Developing New Types of Desalination Cells Using Bi as a Cl-Storage Electrode

Tech Connect 2019

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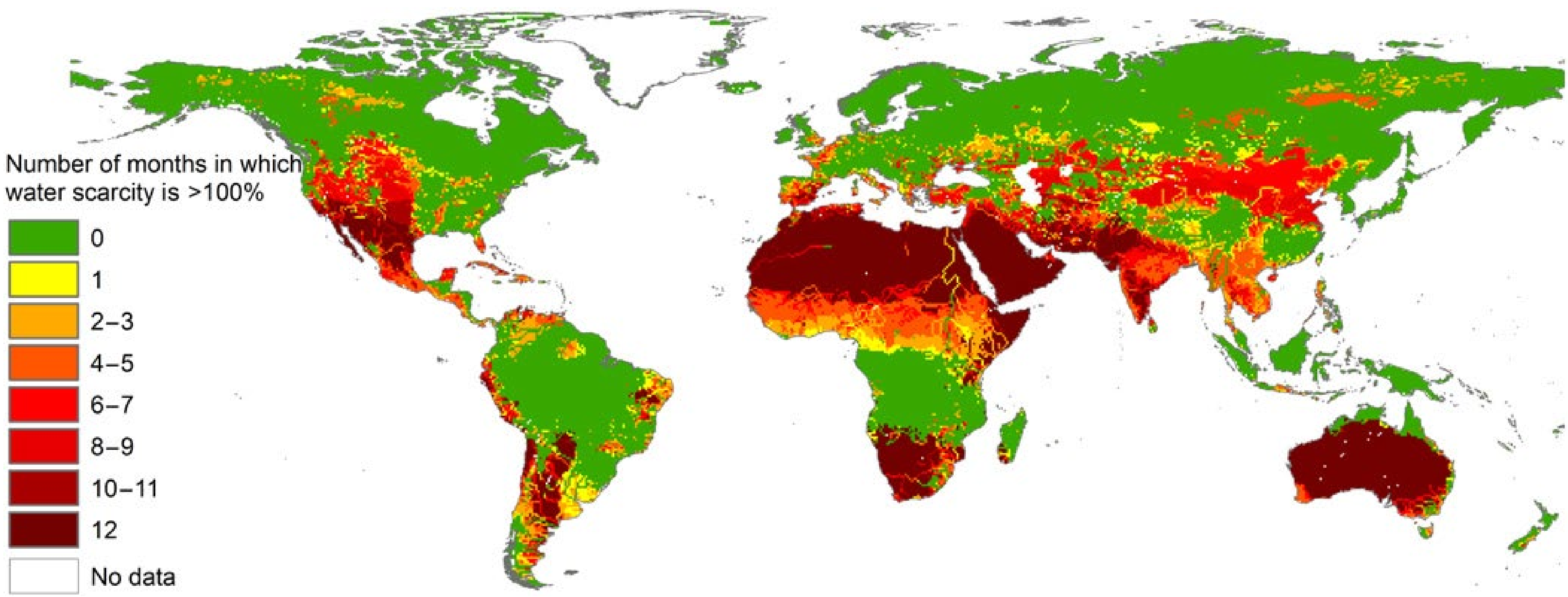
WARF IP:P170083US01 – Bismuth-based chloride-storage electrodes

