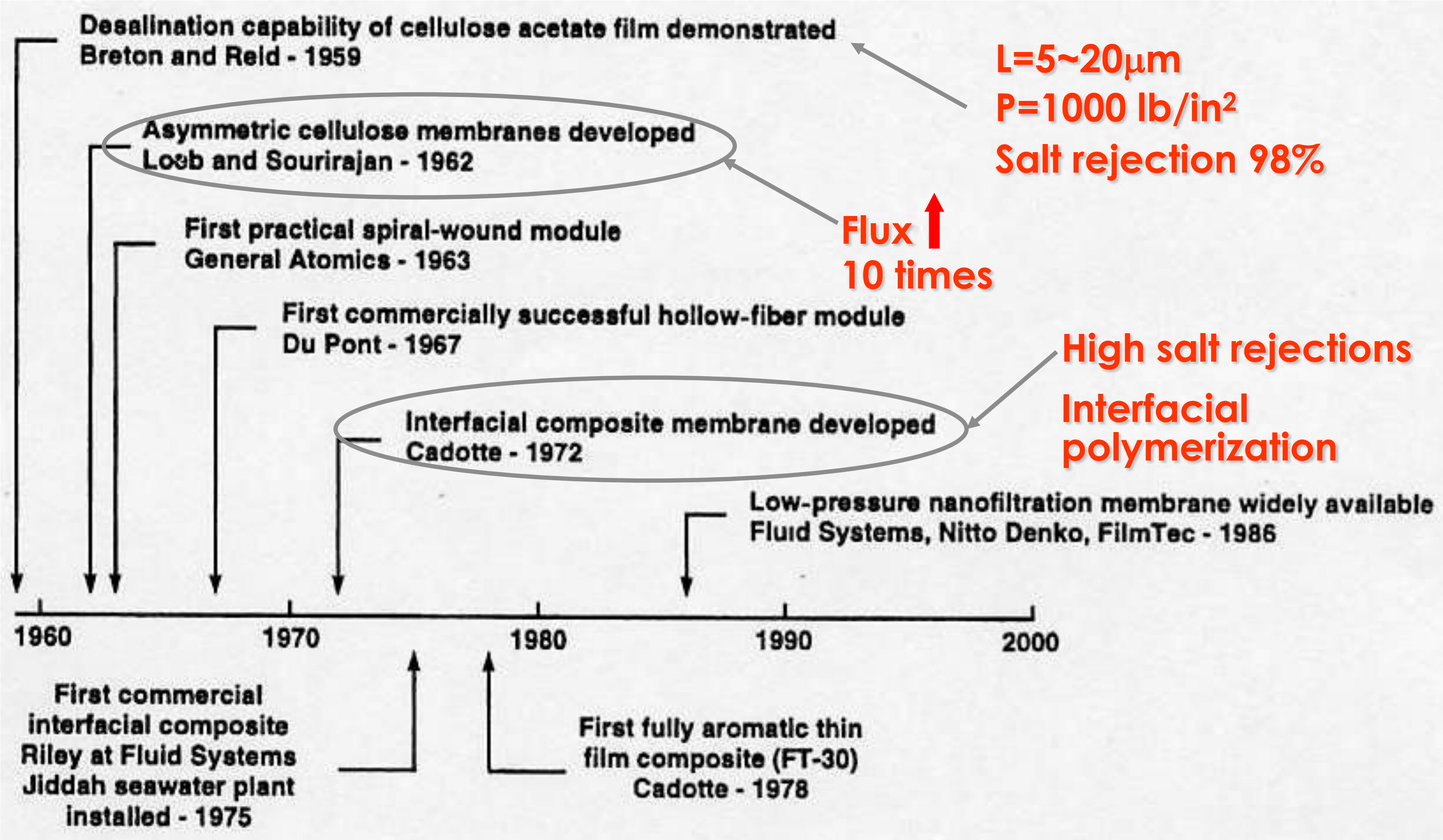


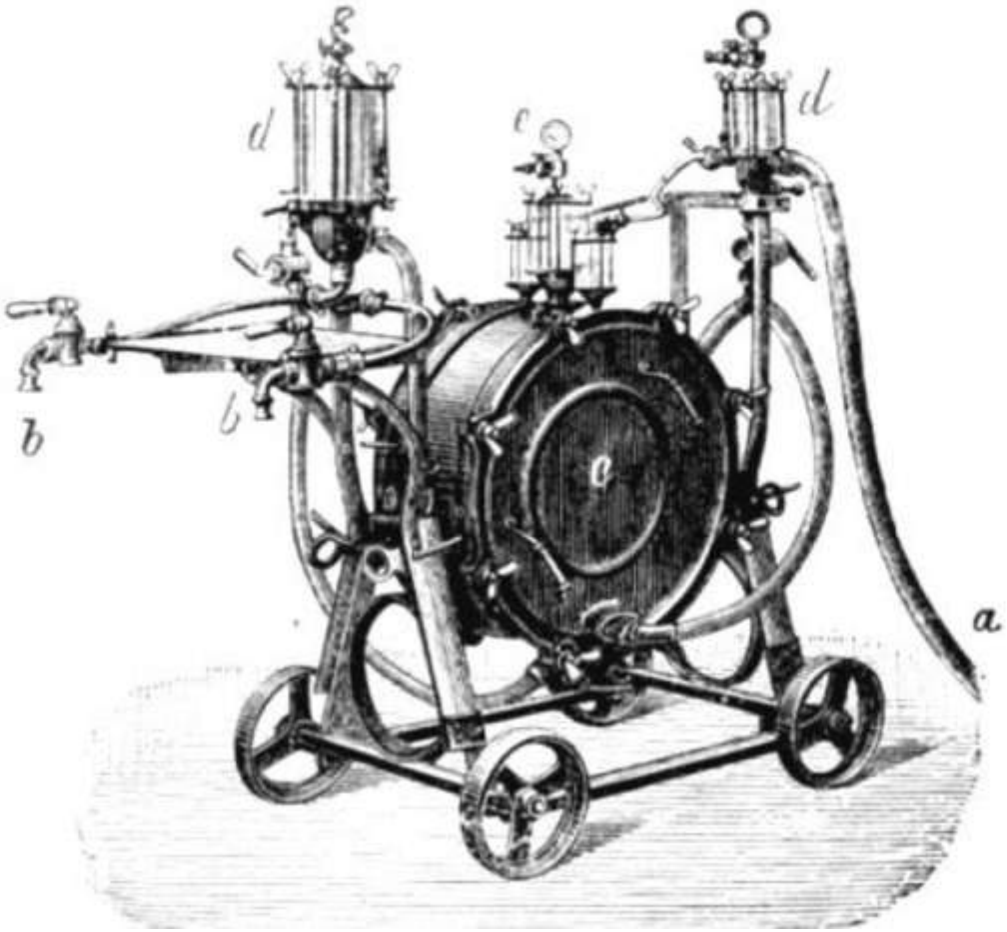


MED
4700 m^3/hr

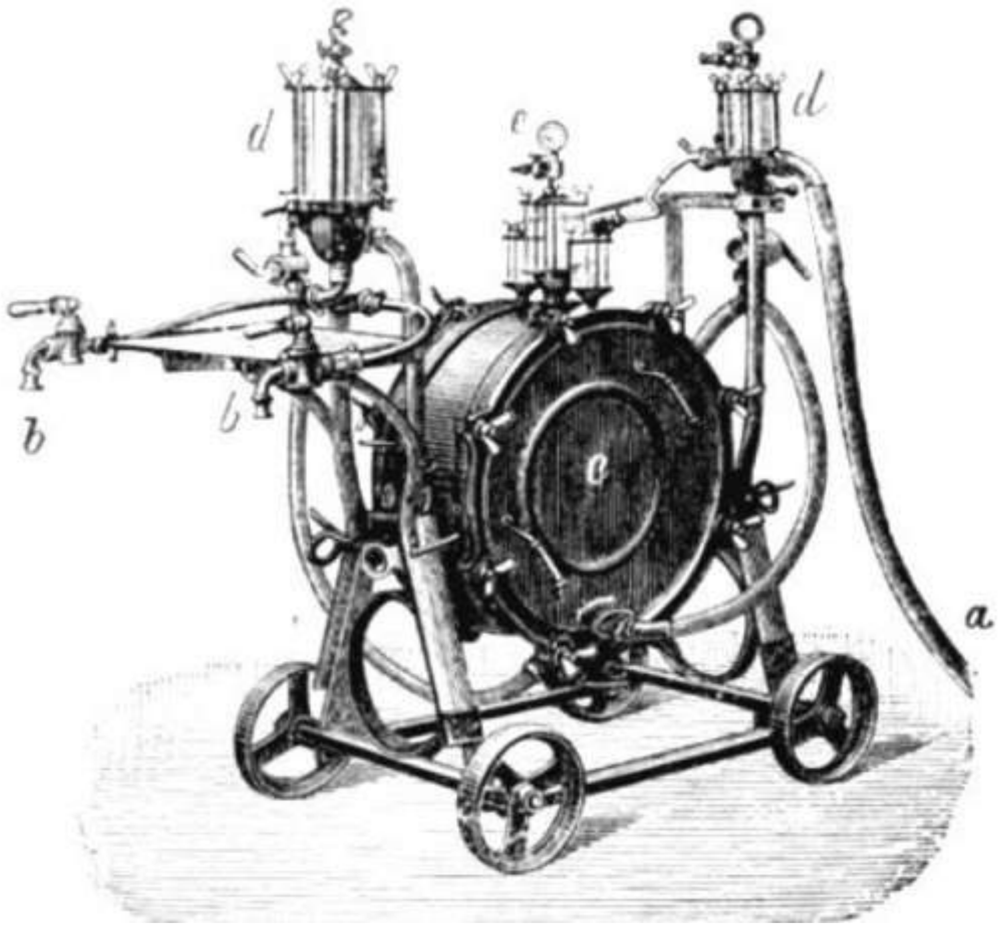
MD
5000 m^3/hr

Milestones in the Development of RO & NF




d
d
c
b
b
e
a


Water Treatment


d
e
d
b
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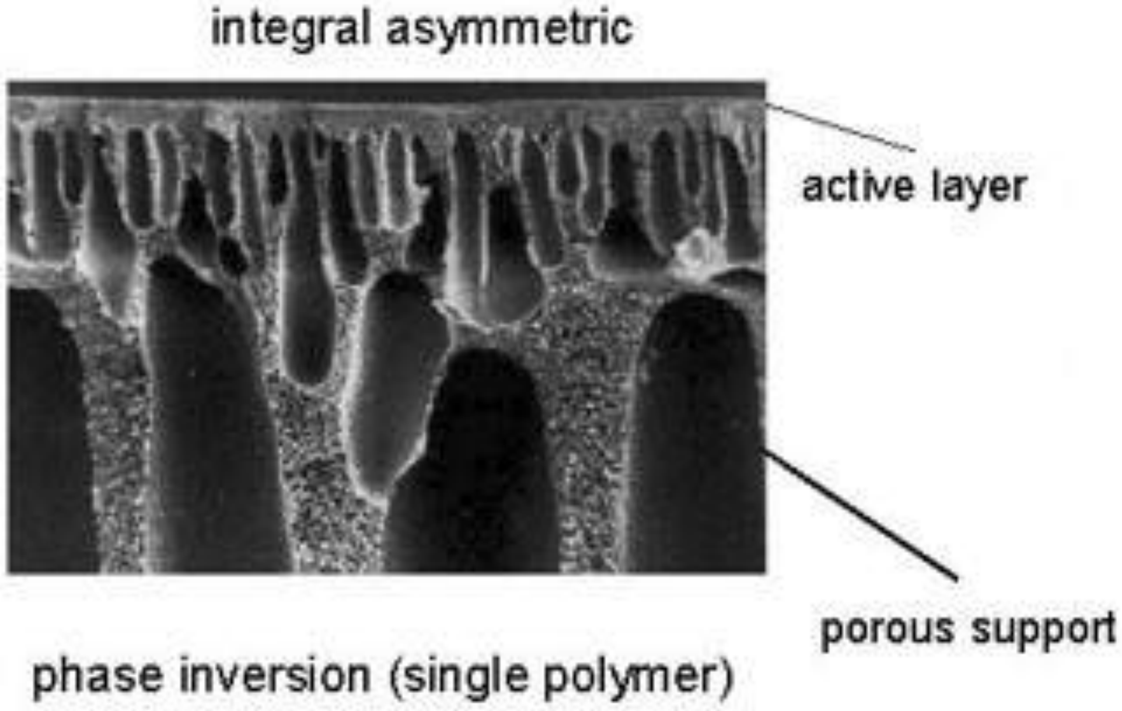
c
a

4. Membrane Filtrations



Loeb-Sourirajan asymmetric membrane

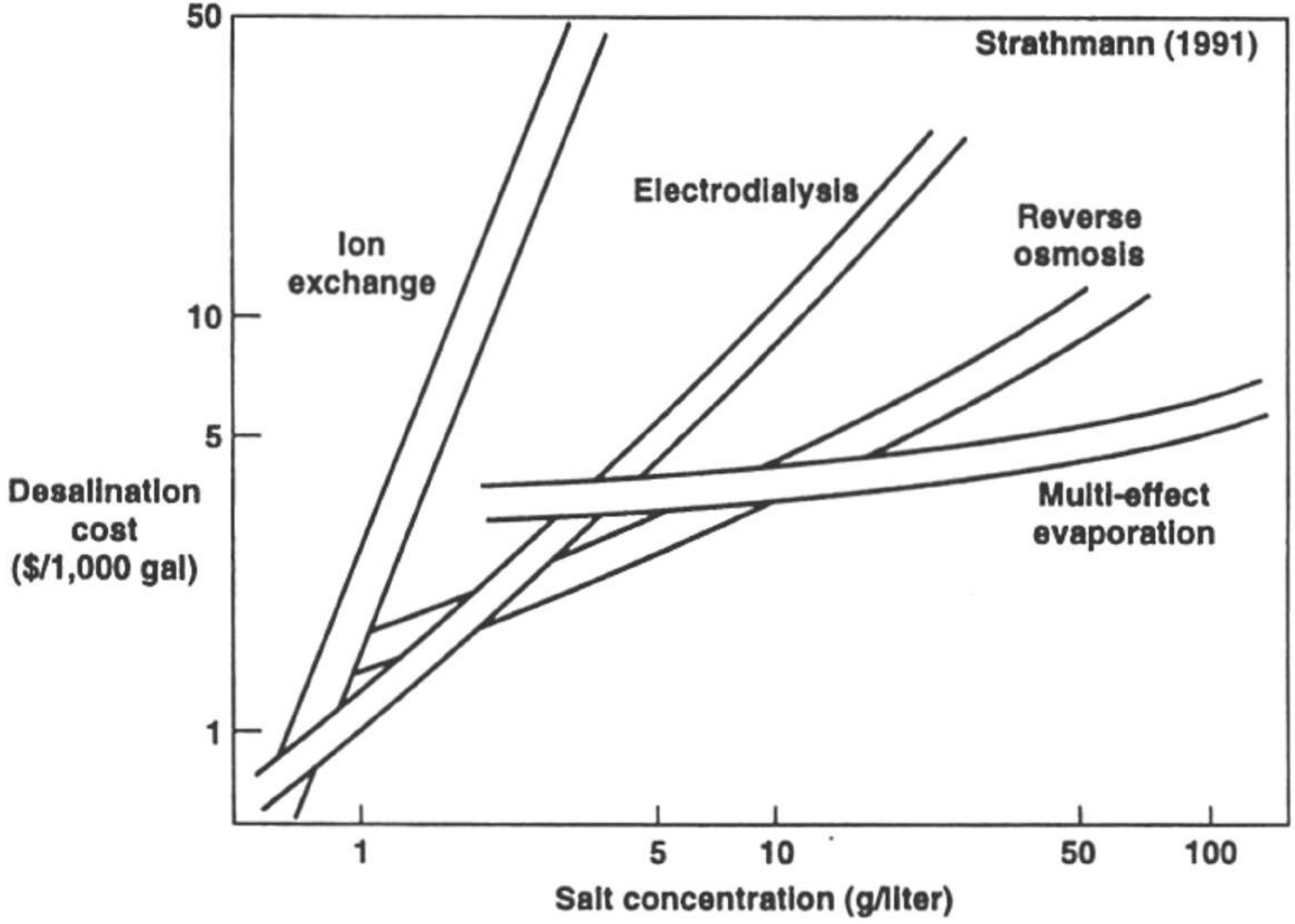
Water Desalination

Feedwater characterisation by salt content

	Minimum salinity TDS [ppm]	Maiximum salinity TDS [ppm]
Seawater	15,000	50,000
Brackish water	1,500	15,000
River water	500	1,500
Pure water	0	500

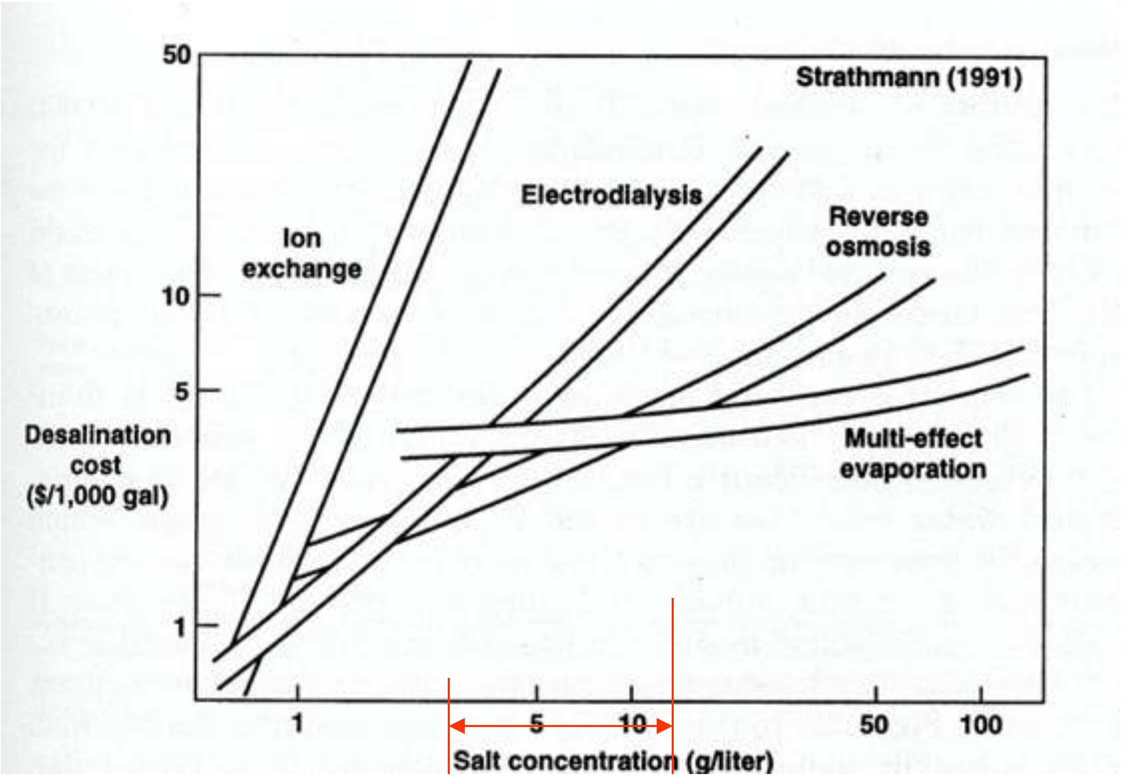
Desalination Technologies

Thermal	Membrane-based
Multi-stage flash distillation (MSF)	Reverse osmosis (RO)
Multi-effect evaporation (MEE)	Nanofiltration (NF)
Vapor compression distillation (VCD)	Electrodialysis (ED)
Membrane Distillation (MD)	



Strathmann (1991)
50
10
5
1
Desalination cost ($/1,000 gal)
Ion exchange
Electrodialysis
Reverse osmosis
Multi-effect evaporation
1
5
10
50
100
Salt concentration (g/liter)

Comparative cost of the major desalination



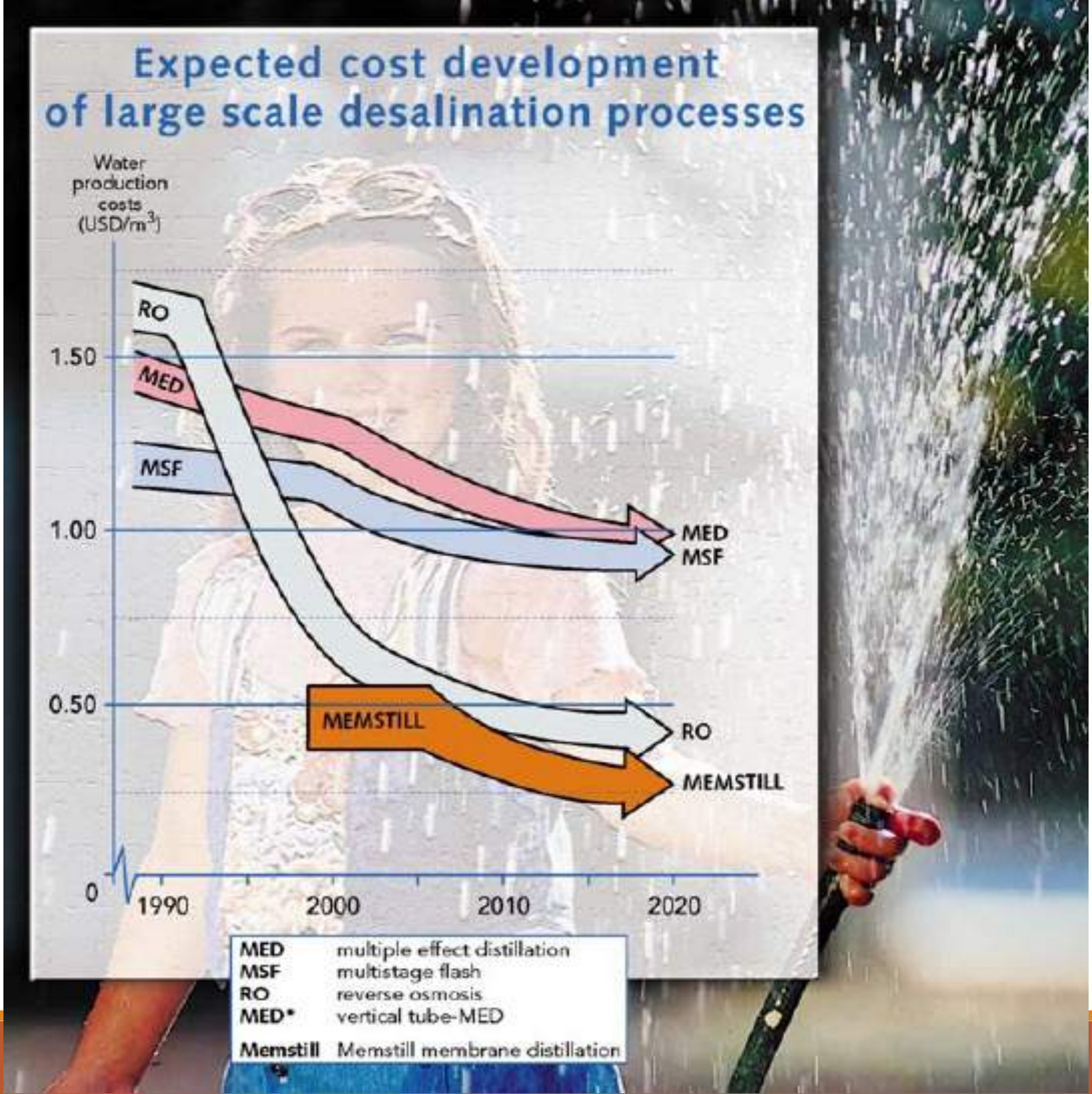
Reverse osmosis is the lowest-cost process at 3000 to 10000 ppm salt solution

Membrane distillation (MD) utilize waste heat

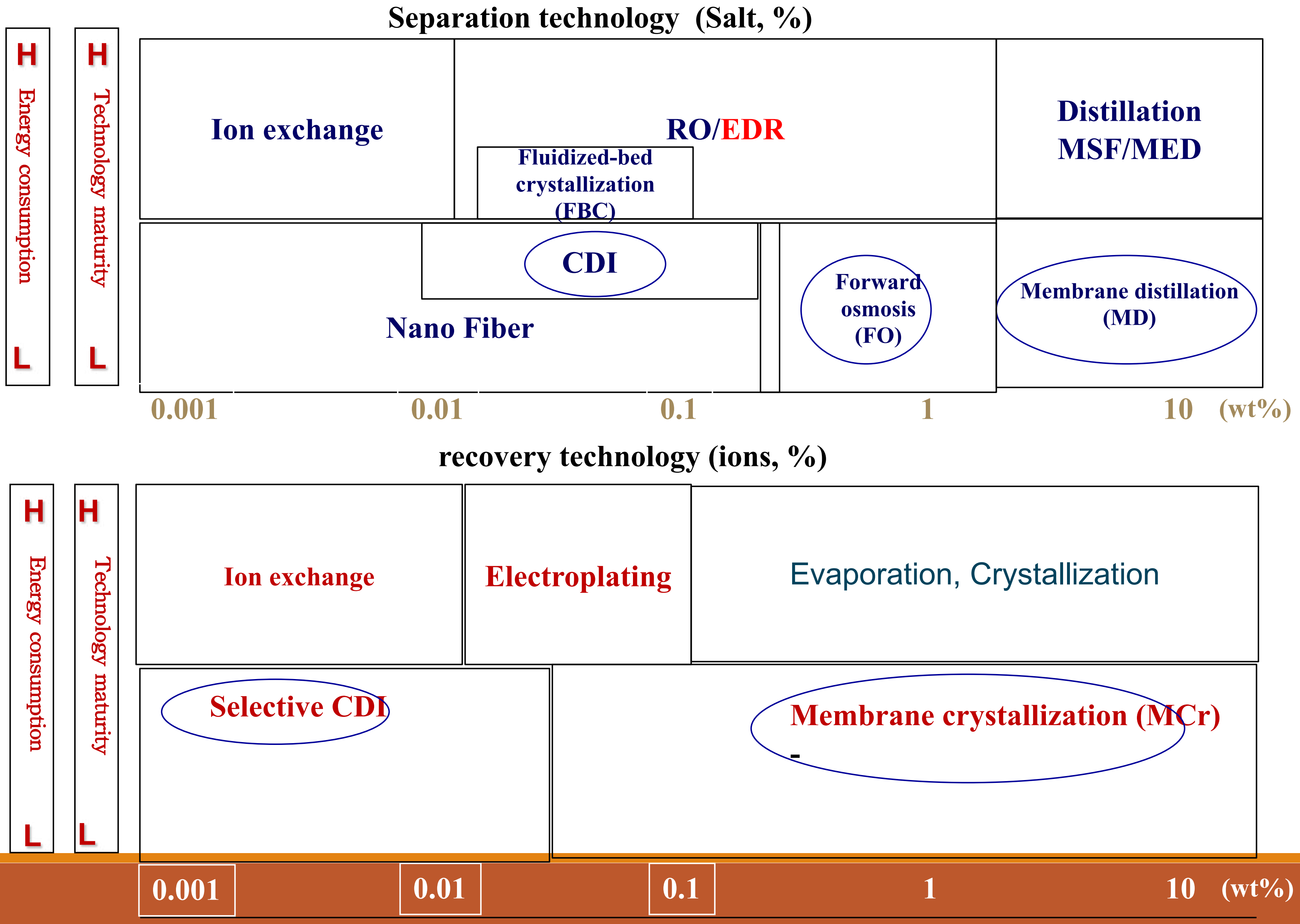
Desalination, 187, 12-19, 2006

Water production costs of Memstill® vs. RO (seawater 105,000 m³/d)

	Memstill®		Memstill®		RO	RO
	Fuel fired	Co-gener.	Waste heat		Min.	Stand.
Energy costs						
Heat, MJ/m³	231	231	139	139	—	—
(Costs in $/GJ)	(1.30)	(0.50)	(0.50)	(0.10)		
Electricity, kWh/m³	0.75	0.75	0.75	0.75	2.5	4.5
Heat costs, $/m³	*0.30*	*0.12*	*0.07*	*0.01*	—	—
Electricity costs, $/m³	*0.03*	*0.03*	*0.03*	*0.03*	*0.10*	*0.18*
Fixed costs						
Hardware, excl. membranes, $/m³.d	165		165		750	1024
Module costs, $/m³.d	214		233		35	49
Hardware costs, $/m³	*0.05*	*0.05*	*0.05*	*0.05*	*0.23*	*0.32*
Module costs, $/m³	*0.11*	*0.11*	*0.12*	*0.12*	*0.02*	*0.03*
Auxiliary costs						
O&M, chemicals, filters etc., $/m³	*0.05*	*0.05*	*0.05*	*0.05*	*0.10*	*0.10*
Water costs total, $/m³	***0.54***	***0.35***	***0.31***	***0.26***	***0.45***	***0.63***

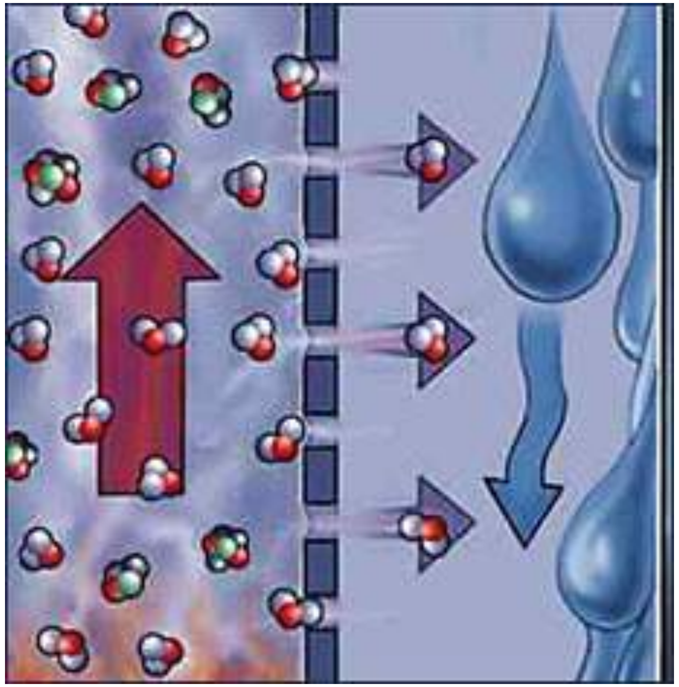

Expected cost development
of large scale desalination processes
Water production costs (USD/m³)
1.50
1.00
0.50
0
1990
2000
2010
2020
RO
MED
MSF
MEMSTILL
MED
MSF
RO
MEMSTILL
MED multiple effect distillation
MSF multistage flash
RO reverse osmosis
MED* vertical tube-MED
Memstill Memstill membrane distillation

Mapping Technologies for Ions



Membrane Distillation

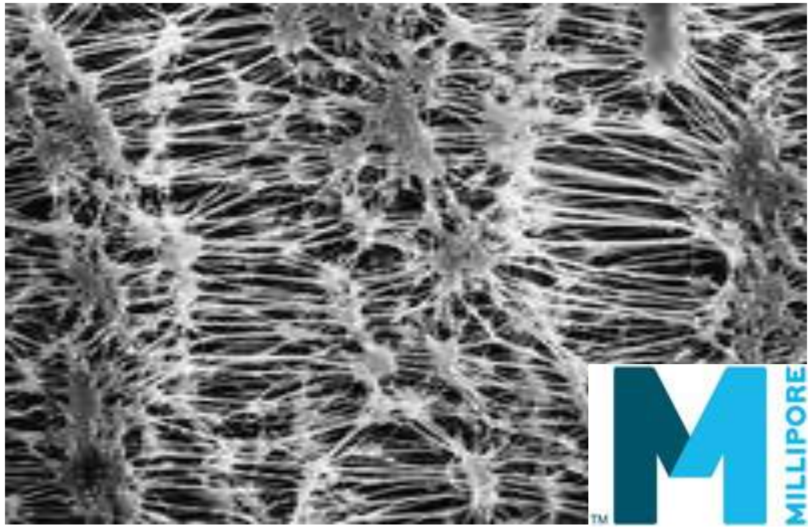
Membrane distillation (MD)



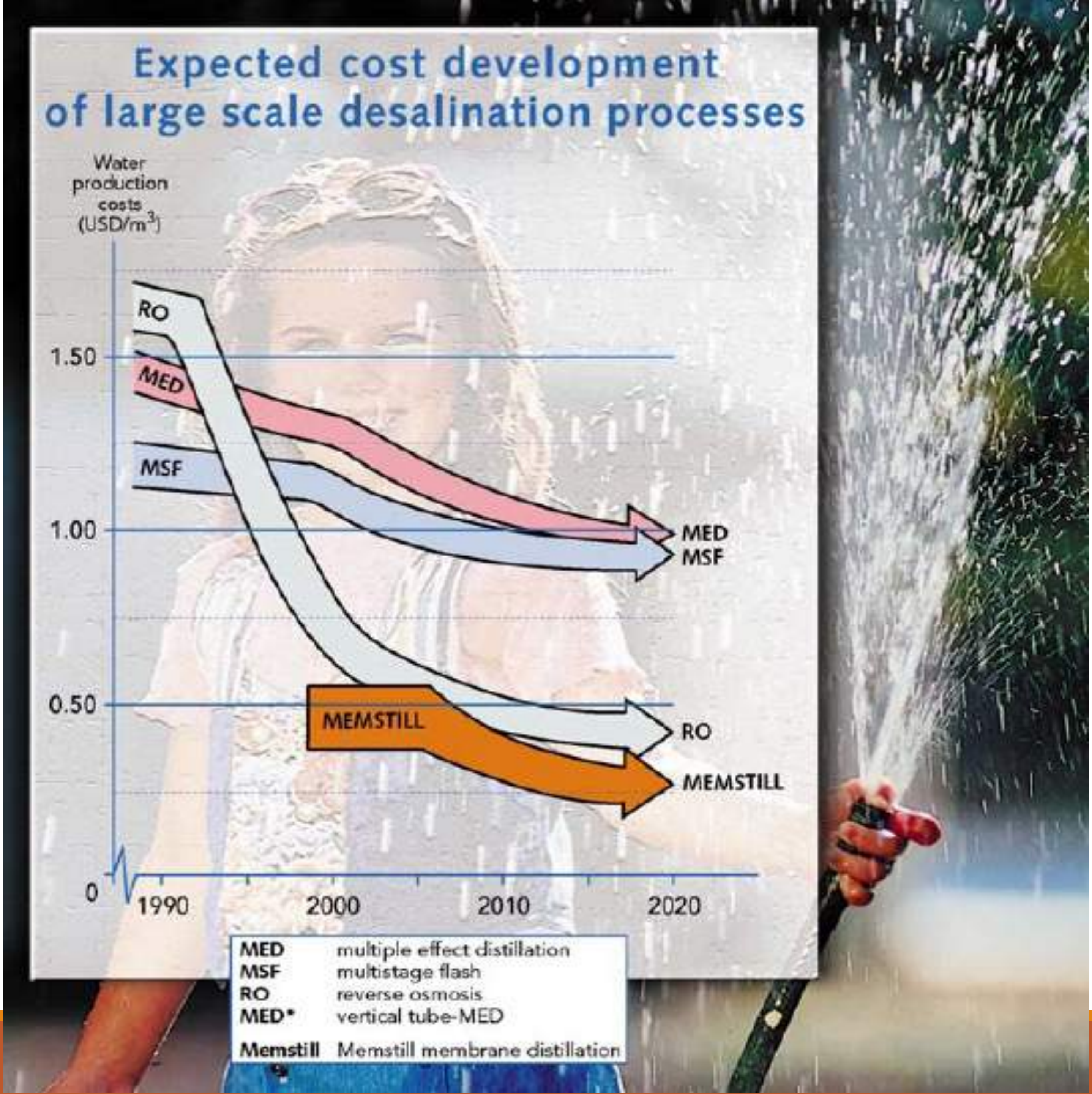
50~80 ºC **15~25 ºC**

Purity AB • Teknikhöjden, Björnnäsvägen 21 •
SE-114 19 Stockholm • SWEDEN

Hydrophobic ePTFE membrane



- hydrophobicity
- porosity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RO
MEMSTILL
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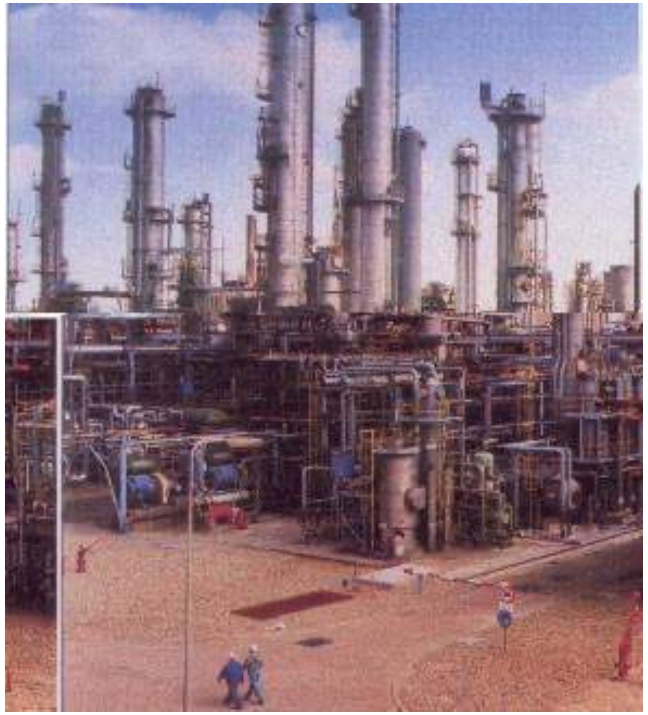
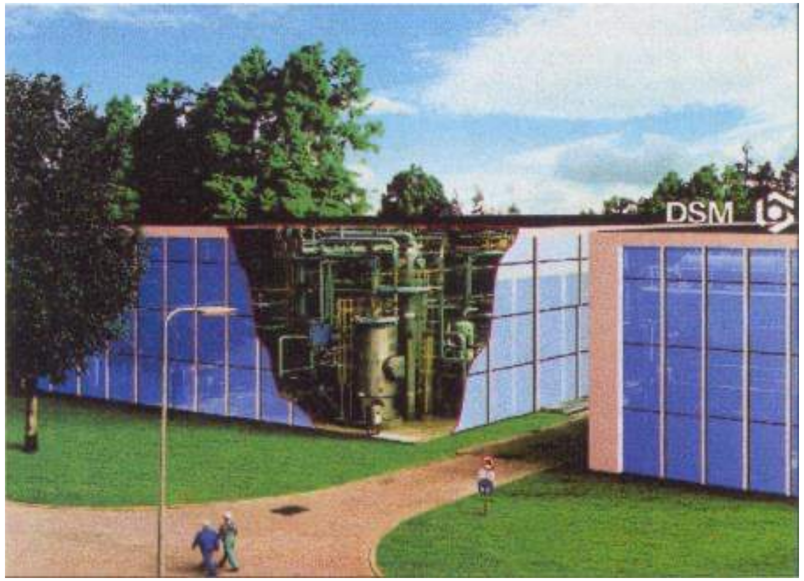
RO reverse osmosis
MED* vertical tube-MED
Memstill Memstill membrane distillation

Present



In **2020**



Operation

Design

Chemical Engineering Progress January 2000 23

Process Intensification: Transforming Chemical Engineering

ANDRZEJ I. STANKIEWICZ,
DSM RESEARCH/DELFT UNIVERSITY OF TECHNOLOGY
JACOB A. MOULIJN,
DELFT UNIVERSITY OF TECHNOLOGY

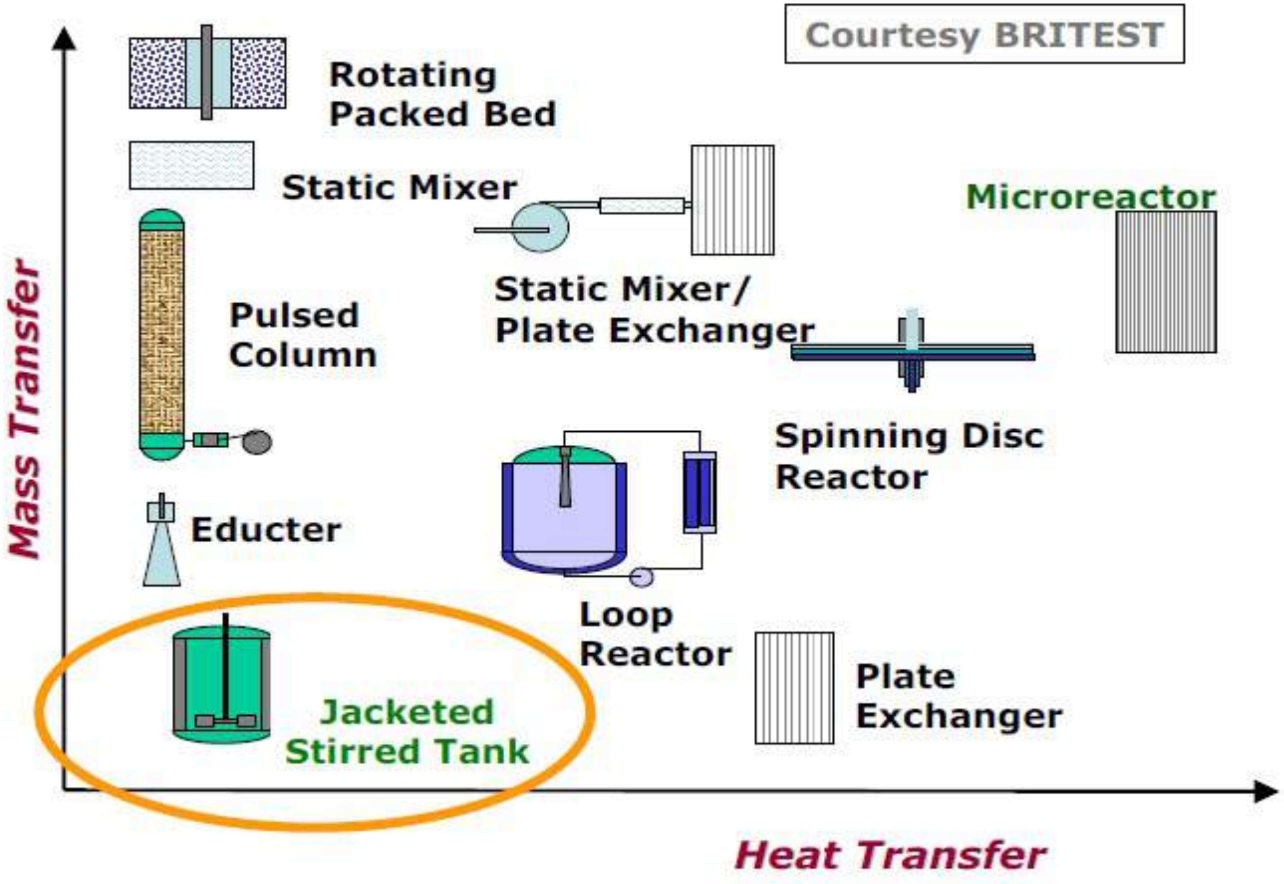
Emerging equipment, processing techniques, and operational methods promise spectacular improvements in process plants, markedly shrinking their size and dramatically boosting their efficiency. These developments may result in the extinction of some traditional types of equipment, if not whole unit operations.

