

Advancements in Desalination

Jim Lozier, P.E
CH2M HILL



SOUTH TEXAS AWWA/WEAT



summer seminar 2013

Emerging Issues in the Water/Wastewater Industry

CH2MHILL

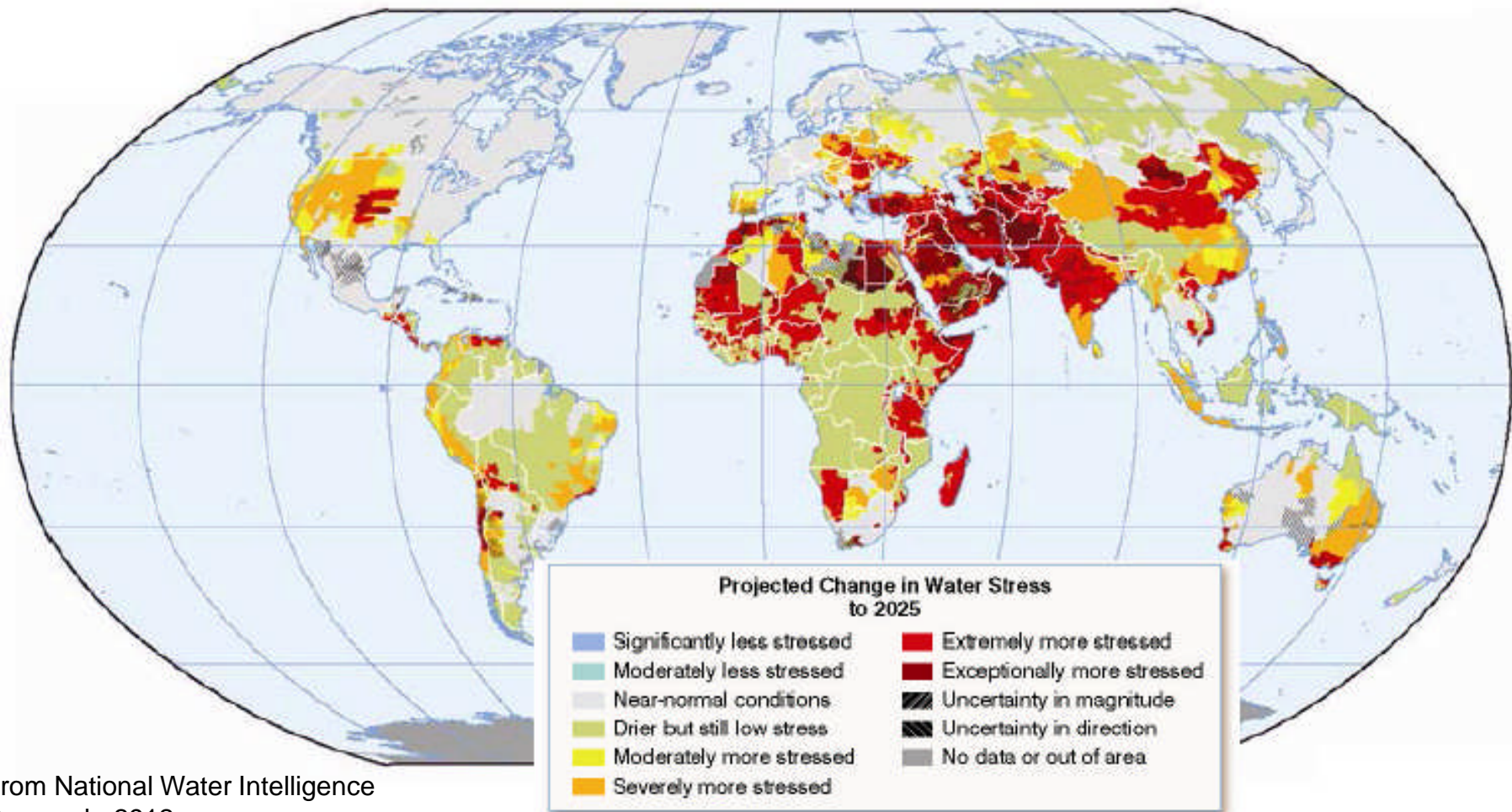
Presentation Outline

- The Need for Desalination
- Technology Overview
- Traditional Desalting Technologies
- Evolution and Current Status of Reverse Osmosis
- Recently Commercial Desalting Technologies
- Developmental Desalting Technologies
- Conclusions



World-Wide Water Stress Is Increasing

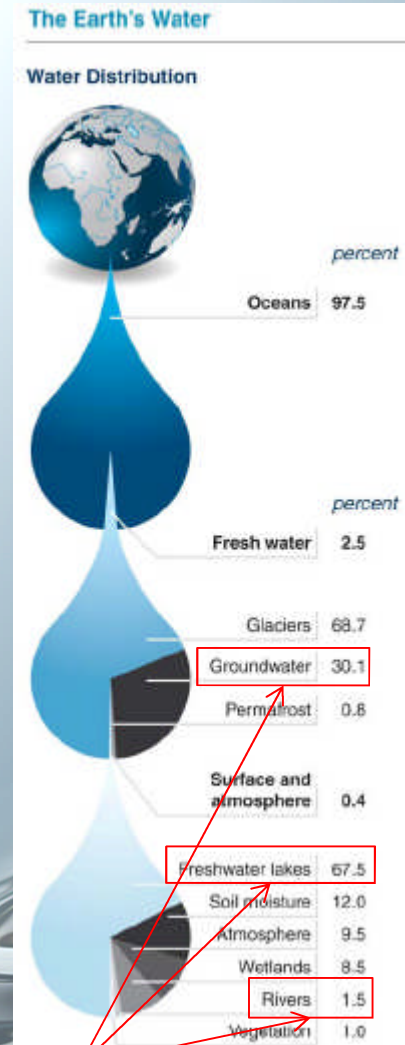
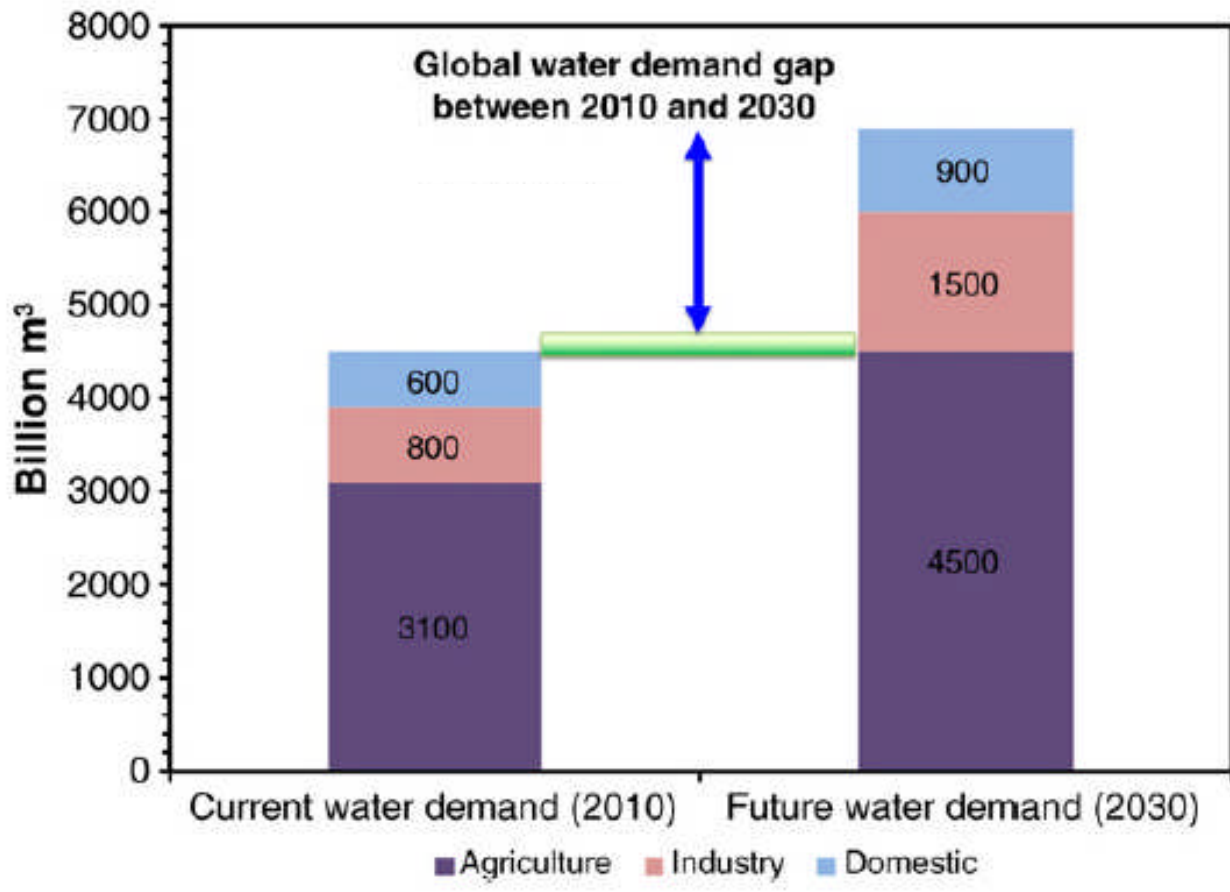
Global Water Picture (2025)