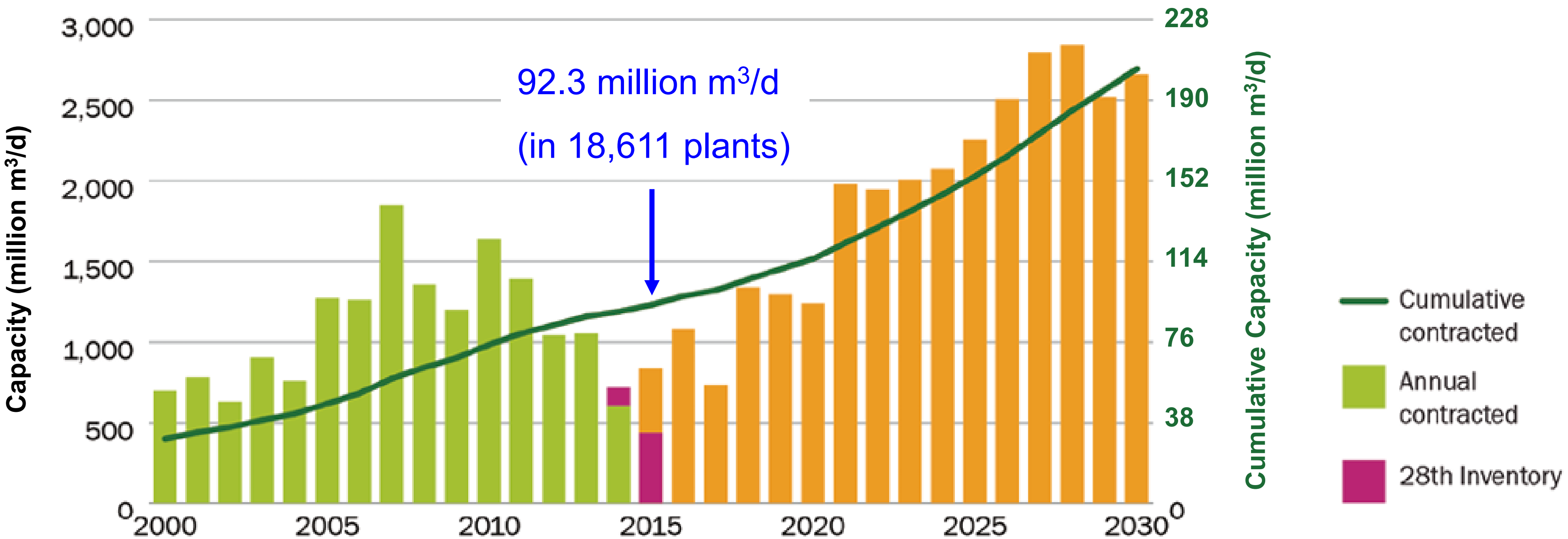
Global water scarcity



- Currently, ~66% of the world's population (~4 billion people) lives without sufficient access to fresh water for at least one month per year
- Rapid growth in human population and development of industry and agriculture are continuing to exacerbate the problem of fresh water scarcity

Hoekstra, A.Y. et al. *Sci. Adv*. **2016**, *1500323.*

Global desalination market forecast



- In 2015, the total global desalination production capacity reached 92 million m^3/day distributed across 18,611 plants globally
- Desalination market value 2015: $12.8 billion total
- Expected desalination market value in 2020: $19.9 billion total

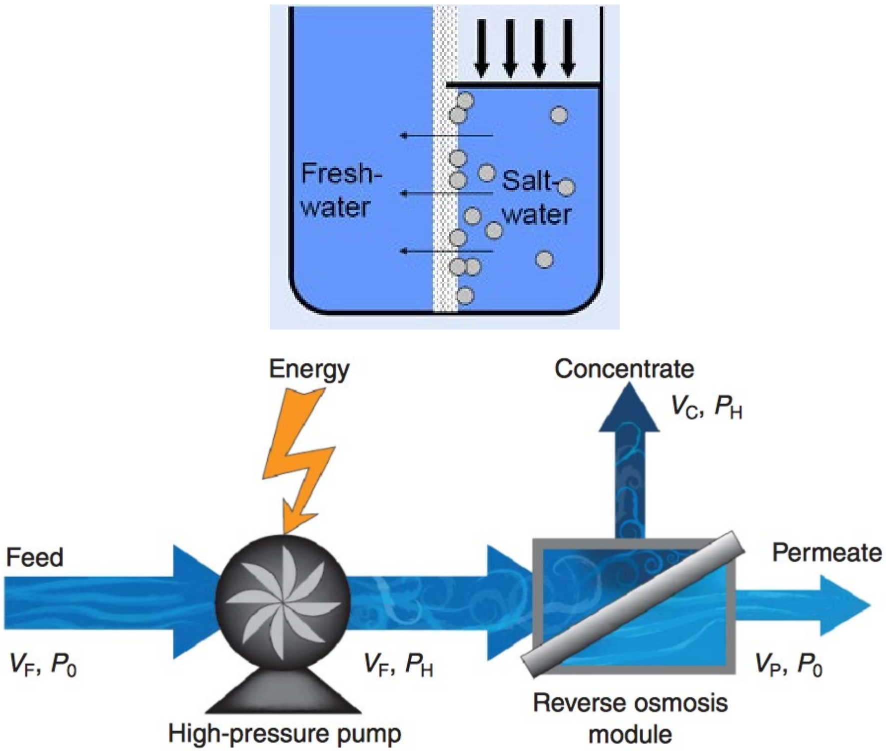
[http://ida.enoah.com/portals/41/newsletter/issues/2015-11-12/article_4.html]