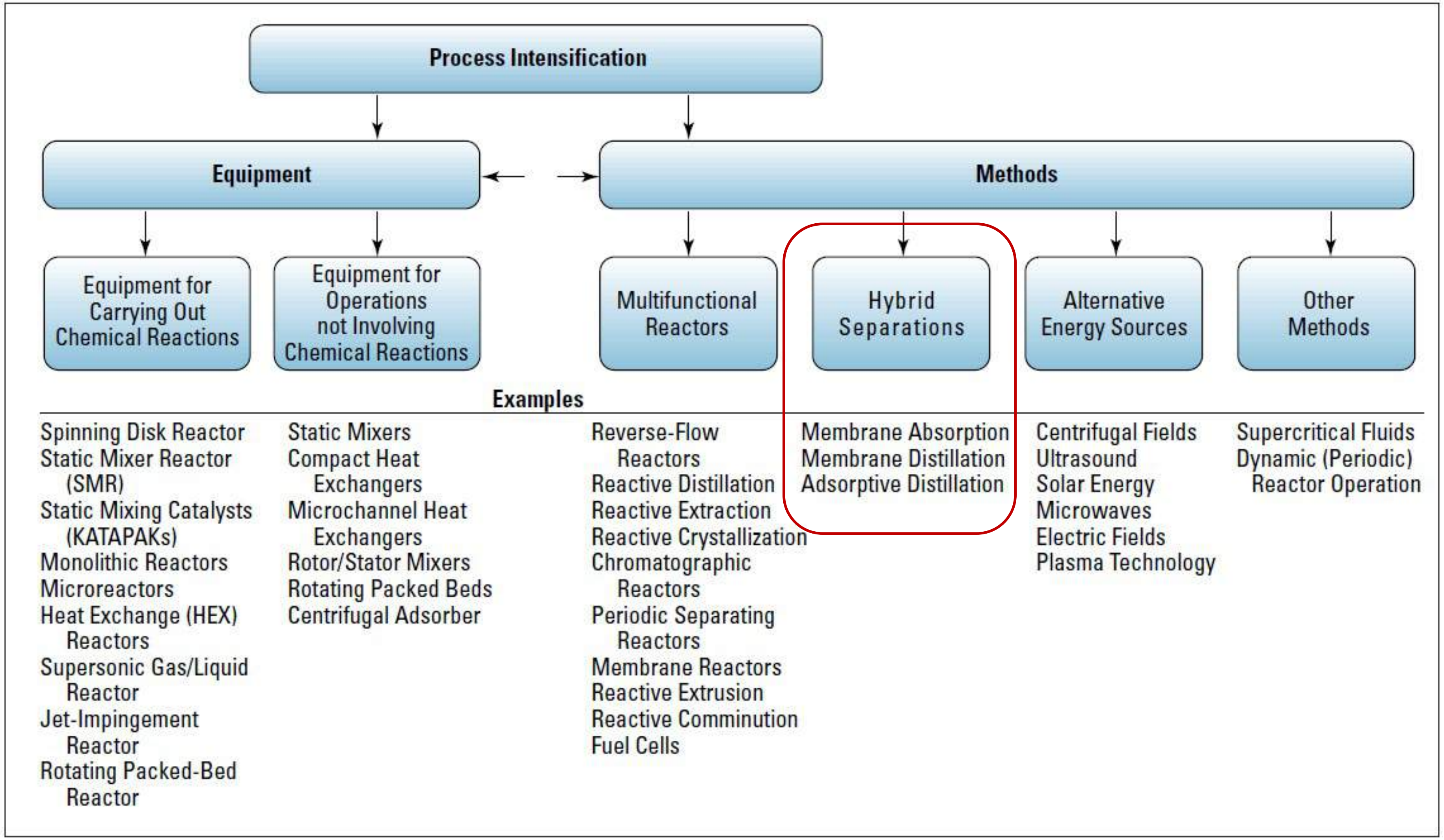
Today, we are witnessing important new developments that go beyond "traditional" chemical engineering. Engineers at many universities and industrial research centers are working on novel

fication, no matter how we define it, does not seem to have had much impact in the field of stirring technology over the last four centuries, or perhaps even longer. But, what actually *is* process intensification?

Intro

Equipment already exist that can be characterized by their E & m transfer performances



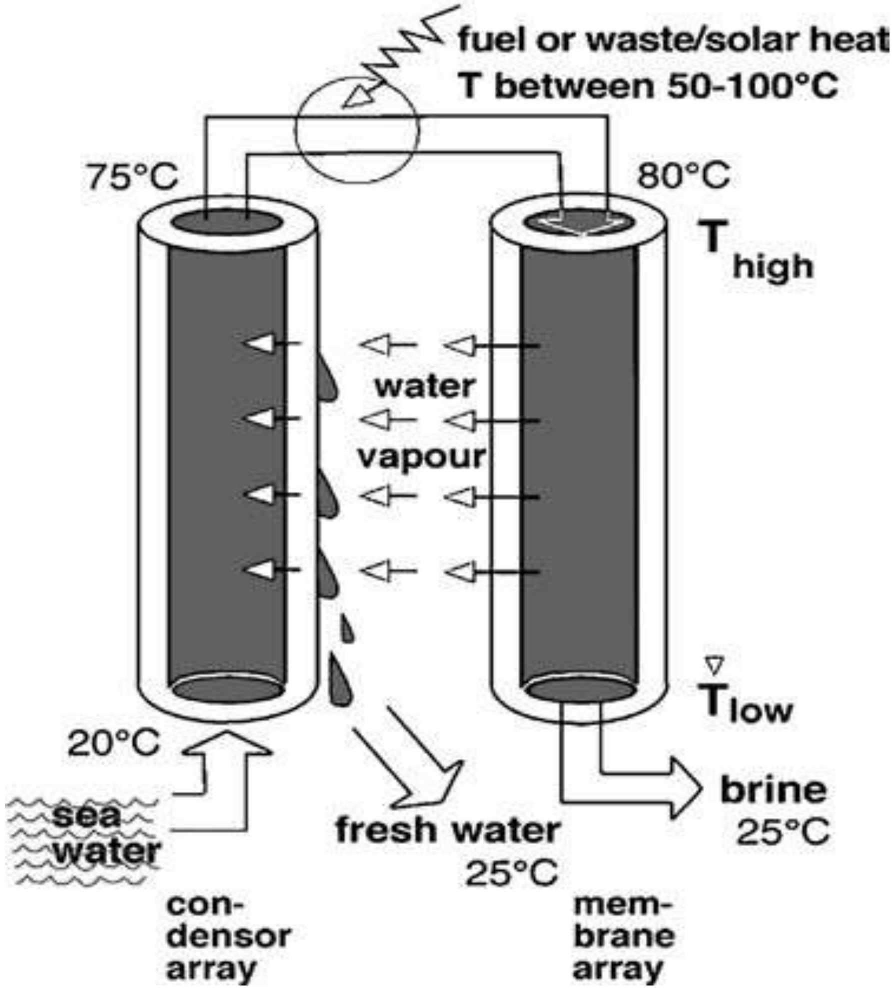


Stankiewicz and Moulijn, "**Process Intensification: Transforming Chemical Engineering**", *CEP*, January 2000

Original Installation: PSA Recovery System

New Installation: Membrane System

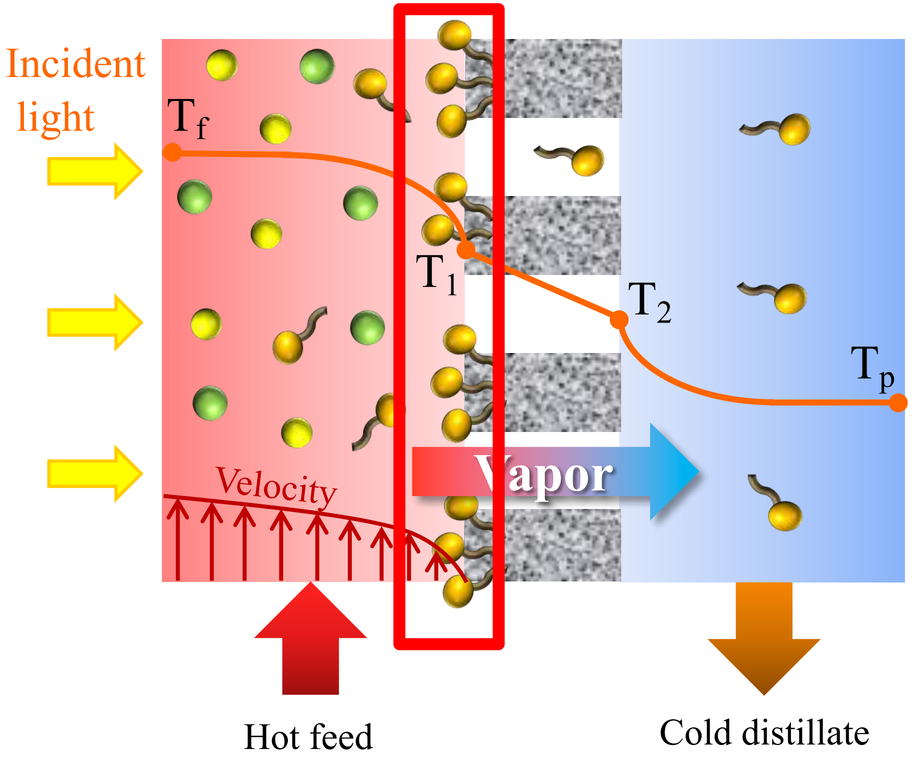
Membrane distillation (MD) utilize waste heat



Desalination, 199, 175-176, 2006

Fig. 1. Membrane modules for pilot plant.

Three major problems in MD process



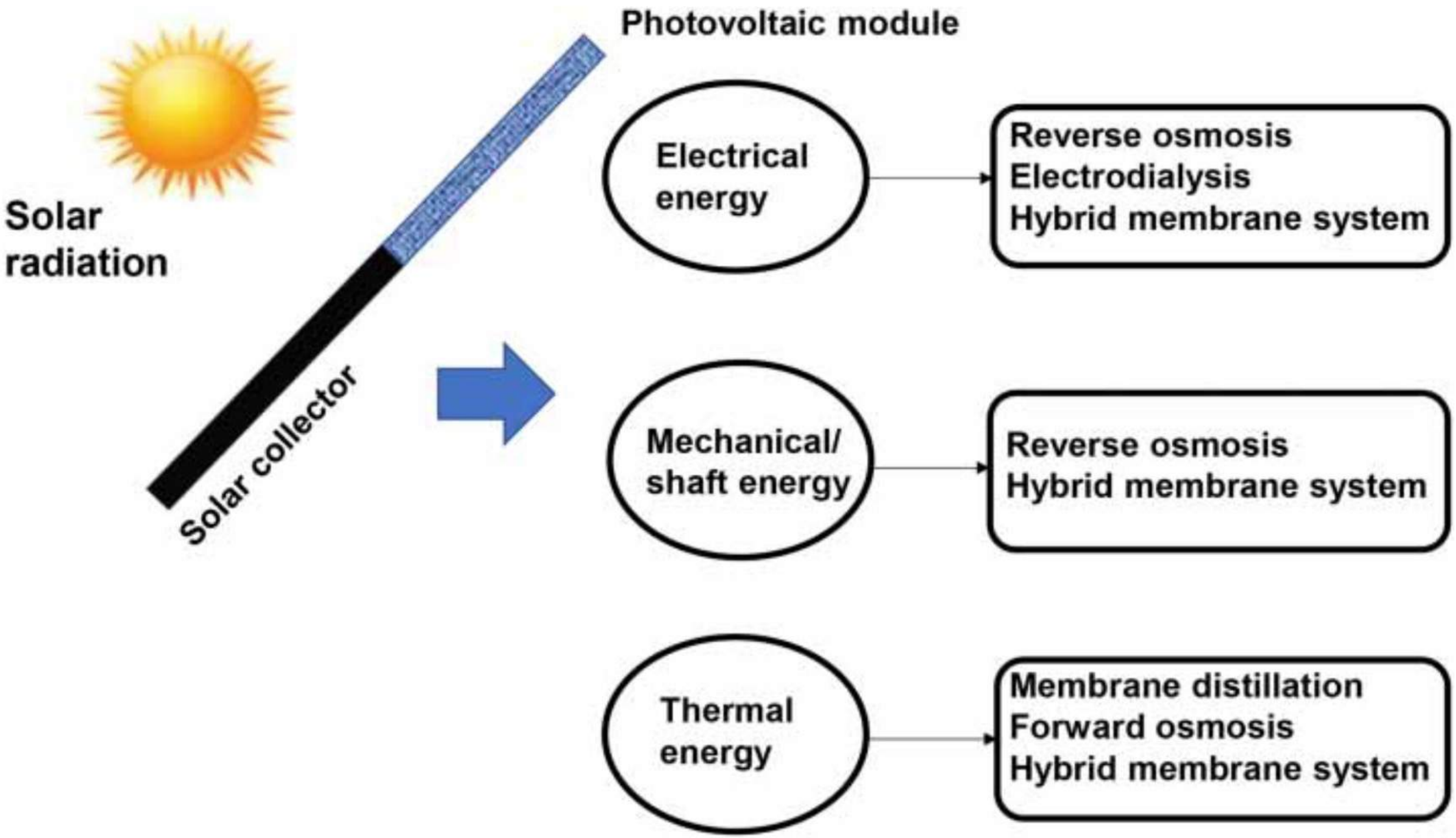
1. Temperature polarization
2. Surfactant wetting membrane pore
3. Low energy efficiency (< 40%)

Alternative Water Resources: Water-Energy Nexus

Water-Energy Nexus

"If we could ever competitively, at a cheap rate, get fresh water from salt water, that it would be in the long-range interests of humanity which would really dwarf any other scientific compliments."

President John F. Kennedy
1962



from Zewdie et al. Water Reuse 11.1 (2021)

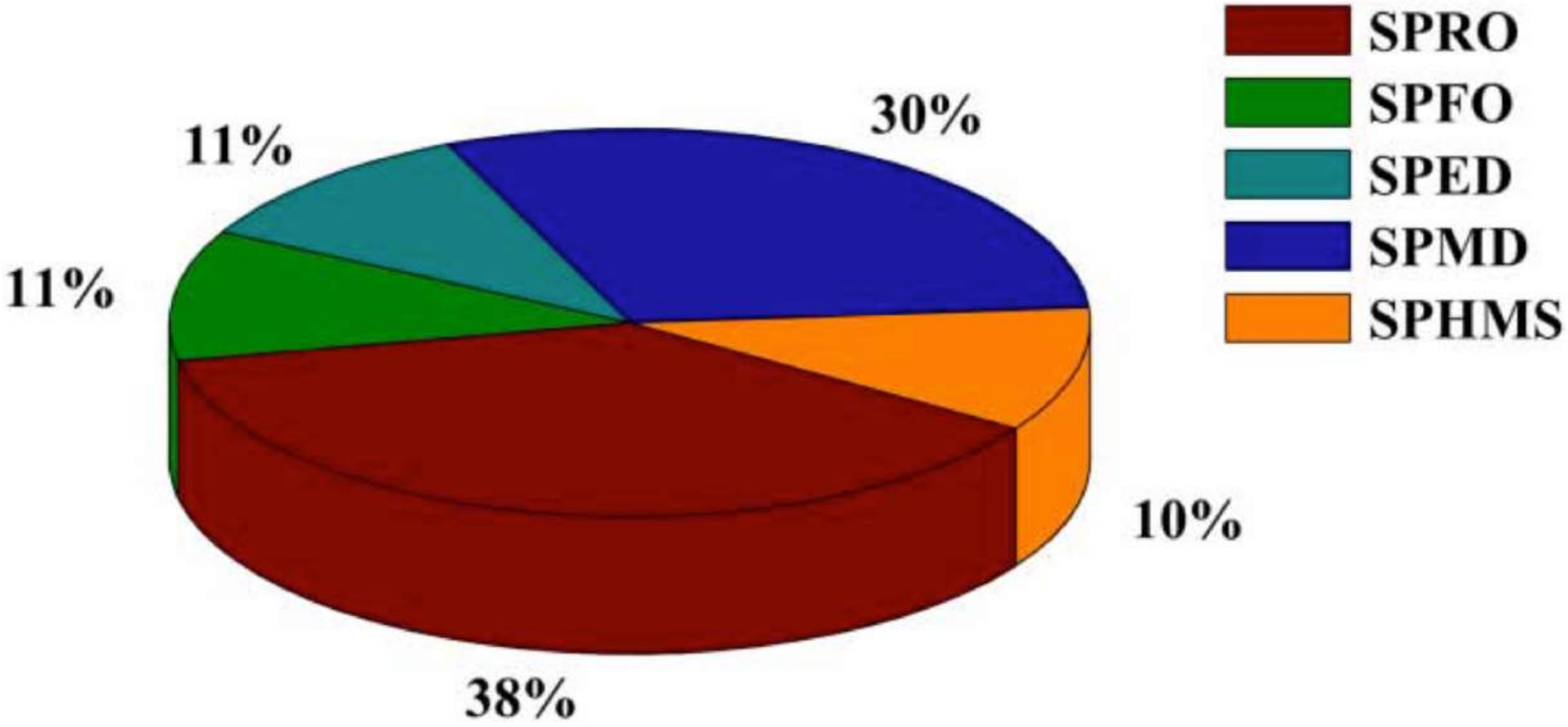
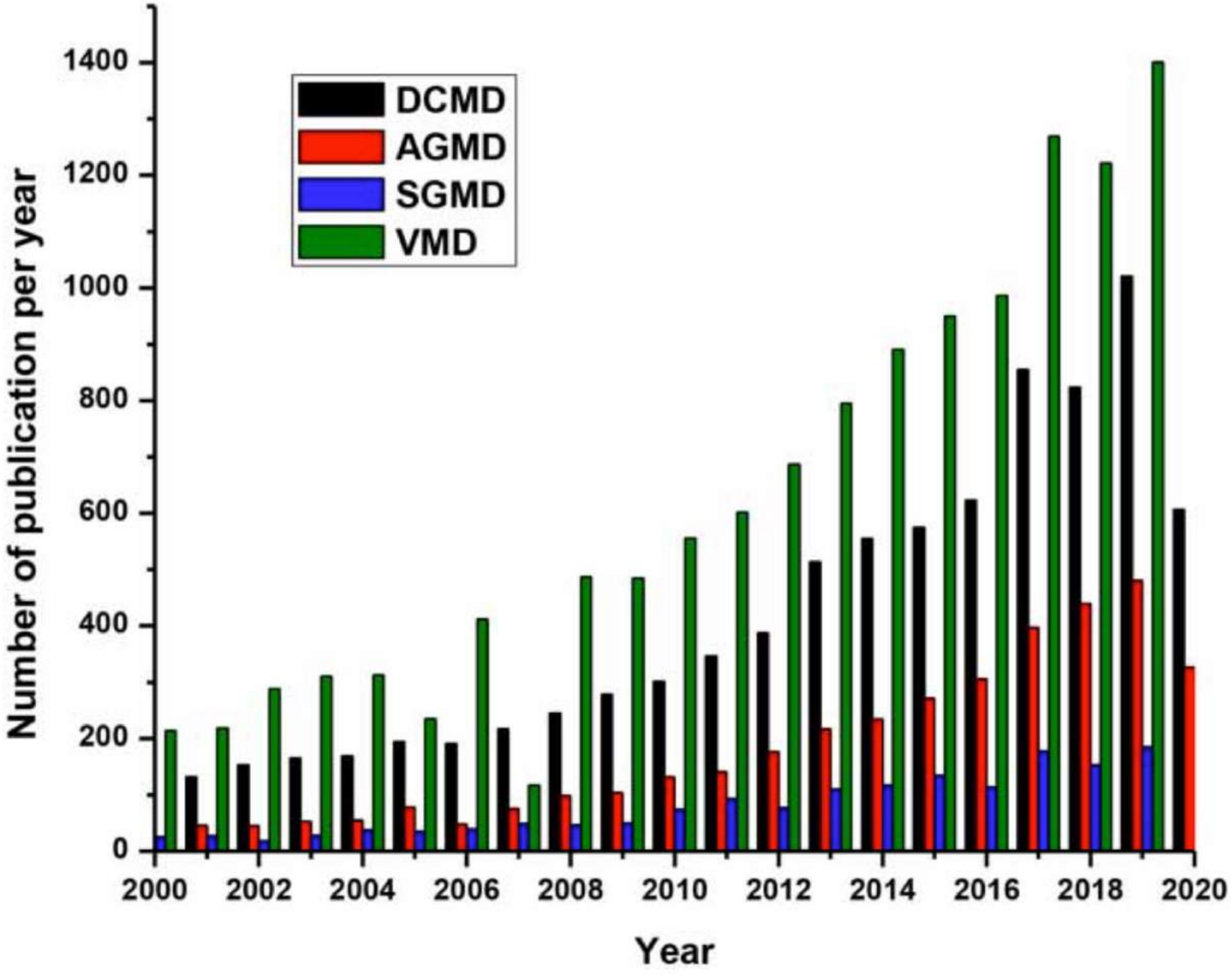
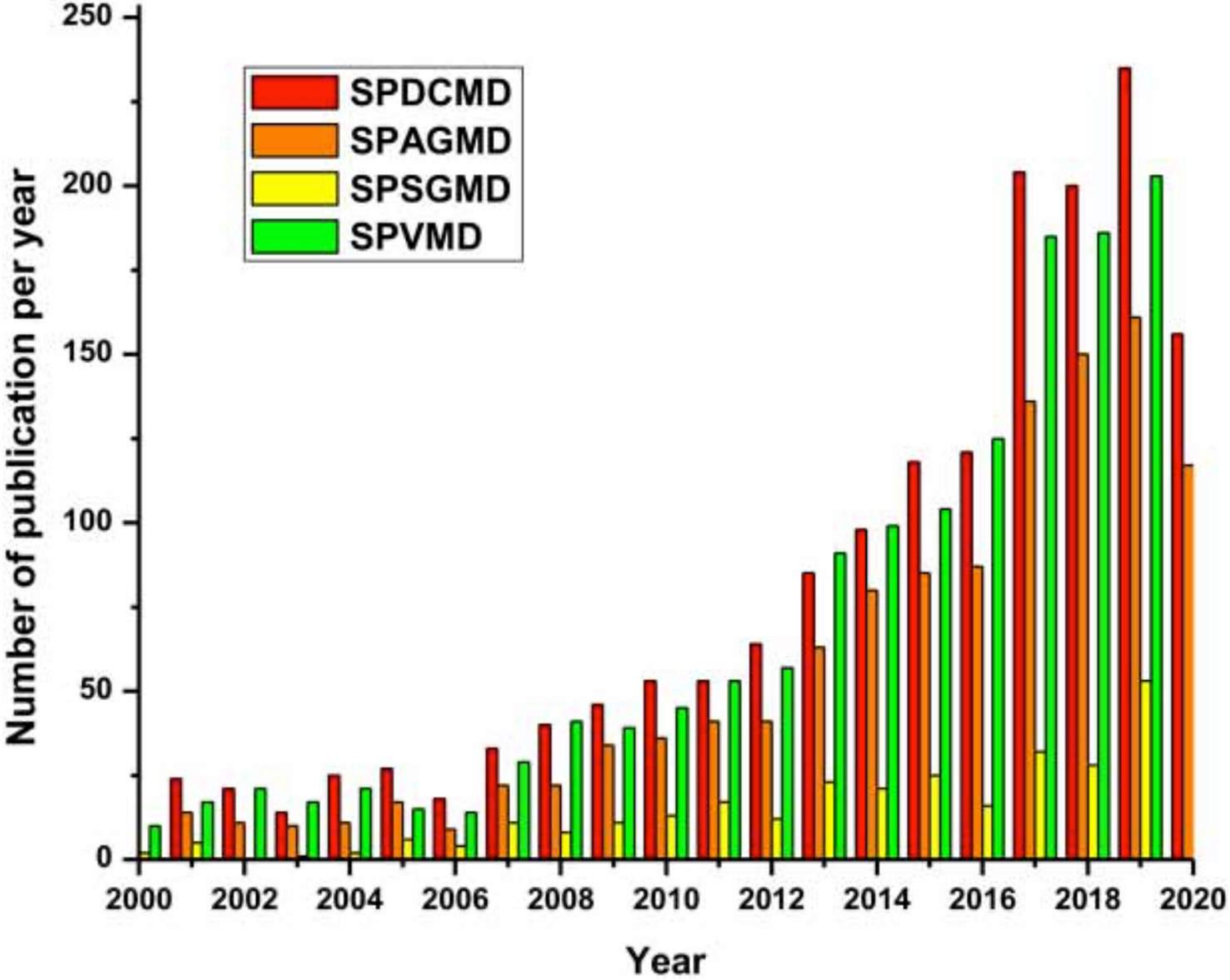


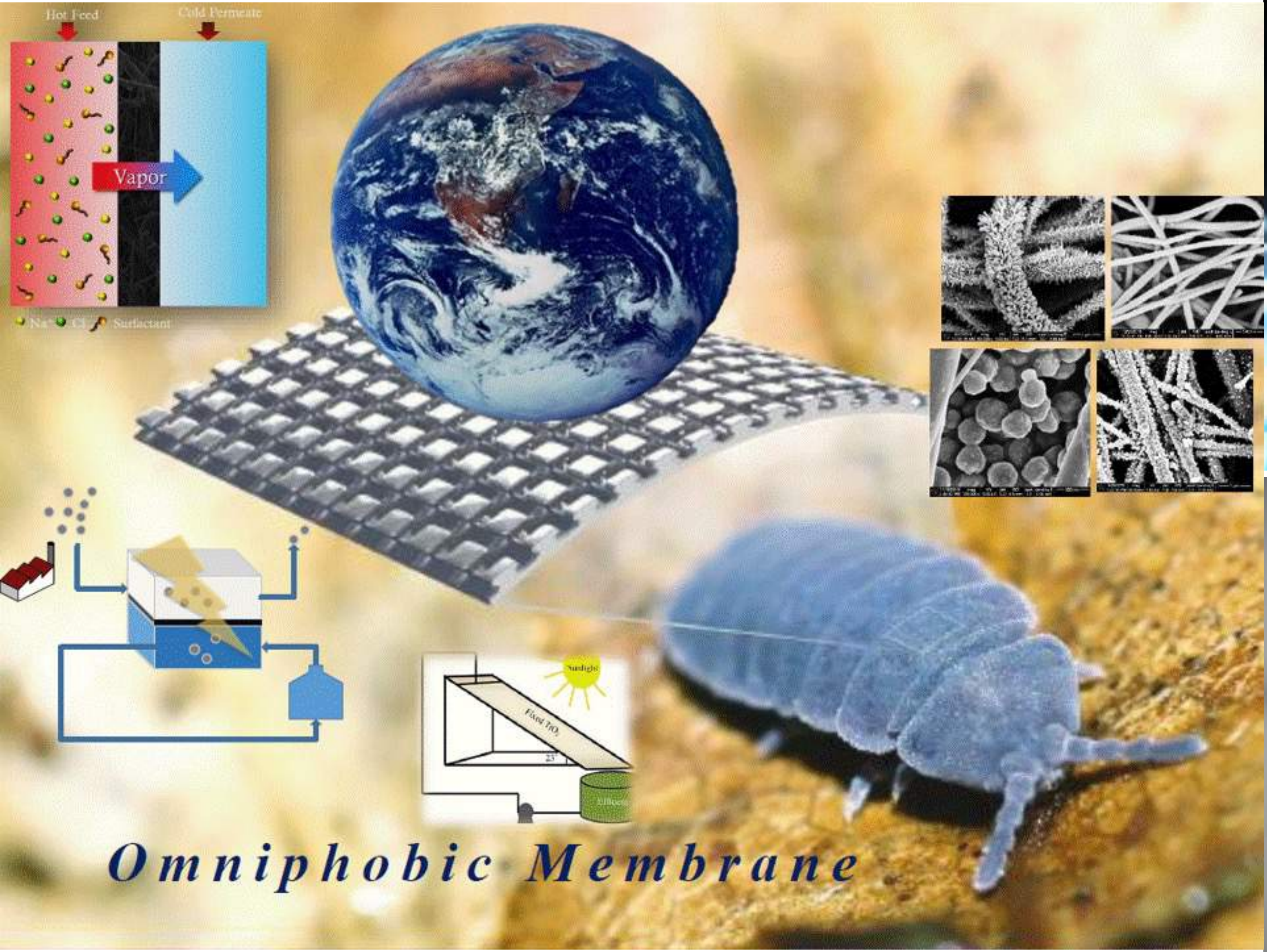
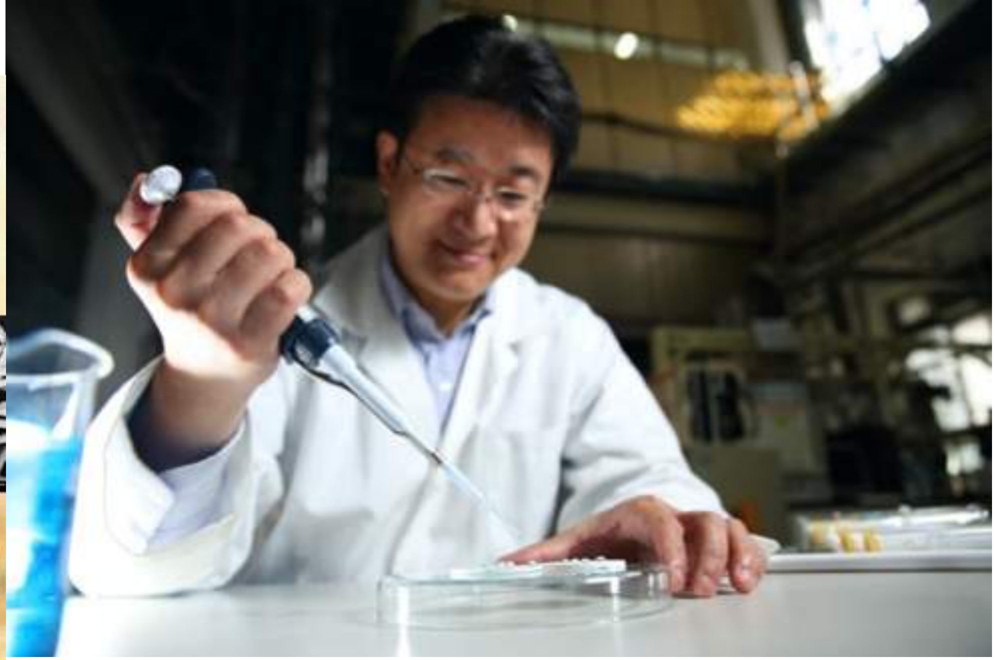
Figure 1 | Overview of the utilization of solar energy in membrane technologies (SPRO, solar-powered reverse osmosis; SPFO, solar-powered forward osmosis; SPED, solar-powered electrodialysis; SPMD, solar-powered membrane distillation; SPHMS, solar-powered hybrid membrane system) (data acquired from Web of Science, accessed on 29 April 2020).



from Zewdie et al. Water Reuse 11.1 (2021)



from Zewdie et al. Water Reuse 11.1 (2021)

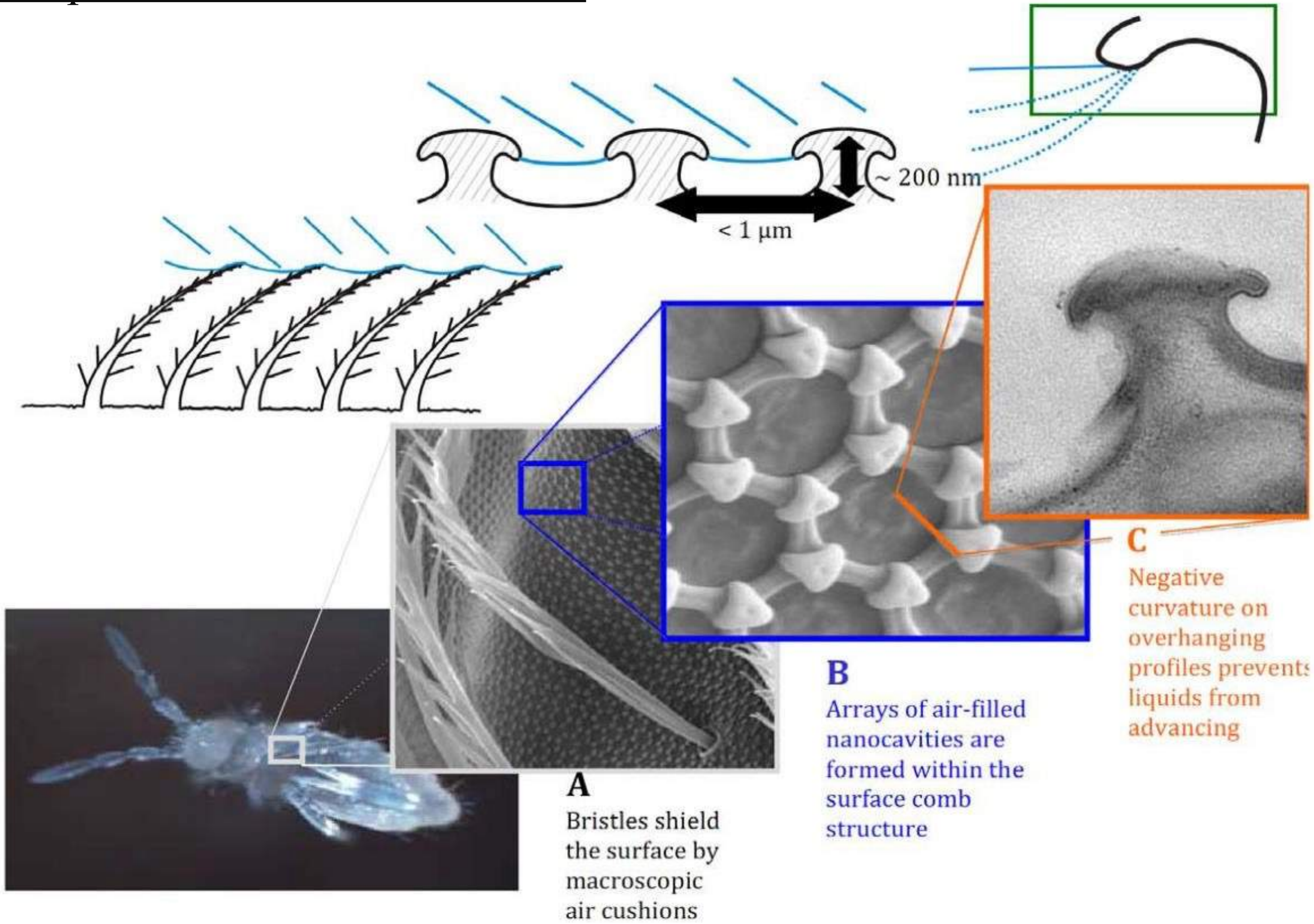

Hot Feed
Cold Permeate
Vapor
Na⁺ Cl⁻ Surfactant
Sunlight
Fixed TiO₂
25°
Omniphobic Membrane



Nature-inspired

Biomimicry

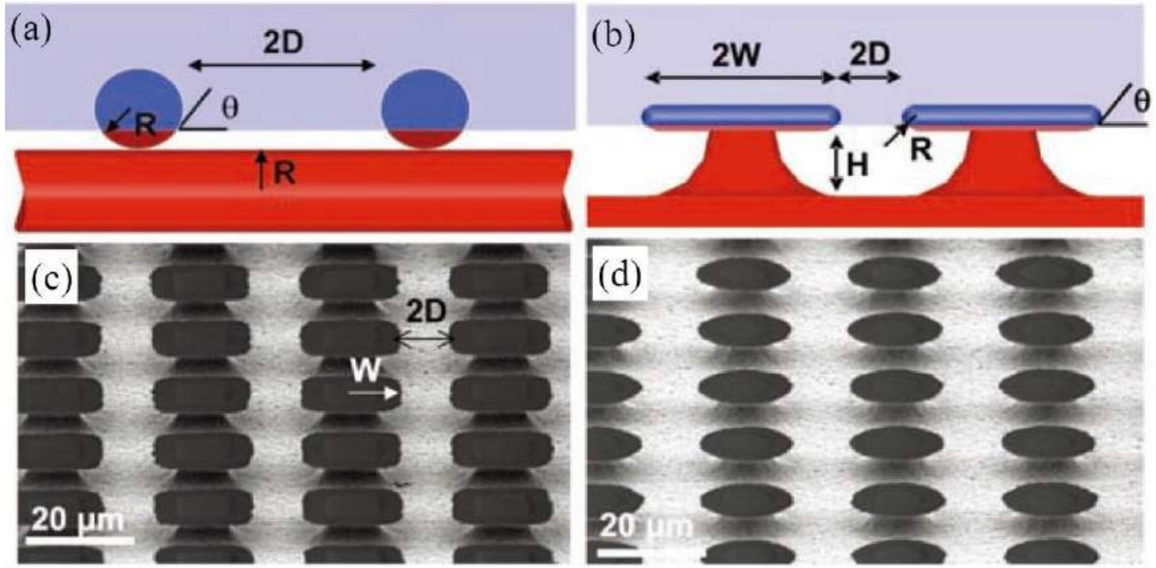
Geomimicry

Superomniphobic Surfaces in Nature

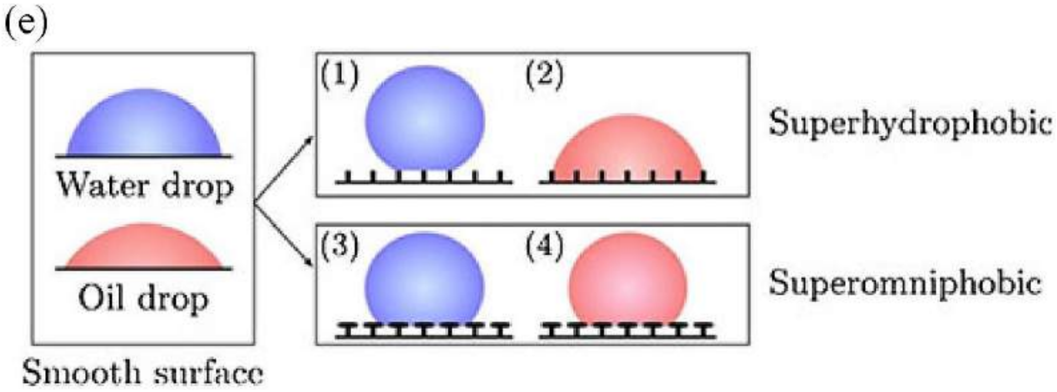


R. Helbig et al., "Smart skin patterns protect springtails", *Plos one*, 6 (2011) e25105.

Re-entrant structures



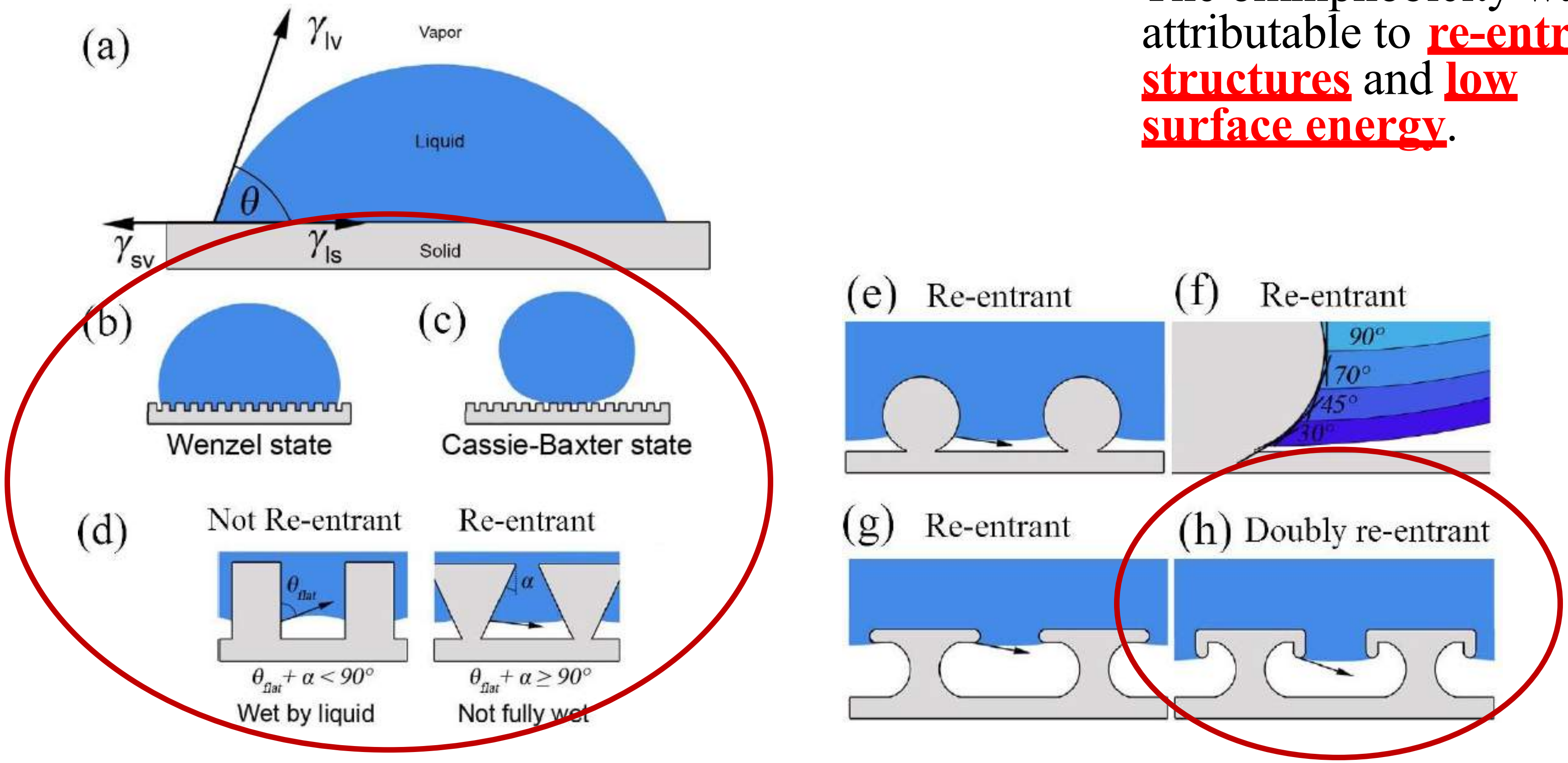
The omniphobicity was attributable to **re-entrant structures** and **low surface energy**.



R. Dufour et al., "From micro to nano reentrant structures: hysteresis on superomniphobic surfaces," *Colloid and Polymer Science*, 291 (2013) 409-415.

Re-entrant structures

The omniphobicity was attributable to **re-entrant structures** and **low surface energy**.



(a) Liquid droplet displaying contact angle of θ on flat surface, (b) droplet exhibiting Wenzel state of wetting, (c) trapped air between droplet and surface in Cassie-Baxter state of wetting, (d) non-re-entrant and re-entrant structure, (e~g) re-entrant structure, (h) doubly re-entrant structure.

P.S. Brown et al., "Designing bioinspired superoleophobic surfaces," *APL Materials*, 4 (2016) 015703.

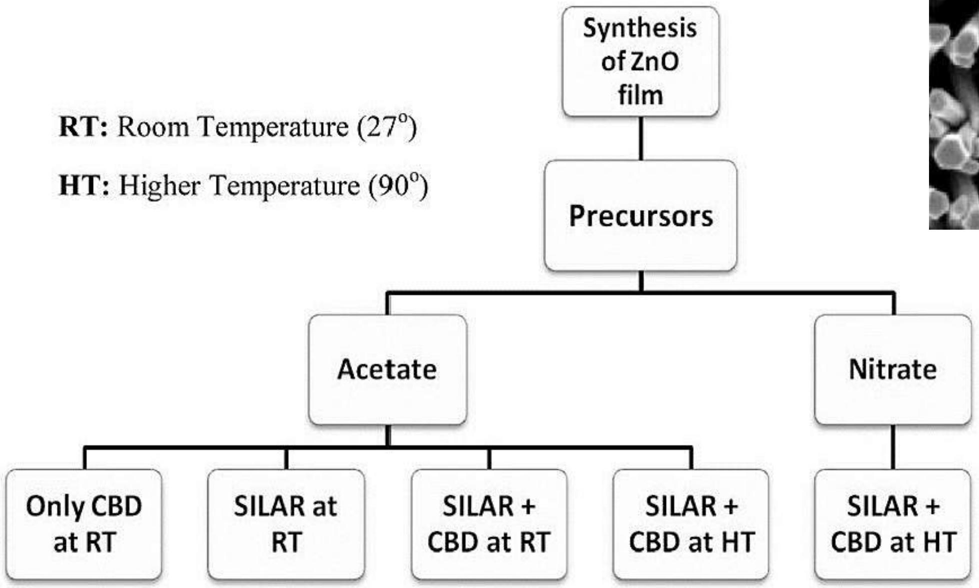


Figure 1 Schematic representation for the synthesis of ZnO via various route using different precursors at different temperature [1].

