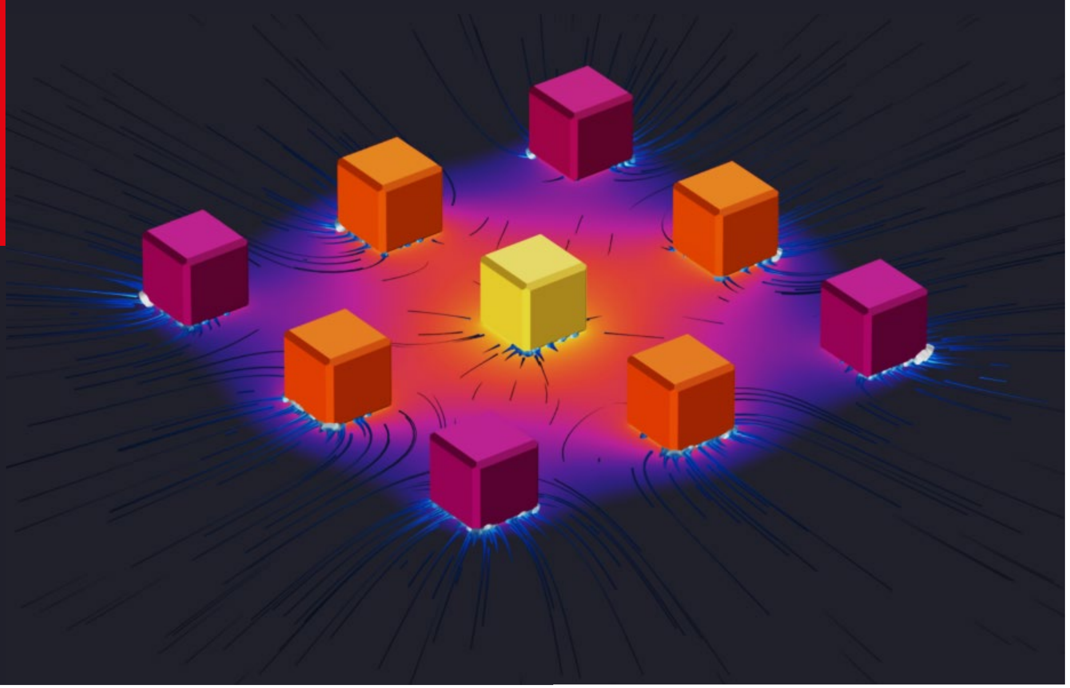
Nanoscale Heat Transfer (and Energy Conversion) ME469

Instructor: Giulia Tagliabue

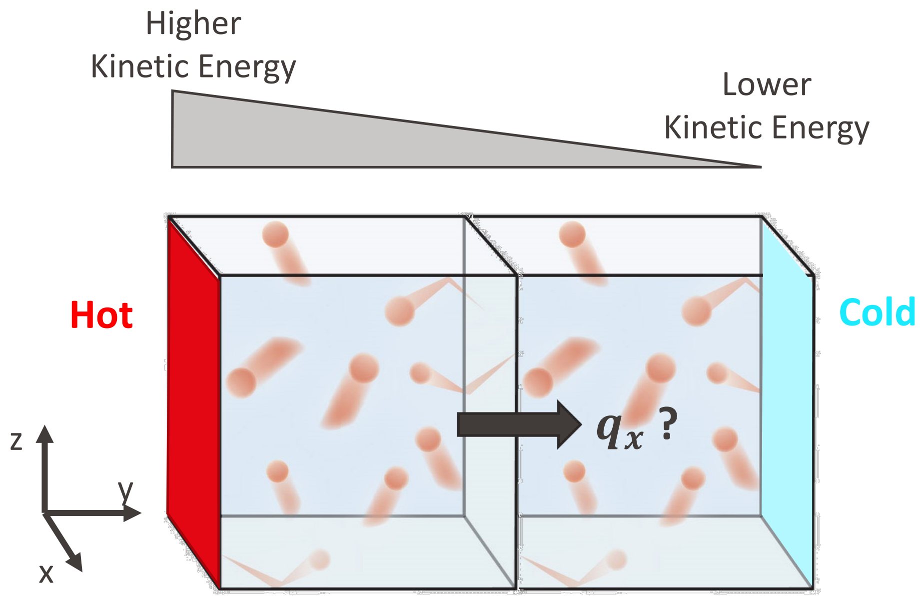


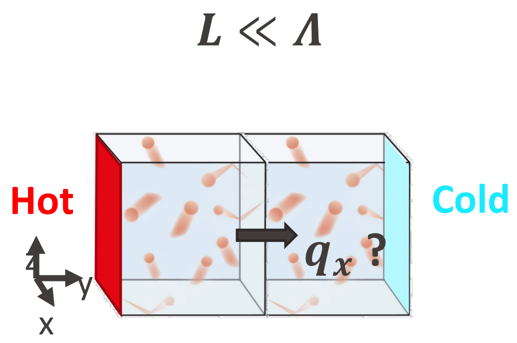
École polytechnique fédérale de Lausanne

Spring Semester

Energy Conversion – Benefit of Nanostructures

EPFL



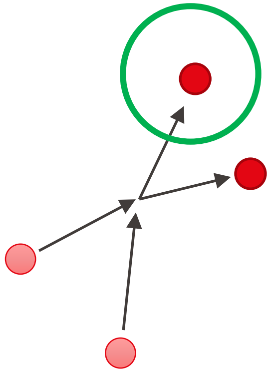


How can we leverage nanoscale structures to improve device performance or realize new energy conversion devices?

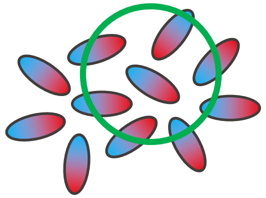
- Thermoelectric devices ✓
- Control of radiative heat transfer
- Light-energy conversion devices ✓
- **Electrokinetic devices (Week 13/14)**

Liquids and their Transport Properties

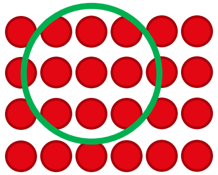
Dilute gases



Liquids



Solids



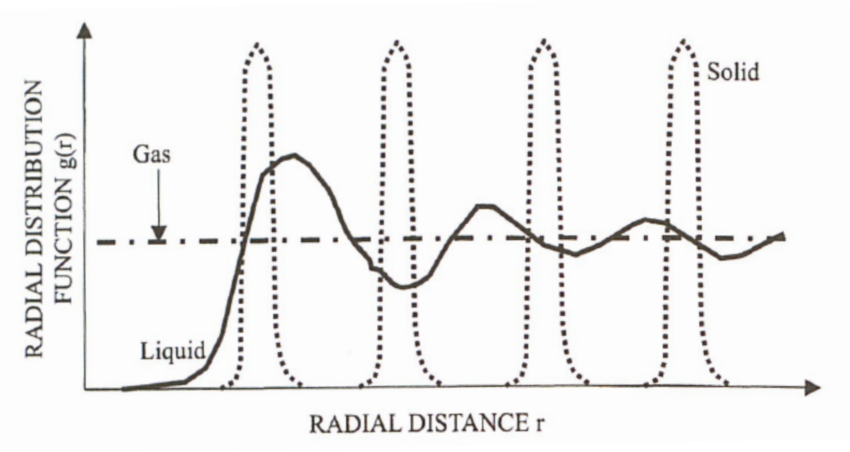
$4\pi r^2 n g(r) dr =$ the number of molecules with centers between r and $r + dr$ measured relative to a specific molecule

If the average potential energy between two particles is $\phi(r)$, then the total potential energy of an N particle system is:

$$\Phi_N = \frac{N}{2}\int_0^\infty 4\pi r^2 \phi(r) n g(r) dr$$

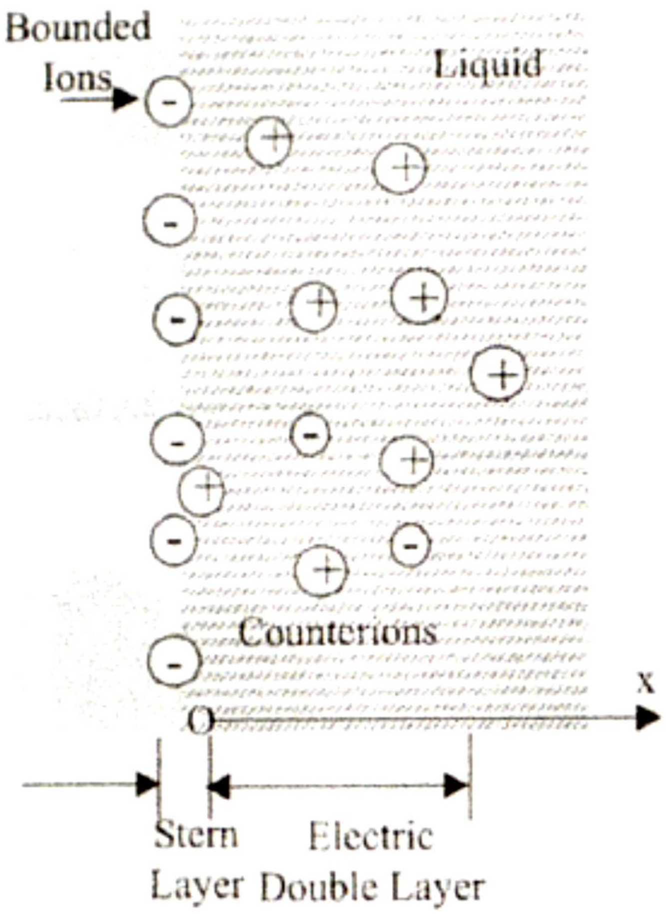
$n = N/V$ particle number density

$g(r)$ **is called *radial distribution function***



Interfacial Interactions 3 – Electric Double Layer (EDL) Potential

Surfaces immersed in liquids are usually charged because of ionization or dissociation of surface groups or adsorption of ions from the solutions onto a previously uncharged surface. The charges accumulated at the surface are balanced by an equal but oppositely charged region of counter-ions. Some of these counterions are also bounded to the surface (Stern or Helmholtz layer) while the majority of them form a **diffuse electric double layer**. An electrostatic potential ψ_s develops at the solid-liquid interface.



$$-\varepsilon_0\varepsilon_r \nabla^2\psi = \sum_i Z_i e n_{0i} \exp\left(-\frac{Z_i e\psi}{\kappa_B T}\right)$$

Poisson-Boltzmann Equation

In the limit (Debye-Huckel theory) $Z_i e\psi \ll \kappa_B T$

$$\Rightarrow \quad -\varepsilon_0\varepsilon_r \nabla^2\psi = \sum_i Z_i e n_{0i} \left(1 - \frac{Z_i e\psi}{\kappa_B T}\right)$$

In a planar geometry the boundary conditions require:

$\sum_i Z_i e n_{0i} = 0.$ No net charge far away from the surface

$x = 0,\ \psi = \psi_s$ and $x \to \infty,\ \psi \to 0$

$$\Rightarrow \quad \frac{d^2\psi}{dx^2} = \psi \sum_i \frac{Z_i^2 e^2 n_{0i}}{\varepsilon_0\varepsilon_r \kappa_B T}$$

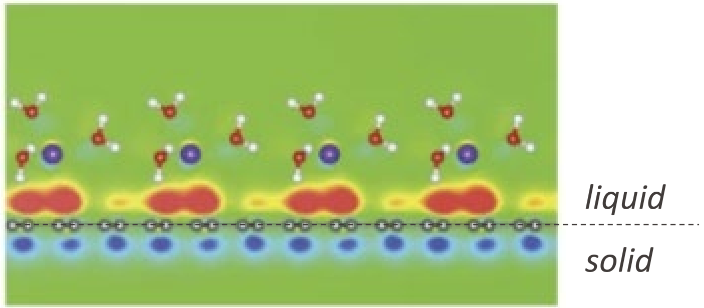
$$\Rightarrow \quad \psi(x) = \psi_s e^{-x/\delta} \qquad \frac{1}{\delta} = \sqrt{\sum_i \frac{Z_i^2 e^2 n_{oi}}{\varepsilon_0\varepsilon_r \kappa_B T}}$$

Debye-length

We will later discuss how EDL affects transport of ions in nanochannels

From Hydro-electric to Hydro-voltaic

Hydro-electric:
kinetic energy of water



Hydro-voltaic:
Solid/liquid interaction

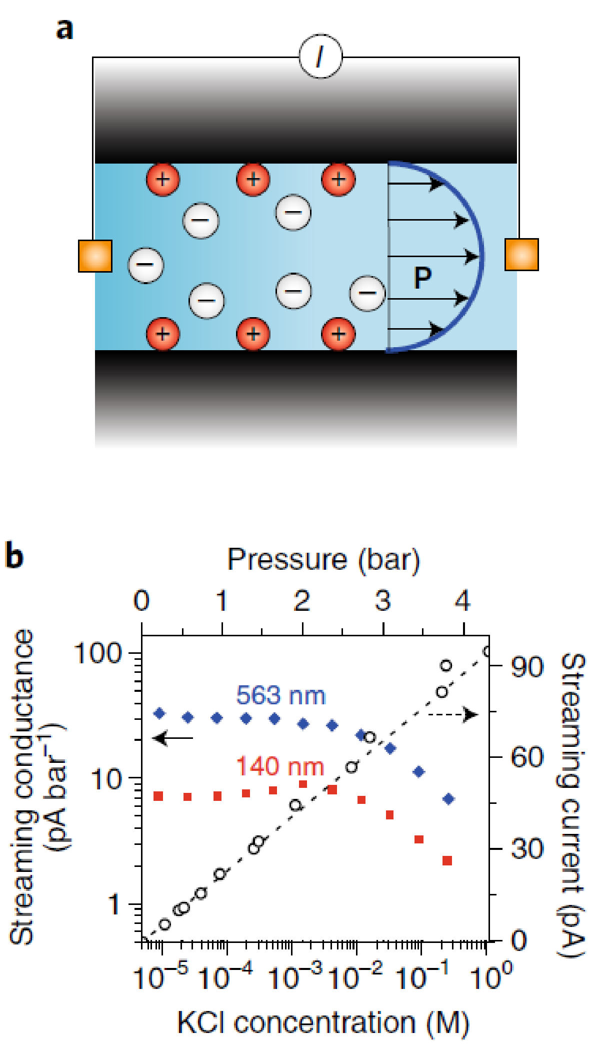
Leveraging water energy conversion at different scales

In This Lecture...

