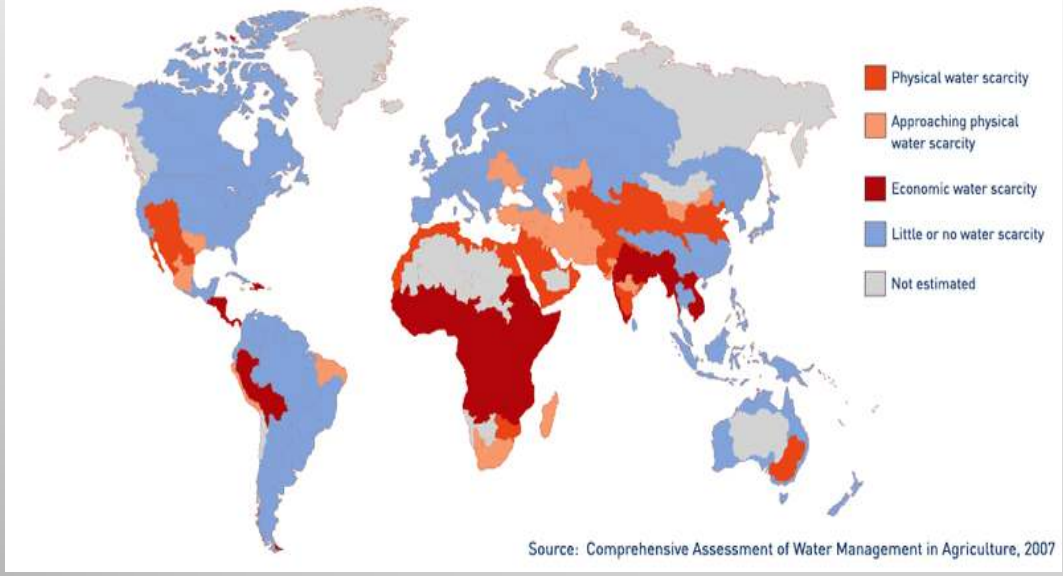
Solar-powered Nanostructured Desalination Systems SONADES

- Michael Stadermann
- Harry Radousky
- Juan Santiago
- Gergely Zimanyi

Water scarcity drives desalination needs



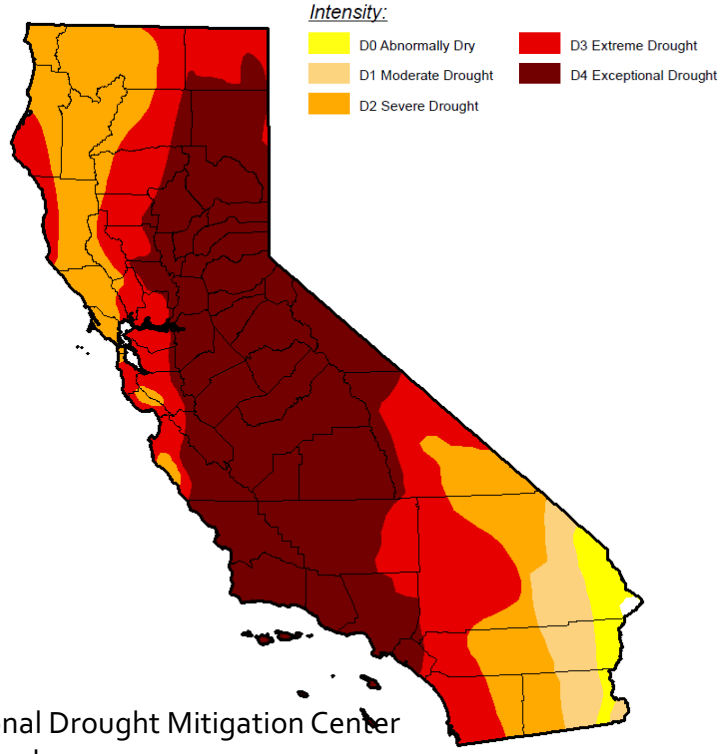
- 1/6th of the world's population does not have daily access to fresh water
- 30+% of the U.S experienced severe drought in 2015
- Water will be major driver of conflicts worldwide
- Global market for desalination is only $12-14 billion/year, because specialized on sea water for Western infrastructure

$20bn for Valentine's day in US

$20bn quarterly shipment on iphones

Current technology is not adjusted to California's needs

- technology has focused on sea water
- inland brackish water desalination would be better suited for California



National Drought Mitigation Center
September 1, 2015

Goal: to develop a photovoltaic desalination system to transcend Reverse Osmosis

Reverse Osmosis:

- uses non-renewable fossil energy source:
  - amplifies the cause of drought
  - increases dependency on increasingly scarce fossil fuels
- operates at high pressures, increasing costs
- lot of mechanical moving parts

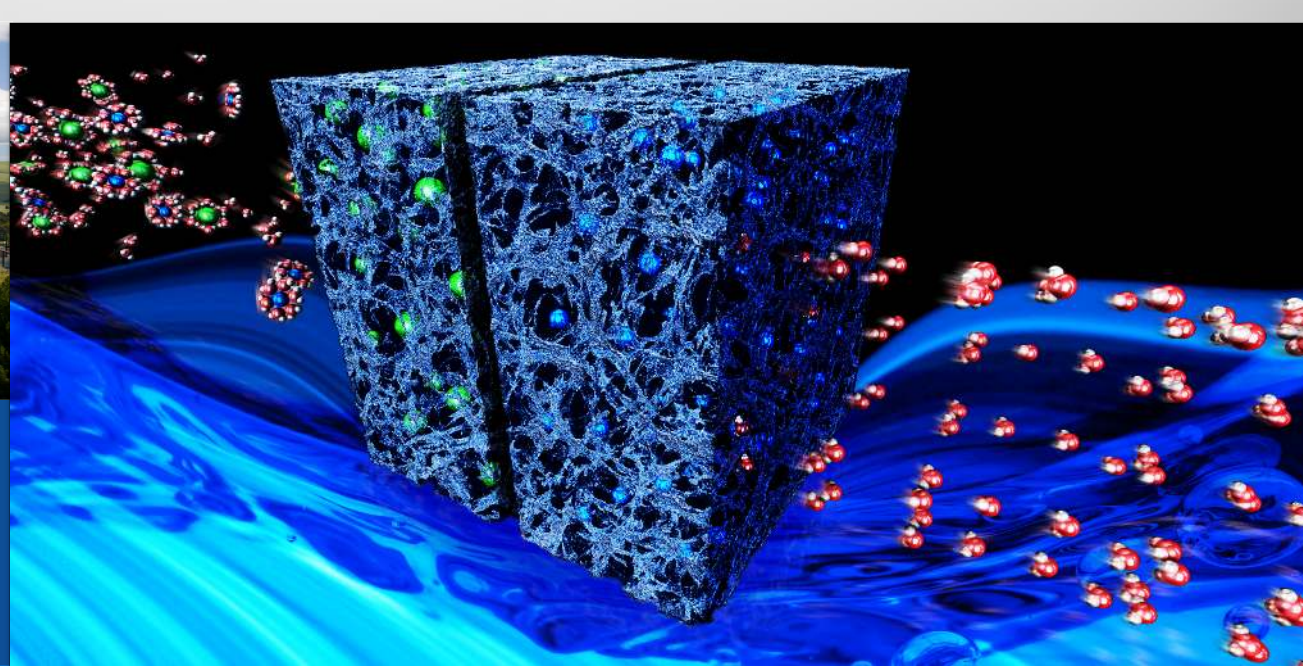
SONADES:

- energized by renewable photovoltaic energy:
  - does not amplify drought
  - photovoltaics developed into a mature, affordable technology
- operates at low pressures, reducing costs
- electronic technology, essentially no moving parts

CA can become a desalination technology leader, generating manufacturing jobs and revenue

1. Discrete Solar Charging: Flow-through electrode capacitive deionization

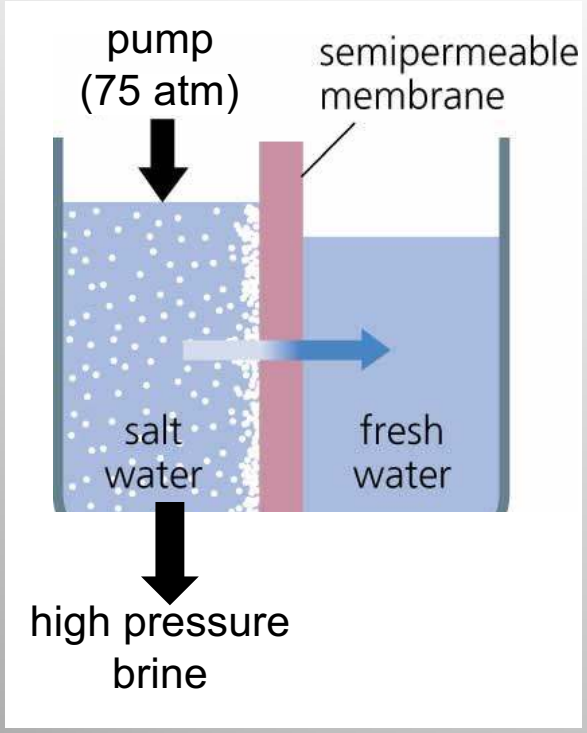
Michael Stadermann, Juan Santiago



LLNL-PRES-649605

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

State-of-the-art: reverse osmosis (RO)

