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Desalination Technology with Low Energy Consumption: Developments and Applications

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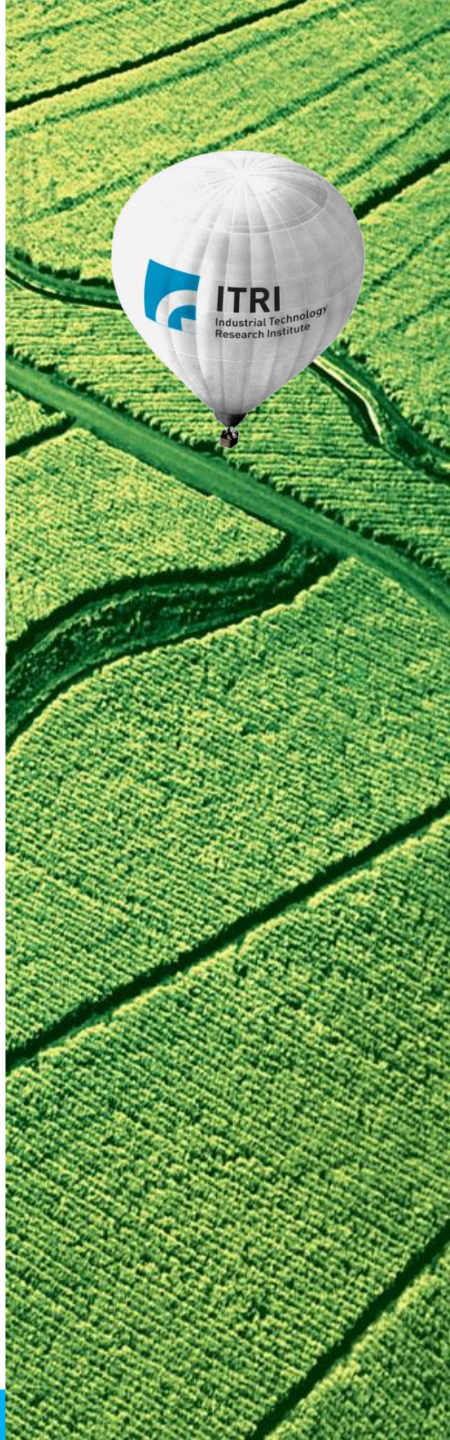
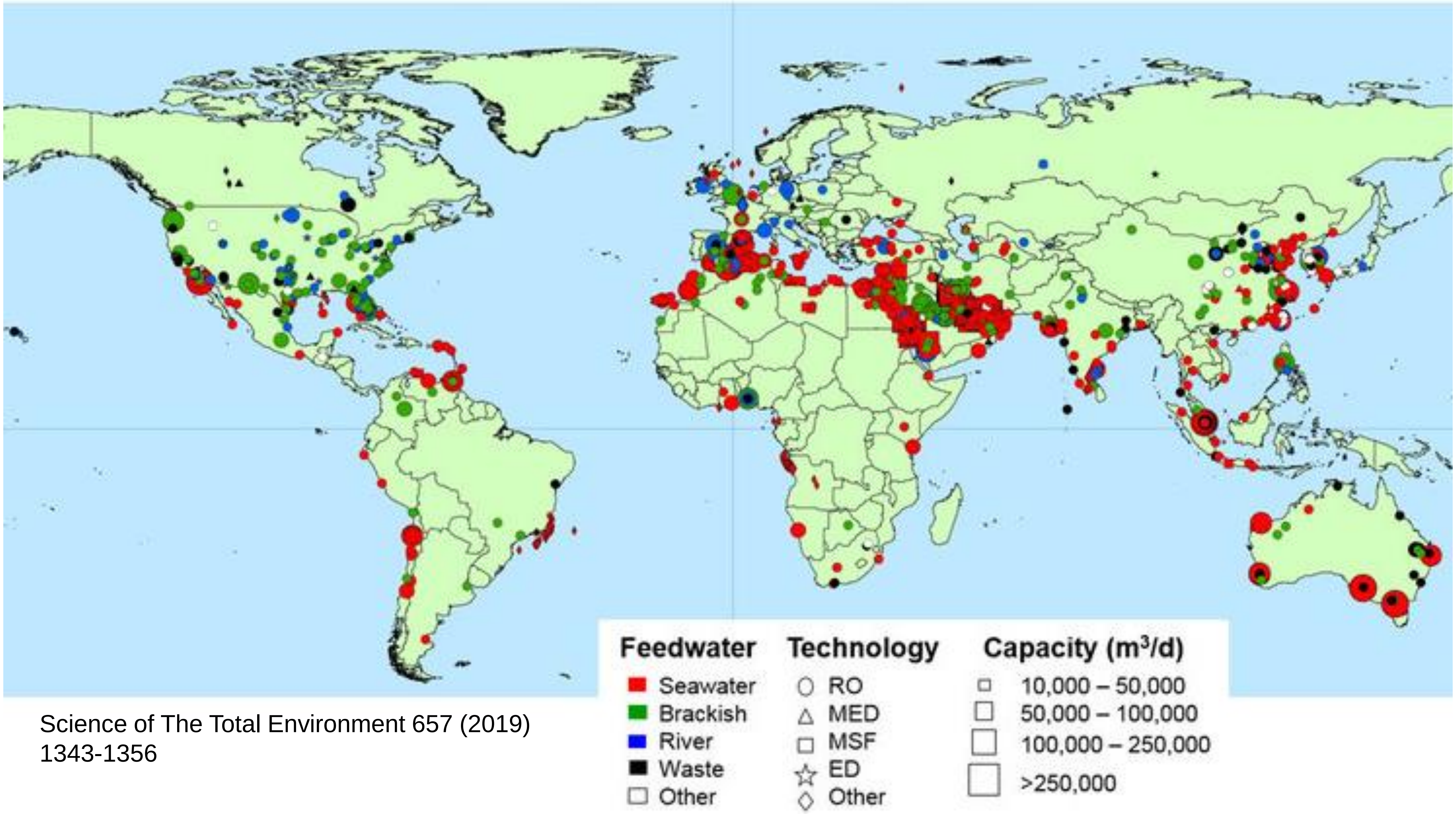