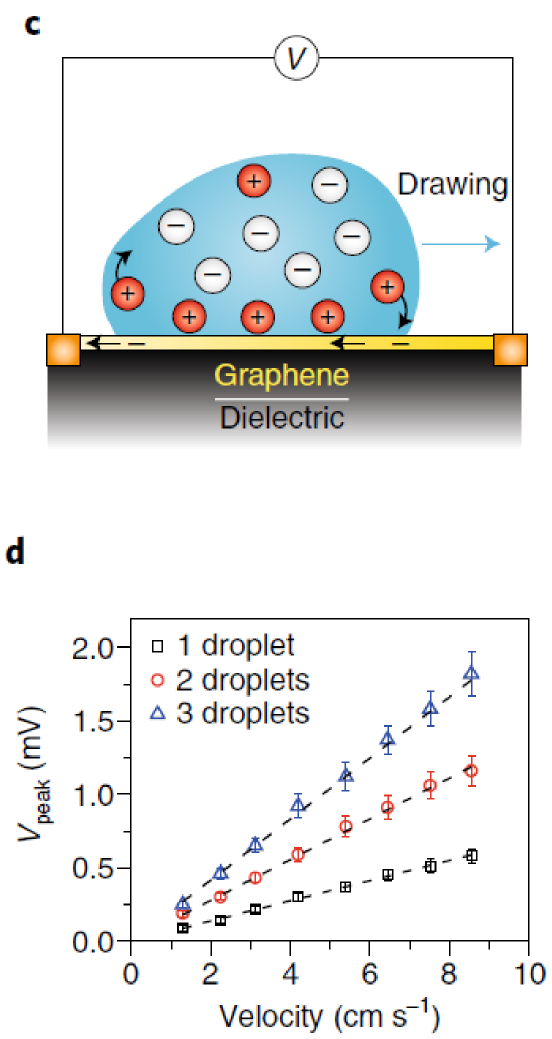
- Hydrovoltaic Devices
  - **Streaming, drawing and waving potentials**
  - Evaporation-driven devices
- Gradient potential
  - Moisture induced potential
  - Osmotic Potential : Blue energy Devices and desalination membranes (flow in nanostructures)
  - Ion pumps
- Outlook

Streaming, Drawing and Waving Potentials

EPFL



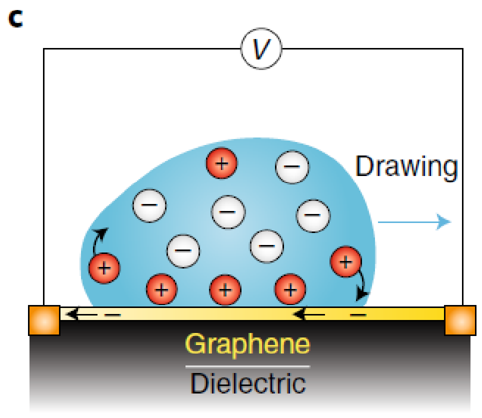
Single interface (Solid/liquid)

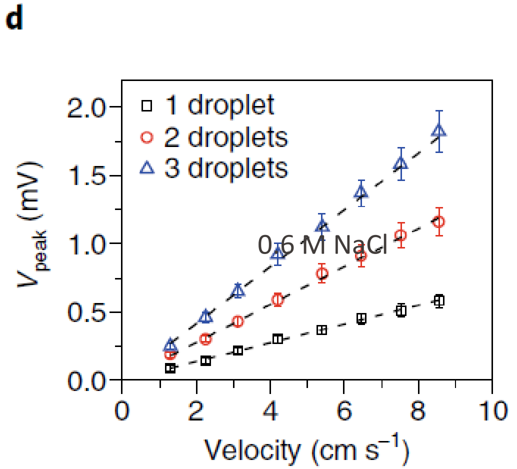


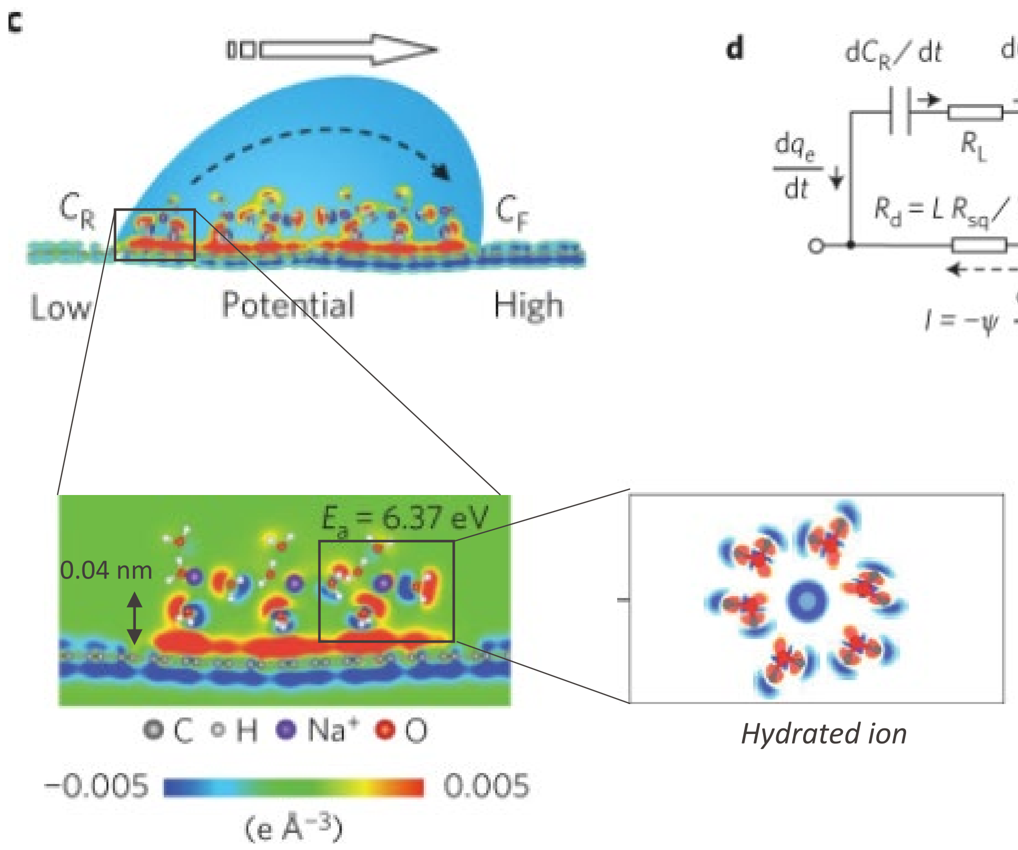
Three-phase interface (Solid/liquid/gas)
Moving boundary

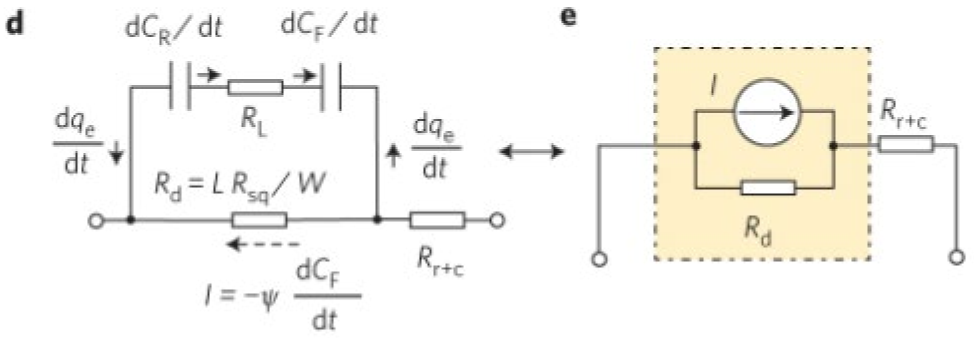
https://www.nature.com/articles/s41565-018-0228-6

Streaming, Drawing and Waving Potentials





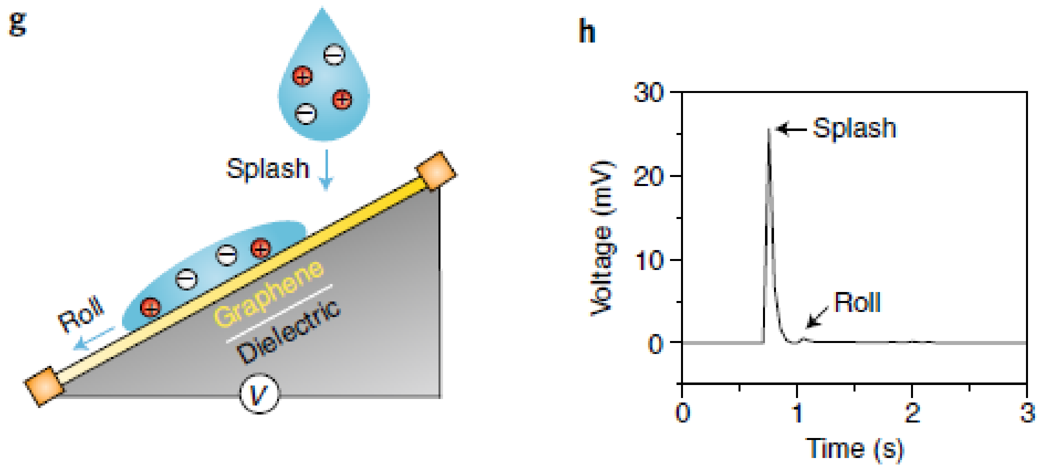


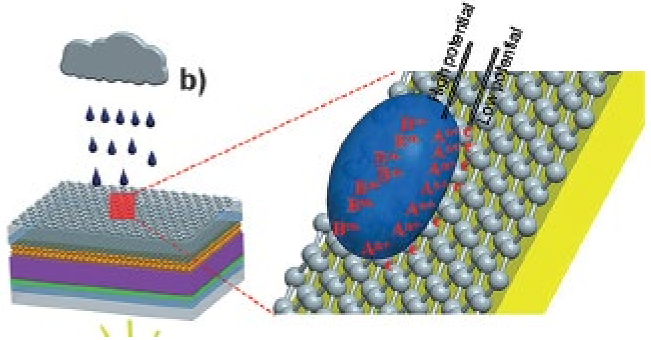


Power density of $40\ \mu W/m^2$

https://www.nature.com/articles/nnano.2014.56

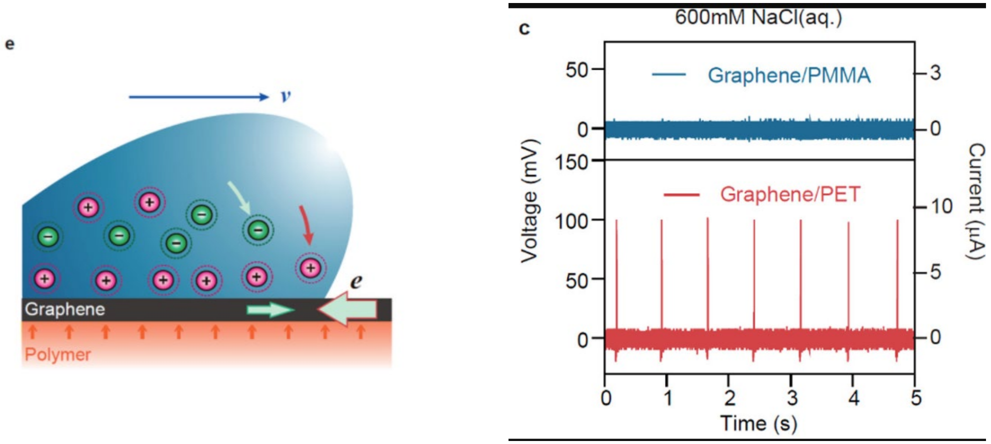
Streaming, Drawing and Waving Potentials