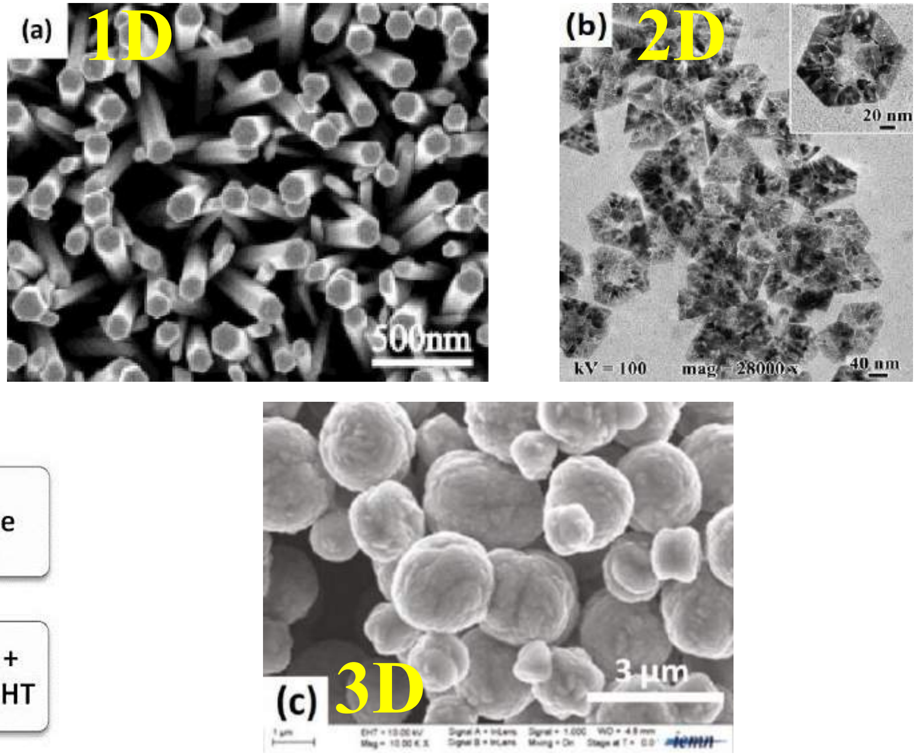


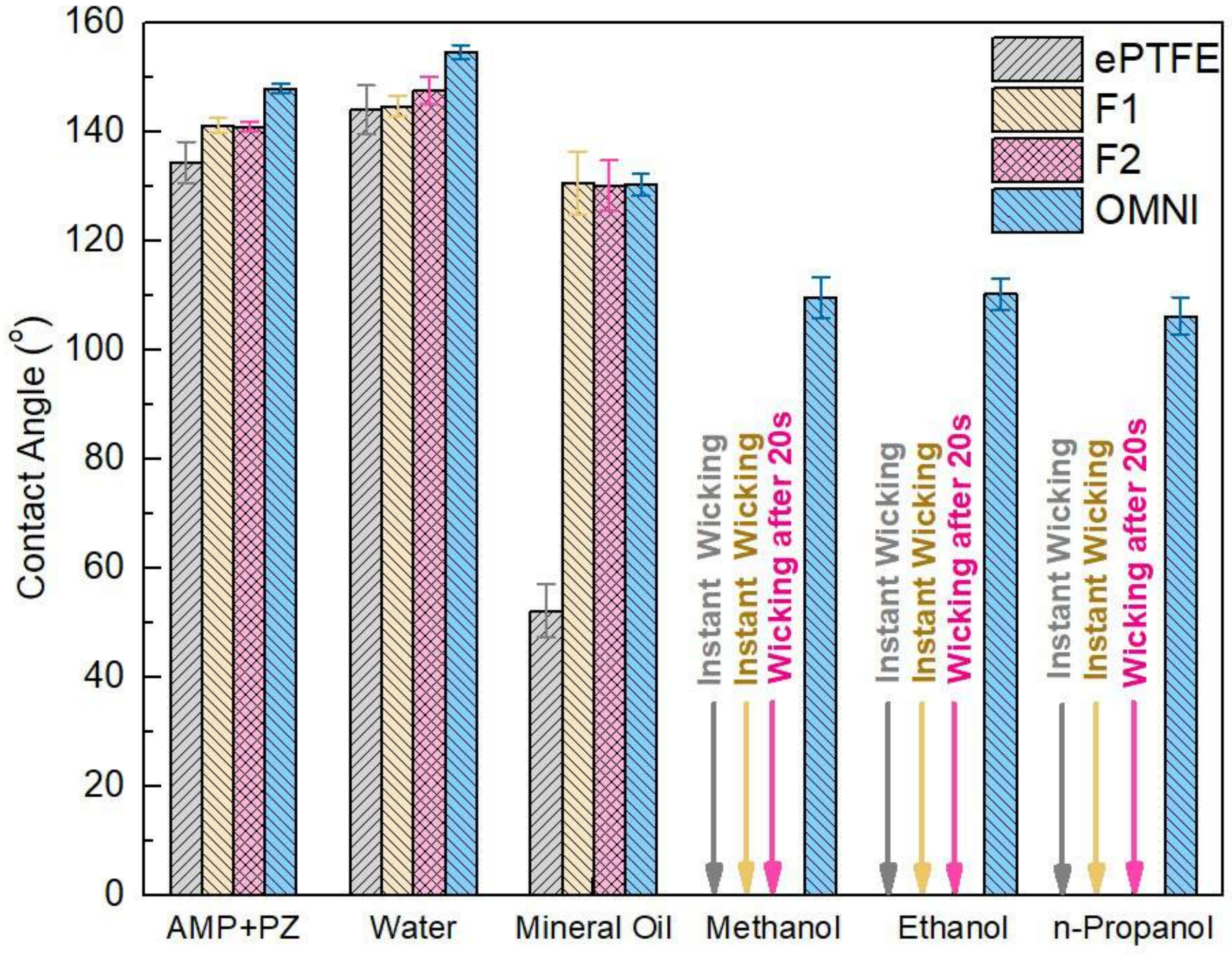
Figure 2 One-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) zinc oxide nano-structures [2, 3, 4].

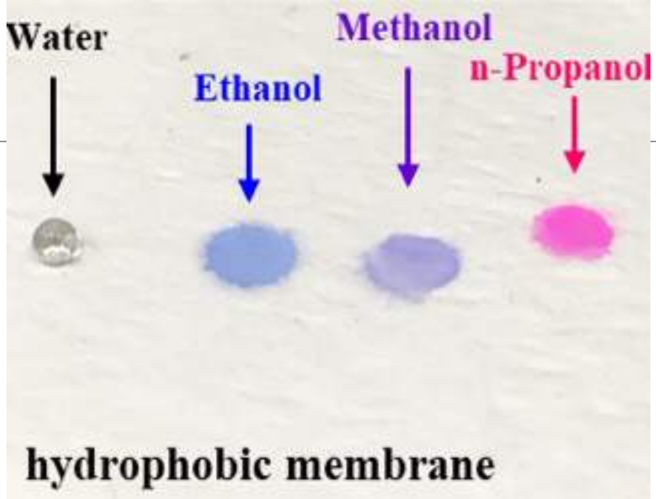
[1] P.K. Baviskar et al., "Controlled synthesis of ZnO nanostructures with assorted morphologies via simple solution chemistry," *Journal of Alloys and Compounds*, 551 (2013) 233-242.

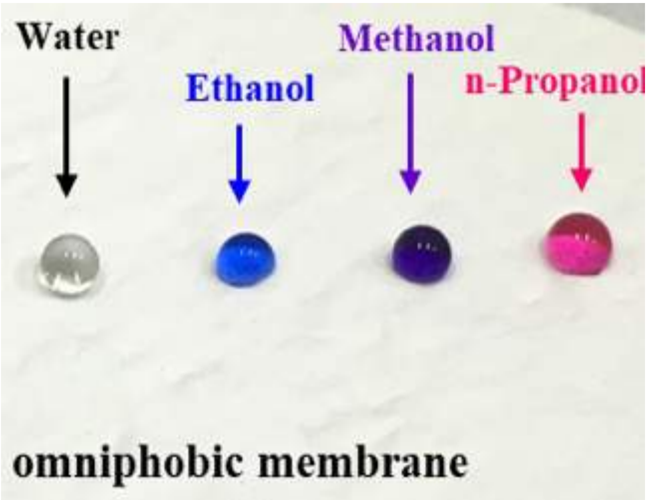
[2] X. Feng et al., "Reversible super-hydrophobicity to super-hydrophilicity transition of aligned ZnO nanorod films," *Journal of the American Chemical Society*, 126 (2004) 62-63.

[3] W. Chiu et al., "Photocatalytic study of two-dimensional ZnO nanopellets in the decomposition of methylene blue," *Chemical Engineering Journal*, 158 (2010) 345-352.

[4] G. Perry et al., "Sliding droplets on superomniphobic zinc oxide nanostructures," *Langmuir*, 28 (2011) 389-395.







Huang, A., L.H. Chen, C.H. Chen, T.Y. Hsu, H.Y. Tsai and K.L. Tung* “Omniphobic Zinc Oxide Membranes with Enhanced CO_2 Absorption Stability in Membrane Contactors,” *J. Membrane Sci.,* 556 **(2018)** 227-237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薄膜接觸器之應用技術開發

Photothermal membrane

Nanophotonics-enabled solar membrane distillation for off-grid water purification

Pratiksha D. Dongare[a,b,c,d,1], Alessandro Alabastri[a,b,d,1], Seth Pedersen[d,e], Katherine R. Zodrow[d,e], Nathaniel J. Hogan[a,b,c], Oara Neumann[a,b,d], Jinjian Wu[d,e], Tianxiao Wang[e], Akshay Deshmukh[d,f], Menachem Elimelech[d,f], Qilin Li[d,e,2], Peter Nordlander[a,b,d,g], and Naomi J. Halas[a,b,d,g,h,2]

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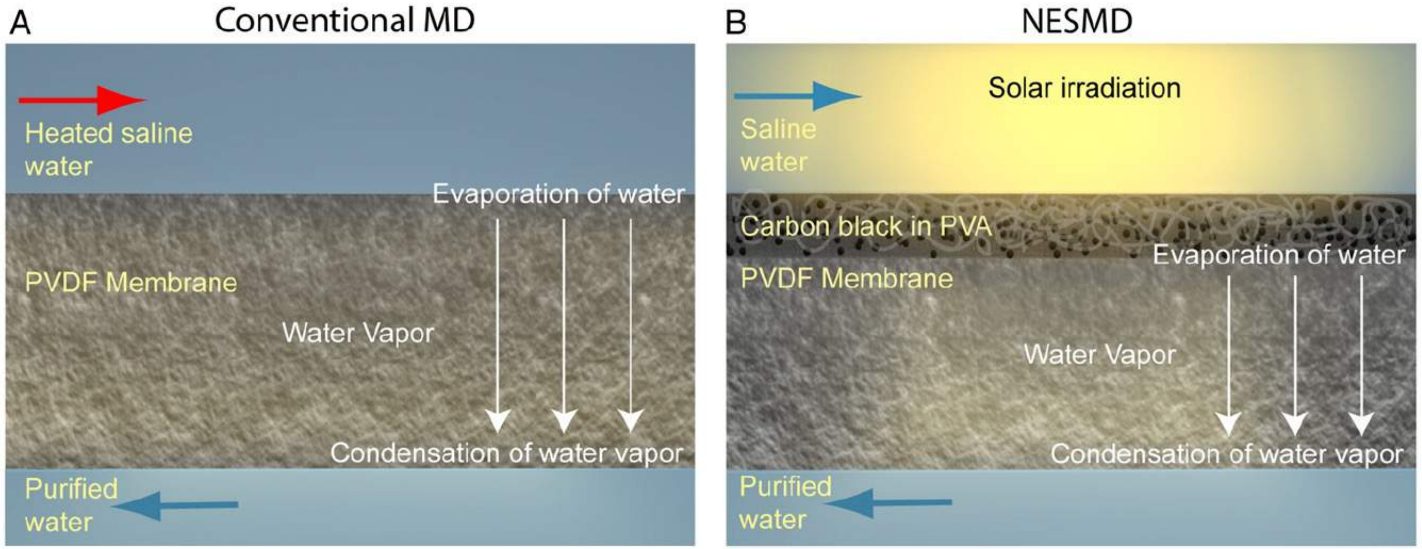
Contributed by Naomi J. Halas, May 16, 2017 (sent for review February 2, 2017; reviewed by Svetlana V. Boriskina and Amy Childress)



Prof Qilin Li group, Nanophotonics-enabled solar membrane distillation for off-grid water purification, Proceedings of the National Academy of Sciences, 114 (2017) 6936-6941.

Photothermal membrane

ARTICLES NATURE NANOTECHNOLOGY DOI: 10.1038/NNANO.2017.102

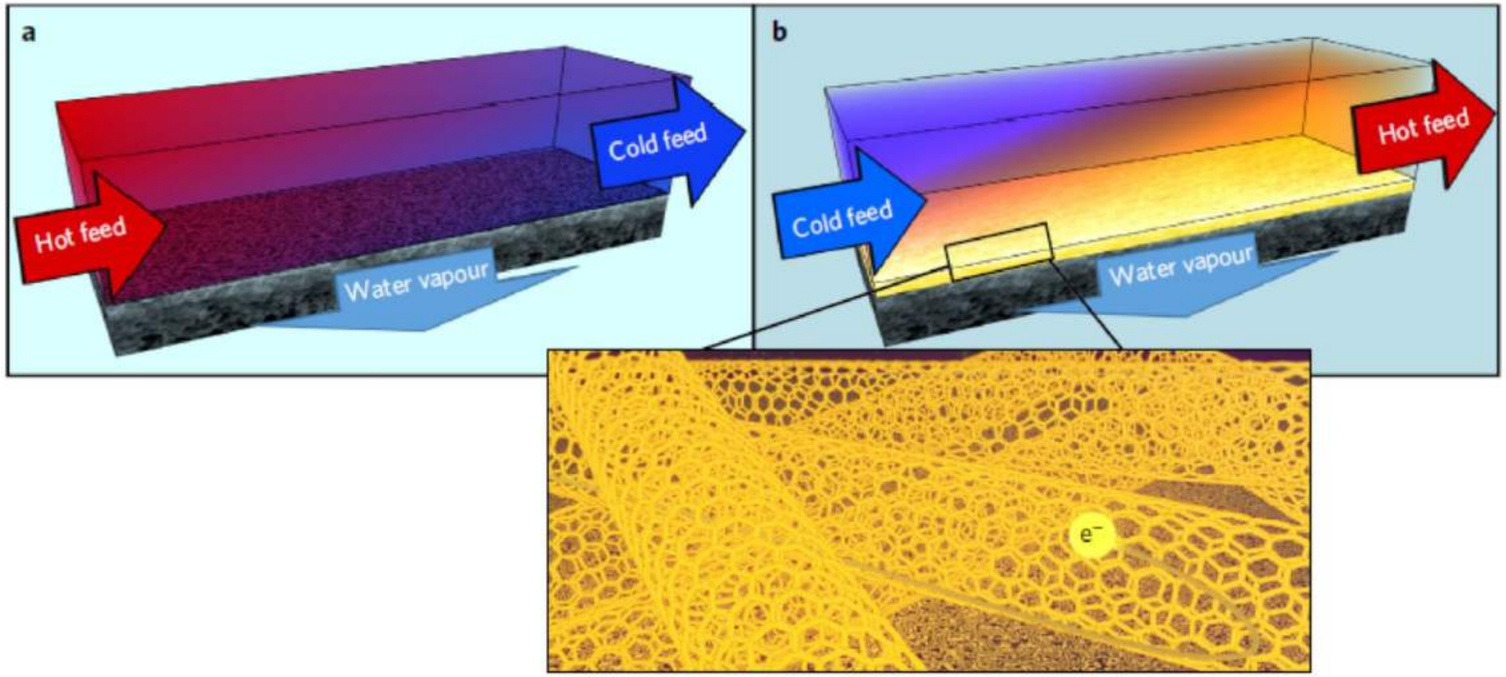
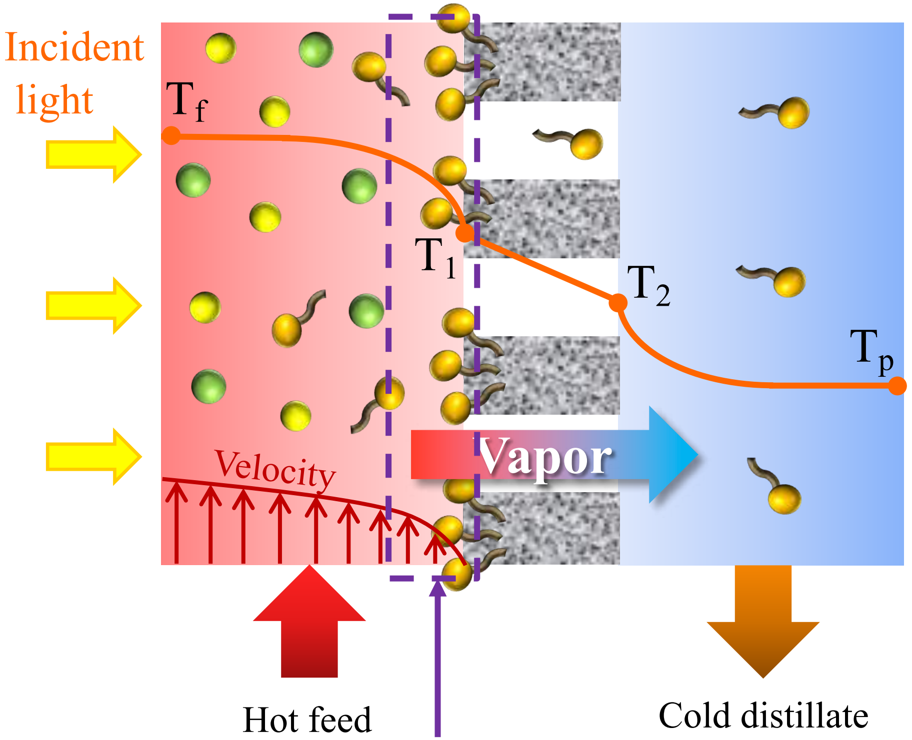


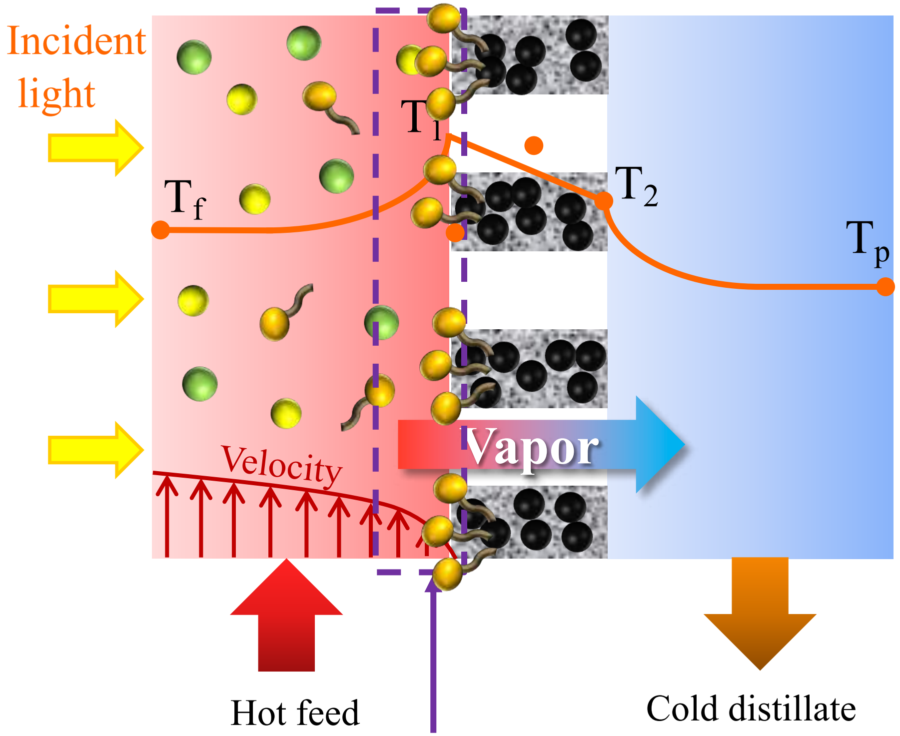
Figure 1 | Comparison of classical and directly heated membrane distillation. a, Diagram of a classical MD process where a hot feed (brine) flows over one side of a hydrophobic membrane and a cold distillate stream flows over the other side, leading to a vapour pressure gradient across the membrane that drives water vapour from the hot, salty feed to the cold distillate. **b**, Direct surface heating of a composite MD membrane composed of a porous CNT-based Joule heater and a hydrophobic porous support. The cold feed (brine) is heated on the membrane surface, which drives water vapour transport across the hydrophobic support into the distillate stream, leaving dissolved ions behind. Inset: zoomed-in rendition of the thin-film CNT Joule heater structure on an MD membrane surface showing electron (e^-) flow and heating.

Previous work: Overcome two major problems in MD

(a) Pristine hydrophobic membrane



(b) Omniphobic and photothermal dual-functional membrane

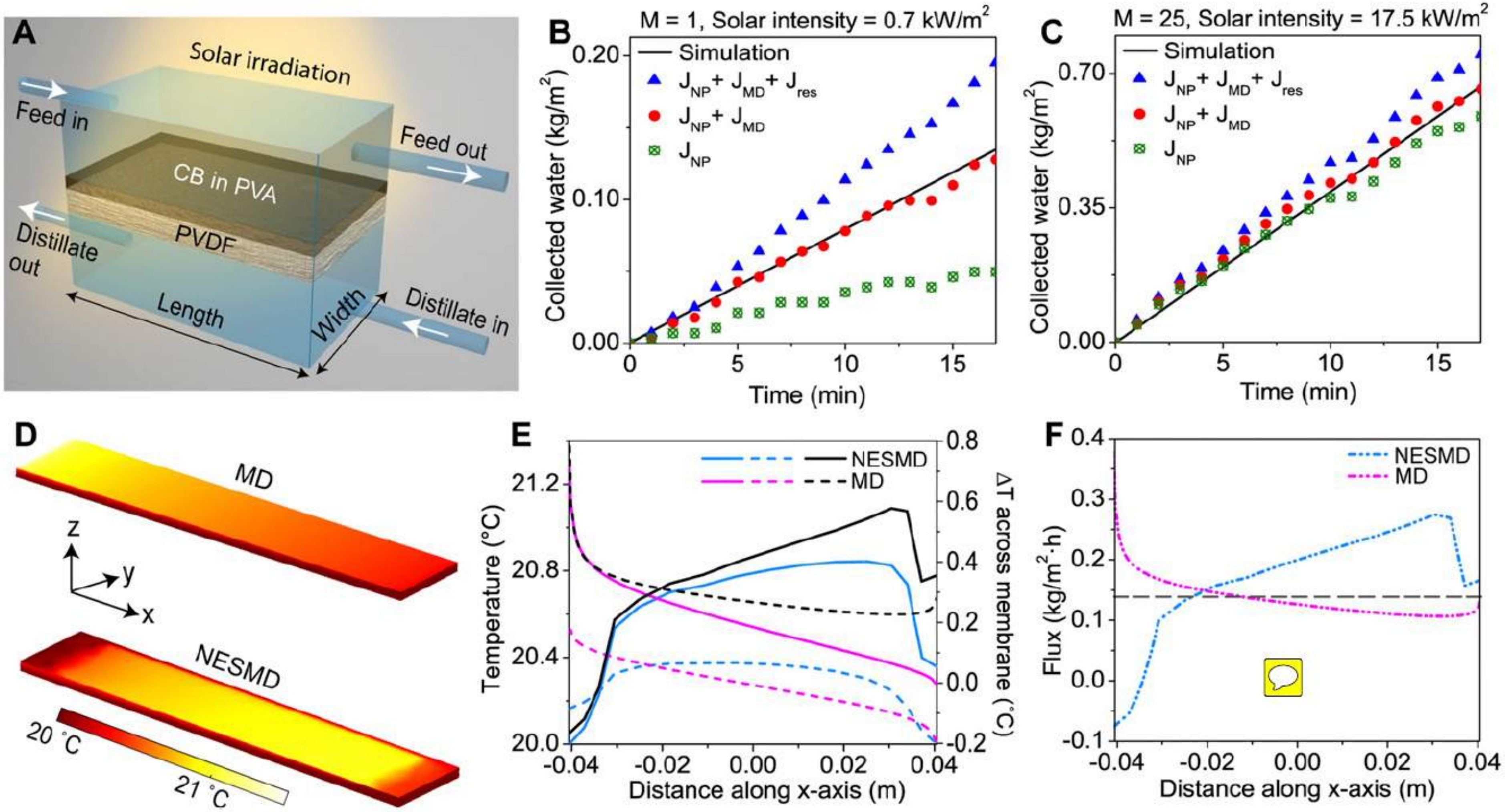


1. **Temperature polarization**
2. Surfactant wetting membrane pore
3. **Low energy efficiency (20~40 %)**

1. **Overcome temperature polarization**
2. Mitigate surfactant wetting membrane pore
3. **High energy efficiency (60~80%)**

Na^+ Cl^- Surfactant CB NPs with omniphobic and photothermal properties

Photothermal membrane



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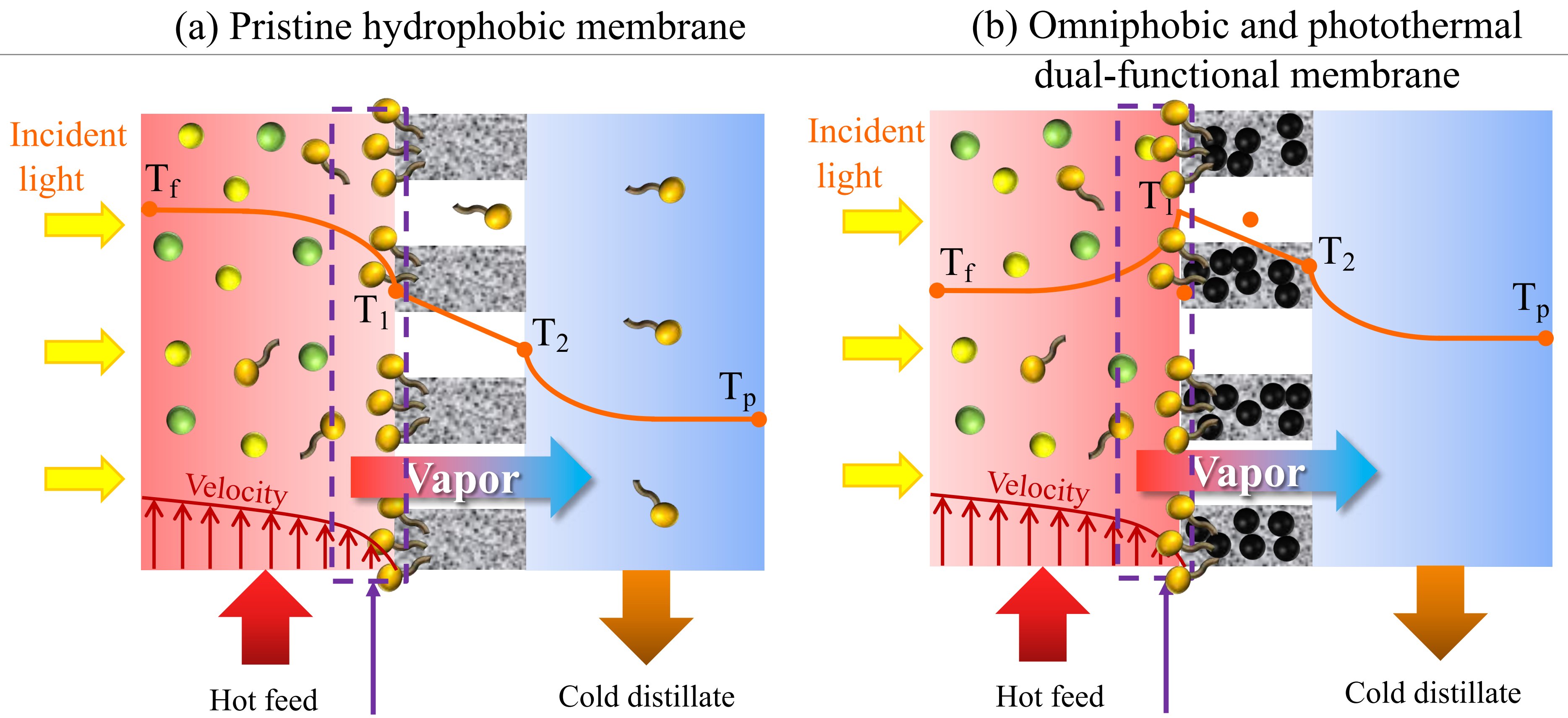
Previous work: Overcome two major problems in MD



1. **Temperature polarization**	1. **Overcome temperature polarization**
2. **Surfactant wetting membrane pore**	2. Mitigate surfactant wetting membrane pore
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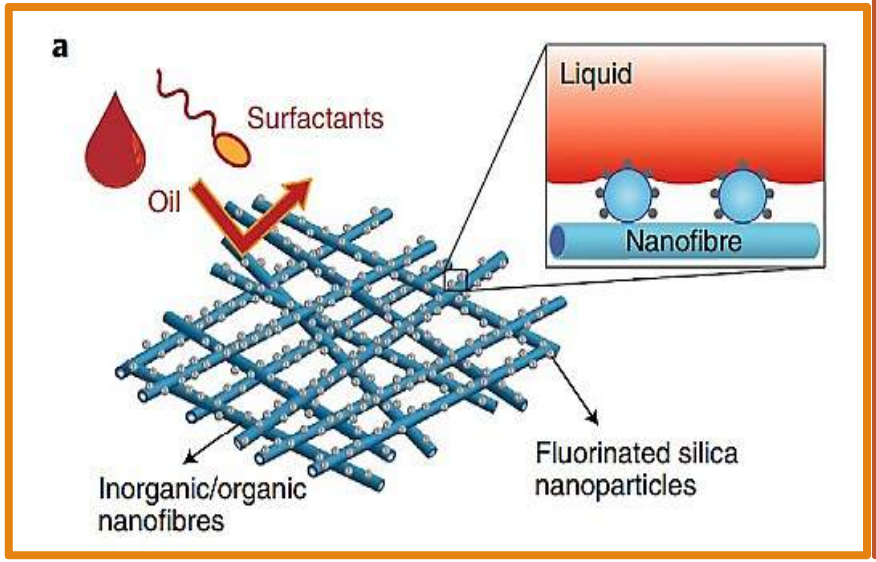
Na^+ Cl^- Surfactant CB NPs with omniphobic and photothermal properties

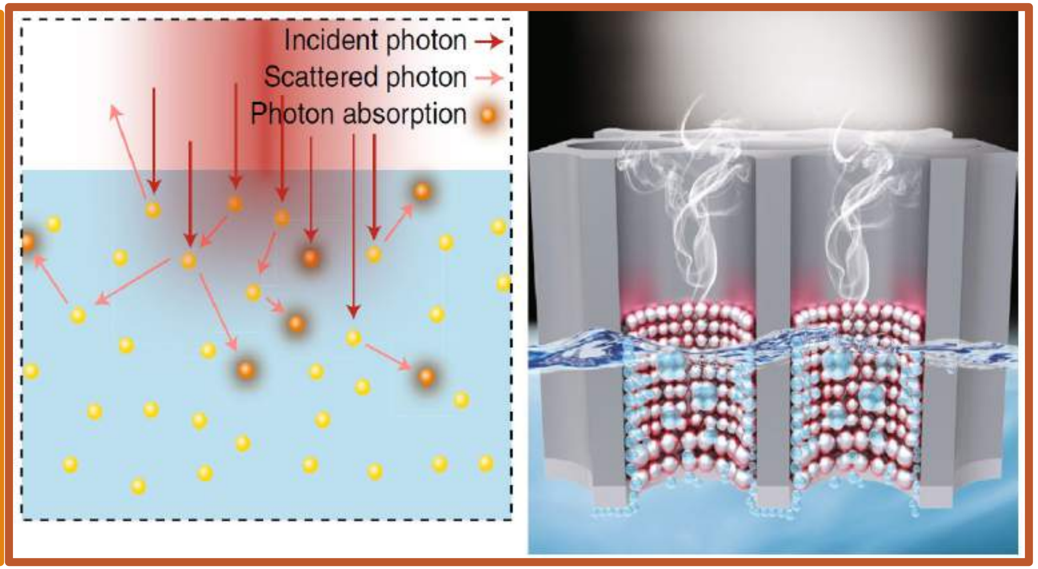
PERSPECTIVE | INSIGHT
https://doi.org/10.1038/s41565-018-0203-2
nature nanotechnology

Emerging opportunities for nanotechnology to enhance water security

Pedro J. J. Alvarez[1]*, Candace K. Chan[2], Menachem Elimelech[3], Naomi J. Halas[4] and Dino Villagrán[5]

(A) Omniphobic membrane **(B) Solar membrane distillation**





The **omniphobic** and **photothermal membrane** are highlight in **nature nanotechnology** (Pedro et al., 2018, 13, 634-641)

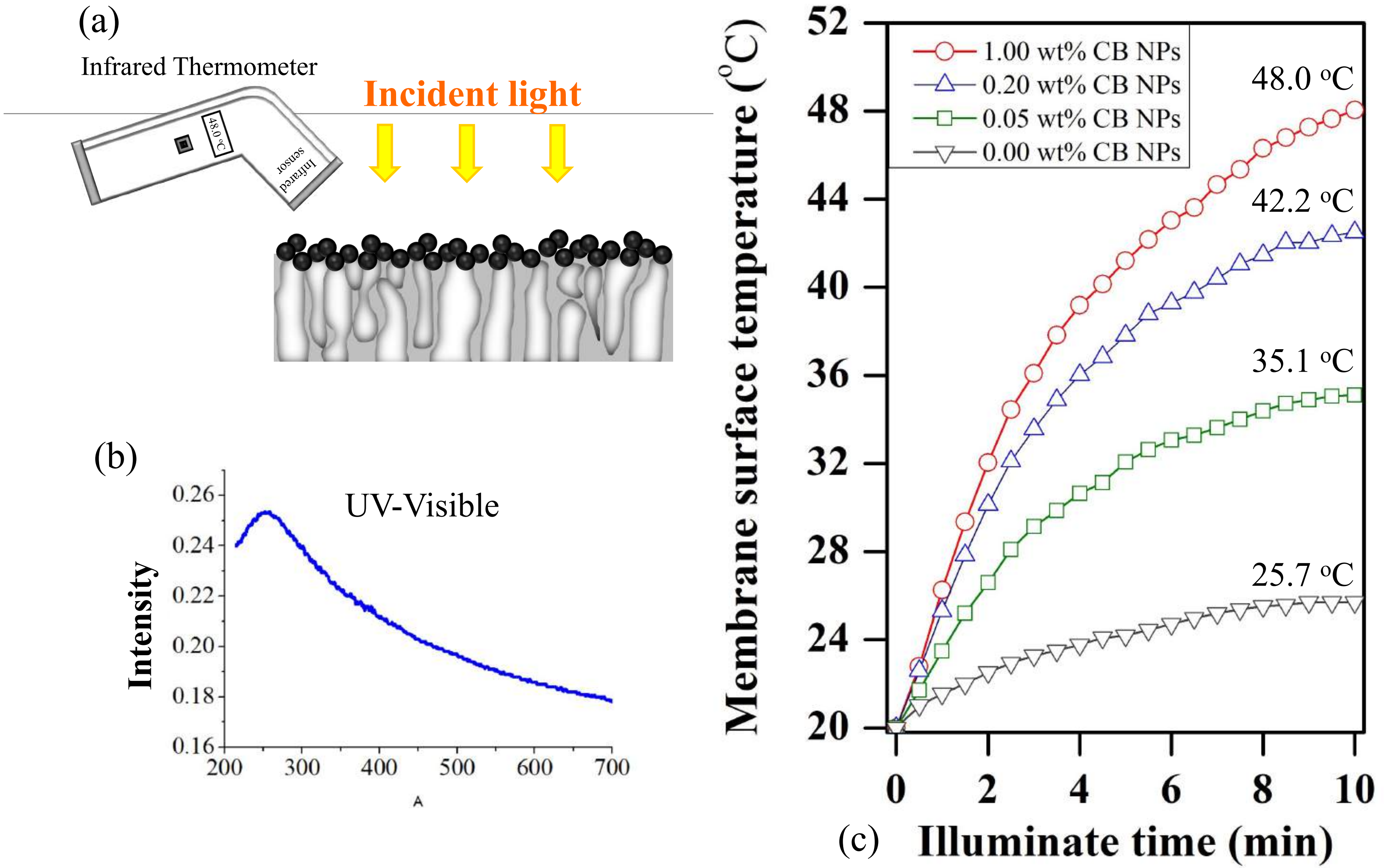


Figure (a) membrane surface temperature measured method, (b) CB NPs absorption spectrum by UV-Visible, and (c) membrane surface temperature increased by absorb sunlight (solar simulator intensity is 1000 kW/m^2).

Fig. 4
DSMD

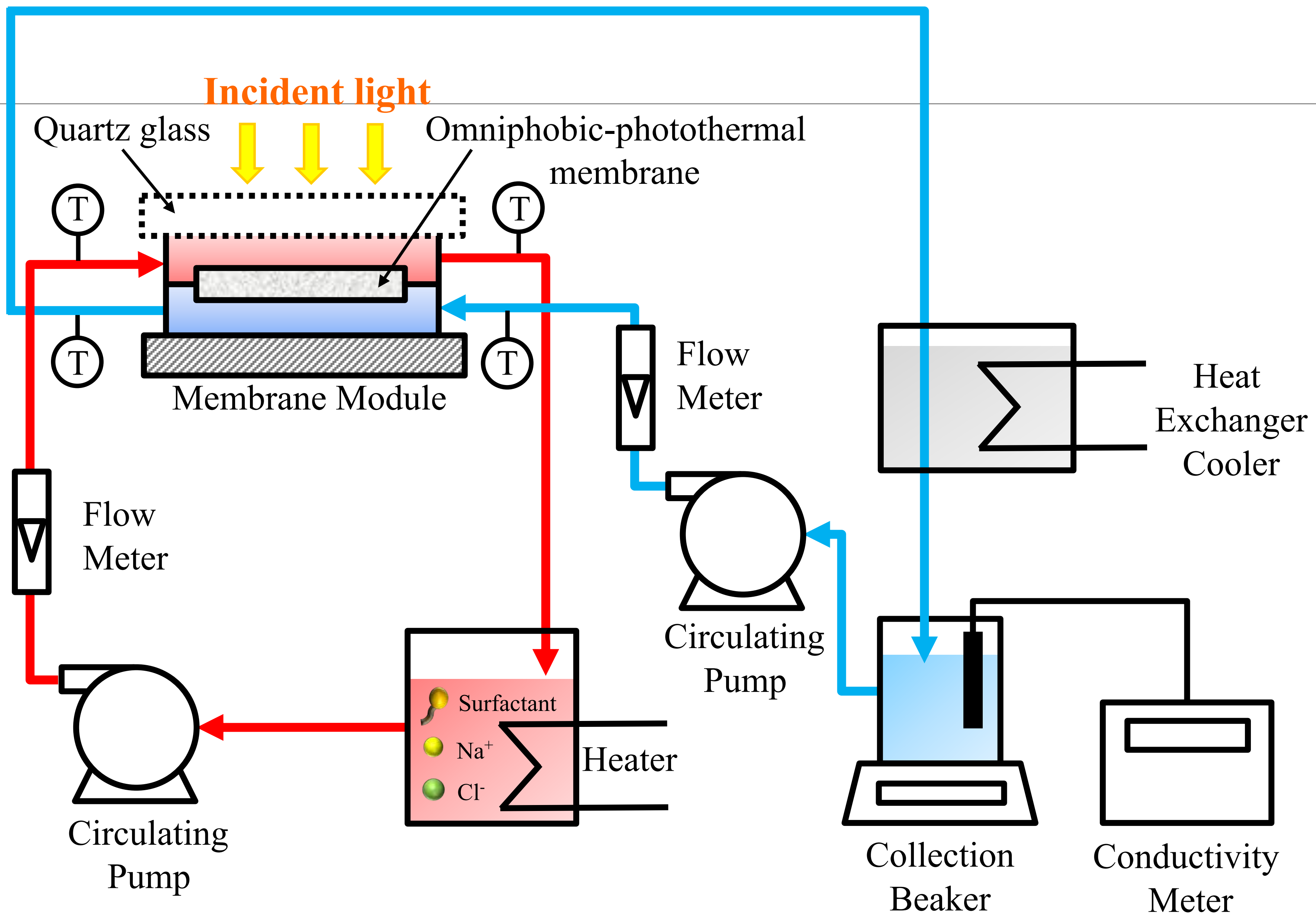


Figure Schematic diagram of the direct solar membrane distillation setup.

Direct Solar Membrane Distillation (DSMD)

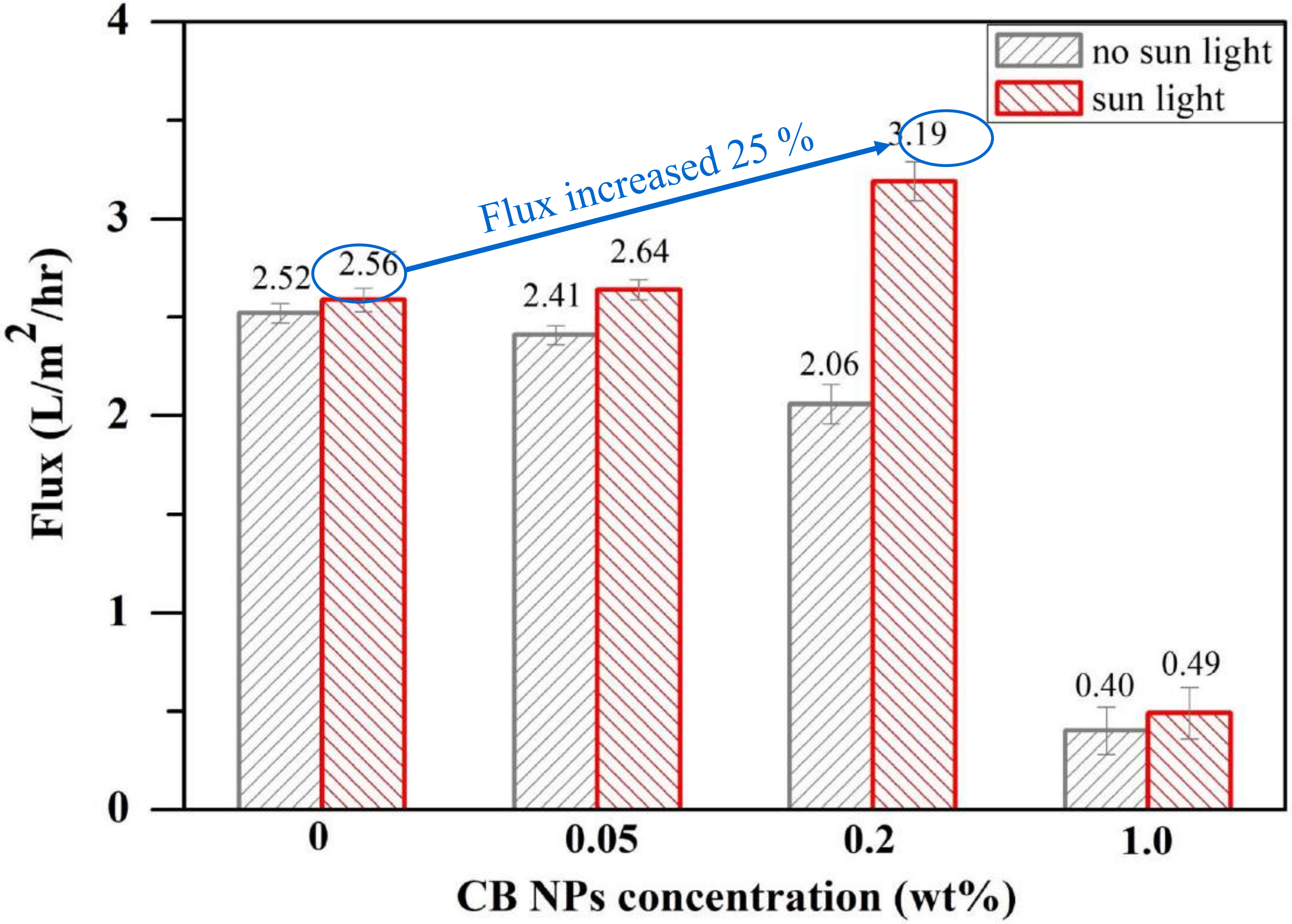


Figure Permeate flux for pristine hydrophobic membrane and dual-functional membranes with and without light irradiance. The solar simulator intensity is 1 sun unit (1000 W/m^2).

Direct Solar Membrane Distillation (DSMD)

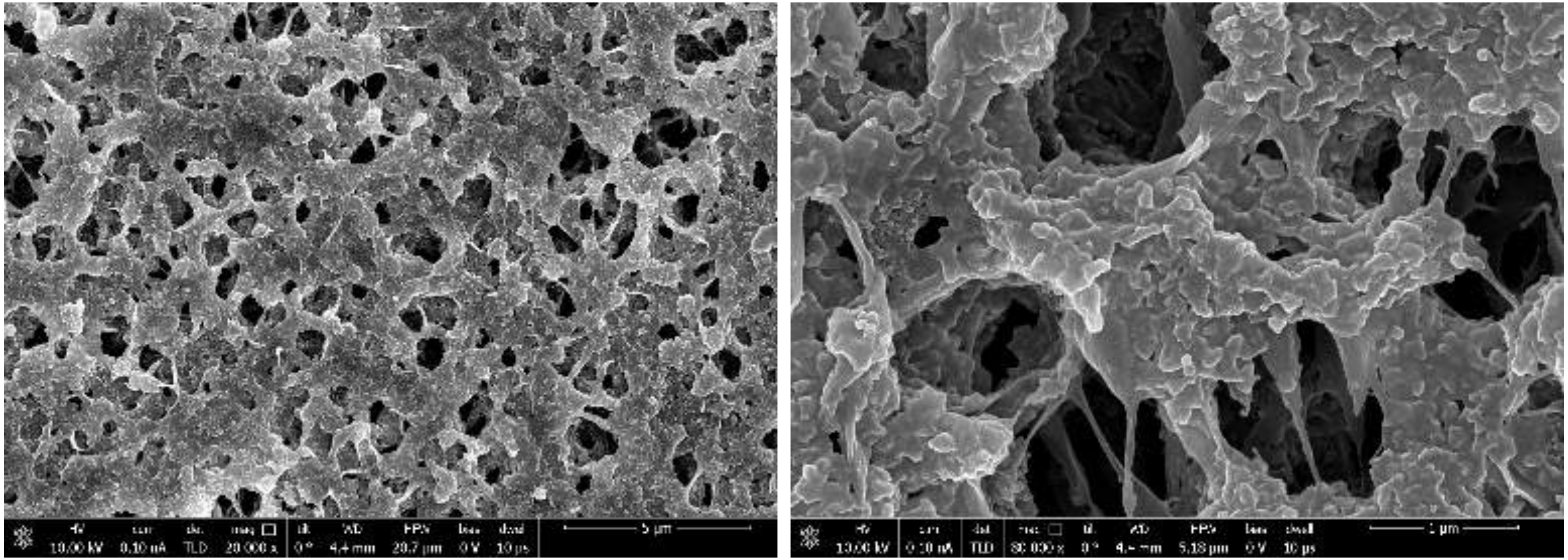


Figure SEM images of the outer surfaces of dual-functional membrane after DSMD test.