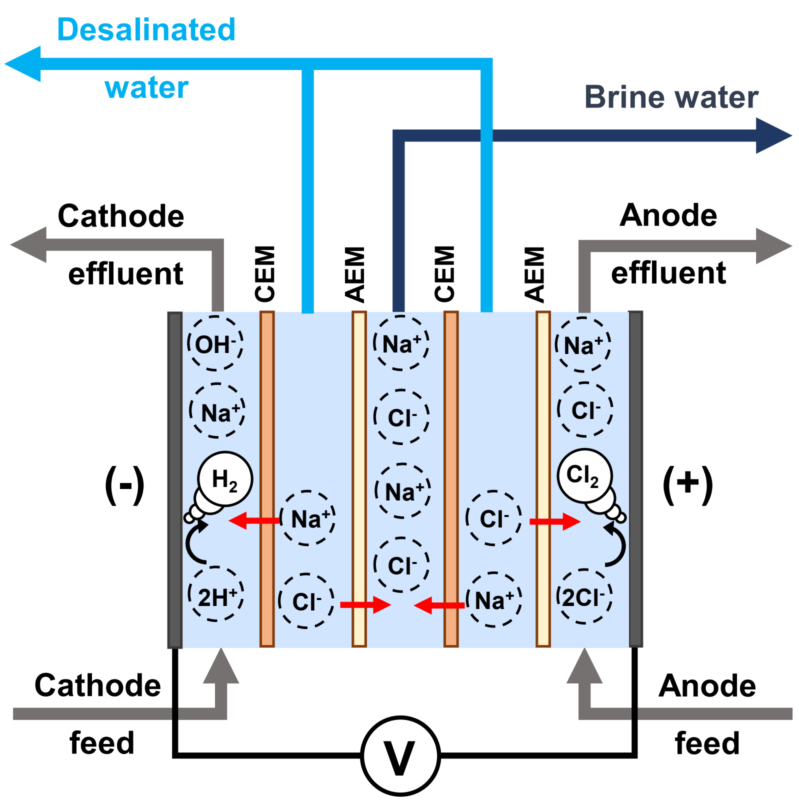
Conventional desalination methods

Distillation: High energy requirements limit commercial applications
MSF (Multi-stage flash distillation)
MED (Multi-effect distillation)
VC (Mechanical vapor compression distillation)

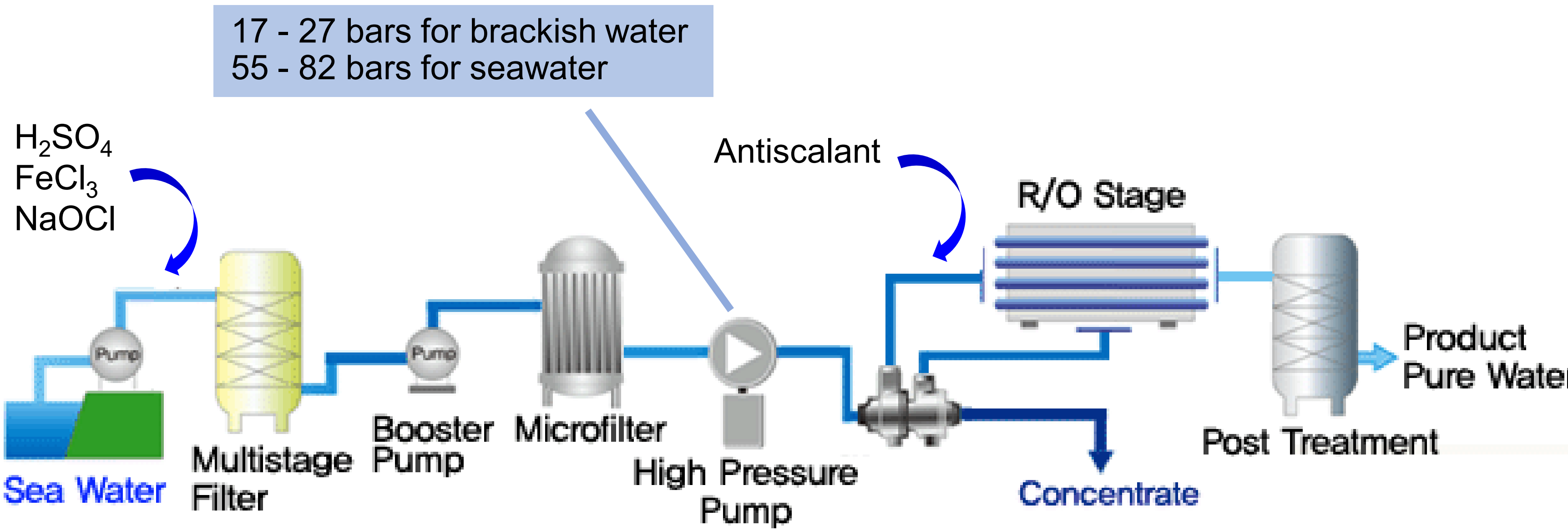
Reverse Osmosis (RO): Operation of high-pressure pumps and processes required to prevent membrane fouling keep the cost high

Electrodialysis (ED): High voltage requirements limit applications to brackish water desalination