From National Water Intelligence Research, 2012

Water Demand/Supply Gap Drives Need for Lower-Cost Desalting Technologies

Desalination represents best source of new fresh water

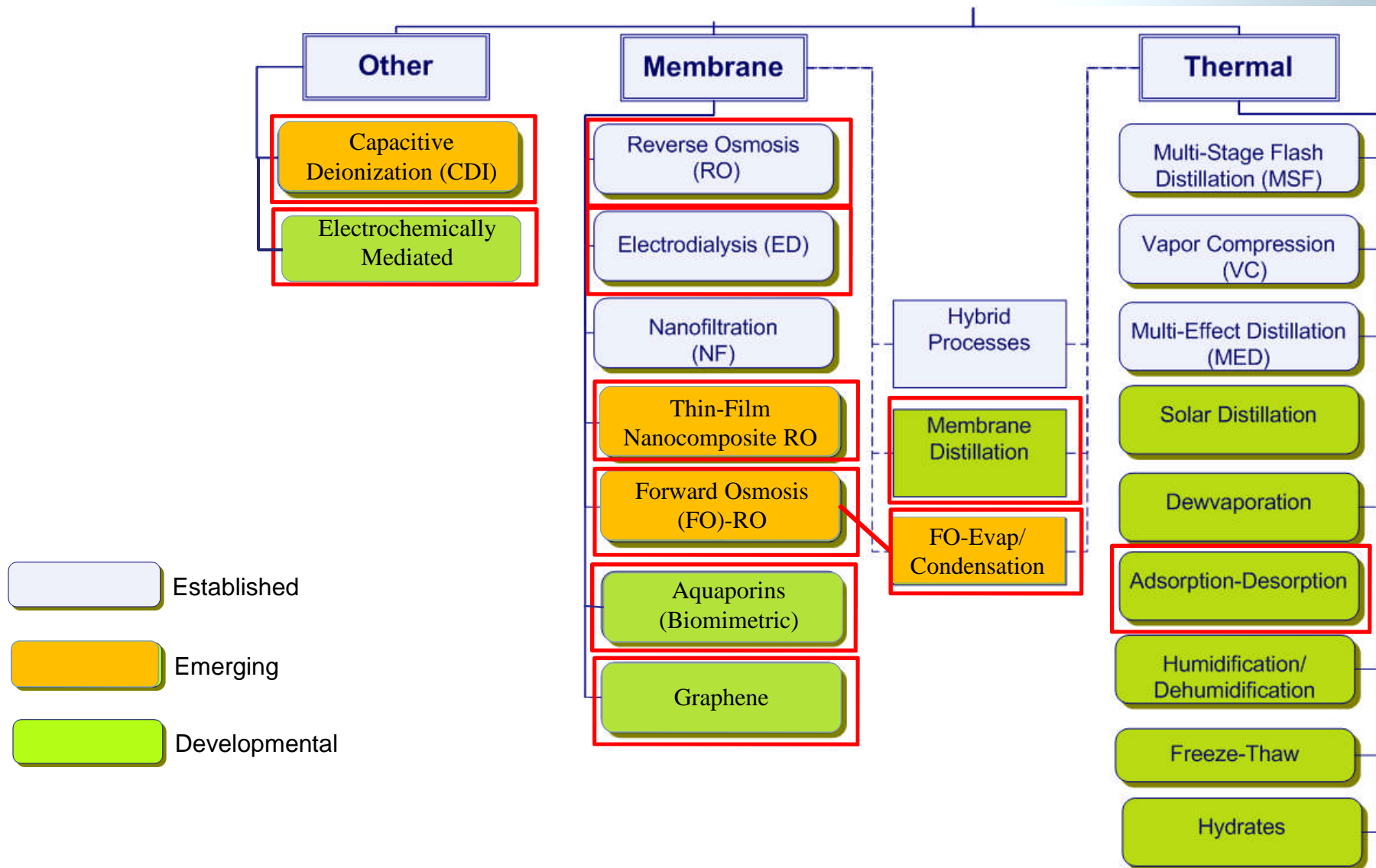


<1% readily accessible

HILL

From Ng et. Al, Desalination , 308, 2013

Overview of Desalting Technologies



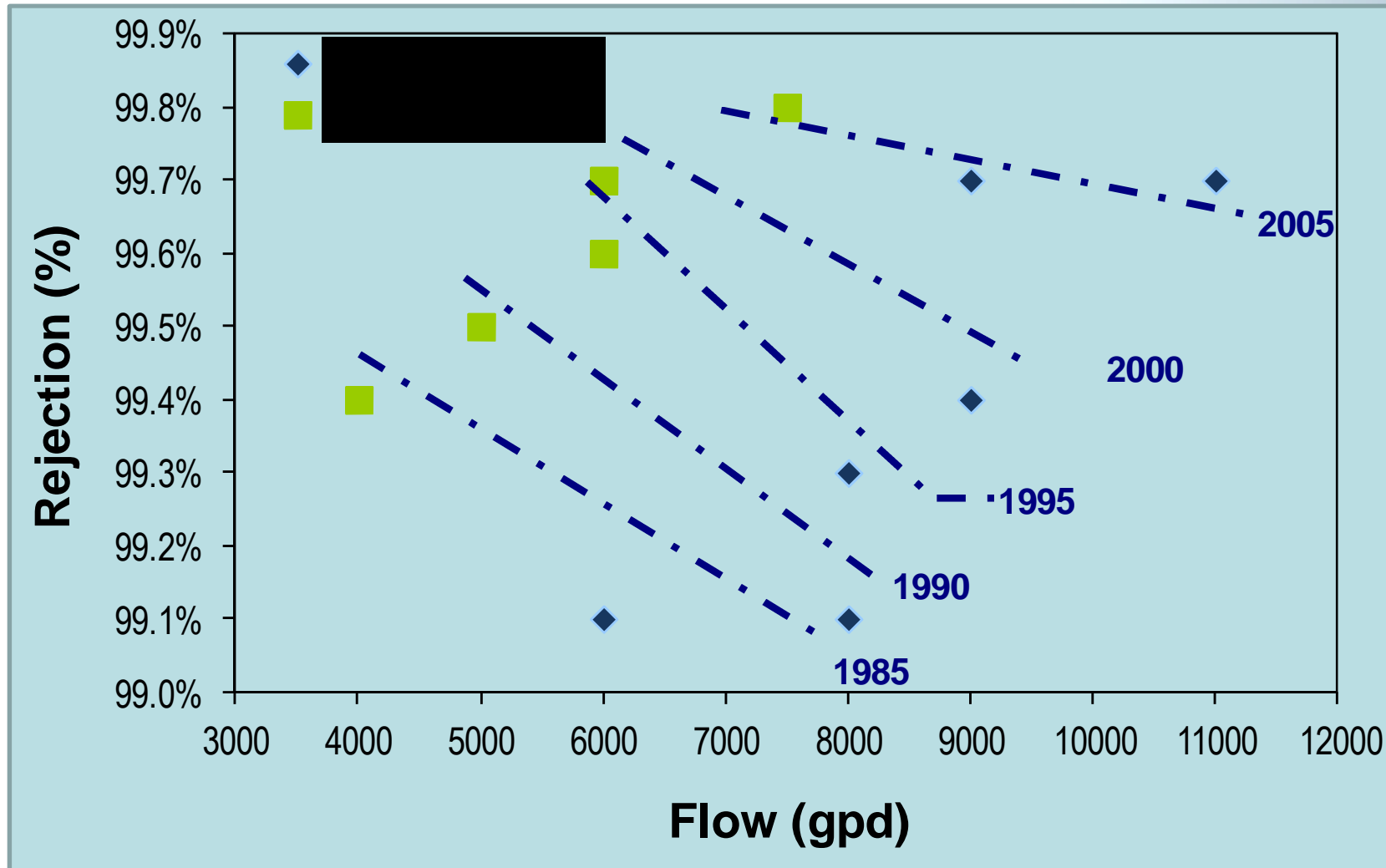
