Seawater Desalination Waste Brine Valorization: A New Frontier for Sustainable feedstock for salt-based chemical industries

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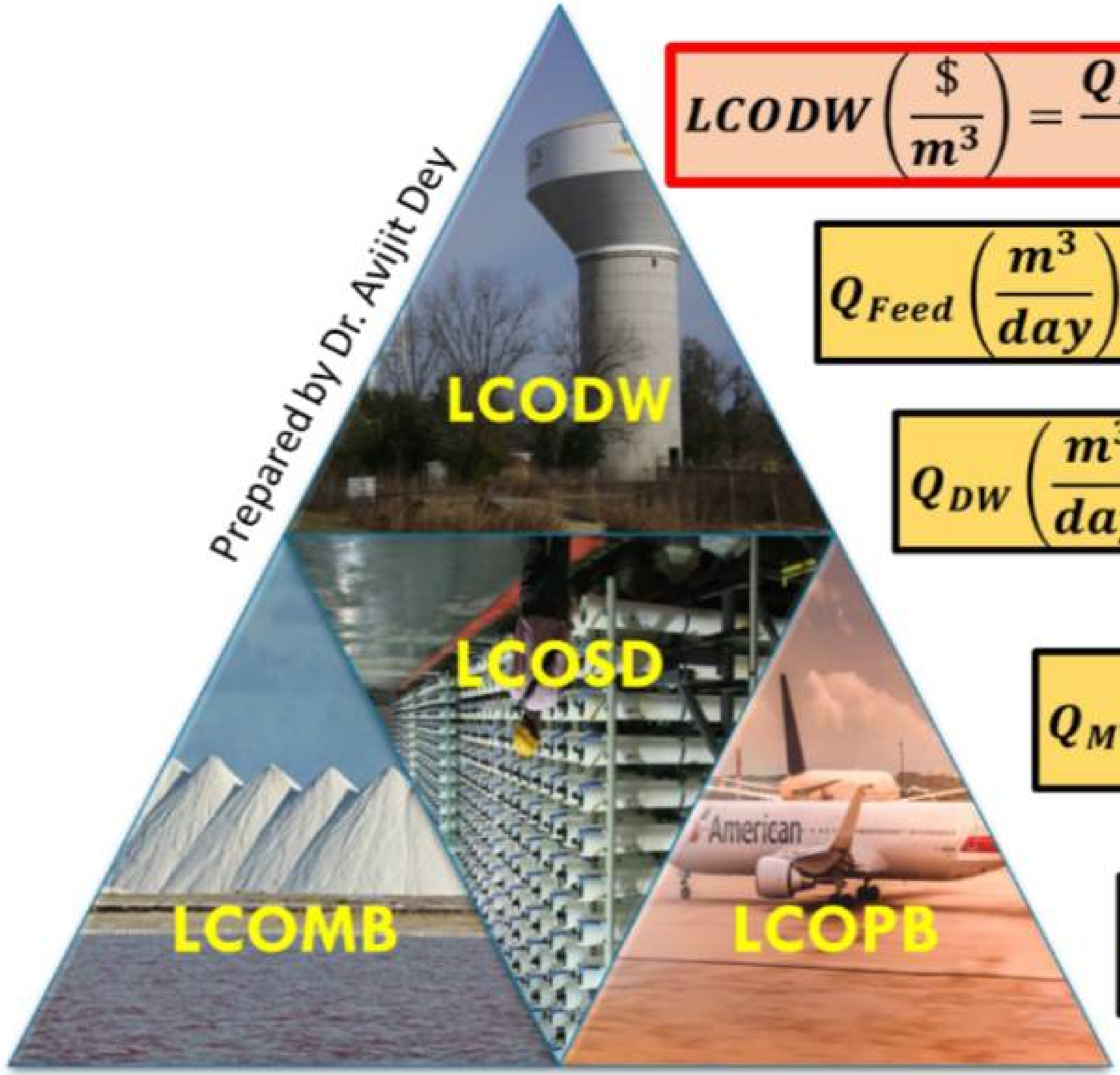
Brine Valorization: A Circular Economy approach

Why Circular economy?

- A **linear economy** operates on a "take-make-dispose" model, extracting raw materials to create products that are used and then discarded as waste.
- Conversely, a **circular economy** aims to eliminate waste by keeping materials in use through, recycling, repairing, and reusing products, focusing on sustainable resource regeneration.
- **Waste Brine valorization** from seawater desalination simultaneously eliminates burden of disposal and reduces raw material demand for salt-based chemical industries e.g., synthetic soda ash and chlor-alkali.

Singh, Varun & Buelens, Lukas & Poelman, H. & Marin, Bryan & Galvita, Vladimir. (2023). Chemical looping: a technology platform for upcycling low-grade industrial resources. Discover Chemical Engineering.

Seawater Brine Valorization



$$LCODW\left(\frac{\$}{m^3}\right) = \frac{Q_{Feed} \times LCOSD - Q_{MVR} \times LCOMB - Q_{PVR} \times LCOPB}{Q_{DW}}$$

$$Q_{Feed}\left(\frac{m^3}{day}\right) = Feed\ Flow\ rate\ to\ SDP$$

$$Q_{DW}\left(\frac{m^3}{day}\right) = Desalinated\ water\ Flow\ rate\ from\ SDP$$

$$Q_{MVR}\left(\frac{m^3}{day}\right) = MVR\ Brine\ Flow\ rate\ from\ SDP$$

$$Q_{PVR}\left(\frac{m^3}{day}\right) = PVR\ Brine\ Flow\ rate\ from\ SDP$$

LCOSD: Levelized Cost of Selective Desal; LCODW: Levelized Cost of Desal Water, LCOMB: Levelized Cost of MVR brine; LCOPB: Levelized Cost of PVR brine

Monetization of Excess Water in Chemical Plants with integrated Brine Valorization

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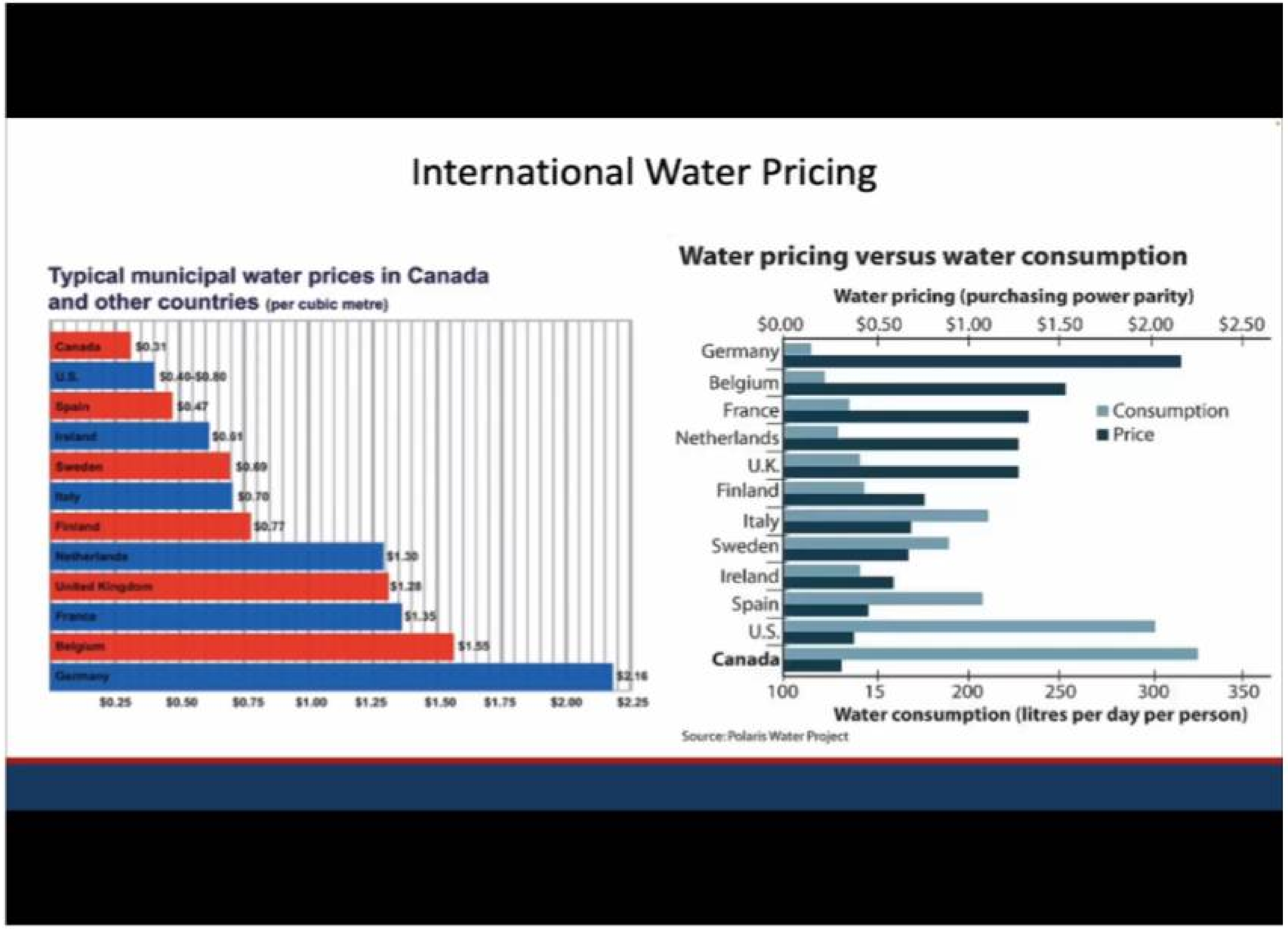

- ❑ In both synthetic soda ash and chlor-alkali facilities, partial reduction of salt demand by generating NaCl brine utilizing advanced membrane-based valorization unit operations at or above 225 grams per liter concentrations will lead to co-production of significant excess desalinated water which needs to be monetized to achieve reasonable ROI.
- ❑ In India, low industrial water tariffs present a significant barrier to the cost recovery of expensive seawater desalination, although some coastal industries are adopting the technology for its reliability.
- ❑ In India, increasing industrial tariffs for desalinated water is a critical strategy for ensuring cost recovery and the financial viability of desalination projects. Industrial users, who require high-quality water for manufacturing and processing, represent a key market for this

Brine Valorization and Sustainability

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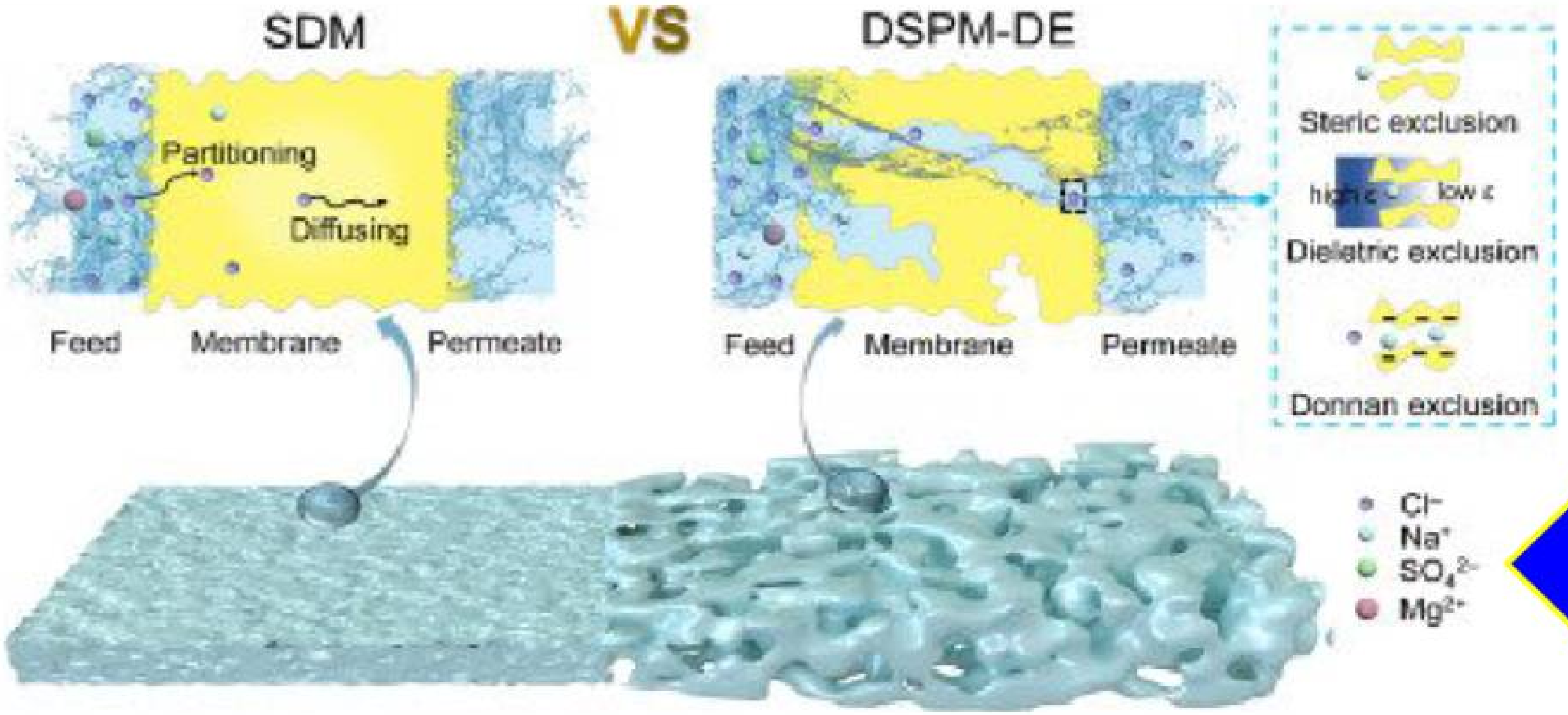
- The UN's 17 Sustainable Development Goals (SDGs) aim to end poverty, protect the planet, and ensure prosperity for all by 2030. These interconnected goals provide a shared blueprint for a sustainable future.

- Brine valorization is aimed to serve the following objectives as explained below:
  6: generating desalinated water
  7: hydrogen-based energy from water
  8: spur economic growth by supplying feedstock to chemical industries
  9: brine valorization stimulate innovations
  12: optimize production with limited feedstock
  13: helps in decarbonization (e.g., green

Source: United Nations; Department of Economic and Social Affairs. Do you know all 17 SDGs? Available online: https://climate-wise.com/industry-news/do-you-know-all-17-sdgs/ (accessed on 4 August 2022).

Brine Valorization Starts with Selective Separation: NF

Solution Diffusion Model (SDM): Appropriate for RO is not Appropriate for NF

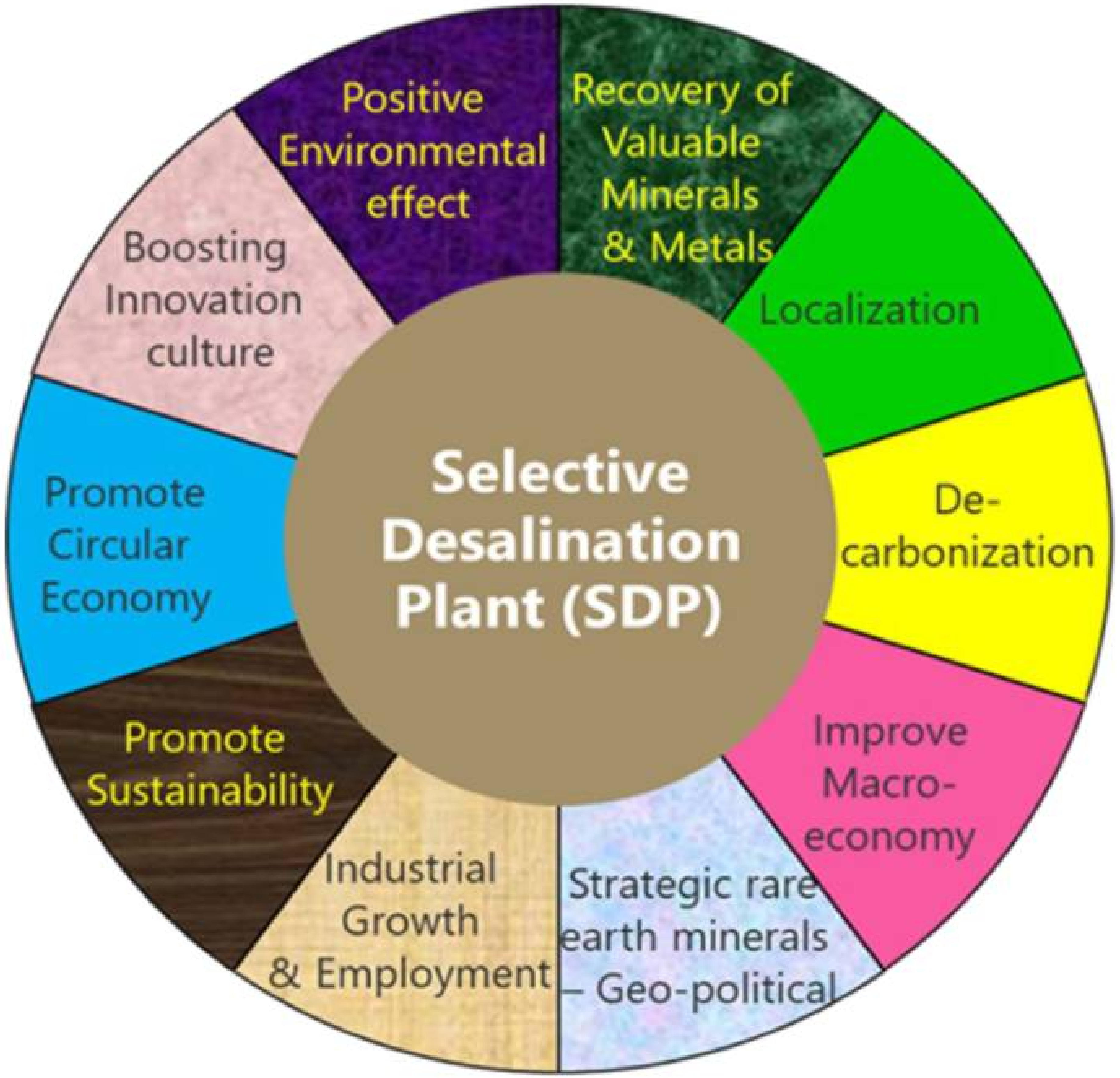


Source: Sun et al., "Exploring mass transfer mechanisms in reverse osmosis membranes: A comparative study of SDM and DSPM-DE models", Desalination, Volume 586, 1 October 2024.