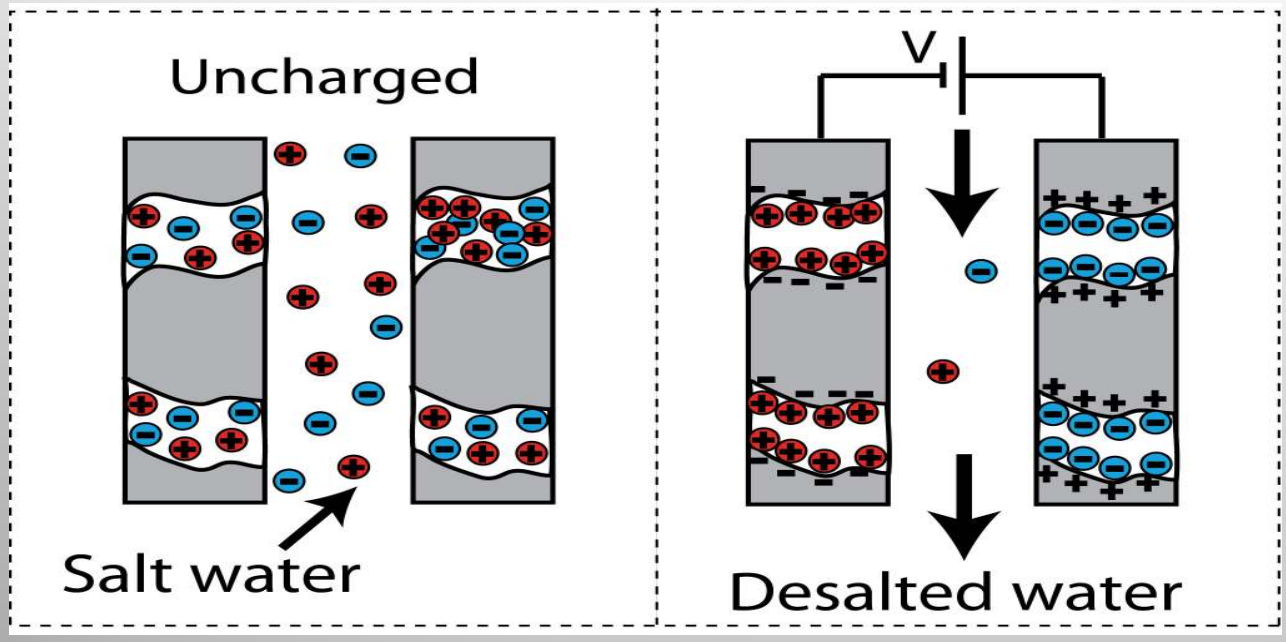


- high energy efficiency (2.5 kWh/m³ for seawater, 1.0 kWh/m³ for brackish water)

$$E \sim (p_{osmotic} + p_{membrane}) \cdot V$$

- requires 40-80 bar of pressure for sea water
- requires extensive water pre- and post-treatment
- cost increases at small scale

Capacitive deionization

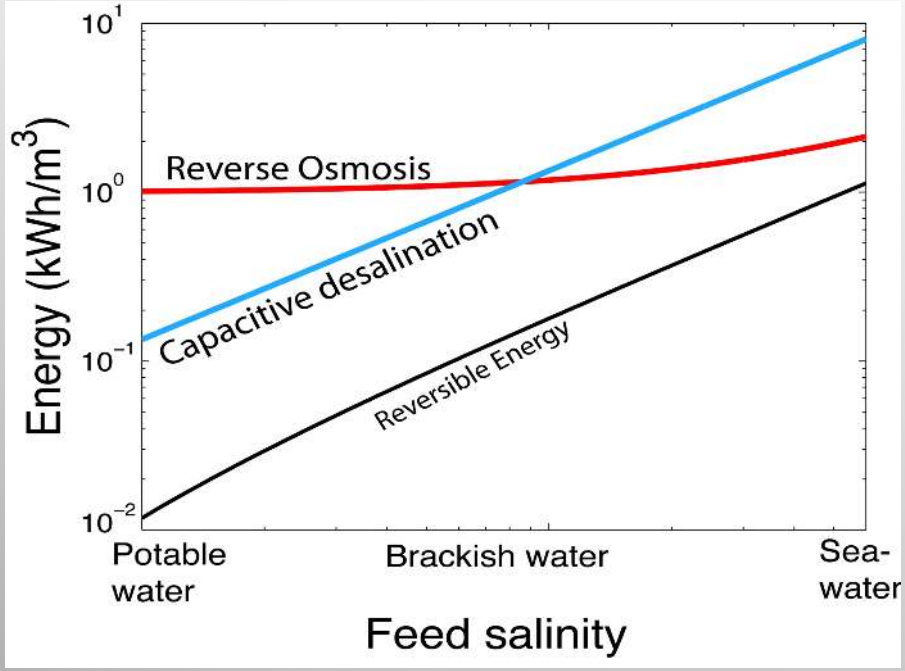


- removes salt from water

$$E \sim I^2 \cdot R$$

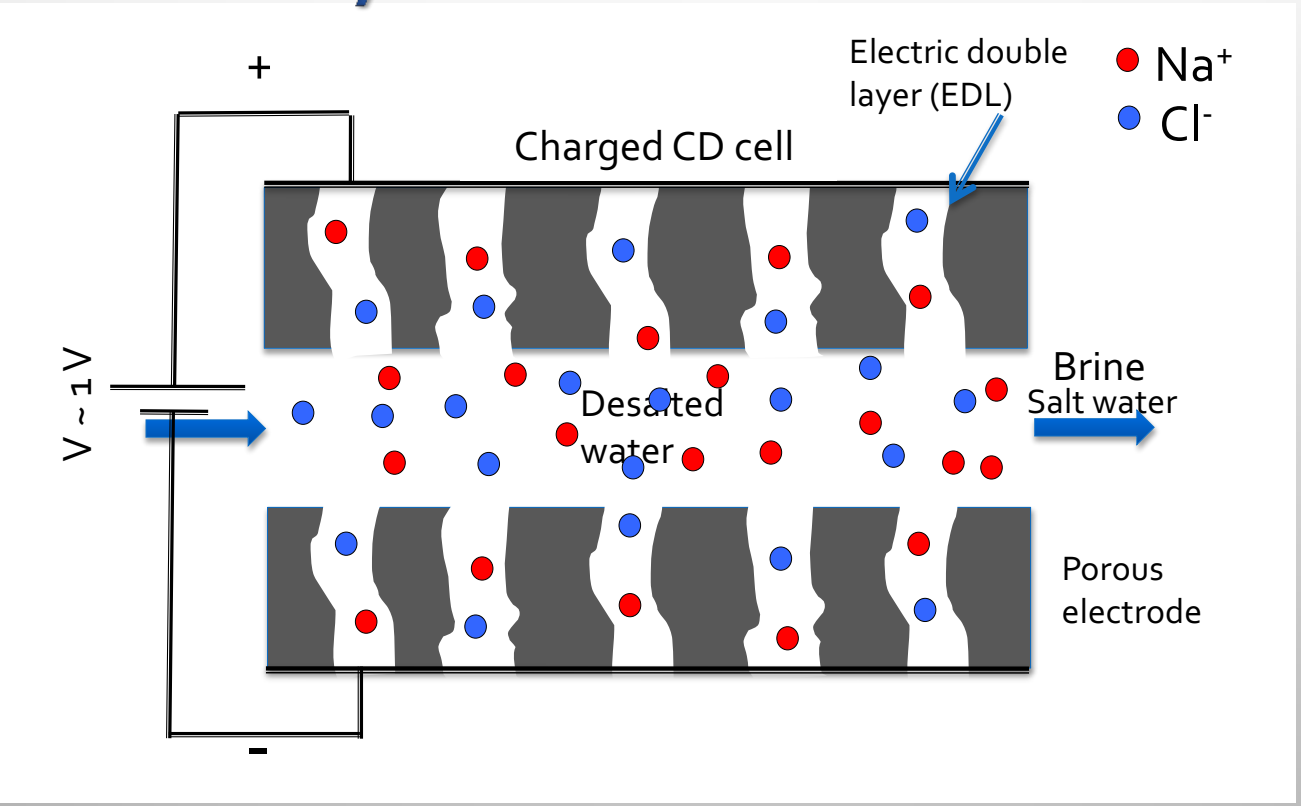
- energy efficiencies of <0.5 kWh/m^3 are possible

CDI is more efficient than RO for brackish water

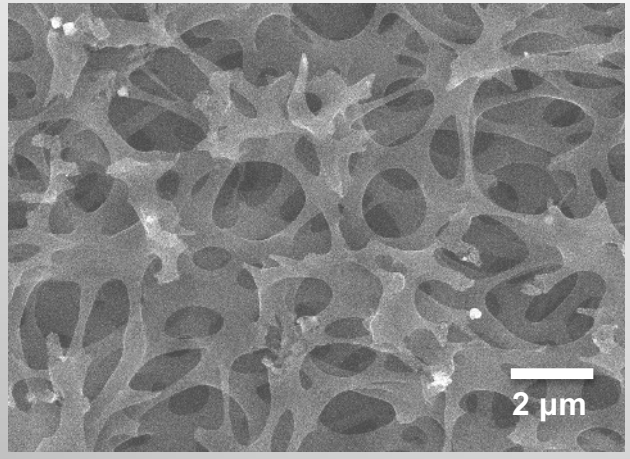


- RO lower limit is given by membrane resistance
- CD energy cost scales with concentration throughout
- energy cost for CD is much lower for low salt concentrations

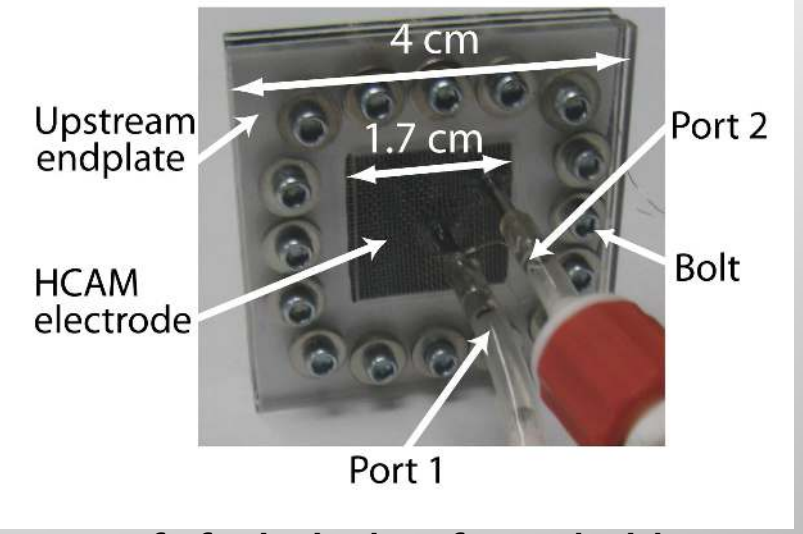
Capacitive deionization removes salt from water electrostatically



Novel carbon aerogel material enables flow-through geometry



- hierarchical carbon aerogel (HCAM)
- 1-5 µm macropores
- 1-2 nm nanopores
- robust carbon material



- proof of principal performed with a 0.4 ml test cell

Native charge model

- Modified Donnan model

$$c_{m,i} = c_{M,i}\exp(-z_i \frac{\Delta\phi_D}{V_T})$$

- Charge balance

$$q_m + q_{native} + q_{elec} = 0$$

- Mass transport in macropores

$$p_M \frac{\partial}{\partial t}(c_{M,i}) + \nabla \cdot \left[c_{M,i} u_{sup} - p_M D_{e,i}\left(\nabla c_{M,i} + \frac{z_i}{V_T} c_{M,i} \nabla \Phi\right)\right] = -p_m \frac{\partial}{\partial t}(c_{m,i})$$