Sustainable Development Goals

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.**

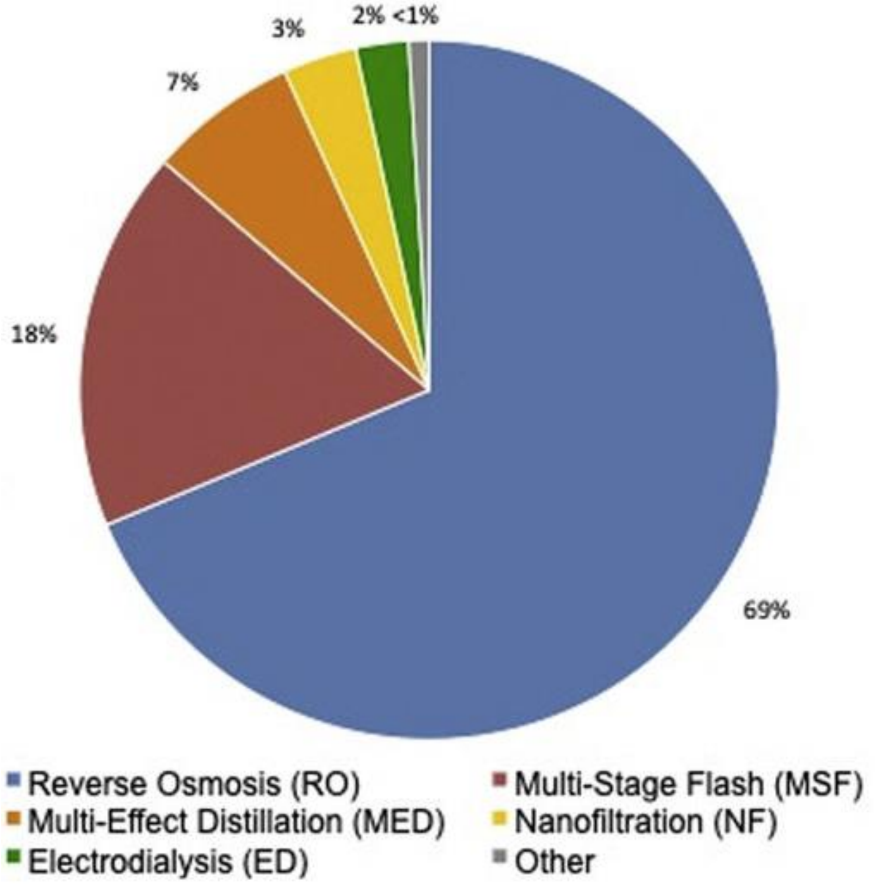
Global Distribution of Large Desalination Plants



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

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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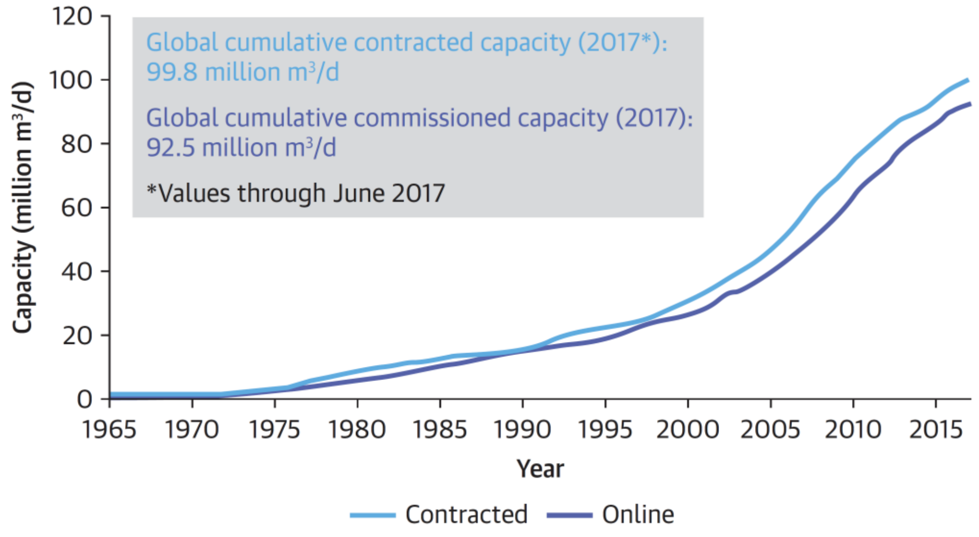
Current Status of Desalination Technology