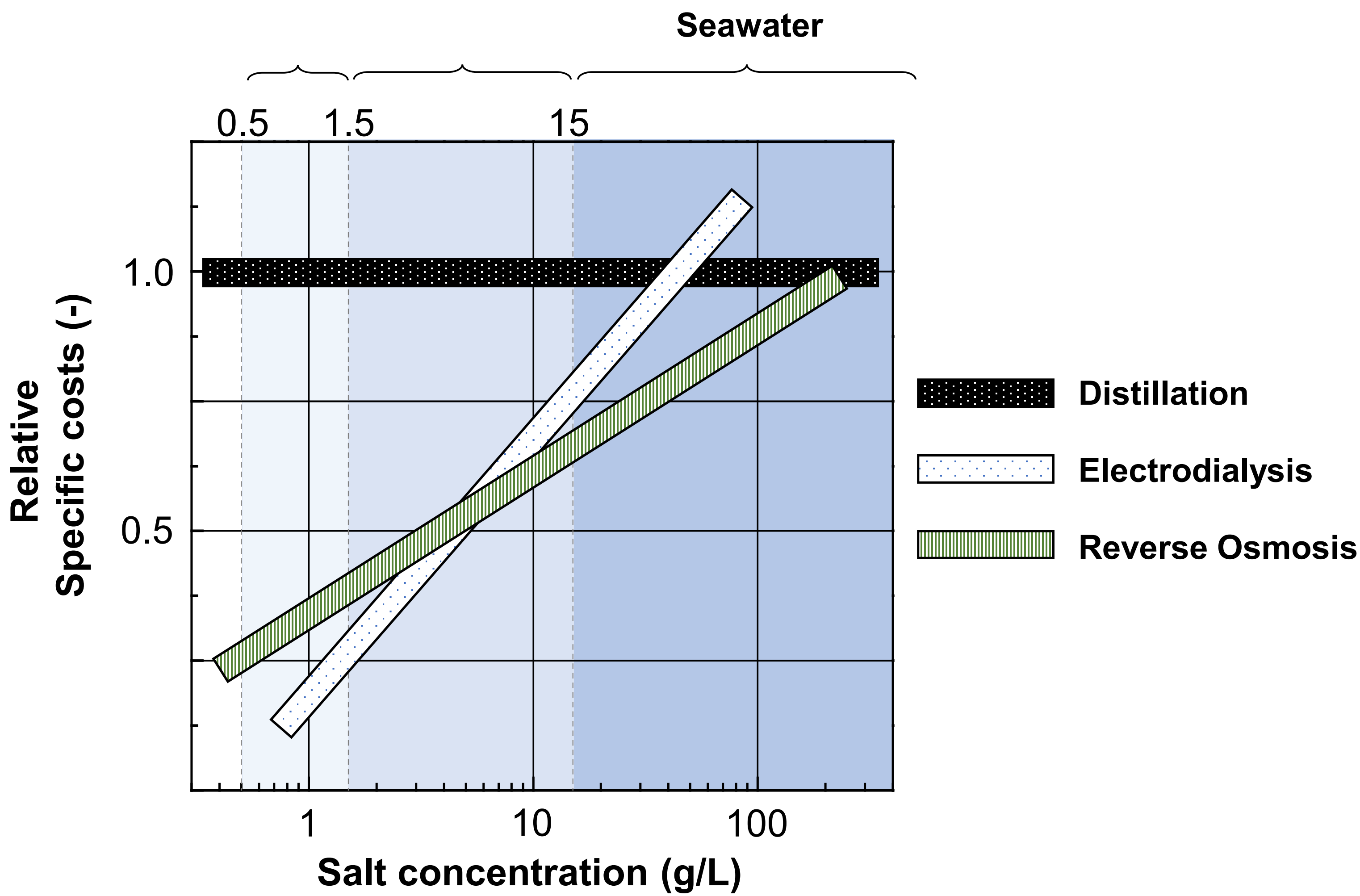
Requirements for desalination by RO



- Pre-treatments of water are required to prevent membrane fouling and protect chlorine-sensitive membranes
- The pressure required for desalination increases as the salt concentration increases
- The use of RO is not favored for water at high temperature or with high bacterial activity
- Pre-treatment steps may represent as much a one-third of the operating and capital costs of an RO plant

Scheme from Roplant website

Cost comparison of various desalination methods

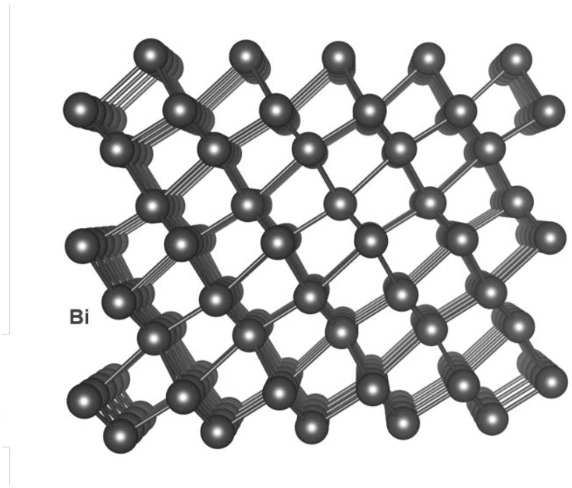


- ED should be less expensive than RO for seawater desalination but high energy requirements of current ED systems limit its commercial use to brackish water desalination

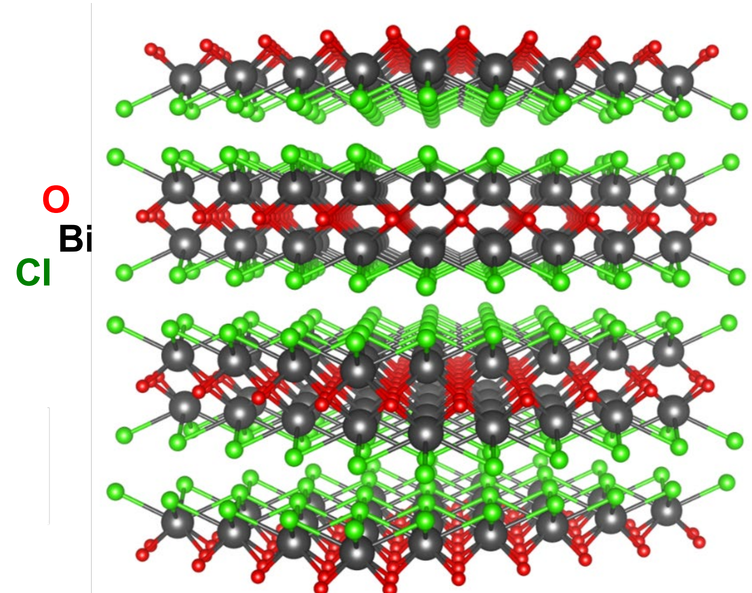
Developing new electrochemical desalination methods

- Developing desalination methods that can manage energy, water, and salts differently from RO can be beneficial to provide more flexibility in complementarily advancing desalination systems
- In 2017, our group discovered that we can use Bi as a Cl-storage electrode, enabling the construction of new types of desalination cells

Bi



BiOCl



$$\mathbf{Bi + Cl^- + H_2O \rightleftharpoons BiOCl + 2H^+ + 3e^-}$$

$E^o = 0.160$ V vs. SHE

Nam. D.-H. et al. *J. Am. Chem. Soc.* **2017**, *139*, 11055-11063.