- Micropore potential drop

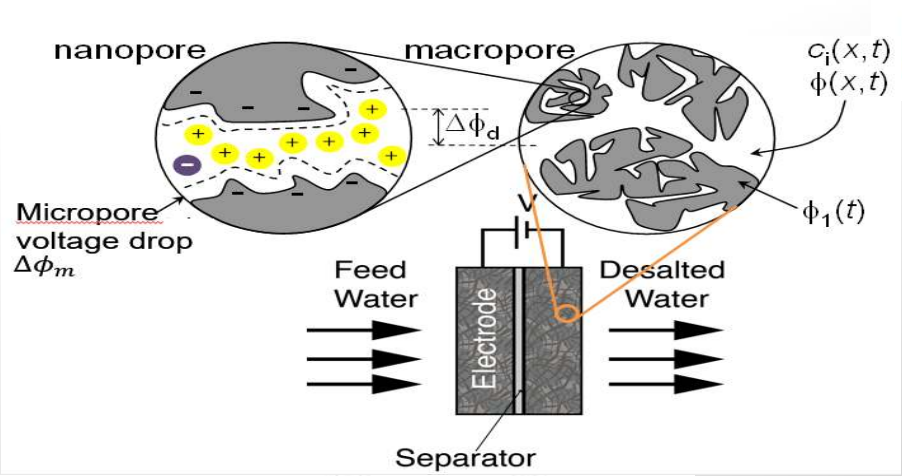
$$\Delta\phi_m = q_{elec} \cdot \frac{F}{C_m}$$

- Voltage equations

$$\Delta\phi_m + \Delta\phi_D + \phi = \phi_e$$

- Conservation of current

$$I_{ext} = -p_m \int \frac{\partial(q_{elec} F)}{\partial t} dV$$



Variables:

$w_m = \frac{1}{2}(c_{m,+} + c_{m,-})$ $q_m = \frac{1}{2}(c_{m,+} - c_{m,-})$ volumetric electrode charge : macropore concentration

c

q_{elec} : Donnan potential

$\Delta\phi_D$:

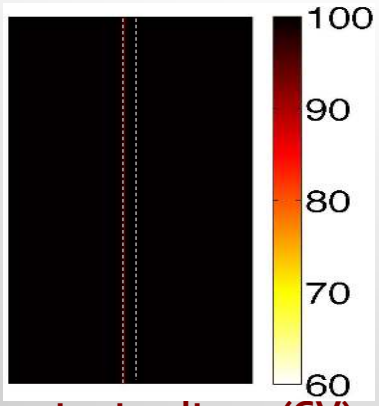
Fitting parameters:

c_m: micropore capacitance

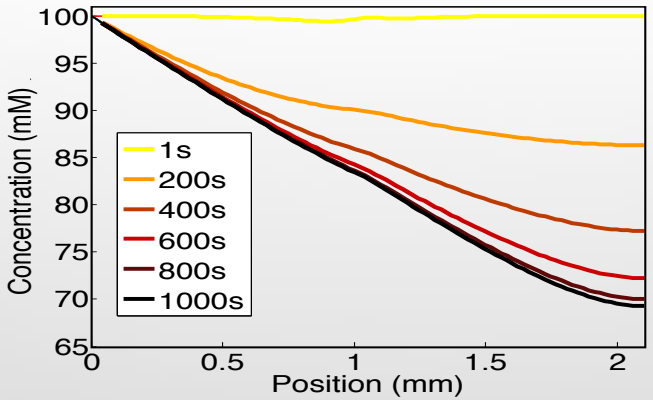
q_{native}: native charge density

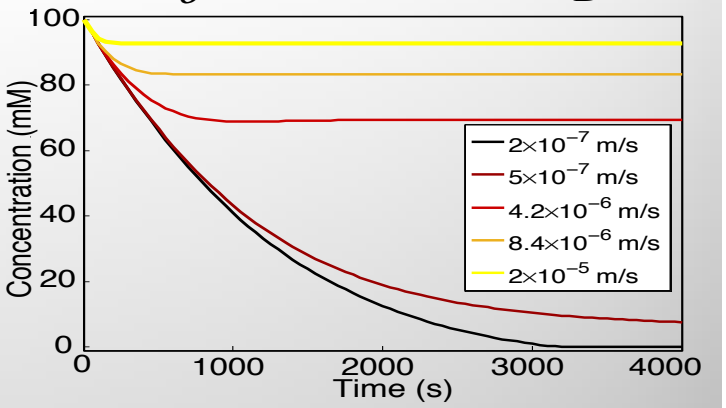
Simulation: constant current vs. constant voltage

Constant current (CC)

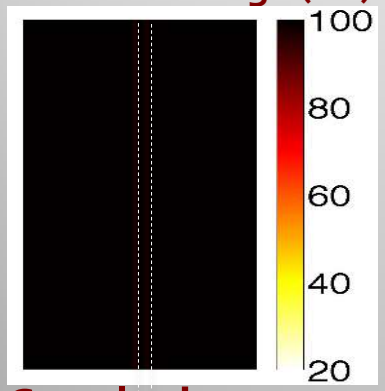


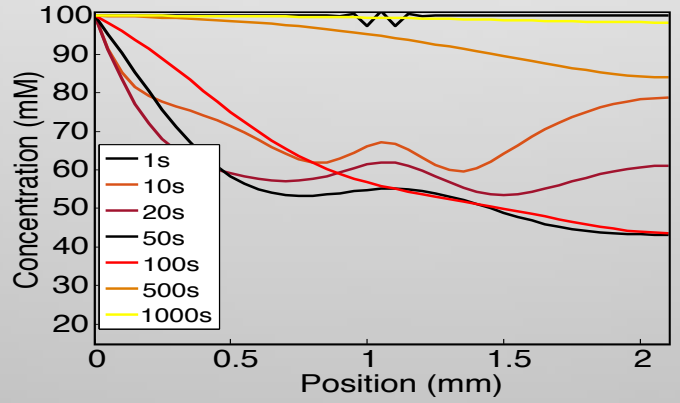
Time scales: RC $t_{RC} = RC$ Convection $t_{conv} = \frac{l_e}{\upsilon}$ Diffusion $t_{diff} = \frac{l_e^2}{D^{eff}}$

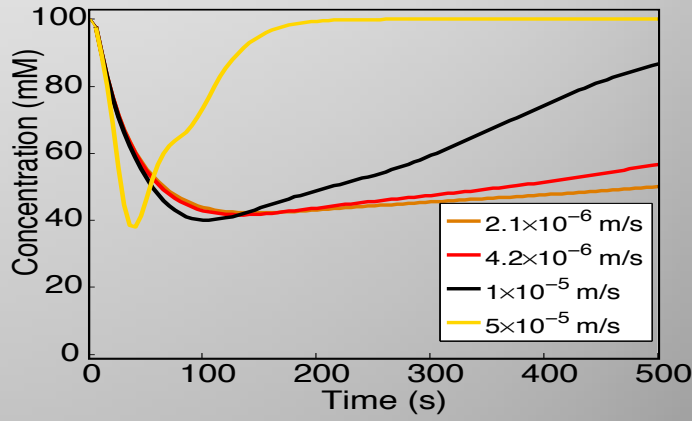




- **Constant voltage (CV)**



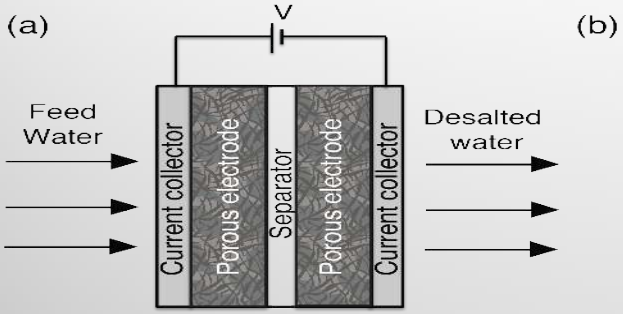




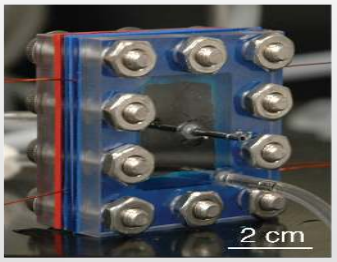
Conclusions:

- Time scales: CC, min(t_{conv}, t_{diff}); CV: min(t_{RC}, t_{conv})
- CV demonstrate constant and controllable effluent concentration; Faster desalination rate with short time of charging

Validation experiments for ftCDI

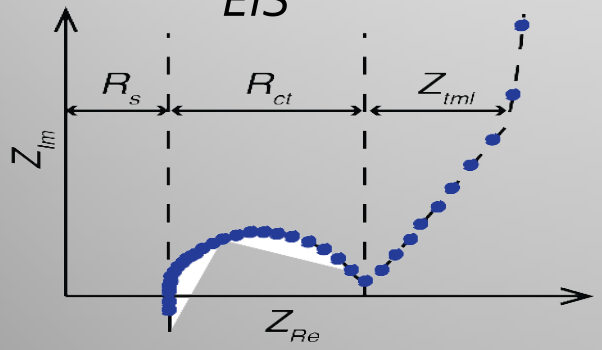


(b)

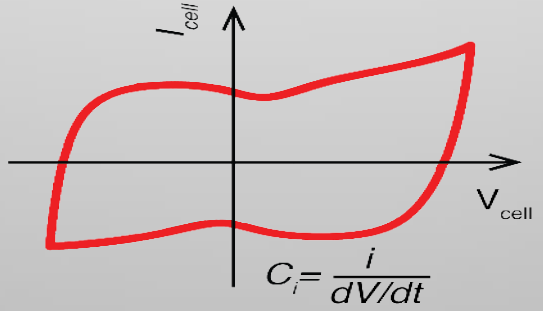


- 300 µm thick HCAM electrodes
- Flow rate: 0.24 mL/min
- I_{ext} = 7.7 mA to 48 mA
- V_{ext} = 1V
- Inlet concentration: 100 mM