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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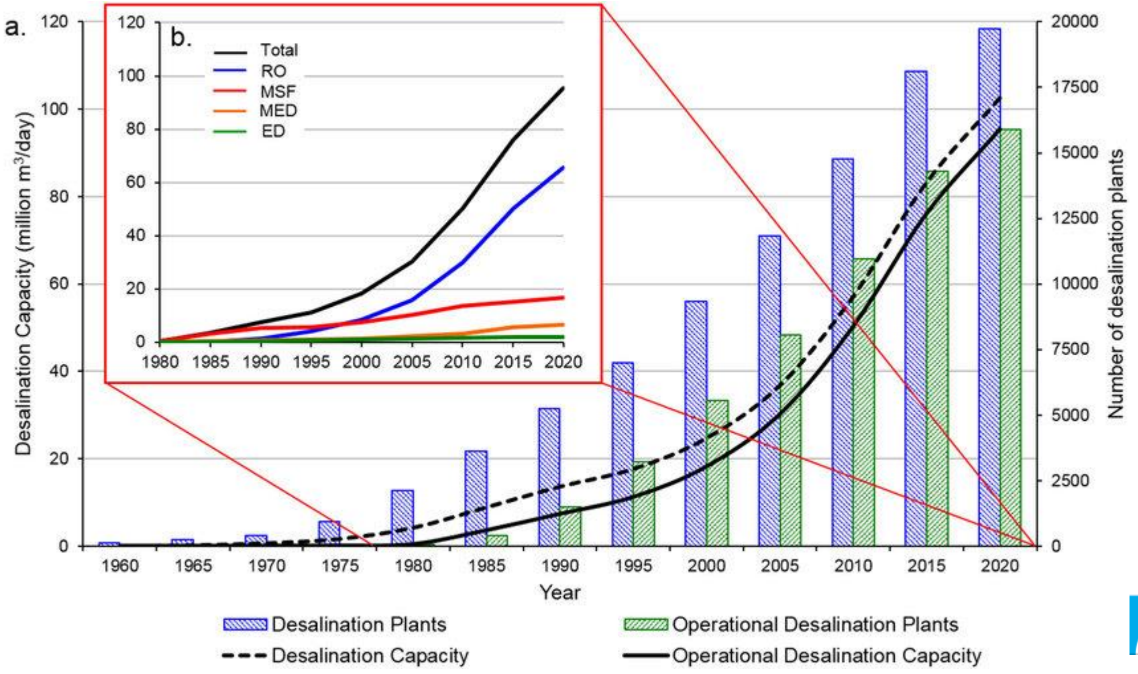
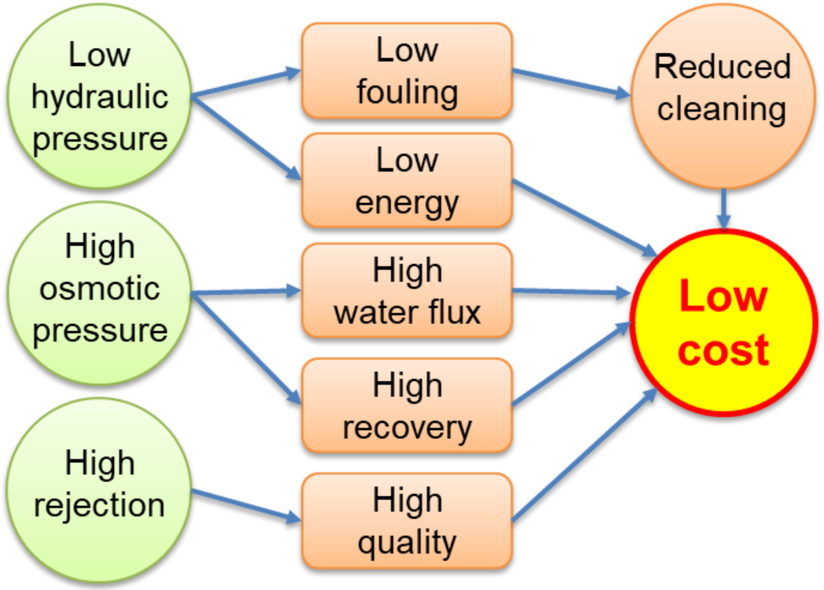
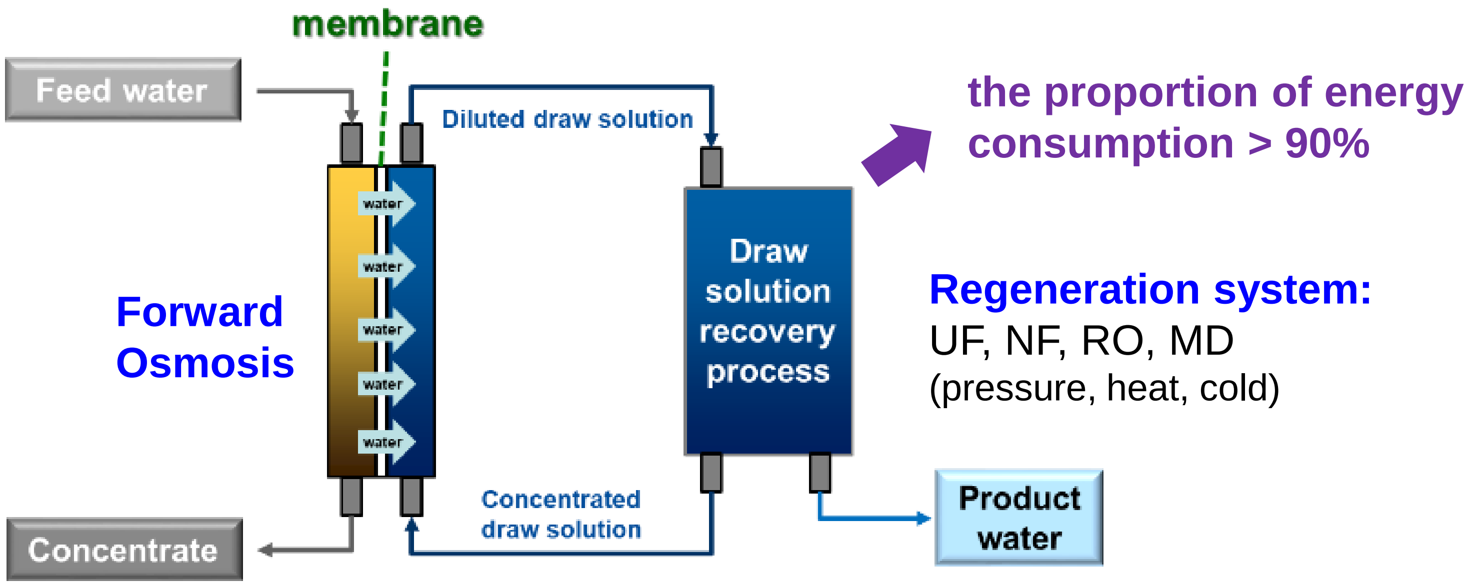