Technologies enabled by using Bi as a Cl-storage electrode

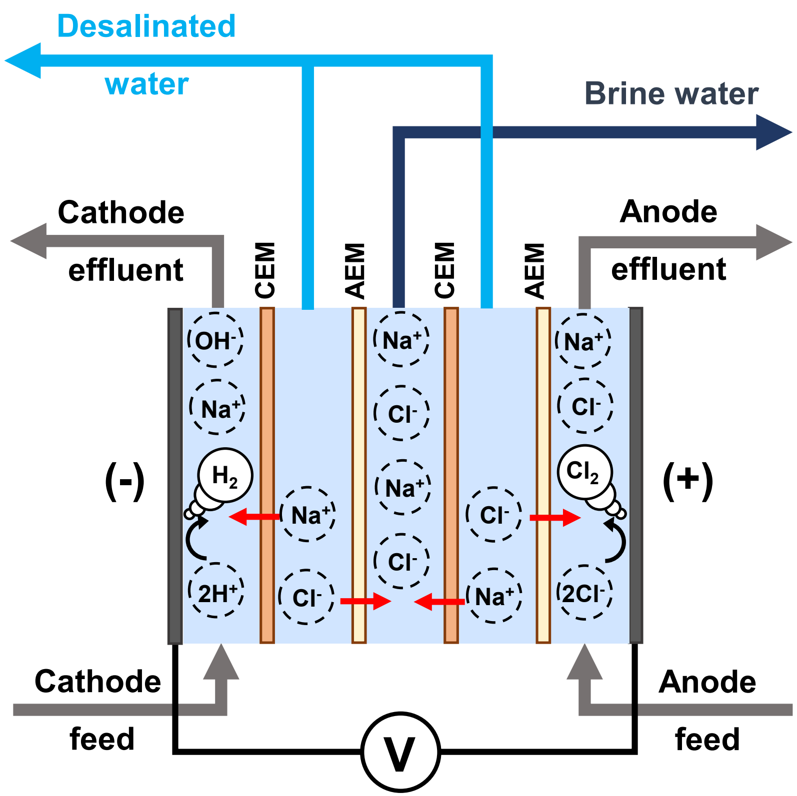
1. **Electrodialysis cell that can operate with a thermodynamic potential of 0 V**
   - ➢ Significantly decreases the potential required for desalination
     - ED may become competitive for seawater desalination
   - ➢ Similarity between the configuration of our Bi/BiOCl cell and conventional ED cells means that ED systems may be easily modified by replacing the electrodes with Bi and BiOCl
     - Low commercialization barrier for our technology

2. **Membrane-free desalination battery**
   - ➢ Couples energy storage and release with the removal and release of Na^+ and Cl^-
     - Energy consumed during charging is at least partially recovered during discharging
   - ➢ Appropriate choice of Na-storage material allows for energy to be generated during desalination
     - Enables the construction of portable desalination devices
   - ➢ Can operate without the use of a membrane, unlike RO
     - Reduction in cost and energy associated with pre- and post-treatments of water

Using Bi as a Cl-storage electrode to develop an ED cell that operates with a lower energy requirement