Steric Hindrance effect

- NF membranes pore size distribution (1-10 nm), and RO Pore size (0.1 to 1 nm).
- NF possess a surface charge, often negative, due to the presence of functional groups within the membrane matrix.
- This charge leads to electrostatic interactions between the membrane and charged solutes (Donnan effect or Donnan exclusion).
- NF involves a combination of steric hindrance (size exclusion) and Donnan and dielectric exclusion.
- Divalent cations like Ca^{2+} and Mg^{2+}, being counter-ions, are less effectively rejected compared to the anions (SO_4^{-2}).
- SDM can not address influence of membrane charge, pore size distribution, and the presence of

Benefits of Seawater Brine Valorization



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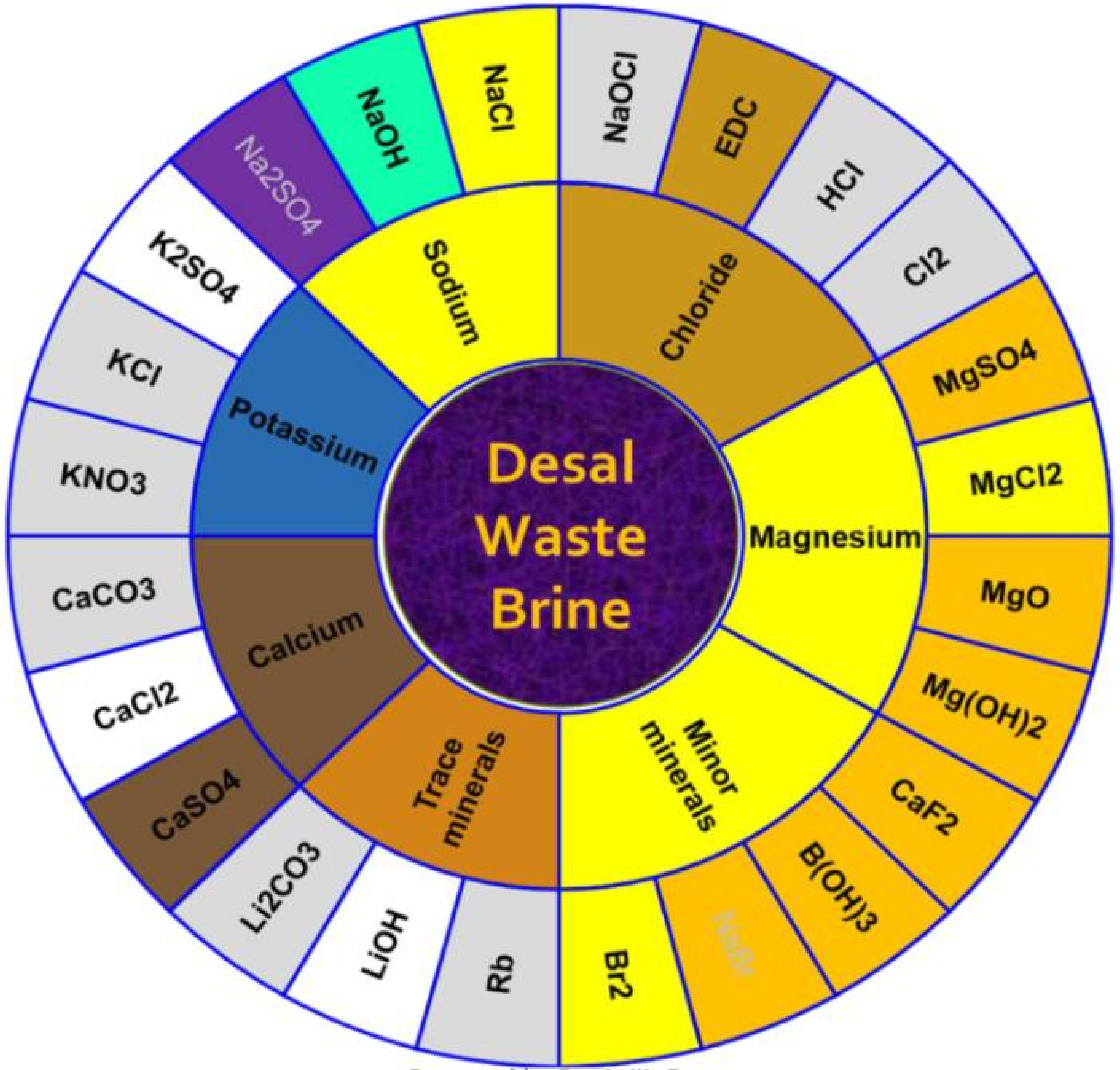
Secondary Resource Recovery from Brine Valorization beyond Supply of Feedstocks to soda ash and chlor-alkali

- ❑ Secondary valorization is attractive, however, comprehensive market research at local, regional, and global level is needed to fathom actual demand-supply gap for any commodity of interest as a potential candidate.
- ❑ Commodity prices at local, regional, and global level should be reviewed by multiple market research agencies to perform financial analysis.
- ❑ It is recommended to secure long-term stakeholder contracts for such valorized products.
- ❑ Entry strategy needs to be formulated for any commodity without flooding the market which may cause depression of its selling price.
- ❑ Critical review of technology readiness levels (TRLs) is mandatory to avoid operational challenges.
- ❑ Critical review of technology obsolesce is recommended to achieve sustainability goals.



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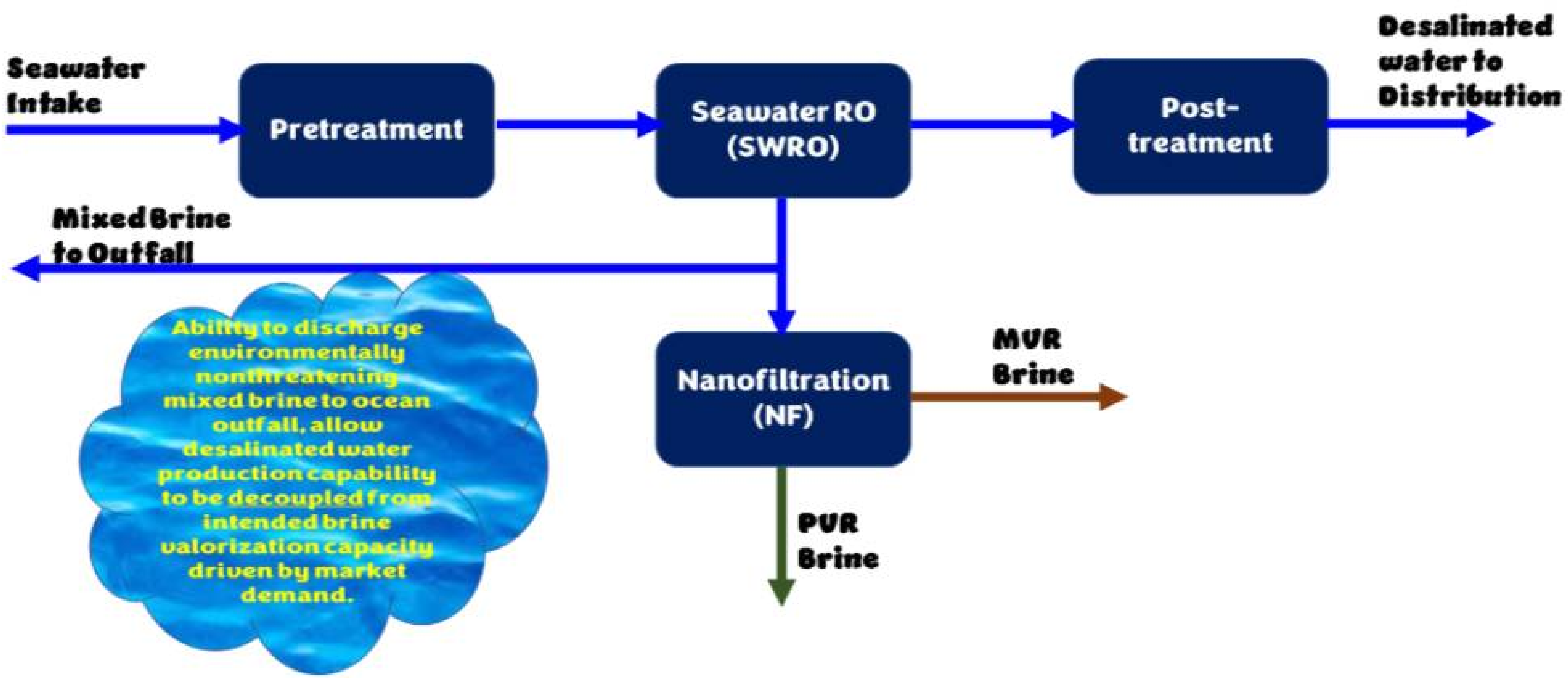
Brine Valorization for Water Utilities: Decoupled configuration

- In Decoupled brine valorization configuration, selective separation NF unit is positioned downstream of SWRO unit and NF is sized for partial flowrate from SWRO concentrate commensurate with demand-supply gap of target end-products of brine valorization.
- To meet large desalinated water demand, **variable "Water: MVR: PVR" ratio** is attractive as it allows operation with low brine valorization commensurate with market demand while maintaining a large desalination capacity.

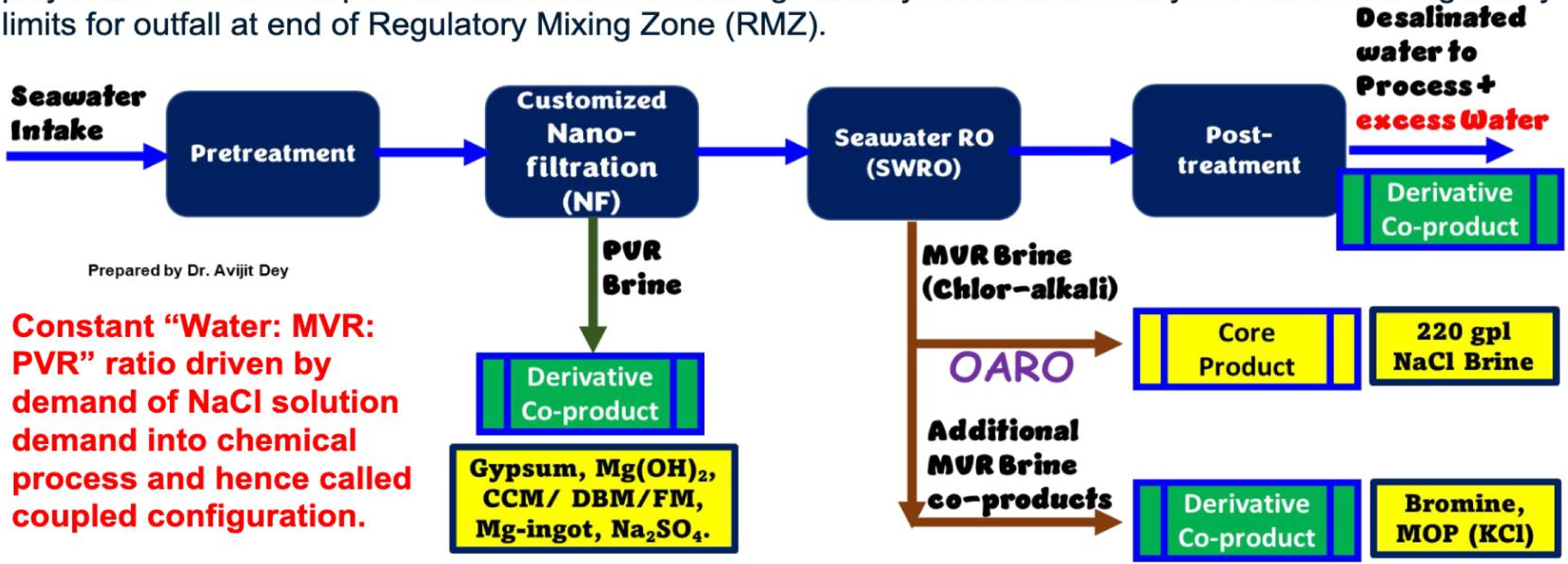
Why Decoupled Configuration?



MVR: Mono-valent rich brine e.g., NF permeate
PVR: Poly-valent rich brine e.g., NF concentrate

Brine Valorization for Chemical Industries: Coupled Configuration

In Coupled brine valorization configuration, NF unit is positioned upstream of SWRO unit which perform selective separation of MVR and PVR streams where respective concentration factors of monovalent and polyvalent ions with respect to native seawater are significantly elevated and may not meet local regulatory limits for outfall at end of Regulatory Mixing Zone (RMZ).



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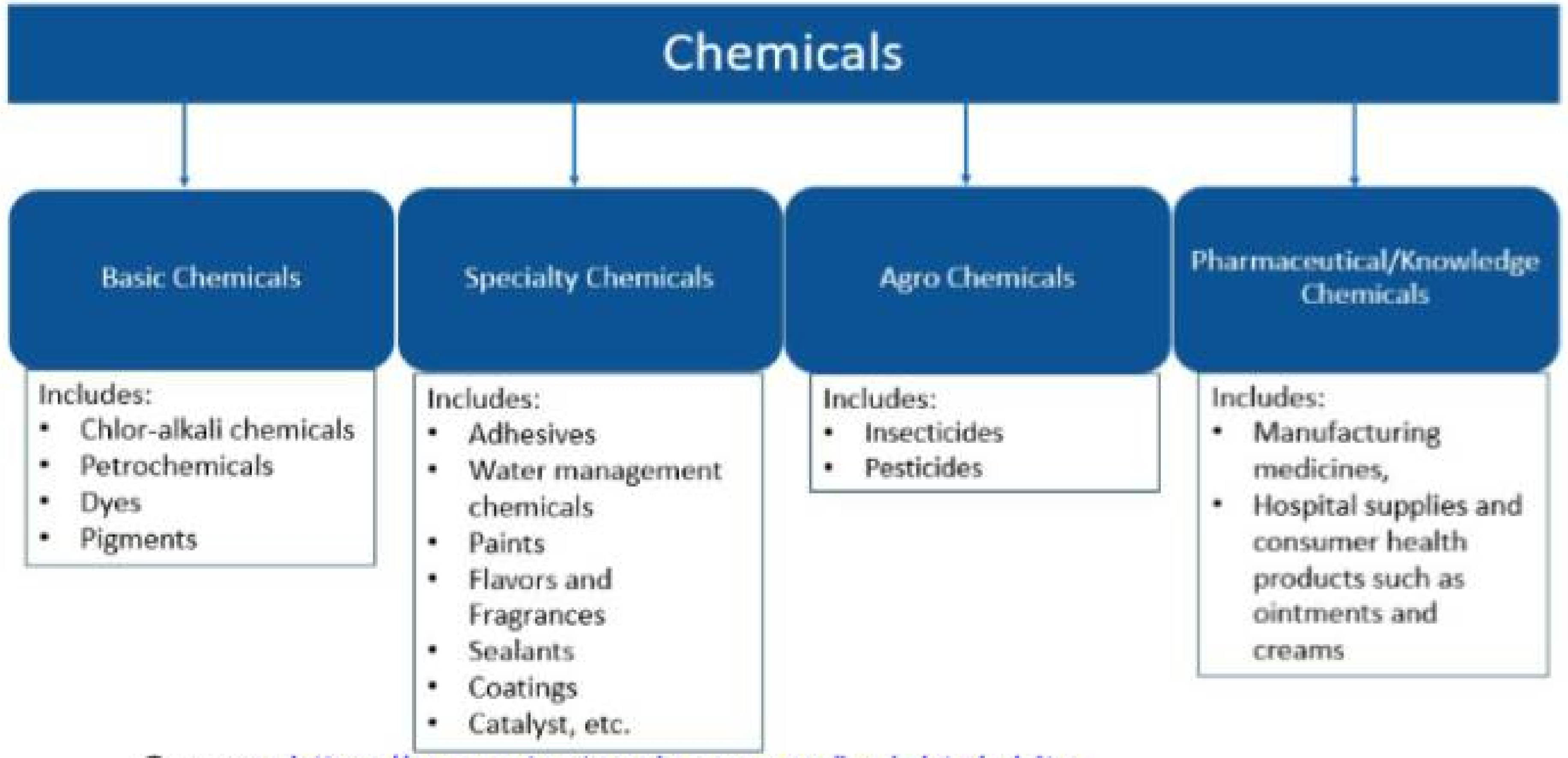
Constant "Water: MVR: PVR" ratio driven by demand of NaCl solution demand into chemical process and hence called coupled configuration.