Forward Osmosis (FO)

- **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

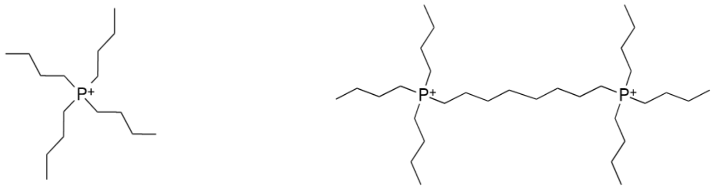




Thermal Responsive Draw Solute

- 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.

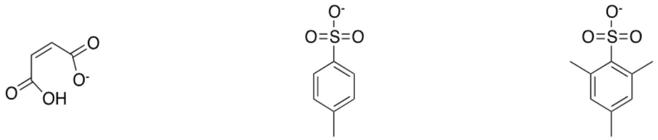
(a) cations



tetrabutylphosphonium cation ($[P_{4444}]^+$, P1)

1,8-octanediyl-bis(tri-n-butylphosphonium cation ($[(P_{4444})_2]^{2+}$, P2)

(b) anions



hydrogen maleate ($[Mal]^-$)

p-toluenesulfonate ($[TSO]^-$)

2,4,6-trimethyl-benzenesulfonate ($[TMBS]^-$)

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.

Phase separable → reducing → Consumption in separation process

High osmotic pressure → Increasing →

- Water flux
- Concentration ratio

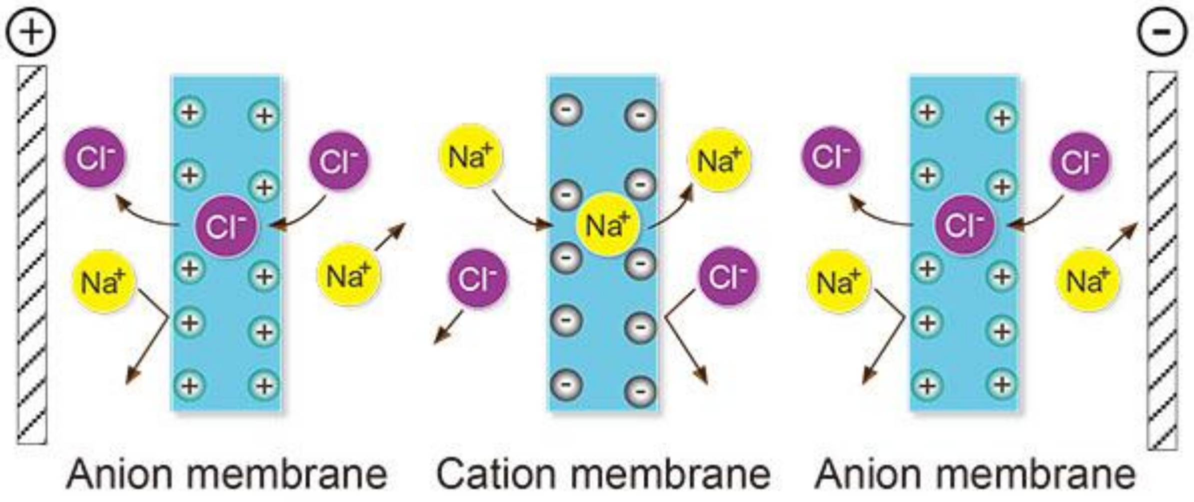
Water content %

90% 80% 70% 60% 50% 40% 30% 20% 10%

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: ≤1%
- Burst strength: ≥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: ≤1%
- Burst strength: ≥5 kg/cm^2
- pH tolerance: 1~13
- Permselectivity: 90%
- Dimension: 50 cm (W) x 100 cm (L)