Capillary coating method
Polydopamine well connect substrate and carbon black nanoparticle

Direct Solar Membrane Distillation (DSMD)

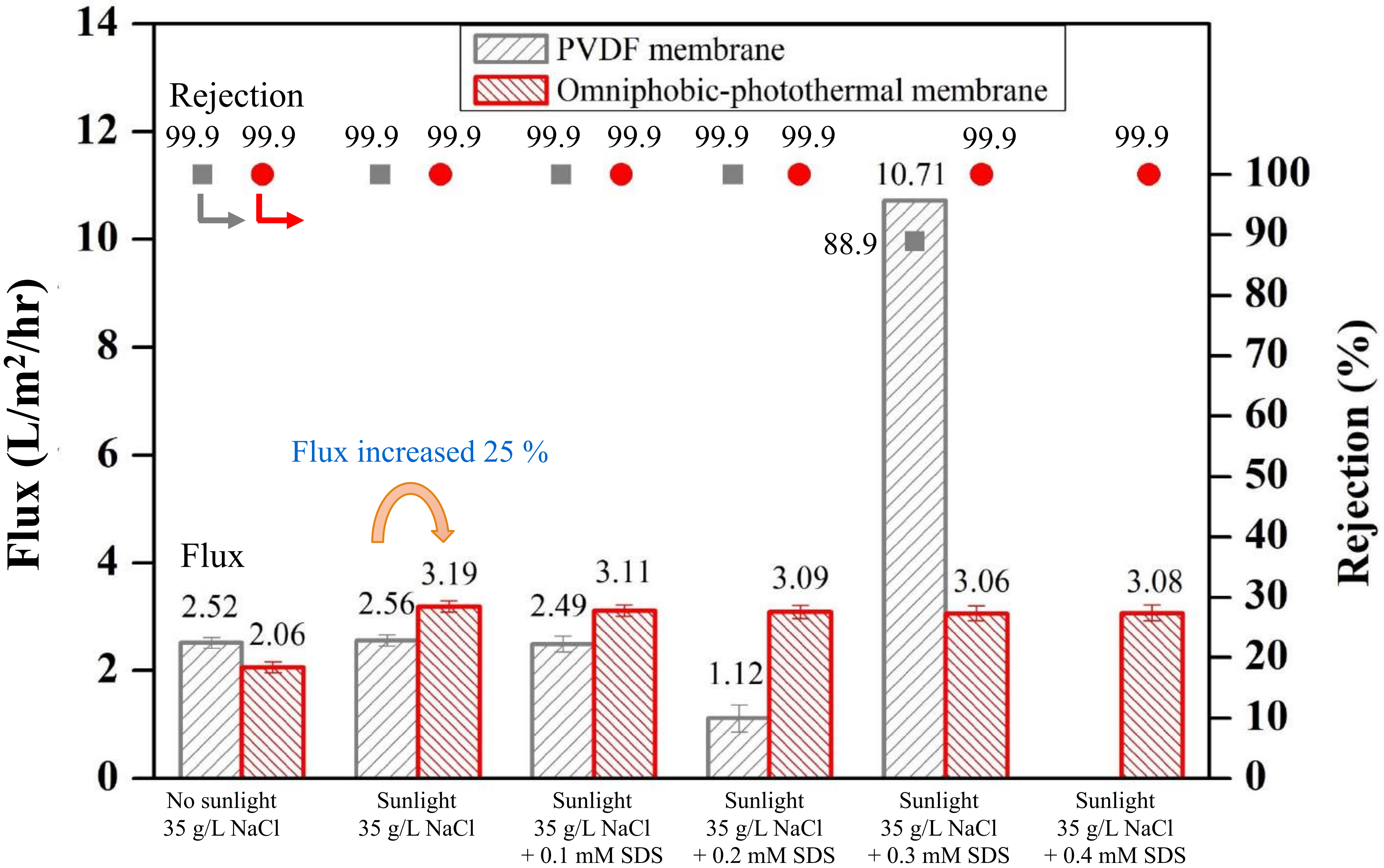


Figure Direct solar membrane distillation test with SDS surfactant for pristine membrane and dual-functional membrane with 0.2 wt% carbon black nanoparticles.

Schematic illustration of the liquid-air interfaces

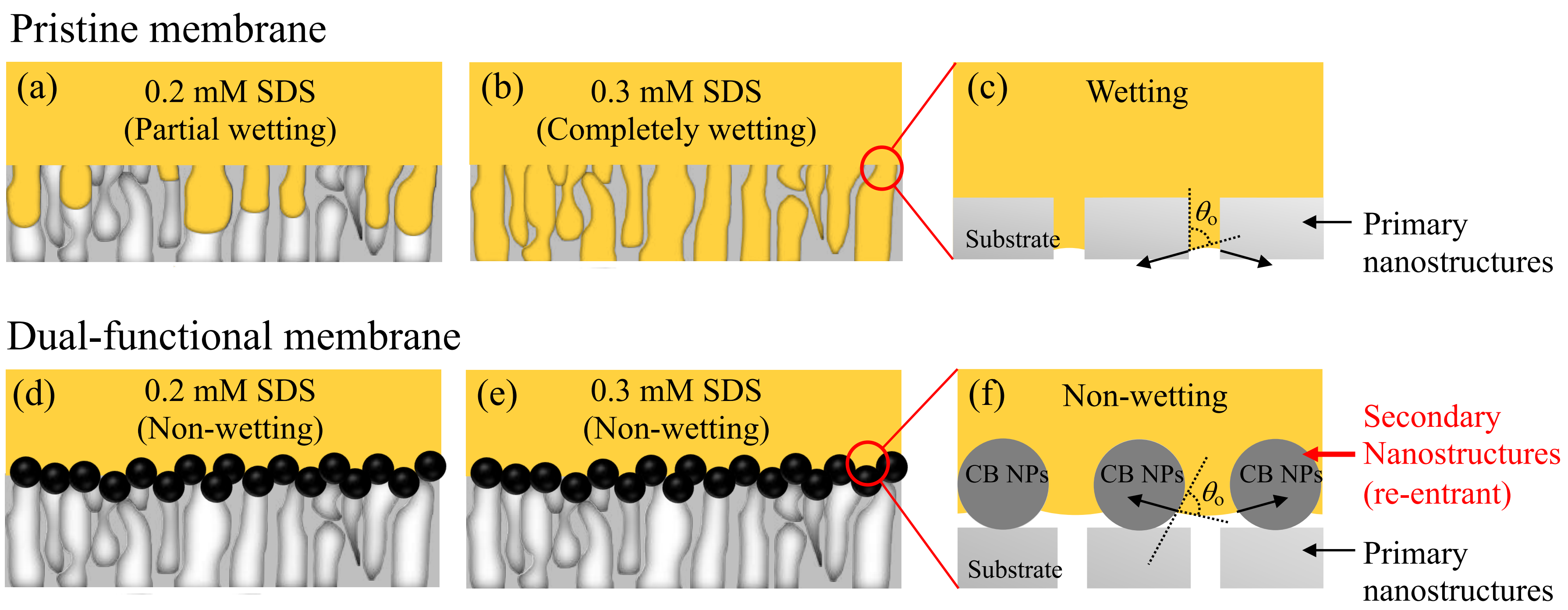
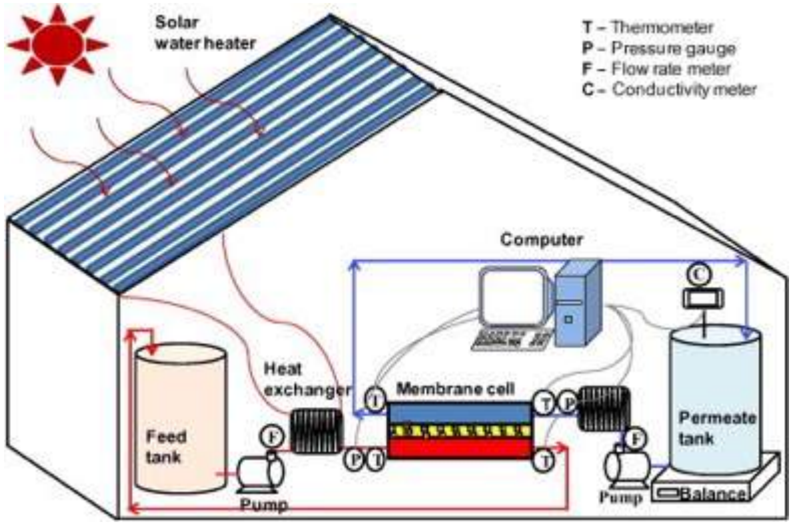
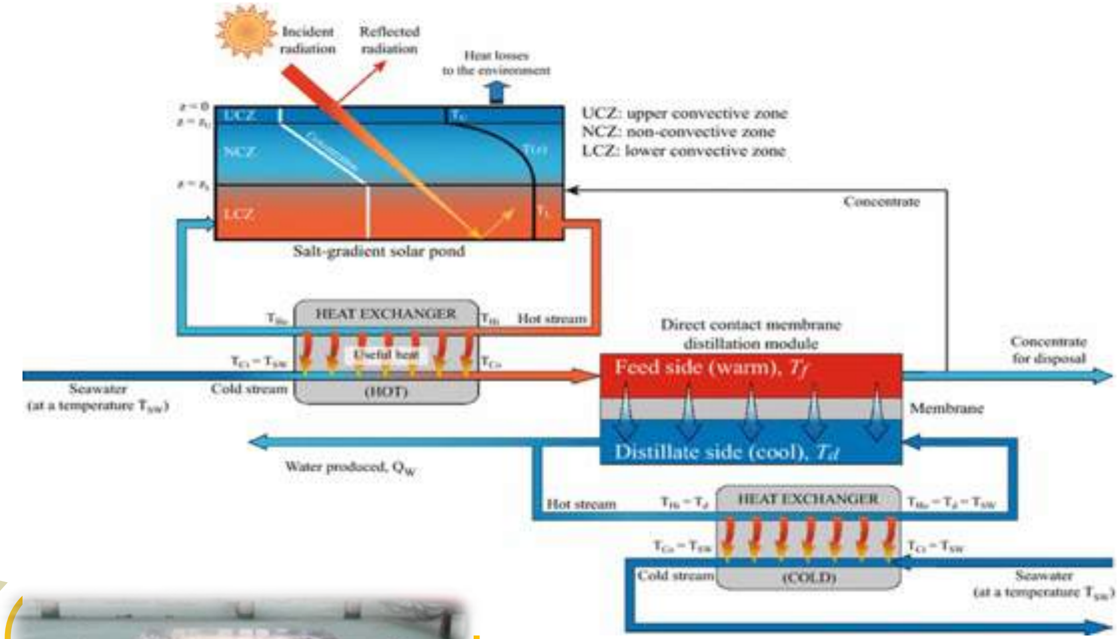
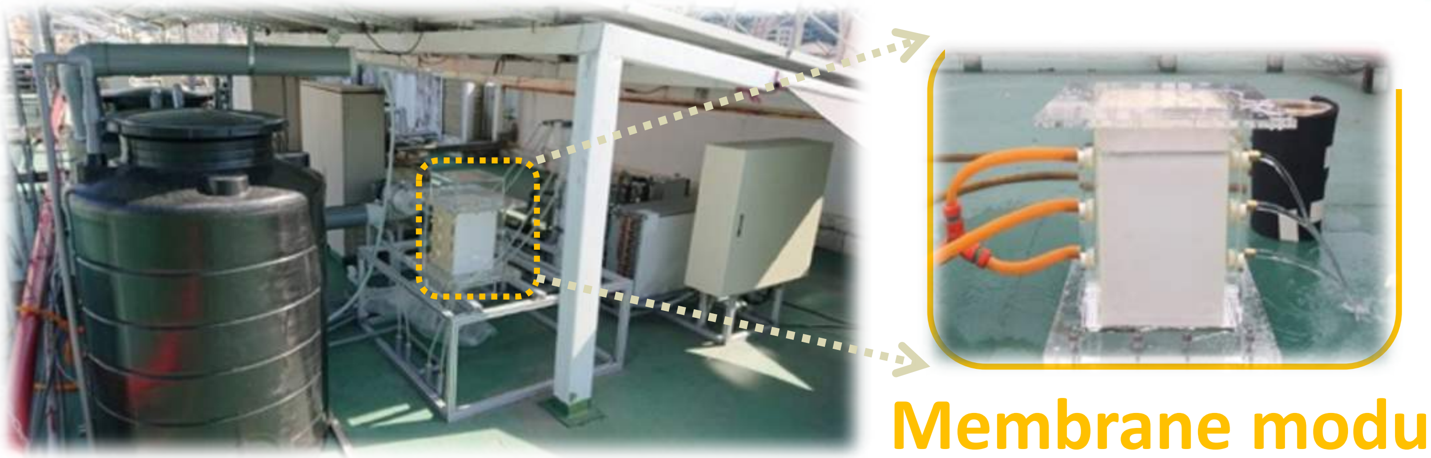


Figure Schematic illustration of the liquid-air interfaces for a low surface tension liquid. The intrinsic contact angles for the low surface tension liquid (θ_o) on the fluorinated surfaces.

Membrane distillation (MD) utilize solar energy



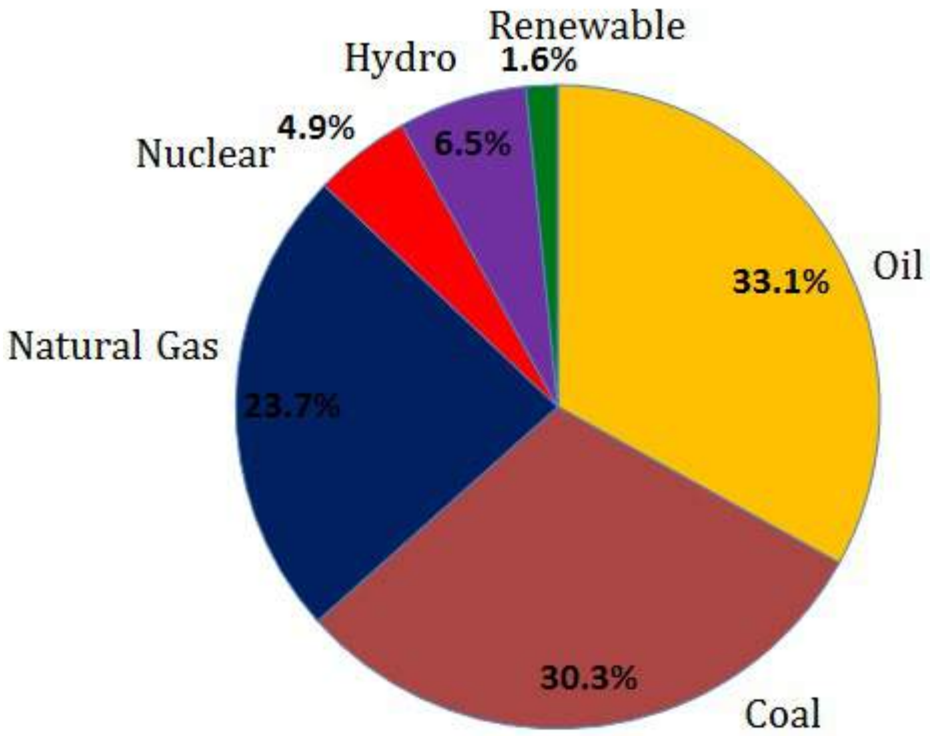




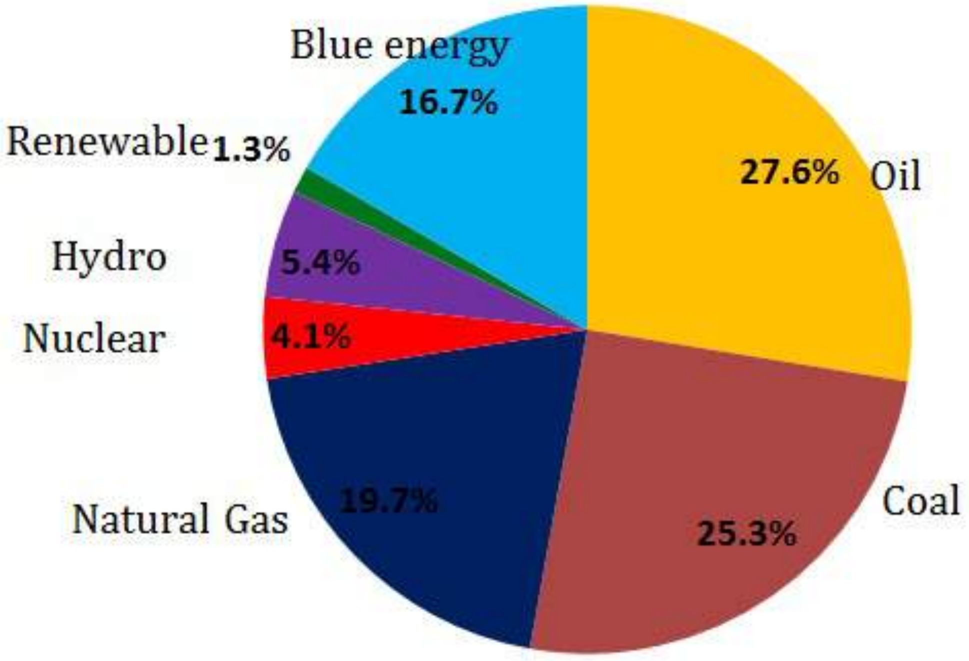
Membrane module

Blue energy and energy resources distribution

About 2 terawatt of blue energy is available globally from the river water falling into the sea.
Waste water discharged into the sea can generate additional 18GW of energy.



BP: Statistical review 2011

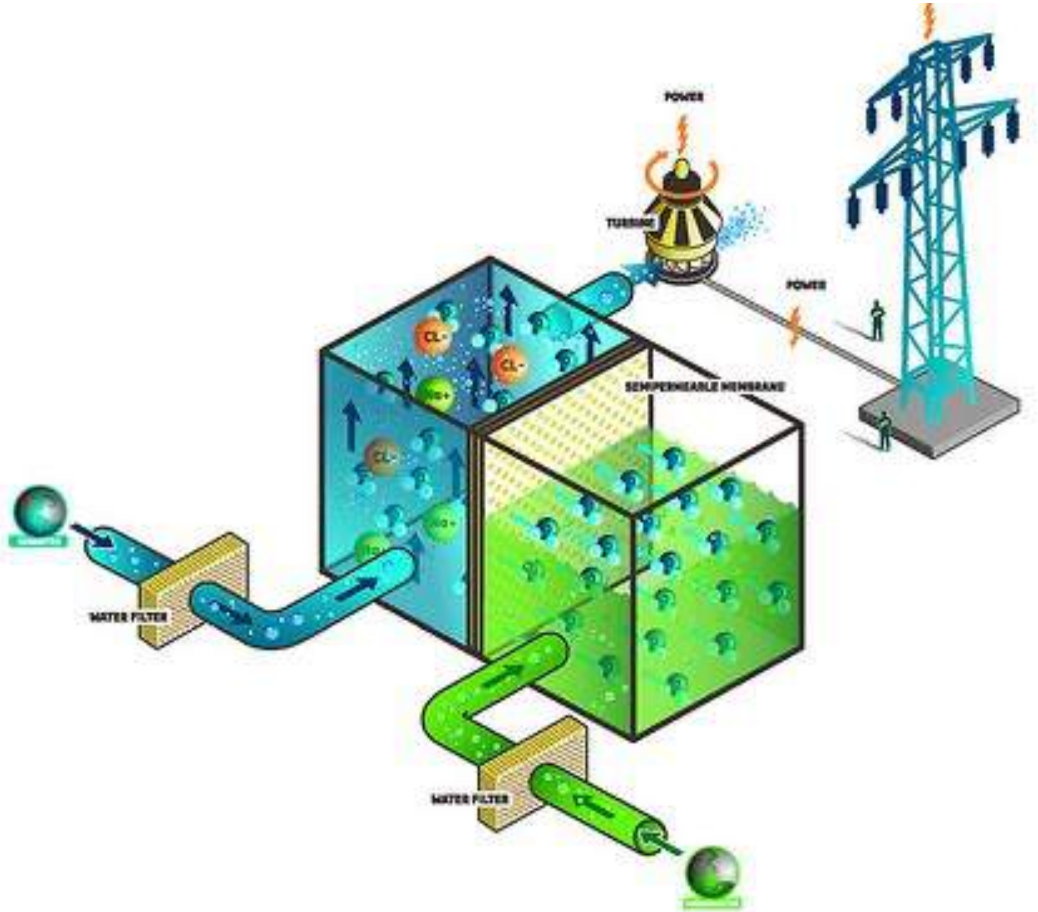


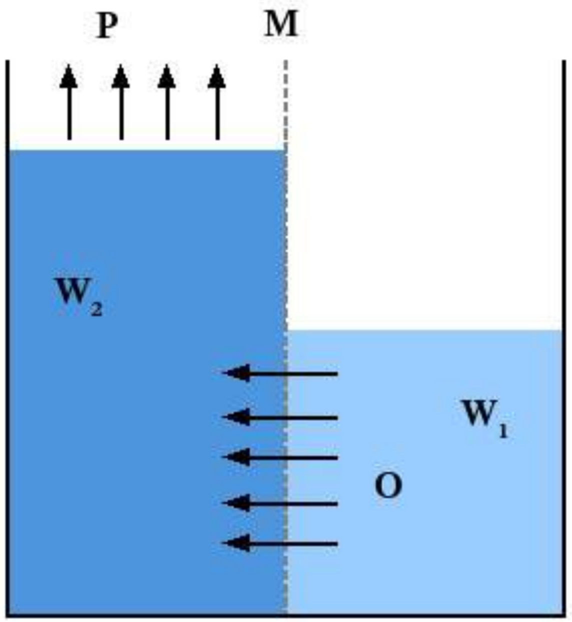
Recalculated

According to some optimistic estimations, 80% of the worlds power consumption can be generated from the salinity gradient. It can reduce 40% emission of green house gases.

J.W. Post, PhD thesis, Wageningen University, Wageningen The Netherlands (2009)

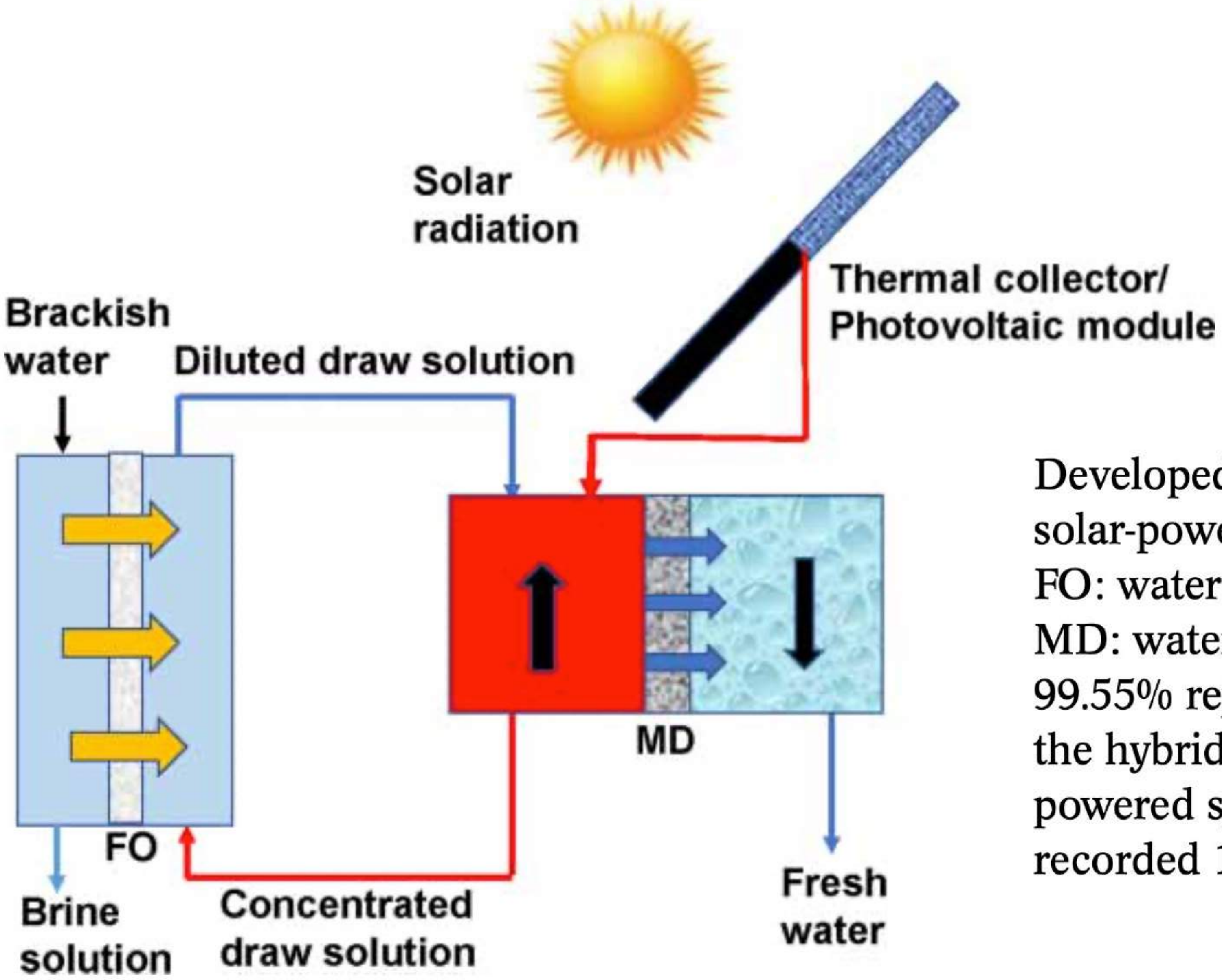
Osmotic power





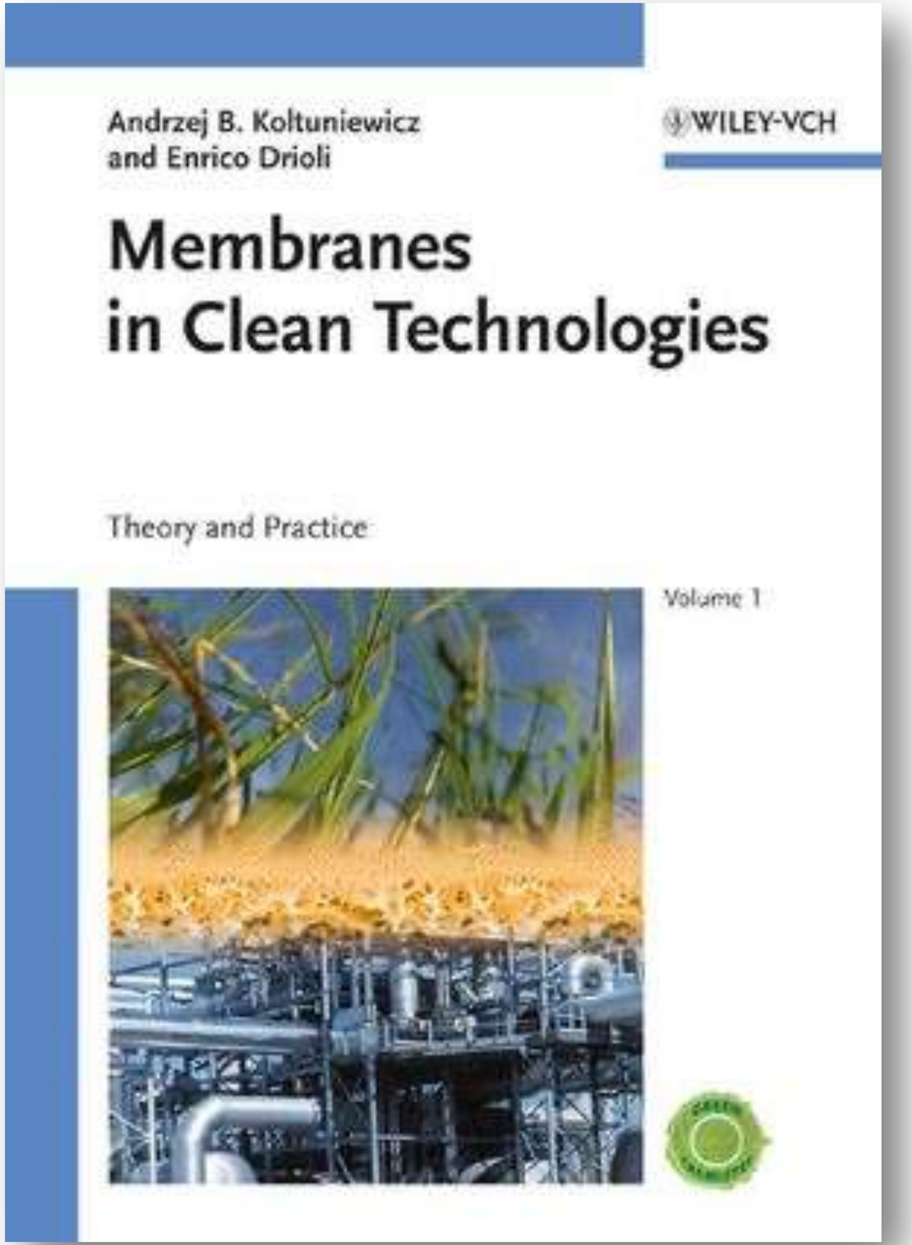
Statkraft is the world's leader in the development of osmotic power. Osmotic power is clean, renewable energy, with a global potential of 1600 to 1700 TWh – **equal to China's total electricity consumption in 2002.**

Statkraft



Developed an integrated forward osmosis-solar-powered membrane distillation system. FO: water recovery of 53.5%. MD: water flux of about 5.7 L/m^2 h and 99.55% rejection rate. Energy consumption of the hybrid system reduced by 67%. MD-solar-powered system energy consumption recorded 1.1 kWh

Suwaileh *et al.* (2019)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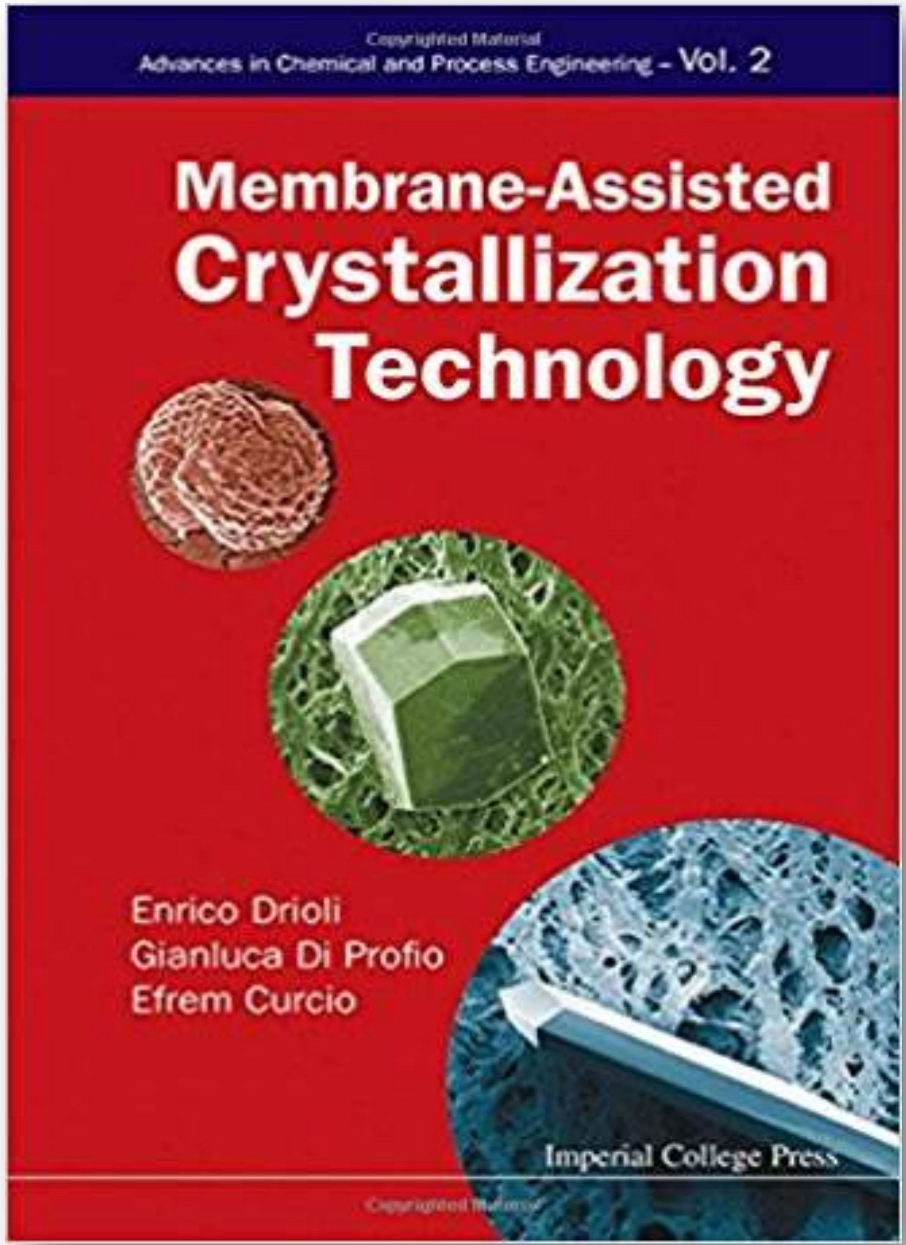
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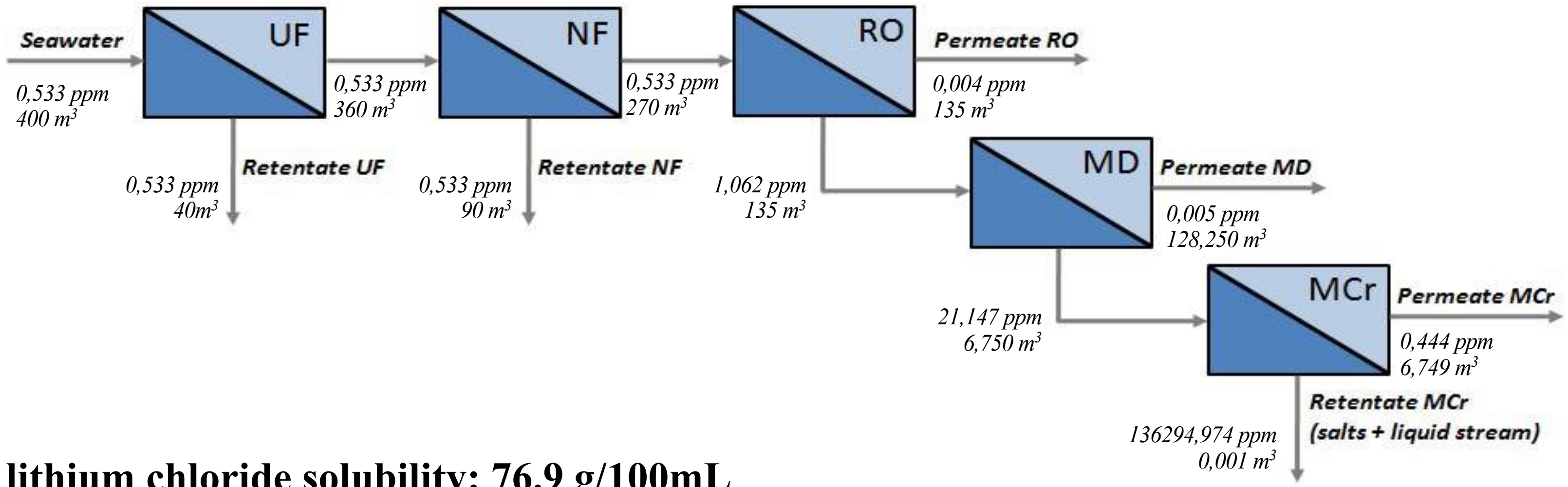
Lithium crystallization

It is necessary to start from 400 m^3 of seawater and to concentrate up to 1L of satured solution to obtain the crystallization of lithium chloride.



lithium chloride solubility: 76.9 g/100mL

	Feed	PT (perm.)	NF (perm.)	RO (ret.)	MD (ret.)	MCr (ret.)
Recovery (%)	-	90	75	50	95	99.98
Rejection (%)	-	0	0	99.25	99.54	97.90
Volume (m^3)	400	360	270	135	6.75	0.001
Concentration (ppm)	0.533	0.533	0.533	1.062	21.147	136295
Concentration factor (-)	-	0	0	2	20	6445

Artificial intelligence 人工智慧


April 2013
Chemical Engineering Progress
CEP
An AIChE Publication
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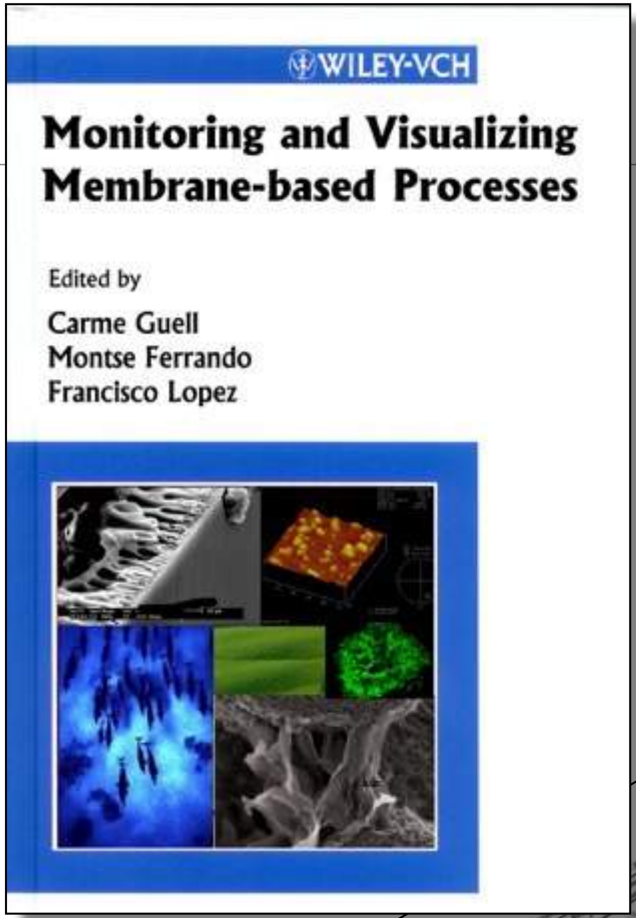
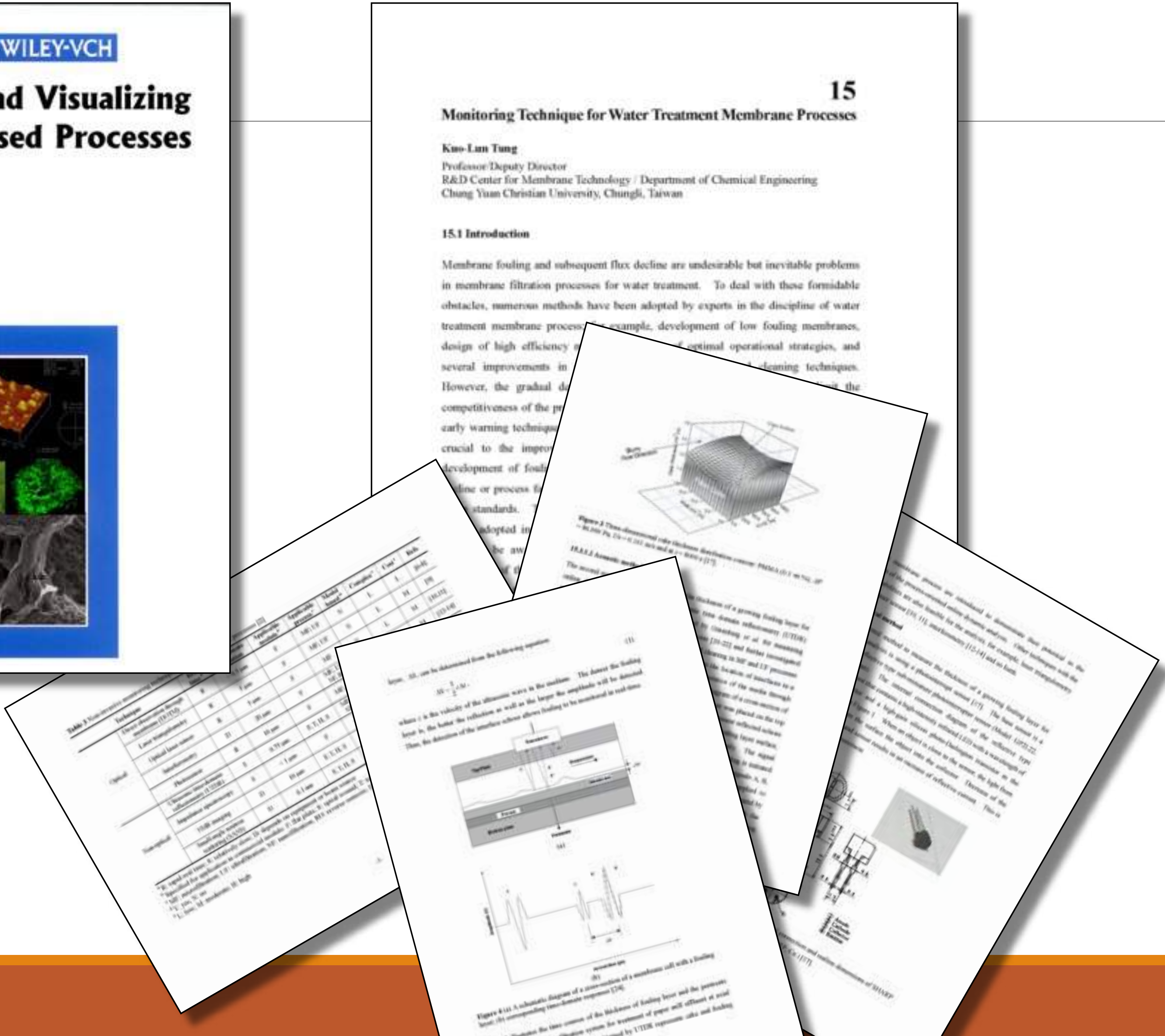
45 High-Capacity Distillation Trays
50 HSE in Engineering Design
56 Global Outlook: Singapore
63 Institute News: 2013 Election Slate


CEP
BIG DATA




15

Monitoring Technique for Water Treatment Membrane Processes

Kuo-Lun Tung
Professor/Deputy Director
R&D Center for Membrane Technology / Department of Chemical Engineering
Chung Yuan Christian University, Chungli, Taiwan

15.1 Introduction

Membrane fouling and subsequent flux decline are undesirable but inevitable problems in membrane filtration processes for water treatment. To deal with these formidable obstacles, numerous methods have been adopted by experts in the discipline of water treatment membrane process ... example, development of low fouling membranes, design of high efficiency ... of optimal operational strategies, and several improvements in ... cleaning techniques. However, the gradual d... competitiveness of the pr... early warning techniqu... crucial to the impro... development of foul... line or process f... standards. ... adopted in...

15

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15.1 Introduction

Membrane fouling and subsequent flux decline are undesirable but inevitable problems in membrane filtration processes for water treatment. To deal with these formidable obstacles, numerous methods have been adopted by experts in the discipline of water treatment membrane process; for example, development of low fouling membranes, design of high efficiency modules, selection of optimal operational strategies, and several improvements in peripheral control, monitoring and cleaning techniques. However, the gradual development and improvement of these methods limit the competitiveness of the process and its wide acceptance during past three decades. An early warning technique for fouling problem in water treatment membrane process is

Monitoring and Visualizing Membrane-Based Processes

RELATED SUBJECTS

- General Mechanical Engineering
- Plant Design in Chemical Engineering
- Chemical Engineering Process Development

RELATED TITLES

General Chemical Engineering

Membranes in Clean Technologies: Theory and Practice, 2 Volume Set
by Andrzej Benedykt Koltuniewicz, Enrico Drioli

Corrosion Handbook: Corrosive Agents and Their Interaction with Materials, Volume 8, Part B: Chlorinated Hydrocarbons - Chloroethanes, Alkanols, Completely Revised and Enlarged, 2nd Edition
by Gerhard Kreysa (Editor), Michael Schütze (Editor)

Monitoring and Visualizing Membrane-Based Processes
Carme Güell (Editor), Montserrat Ferrando (Editor), Francisco López (Editor)

ISBN: 978-3-527-32006-6
Hardcover
346 pages
November 2008

Wiley List Price: **US $190.00**

This price is valid for Taiwan. Change location to view local pricing and availability.