Salt-based Chemical Industries in India

Key Segments Driving Growth of Indian Chemical Industry

- Around 5.5% of India's total exports constitutes chemicals.
- Currently valued at around $160 billion, Indian chemical industry has grown more than 10% for each of the past 10 years.
- This puts India in sixth place globally revenue-wise.
- India ranks third in agro-chemical production, accounts for 16% of global dye production, and has a significant pharmaceutical manufacturing industry.
- Seawater desalination waste brine valorization is beneficial for Salt-based Chemical industries like soda ash, and chlor-alkali.
- Primary functions of soda ash for key Indian chemical industry markets including agro-chemical, dye, and pharmaceutical manufacturing involve pH regulation, chemical synthesis, and serving as a raw material or additive.
- The chlor-a[lkali plants provide critical chemical building]



Source: https://www.stantonchase.com/insights/white-papers/executive-search-trends-geopolitical-shifts-create-opportunities-in-the-indian-chemical-industry

Key Sectors in the Current Indian Chemical Industry with Potential for Brine Valorization

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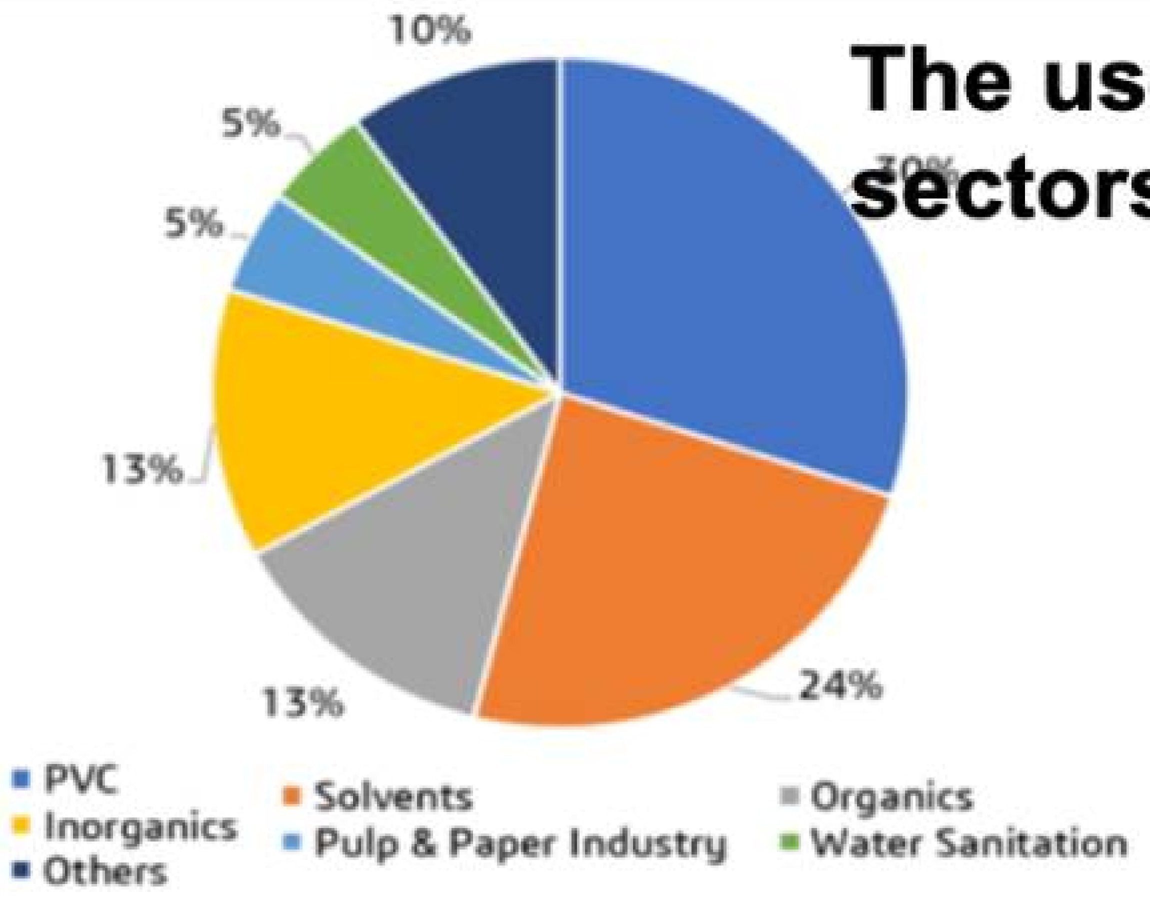
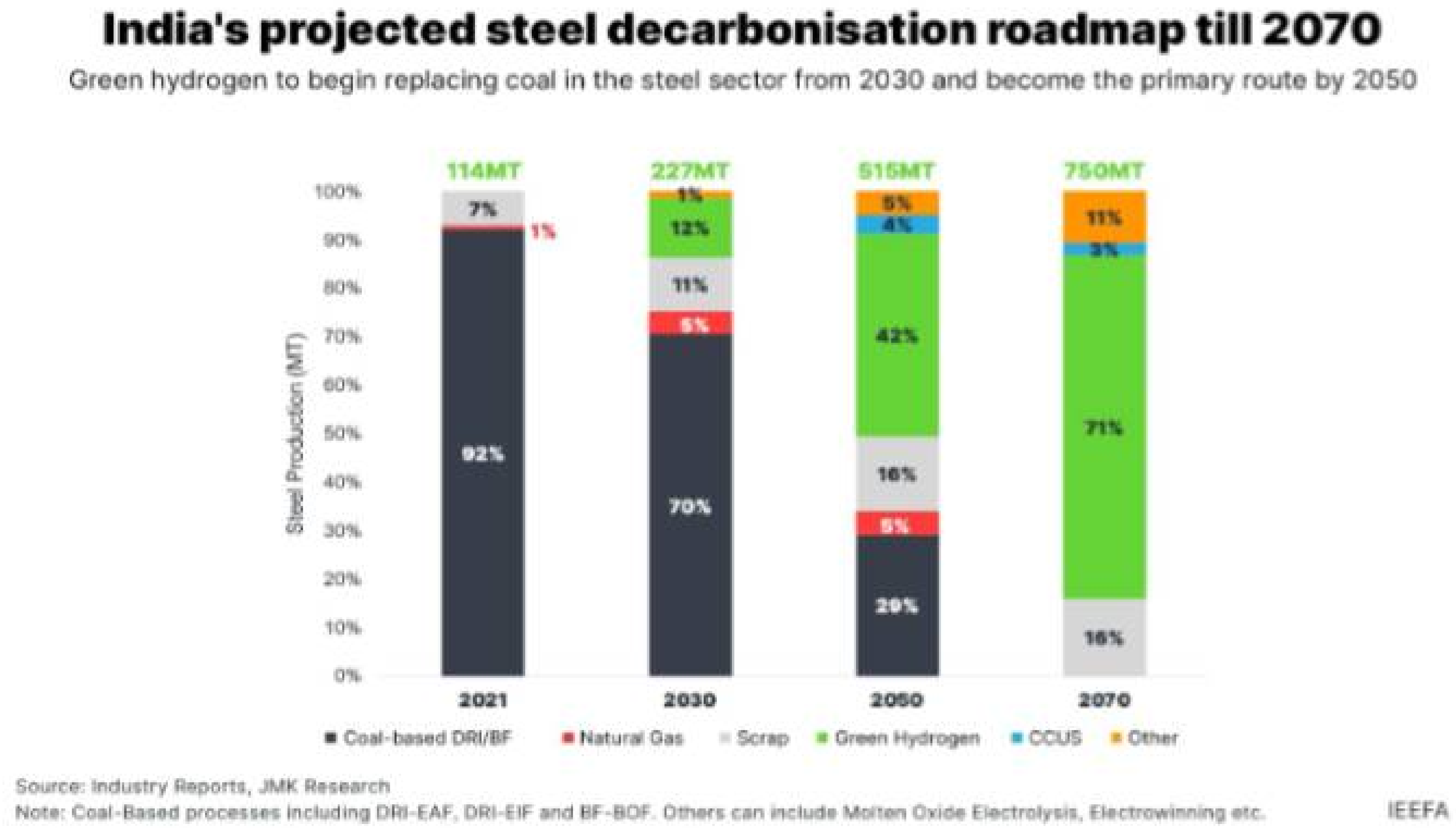
- ❑ Seawater desalination waste brine valorization is beneficial for Salt-based Chemical industries like soda ash, and chlor-alkali.
- ❑ Chlor-alkali and soda ash plants are crucial for various sectors, including plastics, pharmaceuticals, detergents, and glass manufacturing, with the chlor-alkali being a prime example of salt's transformative role in modern industrial processes.
- ❑ Energy source for Indian steel plants primarily coal-intensive. Direct Reduced Iron (DRI) in green steel process uses hydrogen as a clean reducing agent to separate oxygen from iron ore, producing water vapor instead of the carbon dioxide (CO_2) emitted by traditional, coal-fueled blast furnaces.
- ❑ India has pledged to achieve net-zero emissions by 2070, and with the steel sector accounting for a significant portion of total emissions, decarbonizing steel production is crucial for meeting these targets. While brine valorization generated acid/caustic can



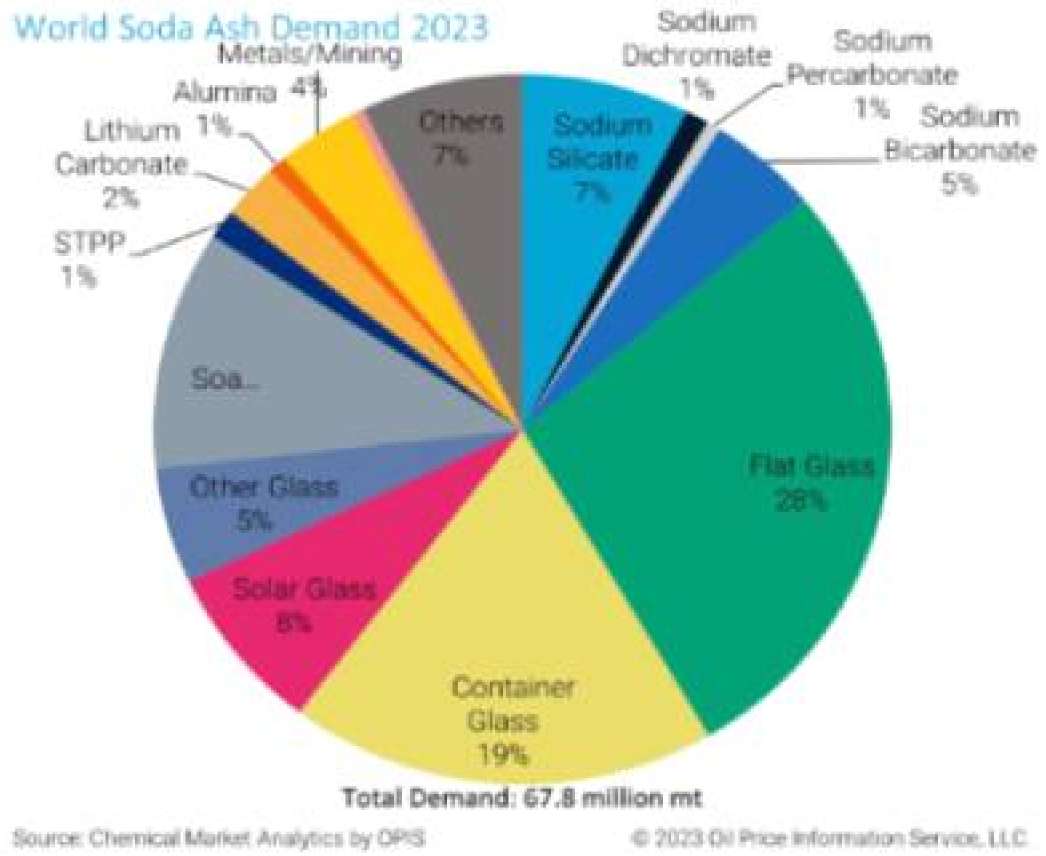
The uses of Cl_2 in various sectors

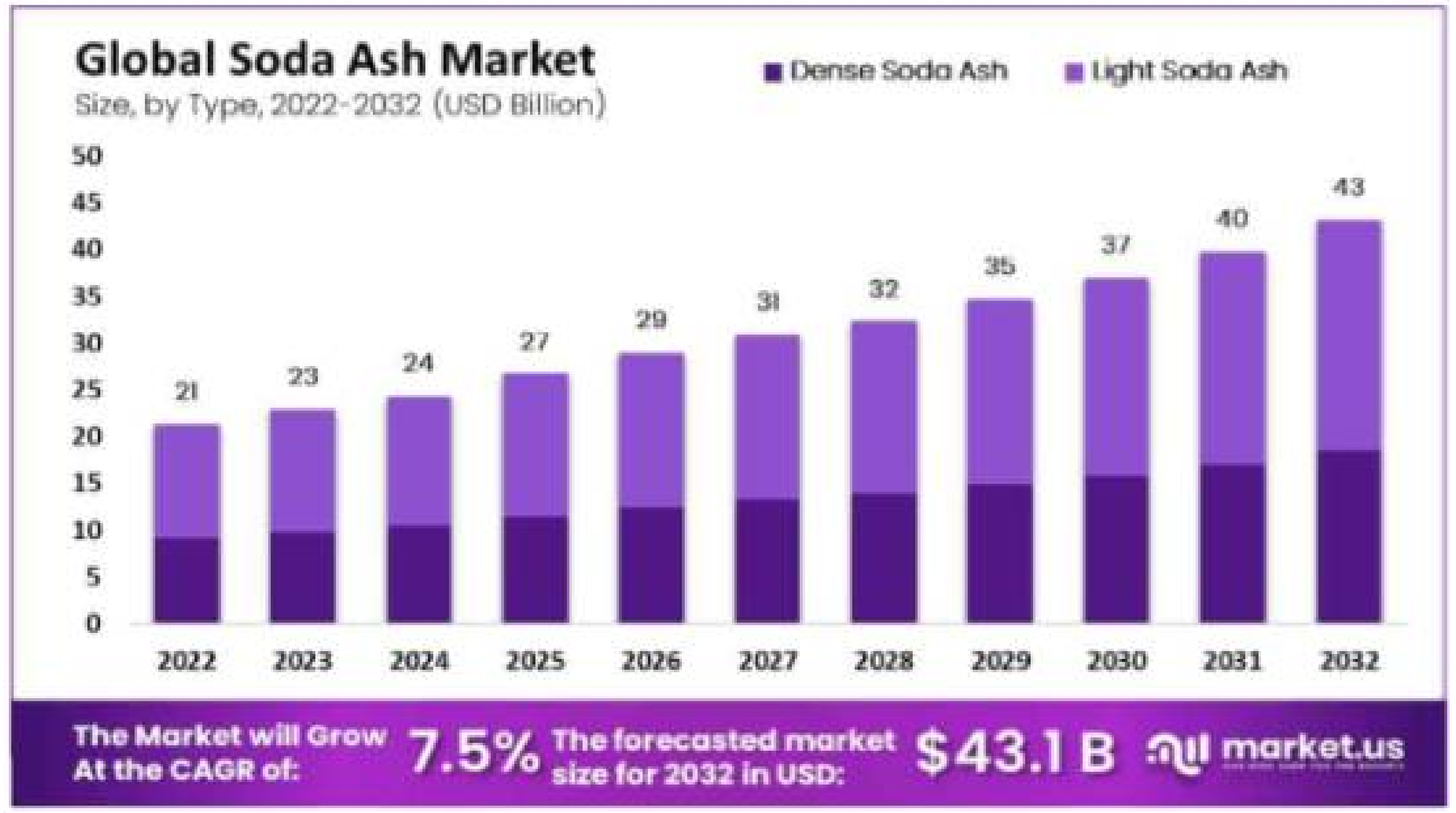
Source: Chlorine, B.C. The Essential Chemical Industry Online. Available: https://www.york.ac.uk/chemistry/news/deptnews/essentialchemind/ (accessed on 17 July 2022).