0.5 Kg/batch

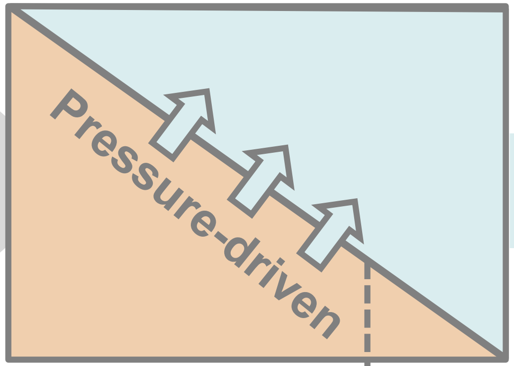

3 Kg/batch


10 Kg/batch

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

Reverse Osmosis (RO)

- **High operational pressure** (P > 15 kg/cm^2)
- **Limitation of influent WQ** (SDI < 15)



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

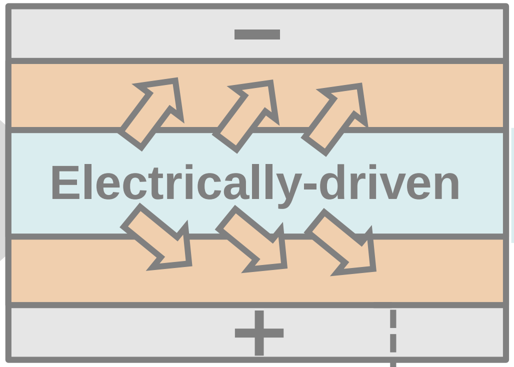
Energy consumption > 2.5 kWh/m^3

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/m^3

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.**

Wastewater treatment effluent → Pretreatment → EDR → Production water → Recycle to cooling tower

Q< 6,000 CMD
Cond.< 6,500 $\mu S/m$

EDR → Concentrate → Discharge

Q> 3,000 CMD
Cond.< 550 $\mu S/m$

EDR wastewater reclamation plant

EDR system for wastewater reclamation

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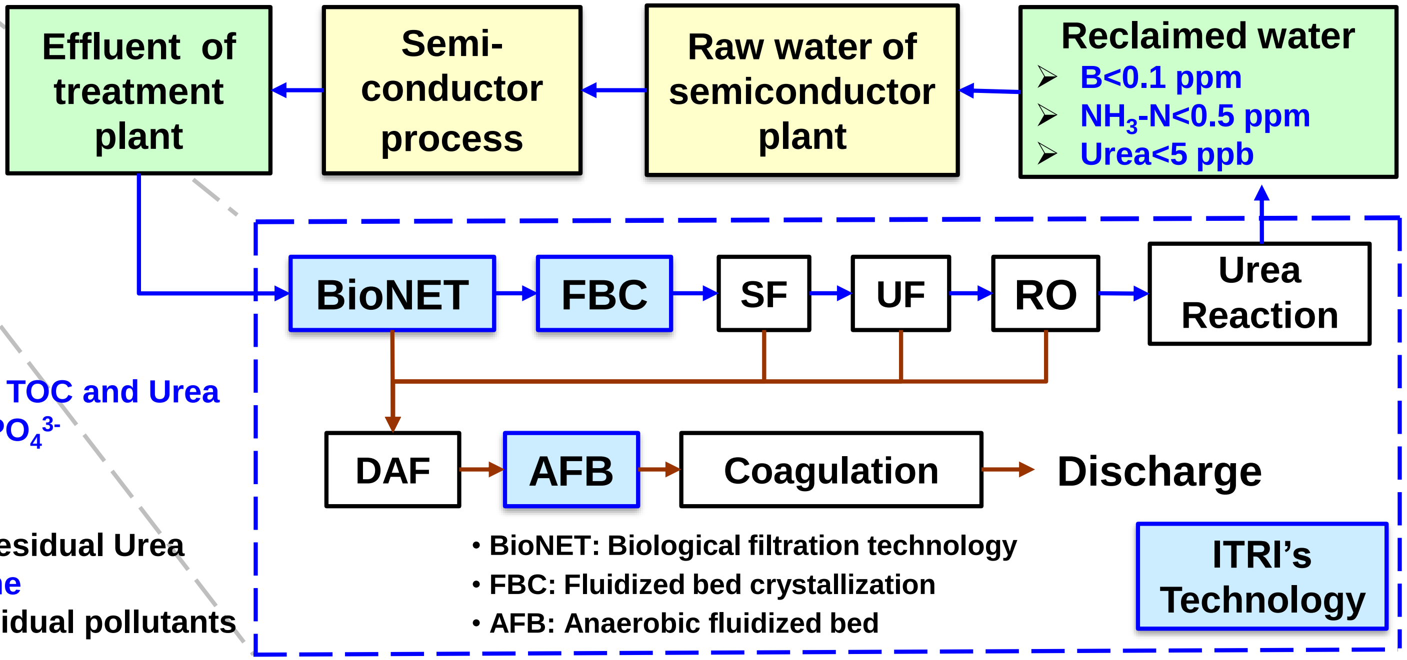
Industrial Wastewater Reclamation for Semiconductor Manufacturing