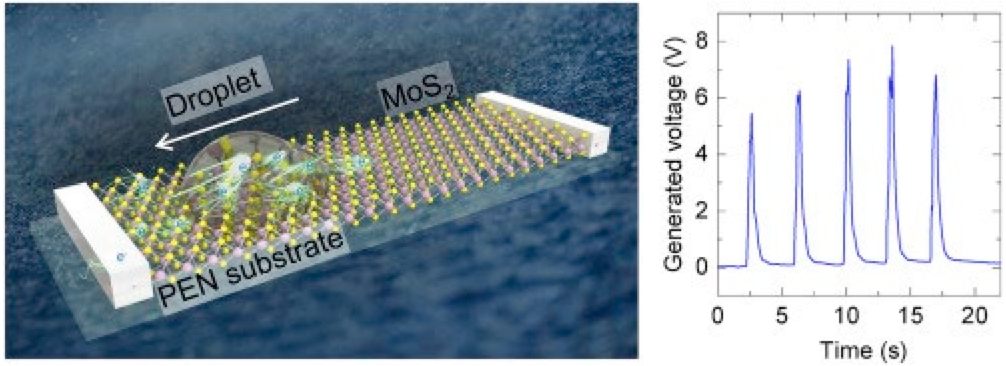




Bi-functional solar-cell

http://dx.doi.org/10.1002/anie.201602114



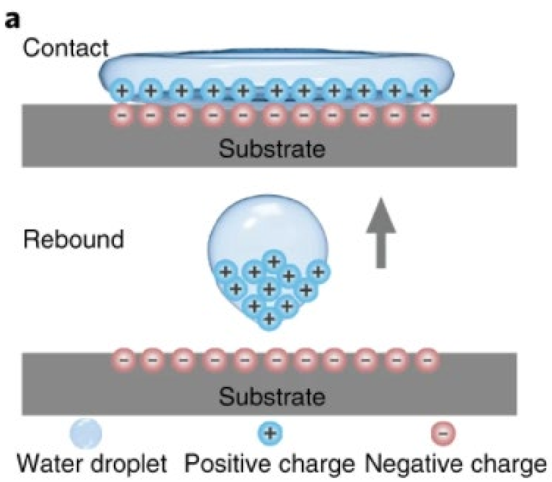


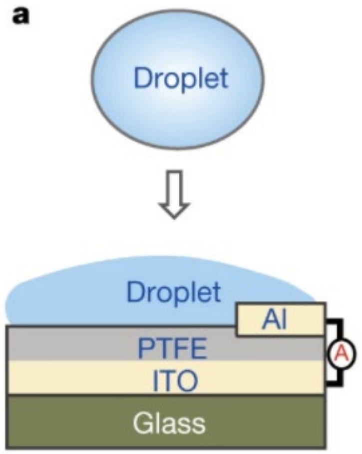
Charged supports can enhance power densities up to $3mW/m^2$

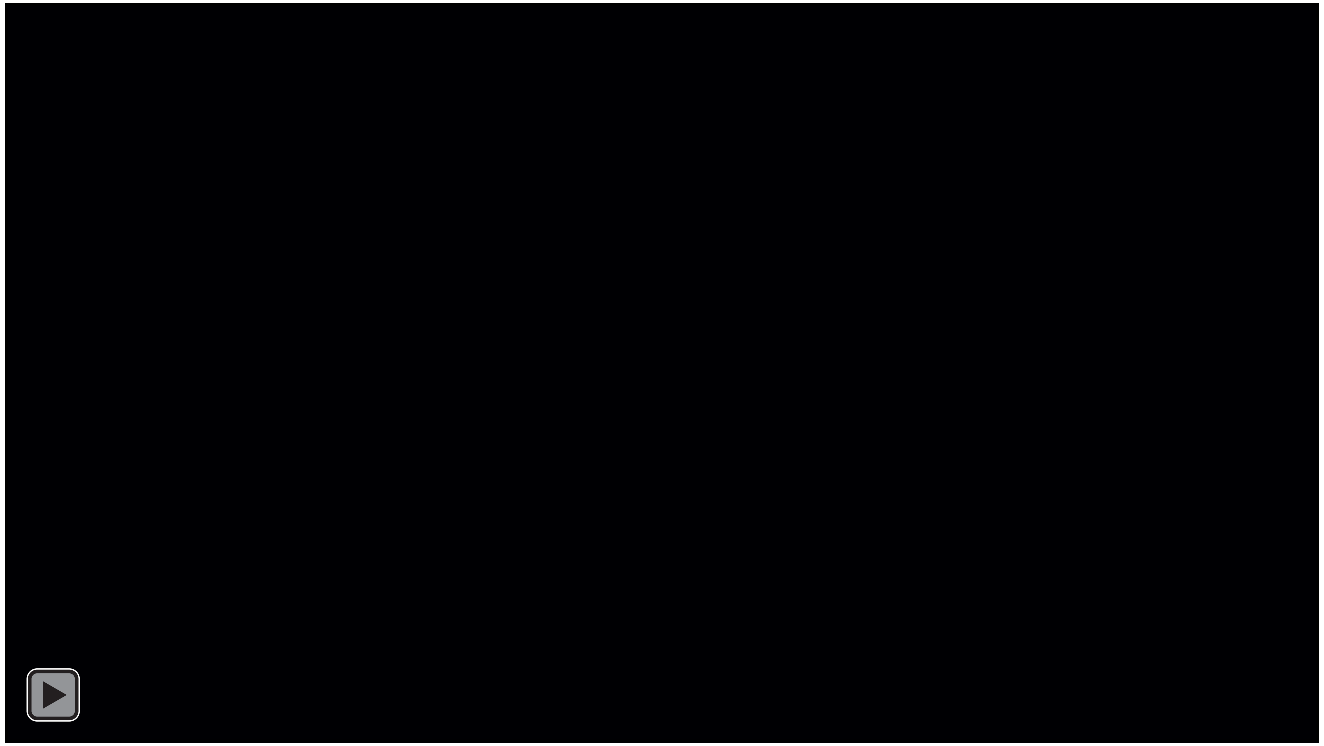
https://pubs.acs.org/doi/10.1021/jacs.8b07778

https://www.sciencedirect.com/science/article/pii/S2211285519310845?via%3Dihub

Streaming, Drawing and Waving Potentials



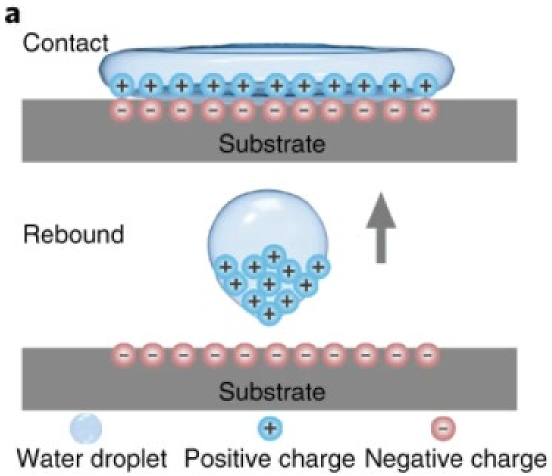


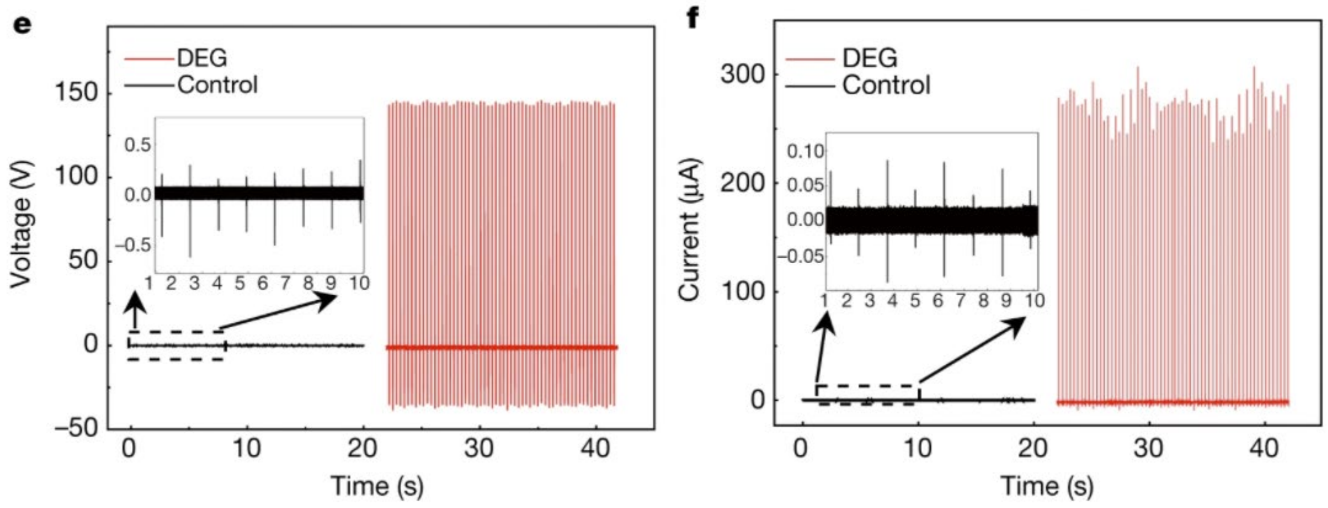


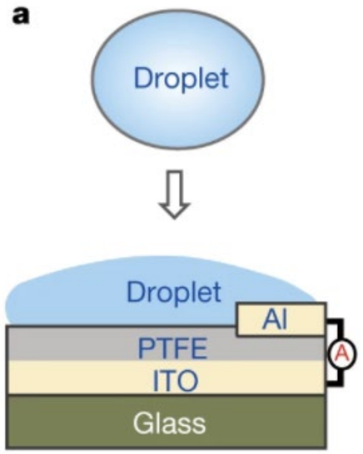
https://www.nature.com/articles/s41586-020-1985-6

https://www.nature.com/articles/s41563-019-0440-2

Streaming, Drawing and Waving Potentials







Power densities up to 50 W/m^2
(for few microseconds)

https://www.nature.com/articles/s41586-020-1985-6

https://www.nature.com/articles/s41563-019-0440-2

Streaming, Drawing and Waving Potentials

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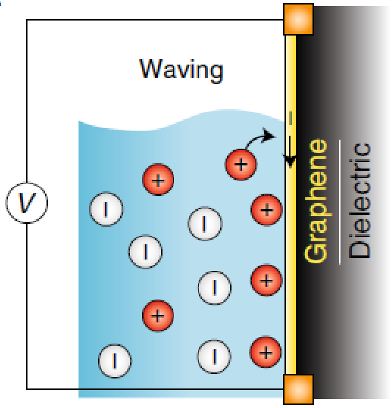

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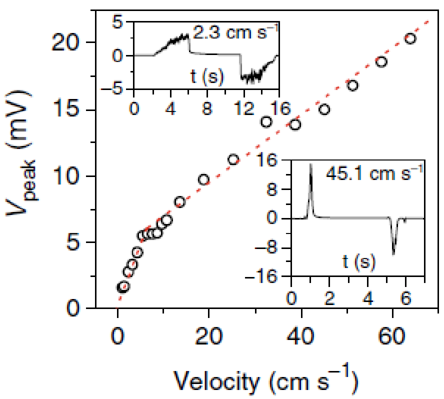
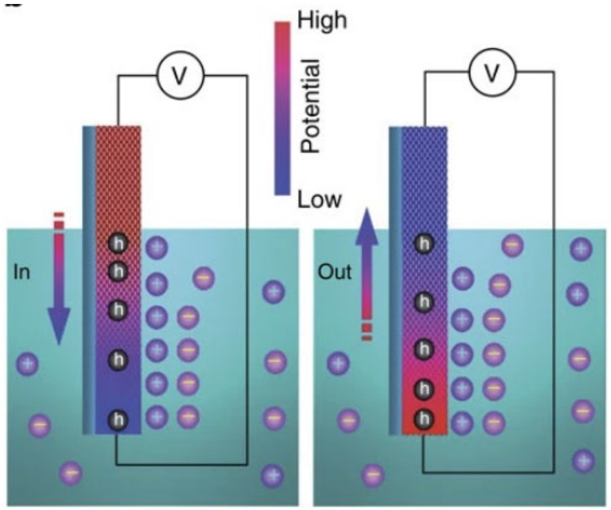
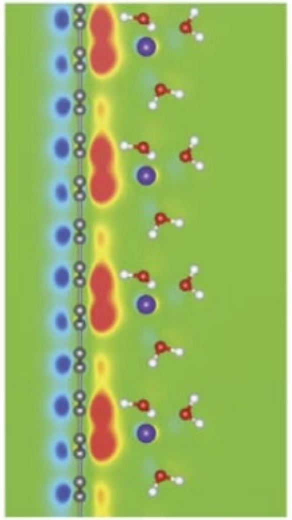
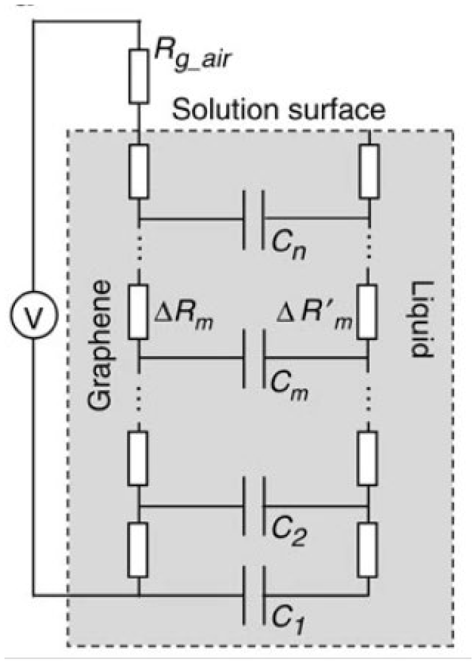