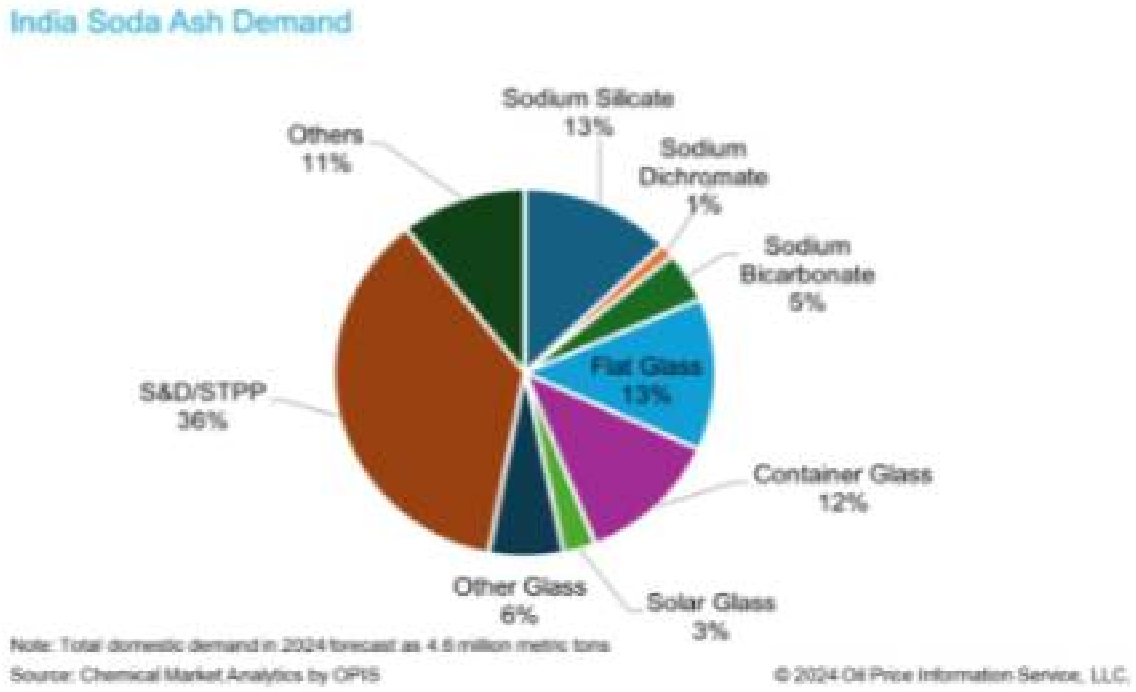


Outlook for Soda Ash Industry in India

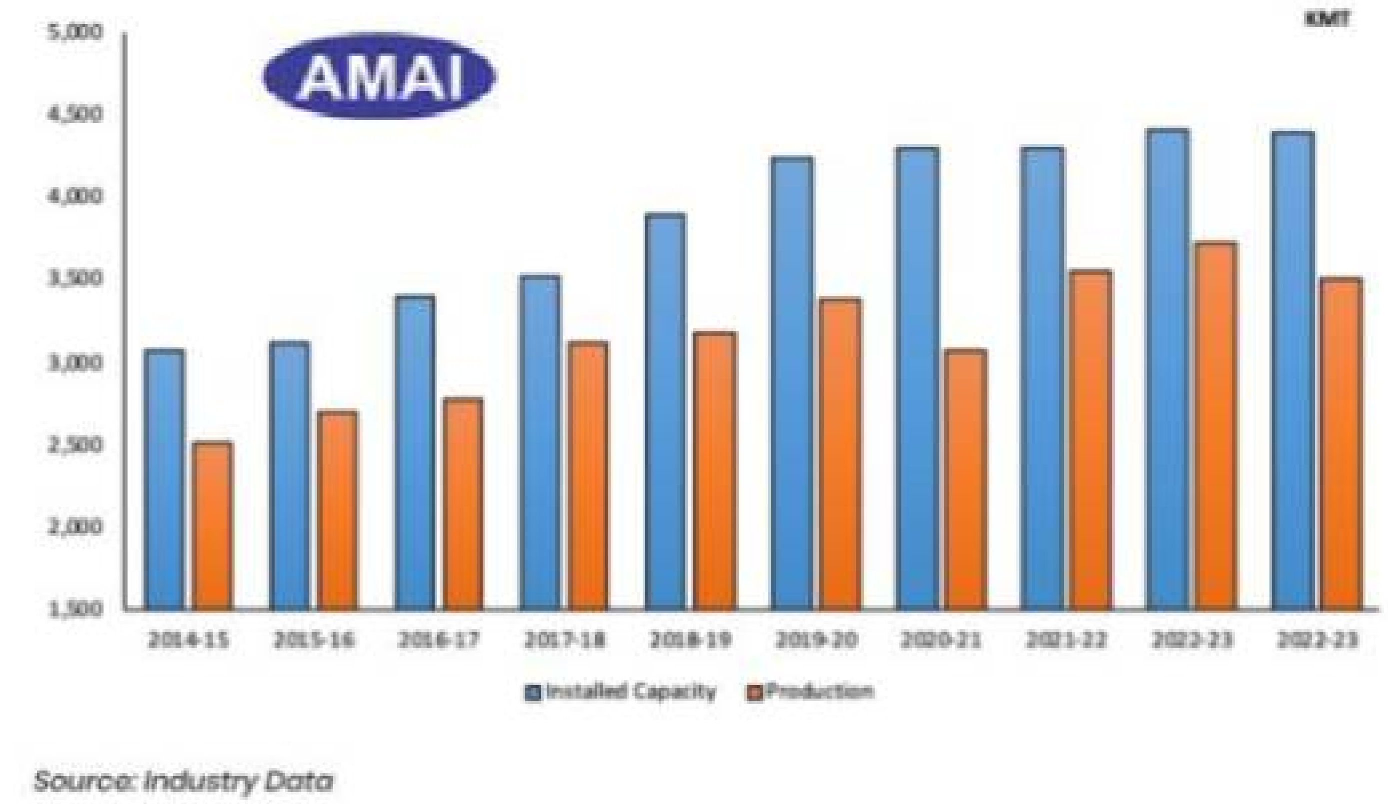
- Nearly 49 million metric tons of soda ash (67% of the total production) are annually worldwide produced by the Solvay process. Consequently, around 25 million metric tons of CO_2 and 49 million metric tons of $CaCl_2$ are yearly emitted into the environment.
- India has installed capacity of 4.4 MTPA with production of 3.5 MTPA (80% capacity utilization).
- The India soda ash market is driven by strong domestic demand from the glass, detergents, and chemical sectors, fueled by rapid urbanization, infrastructure growth, and rising consumer spending.





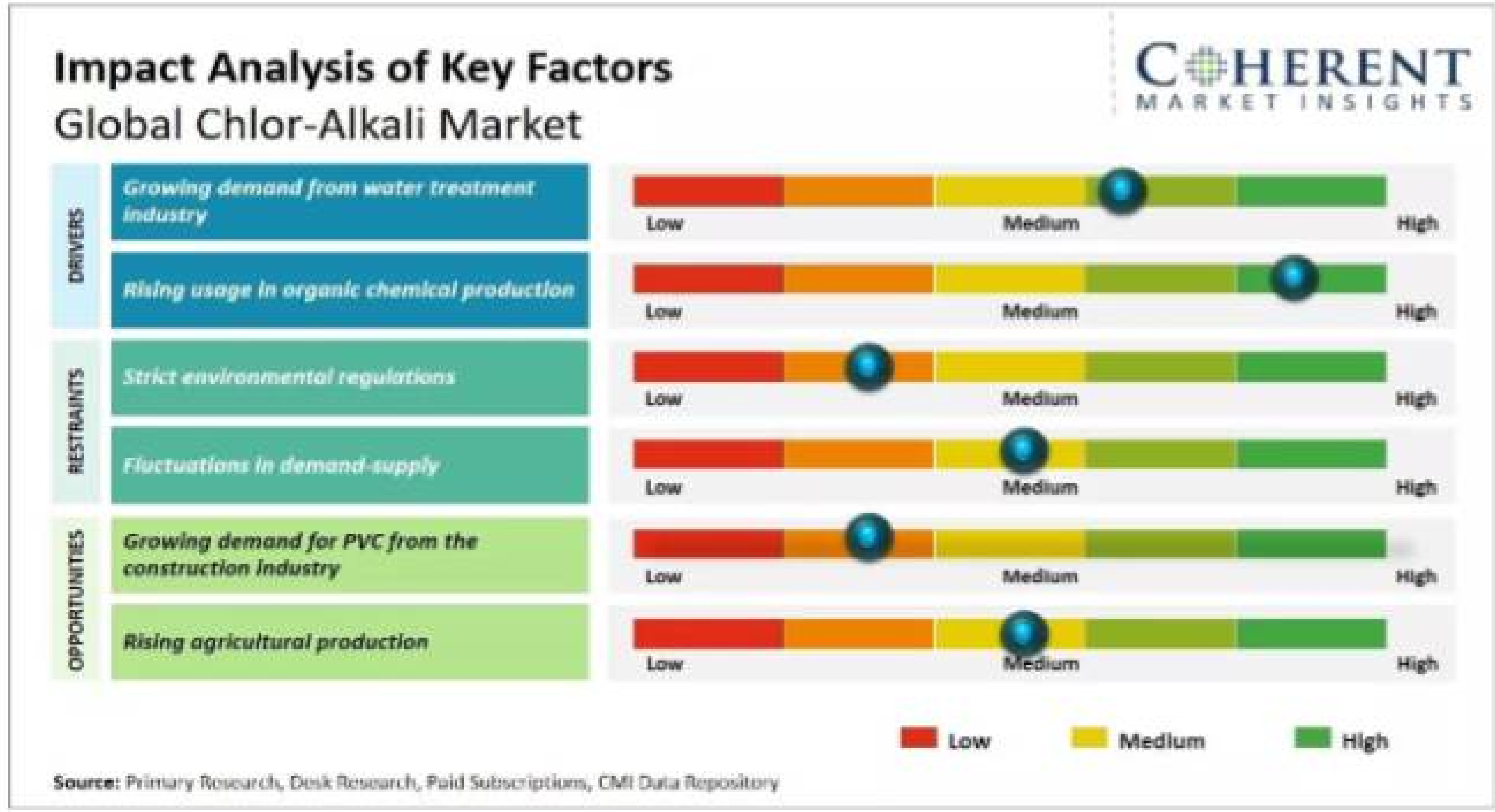


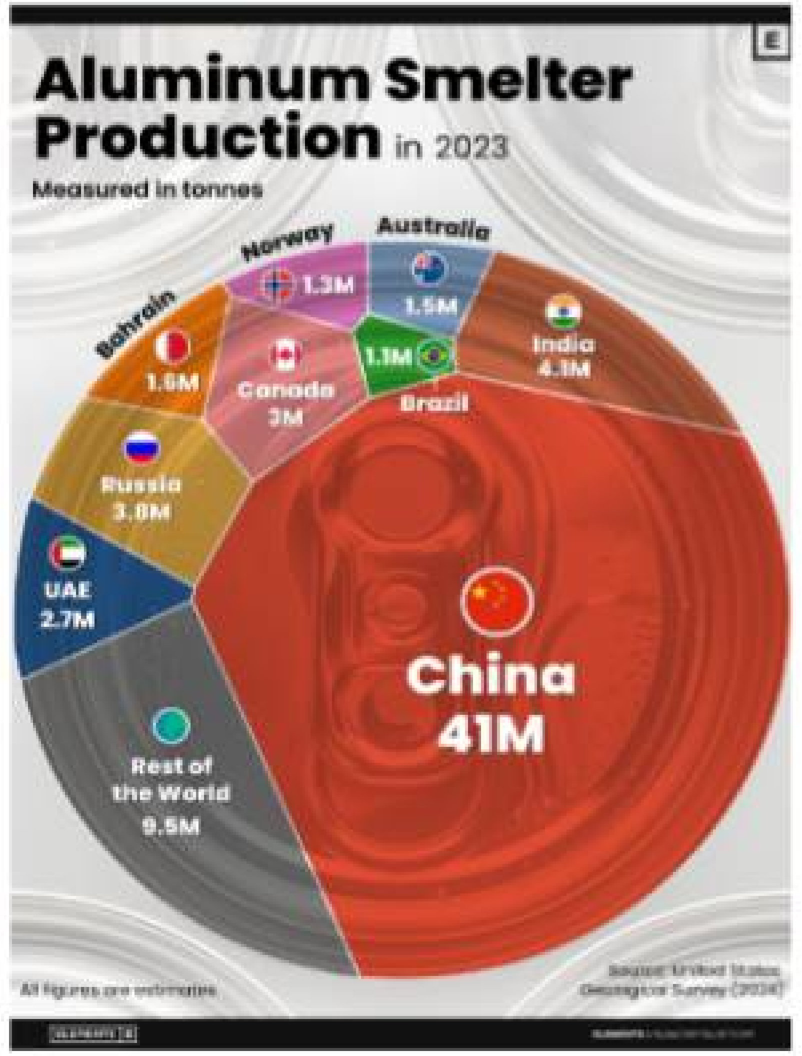
INSTALLED CAPACITY & PRODUCTION IN LAST 10 YEARS (INDIA)