Energy Comparison

	Electrical Energy (kWh/m ³)	Thermal Energy (kWh/m ³)	Total Equivalent Electrical Energy (kWh _e /m ³)
Brackish Water RO ¹	1-1.5	0	1-1.5
Seawater Reverse Osmosis (SWRO) ²	4-4.5	0	4-4.5
Multiple Effect Distillation (MED) ²	1	60-70	16-18.5
Multi-Stage Flash (MSF) ²	5	70-80	22.5-25

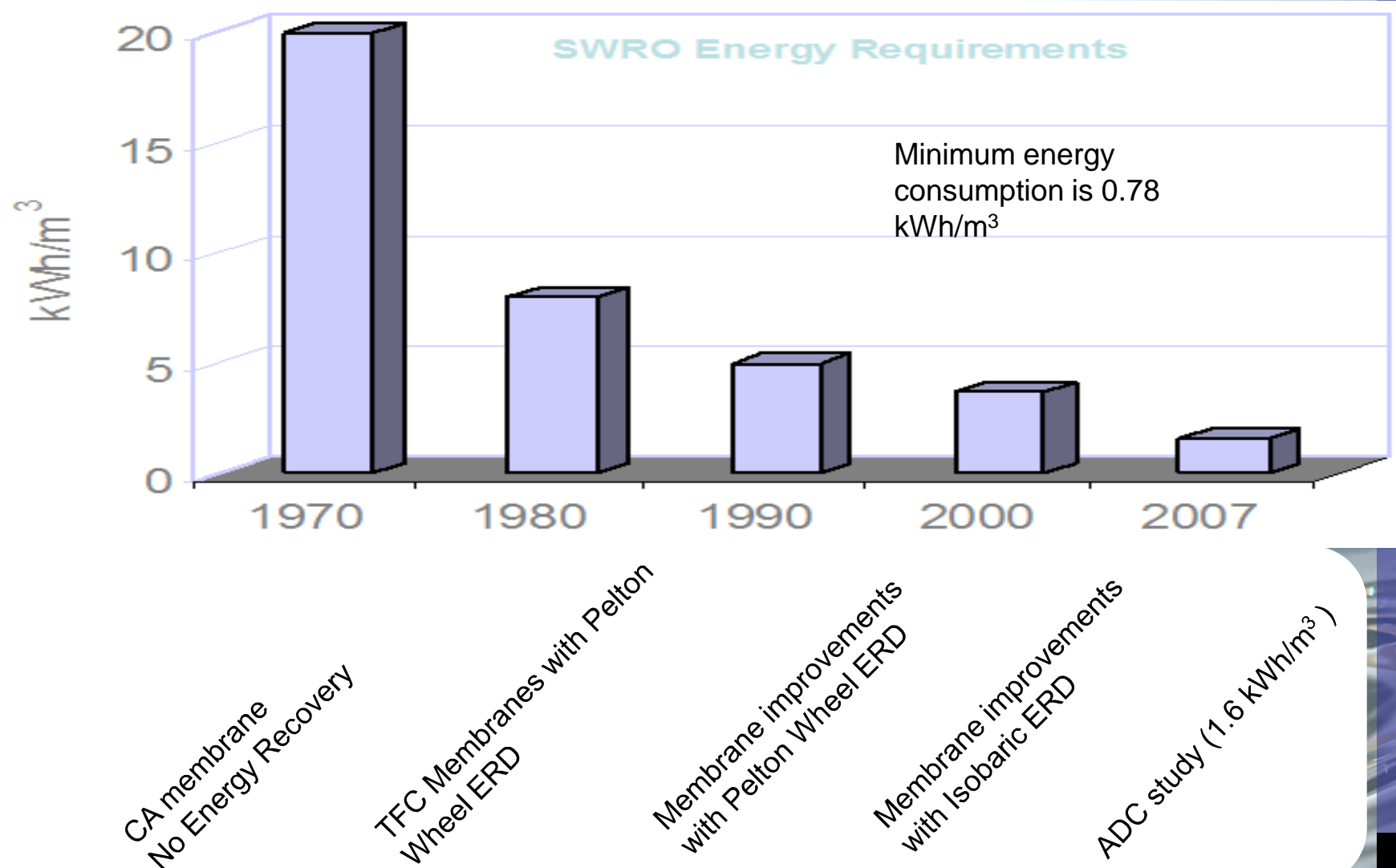
¹GWI 2008 (TDS<4,000 mg/L)