- **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

ED Hybrid System for Seawater Desalination

Traditional Desalination: SWRO

Problem Issue
- High-pressure operation (50~80 kg/cm^2) cause high energy consumption/carbon emission

Seawater → **pretreatment** → **SWRO** → **Desalinated water**

40,000 mg/L

High TDS brine rejection

Low-Carbon Desalination: ED/LPRO

Features
- Tolerance in various influent water quality

Seawater → **pretreatment** → **ED / LPRO** → **Desalinated water**

40,000 mg/L

Brine

Electrodialysis reversal (EDR)
- **High TDS influent pretreatment**
- **Gradient potential control for energy saving**

Low-pressure RO (LPRO)
- **Ensure produced water quality**
- **Lower loading of 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

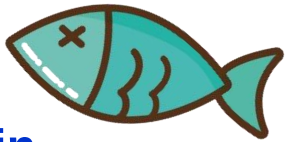
Brine produced from seawater desalination and wastewater reclamation have huge environmental impact on receiving water body.

Desalination Plant

Brine

Desalted Water

Adverse effect to the environment



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

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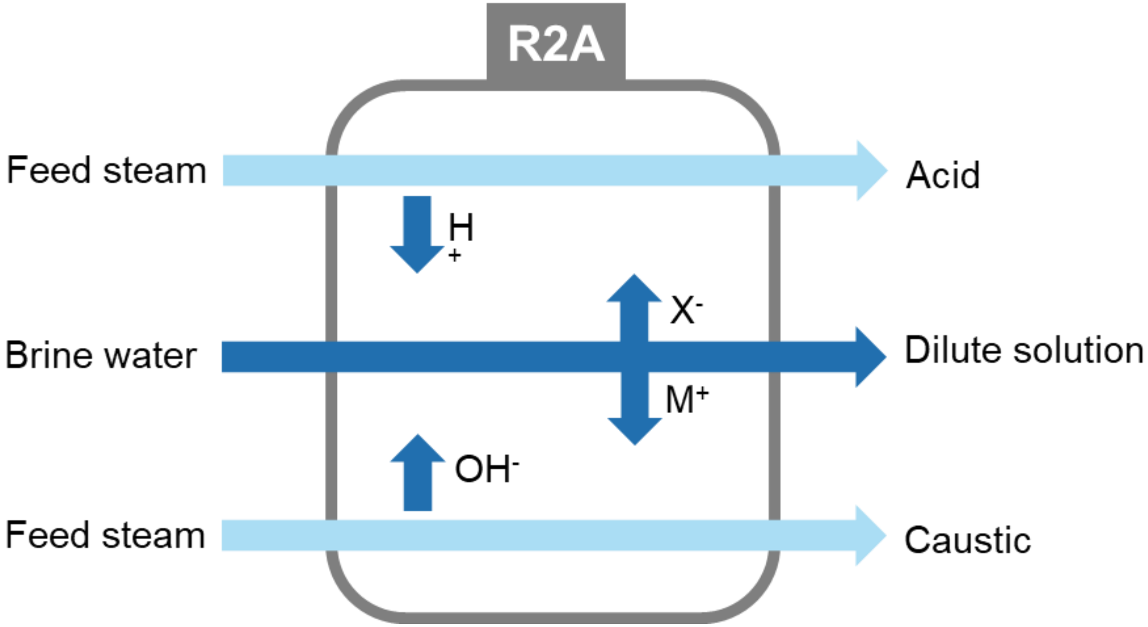
From Waste to Resources?
Valuable Resource Recovery from Brine

Membrane-Based Electro-Separation Technology



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

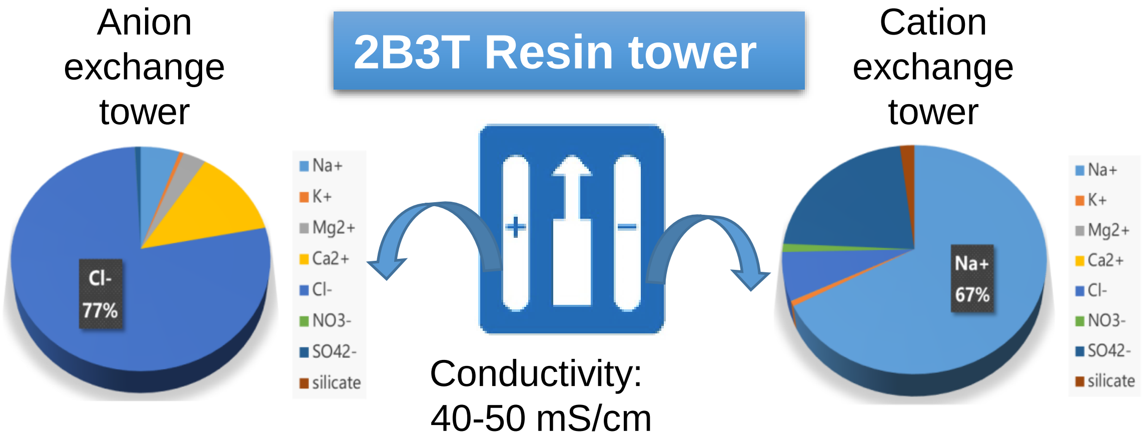
Recovery to Acid and Alkali (R2A)