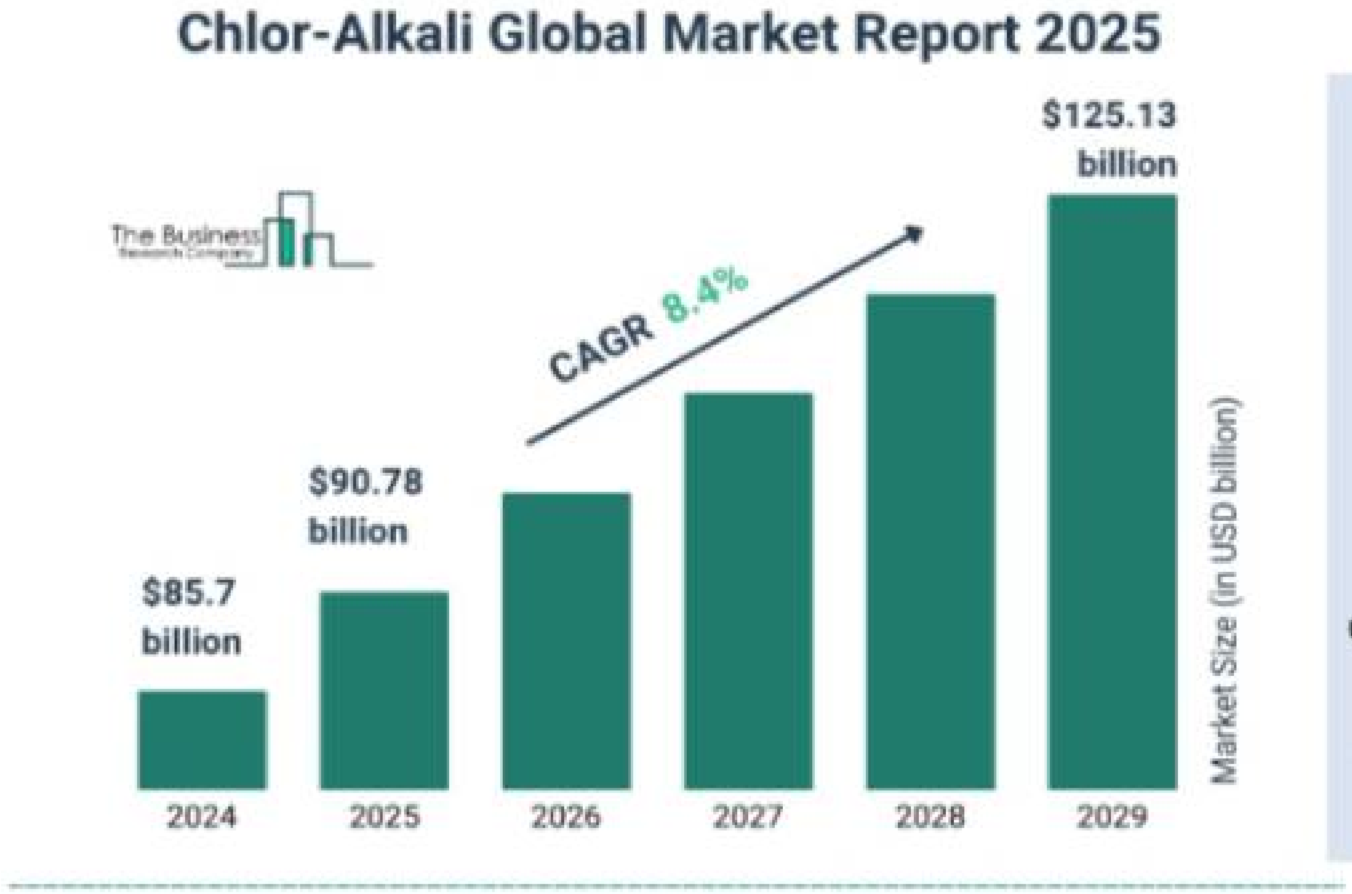


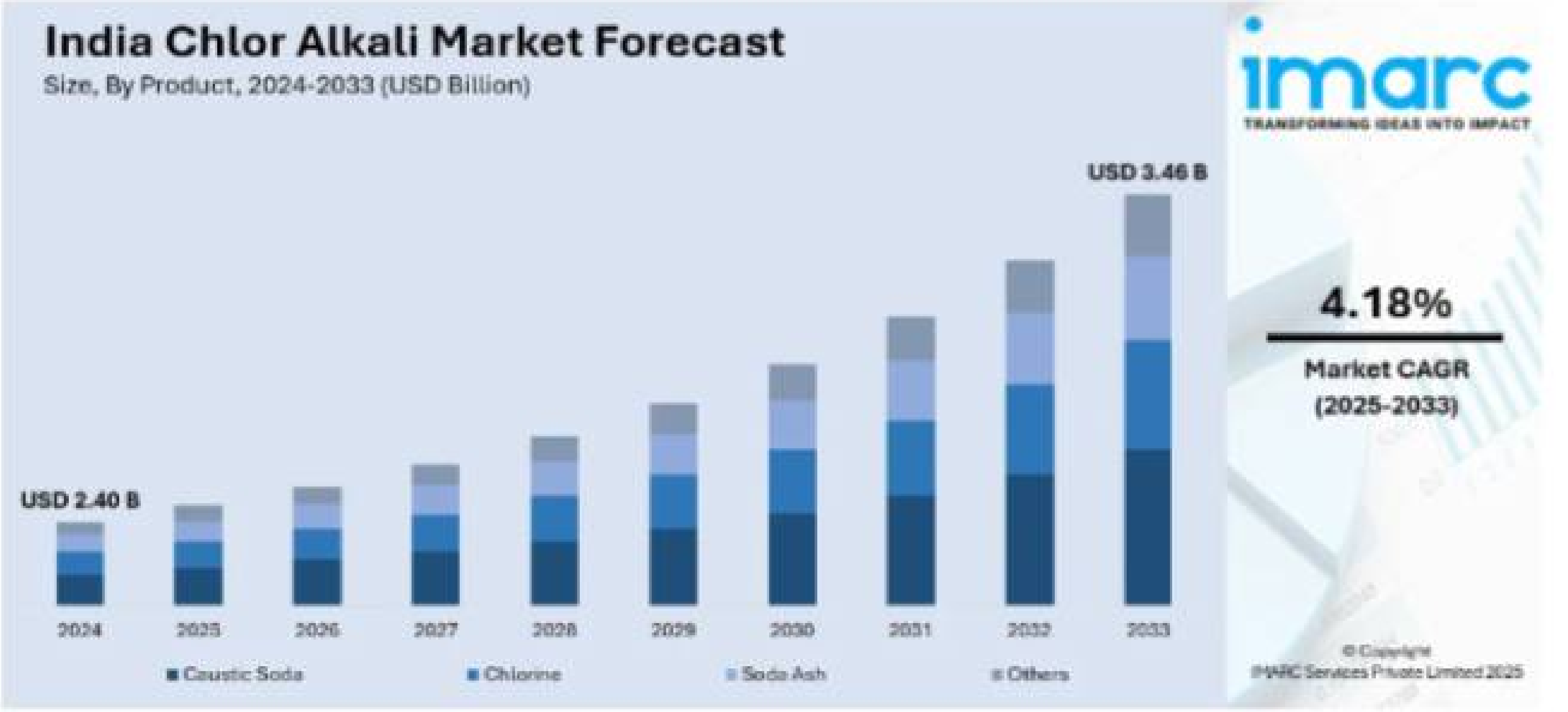
Outlook for Chlor-alkali Industry in India

- The Indian chlor-alkali market is vital for sectors such as textiles, paper, water treatment, and aluminum processing.
- Caustic soda and chlorine are used in bleaching and dyeing processes in textile industry.
- Chemicals are used in the pulping and bleaching of paper.
- Caustic soda is crucial for the extraction of aluminum from its bauxite ore. India is second largest aluminum-producing country (around 4 MTPA)









Waste Brine Valorization to Meet Necessary Brine Spec for Reduction of Salt Demand in Soda Ash Industry

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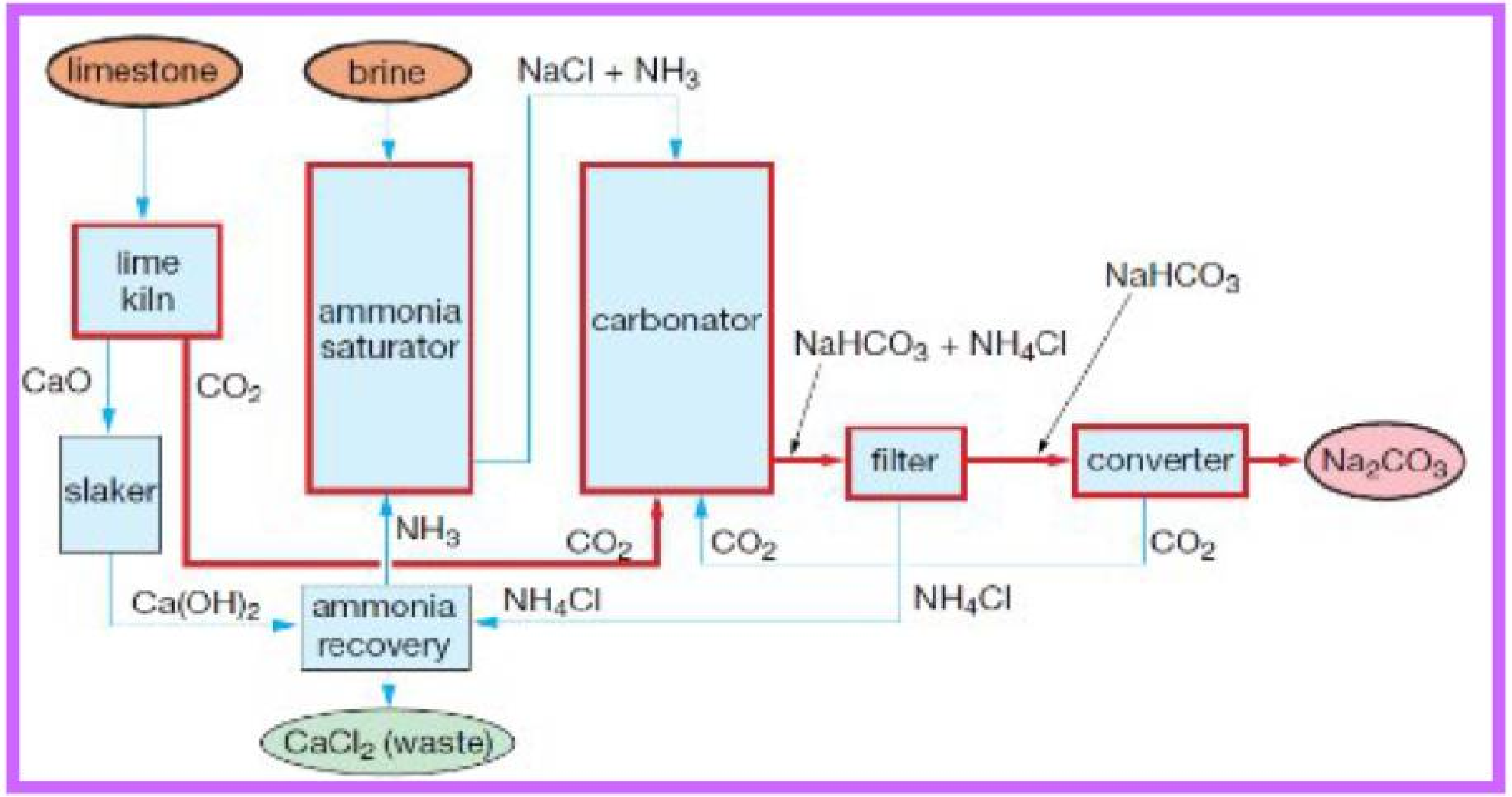
- Brine demand for soda ash is 1.53 – 1.80 t (NaCl)/ t soda ash
- Ammoniation tower in Solvay process accepts saturated brine with concentration of 304 – 310 grams NaCl per liter.
- Ca and Mg limit in saturated brine separately are ~ 10 mg/L as scaling occurs because the high alkalinity and absorption conditions in the tower cause these remaining hardness ions to precipitate as insoluble carbonates, particularly $CaCO_3$.
- In the Solvay process, the saturated brine to ammoniation tower must have a very low hydroxide concentration limit of 100 – 200 mg/L to prevent the precipitation of $Mg(OH)_2$.
- In the Solvay process, the saturated brine to ammoniation tower must have a very low carbonate concentration limit of 300 – 500 mg/L to prevent premature precipitation of



Source: https://www.tsfx.edu.au/resources/1162.pdf

Waste Brine Valorization to Meet Necessary Brine Spec for Reduction of Salt Demand in Chlor-alkali Industry

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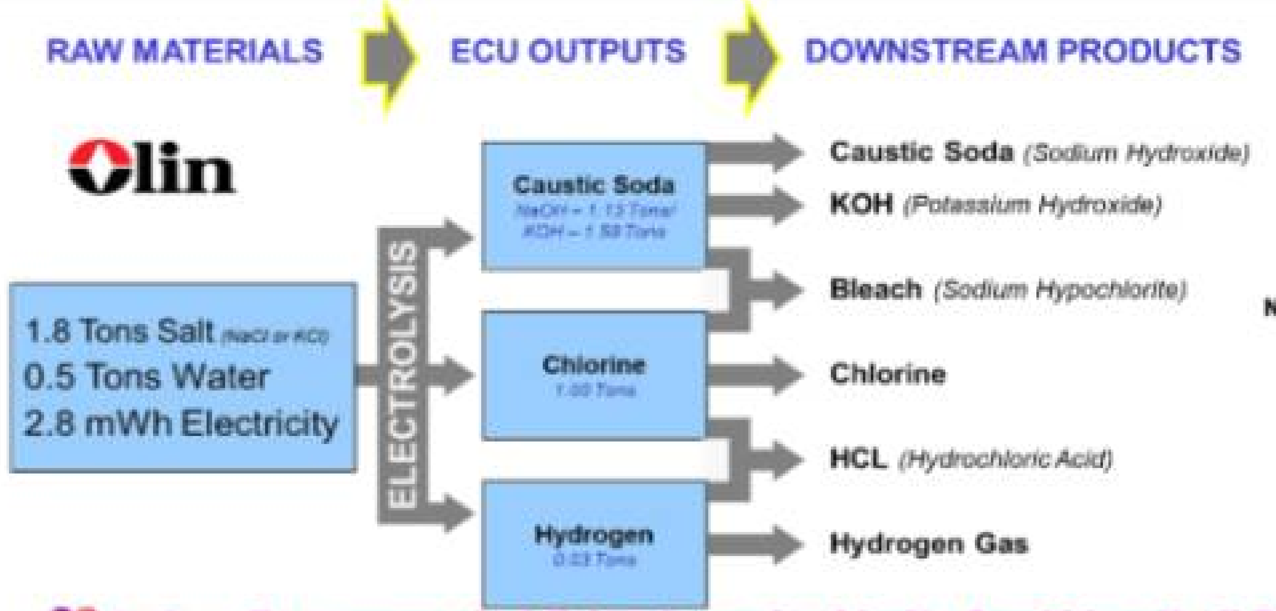
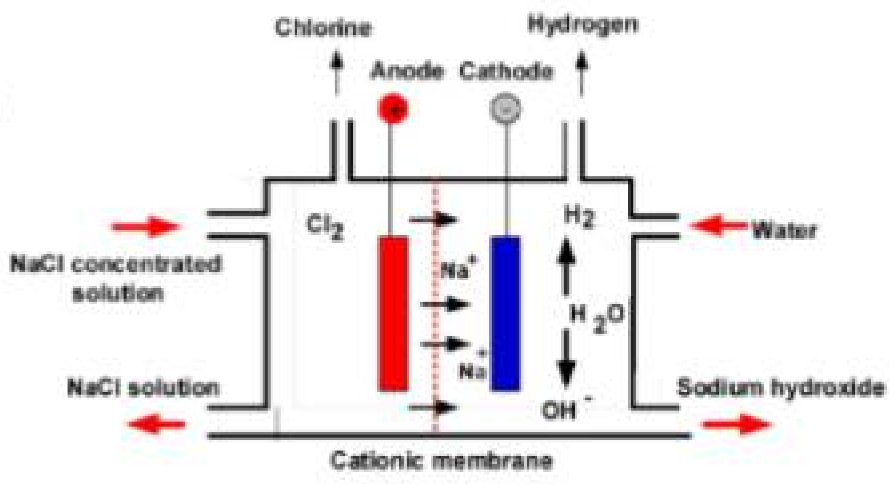
- ❑ Valorization of NaCl brine at or above the depleted brine concentration from membrane electrolyzer using OARO or equivalent membrane technology is used.
- ❑ Need for makeup salt (NaCl) addition in brine saturator is necessary to achieve saturated brine for electrolyzer.
- ❑ Brine purification to achieve brine impurity limits for chlor-alkali plants using NAFION membranes comprises chemical precipitation with soda ash, and caustic soda, primary and secondary filtration (including pressure leaf filters) to eliminate precipitated solids, followed by ion exchange softening or chelating resins to accomplish the ultra-pure brine necessary for modern membrane cells.
- ❑ Energy intensive process: 2.5 MWh/ ton of caustic
- ❑ ECU: Electrochemical Unit; a unit of measure





Nafion Recommended Brine Impurity Limits for Chloralkali Plants Using Nafion™ Membranes Chemours

Impurity	Limit at 4 kA/m²	Limit at 4–6 kA/m²	Limit at 6–7 kA/m²	Primary Effect(s) on Performance if Limit is Exceeded	Method(s) of Control (common)
Calcium and Magnesium (Ca + Mg)	<30 ppb (total)	<20 ppb (total)	<20 ppb (total)	Ca: Current efficiency (CE) decline. Mg: Voltage increase.	Ion exchange
Strontium (Sr)	<500 ppb	<400 ppb	<200 ppb	CE decline, small voltage increase.	Ion exchange
Barium (Ba)	<1.0 ppm	<500 ppb	<200 ppb	CE decline and voltage increase.	Ion exchange
Iodine (I)	<1.0 ppm	<200 ppb	<100 ppb	CE decline, possible voltage increase.	Purge of brine loop
Sodium Sulfate[1] (Na2SO4)	4–10 g/L	4–8 g/L	4–8 g/L	CE decline.	• Primary treatment • Purge of brine loop • Filtration • Ion exchange
Aluminum (Al)	<100 ppb	<100 ppb	<50 ppb	CE decline.	• Primary treatment • Ion exchange
Silica (SiO2)	<10 ppm	<6 ppm	<5 ppm	CE decline.	Primary treatment
Iron (Fe)	<1 ppm	<1 ppm	<100 ppb	None in moderate quantity. In large quantity, voltage can be elevated and permanent void damage can occur.	Monitor anti-caking agent content in raw salt
Total Organic Carbon (TOC)	<7 ppm	<7 ppm	<7 ppm	CE decline, increase in voltage, possible permanent membrane damage.	Elimination of source; filtration with activated carbon

Source: Perry, C., et al.,"Getting the Most Out of Nafion™ Membranes", Clorosur Technical Seminar – Monterrey, Mexico, 15 November 2018.

Water Demand in Chemical sectors with Potential for Brine Valorization

- Seawater desalination waste brine valorization is lucrative for Salt-based Chemical industries like synthetic soda ash and chlor-alkali plants.
- Refer Source 1, apart from the water needed for cooling, typical process water demand for chlor-alkali plant is ~ 2.50 – 2.70 m^3/ton of chlorine produced. Water is a fundamental component in the brine (salt) solution that is electrolyzed in the chlor-alkali process. Water is also used in the process for purges, and the chlorine absorption unit.
- Refer Source 2, typical process water demand for synthetic soda ash by Solvay process is ~ 4.00 m^3/ton soda ash in addition to cooling water demand of 40 - 60 m^3/ ton soda ash. This significant cooling water usage is for controlling the temperature during the exothermic reactions and for dilution of the calcium chloride byproduct.