²Huehmer and Wang 2009 and Sharqawy, 2011

Progressive Advancements in RO Membrane Performance

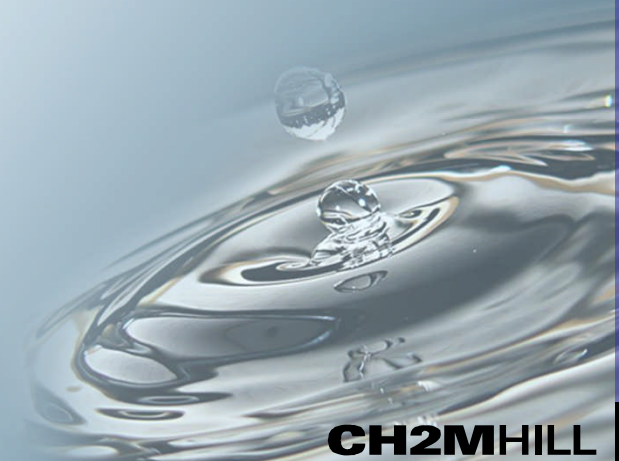


Energy consumption of RO has been reduced significantly



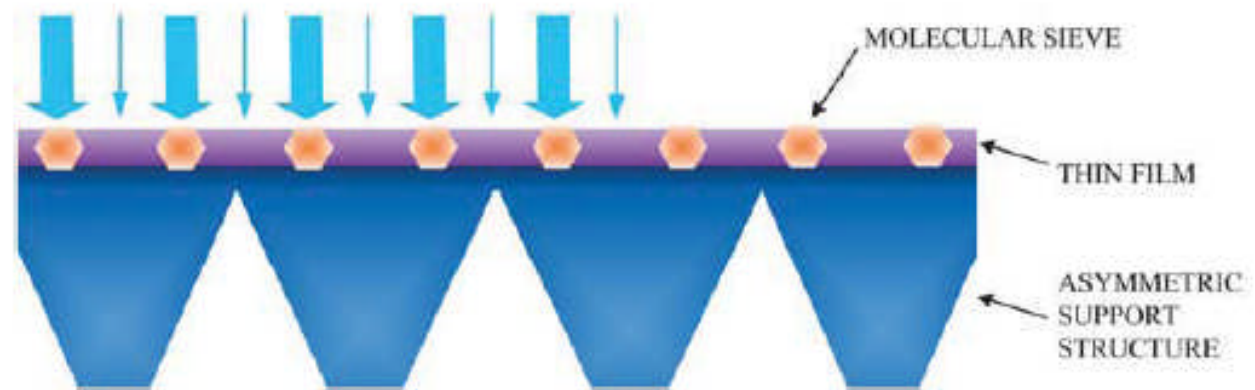
Emerging Technologies

- Nano-composite RO
- Capacitive Deionization
- Forward Osmosis



Thin-Film Nanocomposite PA RO

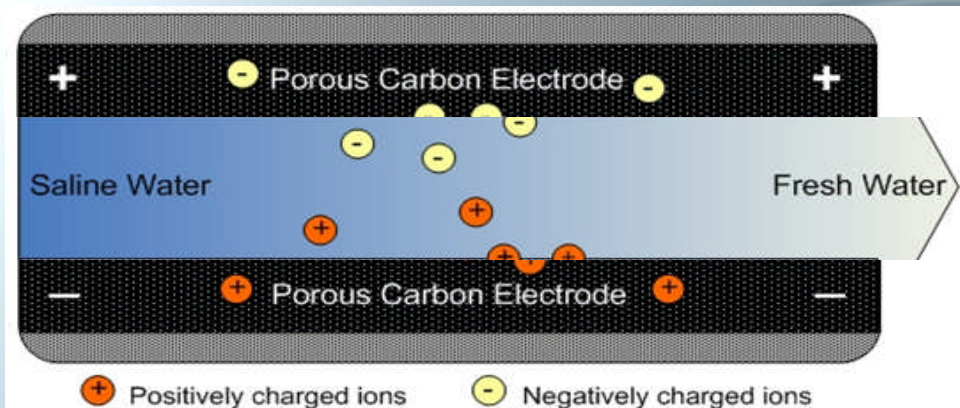
- Thin-film nanocomposite (TFN) membranes incorporate zeolite particles into PA rejecting layer to increase water permeability while retaining salt rejection
- First developed by Dr. Eric Hoek at UCLA
- Commercialized by NanoH₂O
- Practical benefit is reduced energy consumption; most relevant to seawater desalination



From Pendergast and Hoek, *Energy Environ. Sci.*, 4, 2011

Capacitive Deionization (CDI)

- Uses activated carbon to adsorb ions under a low voltage electric field (1-2 V) based on electric double-layer capacitor principle
- System operates in a two-step process:
 - Applied electric field produces ion adsorption
 - Reversal (or relaxation) of electric field produces desorption
- Several commercially available CDI systems on the market (Enpar, Aqua EWP, Voltea)
- Most suitable for brackish water desalination due to limited specific ion adsorption of current carbon materials



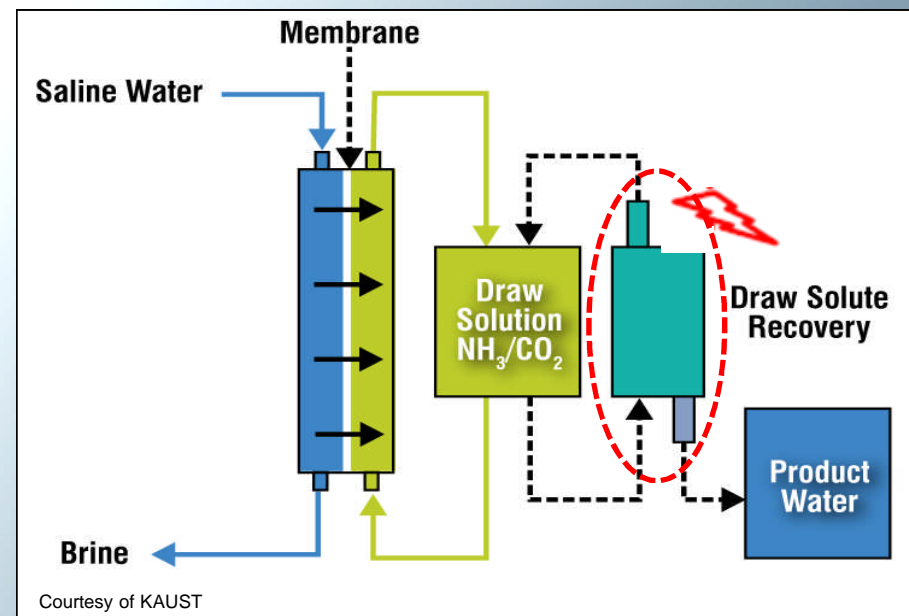
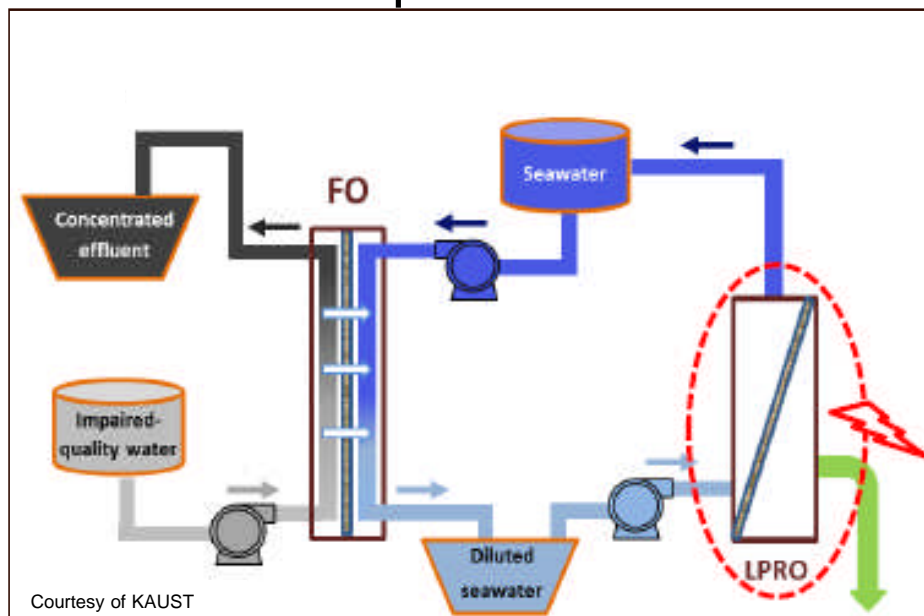
Capacitive Deionization