Advantage of using a Bi/BiOCl ED cell

Conventional ED cell

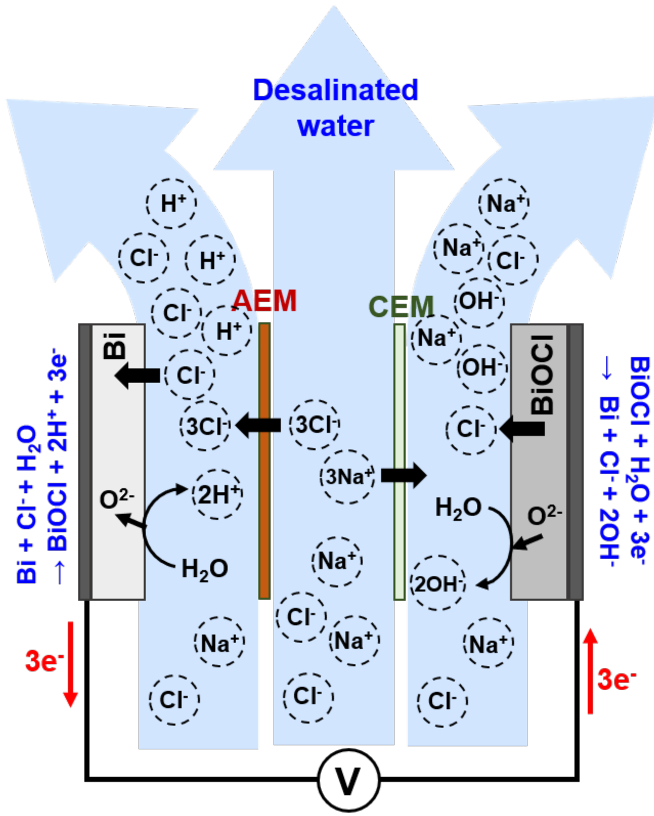


$H^+ + 2e^- \rightleftharpoons H_2$
E = -0.41 V at pH **7**

$2Cl^- + 2e^- \rightleftharpoons Cl_2$
E = 1.40 V

Thermodynamically required potential
~1.8 V

ED cell using Bi/BiOCl electrodes

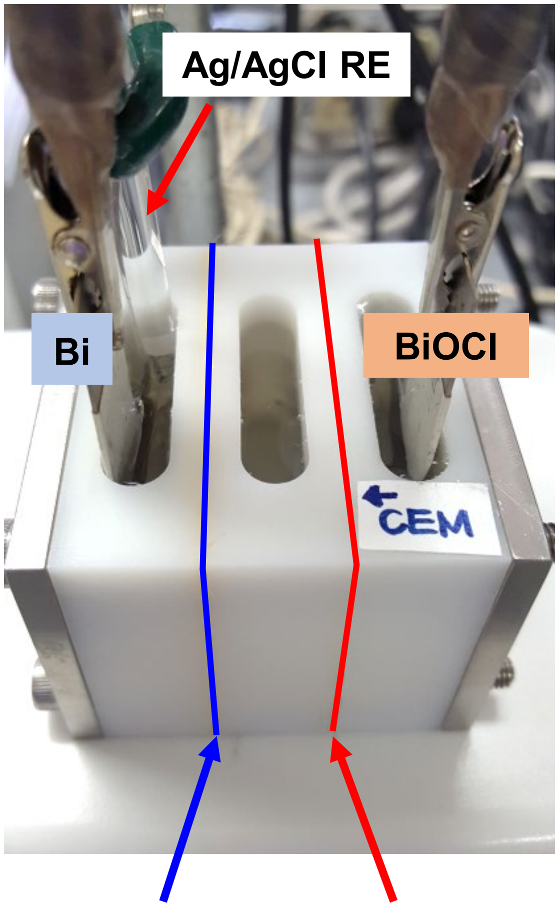


Thermodynamically required potential
0 V!

CEM: cation exchange membrane
AEM: anion exchange membrane

Performance of Bi/BiOCl ED cell

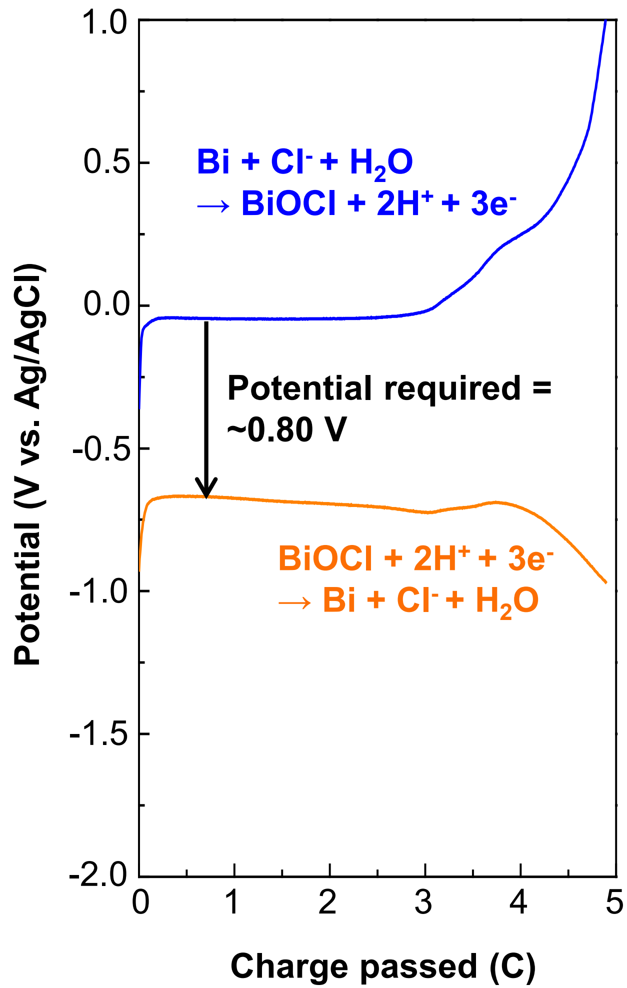
Photograph of Bi/BiOCl cell



PEEK membrane (Anion-exchange membrane)

Nafion membrane (Cation-exchange membrane)

Performance of Bi/BiOCl ED cell



Nam. D.-H. et al. *ACS Sustainable Chem. Eng.* **2018**, *6*, 15455-15462.