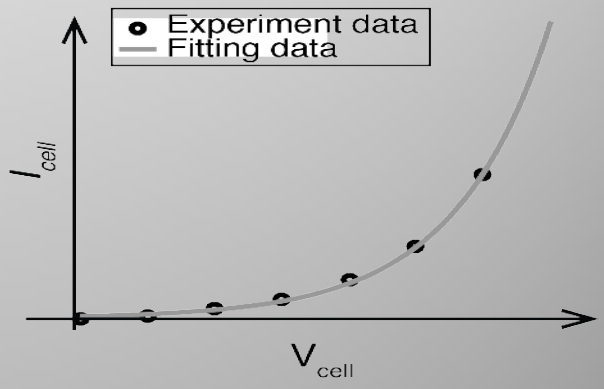
EIS



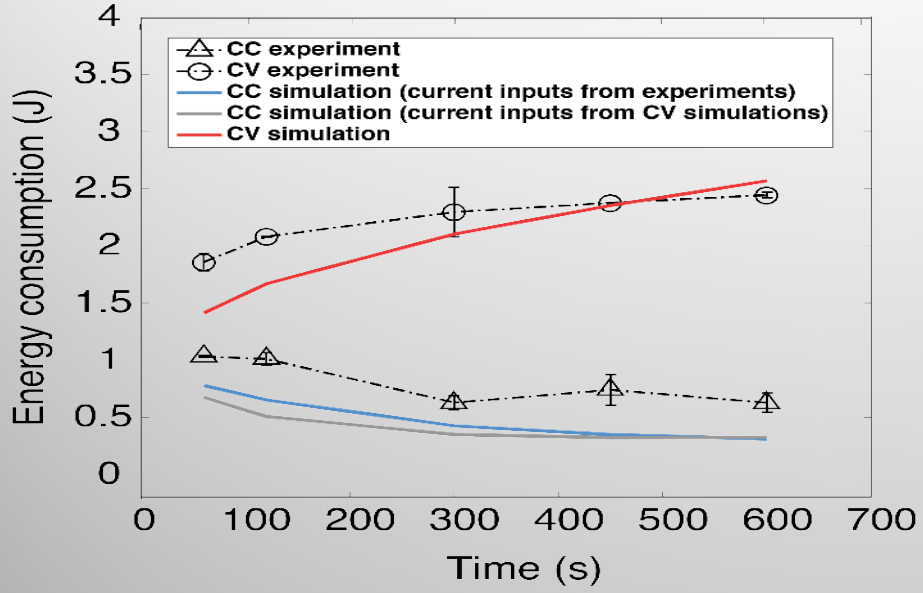
Cyclic voltammetry

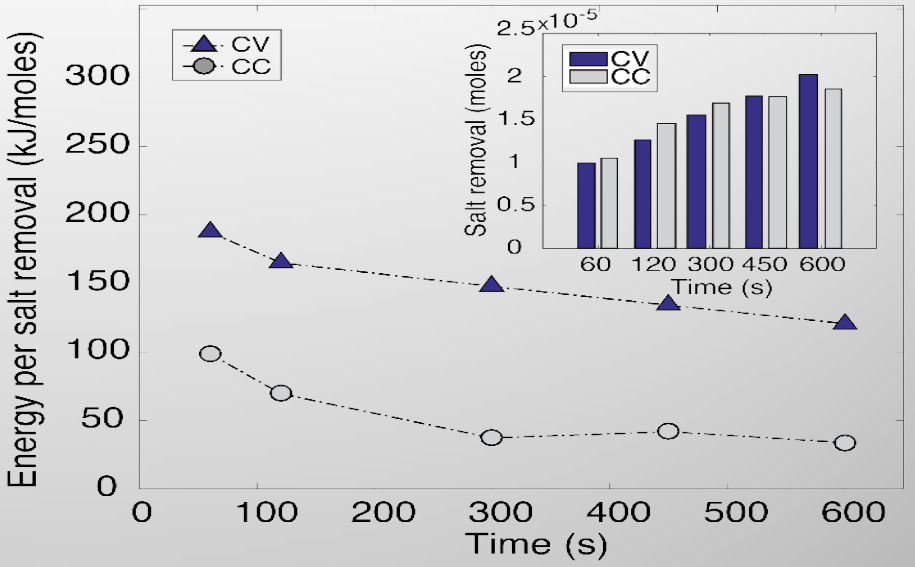


Leakage current



Energy consumption and salt removal





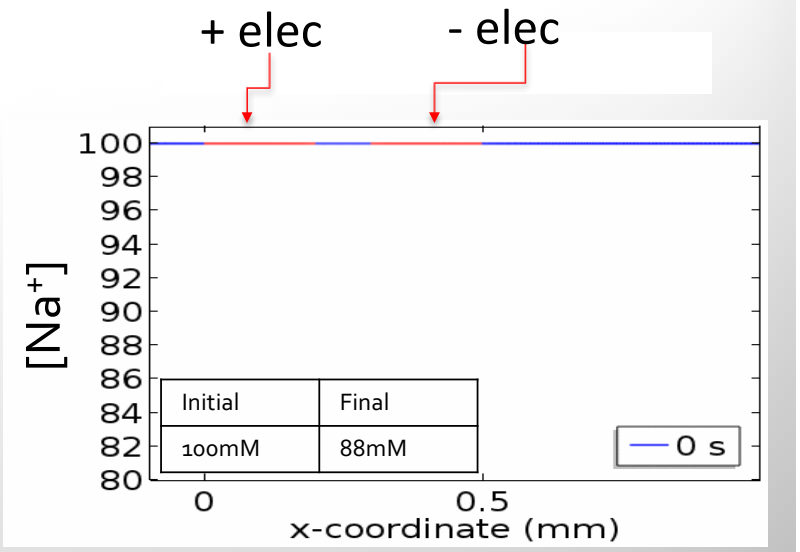
- Under the conditions of the same amounts of charge transfer and identical timespans, CC achieves similar salt removals but consumes much less energy than CV.

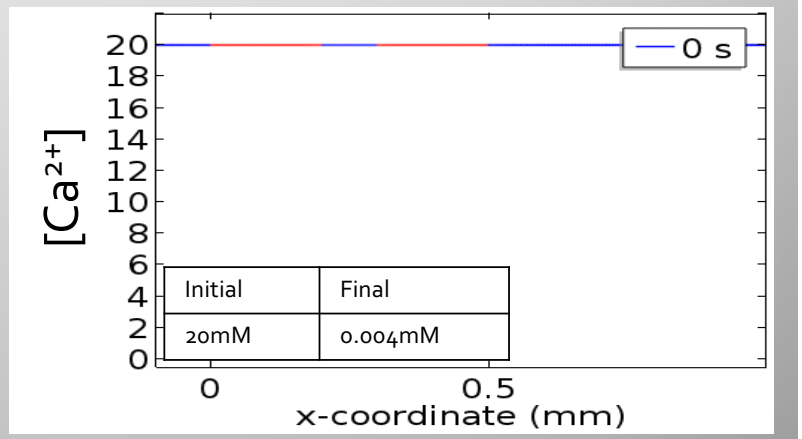
Selective toxin removal

- Flow-through cell, constant current at 500 A/m²
- Strong selectivity for di-valent and tri-valent ions
- Early simulations show near-complete removal of Ca^{2+} and reduced removal of Na^{+}
- Estimate of selectivity

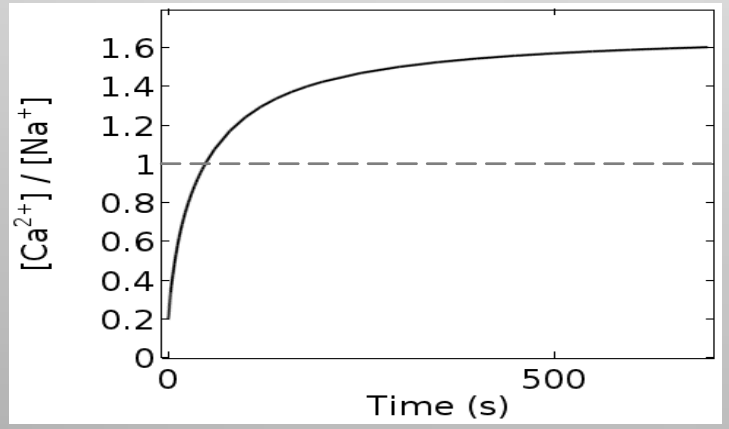
$$\Delta[Ca^{2+}]/[Ca^{2+}]_0/\Delta[Na+]/[Na+]_0=8.3$$

- Experiments under way in nitrate and lead removal



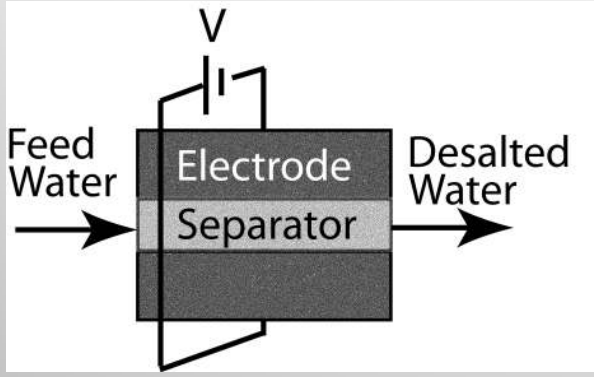


ratio of adsorbed ion



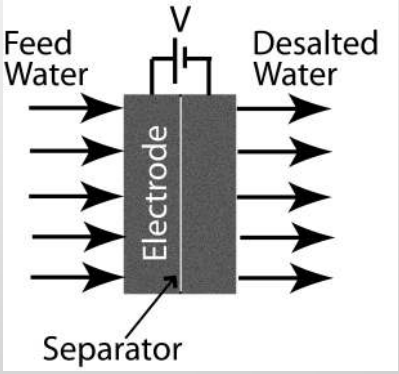
Flow-through electrodes dramatically improve performance

Flow-between architecture



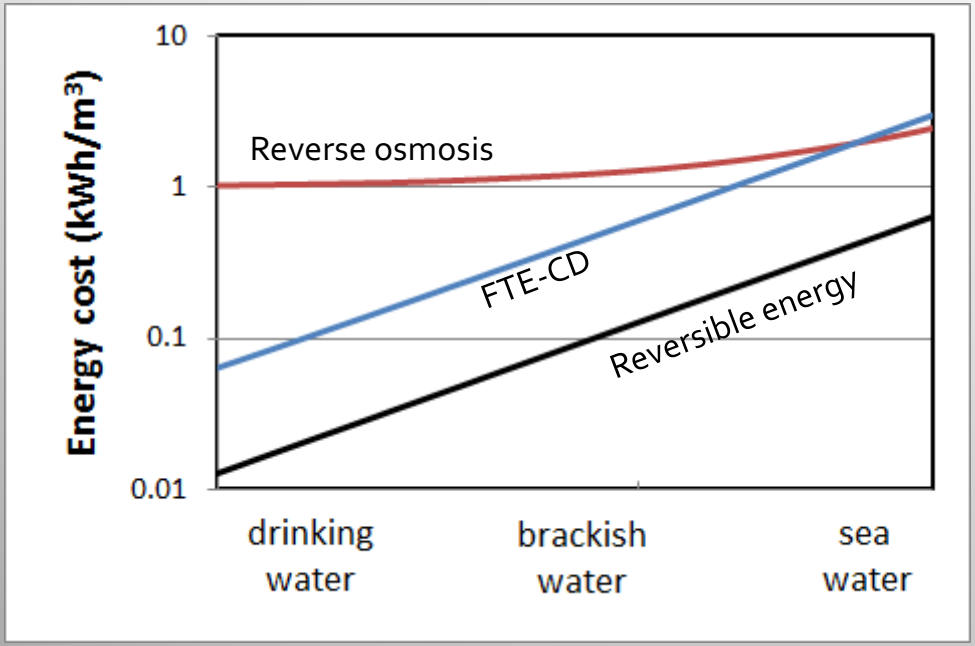
- water in electrode does not contribute to desalination
- slow (60 mins/ cycle)
- high energy cost
- low capacity (removes ~1.5 g/L/charge)