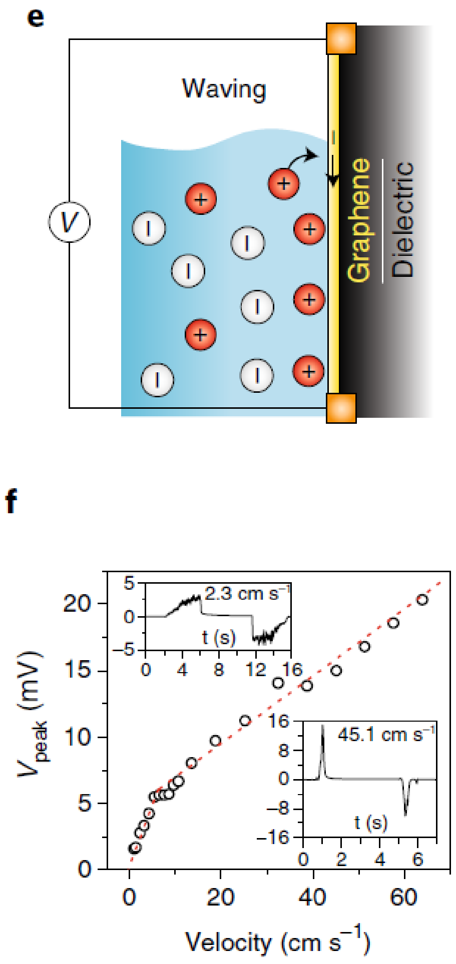


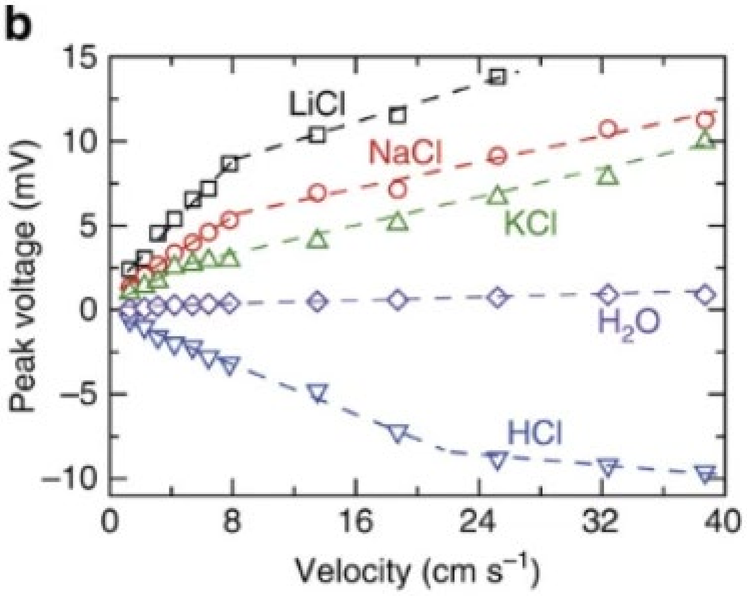


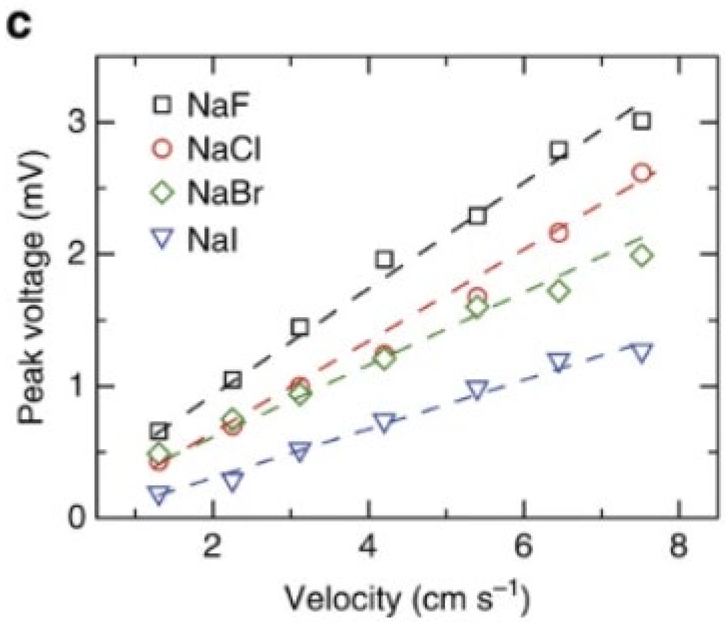


https://www.nature.com/articles/ncomms4582

Streaming, Drawing and Waving Potentials







https://www.nature.com/articles/ncomms4582

In This Lecture…

- Hydrovoltaic Devices
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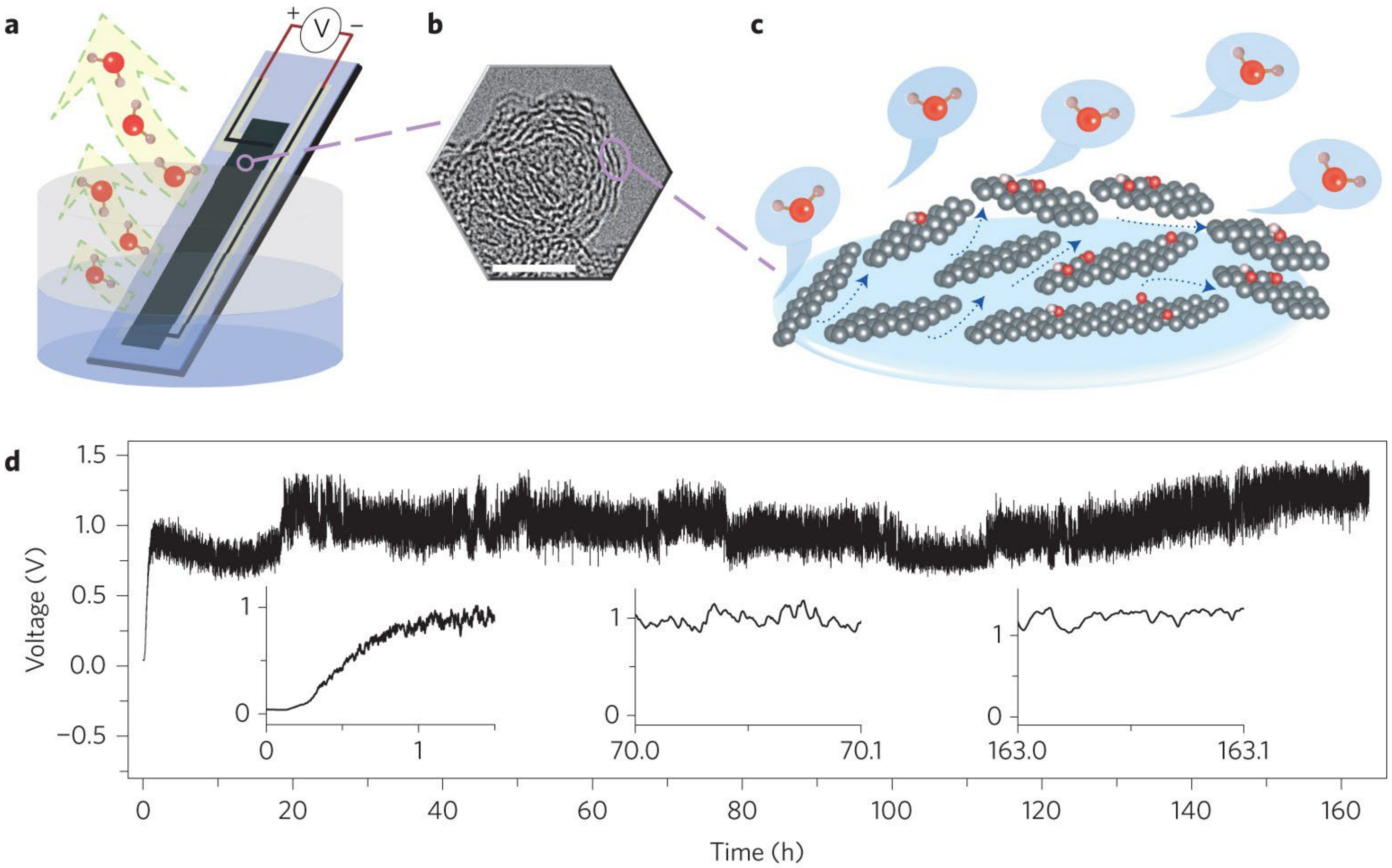
  - Moisture induced potential
  - Osmotic Potential : Blue energy Devices and desalination membranes (flow in nanostructures)
  - Ion pumps
- Outlook