Performance of Bi/BiOCl ED cell

Energy required to remove NaCl in 1 L of 60 mM NaCl

	Bi/BiOCl ED cell
Energy consumption (kWh/m^3)	1.27

Energy required to remove 700 mg/L of salt from well water

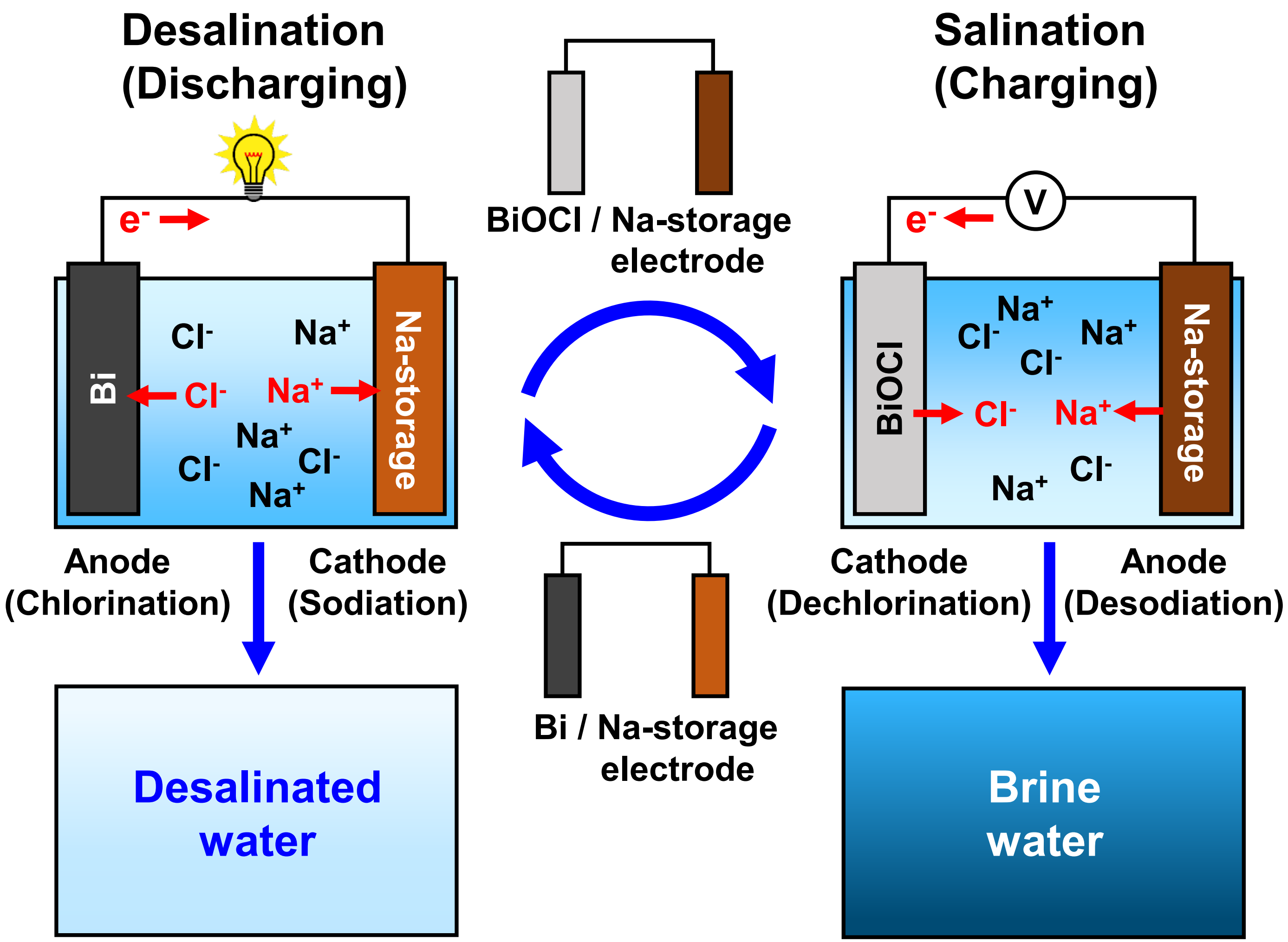
	Energy consumption (kWh/m^3)	**Cost of water ($\$/m^3$)**
Commercial ED system*	4.2	0.25
Bi/BiOCl ED cell	0.42	0.17

- It should be noted that the cost of water from the commercial ED cell includes capital and labor costs while our calculation includes costs only for energy consumption and raw materials

*Singh, R. *Membrane Technology and Engineering for Water Purification: Application, Systems Design and Operation, 2nd Ed.*; Elsevier Ltd.: 2015.