LLNL/Stanford flow-through electrode architecture (ftCDI)



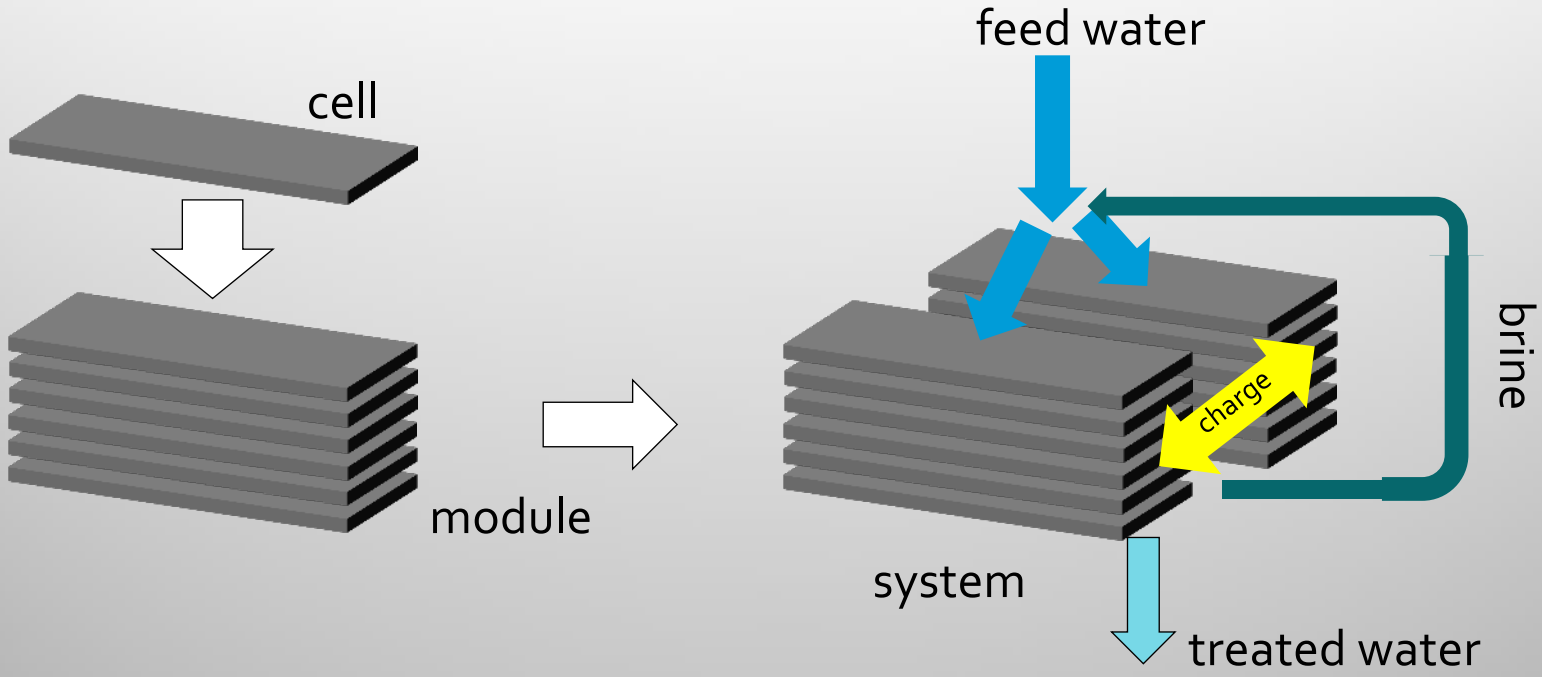
- entire electrode volume contributes to desalination
- faster (10-20x)
- lower energy cost (up to 3x)
- higher capacity (~4.5 g/L/charge)

ftCDI is compatible with solar and well-suited for California



FTE-CDI advantages
Fully electric and robust to variable power supply
Size-independent cost and efficiency
Demonstrated ion selectivity (heavy metals, nitrate)
projected energy use for brackish water: 0.1-0.2 kWh/m³ (5-10x less than RO)

Next steps: further scale up and integration



Next steps: PV integration for solar charging

Stanford Undergraduate Robotics team and Aquas Technology

charging controllers
fluidic controllers
power fluctuations

Discrete Solar Charged Desalination patent filed

(19) **United States**
(12) **Patent Application Publication**
Suss et al.
(10) **Pub. No.: US 2015/0072267 A1**
(43) **Pub. Date: Mar. 12, 2015**

(54) **ENERGY HARVESTING WITH FLOW-THROUGH POROUS ELECTRODES**

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(72) Inventors: **Matthew Suss**, Cambridge, MA (US); **Theodore F. Baumann**, Discovery Bay, CA (US); **Francesco Fornasiero**, Oakland, CA (US); **Michael Stadermann**, Pleasanton, CA (US); **Juan G. Santiago**, Stanford, CA (US)

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Publication Classification

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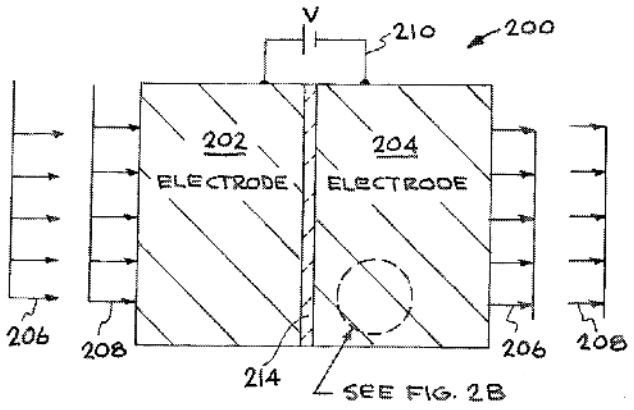
H01M 8/08 (2006.01)

(52) U.S. Cl.
CPC ***H01M 8/08*** (2013.01)
USPC **429/499**

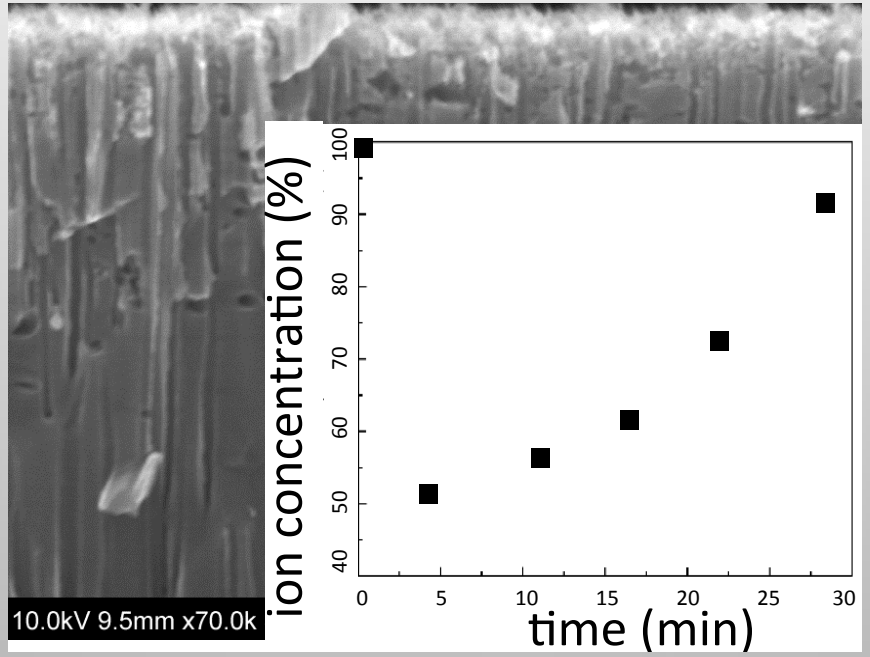
(57) **ABSTRACT**

An apparatus for harvesting energy from fresh water and salt water, including a first porous electrode having first pores, a second porous electrode having second pores, a non-conducting permeable separator between the first porous electrode and the second porous electrode, a system for applying an electric potential difference between the first porous electrode, and the second porous electrode, and a system for flowing the fresh water and the salt water through the first porous electrode having first pores, through the non-conducting permeable separator, and through the second porous electrode having second pores thereby harvesting energy from the fresh water and the salt water.