Chlor-alkali Water demand (Source 1)

	Mercury	Diaphragm	Membrane	Comments
Consumption, per tonne of chlorine produced				
Salt (NaCl)	1 610–2 340 kg			Depends on impurities and additional sources; stoichiometric consumption: 1 650 kg; 3 100–3 800 kg/t for plants using a once-through brine process
Salt (KCl)	2 070–2 200 kg			Depends on impurities and additional sources; stoichiometric consumption: 2 100 kg
Water	0–2.7 m^3			Refers to the generation of process waste water; ~ 10 m^3/t for plants using a once-through brine process
Steam for caustic concentration	NA	2.7–5.3 t	0.5–1.7 t	For 50 wt-% caustic
Electricity for electrolysis	3 000–4 400 AC kWh	2 600–3 100 AC kWh	2 300–3 000 AC kWh	Depends on the current density; chlorine liquefaction/evaporation and auxiliary processes excluded

Input in the Solvay process (Source 2)

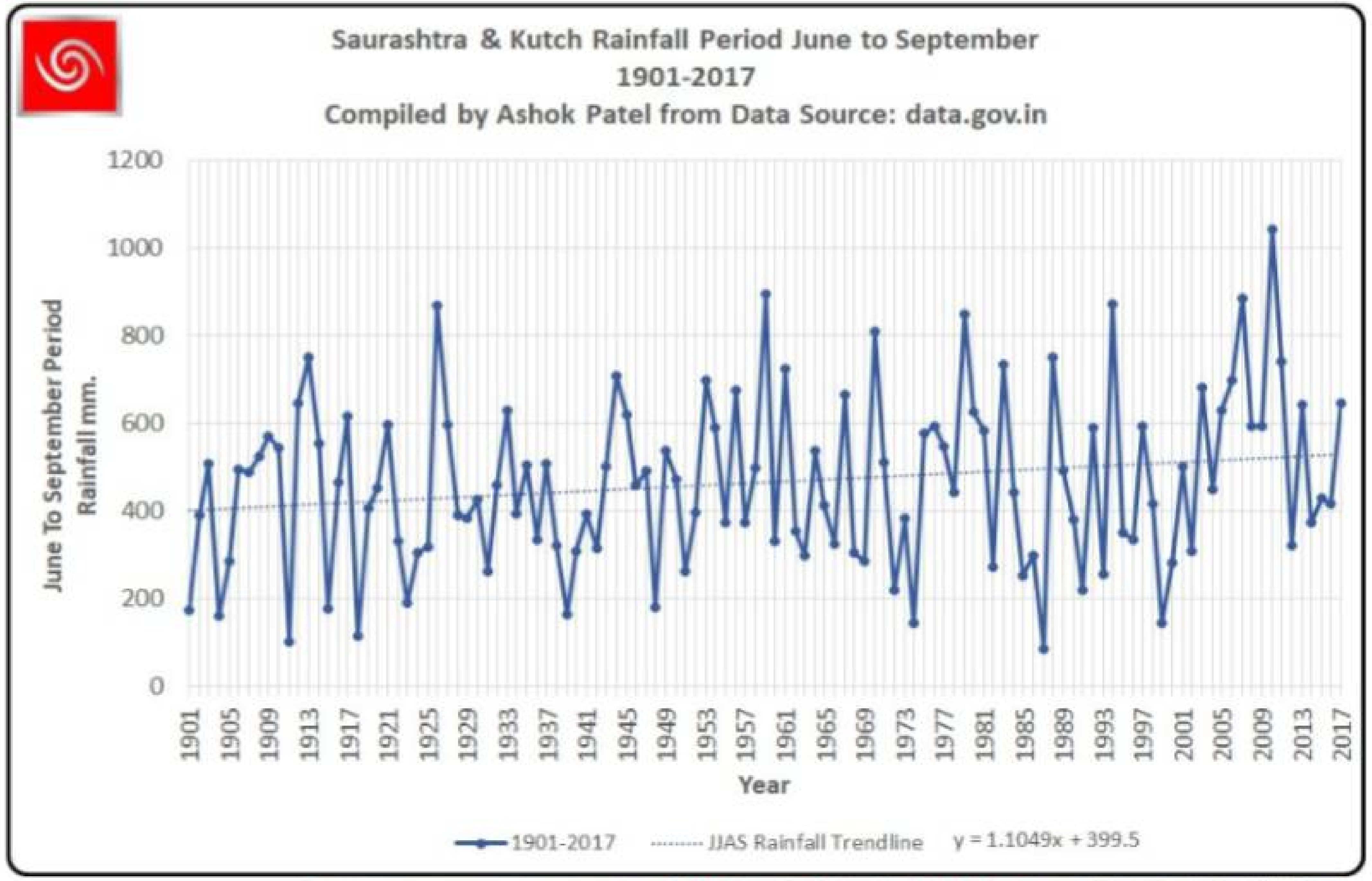
Main input	Range
Limestone (kg/$t_{soda\ ash}$)	1 090-1 820[1]
Raw brine (kg/$t_{soda\ ash}$)	1 530-1 800 (NaCl) / 4 500-5 200 (water)
NH_3 addition (kg/$t_{soda\ ash}$)	0.8-2.1
Electricity (kWh/ $t_{soda\ ash}$)	50-130 (for dense soda ash)
Thermal Energy (GJ/$t_{soda\ ash}$)	9.25-13.2

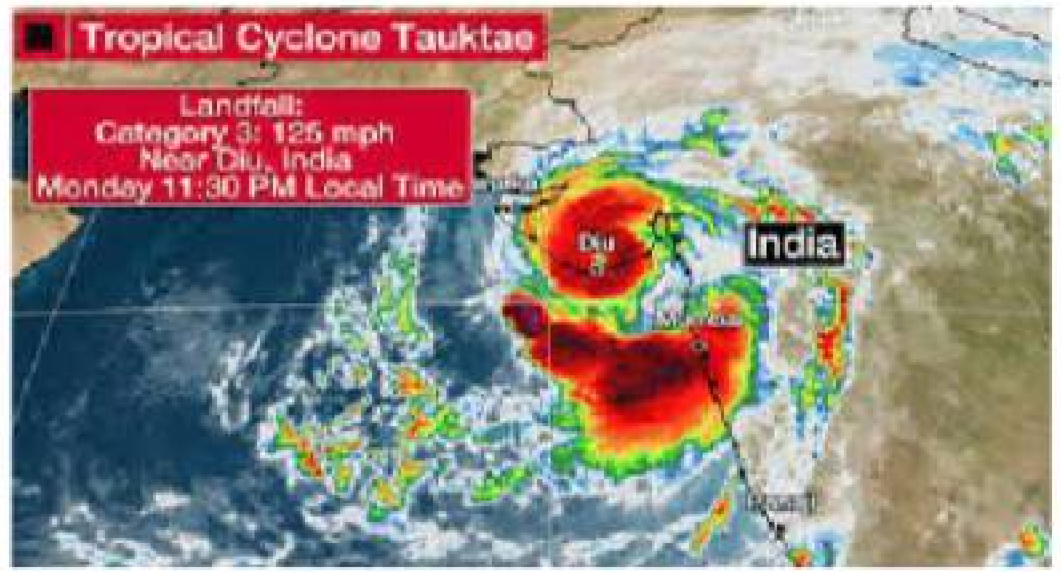
[1] This range refers to the plant gate. The quantity entering the lime kilns is reduced by 4-12 % (1 050-1 600 kg/$t_{soda\ ash}$) due to homogenisation.

Source 1: Brinkmann T, Giner Santonja G, Schorcht F, Roudier S, Delgado Sancho L. Best Available Techniques (BAT) Reference Document for the Production of Chlor-alkali Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control). EUR 26844. Luxembourg (Luxembourg): Publications Office of the European Union; 2014. JRC91156
Source 2: Boulamanti A; Moya Rivera J. Energy efficiency and GHG emissions: Prospective scenarios for the Chemical and Petrochemical Industry. EUR 28471 EN. Luxembourg (Luxembourg): Publications Office of the European Union; 2017. JRC105767

Erratic and intense rainfall during peak salt harvesting season in Gujarat

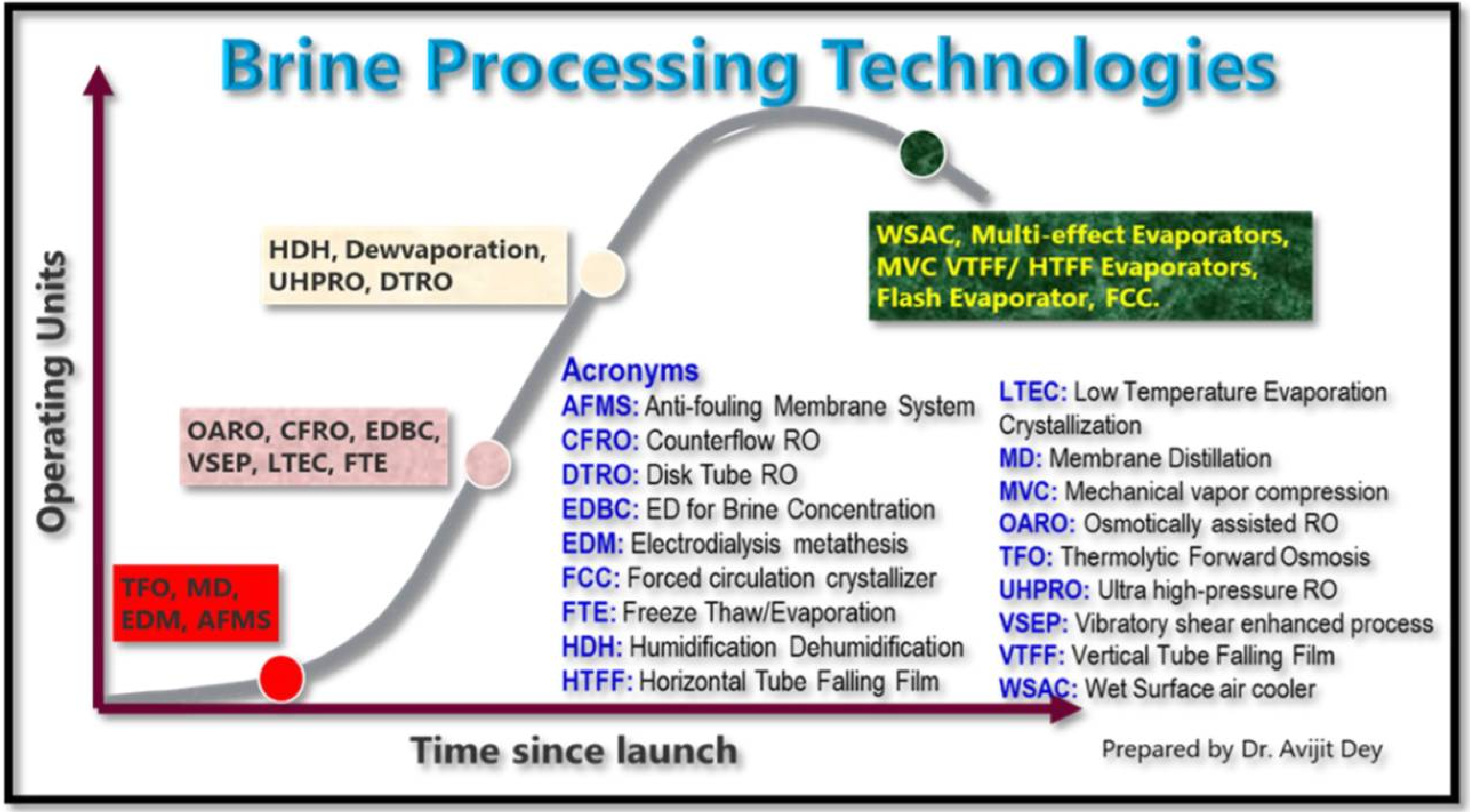
- Gujarat accounts for up to 80% of India's total salt production.
- As a key raw material for synthetic soda ash and chlor-alkali production in India, salt supply disruptions pose a threat to the stability and output of these industries.
- In regions like Kachchh, average annual rainfall has increased by nearly 30% over the last decade - Indian Meteorological Department (IMD).
- Erratic (both excess and deficient) and intense rainfall during peak salt harvesting season (March to May) dissolves salt crystals and can set production back for weeks or months. A single spell of rain can halt production for 7 to 10 days.
- Cyclones in the Arabian Sea, e.g., Tauktae (2021) and Biparjoy (2023), have caused major disruptions and damage to salt pans, leading to early ends to production seasons.
- Reduced yield of industrial-grade salt due to



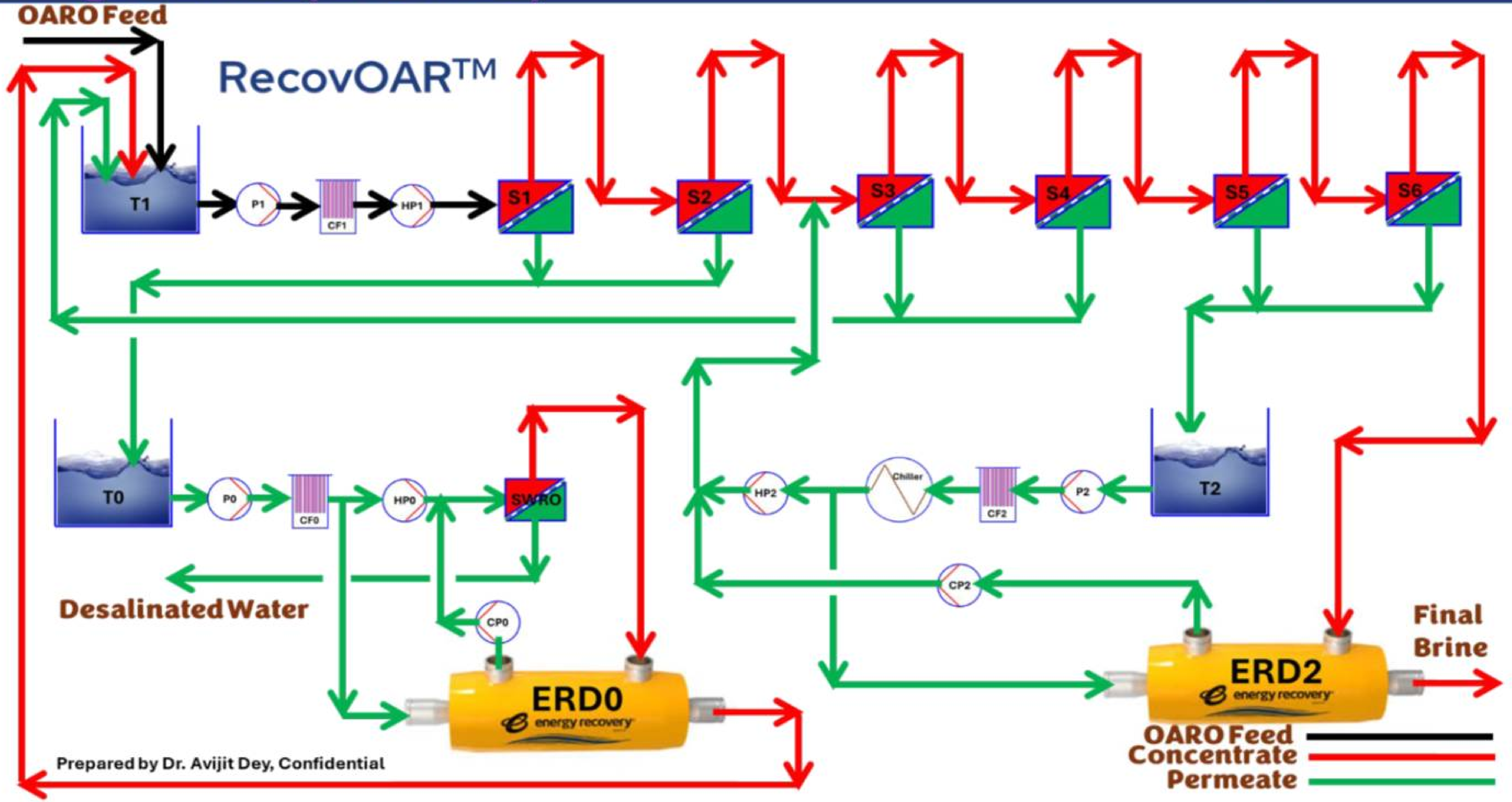


Brine Valorization by Membrane Brine Concentration (MBC): Technology landscape

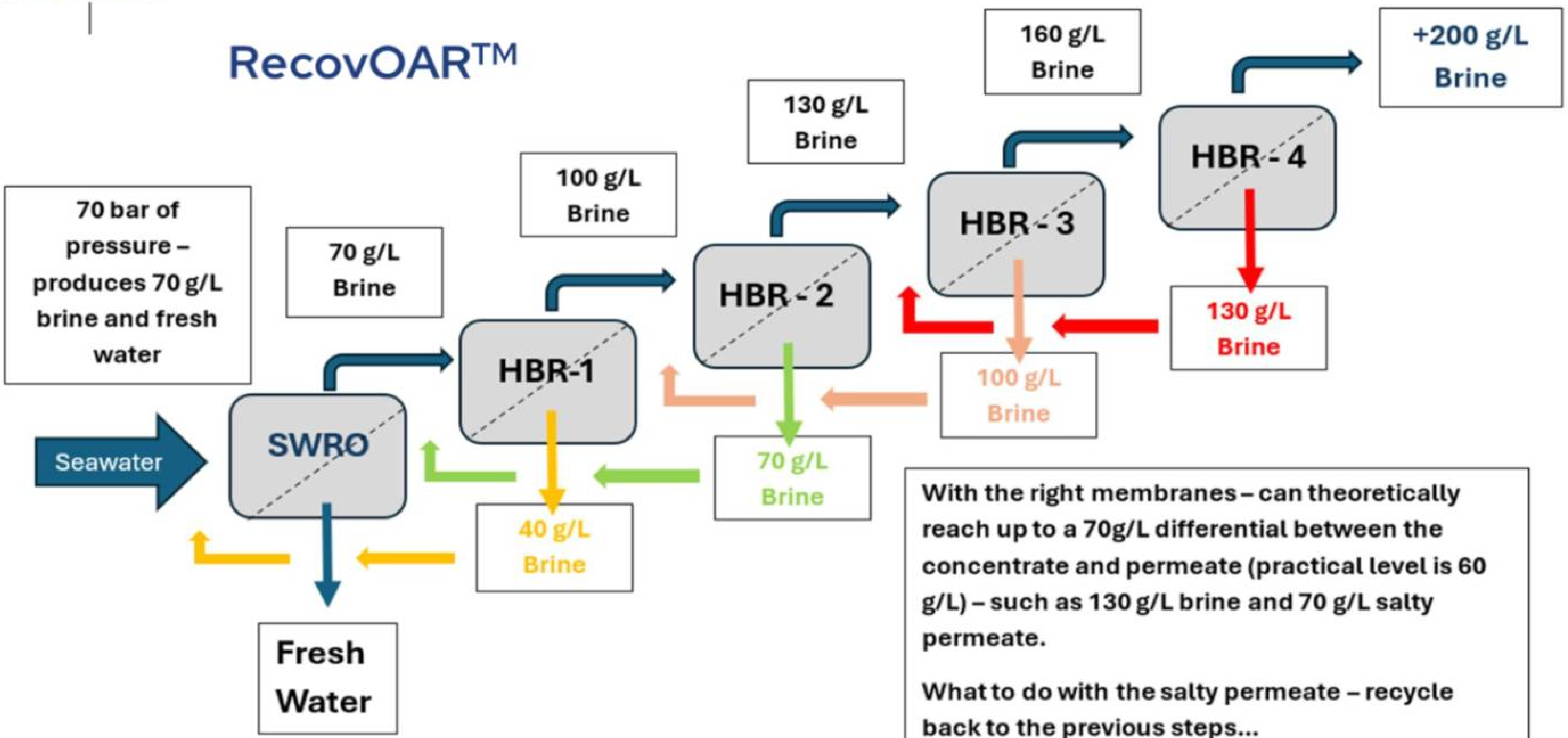
Brine Processing: Technology Options



Brine Valorization: Membrane Technology Landscape – Permeate Recycling OARO (FTSH2O)



Permeate Recycling OARO: Progressive Low Salt Rejection Reverse Osmosis Membranes



With the right membranes – can theoretically reach up to a 70g/L differential between the concentrate and permeate (practical level is 60 g/L) – such as 130 g/L brine and 70 g/L salty permeate.