- Benefits
 - Doesn't concentrate ions as salts → more suitable for high scaling waters w/o need for scale inhibitors
 - Low pressure, can use plastics to reduce cost and corrosion
- Limitations
 - Current carbon materials have:
 - limited salt removal (70-80%)
 - higher energy consumption than RO (1.8 versus 0.4 kWh/m³ for brackish RO)
 - Subject to organic fouling (effluent applications)
- New materials promise improved performance
 - Carbon nanotubes
 - Graphene

Suppliers: Enpar, Aqua-EWP, Voltea

Forward Osmosis

- Uses osmotic pressure gradient ($\Delta\pi$) to transport water across a semi-permeable membrane
- No energy is needed to drive the water flux of an FO process
- A high osmotic pressure 'draw' solution is used as driving force in the FO process.
- Diluted draw solution must then be re-constituted by removing the transported water



Forward Osmosis

Benefits

- 1 atm operating pressure
- Can be constructed of non-metallic components, reducing capital cost
- Lower fouling propensity than RO

Current Limitations

- Requires specially-designed membranes; optimum design still in development to provide improved water flux/reduced ICP
- Draw solution reconstitution represents major energy use; current methods include RO and evaporation/condensation
- Coupling with waste heat or solar for EC is current focus

>Oasys and Modern Water have commercialized and sold systems into industry

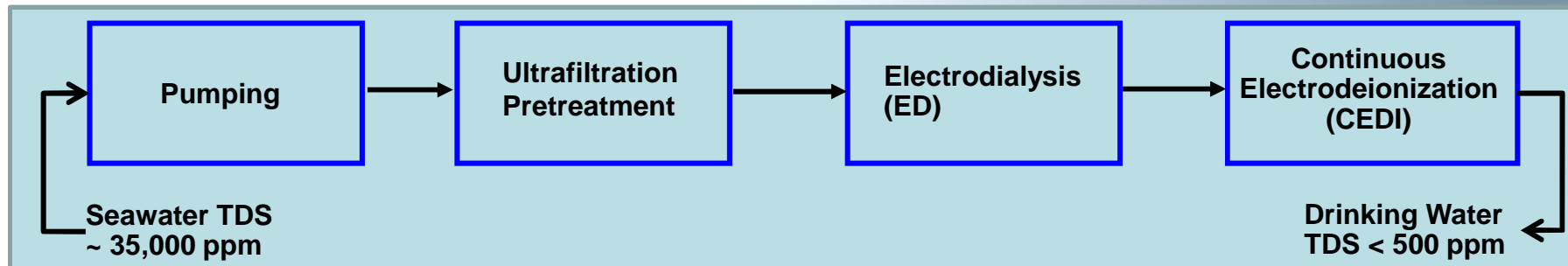
Near-Term Developmental Technologies

- Combined Electrodialysis/Electrodeionization
- Forward Osmosis
- Adsorptive/Desorptive Desalination
- Membrane Distillation
- Biomimetic Membranes
- Graphene Nanoporous Membranes
- Microbial



Siemens Electrochemical Desalination

- Developed under a Challenge Grant from the Government of Singapore (innovative, low energy method of desalting seawater @ $<1.5 \text{ kWh/m}^3$ *)
- Utilizes a innovative combination of existing processes.
- Initial prototype demonstrate energy consumption of 1.8 kWh/m^3 while producing product TDS $<500 \text{ mg/L}$



*Includes pretreatment, desalting and post-treatment.

Electrochemical Desalination

- Advantages (versus RO)
 - Low pressure (40 psi) → non-metallic componentry
 - Low noise → no high pressure pumps, ERDs or valves
 - Chlorine resistant membranes → effective control of biofouling
- Current design
 - 3 modules in series
- Pilot systems currently in operation



Graphic courtesy of Siemens

Silica-Based Adsorption/Desorption (AD) Desalination

Developed at National University of Singapore (NUS) ; demonstrated at KAUST

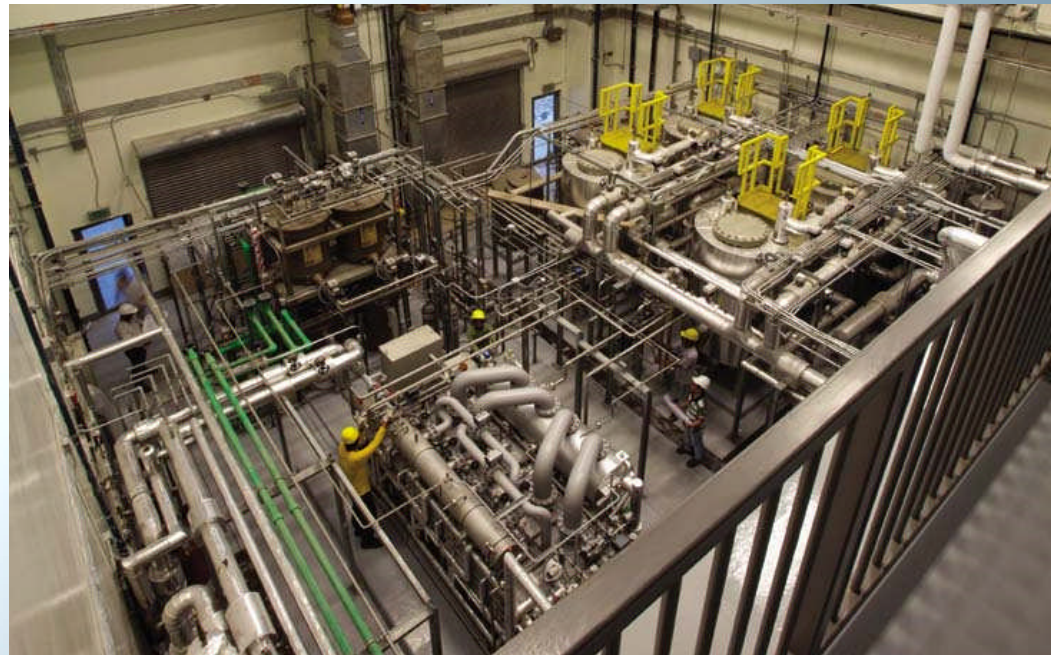
- Uses silica gel to adsorb water vapor evaporated from seawater at low pressure and temperature
- Heat applied to water-adsorbed gel releases vapor which is then condensed as pure water
- Energy for desorption derived from waste heat or renewable sources including solar or geothermal