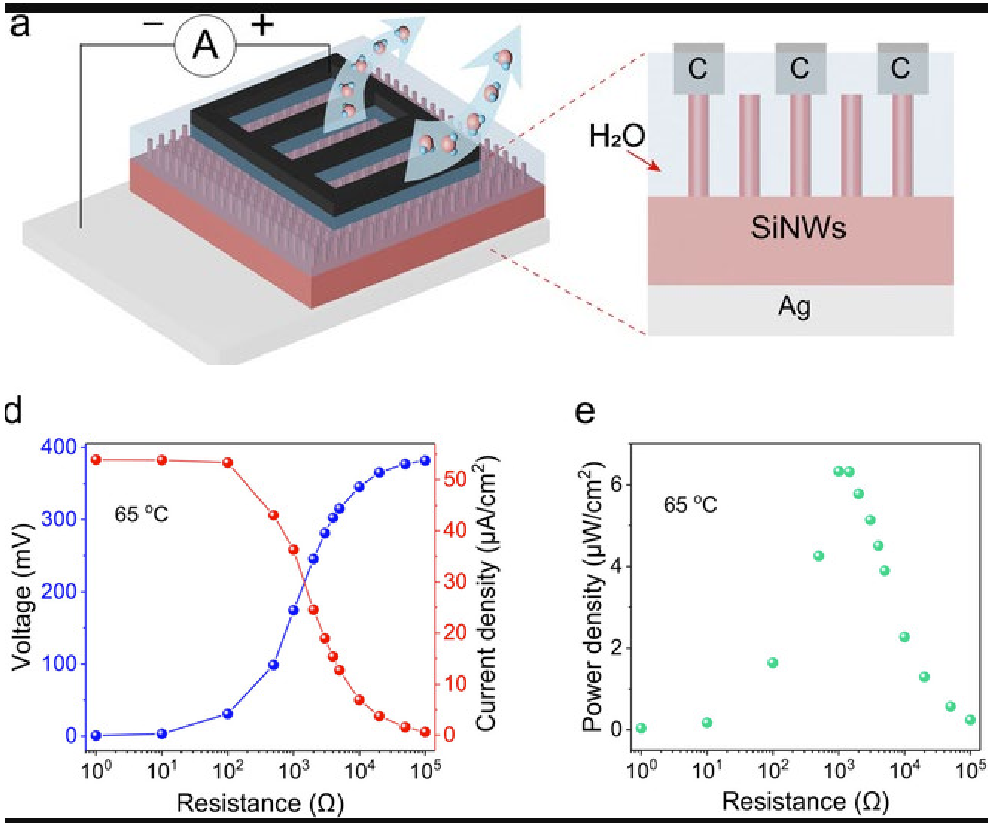
Evaporation Driven Devices

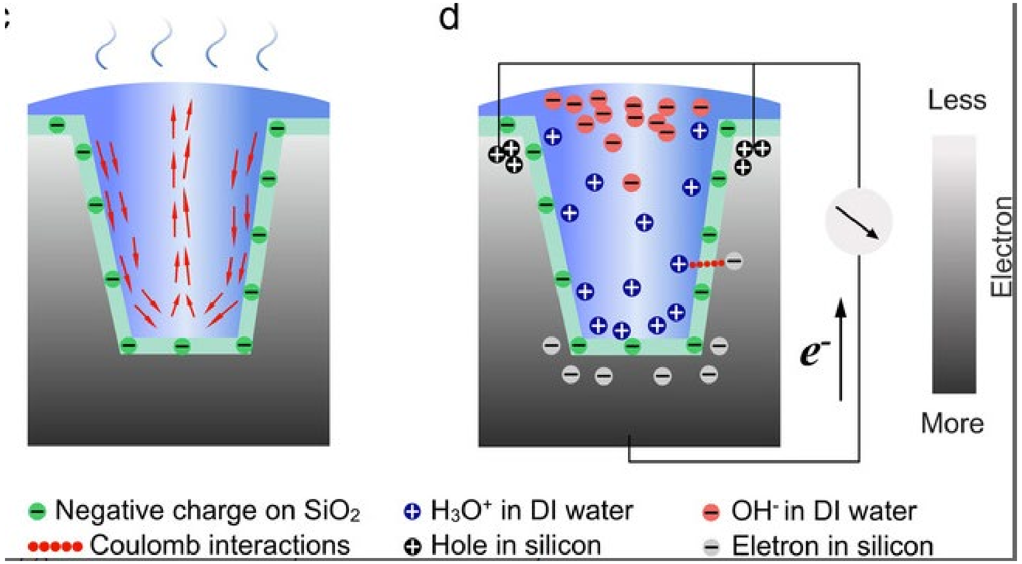


Hydrophilic carbon-black sustains constant voltage generation under evaporation

https://www.nature.com/articles/nnano.2016.300

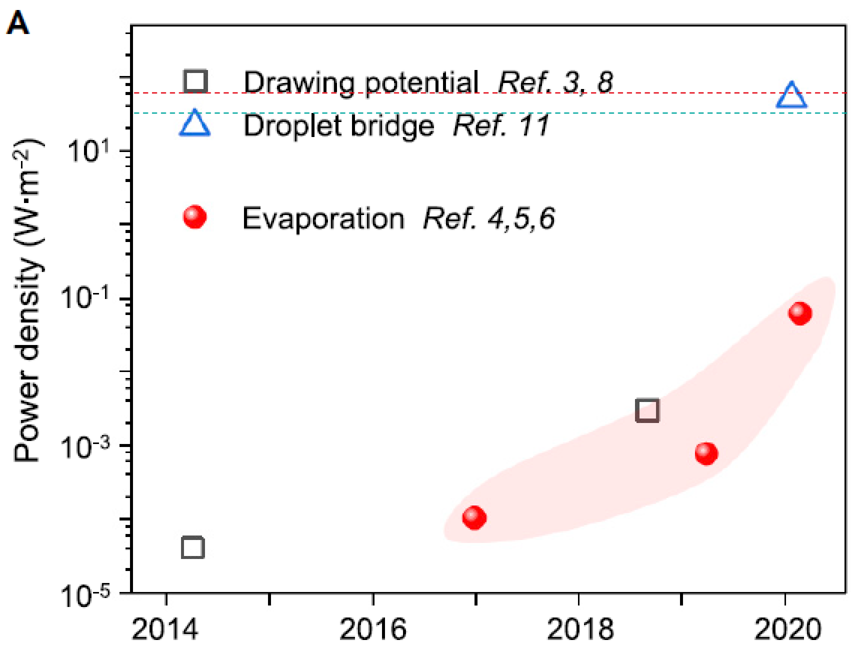
Evaporation Driven Devices

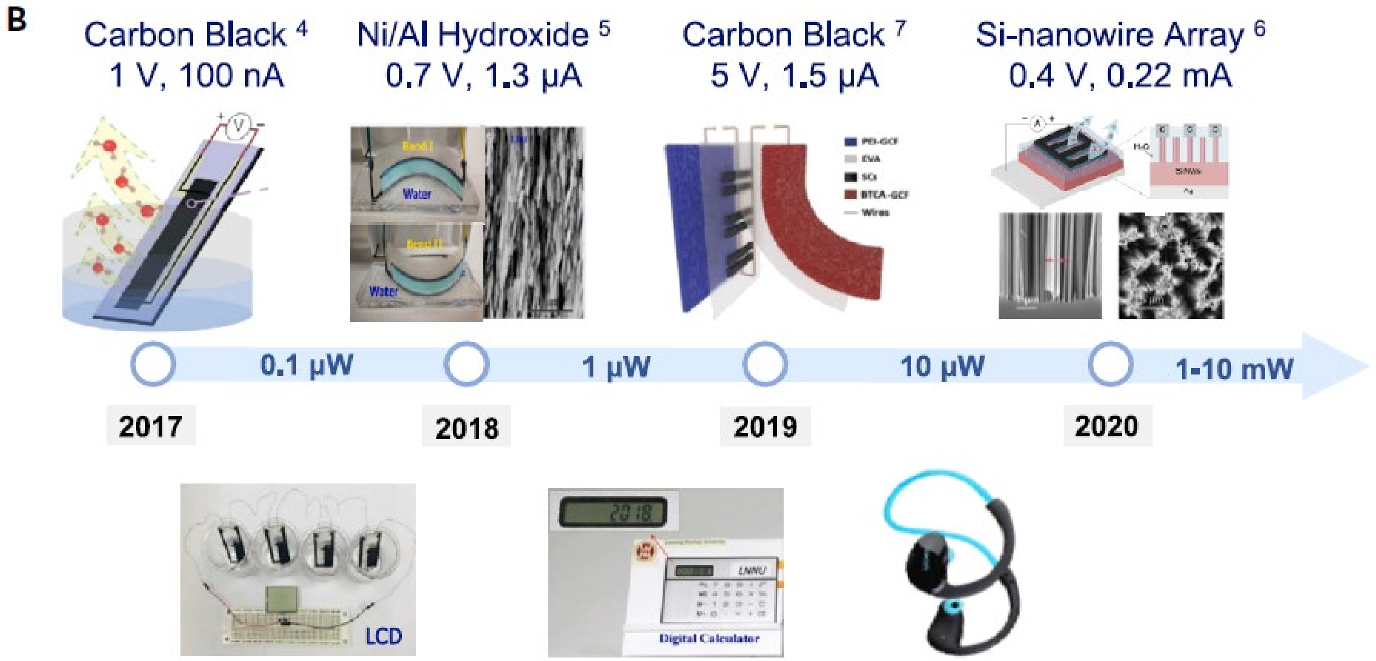




https://onlinelibrary.wiley.com/doi/10.1002/anie.202002762

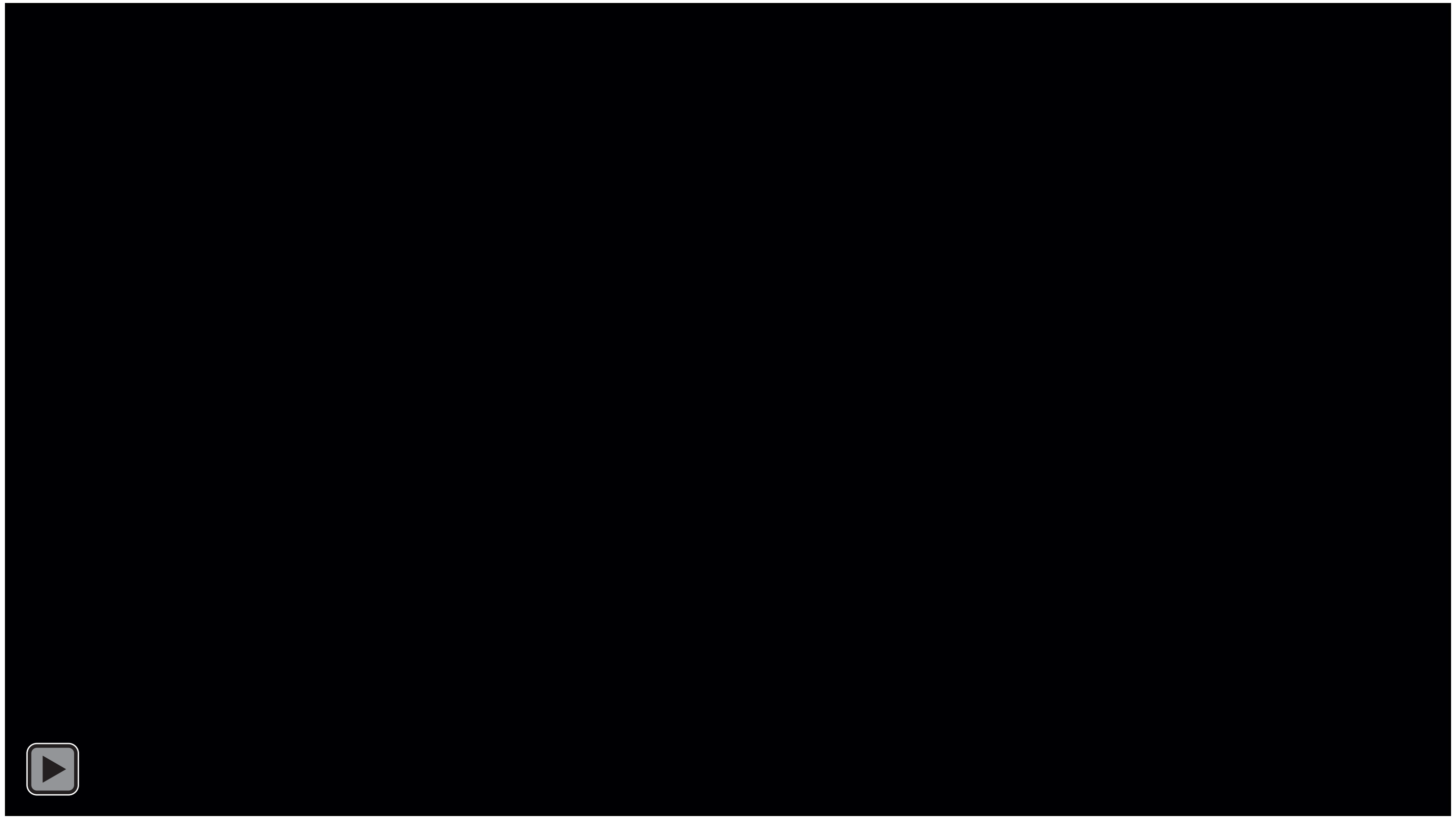
Evaporation Driven Devices





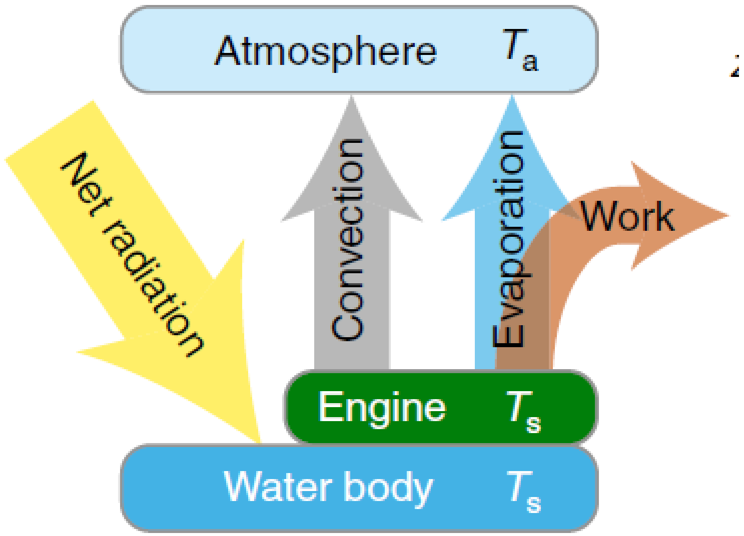
Joule 4, 1852–1855, September 16, 2020

Evaporation Driven Devices



https://www.nature.com/articles/ncomms8346#Sec17

Evaporation Driven Devices



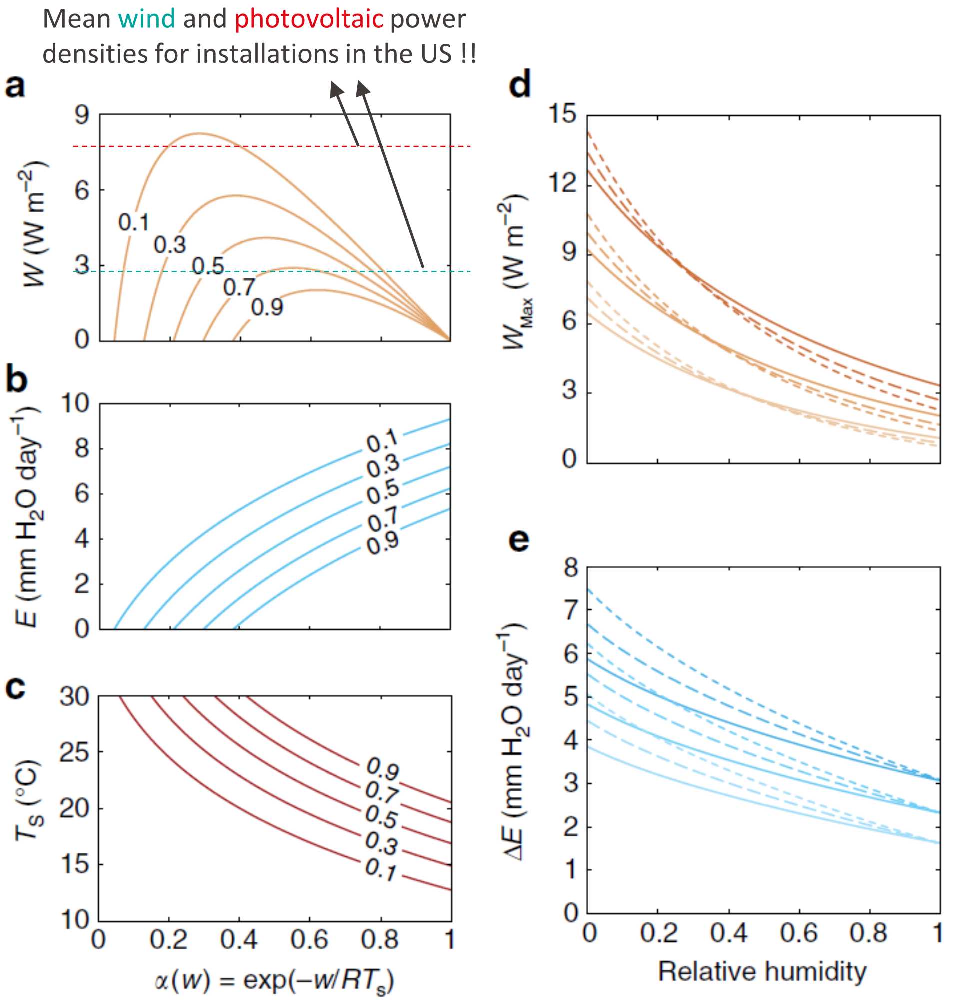


Fig. 2 Steady-state power generation and effects on evaporative losses. **a** Energy fluxes, **b** evaporation rates, and **c** surface temperatures are calculated as a function