What to do with the salty permeate – recycle back to the previous steps...

Permeate Recycling OARO: Various “B” value Membranes in Different Stages

$J_w = A\,(\Delta P - \Delta \pi)$

$J_s = B\,\Delta C$

J_w = Water flux, liter/m^2-h

J_s = Salt flux, grams/m^2-h

A = Membrane permeability, liter/m^2-h-bar

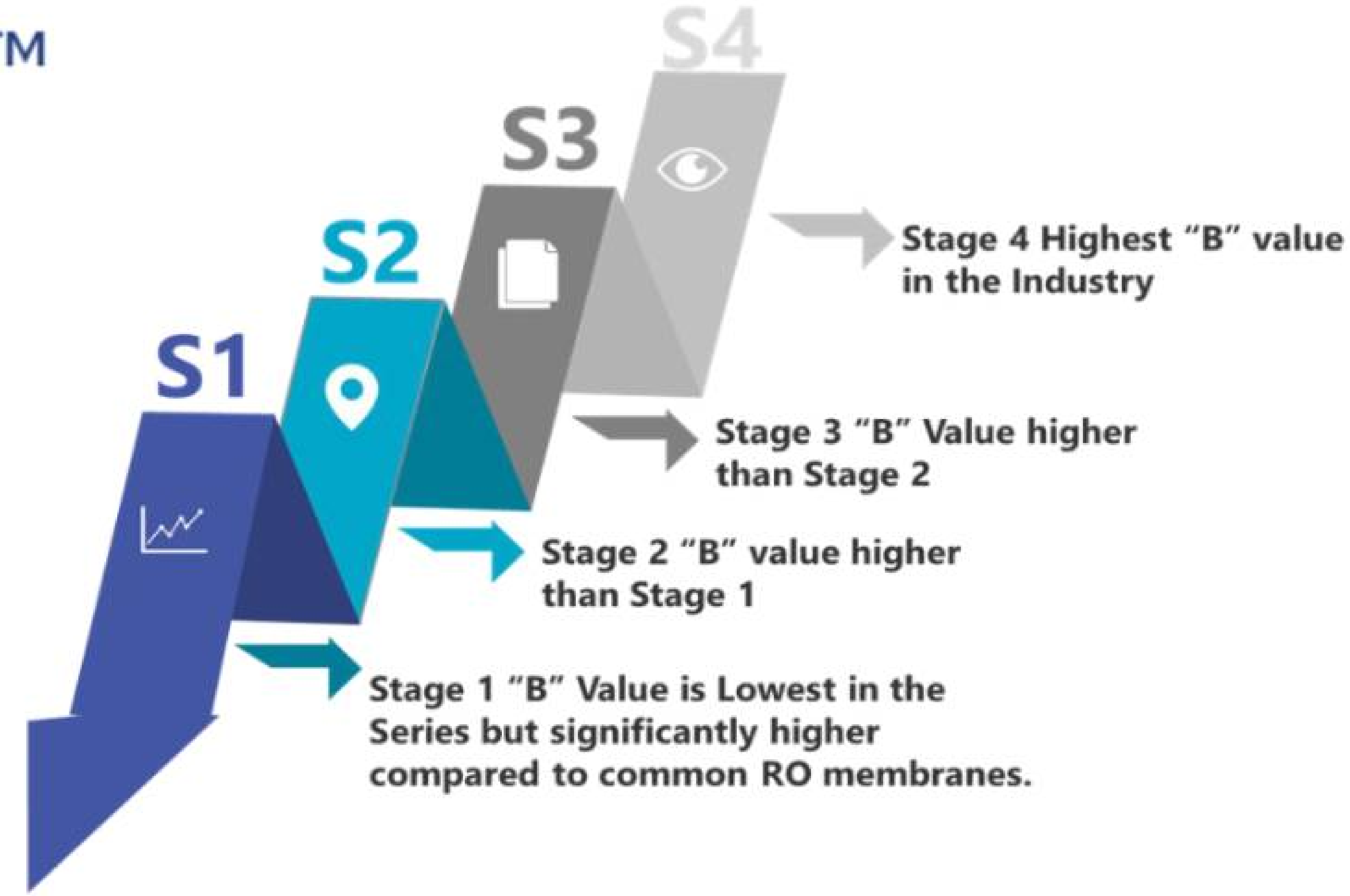
B = Salt permeability, liter/m^2-h

P = Hydraulic pressure, bar

π = Osmotic pressure, bar

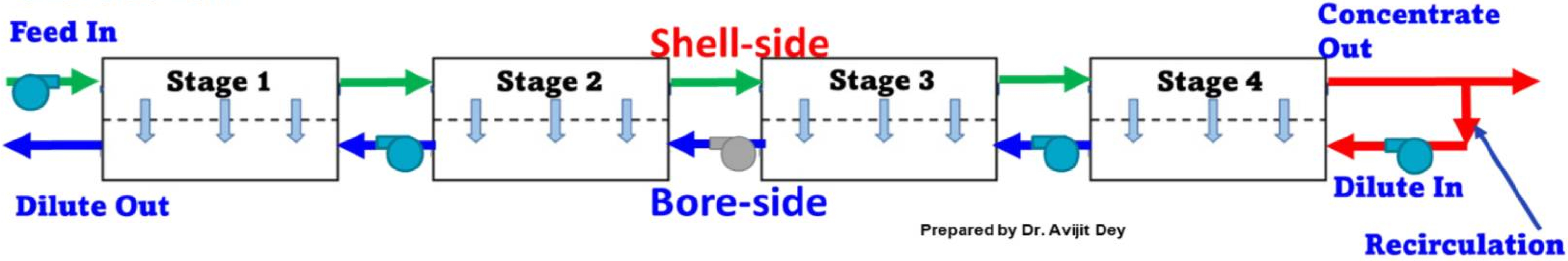
C = Solution centration, grams/liter

RecovOAR™



Brine Valorization: Membrane Technology Landscape – Concentrate Recycling OARO

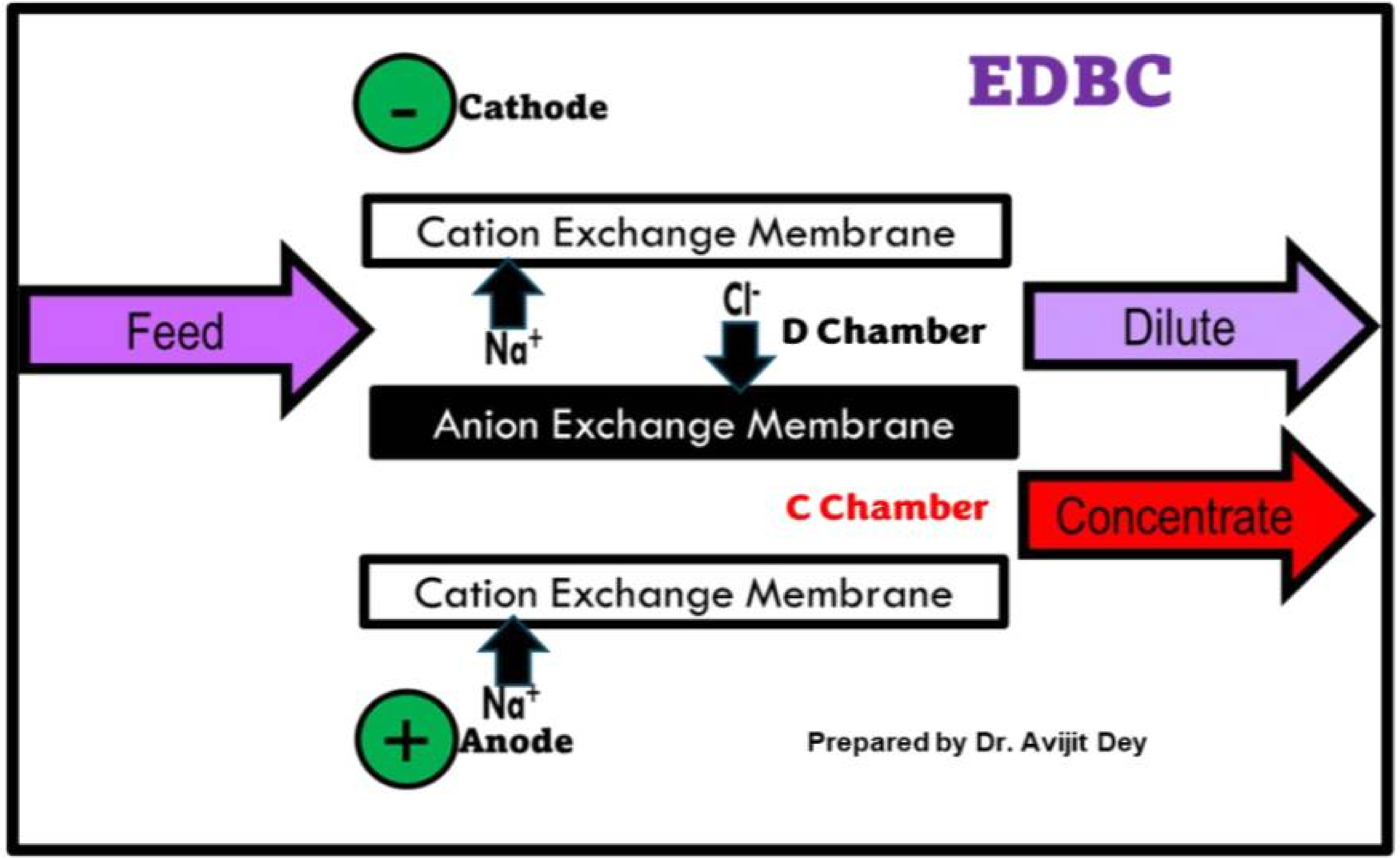
- This configuration employs cellulose triacetate (CTA) membrane material in hollow fiber configuration.
- Feed flow to OARO system enters center tube and radially flows in the shell side of the element from center to outer side.
- A portion of the finally concentrated brine from the last stage flow into bore side in a direction opposite to shell side flow.



Brine Valorization: Membrane Technology Landscape – Electrodialysis Brine Concentrator (EDBC)

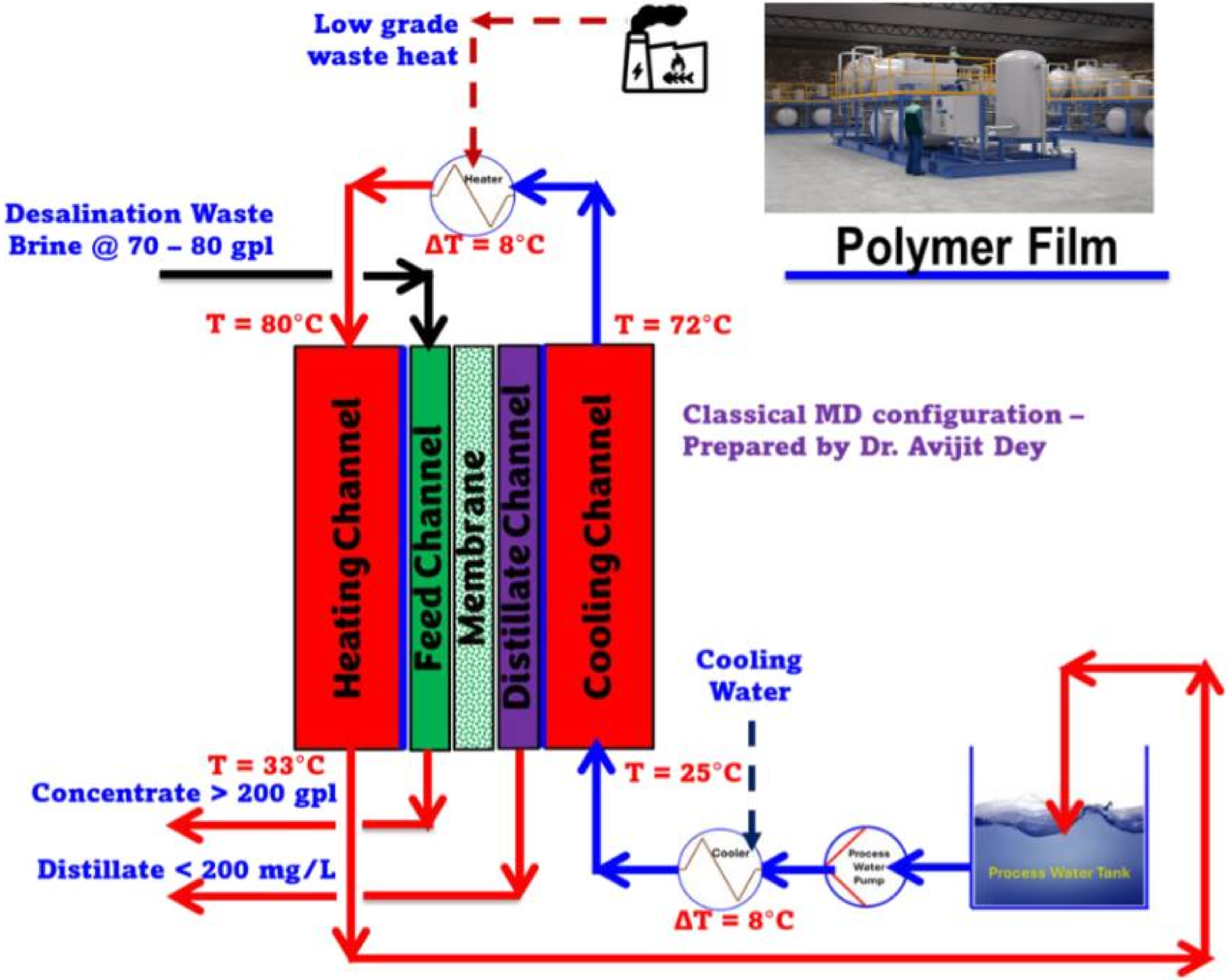
- In regular electrodialysis (ED) or electrodialysis reversal (EDR) units, water molecules transfer with every ion migration into the concentrate chamber (C chamber) from dilute chamber (D Chamber) primarily through 2 mechanisms: electro-osmosis and normal osmosis and 3– 10 Water molecules transferred with each ionic transport from dilute to concentrate chamber.