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Description | Table of Contents | Author Information

This much-needed critical review of the main monitoring techniques conveys profound knowledge of their fundamentals, possibilities and limits, strengths and weaknesses when applied to membrane processes, clearly demonstrating which technique is most suitable for a given process. A practical approach is adopted throughout, providing case studies for the monitoring of selected membrane-based processes.
After an introductory section, the book goes on to look at optical and electronic microscopic techniques, followed by electrical, laser and acoustic techniques, and finishes off with process-oriented monitoring techniques.
For both researchers and professionals working in the industry.


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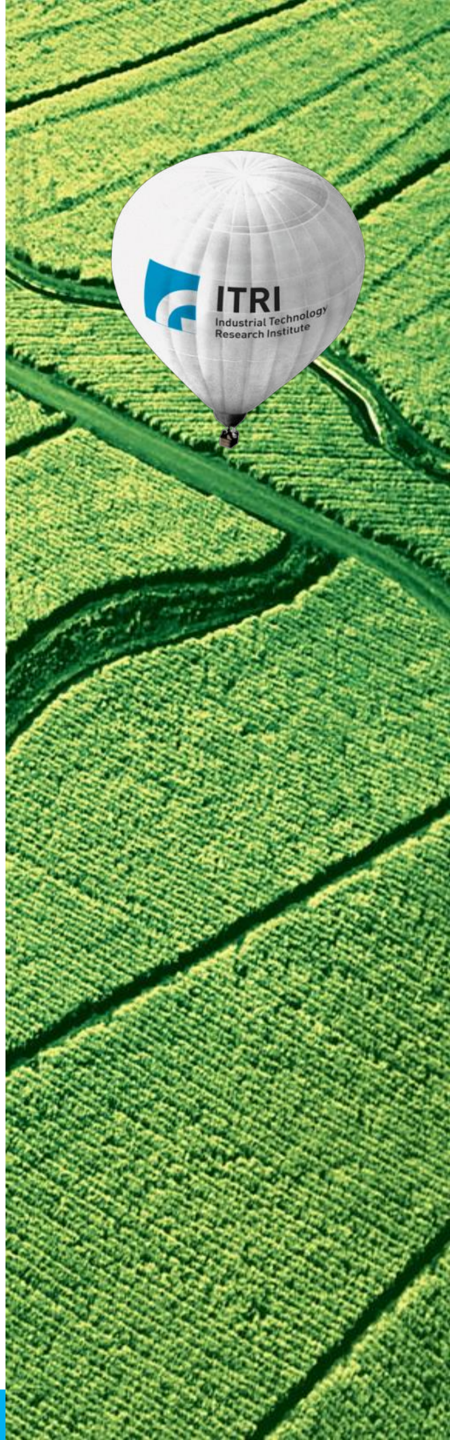


Desalination Technology with Low Energy Consumption: Developments and Applications

Dr. Wang-Kuan Chang
Deputy Division Director
Div. of Water Technology Research
Material and Chemical Research Laboratories

2021.10.15

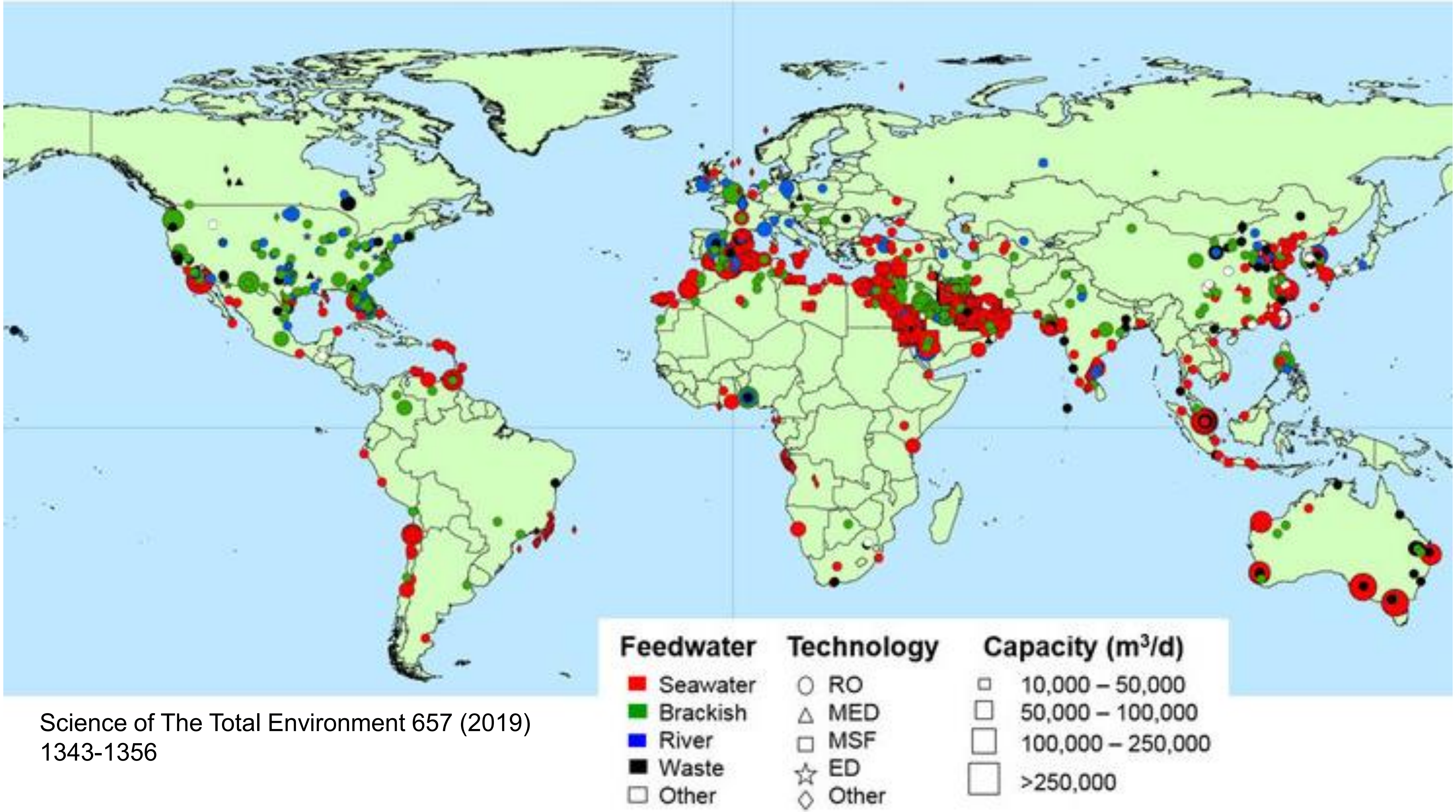
wkchang@itri.org.tw

Sustainable Development Goals

6 CLEAN WATER AND SANITATION

- Unconventional water resources, such as desalinated water, are key to support SDG 6 achievement.
- Currently, desalinated water production is 95.37 million m^3/day.
- With glowing water scarcity, desalination of various water source is one of the viable options to fulfill the water supply-demand gap.

Global Distribution of Large Desalination Plants



Science of The Total Environment 657 (2019) 1343-1356

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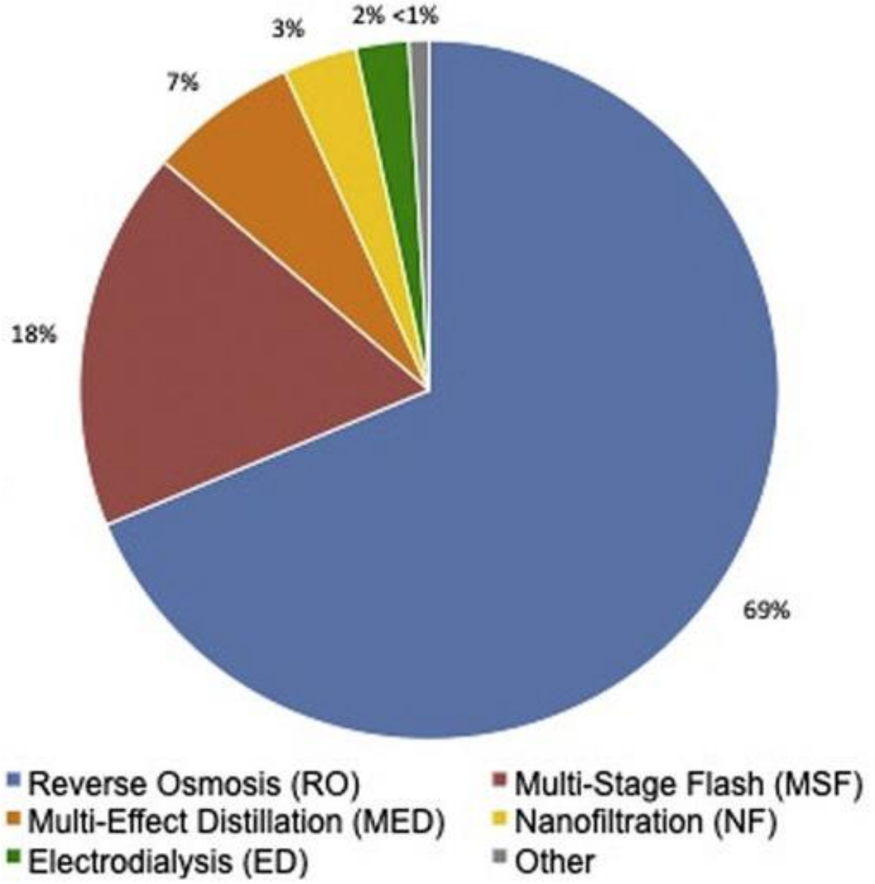
Operational Desalination Facilities by Technology and Feed Water Type

- Membrane technology (RO) and thermal technology (i.e., MSF & MED) are the two main desalination methods.
- Energy consumption and brine production are key barriers to desalination expansion.



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Recovery ratio of different feed water-technology combinations producing desalinated water

Feedwater type	Technology							
	RO	MSF	MED	NF	ED	EDI	EDR	Other
Seawater (SW)	0.42	0.22	0.25	0.69	0.86	0.90		0.40
Brackish (BW)	0.65	0.33	0.34	0.83	0.90	0.97	0.90	0.60
River (RW)	0.81		0.35	0.86	0.90	0.97	0.96	0.60
Pure (PW)[a]	0.86	0.35		0.89	0.90	0.97	0.96	0.60
Brine (BR)	0.19	0.09	0.12		0.85			0.40
Wastewater (WW)[b]	0.65	0.33	0.34	0.83	0.90	0.97		0.60

Based on data from: Ahmed et al. (2001), Allison (1993), Almulla et al. (2003

Average recovery ratio:

Electrodialysis (ED, EDR) > Membrane (RO, NF) > Thermal (MSF, MED)

Can be optimized by systematic design

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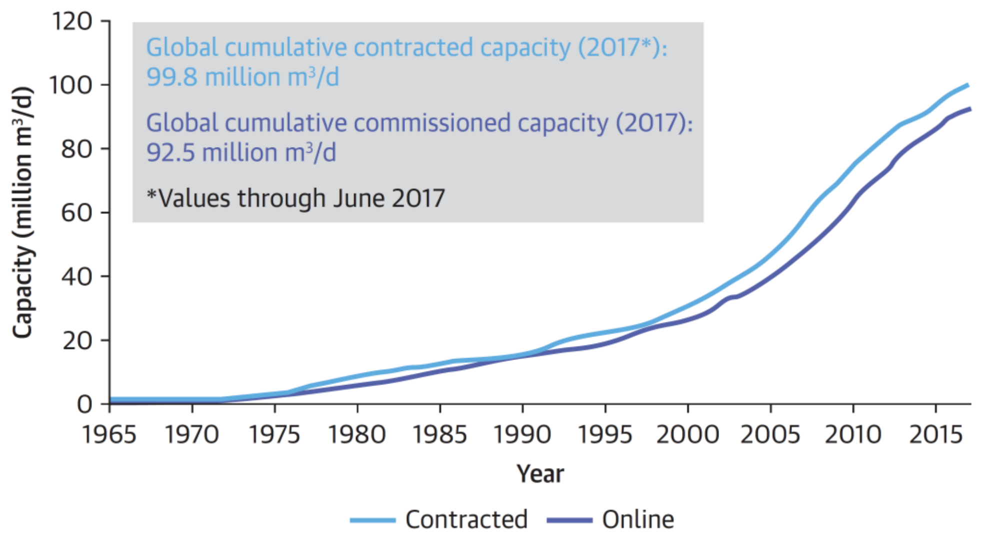
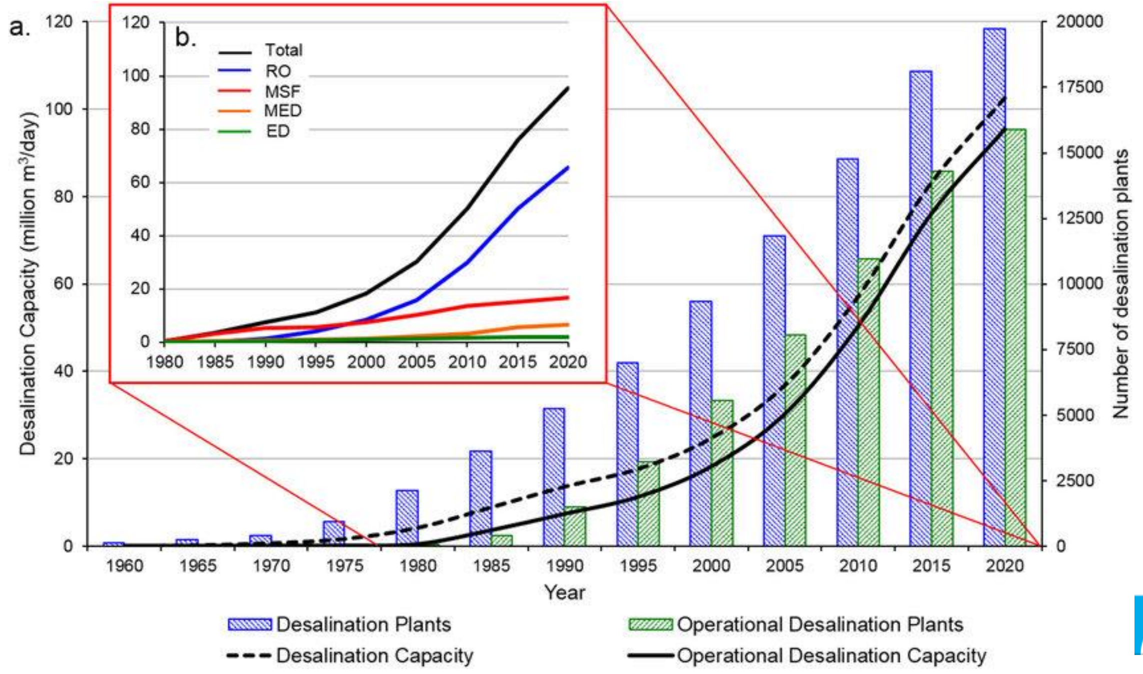
Current Status of Desalination Technology

Category	Membrane					Thermal				Adsorption	
Technology	Reverse Osmosis (RO)	Forward Osmosis (FO)	Membrane Distillation (MD)	Electro-Dialysis (ED)	Nano-filtration (NF)	Multi-Stage Flash (MSF)	Multi-effect Distillation (MED)	Vapor Com-pression (VC)	Adsorption/ Desorption Desalination (AD)	Capacitive Deionization (CDI)	Ion Exchange (IE)
technological readiness level	9	5	6	8-9	8-9	9	9	9	5	4	9
Capital cost	Medium	Medium	High	Medium	Medium	Medium	Medium	Medium	Medium-high	High	Medium
Operating cost	High	Medium	Medium	Medium	Medium	High	High	Medium	Low	Medium	High
Full scale applications	+++	+	+	++	++	+++	+++	++	-	-	+





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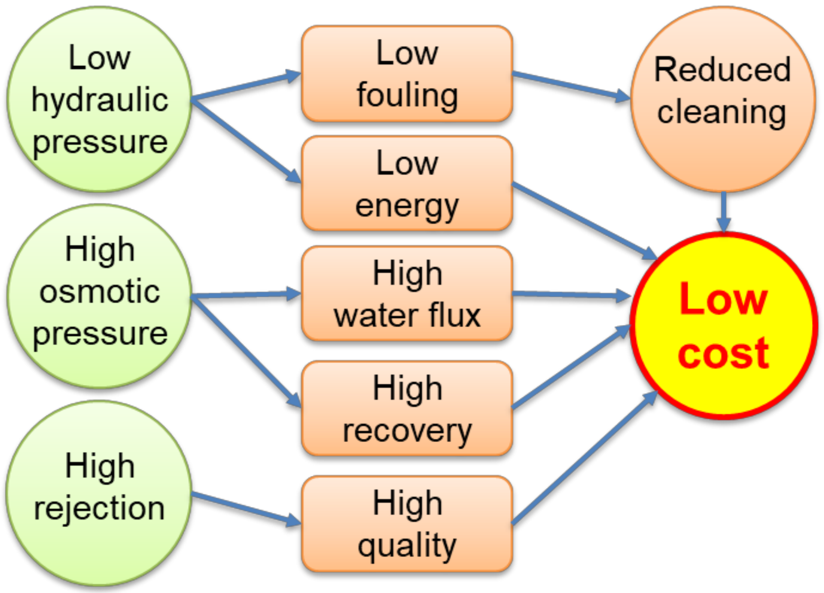
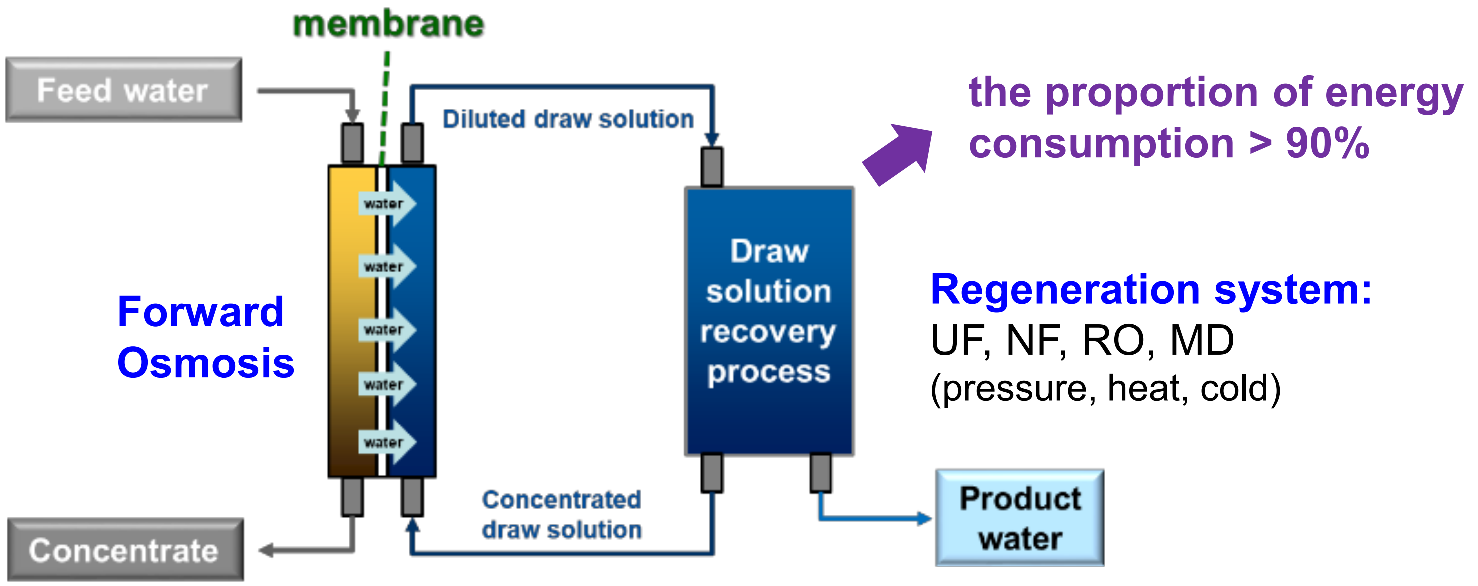
Forward Osmosis (FO)

- **Key barriers/needs for FO:**
  - **FO membrane** with high permeate flux, low concentration polarization, low reverse solute flux and low fouling potential
  - **Recyclable draw solution** with low energy consumption for recovery (**the proportion of consumption in FO process for draw solution separation: > 90%**)

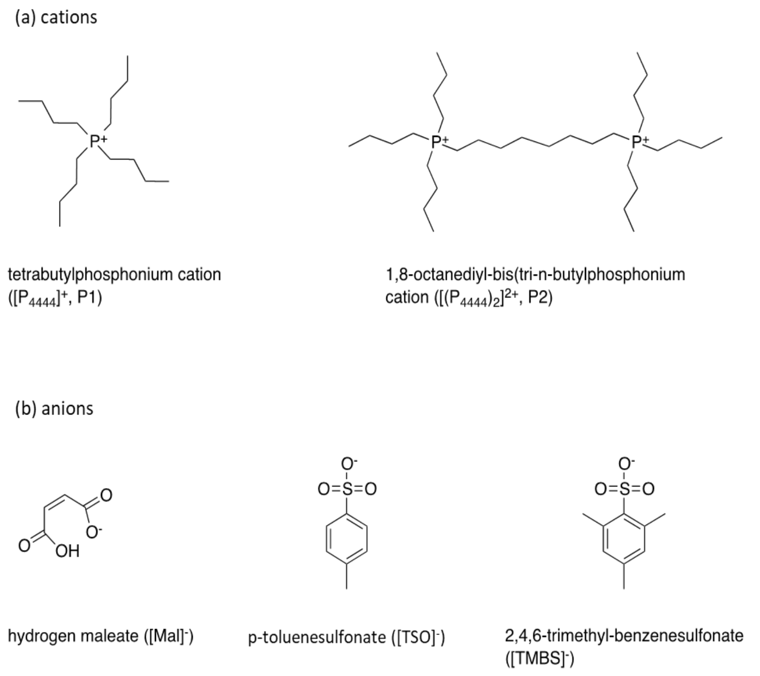
The potential benefits of FO





Thermal Responsive Draw Solute

- The LCST type mono-cationic and di-cationic phosphonium-based IL draw solutes with several anions, including p-toluenesulfonate (TSO), hydrogen maleate (Mal), and trimethylbenzenesulfonate (TMBS) were developed in ITRI.



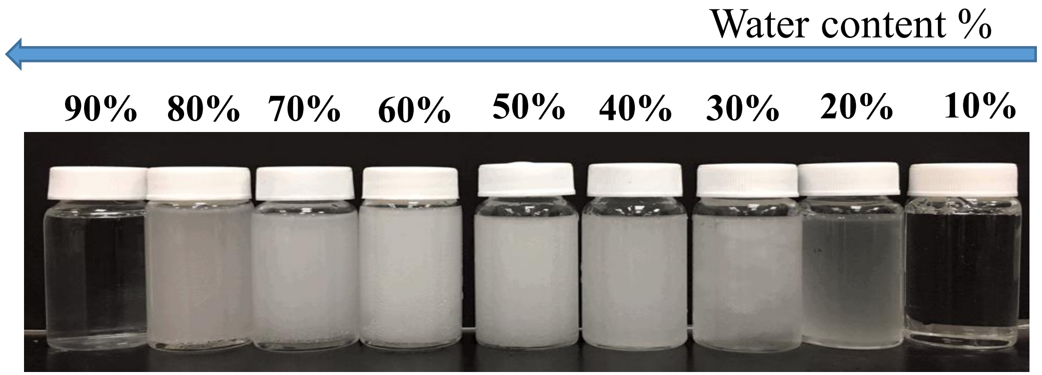
P.-I. Liu et al. / Desalination and Water Treatment 200 (2020) 1–7

Thermal responsive → **Draw solute**

LCST: separate into two phase with temperature raised.

Draw solute → Phase separable → reducing → Consumption in separation process

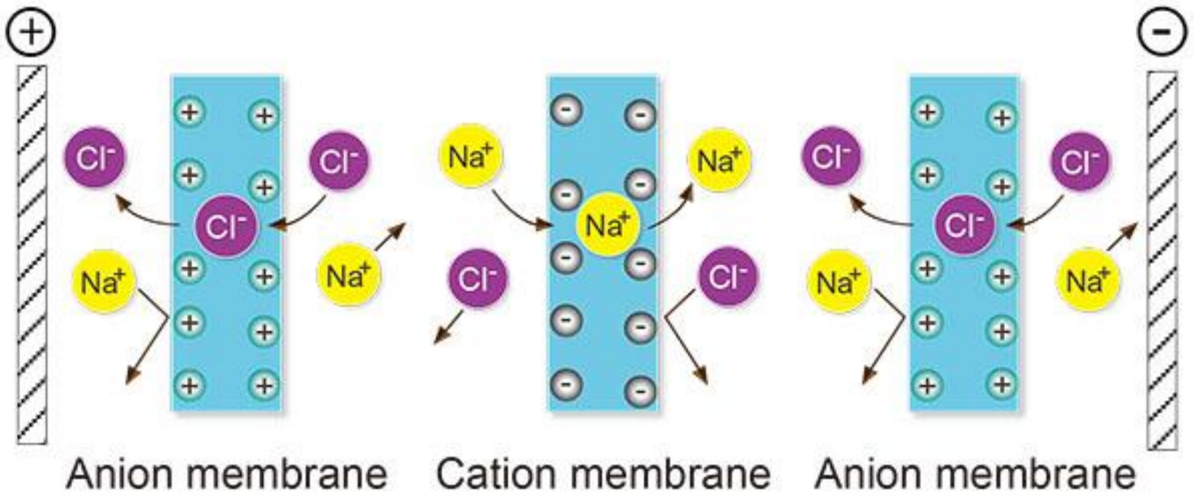
Draw solute → High osmotic pressure → Increasing →
- Water flux
- Concentration ratio



ED/EDR technology

Electrodialysis (ED)

removes ions from water and wastewater using a direct electric charge to drive the ions in anion or cation exchange membranes. The cations migrate to cathodes and anion migrate to anodes.



Electro-Dialysis Reversal (EDR)

reverses the polarity of electrodes periodically to improve anti-scaling and anti-fouling property, and also extends the life of ion exchange membranes.

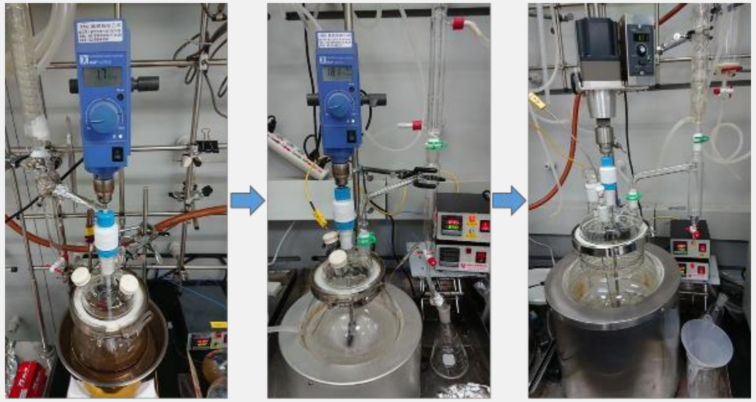
Ion-exchange Membrane from ITRI

Low Membrane Resistance

- Membrane resistance:
  CEM<10 Ω-cm^2 / AEM<5 Ω-cm^2
- Swelling ratio: $\leq$1%
- Burst strength: $\geq$5 kg/cm^2
- pH tolerance: 2~12
- Permselectivity: 90%
- Dimension: 40 cm (W) x 80 cm (L)

High Chemical Tolerance

- Membrane resistance:
  CEM<20 Ω-cm^2 / AEM<20 Ω-cm^2
- Swelling ratio: $\leq$1%
- Burst strength: $\geq$5 kg/cm^2
- pH tolerance: 1~13
- Permselectivity: 90%
- Dimension: 50 cm (W) x 100 cm (L)

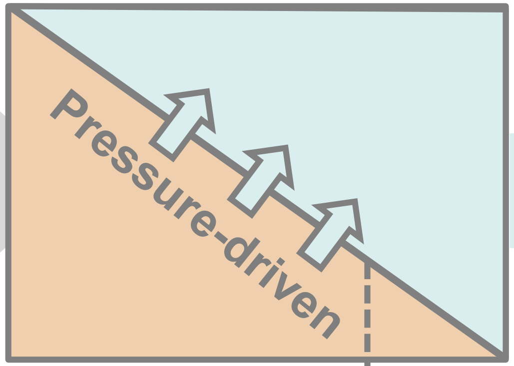


0.5 Kg/batch 3 Kg/batch 10 Kg/batch

Comparison of Desalination Technology (EDR v.s. RO)

Reverse Osmosis (RO)

- **High operational pressure** (P > 15 kg/cm²)
- **Limitation of influent WQ** (SDI < 15)



Water Recovery Rate **< 50%**
(affect by influent WQ)

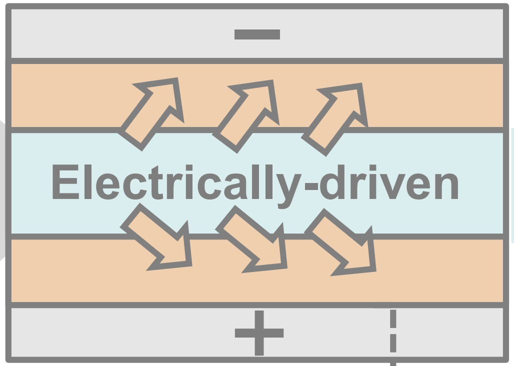
Energy consumption **> 2.5** kWh/m³

Maintenance method for Fouling prevention

Chemical cleaning
(acid/alkali, anti-scalants, etc.)

Electrodialysis reversal (EDR)

- **Electrical drive for ion separation**
- **Less influent requirement** (SDI > 15)
- **Simple process** (less pretreatment requirements)



Water Recovery Rate **> 70%**
(higher tolerance for complex influent WQ)

Energy consumption **< 1.5** kWh/m³

Maintenance method for Fouling prevention

Polarity reversal
(membrane self-cleaning with less chemicals usage)

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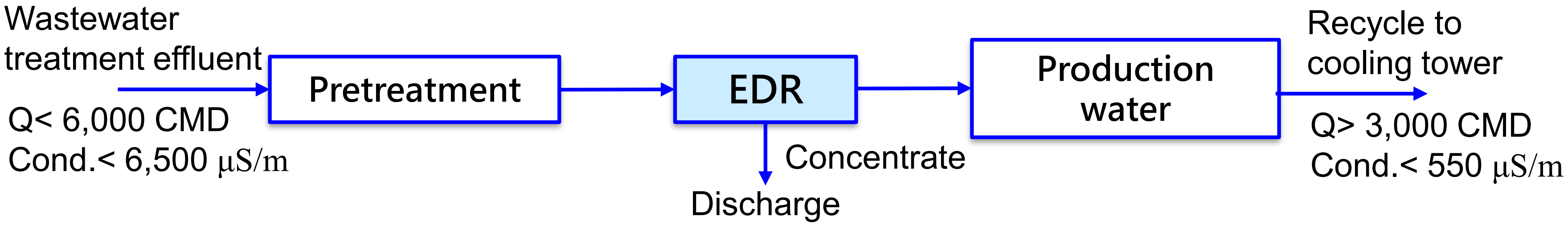
Industrial Wastewater Reclamation for Petrochemical Plant

- **Wastewater treatment effluent contains high concentration of Ca^{+2} and SO_4^{-2} with high scaling potential.**
- **EDR is used as the major desalination unit for wastewater reclamation and the treated water is recycled as cooling tower make up.**
- **The wastewater reclamation plant is completed at 2020 with a daily production of 3,000 m^3 of reclaim water.**



EDR wastewater reclamation plant

EDR system for wastewater reclamation

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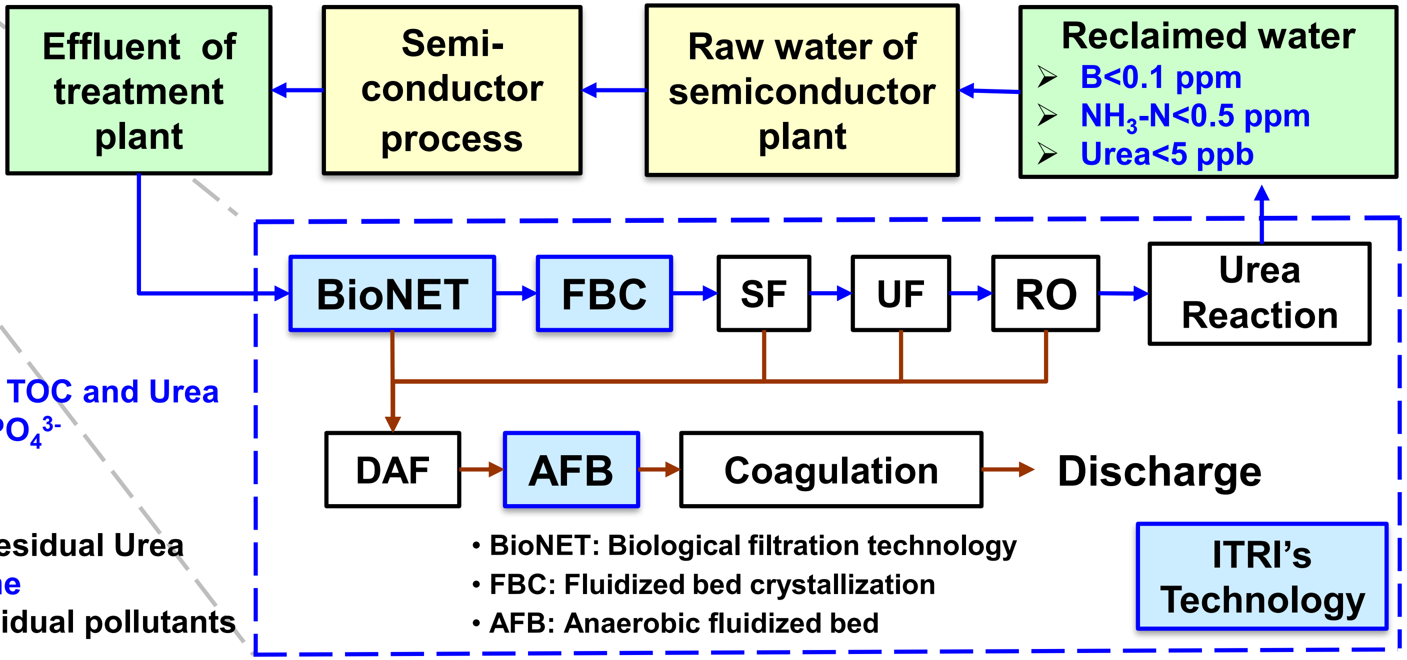
Industrial Wastewater Reclamation for Semiconductor Manufacturing

- Pretreatment and post-treatment are key factors for successful wastewater reclamation from industrial effluent.
- Integration of physical, biological and desalination technologies to achieve high quality requirement of reclaimed water applying to semiconductor manufacturing.
- The wastewater reclamation plant is expected to completed at the end of 2021 with a daily production of 20,000 m3 of reclaim water.



Treatment efficacy :

- BioNET：remove NH_3-N、TOC and Urea
- FBC：remove Ca、Mg、PO_4^{3-}
- UF/RO：desalination
- DAF：flotation of solids
- Urea Reaction：remove residual Urea
- AFB：remove NO_3^- in brine
- Coagulation：remove residual pollutants

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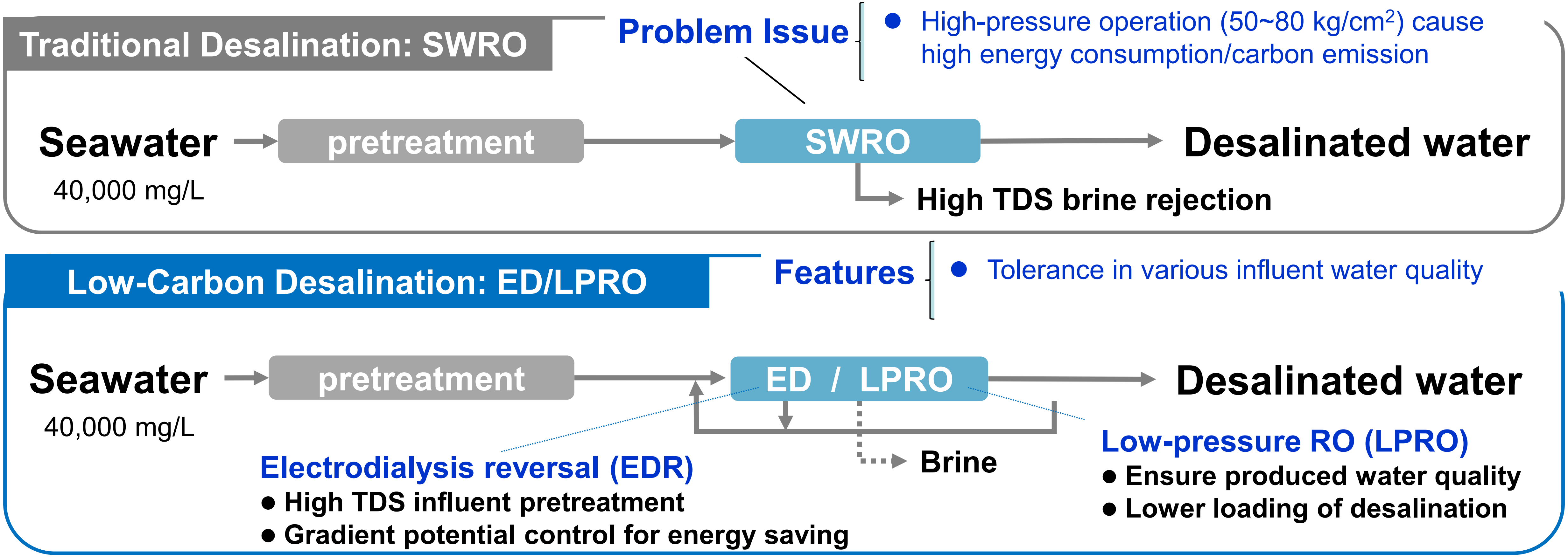
ED Hybrid System for Seawater Desalination



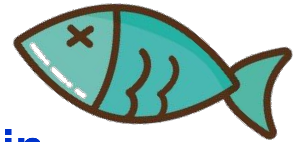
	SWRO	ED/LPRO	REMARKS
CapEX (NTD/CMD)	50,000 - 60,000	30,000 - 40,000	Expense of desalination unit
OpEX (NTD/m^3)	30 - 65	25 - 30	Including EC, chemicals, manpower, etc.
EC (kwh/m^3)	3.5 - 4.5	2.0 - 2.5	Based on TDS of produced water < 400 mg/L

Brine Management Is Critical for Desalination

Brine produced from seawater desalination and wastewater reclamation have huge environmental impact on receiving water body.

Desalination Plant → **Brine** → Adverse effect to the environment

Desalination Plant → **Desalted Water**



-Innovation and developments in brine management and disposal options are required.

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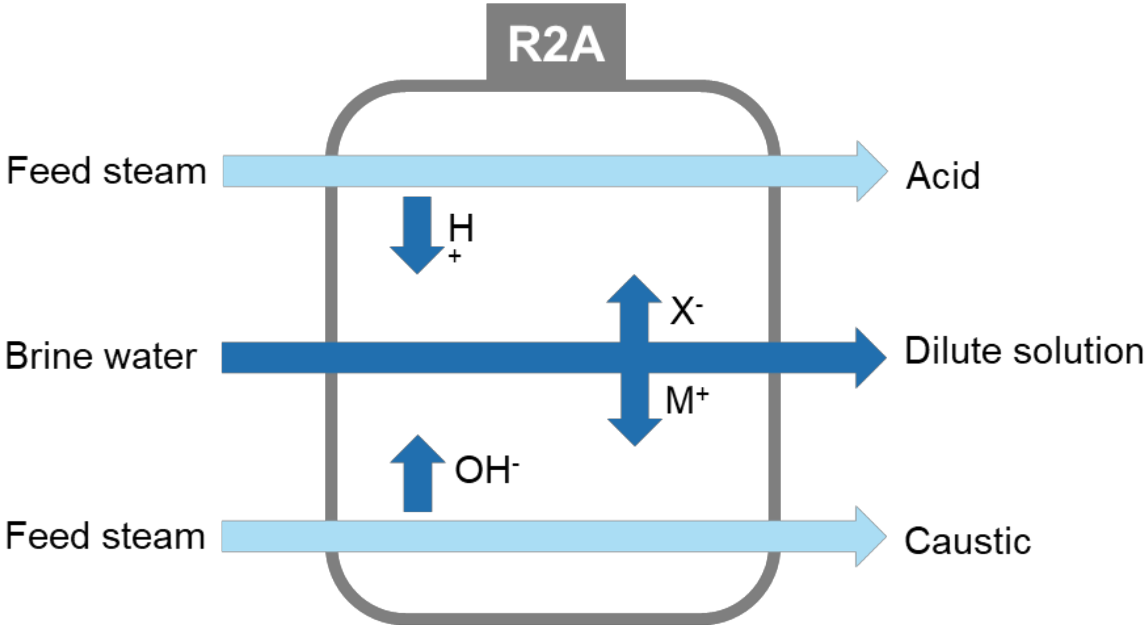
From Waste to Resources?
Valuable Resource Recovery from Brine

Membrane-Based Electro-Separation Technology



- In-line separation anionic/cationic ions
- Selective production of $HCl/H_2SO_4/NaOH$

Recovery to Acid and Alkali (R2A)

an IEM processes applies a selective membrane to split water into H^+ and OH^- for acid and alkali production.

Applications

- Brine recovery (cation/anion)
- Production of acid/caustic from mixed salt in liquid phase
- Pretreatment for final MVR/MED of ZLD process

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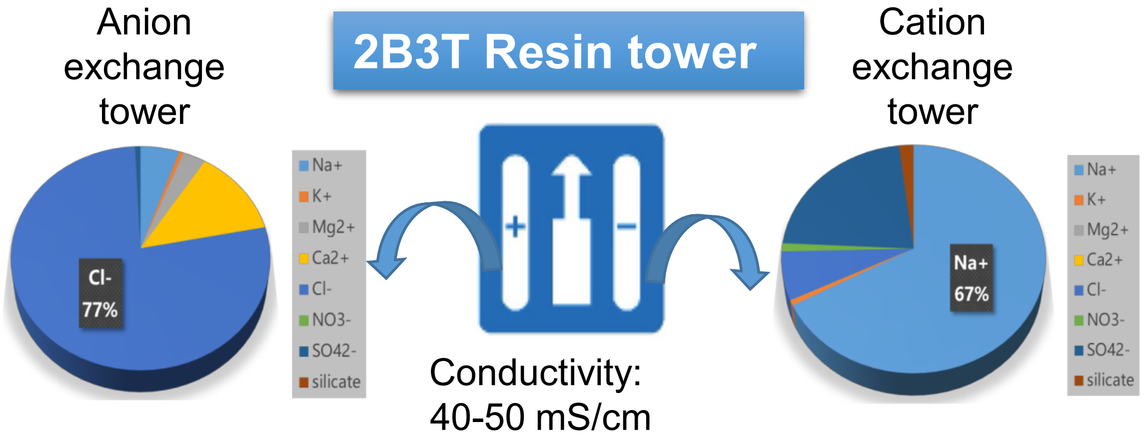
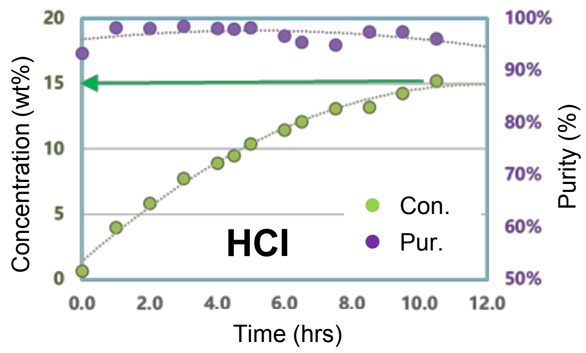
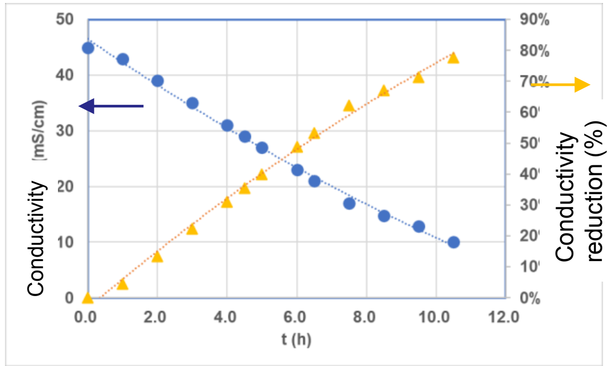
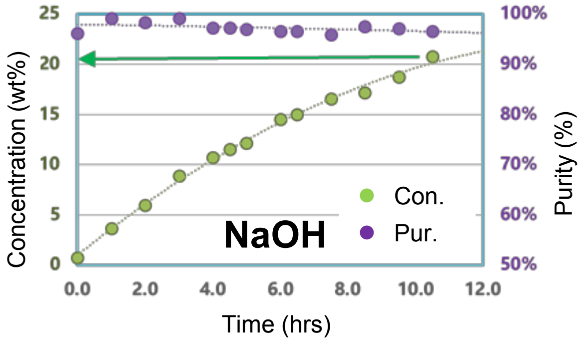
High Conductivity Waste Liquor Converting to Acid/Caustic Soda



Product:
- ✓ HCl/NaOH: concentration > 10 wt% and purity > 90%
- ✓ Waste liquor Conductivity reduce to below 1 mS/cm







- For 90 CMD waste liquor, 3.0 t/d of 20.8 wt% NaOH and 3.0 t/d of 15.3 wt% HCl are produced.
- Purity of acid and caustic soda >90% and energy consumption of 3.4 kwh/kg-NaOH.
- ROI for investment is about 5.3 years.