AD Desalination

- Features

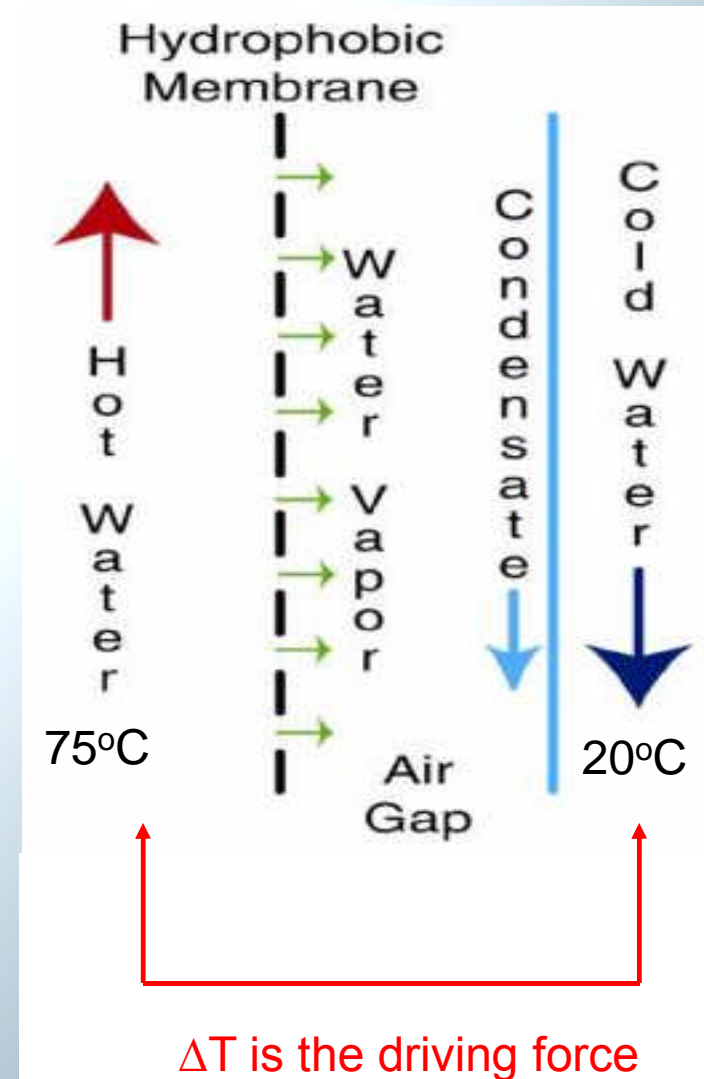
- reduced scaling and corrosion issues (low temperature saline water)
- reduced energy requirements - 1.4 kWh/m³ if 'free' waste heat available (versus 3.5 kWh/m³ for SWRO)
- still requires significant capital and operating cost associated with cooling load to exhaust heat associated with adsorption and condensation



Demonstration Unit at KAUST

Membrane Distillation (MD)

- Couples membrane technology and distillation in a single unit process
- Microporous, hydrophobic membrane passes water vapor while retaining liquid water
- Driving force for vapor transport is temperature differential across the membrane, typically 30-50 deg C.
- Rate of vapor transport (water flux) is proportional to temperature differential
- Produces very low TDS distillate



Membrane Distillation

- Benefits
 - Low-pressure and -energy process
 - Potential to use low-grade, waste heat or heat derived from solar energy
 - Lower membrane fouling potential → less expensive pretreatment than RO and more robust cleaning capability
 - Product quality (TDS) is independent of feed TDS (can treat more saline sources than RO)
- Limitations
 - Higher-flux membranes required to reduce capital cost
 - Membrane wetting by organic agents must be minimized to avoid pore filling by water and passage of contaminants
- Commercial systems manufactured by MemSys and Memstill, among others

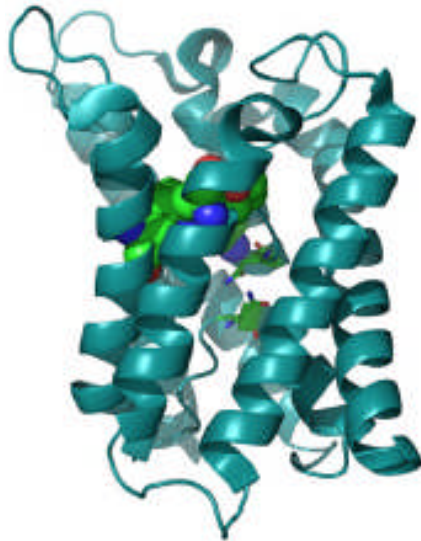
Longer-Term Developmental Technologies

- Electrochemically-Mediated Desalination
- Biomimetic Membranes
- Graphene Nanoporous Membranes

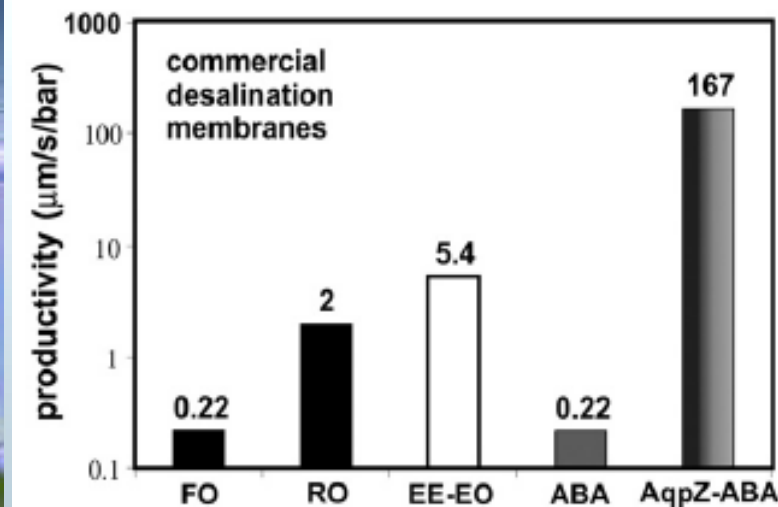
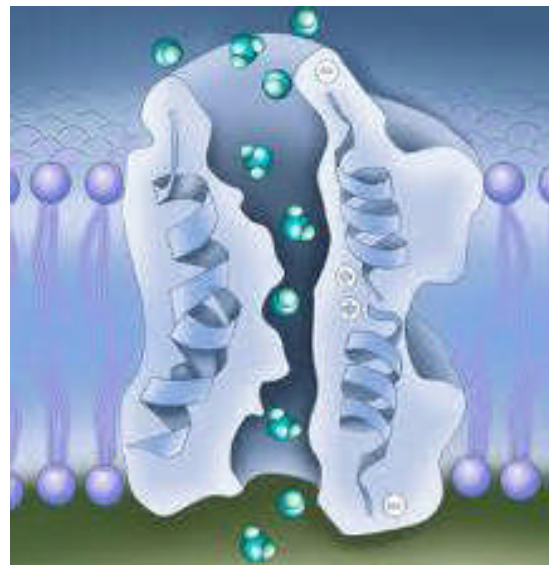