- ED brine concentrator (EDBC) is an evolving technology established to concentrate brine above 225 g/L TDS even with elevated levels of weakly ionized species like silica by utilizing thin (<100 μm) ion selective membranes with limited water transfer (<1 water molecule/ion movement from dilute chamber (D chamber) to concentrate chamber (C chamber)



Brine Valorization: Membrane Technology Landscape – Membrane Distillation (MD)

- ❑ Membrane distillation (MD) inhibit passage of water while allowing permeability for water vapor using non-polar hydrophobic synthetic material (e.g. PTFE, PVDF or PP) and offer pores with a standard diameter between 0.1 and 0.5 μm.
- ❑ Air Gap Membrane Distillation (AGMD) utilizes an air gap for thermal insulation, cultivating efficiency by dropping heat loss, while Vacuum Membrane Distillation (VMD) uses a vacuum to generate a large pressure gradient, resulting in higher permeate flux.
- ❑ Advanced vacuum MD (AVMD) marketed by Aquatech uses an applied vacuum to pull water vapor across the membranes and constantly recirculates brine without allowing salt crystals to reach the membrane.



Polymer Film

Global Brine Management Opportunities

Aquatech

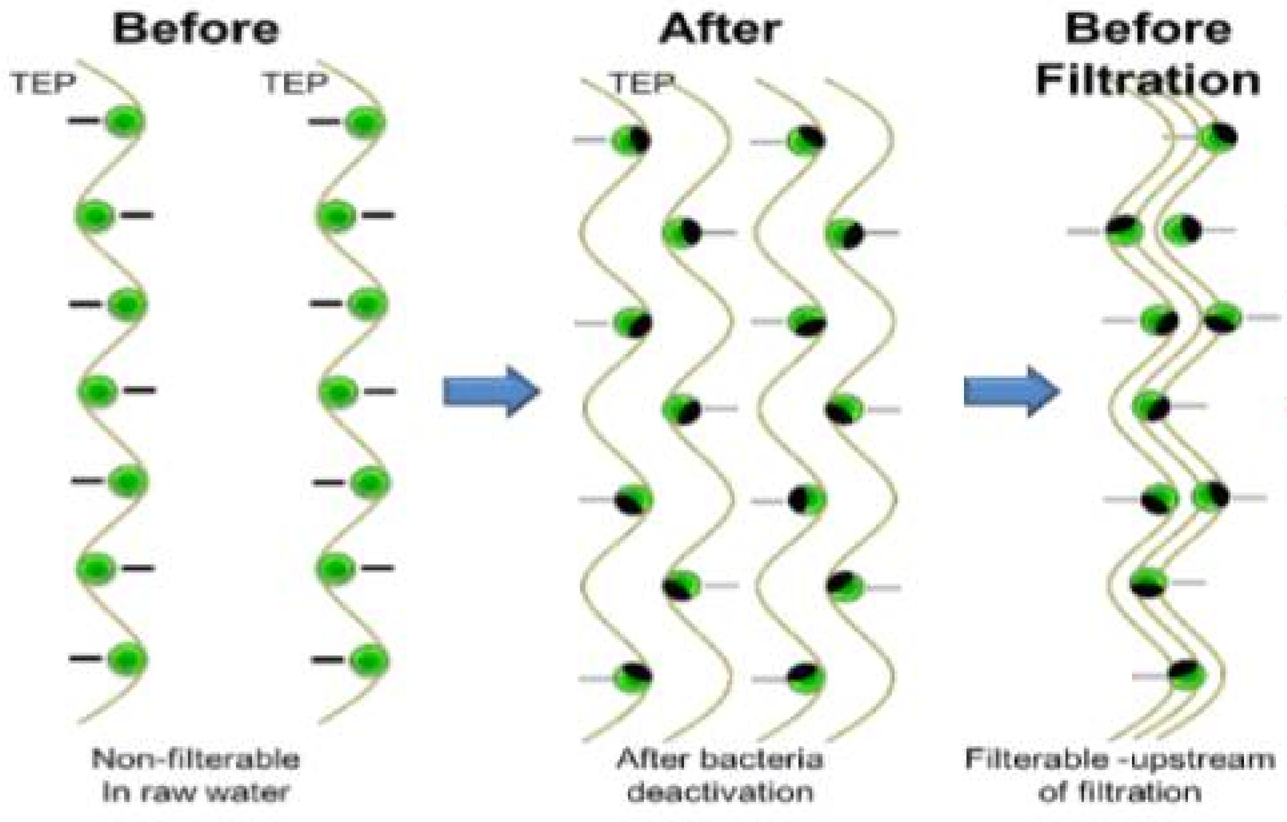
Global Brine Management Opportunities (2025 Outlook)

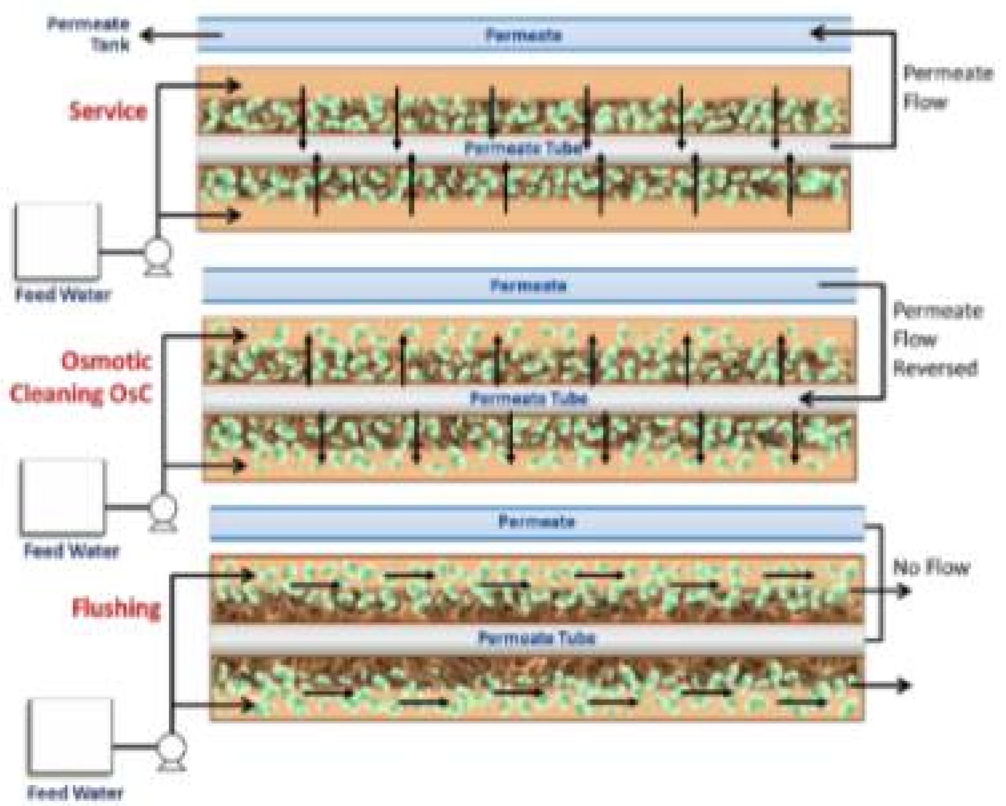
Region/Area	Primary Opportunity	Key Technologies	2025 Outlook
United States	MLD (Industrial reuse, produced water)	CCRO, HERO, OBS	Mature / Expanding
India	ZLD (Textiles, power plants)	MVC, Crystallizer, FO + Crystallizer	Regulated & Growing
China	ZLD (Coal & chemical industries)	OARO, Bipolar ED, Crystallizers	Policy-Driven Growth
Middle East	ZLD & Brine Valorisation (seawater RO)	FO, UHP-RO, MDC, Crystallizers	Strategic Priority
Chile	Brine Valorisation (Lithium recovery)	DLE, Bipolar ED	High Growth
Argentina	ZLD & Brine Valorisation	Crystallizer, Selective Precipitation	Emerging
Europe (EU)	MLD (Tightening reuse regulations)	CCRO, MAXH2O, HERO	Mature
Australia	MLD (Mining, inland desalination)	HERO, VSEP, UHP-RO	Stable
South Africa	Brine Valorisation (Mining, salt recovery)	Selective Precipitation, FO	Emerging

Source: Brine Consulting | LinkedIn

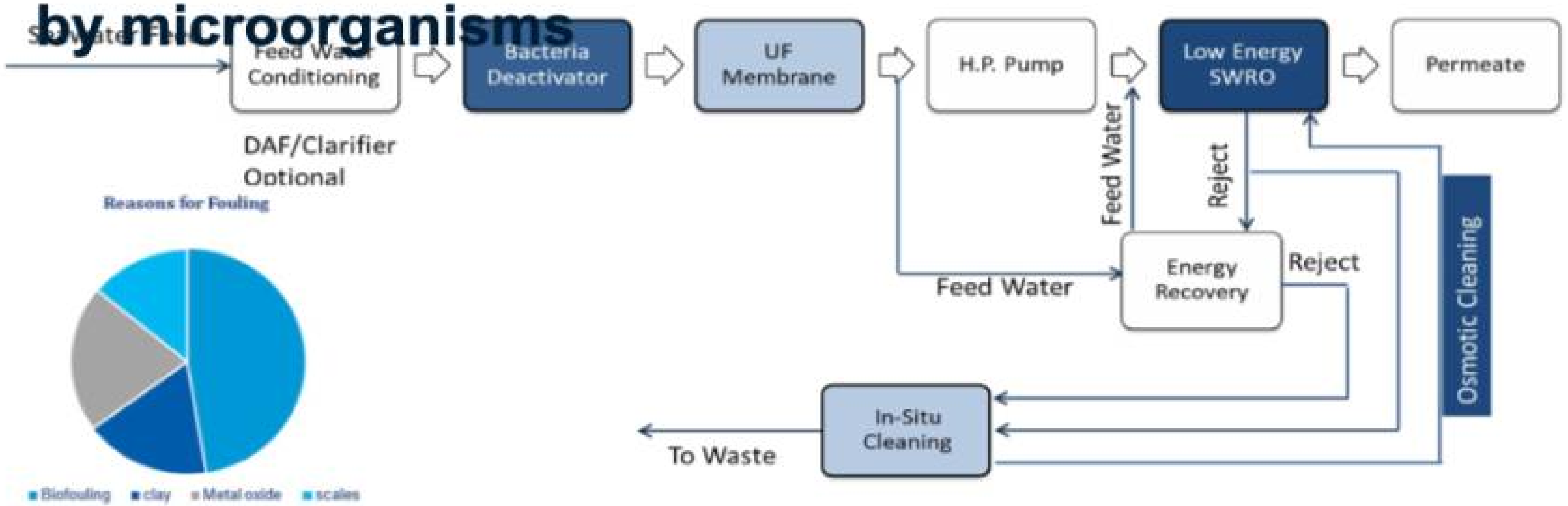
Energy Optimization in Seawater Desalination: LoWatt

- **Main Challenges Addressed**: Biofouling, high energy use, and chemical consumption.
- **How It Works**:
  - **UF Pretreatment** – reliable particle/microbe removal.
  - **Non-chemical biofouling prevention** – innovative bacteria deactivation.
  - **Optimized system design** – reduces energy consumption.
  - **Unique online cleaning method** – minimizes fouling & chemical dosing.
  - **Digital Optimizer** – dynamic process control for efficiency.
- **Results**:**20–30% lower energy use, 10% reduction in chemicals & cleaning cycles**





TEP in seawater refers to Transparent Exopolymer Particles, which are abundant, sticky substances produced by microorganisms

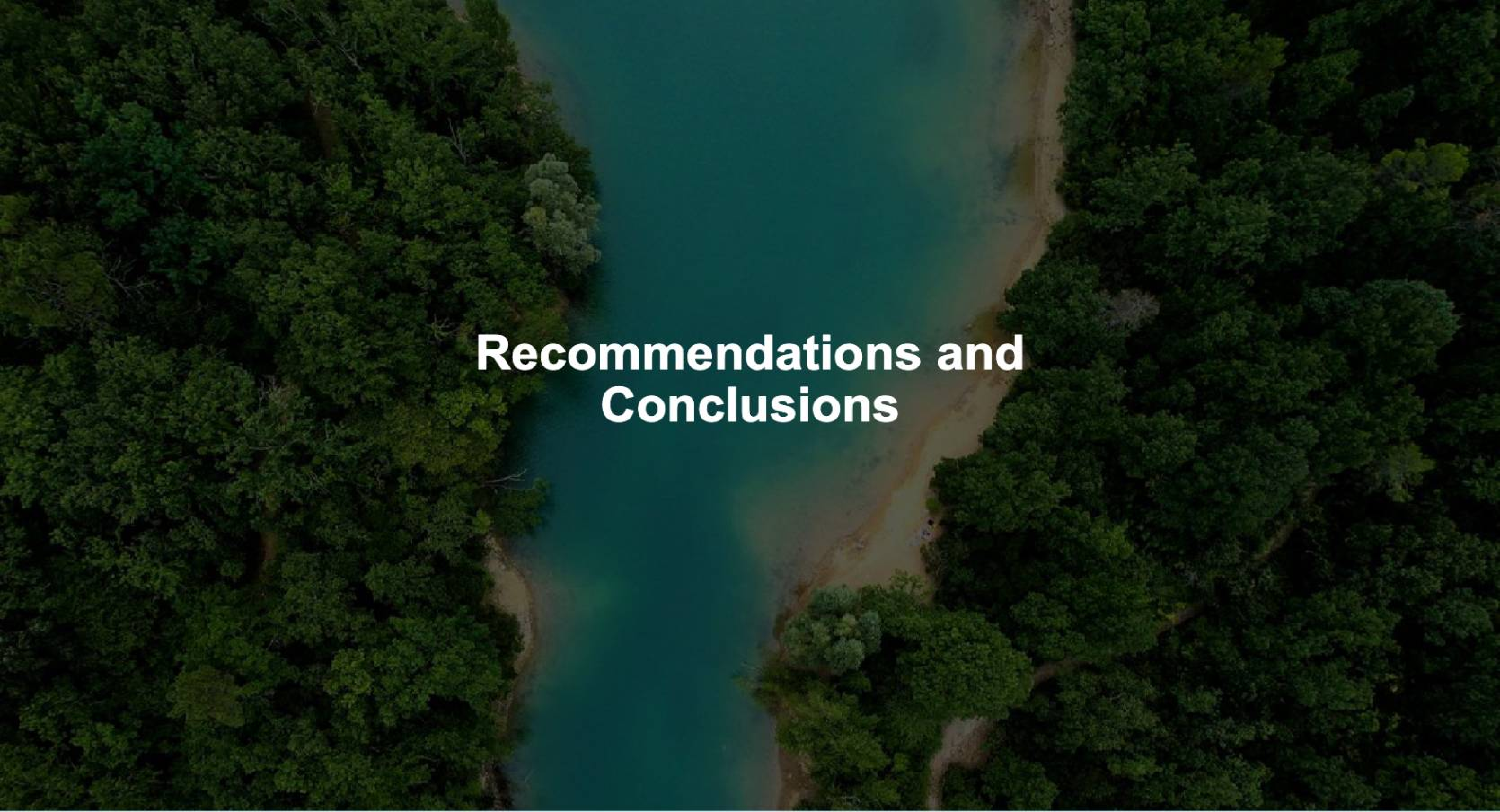


Comparison of Membrane Brine Concentration (MBC) Options

- **Permeating recycling OARO** (FTSH2O) maintains osmotic gradient across the spiral-wound membrane surface below standard maximum membrane element pressure limit of 1,200 psi by harnessing full recycle of permeate flows from lag stages to lead stages. Considering permeate flows are pure streams, such configurations are not challenged by scaling and fouling problems. However, their power consumptions are marginally higher than their hollow-fiber counterparts.

- **Concentrate recycling OARO** (Toyobo) maintains osmotic gradient across the hollow-fiber membrane surface below standard maximum membrane element pressure limit of 1,200 psi by harnessing partial recycle of concentrate flows from last stage in counterflow manner via bore side while feed-concentrate is managed via shell-side. Considering concentrate flows are loaded with scaling and fouling constituents which needs antiscalants to protect them. Such configurations are significantly challenged by scaling and fouling problems as the residence time of concentrate stream flows exceeds induction time of such antiscalants.

- **EDBC** is significantly more capital and energy intensive compared to OARO process but provides a significant benefits for achieving brine concentration while not allowing weakly ionized species like silica and boron to concentrate. This provides unique benefits in some geothermal brine and lithium salar applications.



Recommendations and Conclusions

Recommendations and Conclusions

- Brine valorization in synthetic soda ash, and chlor-alkali may provide a more sustainable and efficient operation pathway ensuring better ROI when co-produced desalinated water is monetized.
- Further improvement in ROI can be secured via secondary commodity valorization beyond supply of feedstocks.
- A comprehensive market research for secondary valorization products at local, regional, and global level should be performed to determine demand-supply gap along with actual commodity price.
- In India, increasing industrial water tariffs for co-produced excess desalinated water is a critical strategy for ensuring cost recovery and the financial viability of desalination projects.
- India's commitment to net-zero emissions by 2070 necessitates a large-scale transition to green steel to meet climate targets where brine valorization can be effectively integrated. Tata Motors and Mahindra & Mahindra, are part of the Steel-Zero initiative, which commits companies to using 100% net-zero steel by 2050.
- The EU's Carbon Border Adjustment Mechanism (CBAM) imposes a carbon cost on imports from countries with less stringent environmental regulations. This compels Indian exporters to


Thank You!
Q&A