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

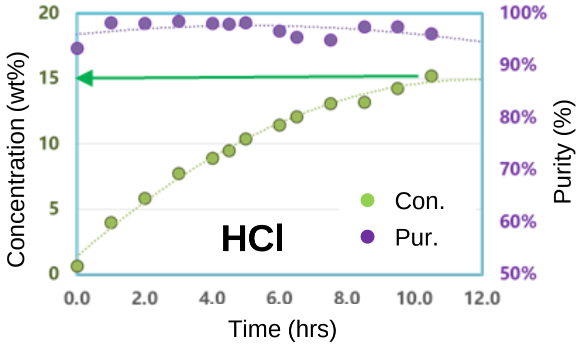
Applications

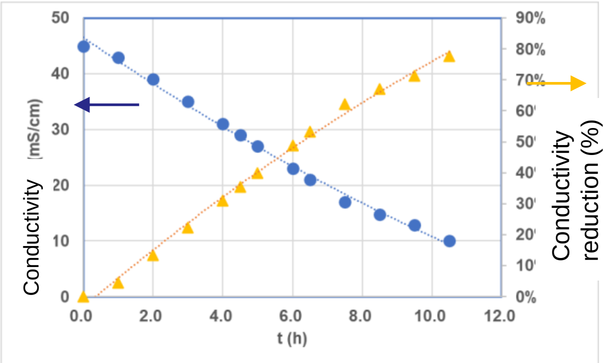
- Brine recovery (cation/anion)
- Production of acid/caustic from mixed salt in liquid phase
- Pretreatment for final MVR/MED of ZLD process

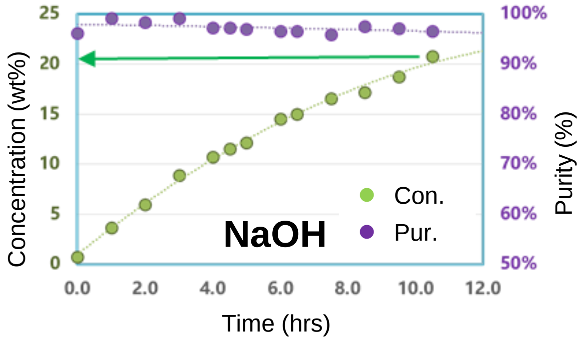
High Conductivity Waste Liquor Converting to Acid/Caustic Soda



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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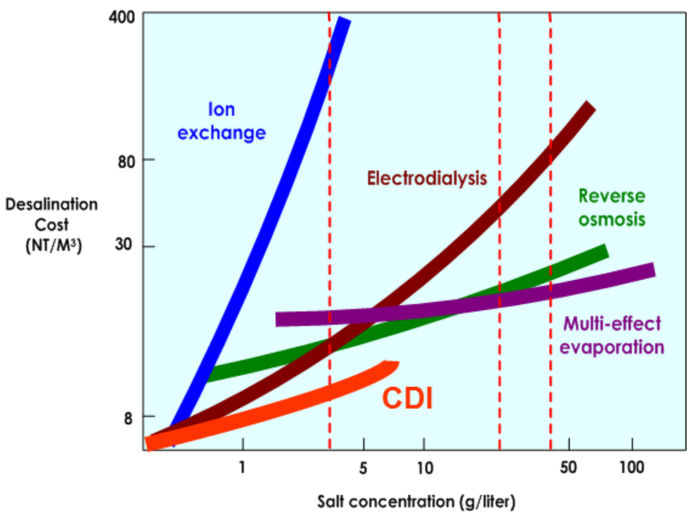
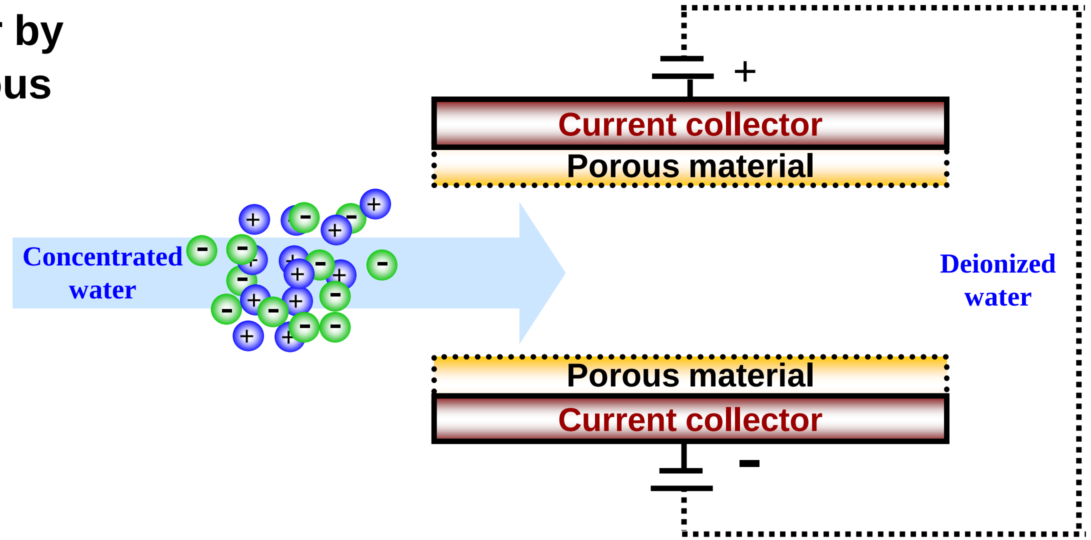
Capacitive Deionization (CDI)