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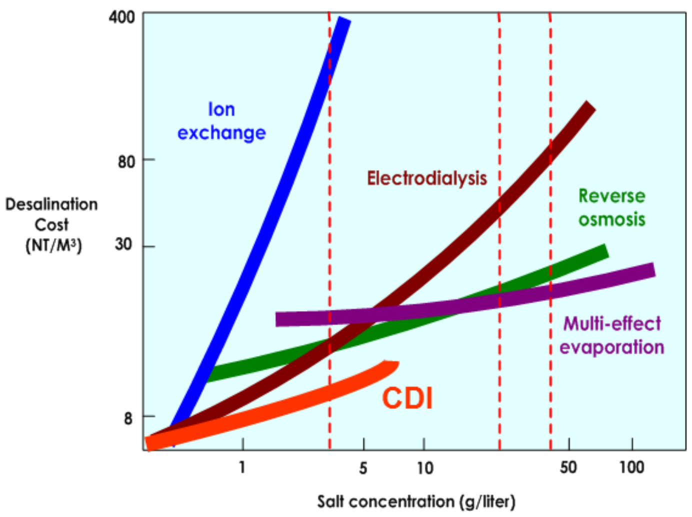
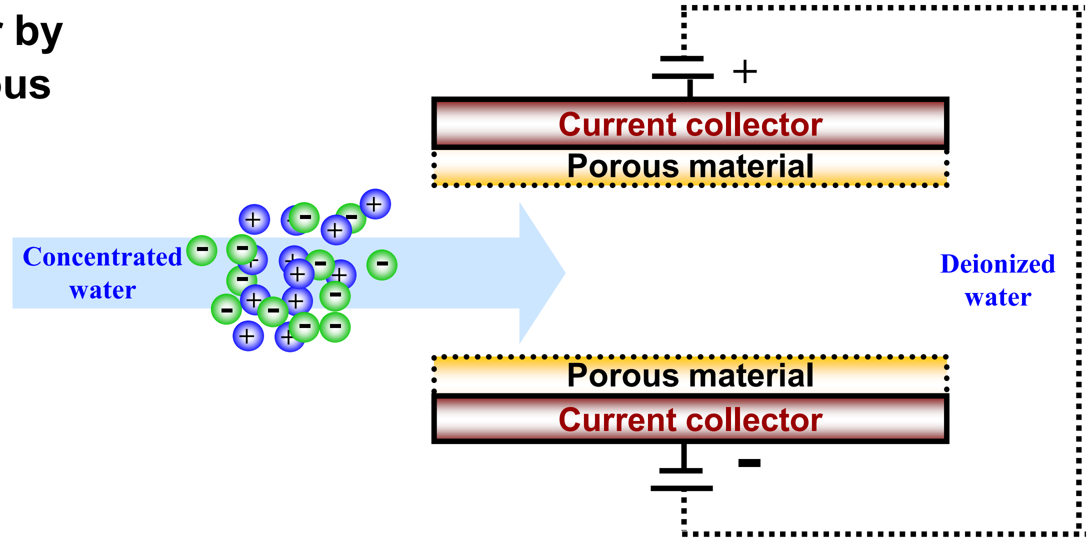
Capacitive Deionization (CDI)

Existing desalination technologies

	Reversed osmosis (RO)	Electrodialysis reversal (EDR)	Capacitive deionization (CDI)
Process	Pressure-driven	Electrical-driven	Electrical-driven
Property	• High energy consumption (1.5~ 1.85 kWh/m^3) • Membrane fouling • Mature technology	• High energy consumption (1.1~ 1.35 kWh/m^3) • Membrane fouling • Mature technology	• **Low energy consumption (0.3~0.6 kWh/m^3)** • **No membrane needed** • **Developing technology**

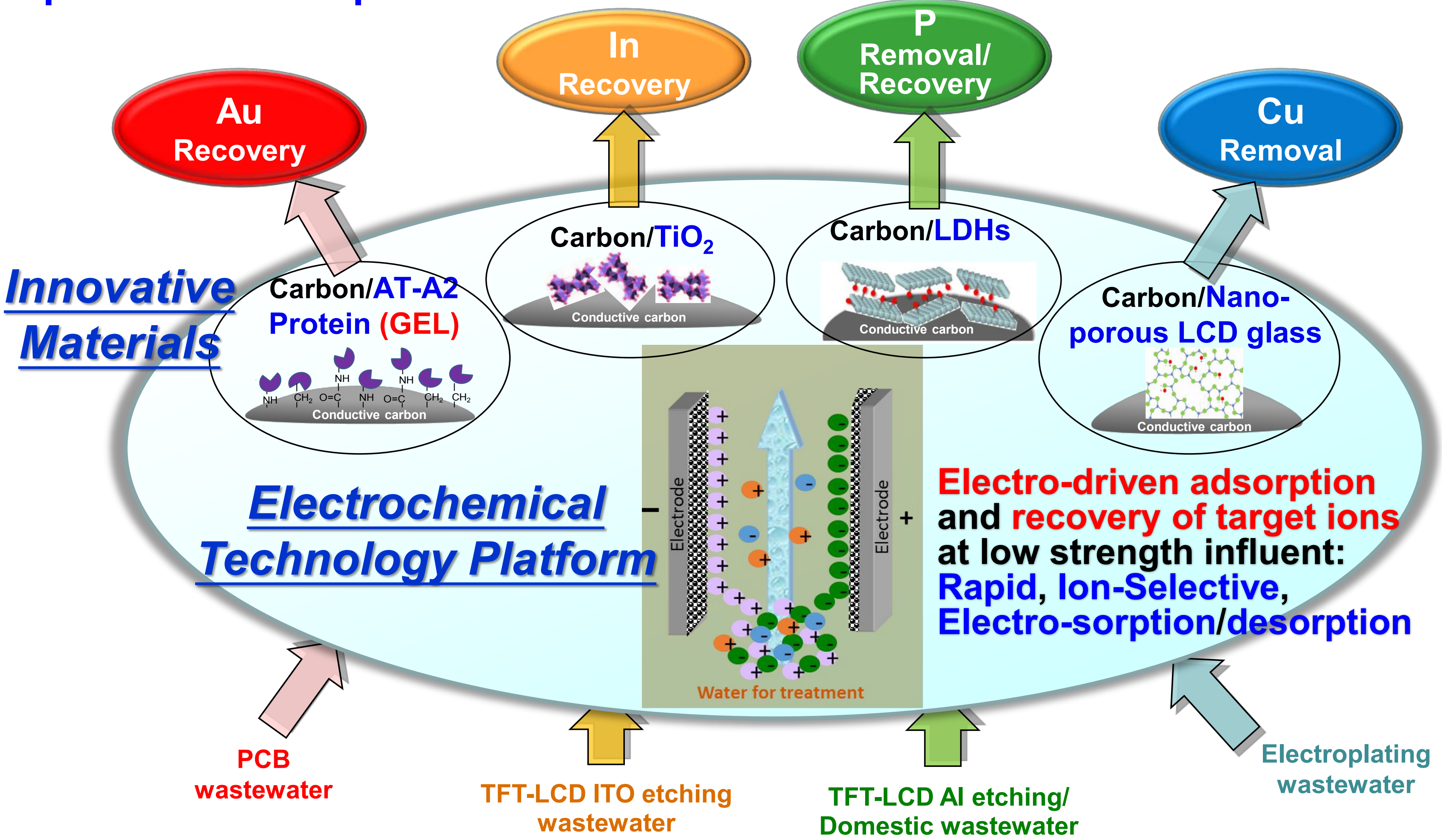


- **CDI technology**
  Salts and minerals are removed from water by applying an electric field between two porous electrodes
- **Ideal electrode materials for CDI**
  Highly conductive, high surface area, suitable pore size distribution
- **Application**
  More economical at lower concentrations



Selective CDI Technology for Various Ion Recovery

Tailoring inorganic/organic functional electrode materials for specific ion electro-adsorption and desorption



Conclusion

- Unconventional water resources are key to support SDG 6 achievement. With glowing water scarcity, desalination as a water supply option has risen globally.
- Generally, membrane technology and thermal technology are the major desalination methods. Both technologies face drawbacks such as high freshwater production cost, intensive carbon emission and significant impact to environment. Innovative technologies with economic benefit and low environmental impact are critical to desalination expansion.
- Innovation and developments in brine management and disposal options are key factors in desalination plants. R2A system is promising for brine treatment and further producing valuable resources for reuse.

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Thanks for your attention!

Dr. Wang-Kuan Chang
Deputy Division Director
Div. of Water Technology Research
Material and Chemical Research Laboratories

2021.10.15

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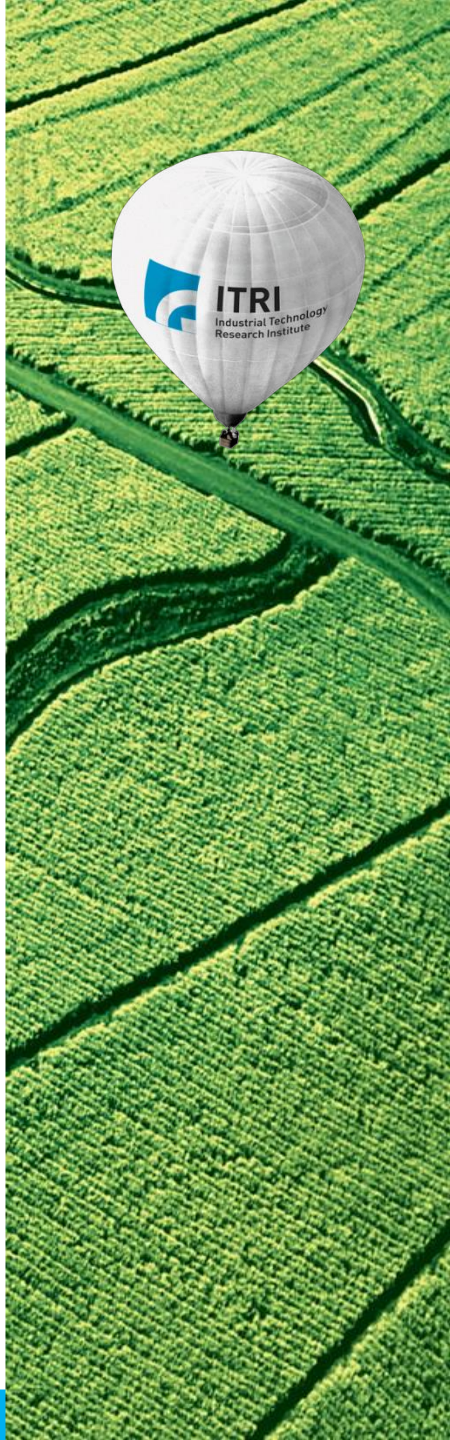

海水淡化與環境營造-淺談吉寶濱海東部海淡廠
Desalination with the Environmentally Friendly Design-Keppel Marian East Desalination Plant

GOH Eng kwang
TAY Parng tzuan

CHIU Kuang-ping
GOH Kai shen
CHEE Sai kit
LEO Song tong
Taranveer MANN
Kelvin KHOO
Tony ATTENBOROUGH

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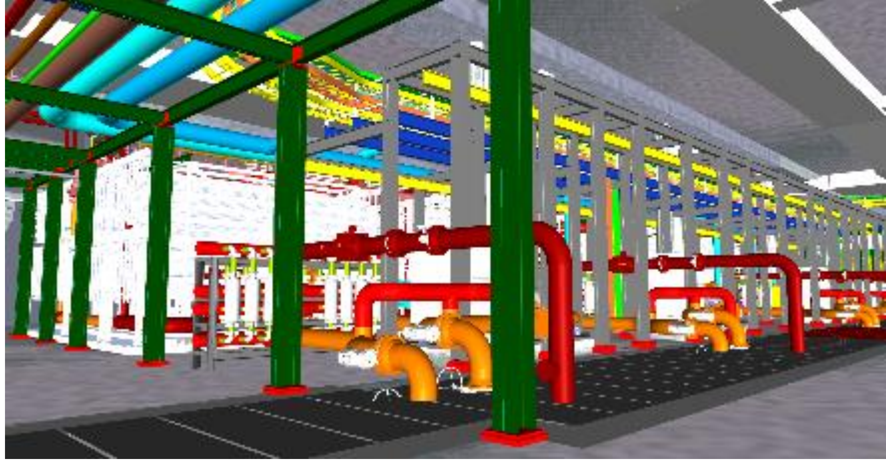
Agenda

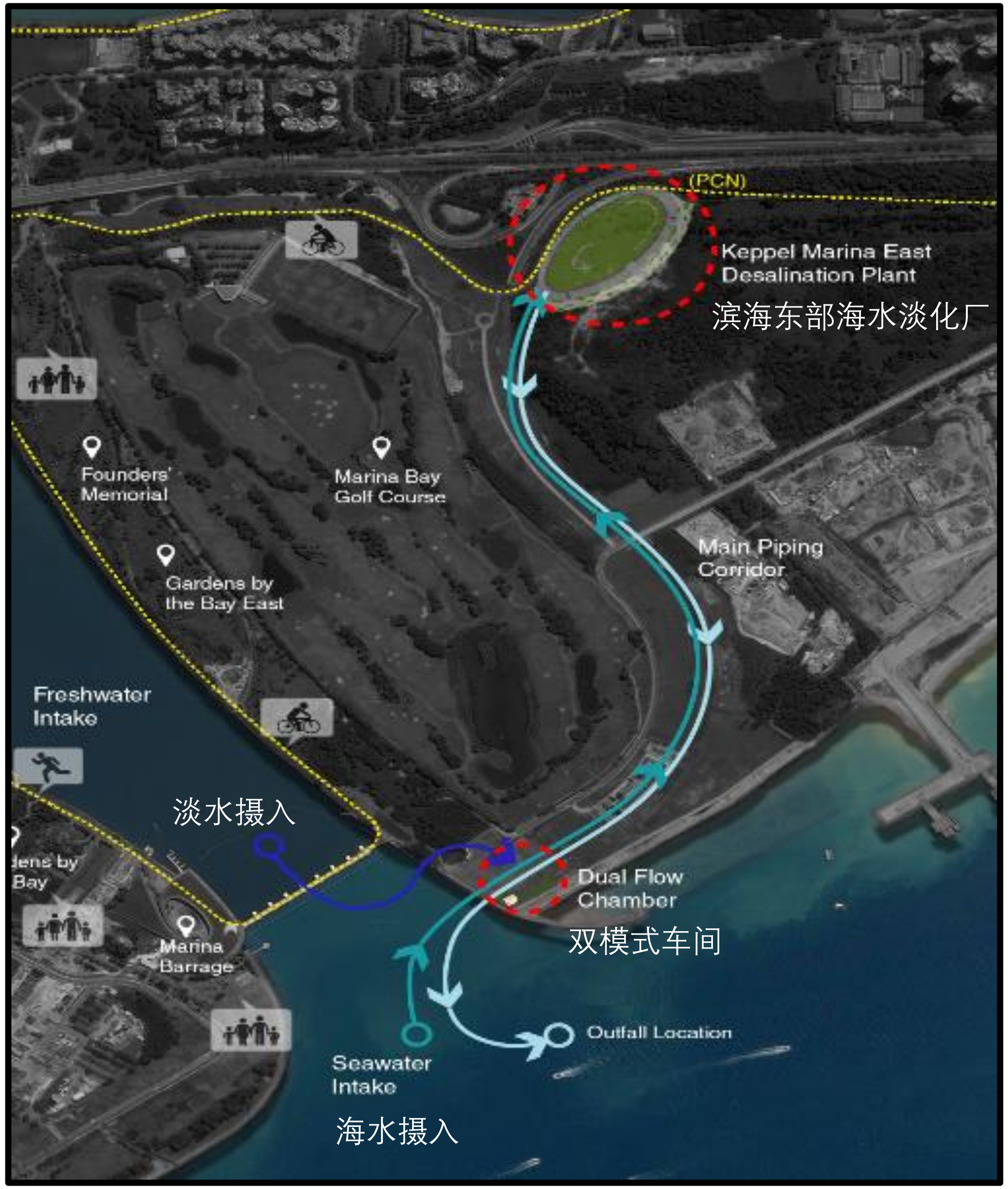
- Introduction of KMEDP
- KMEDP Process design
  - Dual mode
  - Direct coupling
  - Other energy saving approaches
- Conclusions



Background

- 137,000 m^3/d capacity
- Design Build Own Operate (DBOO) with 25 years operation
- Dual intakes with Sea Water and Reservoir Water
- Green roof top link to Park Connector (accessible to the public)
- Viewing gallery

Project Background and Key Features Overview
計畫背景和主要功能概述



The KMEDP is **Singapore's fourth** desalination plant and is a public private partnership (PPP) between Keppel Infrastructure (through its wholly-owned subsidiary, Marina East Water) and PUB, Singapore's national water agency.
吉寶濱海東部海水淡化廠是新加坡的第四座海水淡化廠，是吉寶基礎設施籌設的全資子公司Marina East Water與新加坡公用事業局之間的公私合作夥伴關係（PPP）。

The plant can produce up to 137,000m^3 of fresh drinking water daily.
該廠每天可生產多達137,000 m^{3}的民生自來水。

Singapore's First Direct Coupling Desalination Plant 新加坡第一座直接連接海淡廠
Direct coupling of ultrafiltration and reverse osmosis systems – Omitting ONE pumping cycle results in saving of 15% of energy used in a pumping cycle.
超濾系統和逆滲透系統直接連接可省一個水泵循環，約可節省15％的循環能耗。

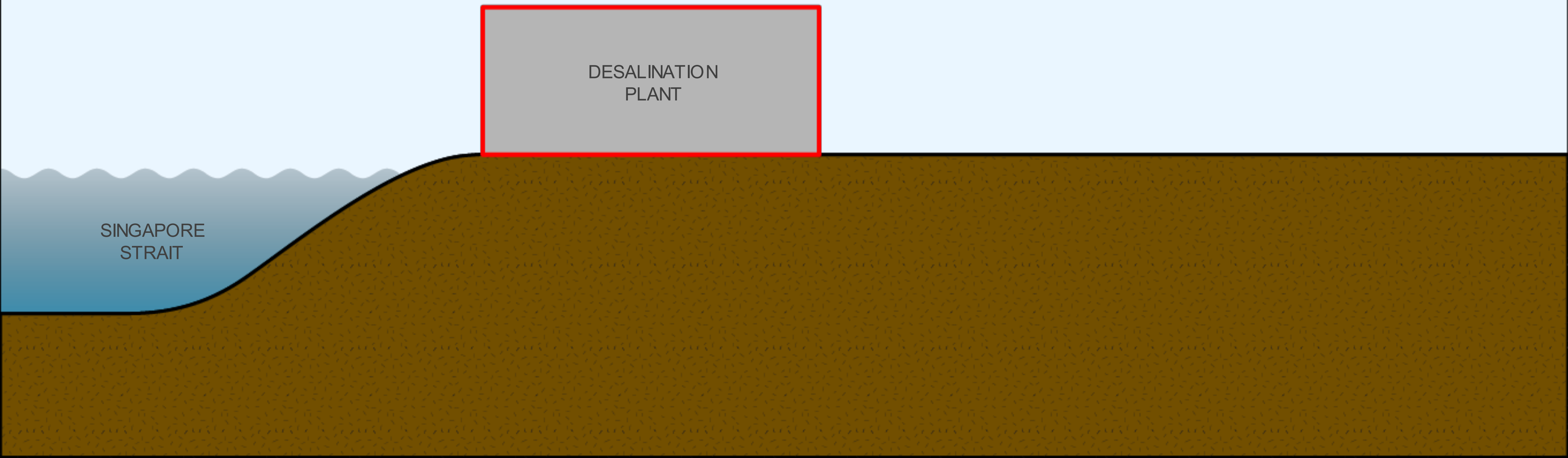
Incorporation of advanced system / equipment 整合先進的系統/設備
Singapore's first water desalination plant using UV as primary disinfection
新加坡首座使用紫外線作為主要消毒劑的海水淡化廠。

One of the most compact desalination plants in Singapore新加坡最精簡的海水淡化廠之一
Compact Pre-treatment achieving nearly 30% reduction in space
精簡的預處理程序減少近 30% 的土地使用

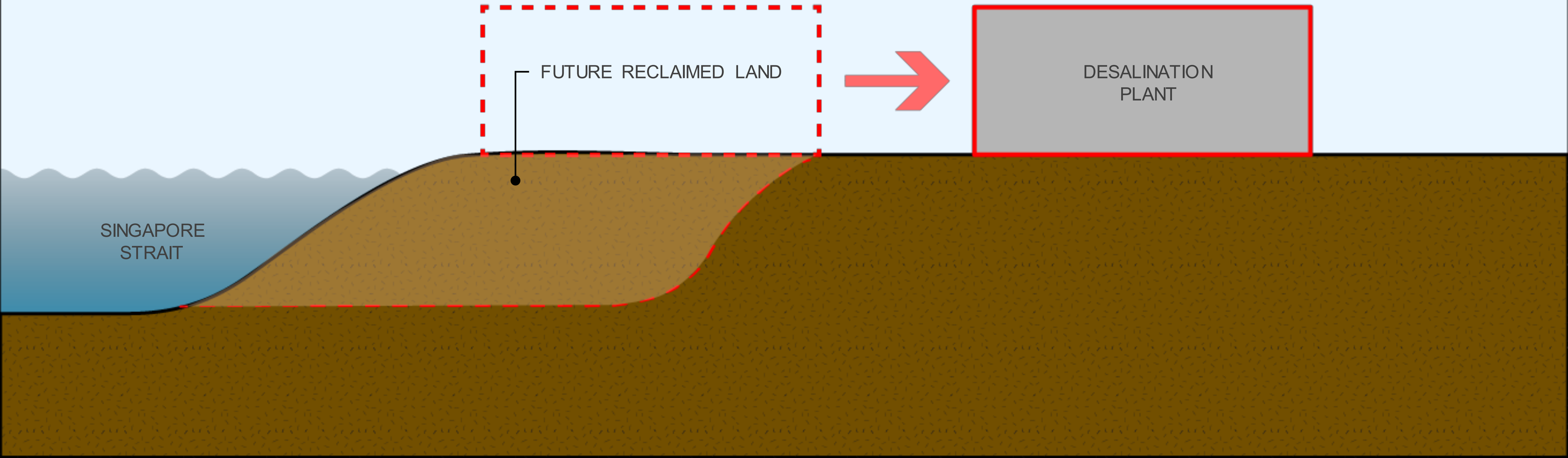
Direct coupling design with omission of booster pump, cartridge filters and UF filtrate tank
直接連接設計，可省略增壓泵、筒式過濾器和超濾產水槽

Smaller footprint of UV disinfection system compared to conventional chlorine-based disinfection
與傳統的加氯消毒相比，紫外線消毒系統的佔地面積較小

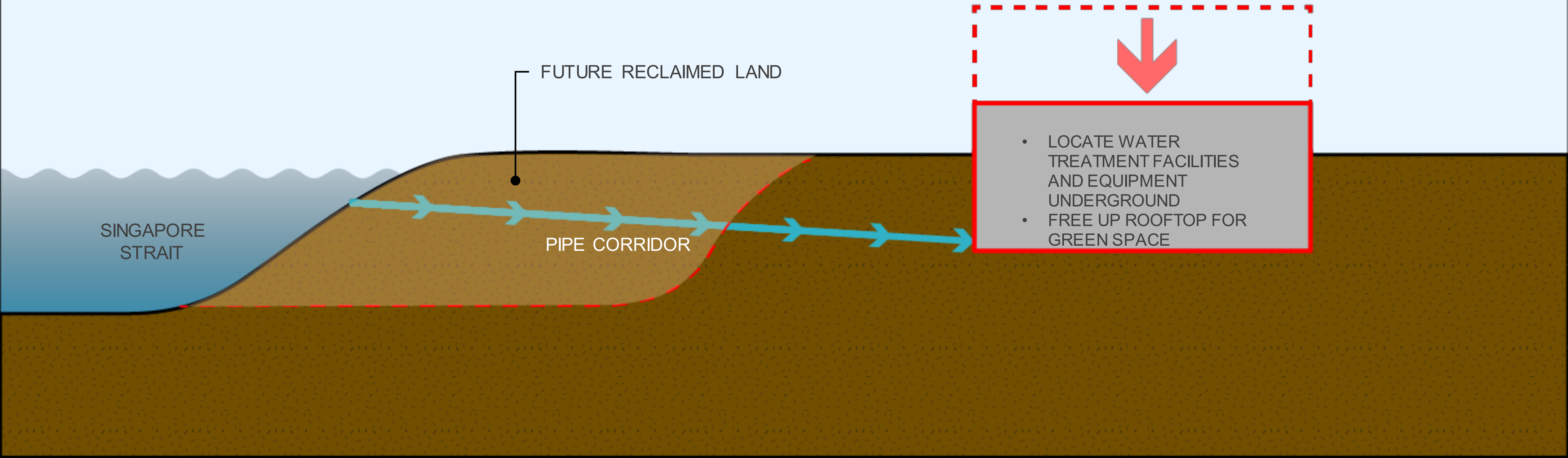
Design Concept Overview– Main Plant 設計概念(1/4)



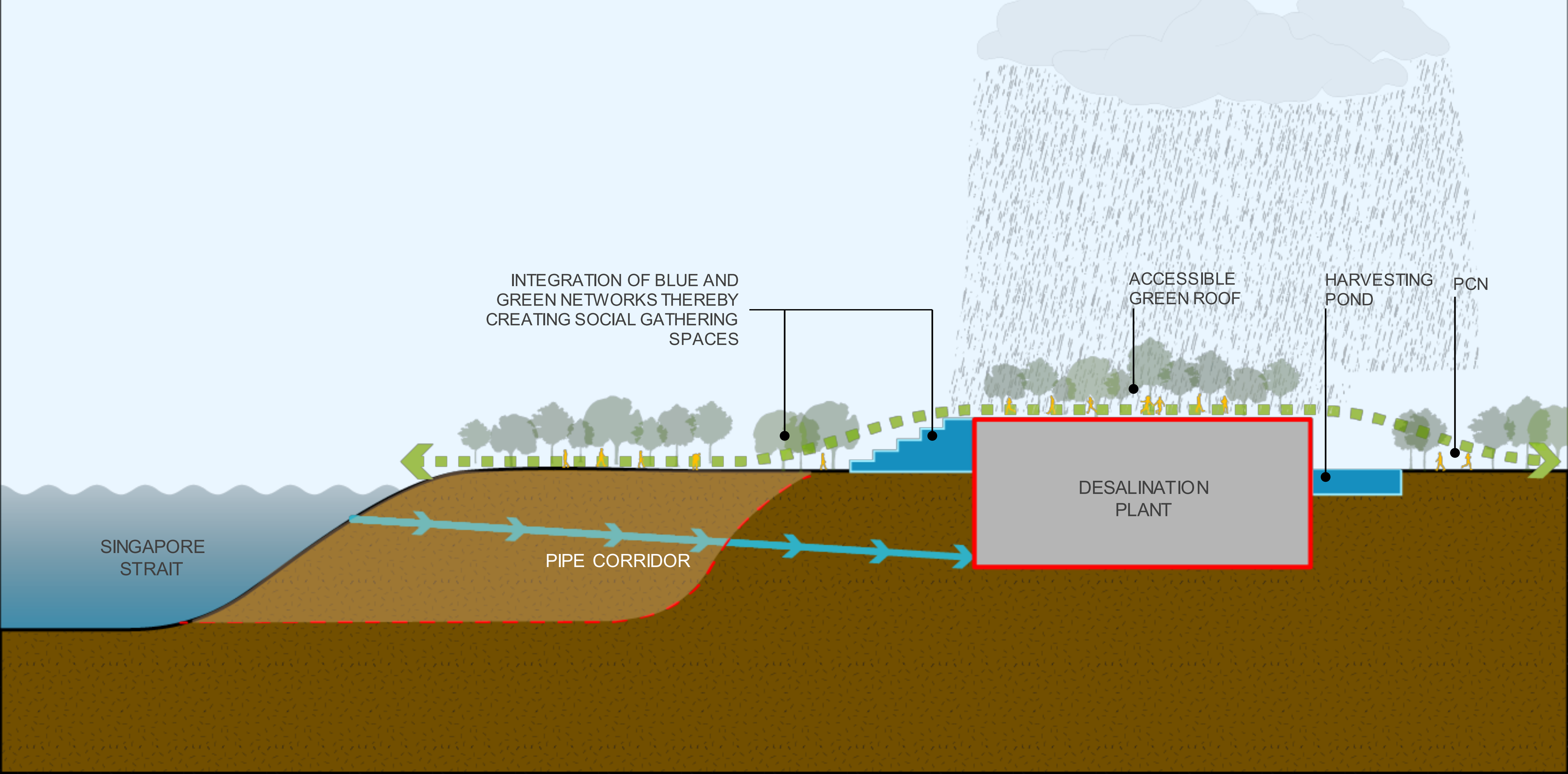
Design Concept Overview– Main Plant 設計概念(2/4)



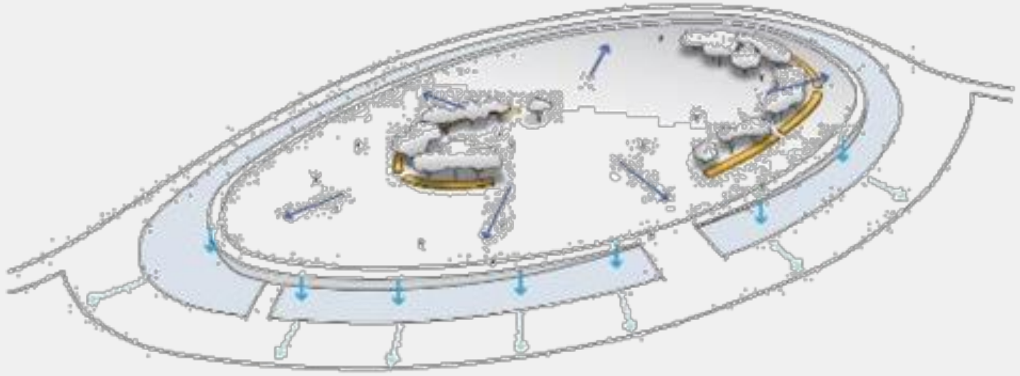
Design Concept Overview– Main Plant 設計概念(3/4)



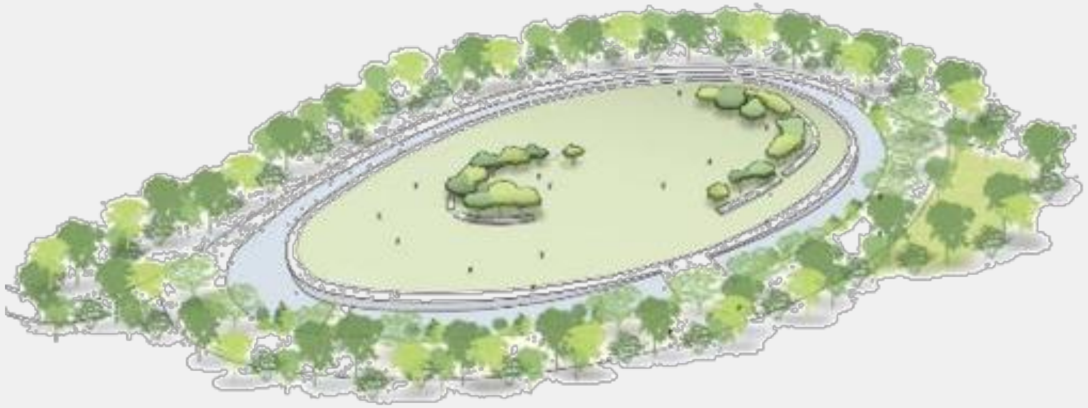
Design Concept Overview– Main Plant 設計概念(4/4)



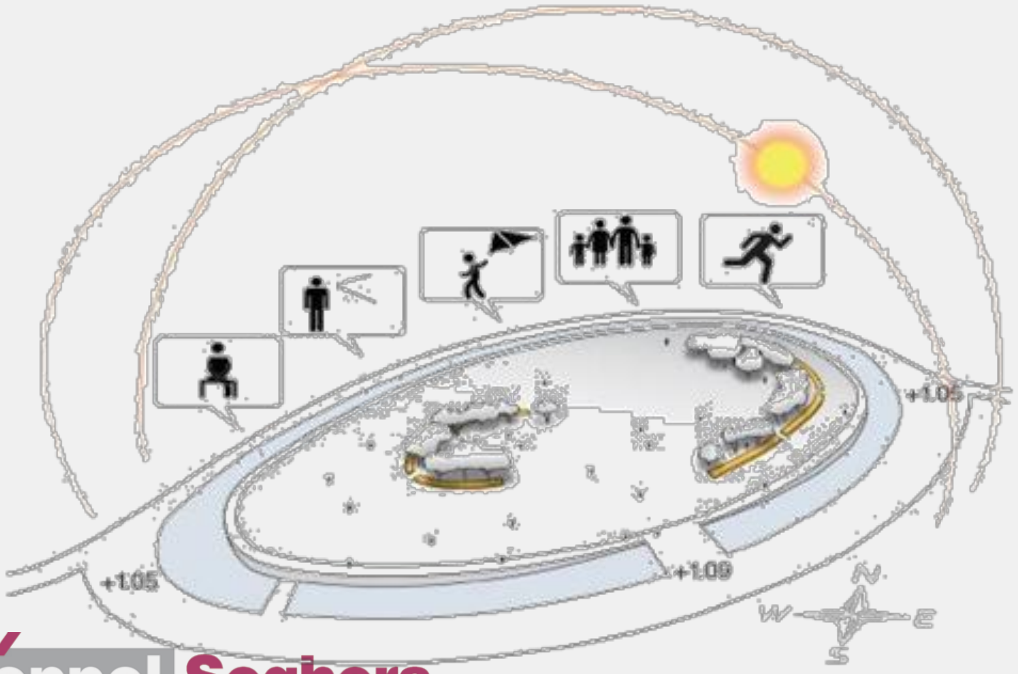
Design Concept Overview – Sustainability Features
設計概念 - 永續功能



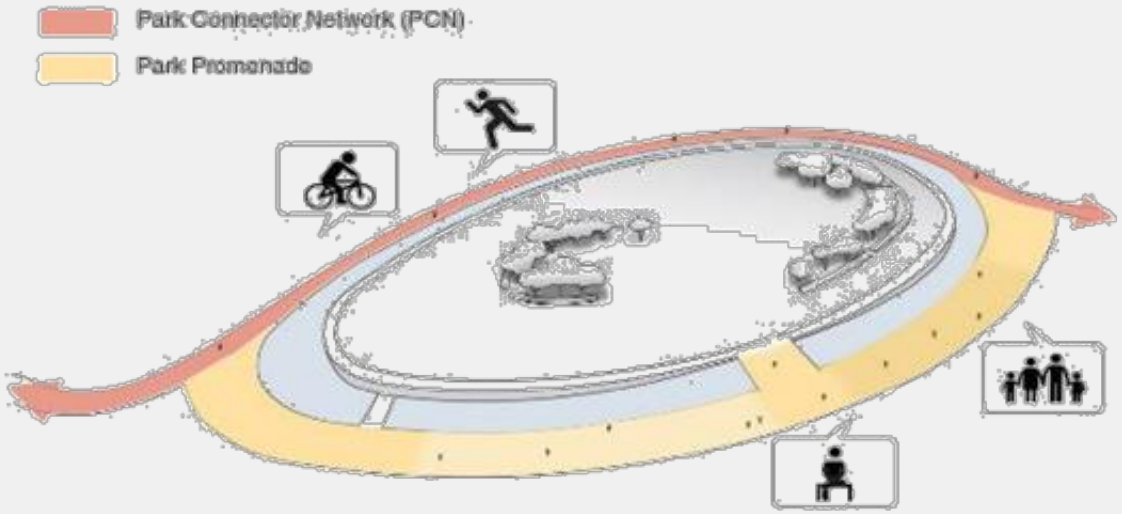
RESILIENT DESIGN



GREEN FABRIC AND BIODIVERISTY



INFRASTRUCTURE AS PUBLIC SPACE



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KMEDP's Sustainability Design Features 永續性功能設計

The design of the KMEDP challenges conventional approaches to what large infrastructural facilities should look like.
濱海東部海水淡化廠設計對於傳統基礎設施的常規方法提出了挑戰。

Designed exclusively for people, the green roof blends into the existing environment to demonstrate that buildings as large as these can not only coexist, but be effortlessly integrated into an inclusive, park-like attraction.
人性化的綠色屋頂與週邊環境融合，此證明如此大的建築物亦可如此完美的融入到一個整合性的公園式景點中。

The Plant incorporates environmentally friendly elements within its landscape design, such as a stormwater managing strategy and a water harvesting system to retain rainwater as features and recycles water for irrigation and other uses.
该廠在景觀設計中融入了環保元素，例如雨水管理策略和集水系統，以保留雨水作為景觀特色，並回收水用於灌溉和其他用途。

The KMEDP allows people to adopt the building as their own and to ultimately understand the importance of water as an significant natural resource in the life of a nation.
濱海東部海水淡化廠讓人們將基礎設施視為自成一格的建築物，並了解水是國家生命中重要的自然資源。

Design Concept Overview– Main Plant 設計概念—主廠房

Design Concept Overview – Dual Flow Chamber
設計概念—雙水源模式取水泵站

Artist's Impression – Bird's Eye View

As Built – Bird's Eye View

Artist's Impression – Viewing Gallery Entrance

As Built – Viewing Gallery Entrance

Artist's Impression – Green Roof and Promenade Area

As Built – Green Roof and Promenade Area

Artist's Impression – Harvesting Pond

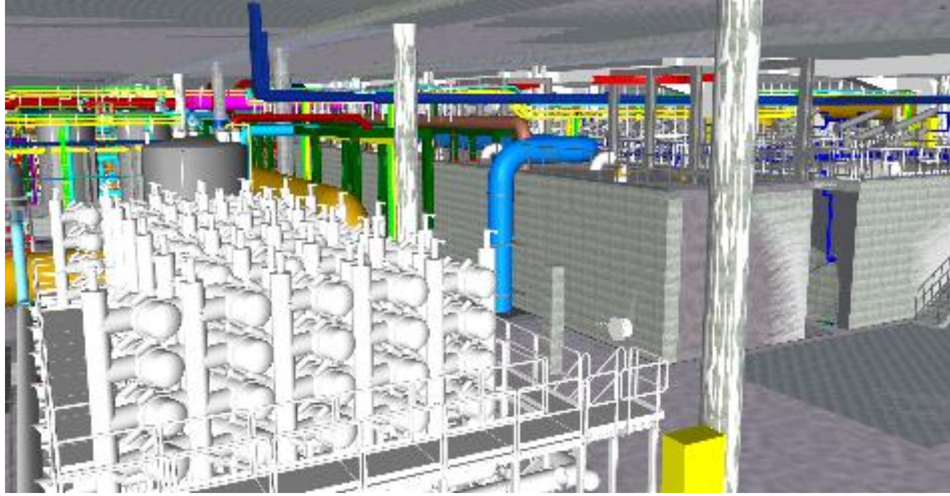
As Built – Harvesting Pond

Introduction of KMEDP

KMEDP Process design

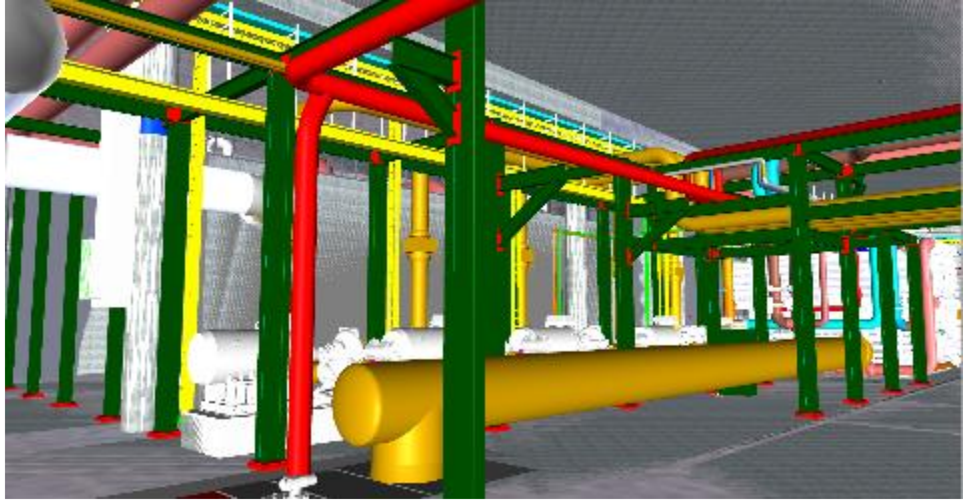
Conclusions

Energy Efficiency Improvement



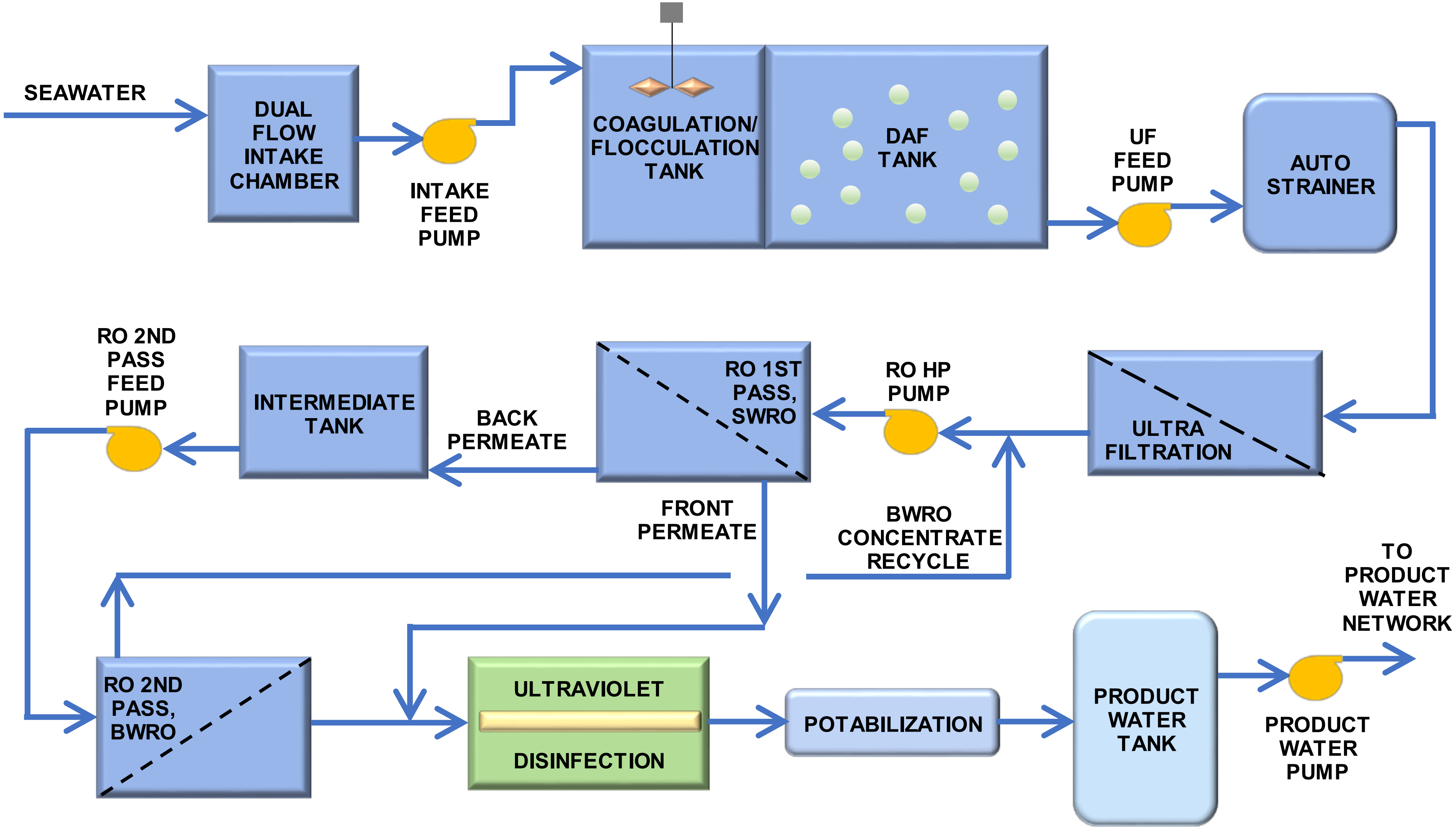
- Dual mode
  - Sea water: SWRO+ Low pressure RO (LPRO)
  - Reservoir water: LPRO
- Direct coupling
- Split permeate
- Energy recovery device
- Variable frequency drive pump