Biomimetic Membranes - Aquaporins

- Aquaporins are pore-forming proteins, ubiquitous in living cells
- Incorporate water channels that provide extremely high permeability and selectivity (orders of magnitude greater than RO)
- Offer best chance to revolutionize desalination but are furthest from commercialization (Pendergast et. al, Energy Env. Sciences, 2011)



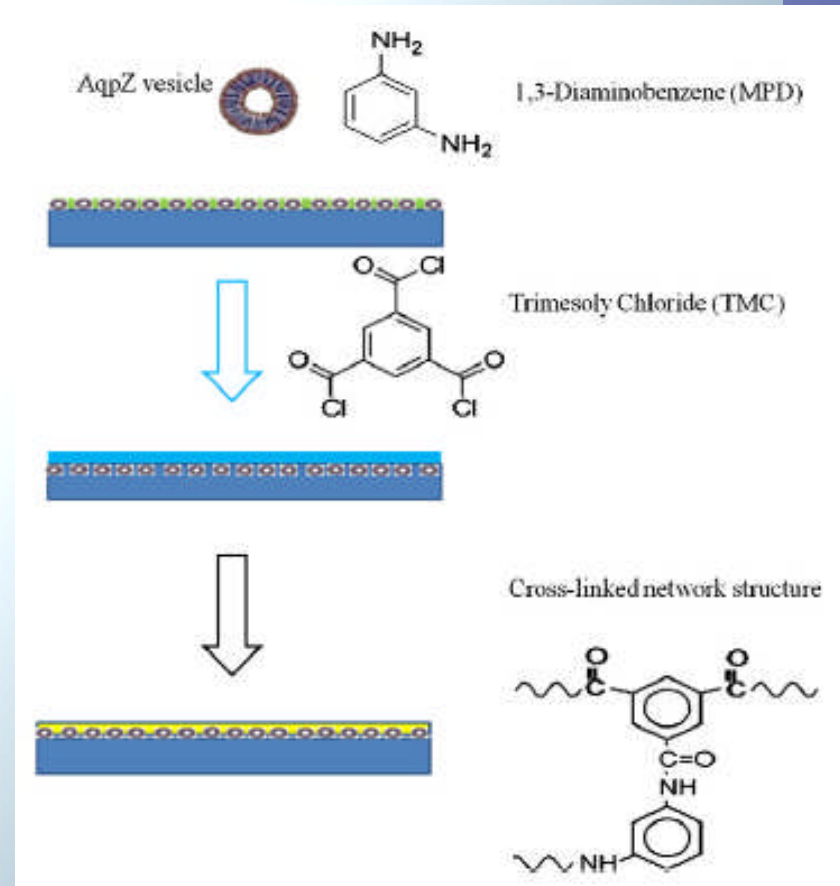
side view of AqpZ
(from Tang et. al, Desalination, 2013)



(from Kumar et. al, Proc. Nat'l Acad. of Sci., 2009)

Aquaporins – Current status

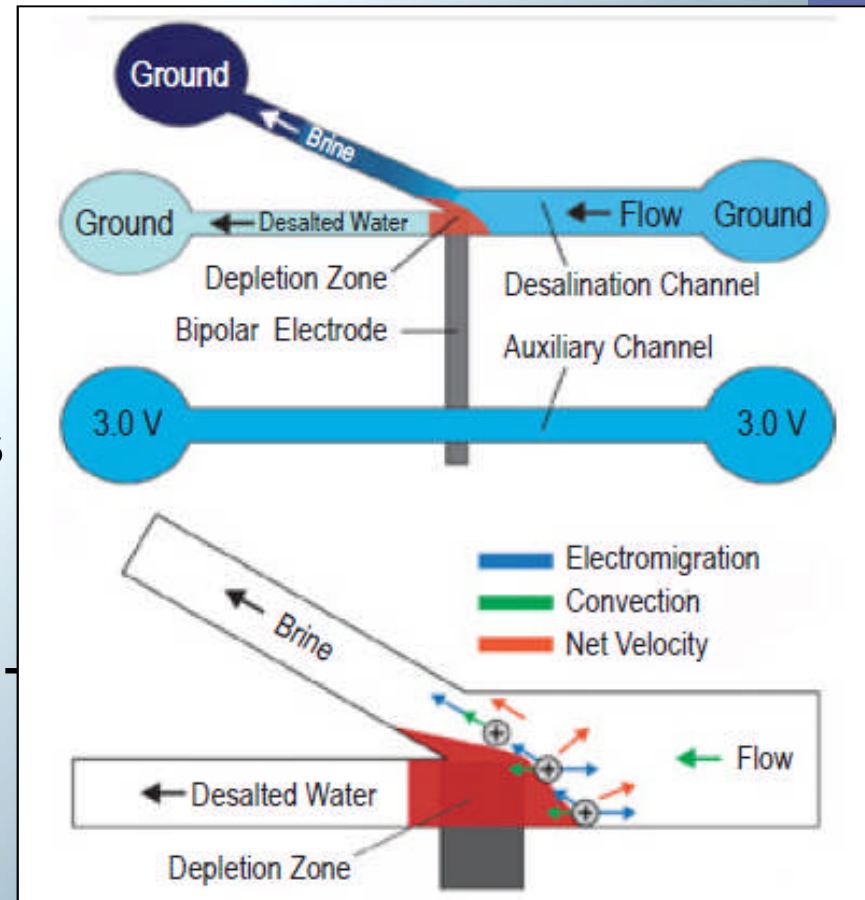
- Aquaporins have been synthesized outside the cell (cell-free synthesis)
- Practical desal membrane has been fabricated by incorporating Aqp proteoliposomes within a conventional polyamide structure.
- Aqp-PA composite membrane has:
 - 4.0 LMH/bar (9.8 GFD/psi) permeability
 - 96.3% salt rejection
- Other fabrication methods have been employed but are limited by complexity, lack of robustness or cost



(From Tang et. al, Desalination, 2013)