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**

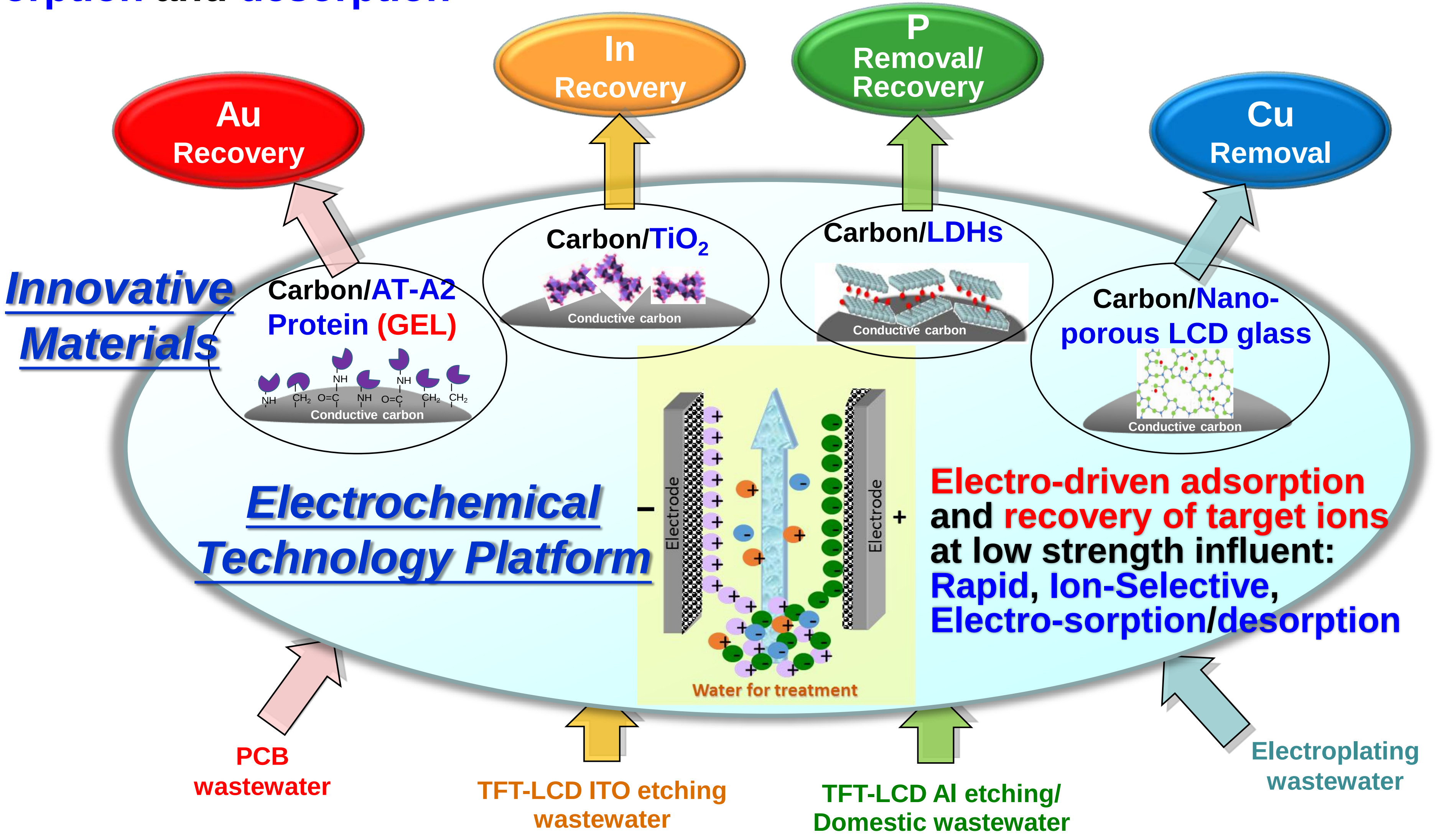


- **CDI technology**
  Salts and minerals are removed from water by applying an electric field between two porous electrodes
- **Ideal electrode materials for CDI**
  Highly conductive, high surface area, suitable pore size distribution
- **Application**
  More economical at lower concentrations



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!

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