of $\alpha(w,T_s)$ for weather conditions of 200 W m^{-2} *I*, 16 °C T_a, 101.3 kPa *P*, and 2.7 m s^{-1} (6 mph) *u* at 5 values of RH (mild conditions). **d** Maximum energy flux and **e** water saved from evaporation as a function of RH at cool (*pale*, 12 °C, 150 W m^{-2}), mild (*neutral*, 16 °C, 200 W m^{-2}), and warm (*dark*, 20 °C, 250 W m^{-2}) weather conditions and three wind speeds: 1.8 (4 mph, *solid*), 2.7 (6 mph, *dashed*), and 3.6 m s^{-1} (8 mph, *dotted*)

NATURE COMMUNICATIONS | 8: 617 | DOI: 10.1038/s41467-017-00581-w |

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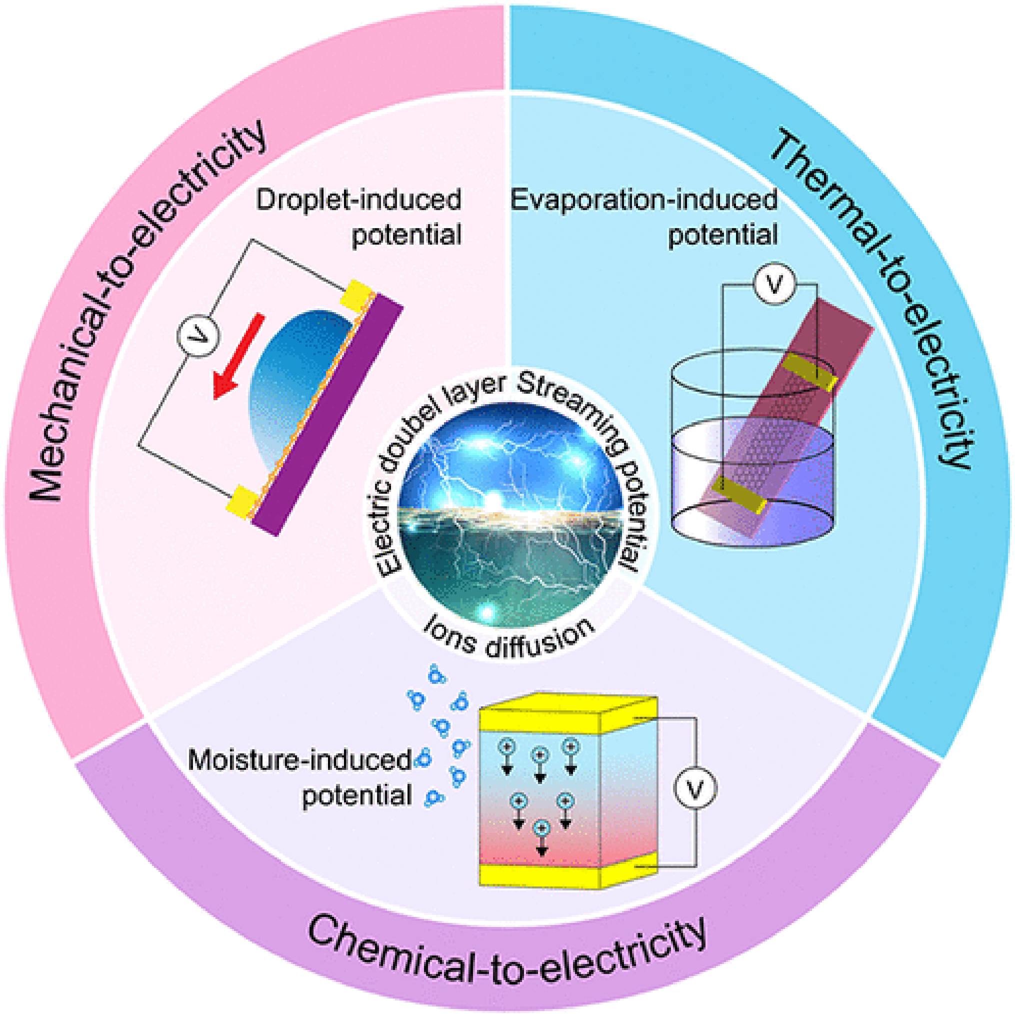
Moisture-induced Potential



https://pubs.acs.org/doi/full/10.1021/acsmaterialslett.0c00474

Moisture-induced Potential

EPFL

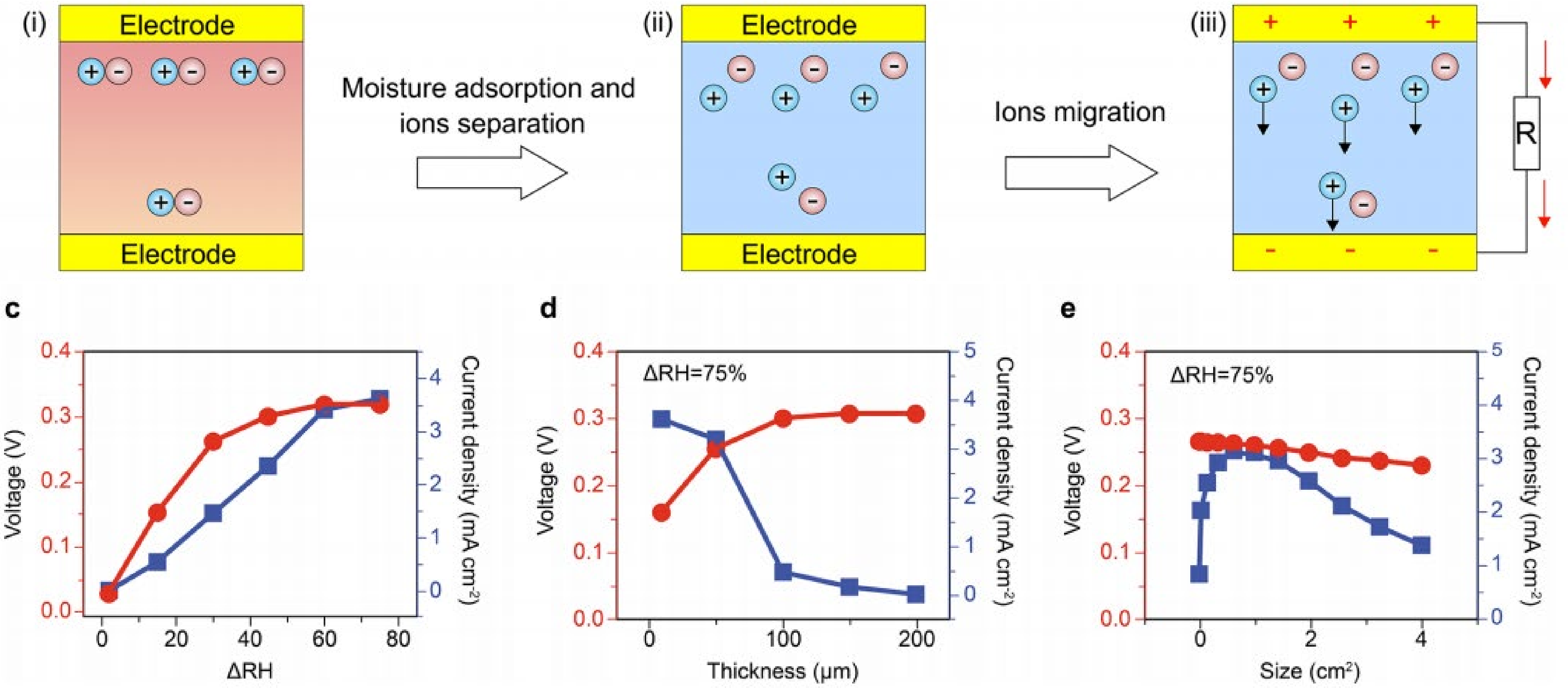
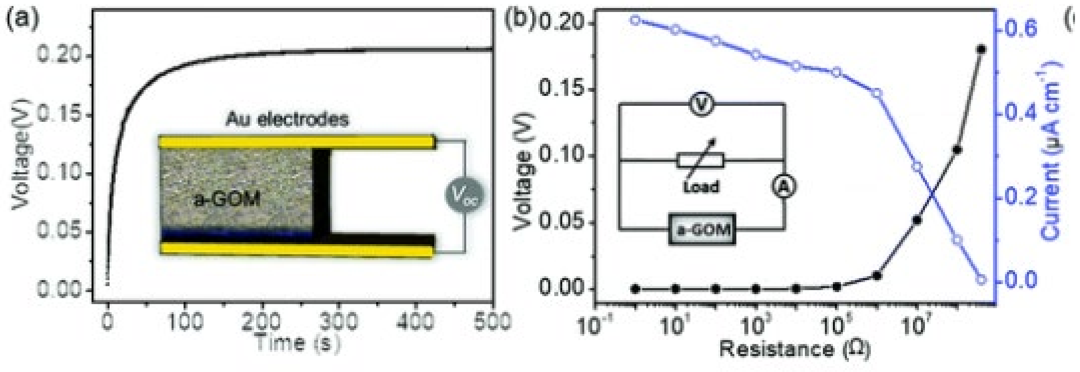
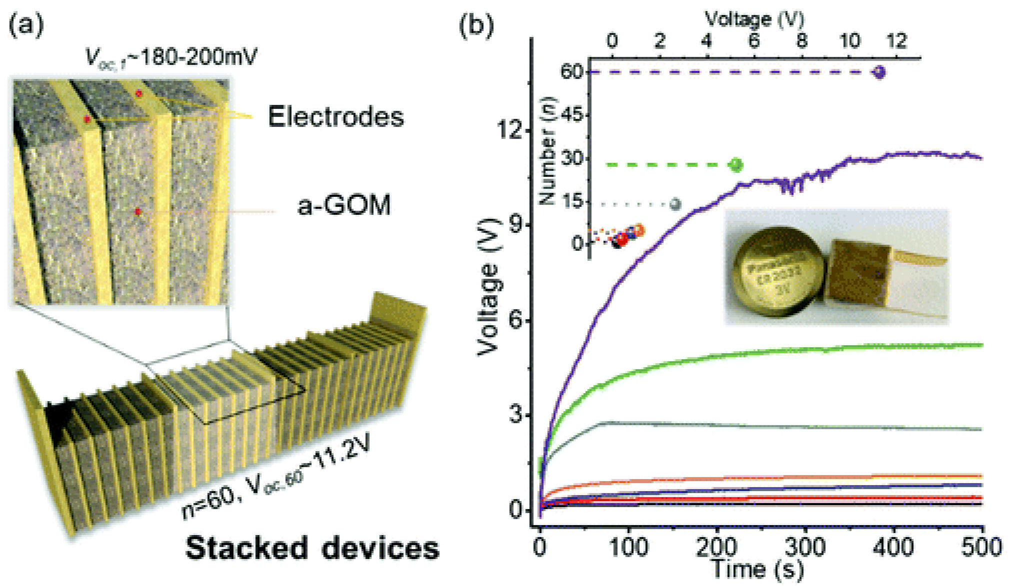