Using Bi as a Cl-storage electrode to construct a membrane-free desalination battery

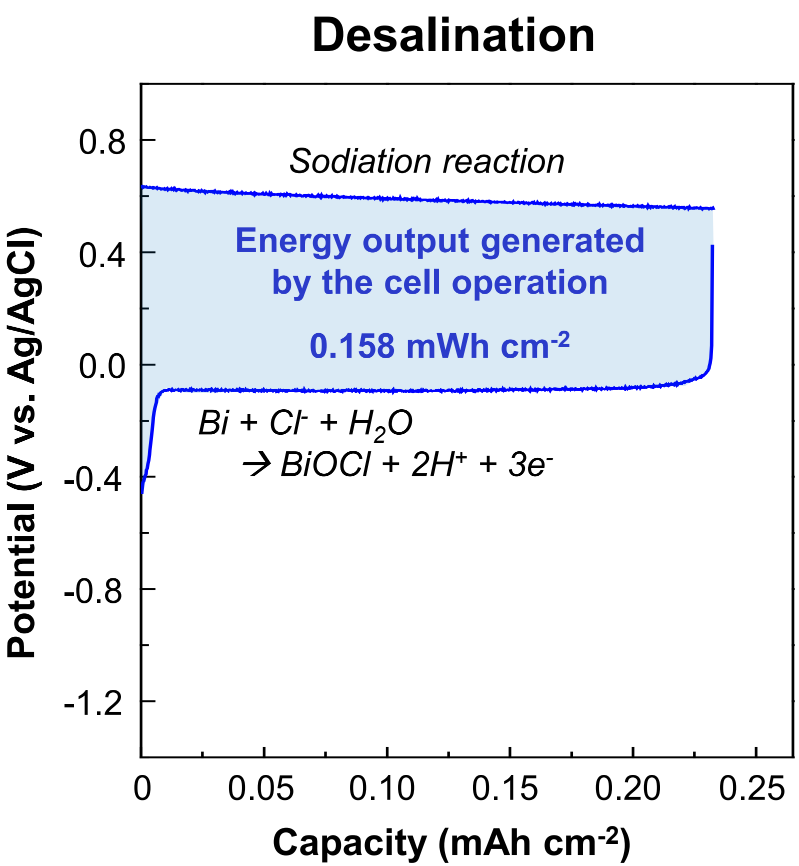
Operating principle of desalination battery

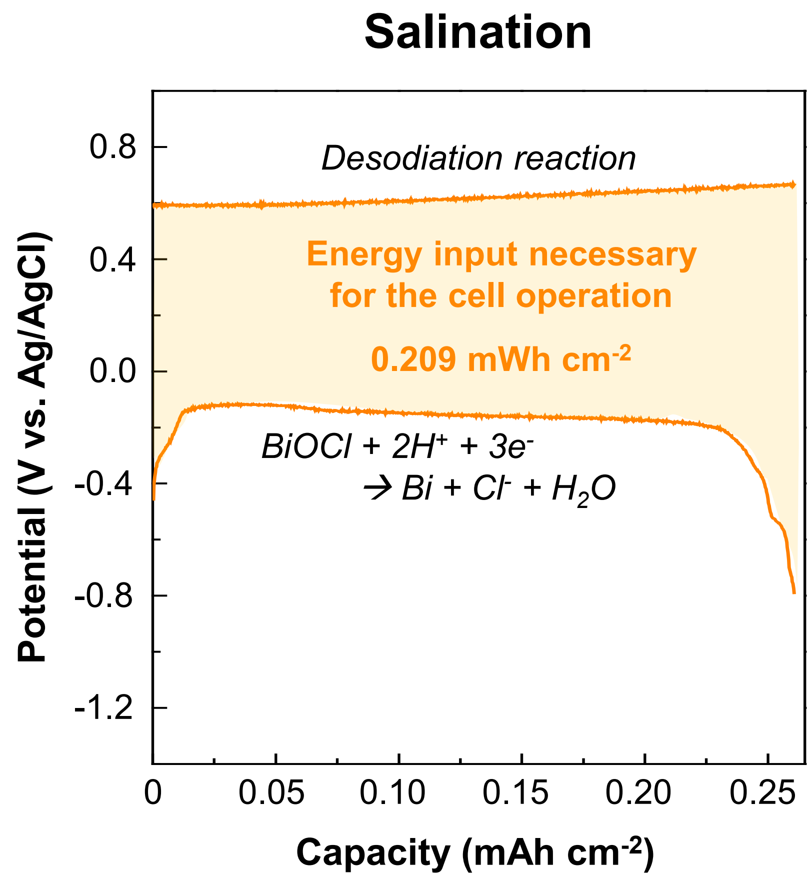


Cl-storage: $Bi + Cl^- + H_2O \rightleftharpoons BiOCl + 2H^+ + 3e^-$

Na-storage: There are many candidates for Na-storage electrodes because of work on Na-ion batteries

Performance of our desalination battery





- By integrating the area of the potential-capacity plots we find that **76%** of the **energy** required for salination is **recovered** during desalination

Nam. D.-H. et al. *Chem. Mater.* **2019**, *31*, 1460-1468.

Comparison to RO

Energy required to remove NaCl present in 1 L of 0.6 M NaCl

	Sea water RO (SWRO)	Desalination battery
Energy consumption (kWh/m^3)	3.5-4.0	6.9

- The energy consumption reported for SWRO does not take into account the energy required for pre- and post-treatments of water

Voutchkov, N. Energy Use for Membrane Seawater Desalination. *Desalination* **2018**, *431*, 2−14.

Summary

- The discovery of Bi as a Cl-storage electrode enables the design of practical and efficient desalination technologies
- Using Bi and BiOCl electrodes for ED reduces the energy required for desalination of brackish water by a factor of ten
- Using Bi in combination with a Na-storage electrode to construct a desalination battery enables membrane-free desalination
- The desalination battery can also generate energy during desalination, providing a unique opportunity for the construction of portable desalination devices