Process



- Intake passive screens
- Dual flow chamber
- Dissolved air flotation (DAF)
- Micro strainer
- Ultrafiltration (UF)
- RO: SWRO and LPRO
- Post treatment (i.e., UV, mono-chloramine, lime, CO_2, Fluoridation)

Sea Water Mode



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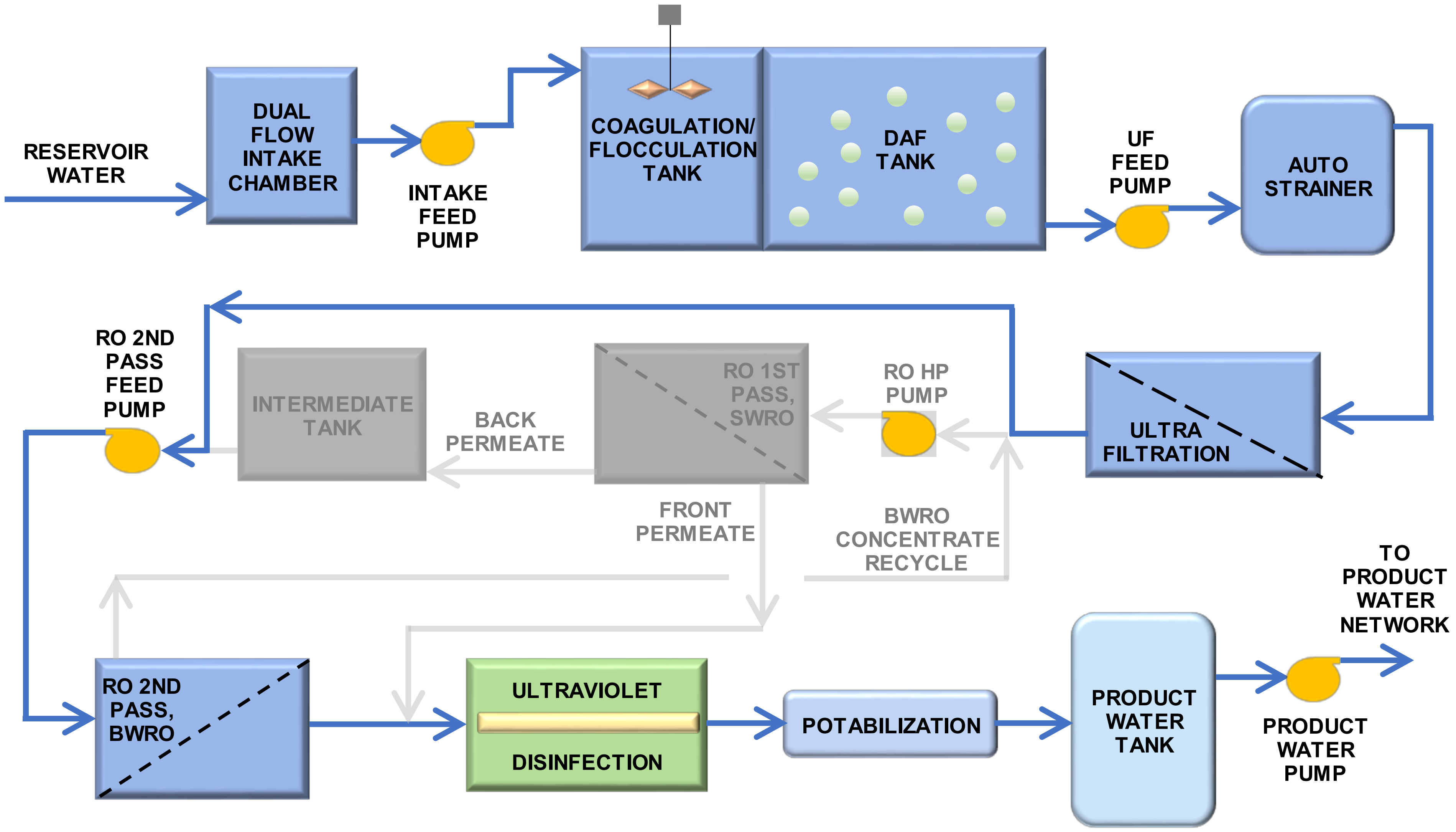
Reservoir water Mode



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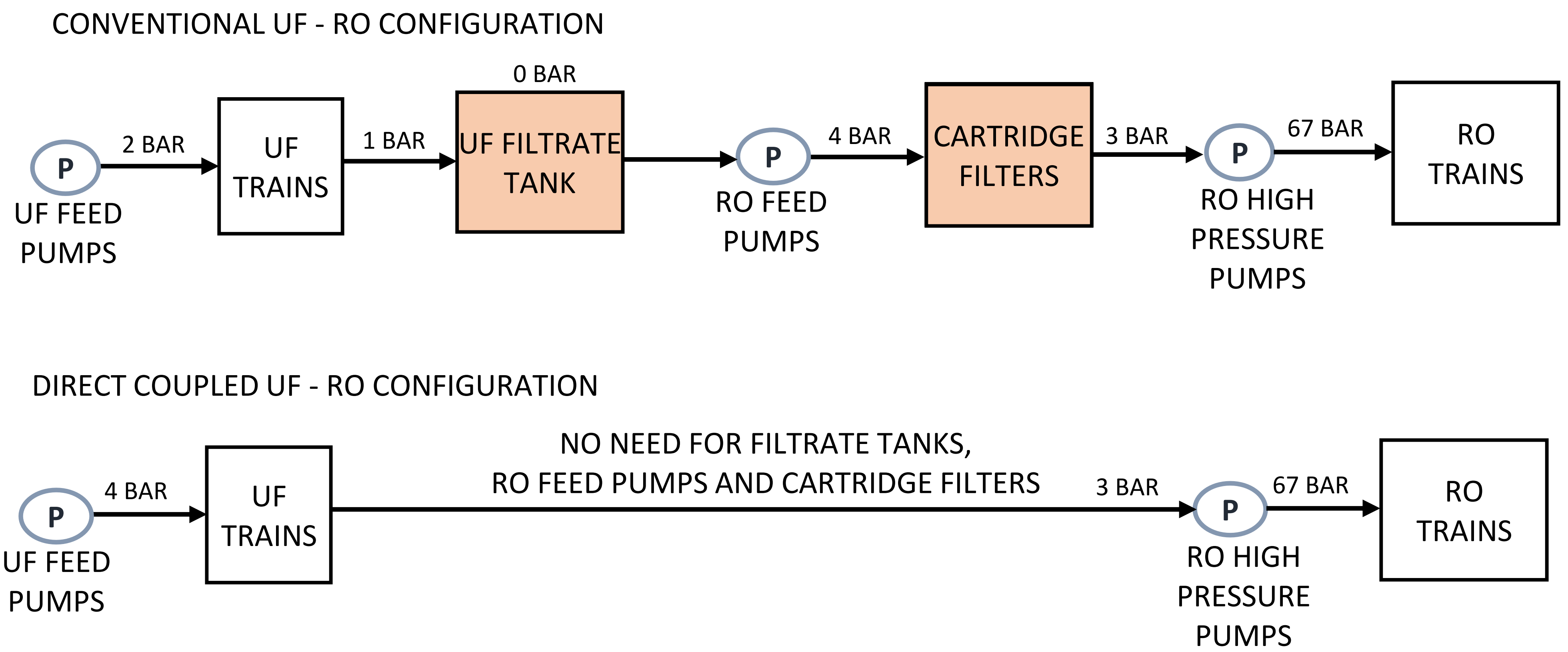
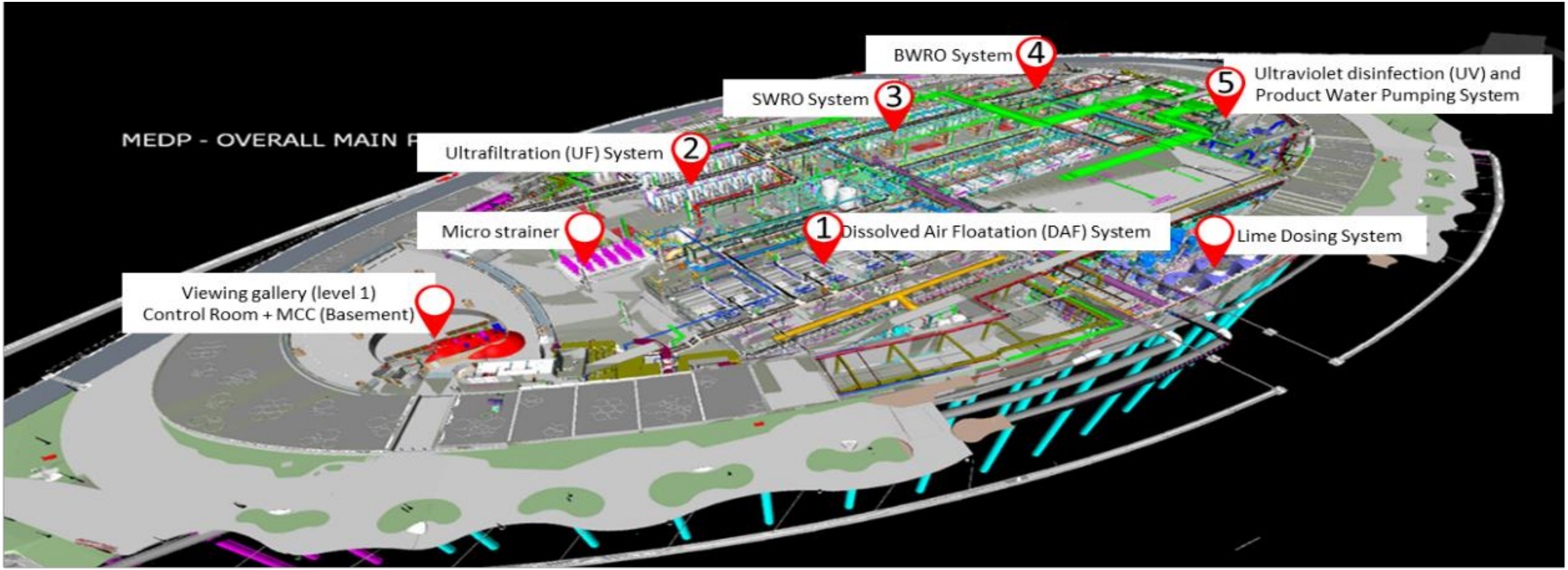
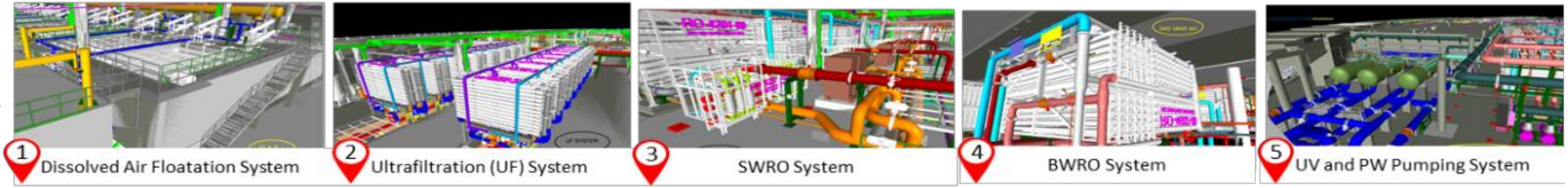
Direct coupling



Enhanced Engineering Process – 3D BIM 先進工程設計



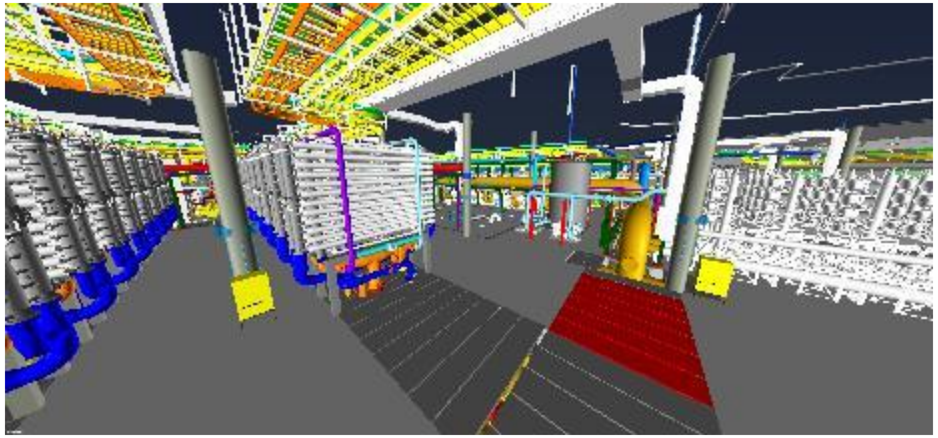


Introduction of KMEDP
KMEDP Process design
Conclusions

Conclusions

- KMEDP provides an environmentally friendly community space
- KMEDP includes sustainable features in landscape
- KMEDP with capability to operate in both sea water and reservoir water mode
- KMEDP utilizes direct coupling to save more energy
- KMEDP provides highly efficient energy recovery devices (ERD) for the 1st pass SWRO system
- KMEDP utilizes the split partial configuration hence reduce pumping costs as well as reduce the capital costs of the plant
- KMEDP uses micro strainers as pre-treatment before UF and RO systems
- High-power consumption pumps are equipped with VFD

Video



Thank You

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Reducing Environmental Impact in Desalination

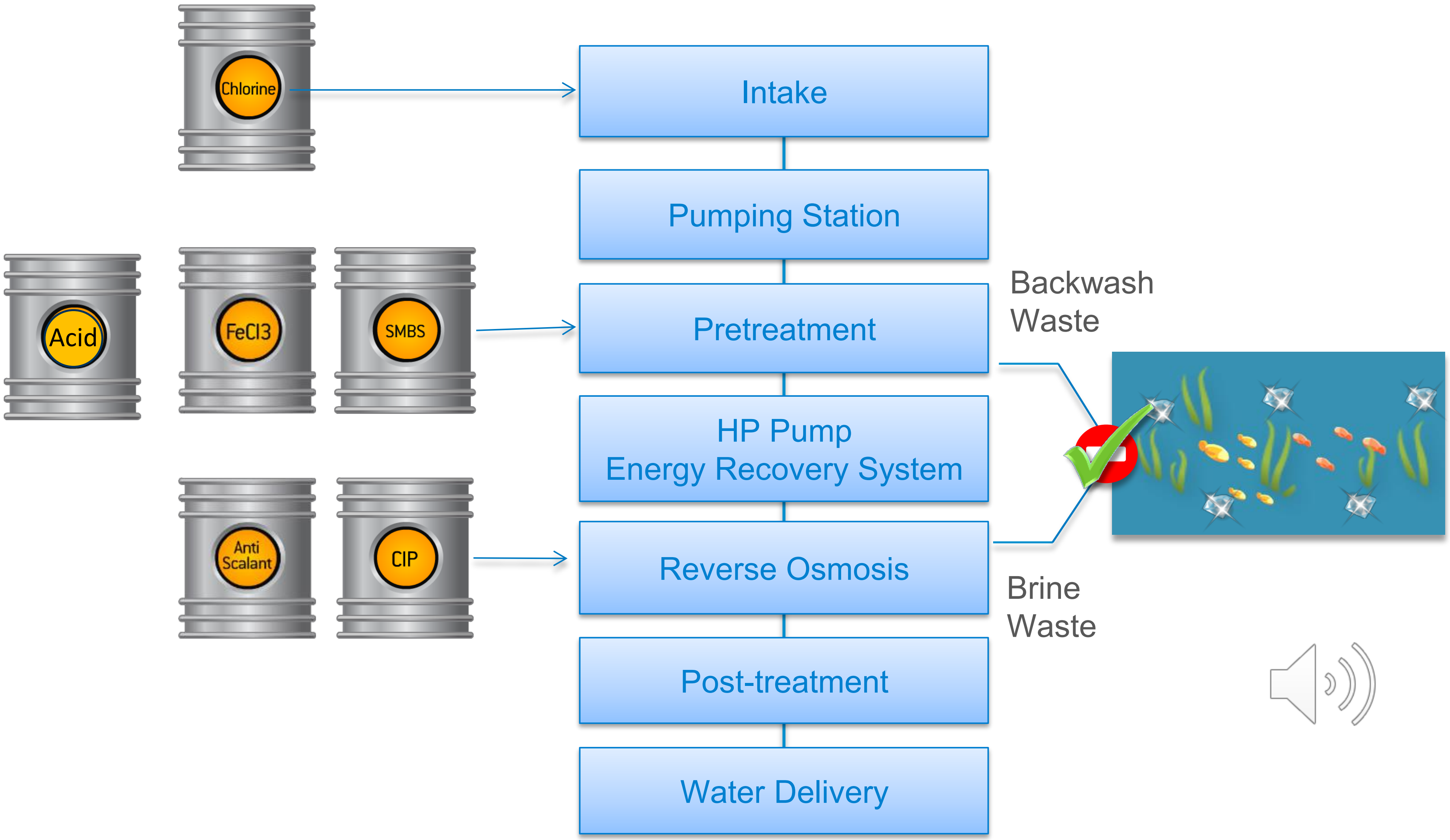
Dr. Boris Liberman

VP and CTO, IDE Water Technologies

Main Goals of Desalination Plant Design

- Safe working conditions for staff
- Environmentally friendly operation
- Keeping the RO membranes clean
- Low power consumptions
- Low water cost

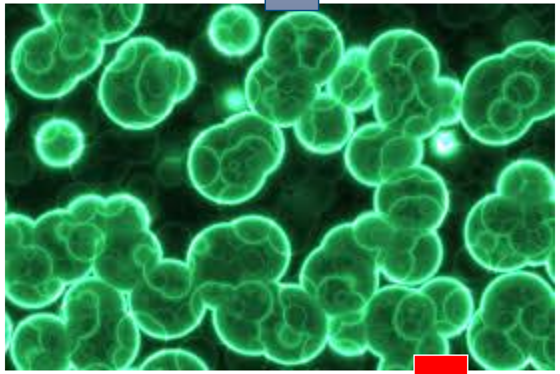
Chemicals in Conventional SWRO Plant Design

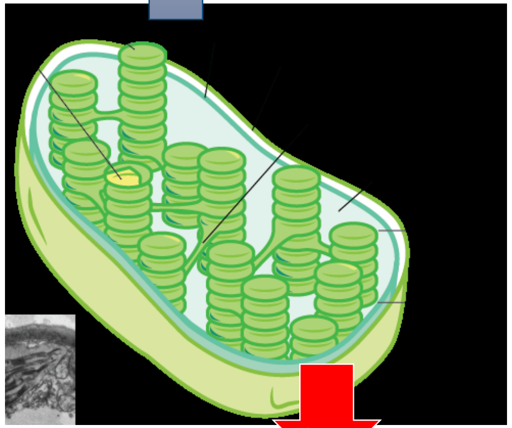


Super-saturation of Oxygen in Seawater

Used in pretreatment for safe and environmentally friendly operation

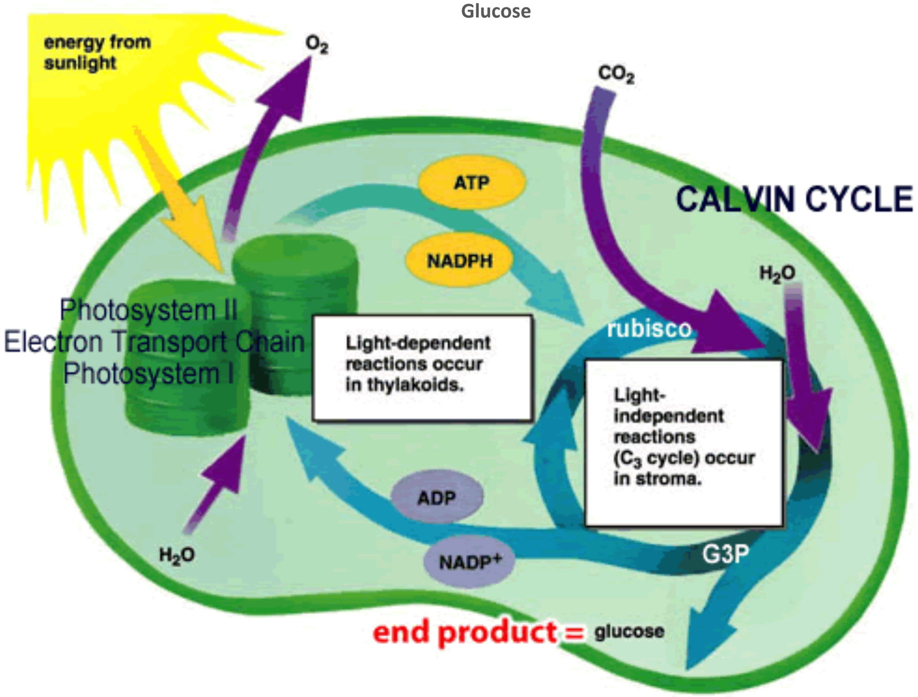
O_2 O_2 O_2





Glucose Glucose

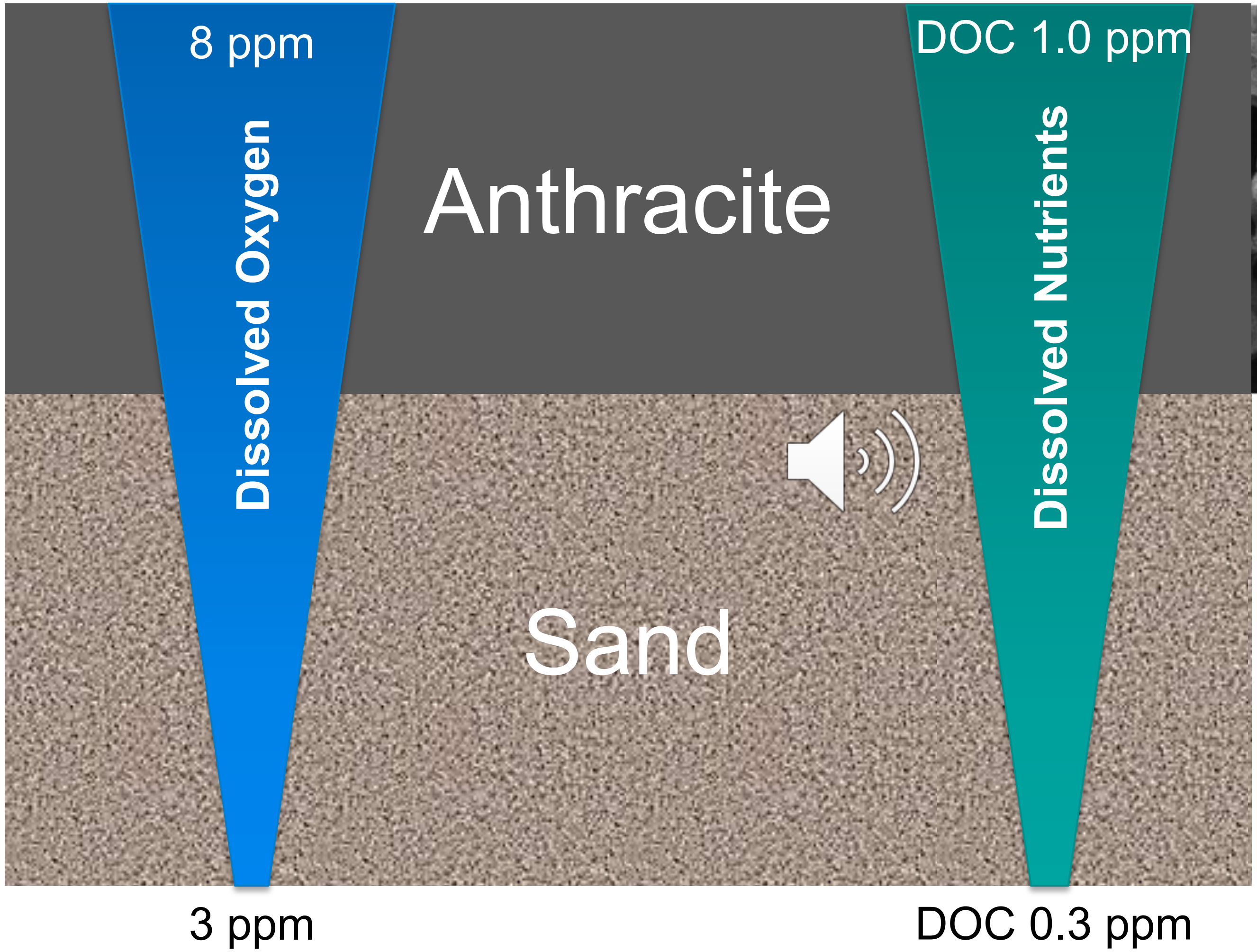
Glucose

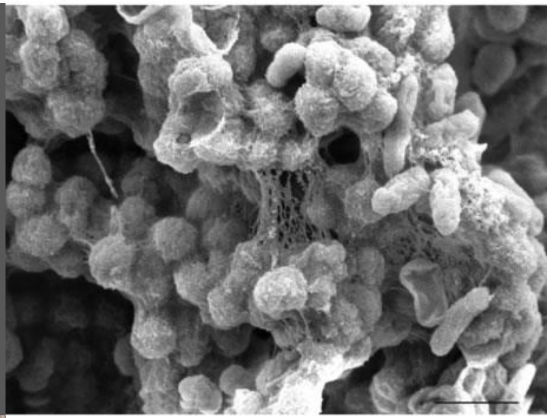


High concentration of **oxygen and glucose** in seawater due to photosynthesis

Media Filtration

- Bacteria consume nutrients and oxygen





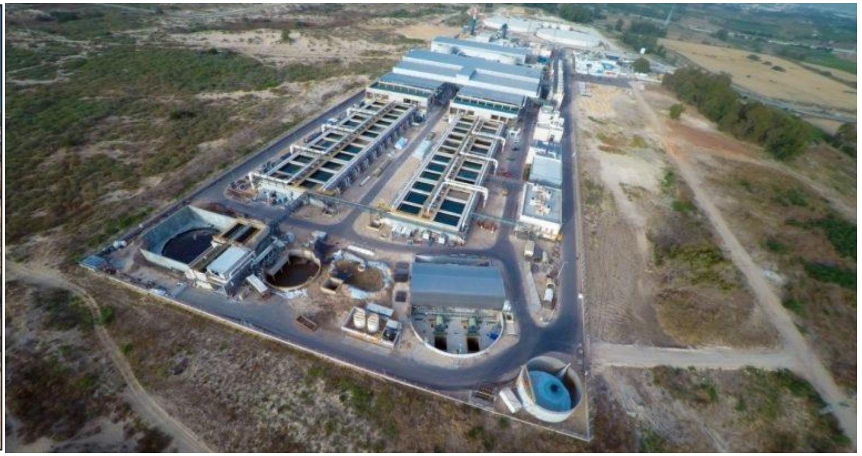
IDE Technologies Your Water Partner

Pressure Center Design

Low power consumptions, low water cost achieved by Pressure Center Design

Ashkelon 400,000 m^3/day

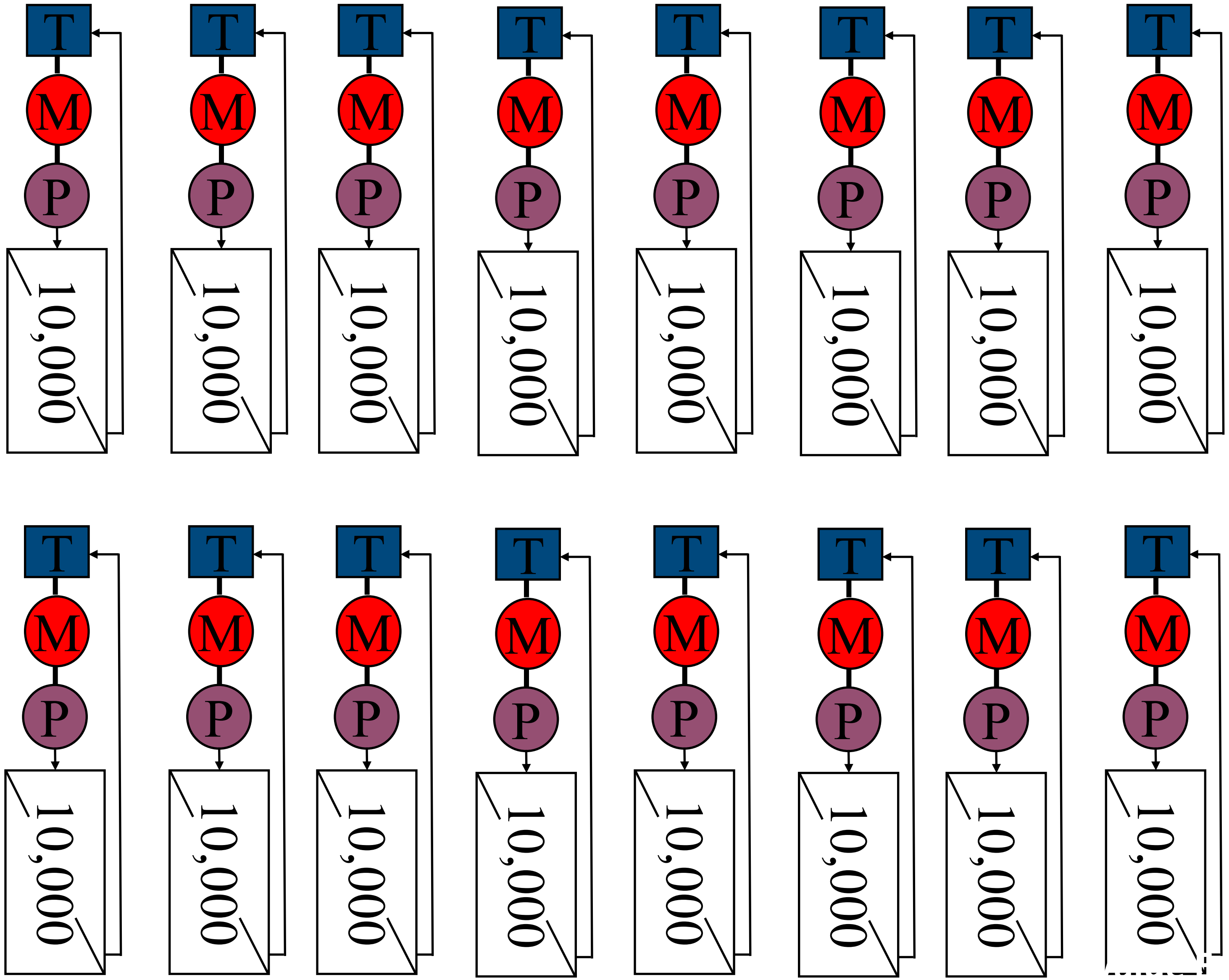
Hadera 500,000m^3/day



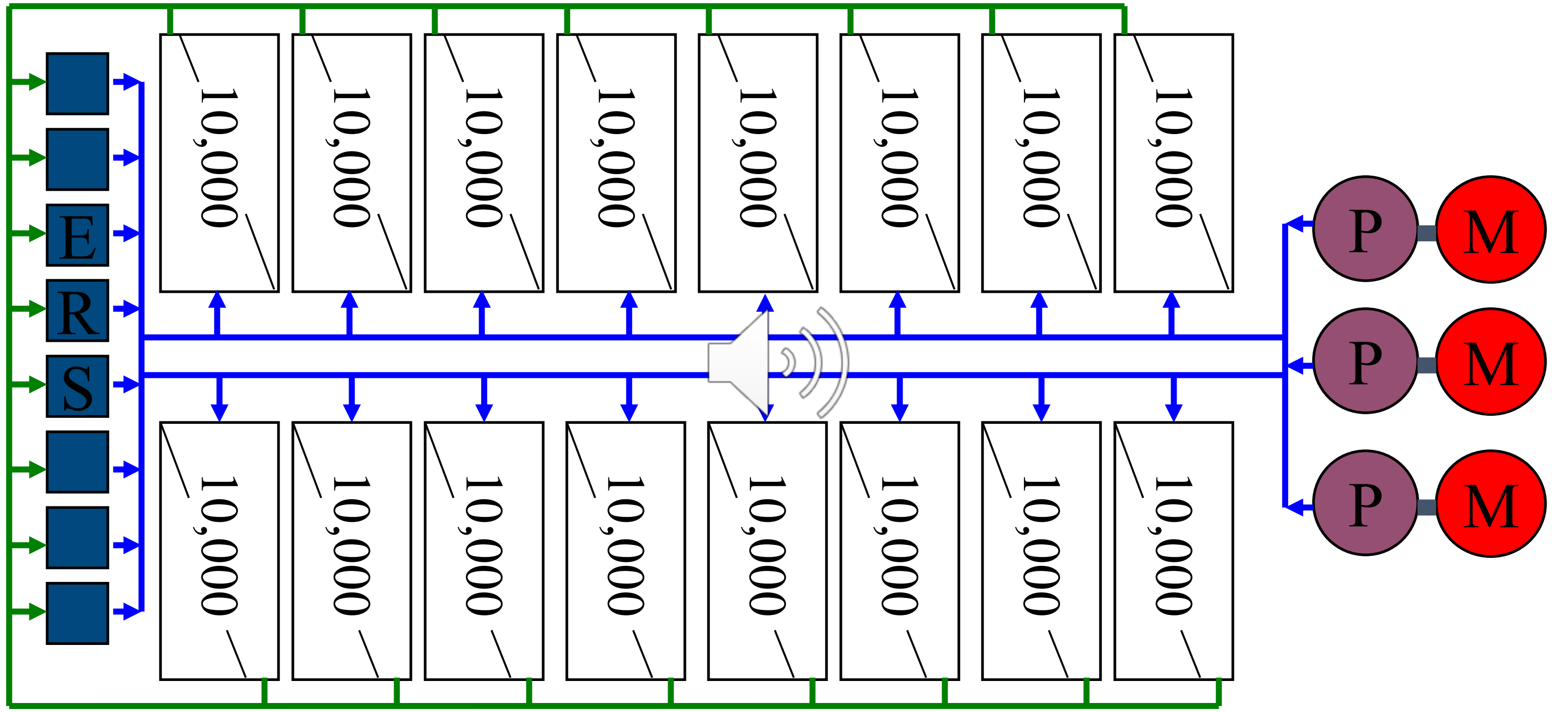
Sorek 600,000 m^3/day

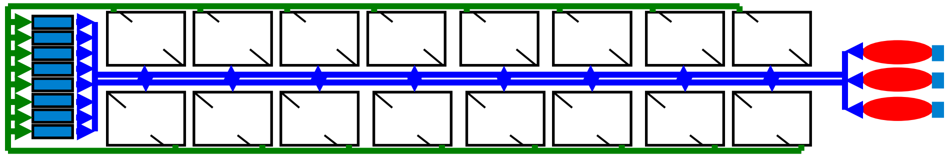
IDE Technologies Your Water Partners

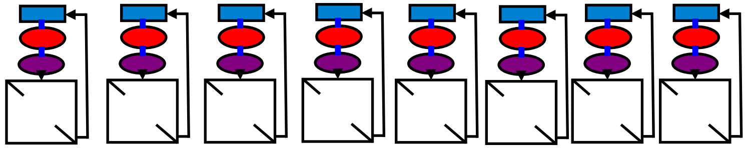
Conventional RO Plant Design: membranes, pump, motor, ERS



Pressure Center Design







Optimum Size of one RO Bank

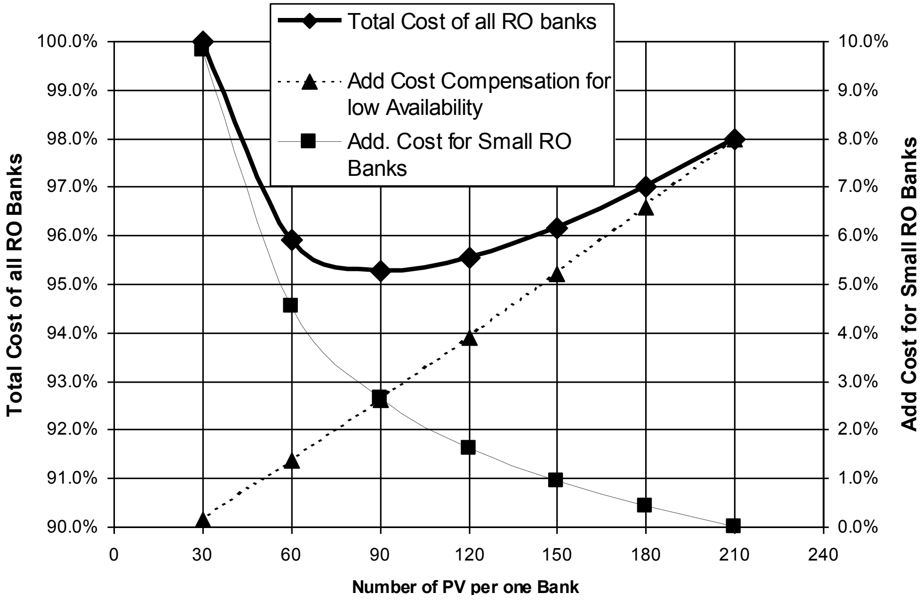
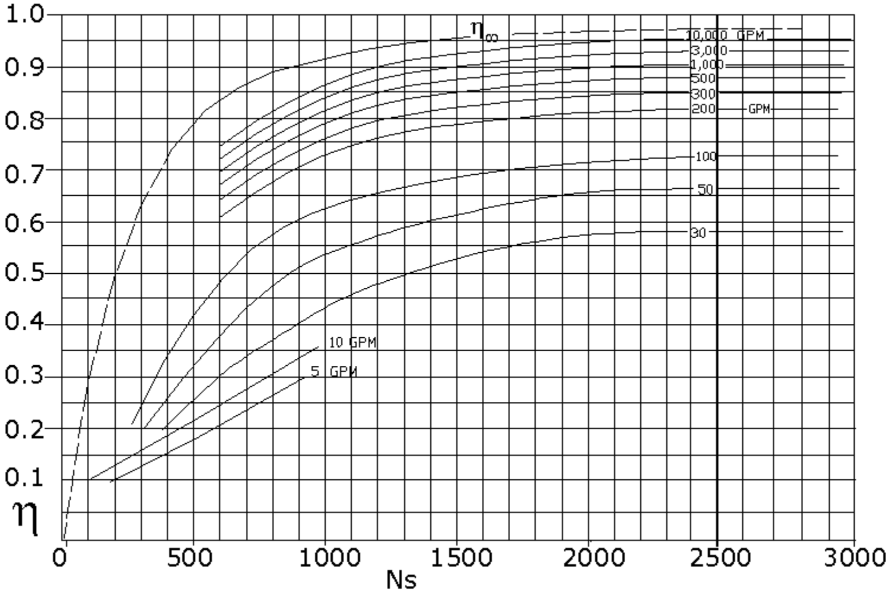


Figure 3 Pump efficiency as a function of specific speed and capacity.