Figure 7. Moisture-based WEGs and the working principles. (a) Working mechanism of the moist-electric generator (MEG): (i) water molecules are first adsorbed onto functional materials with prefabricated chemical gradient; (ii) positively and negatively charged ion pairs are subsequently dissociated and give birth to movable ions (mainly protons); (iii) protons transport directionally from the high concentration region to the low concentration region under the drive of concentration gradient, thus generating electric current in external

https://pubs.acs.org/doi/full/10.1021/acsmaterialslett.0c00474

Moisture-induced Potential





https://pubs.rsc.org/en/content/articlelanding/2018/EE/C8EE01502C#!divAbstract

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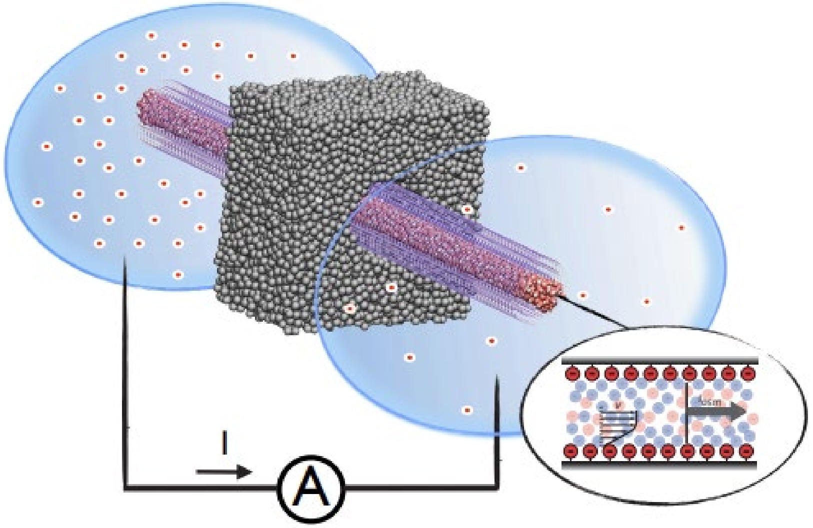
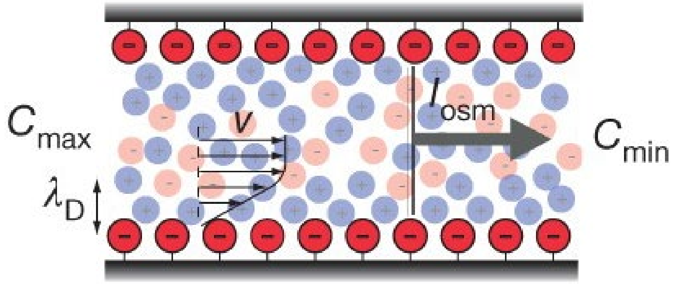
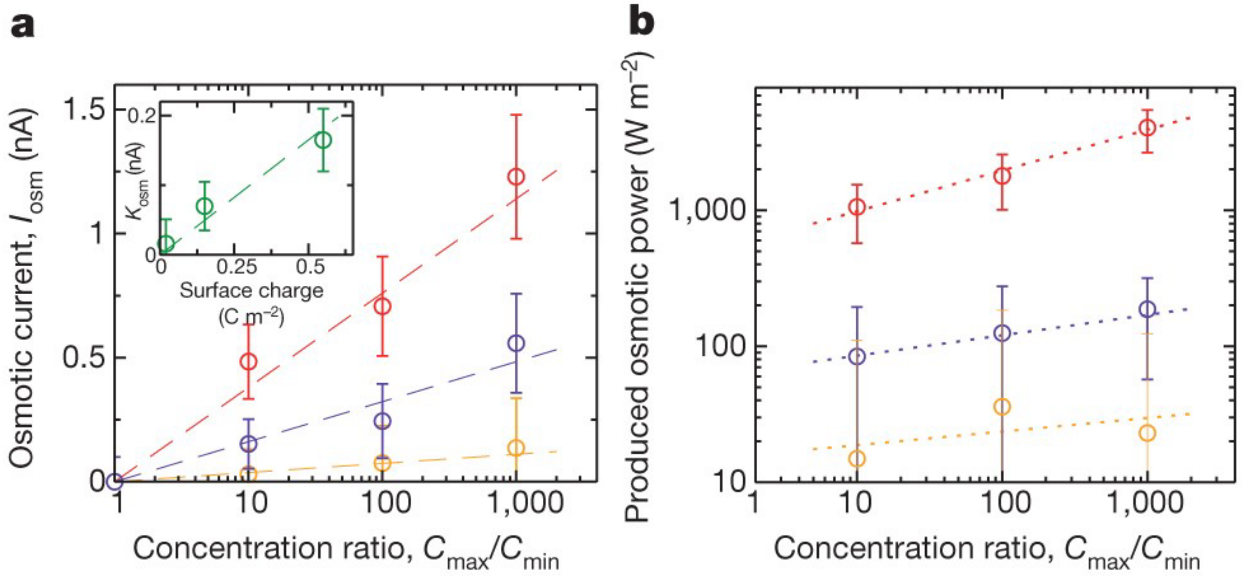
Osmotic Potential





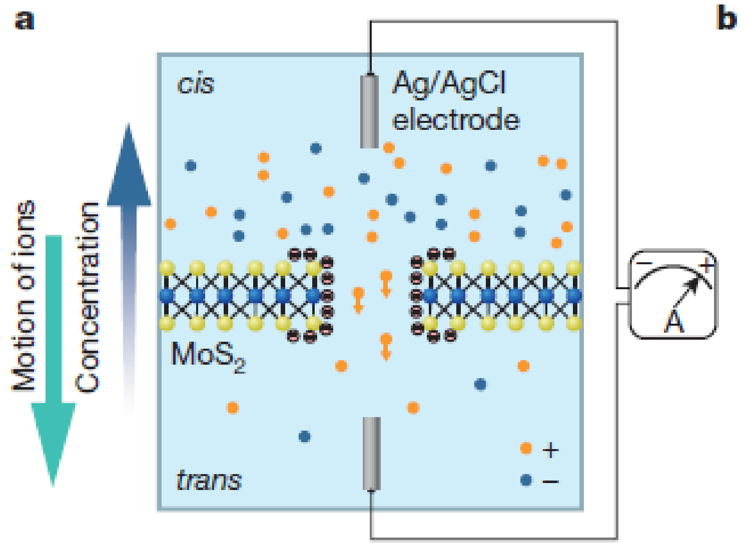
Diffusio-osmotic streaming current

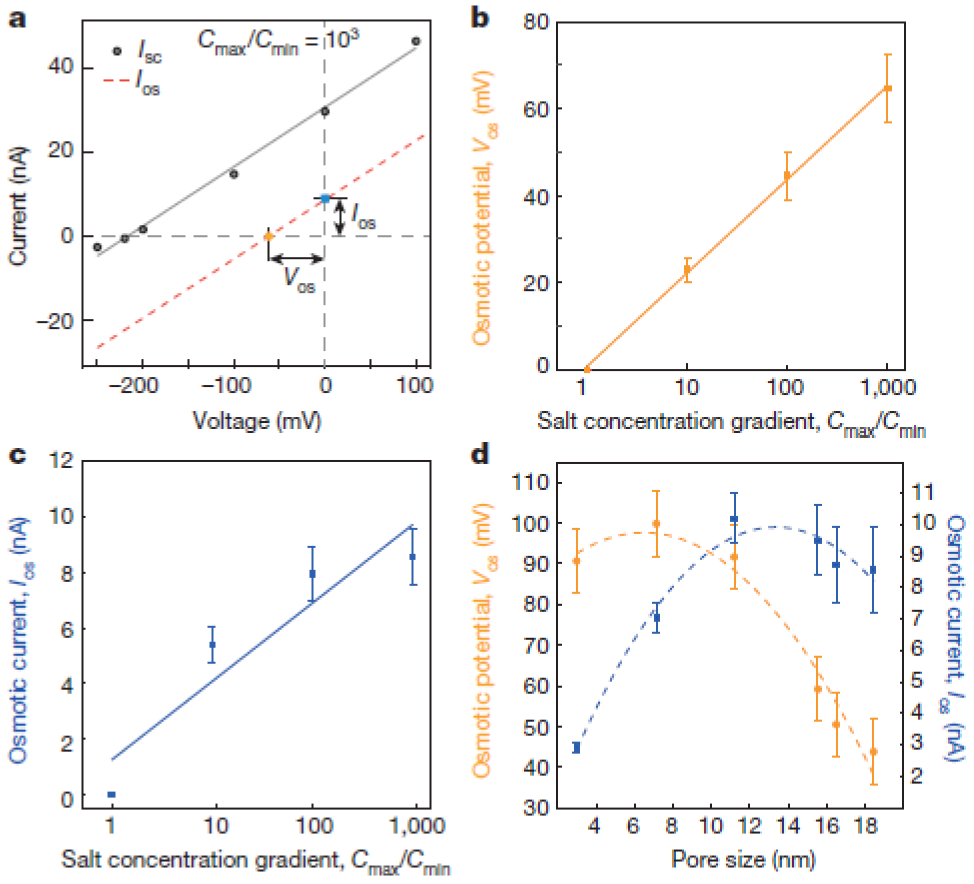


Flow slip can significantly affect the transport of ions and water along the nanochannel

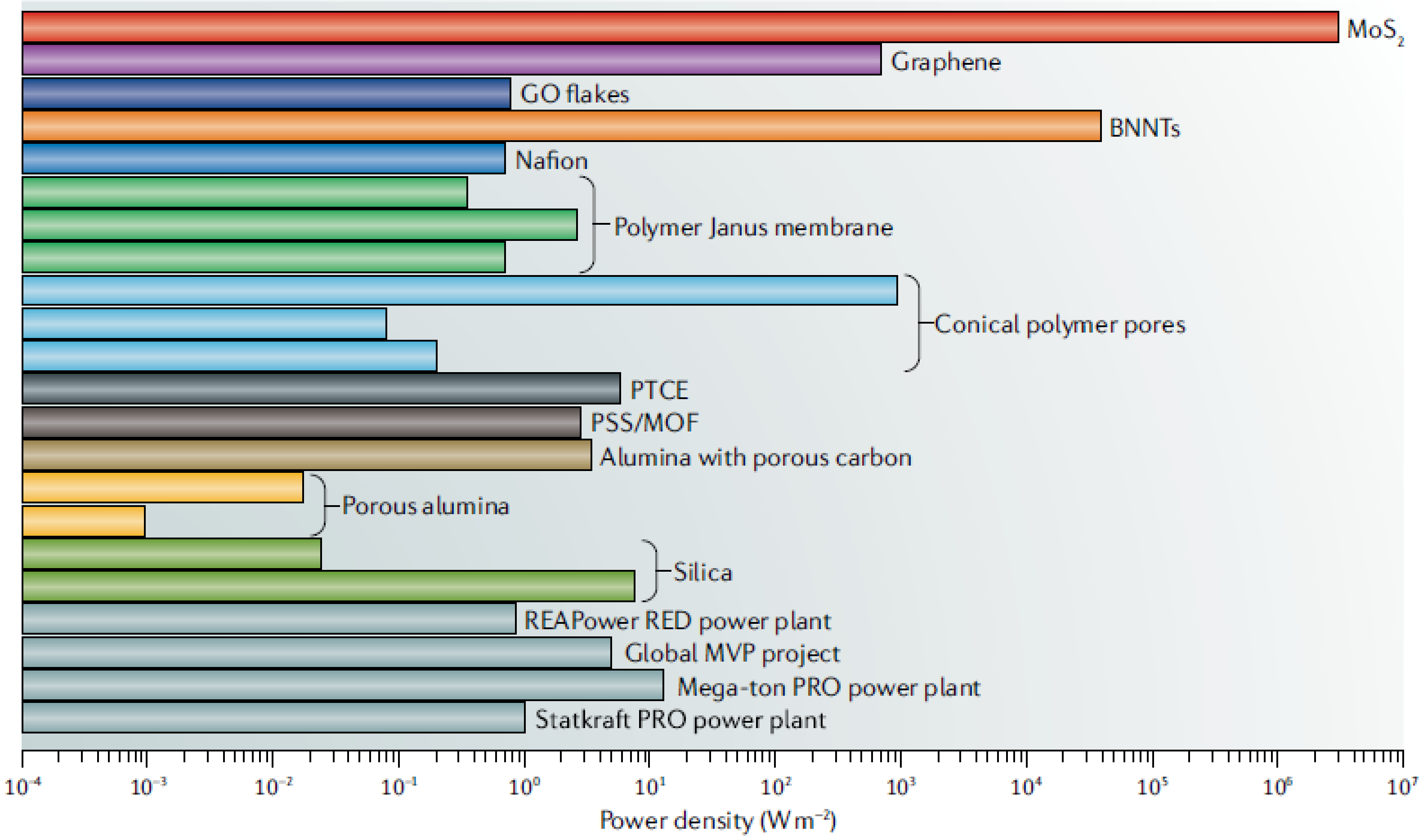
https://www.nature.com/articles/nature11876