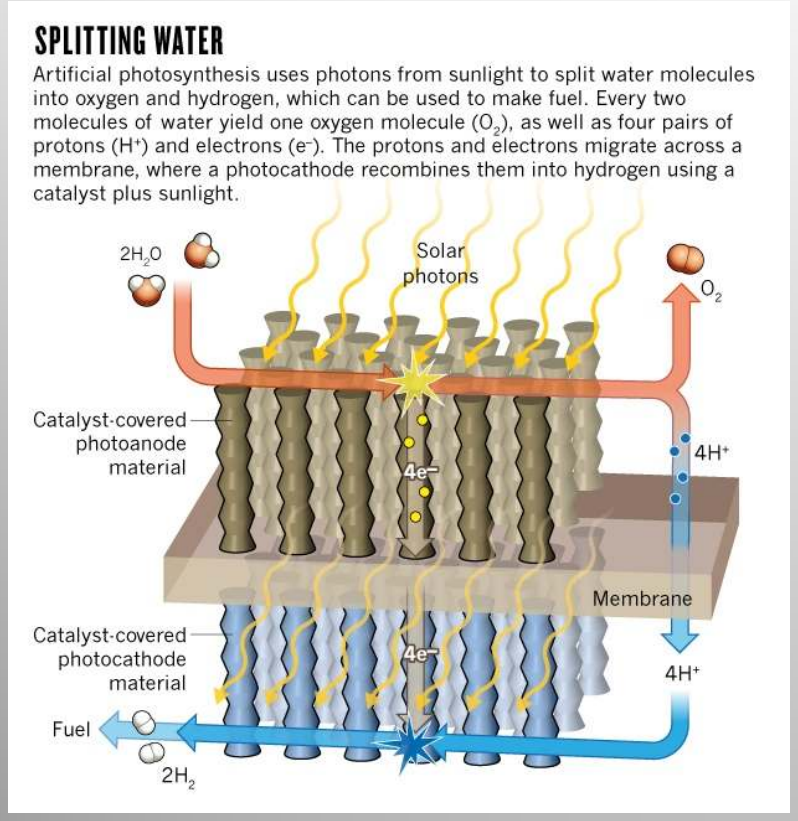


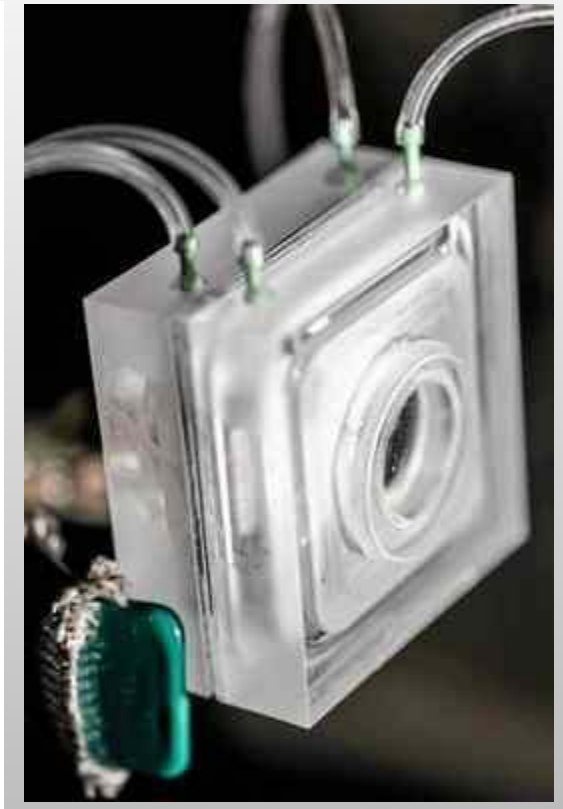
2. Integrated Solar Charging: Flow-through photovoltaic cell

Harry Radousky, Gergely Zimanyi



Idea: To fully integrate the photovoltaic energy harvesting and the desalination unit

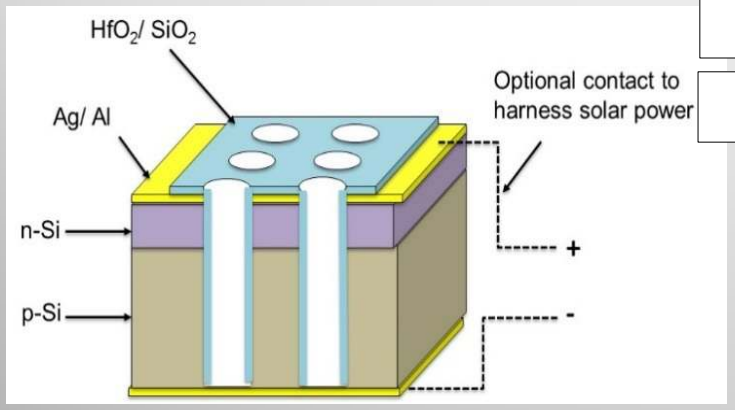


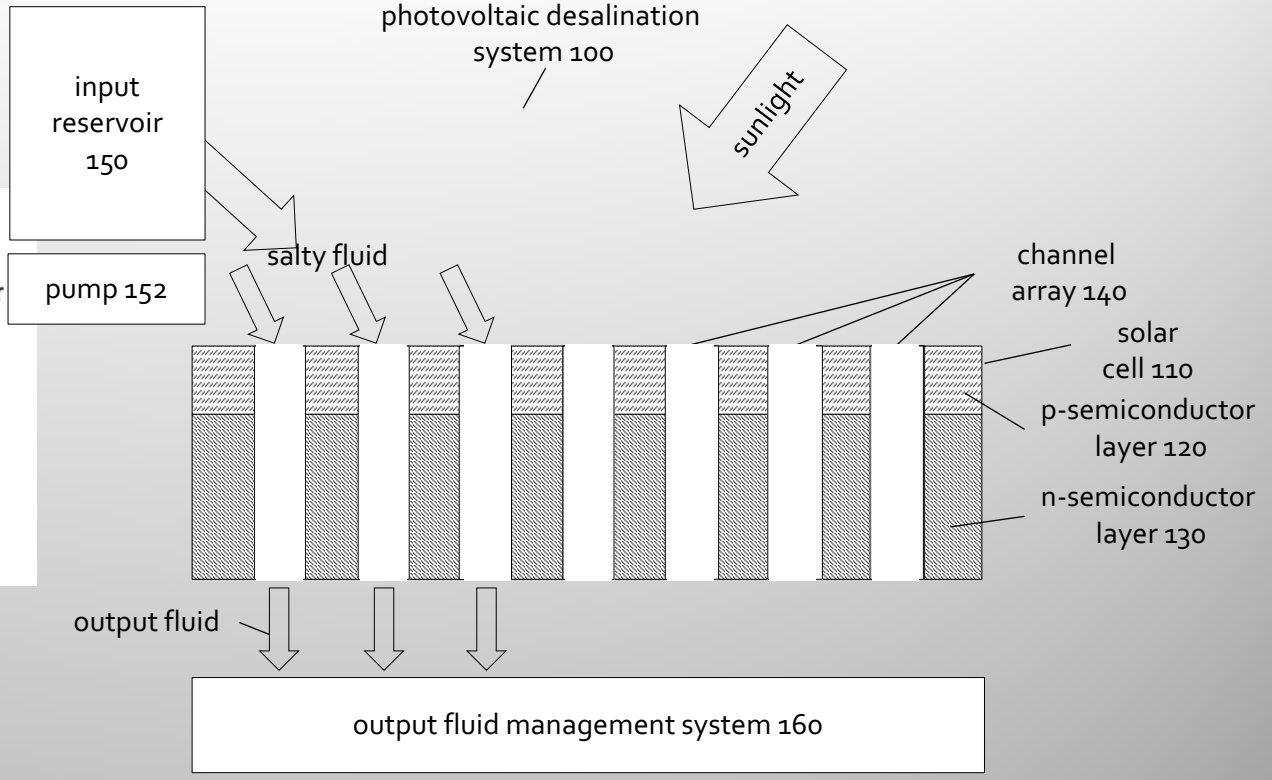


Equivalent to the founding concept of JCAP, the Joint Center for Artificial Photo-synthesis:

- Fully integrate energy source and water splitting unit
- The integrated system eliminate energy conversion losses

Structure, operation





Operation

- Incident sunlight photogenerates +/– charges in the p and n layers of the PV cell
- +/- ions of saltwater, flowing in channel through the p and n layers get adsorbed to the walls, salinity of output water is reduced
- adsorbed ions are cyclically flushed by blocking sunlight

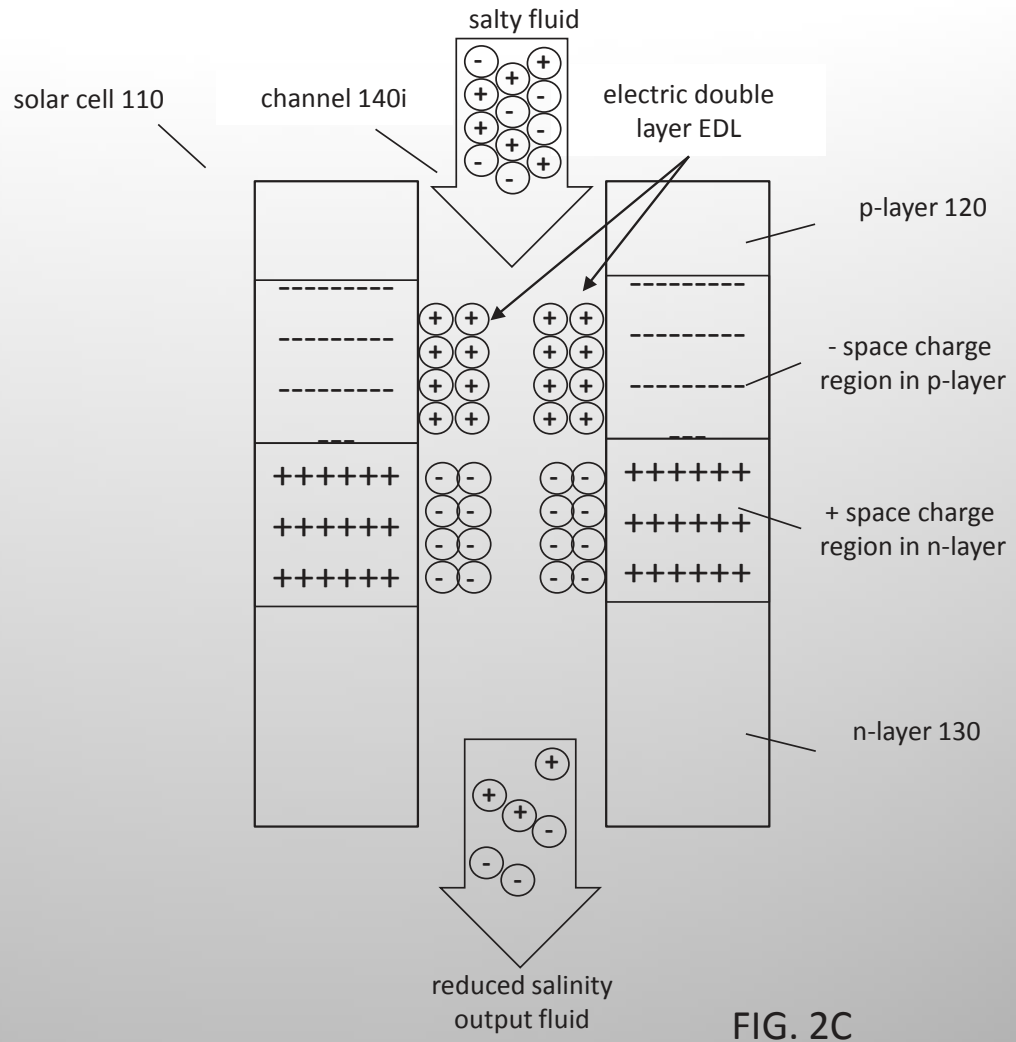
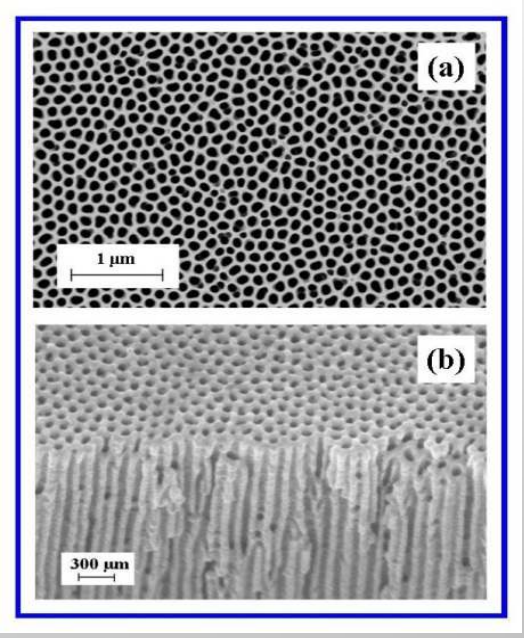