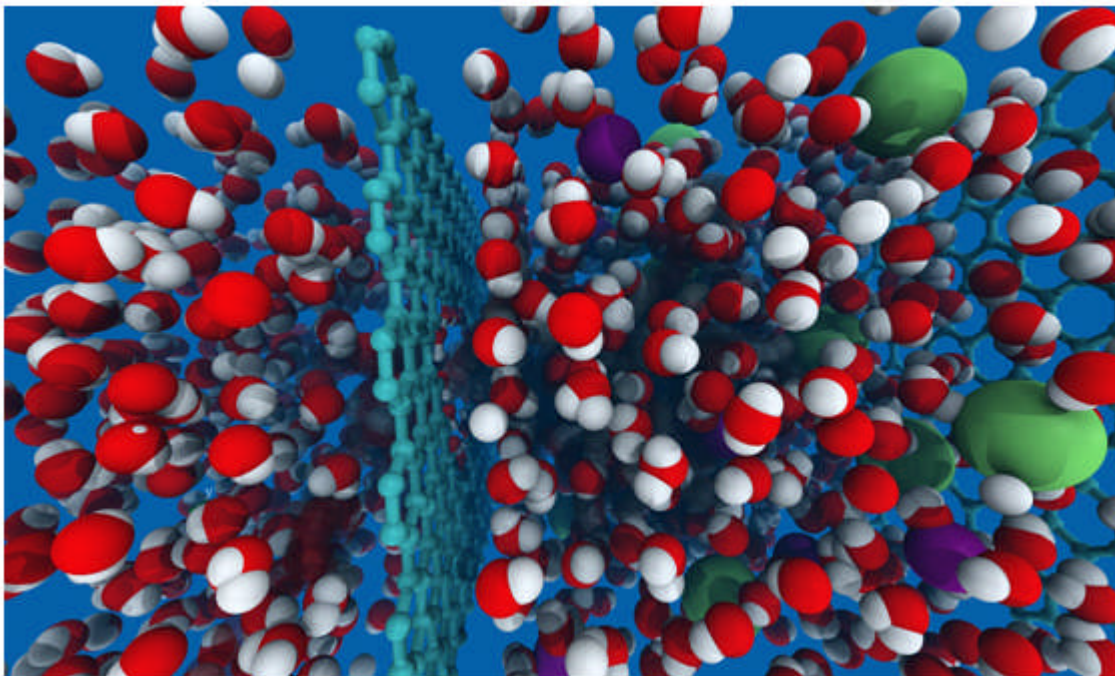
Electrochemically-Mediated Desalination

- Water is desalted as it passes through branched micro channels
- Electric field creates an ion depletion zone (3V)
- Ions are directed into one channel; water into another.
- Bipolar electrode used
- Projected specific energy use is 1.0 kWh/m³ (ideal conditions)
- Developed by Okeanos Technologies; testing done at U and Marburg University

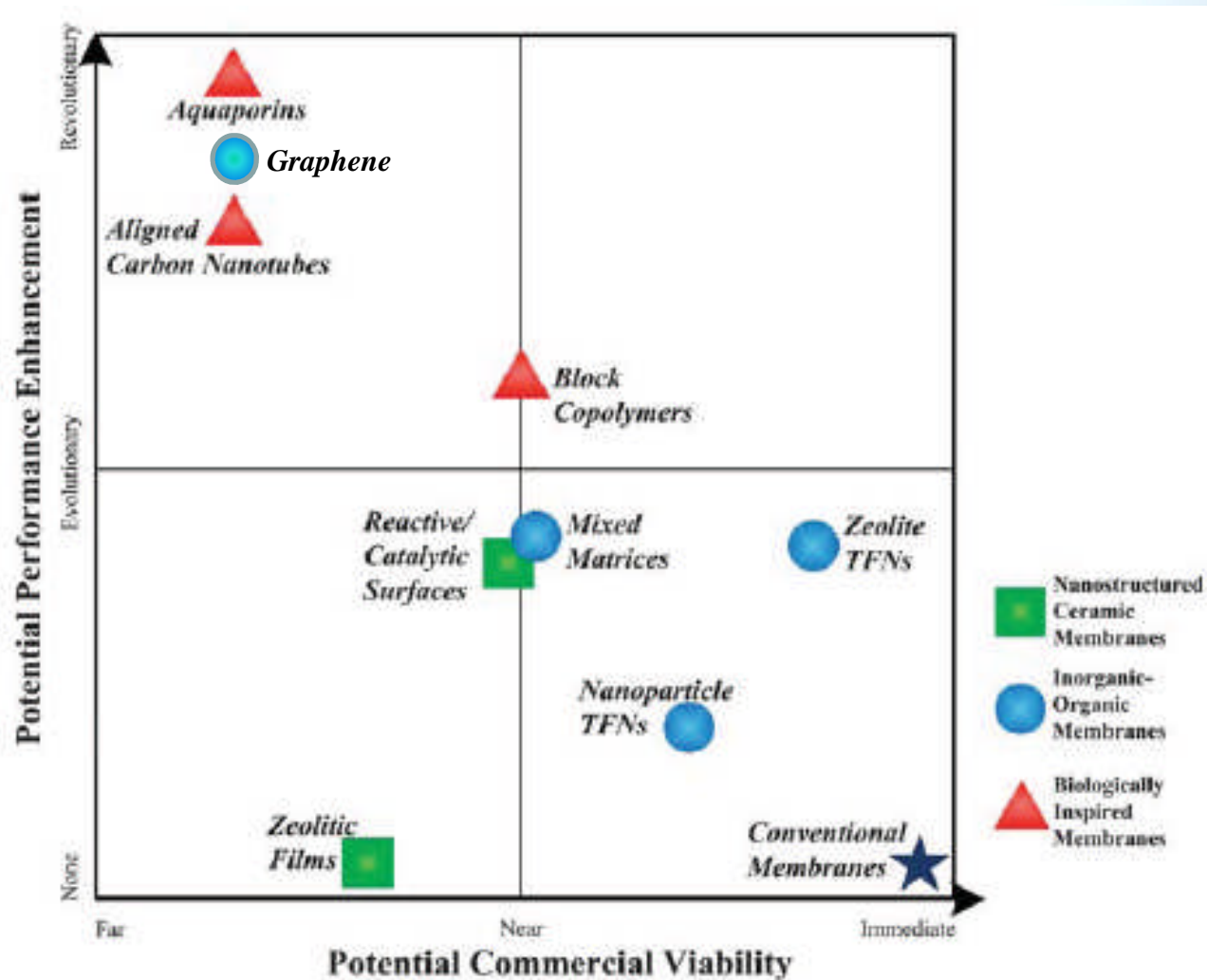


Nanoporous Graphene

- Cohen-Tanugi and Grossman at MIT/Nano Letters
- Using computer simulations via molecular dynamics, demonstrated that an atom-thick graphene sheet containing 1-nm holes can separate NaCl from water at several orders of magnitude the water flux of RO membranes
- No current methods available to fabricate such graphene sheets



Ranking of Nanotechnology-Enabled Desalination Membranes



Modified from Pendergast and Hoek, *Energy Environ. Sci.*, 4, 2011

Conclusions

- Innovations in desalting technologies are occurring in many areas and at varying pace.
- Enhancements to RO and ED have occurred and will continue.
- Availability of low grade or solar heat for coupling with MD, FO and adsorptive technologies represent means to reduce energy consumption and life cycle costs, particularly for higher salinity feeds.
- Advancements in membrane fabrication are key for commercialization of MD, FO in short term and nanomaterial, graphene and biomimetic membranes in long term