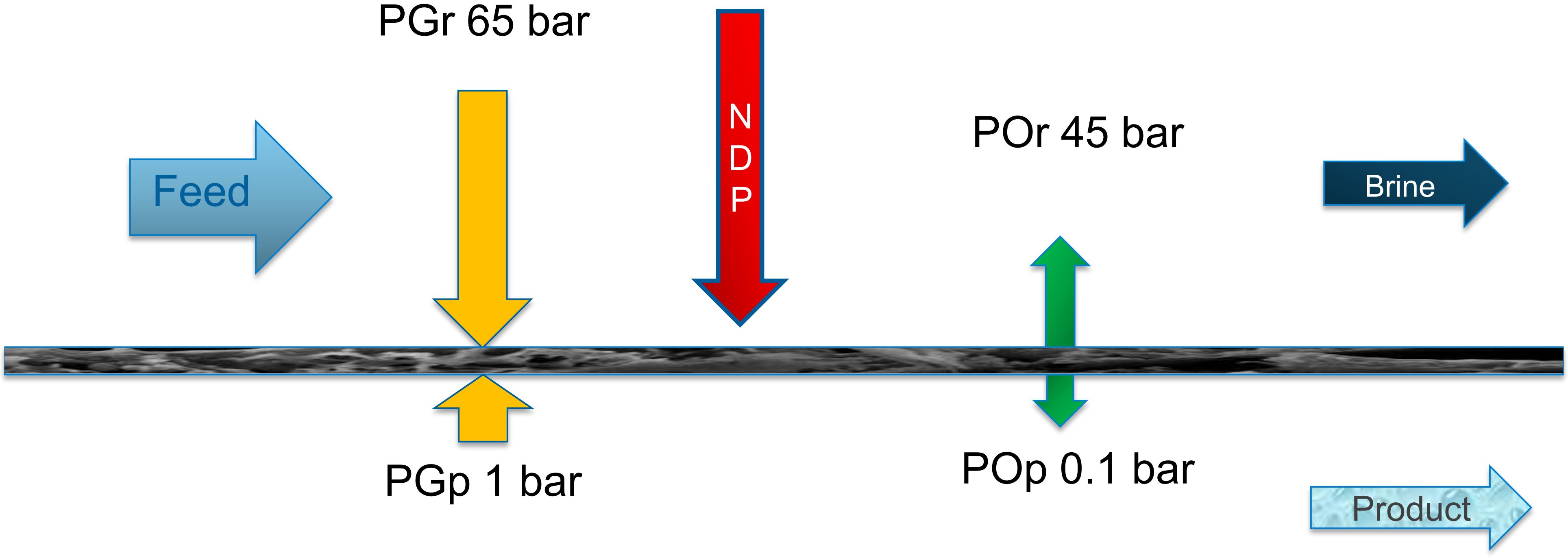
Keeping RO Membranes Clean

- Physical methods instead of harsh chemicals
  - Direct Osmosis High Salinity - **DOHS**

    and

  - Direct Osmosis Cleaning - **DOC**

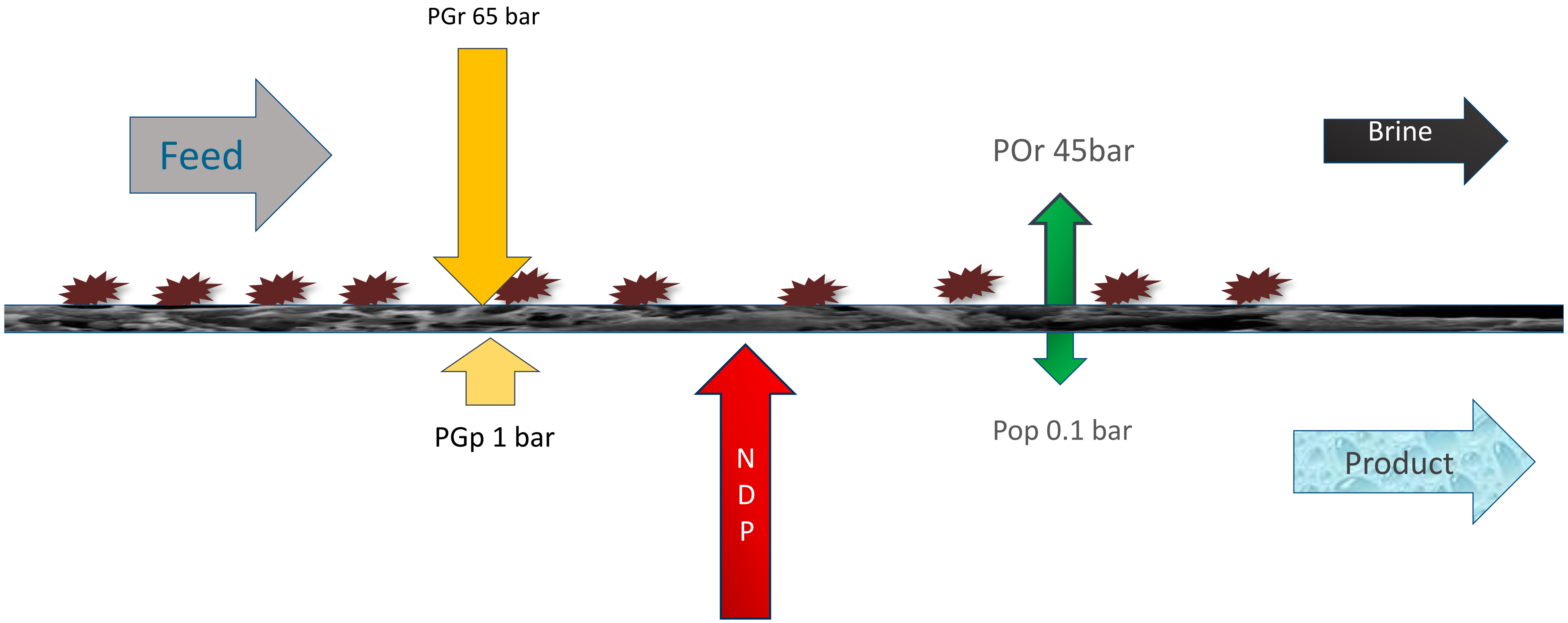
Normal RO Process



$$NDP_{RO} = PGr - POr - PGp + Pop$$

$$NDP_{RO} = 65 - 45 - 1 + 0.1 = +19.1 \text{ bar}$$

DOHS – Direct (Forward) Osmosis High Salinity Osmotic Backwash

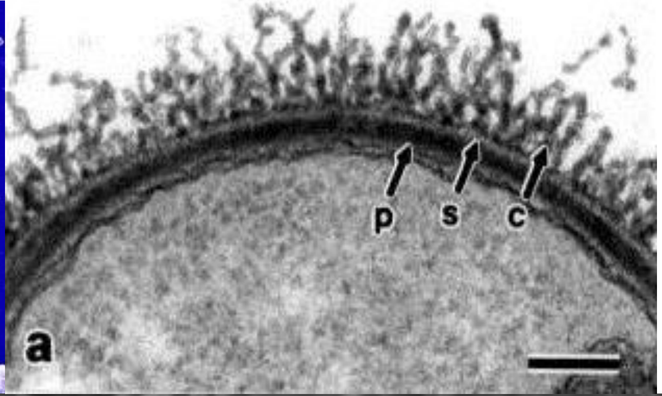


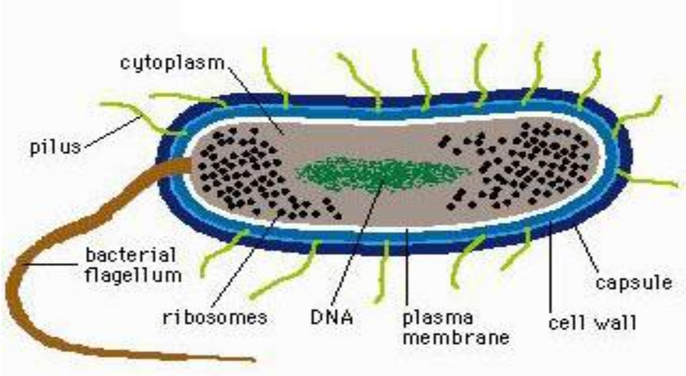
$NDP_{RO} = PGr - POr - PGp + Pop$

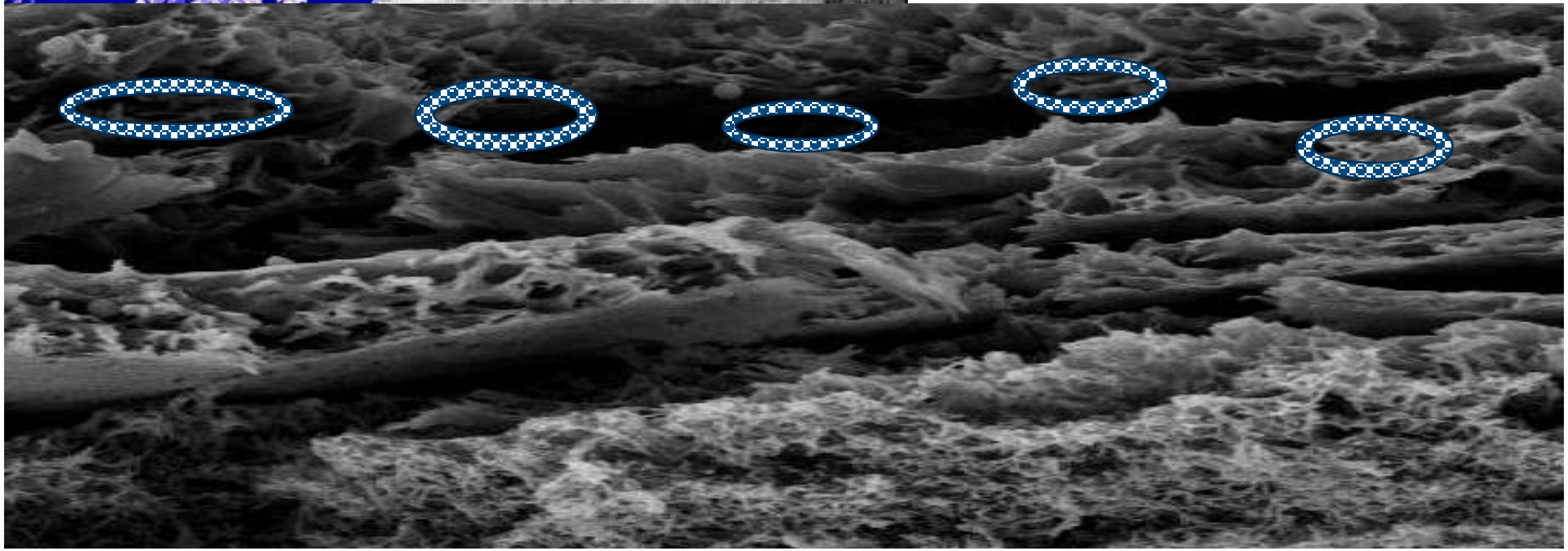
$NDP_{RO} = 65 - 45 - 1 + 0.1 = +19.1$ bar

$NDP_{DO\,(FO)} = 65 - 100 - 1 + 0.1 = -35.9$ bar

Osmotic Dehydration of Bacteria

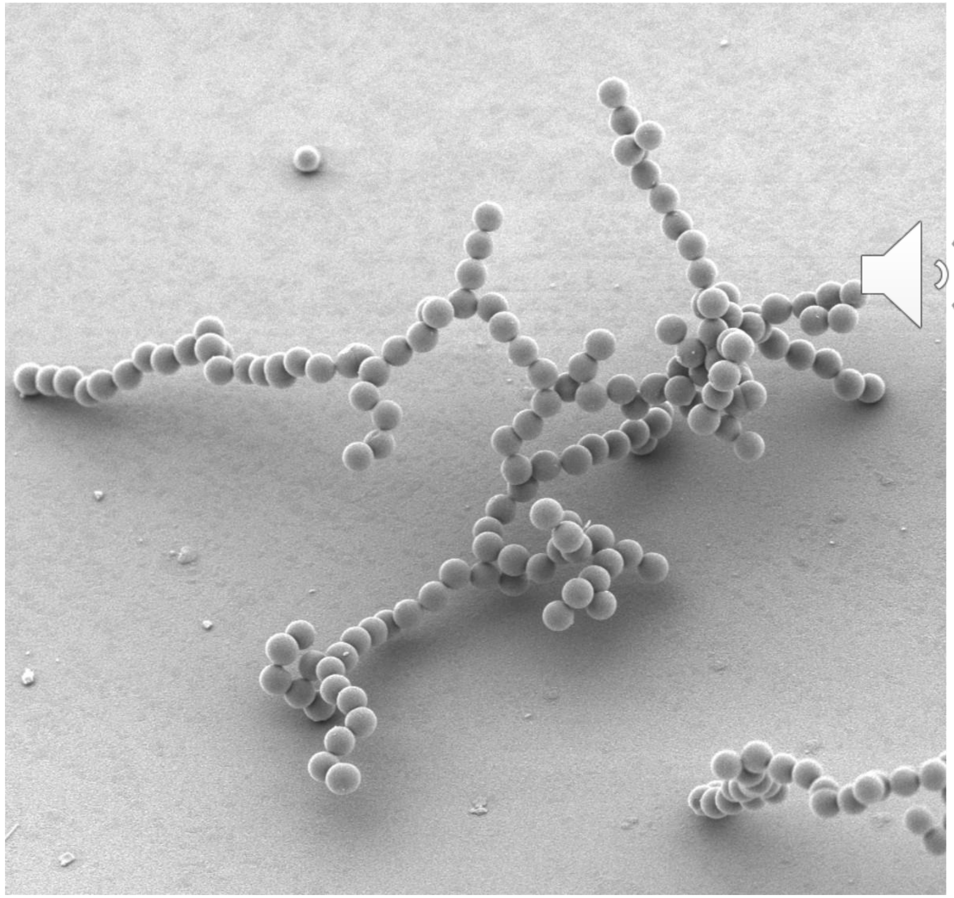


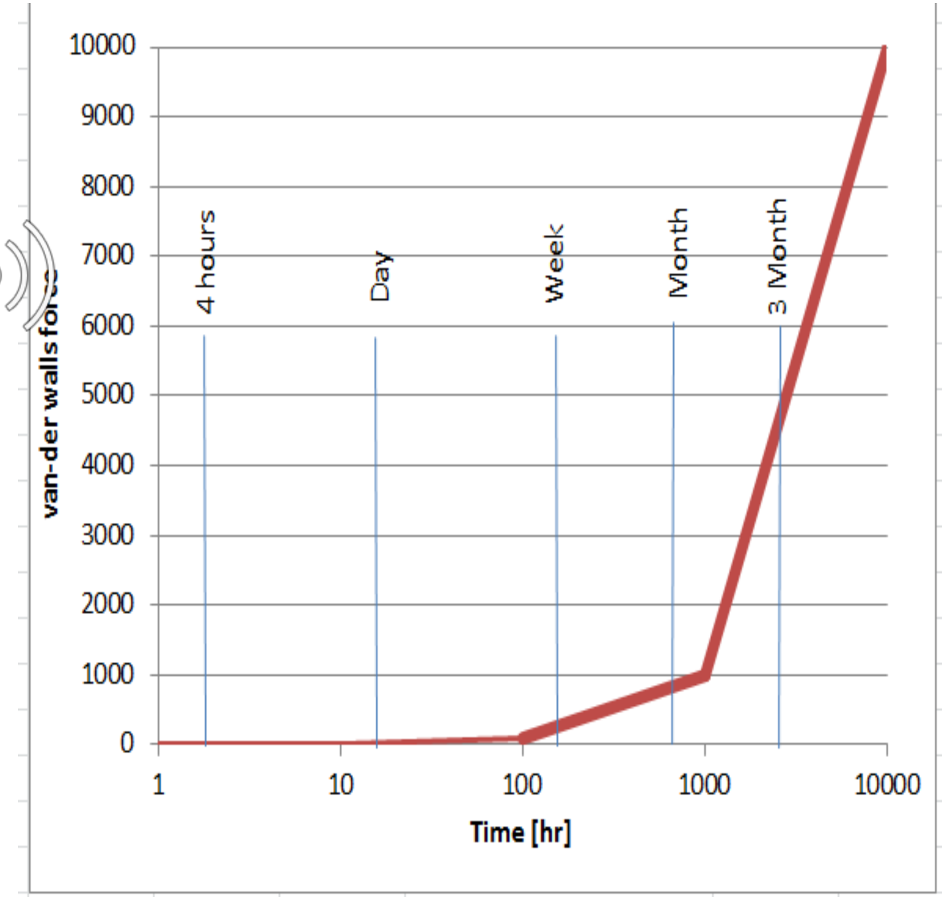




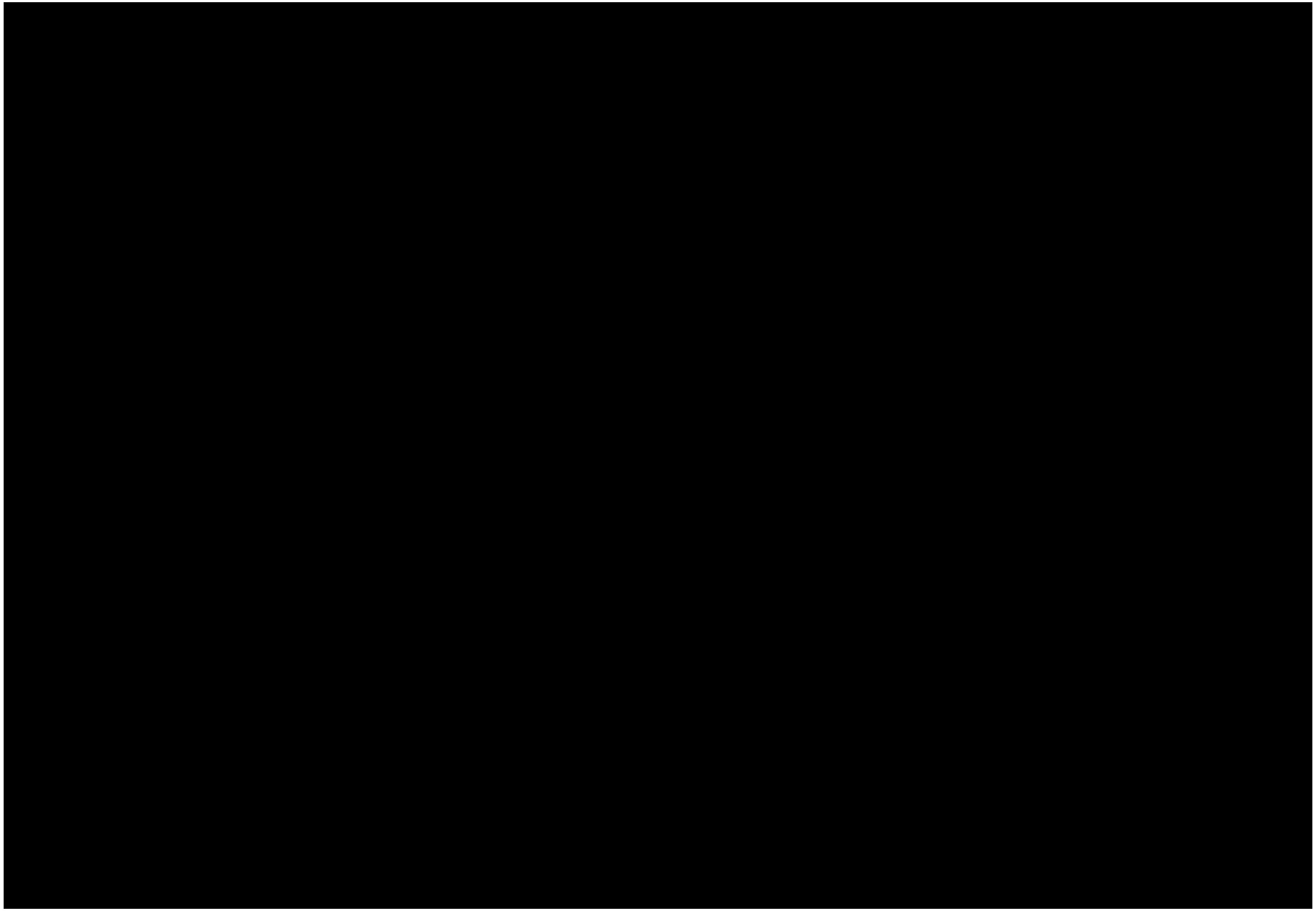
USA Pat.7,658,852; Australia Pat. 2005254337; Singapore Pat. 153812 Israel Pat. 169882 GB Pat. 1414263.2 GB PCT/IB2015/055665

Frequent removal of particles before a strong Van der Waals interaction is created with the surface





RO Membrane Direct Osmosis Cleaning



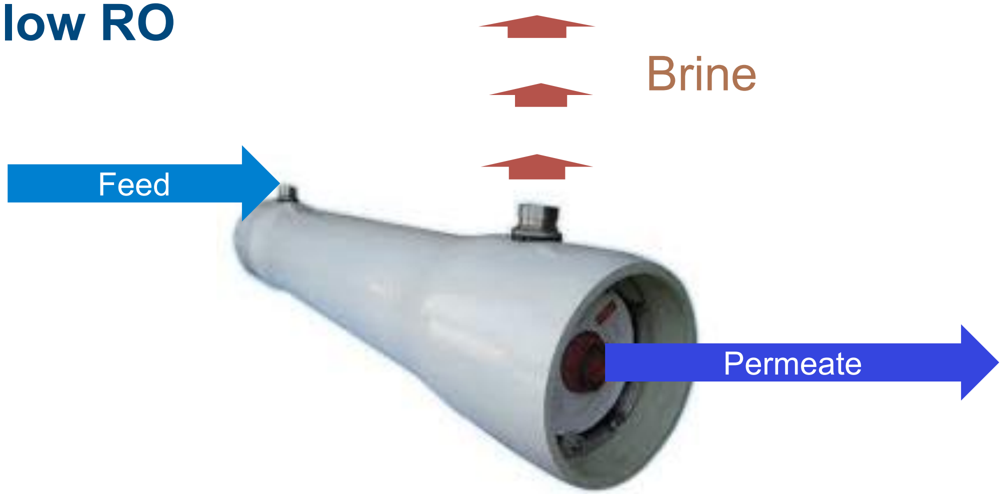
Pulse Flow RO Technology Implementation

- In wastewater applications allows:
  - Chloramine free water reuse desalination
  - Up to 95% recovery in single stage operation
  - High flux operation 28 LMH
  - 100% transmission of UV light
  - 20% saving in water cost

- In brackish water applications allows:
  - Extremely high recovery operation

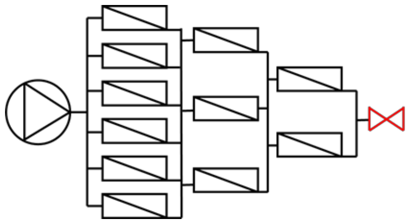
Conventional RO

Pulse Flow RO



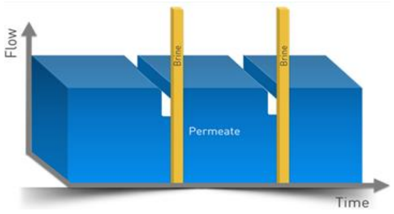
Conventional RO vs Pulse Flow RO

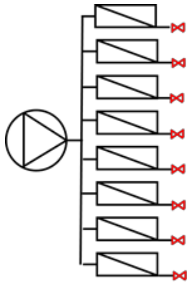
Continuous brine discharge



90% Recovery
Multi stage

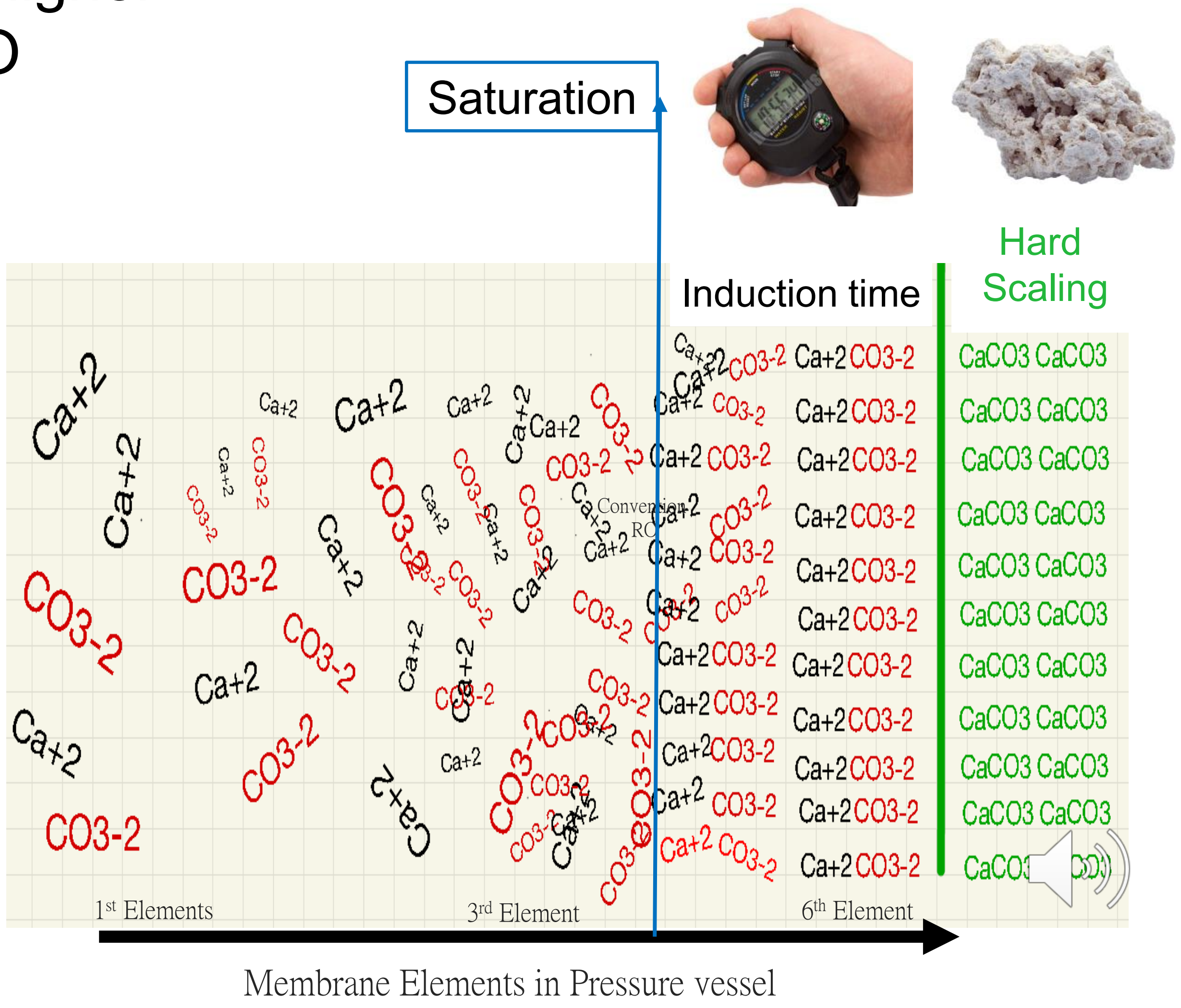
Brine discharge in pulses



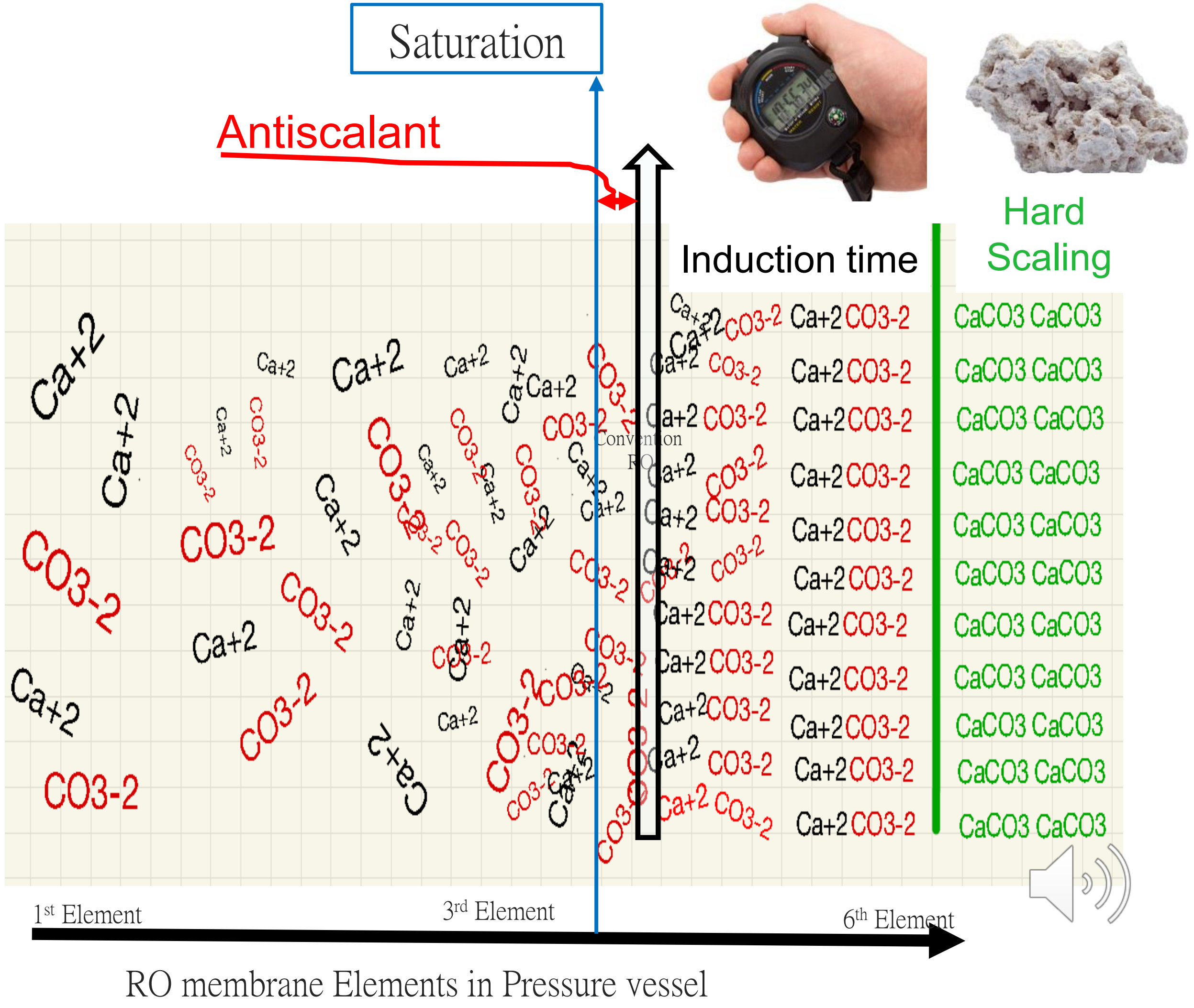


95% Recovery
Single stage

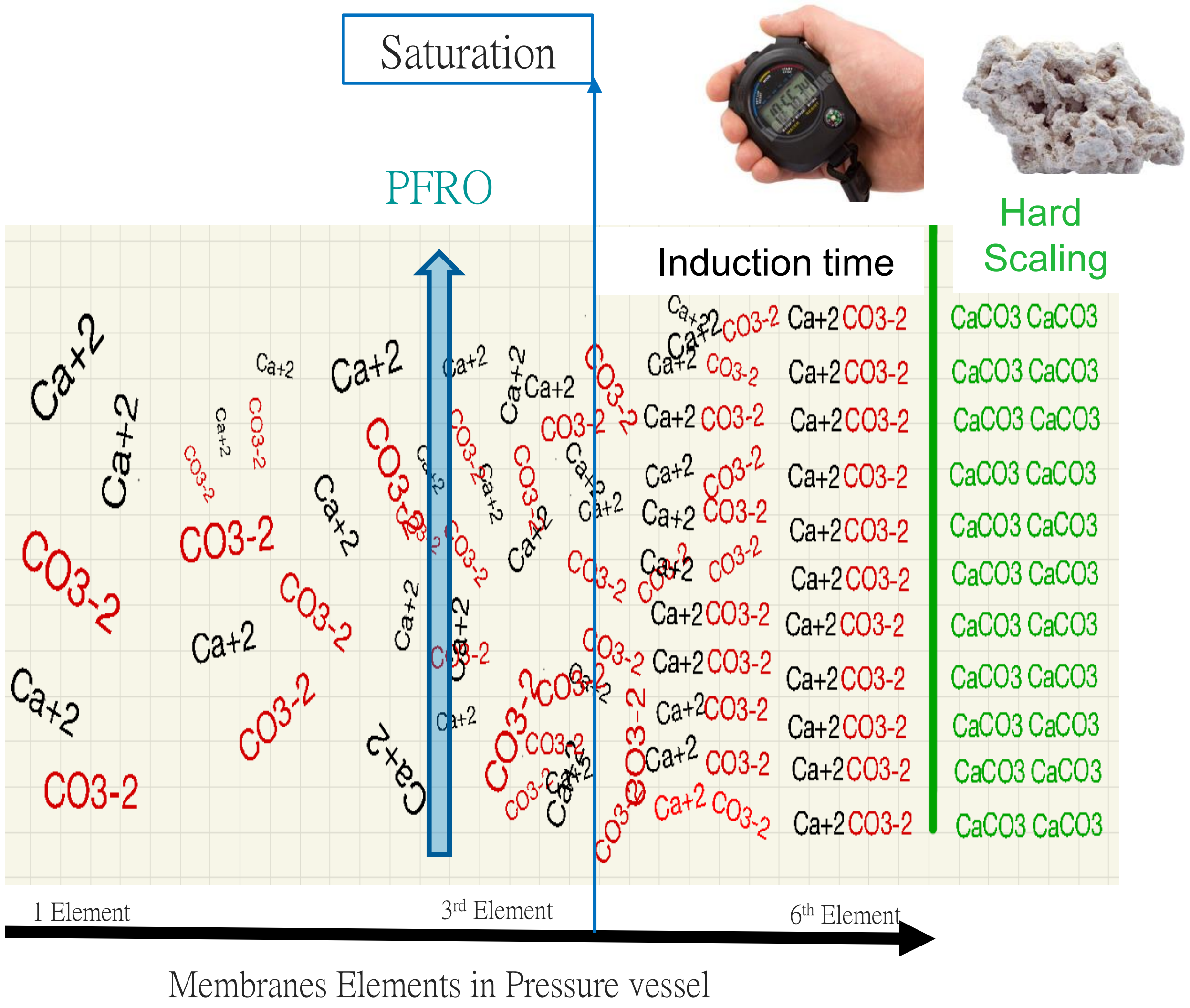
PFRO can reach significantly higher recovery than conventional RO



In conventional RO the induction time is endless



Pulse Flow RO
Higher recovery



PFRO Wastewater Demonstration Plant. Pismo Beach CA

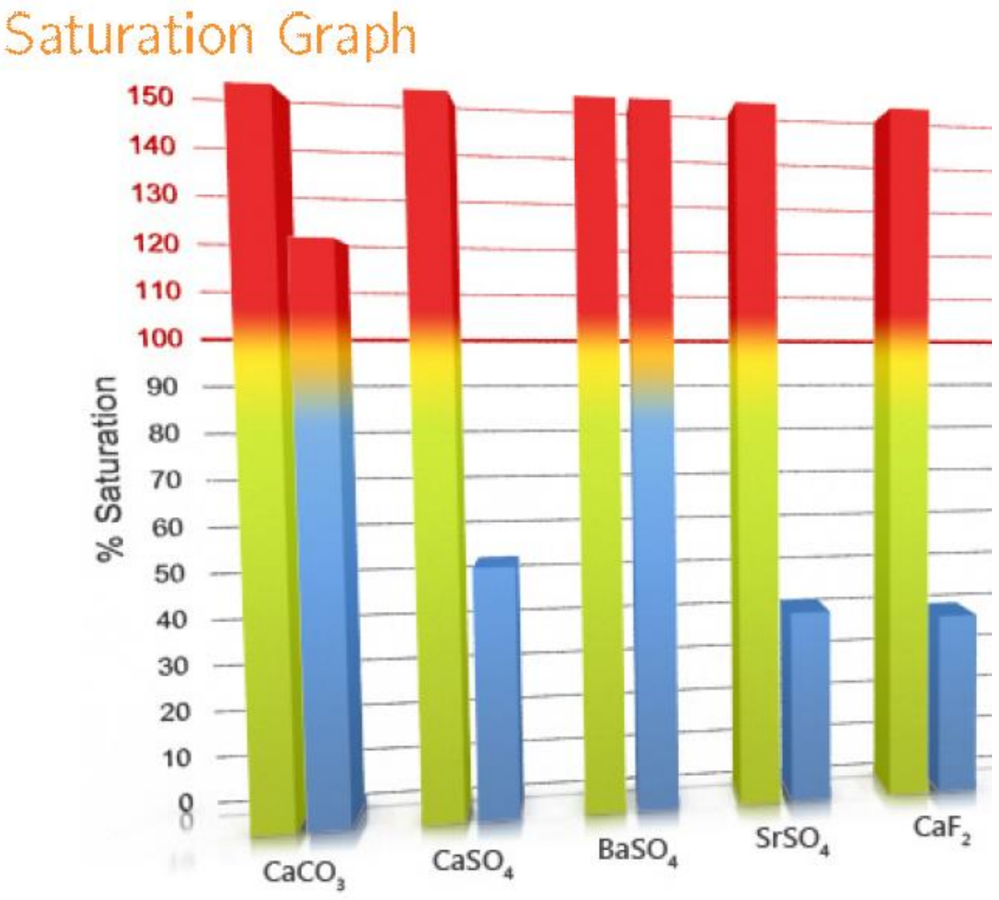
- Under the supervision of Carollo Engineers Inc
- The source - secondary effluent, municipal wastewater
- 86% recovery, no chloramine dosing

PFRO Brackish Water application
City of Abilene TX

- 80% recovery over final City brine

PFRO Demonstration Plant Abilene

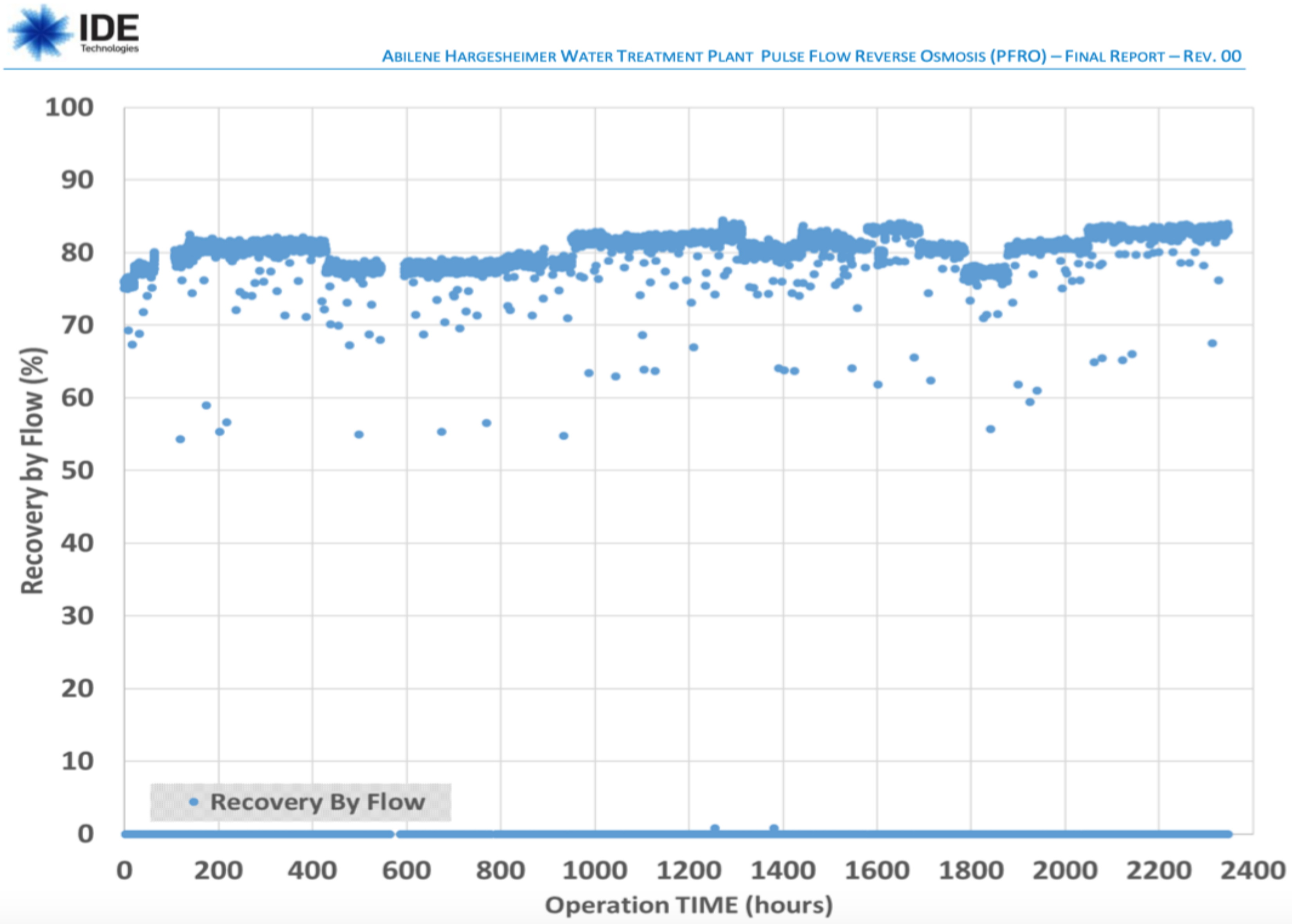
- Brackish water application
- 80% recovery over final City brine



Scaling Indices

	$CaCO_3$	$CaSO_4$	$BaSO_4$	$SrSO_4$	CaF_2	$Ca_3($
Conc. Untreated	222.30	409.17	51632	404.91	5249	0.

Recovery (%). Abilene



Specific Flux (GFD/PSI) Abilene

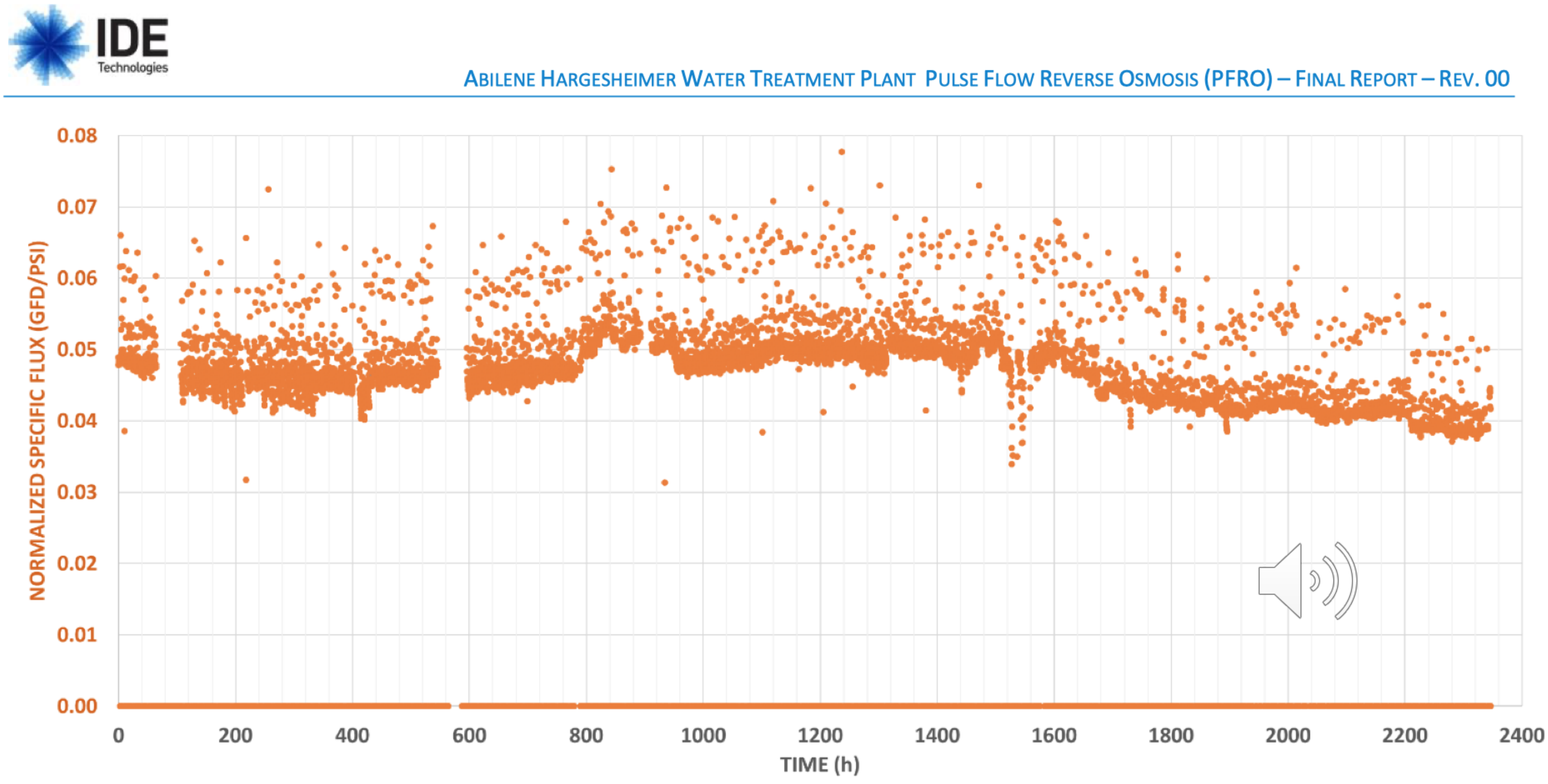


Figure 11: Specific Flux vs. Time

Product Conductivity

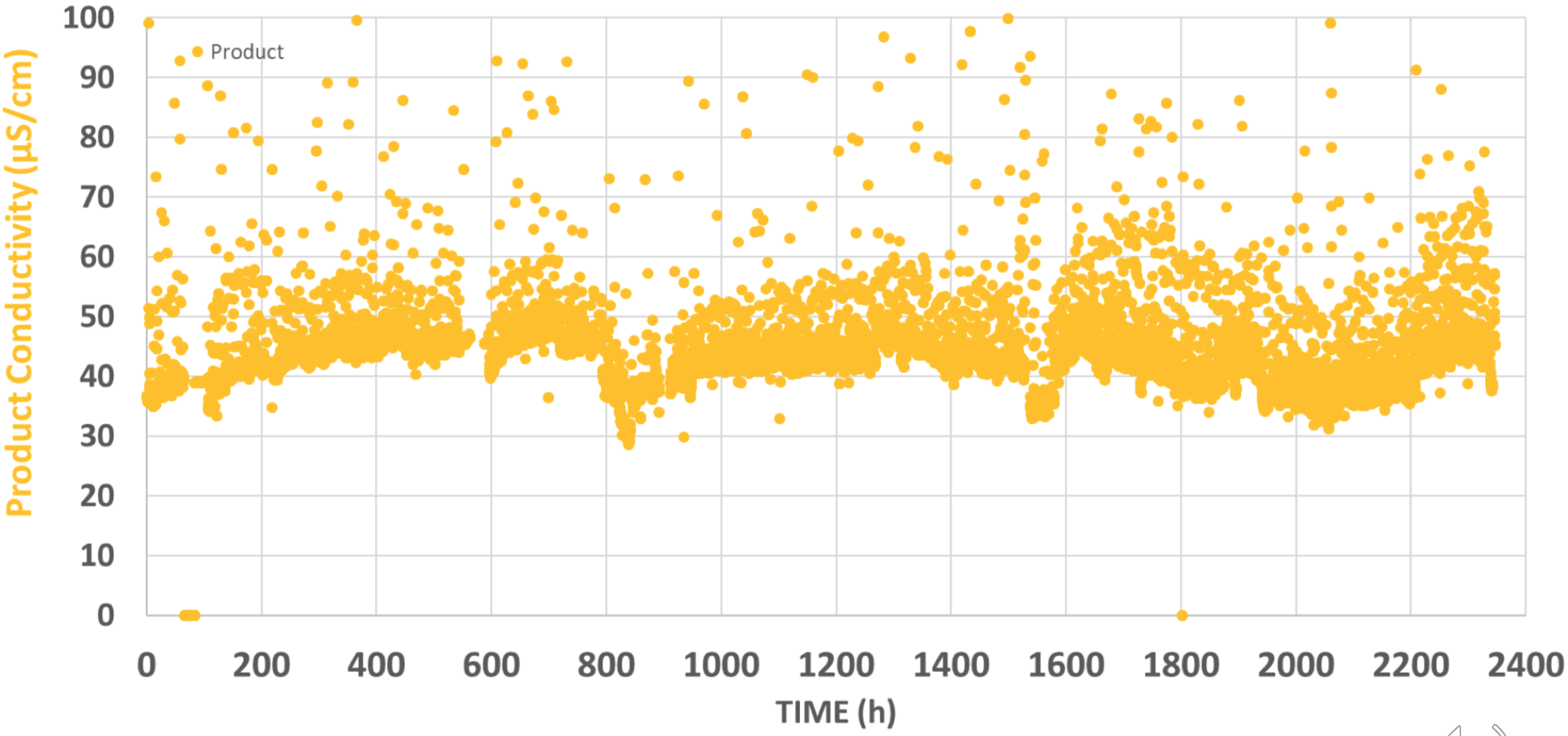


Figure 10: Permeate Conductivity vs. Time

THANK YOU

IDE | YOUR WATER PARTNERS