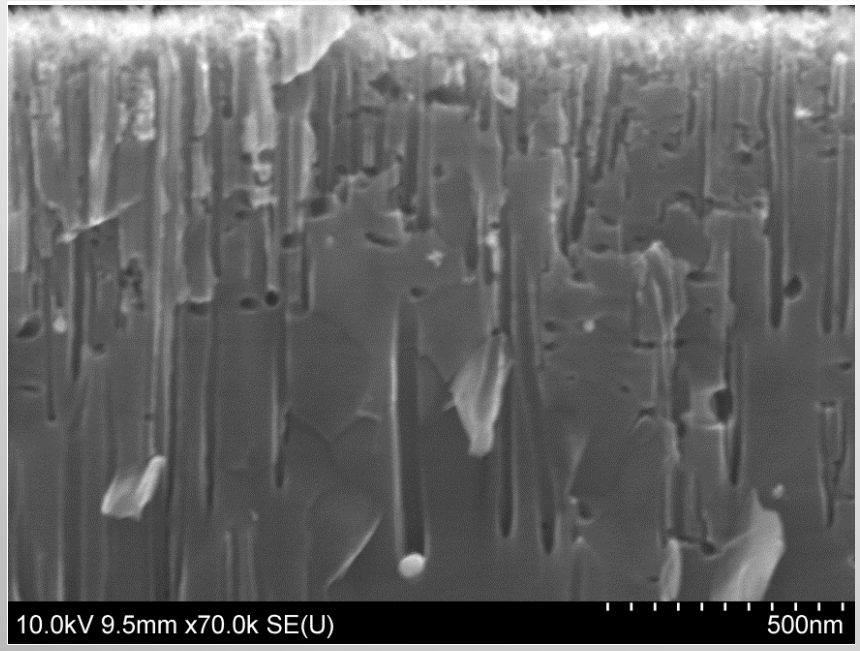
FIG. 2C

Proof of concept: 1. Single type of charging: Nanochannel array in AAO

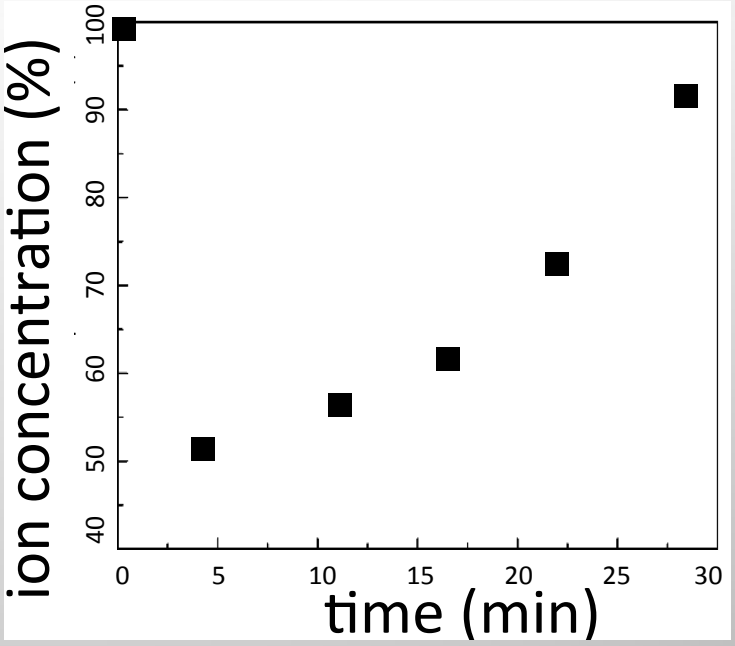


- drilled millions of 50-100 nm diameter channels into anodic aluminum oxide (AAO) layer with metal assisted chemical etching, coated channel surfaces with insulating HfO_2
- substantial reduction of salinity achieved

Proof of concept: 2. Nanochannel array in PV cells

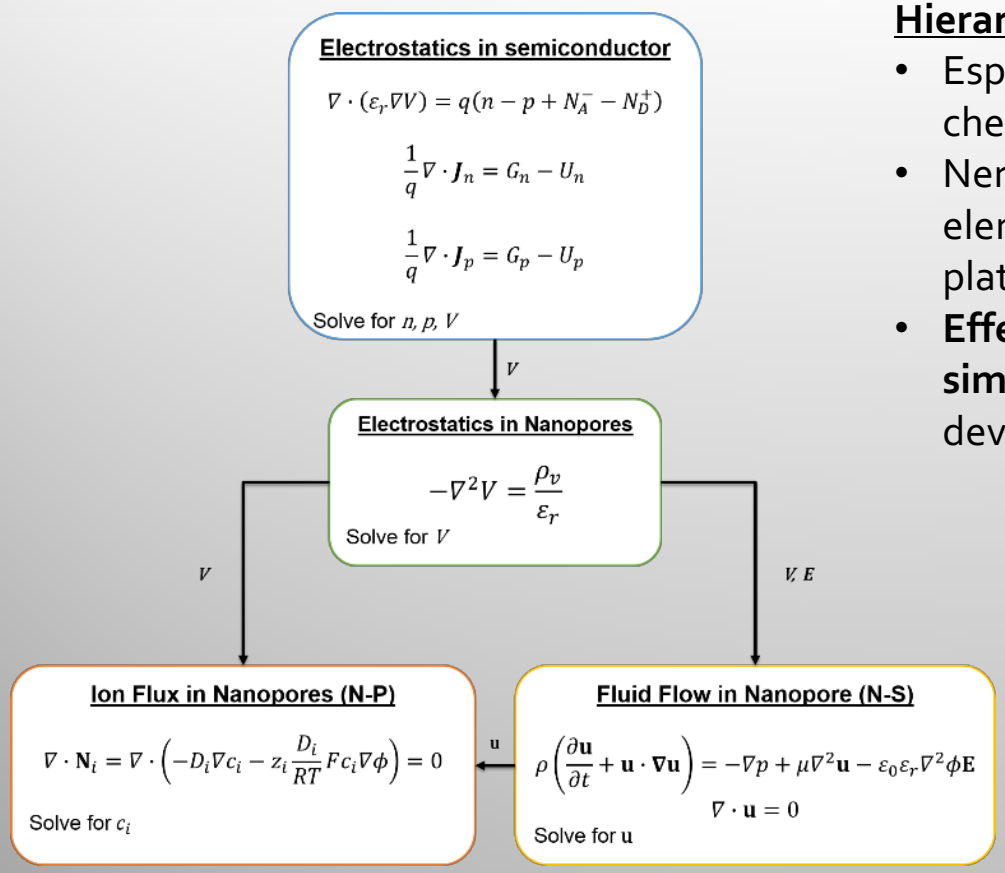


- Drilled millions of 50-100 nm diameter channels into Si PV cell with silver particle assisted chemical etching
- Coated channel surfaces with insulating HfO_2



- **50% reduction of salinity achieved in few minutes under illumination**
- channels need to be flushed

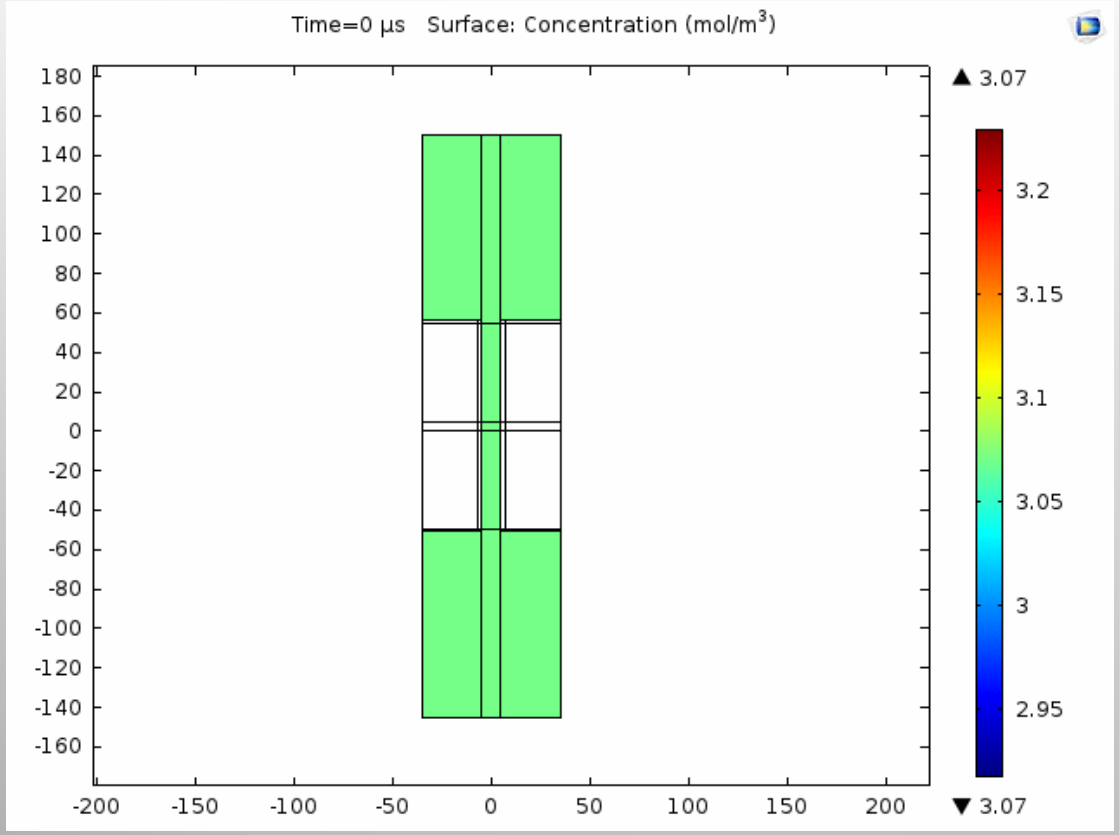
Simulations



Hierarchical simulation infrastructure:

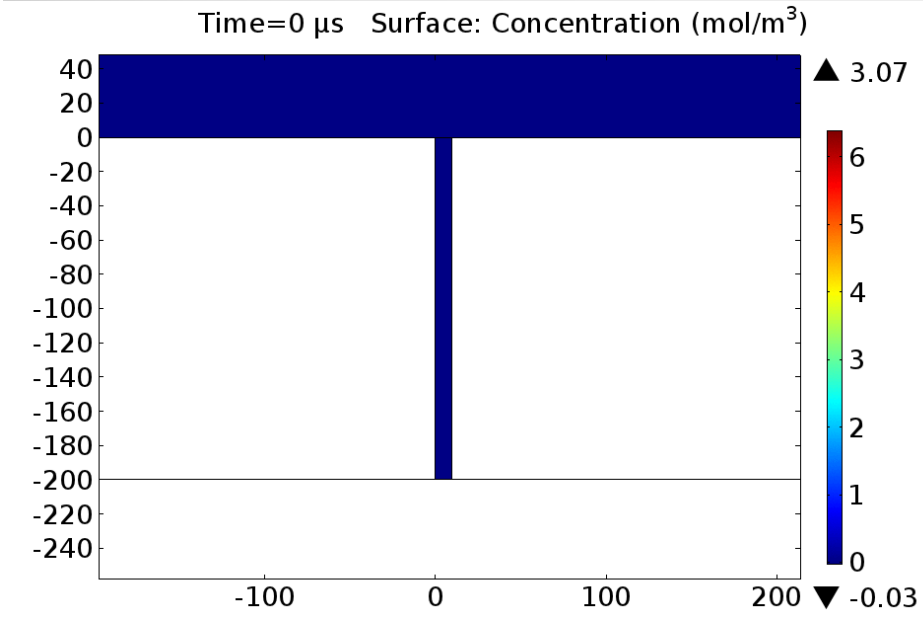
- Espresso platform for physics and chemistry of adsorption at walls ~1nm
- Nernst-Planck inspire microfluidics, finite element simulation with Openfoam platform 50-500nm
- **Effective medium theory for Stanford simulations** for meso- and macroscopic device simulation

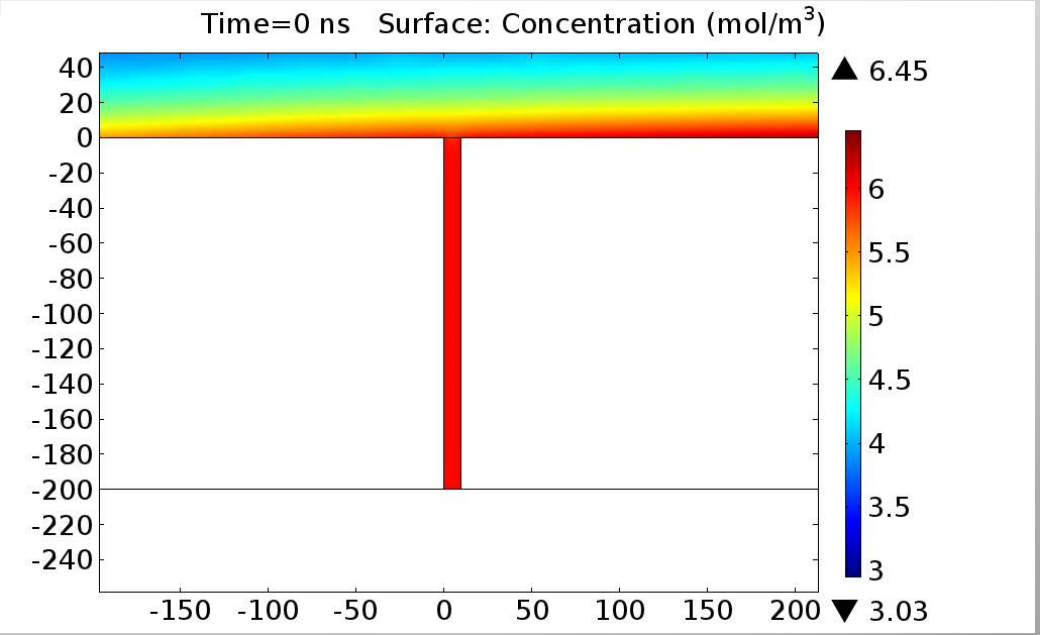
Time dependence of adsorption



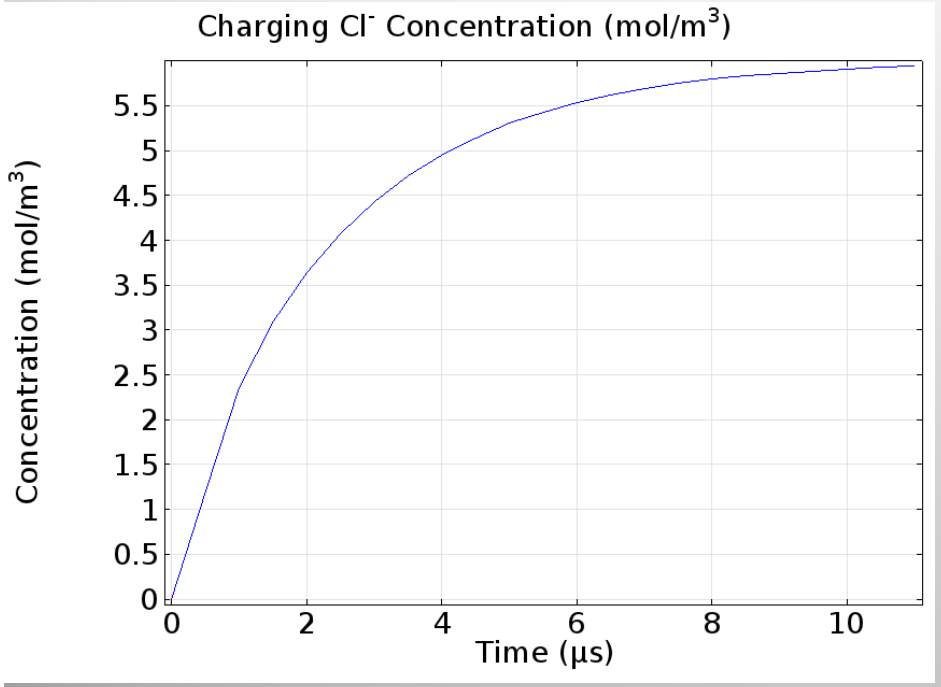
Minimizing flushing losses via simulations

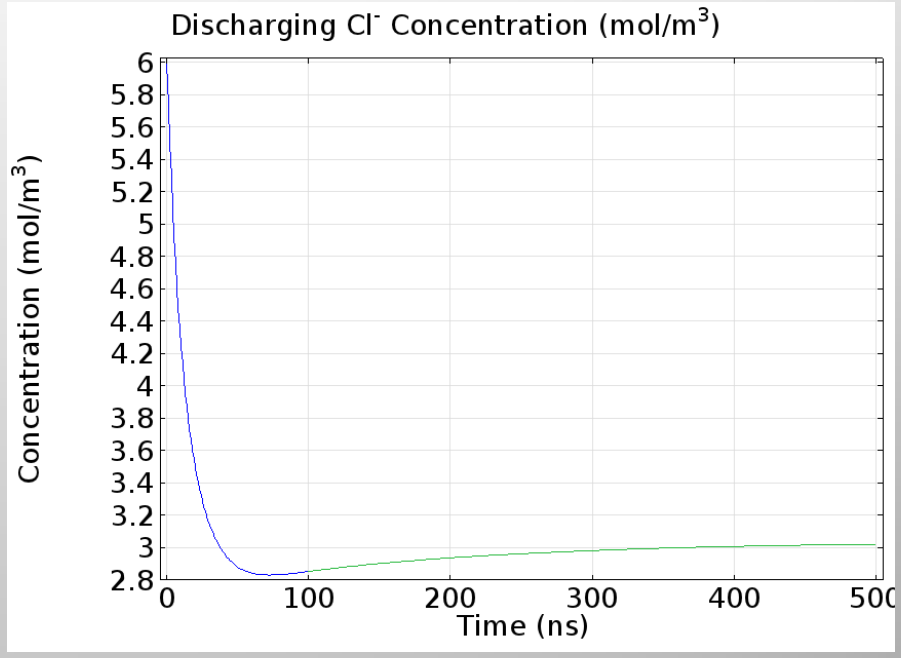
- Flushing cycle is lost time for operation
- High priority R&D goal: minimize duration of flushing cycle relative to charging/adsorption cycle





Flushing cycle can be reduced to a few percent of period





Integrated Solar Charged Desalination patent filed

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(54) **PHOTOVOLTAIC DESALINATION SYSTEM**

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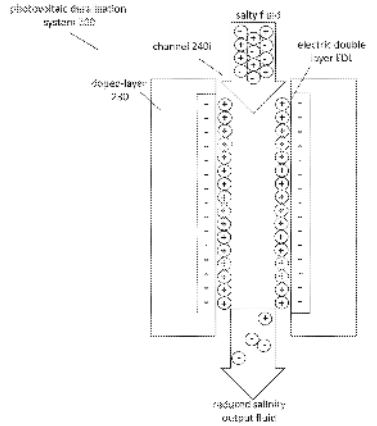
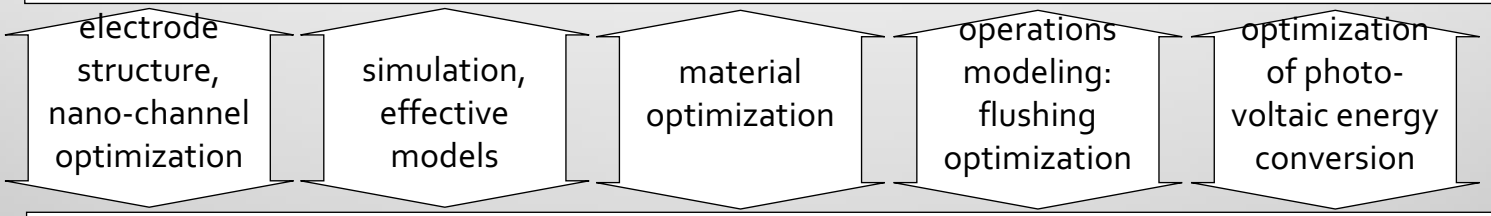
(57) **ABSTRACT**

A photovoltaic desalination system can comprise a solar cell, configured to receive solar radiation, including an n-doped semiconductor layer, a p-doped semiconductor layer, the two semiconductor layers forming a p-n junction, and an channel array, formed in the p-n junction; an input reservoir, coupled to the solar cell, the input reservoir configured to contain a salty fluid, and to release the salty fluid to the solar cell; an output fluid management system, coupled to the solar cell, the output fluid management system configured to receive an output fluid from the solar cell; wherein the channel array is configured to receive the salty fluid from the input reservoir, and to output the output fluid to the output fluid management system.



Synergy of DSC and ISC projects: Bringing a new paradigm to life

Discrete Solar Charging project is predictable to deliver high flow-rate prototypes ready for scale-up in about 2 years



Integrated Solar Charging project is high risk-high reward, eliminates energy conversion losses, promises to deliver efficient prototypes in about 2 years

THANK YOU