Osmotic Potential

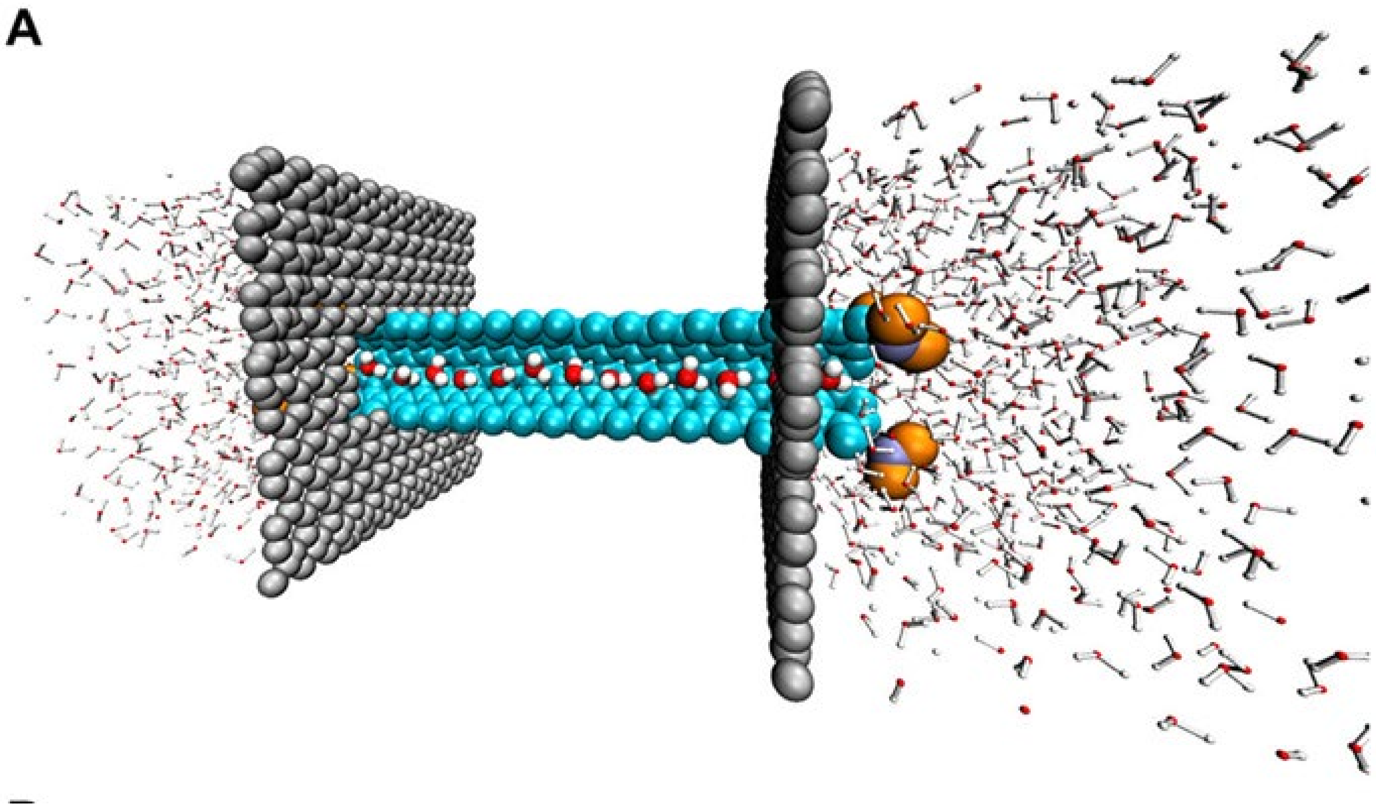




Osmotic Potential – Blue Energy



Osmotic Potential - Desalination



https://advances.sciencemag.org/content/6/38/eaba9966/tab-article-info

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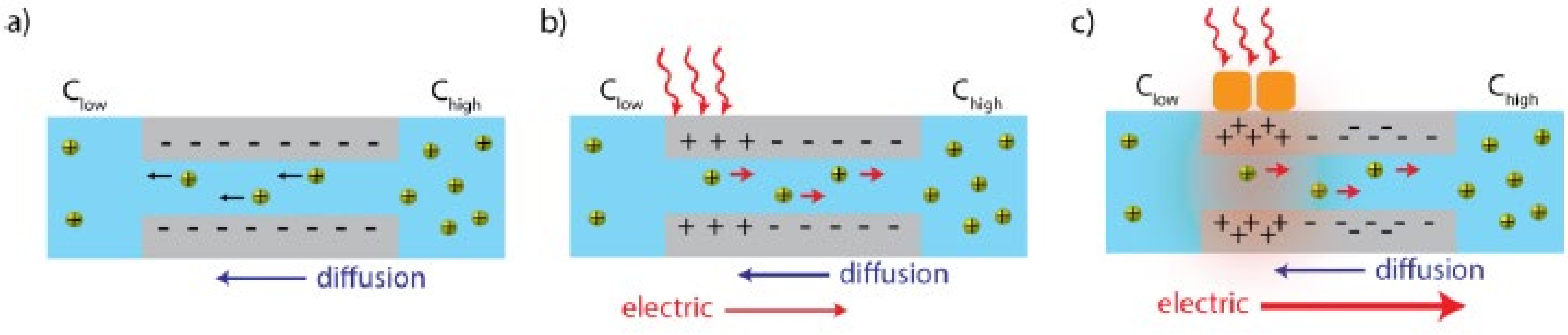
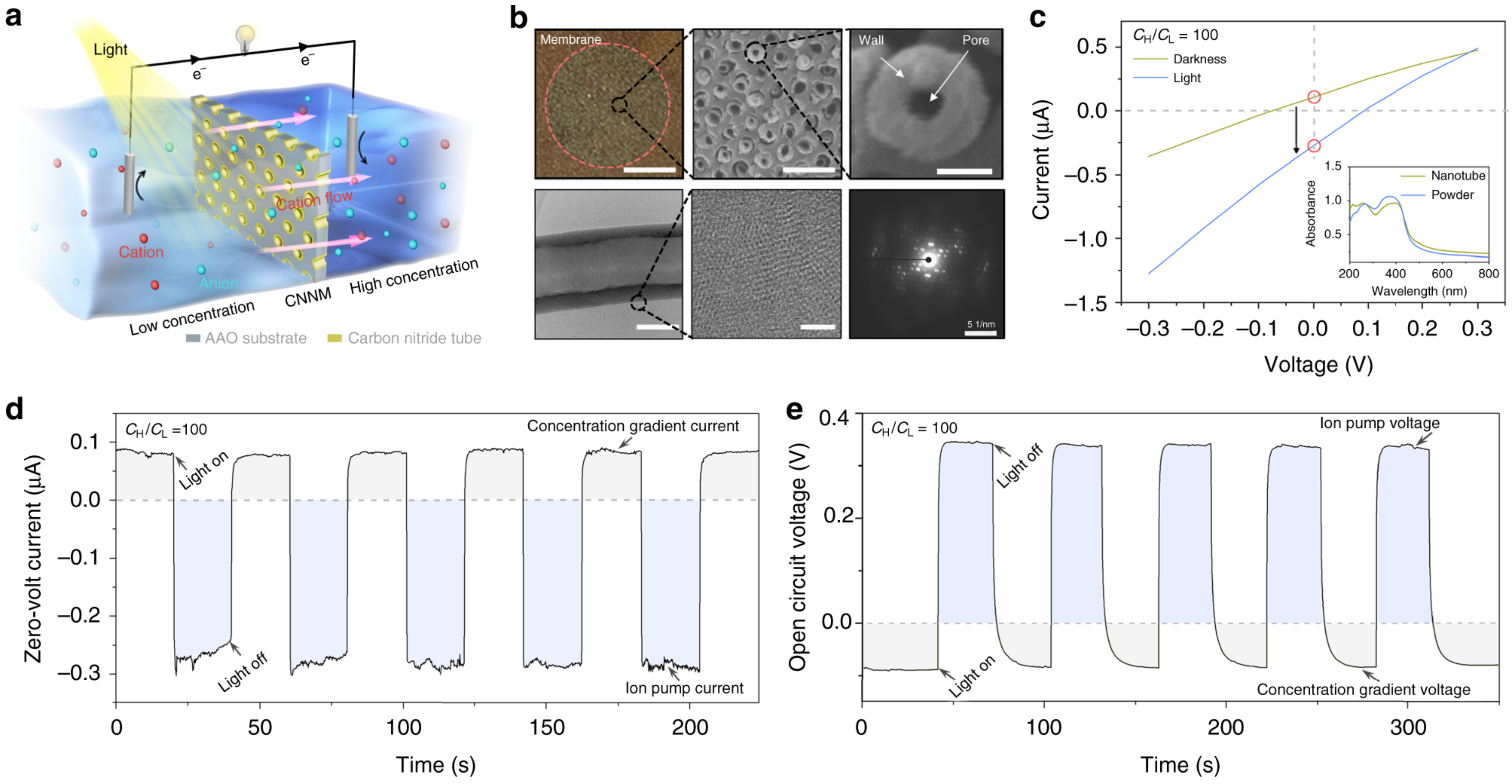
Ion Pumps



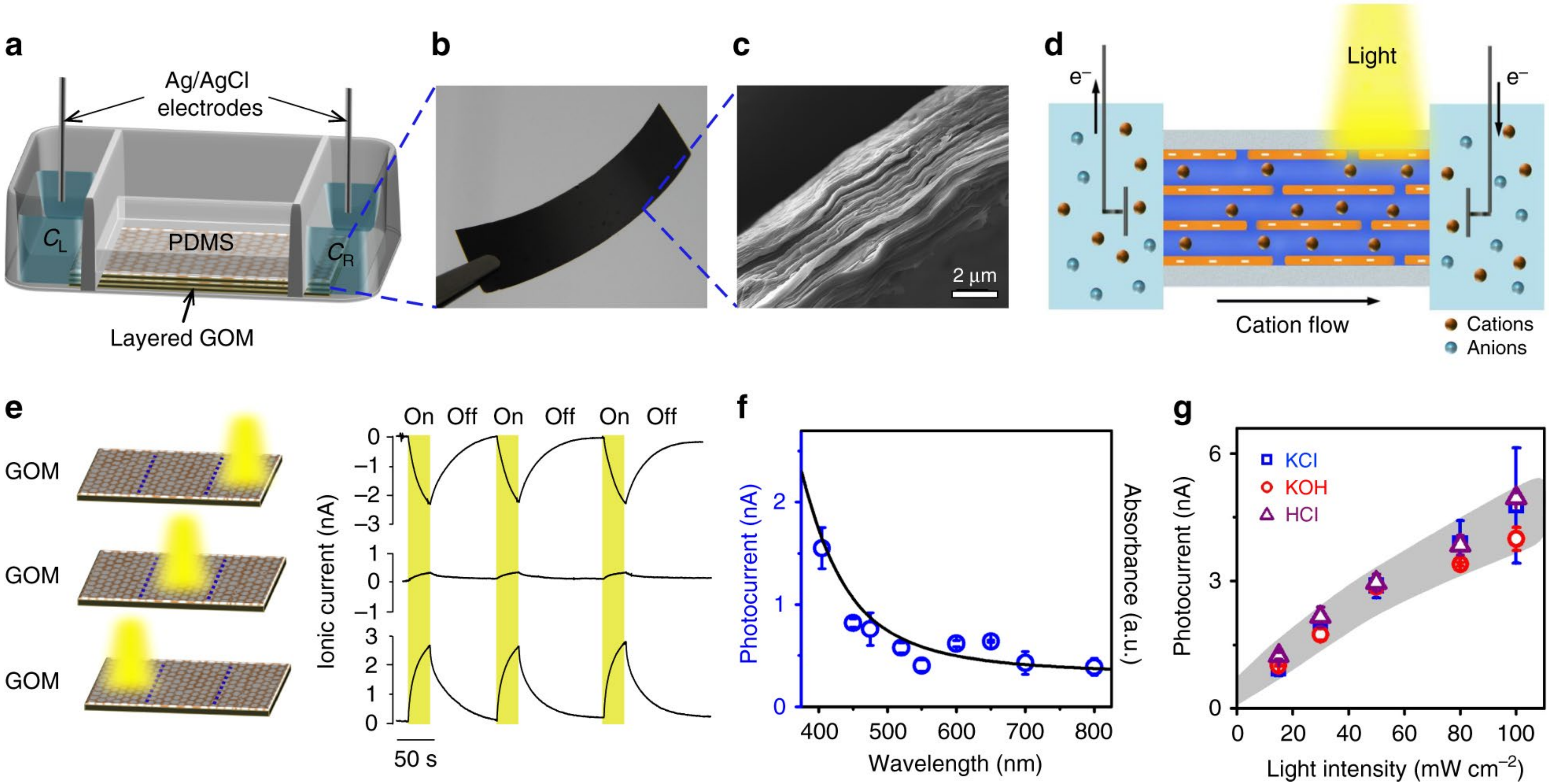
Ionic-based light-energy storage devices

Ion Pumps



https://www.nature.com/articles/s41467-018-08029-5

Ion Pumps



https://www.nature.com/articles/s41467-019-09178-x

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- Gradient potential
  - Moisture induced potential
  - Osmotic Potential : Blue energy Devices and desalination membranes (flow in nanostructures)
  - Ion pumps
- **Outlook**

Outlook – Solid-Water Interactions

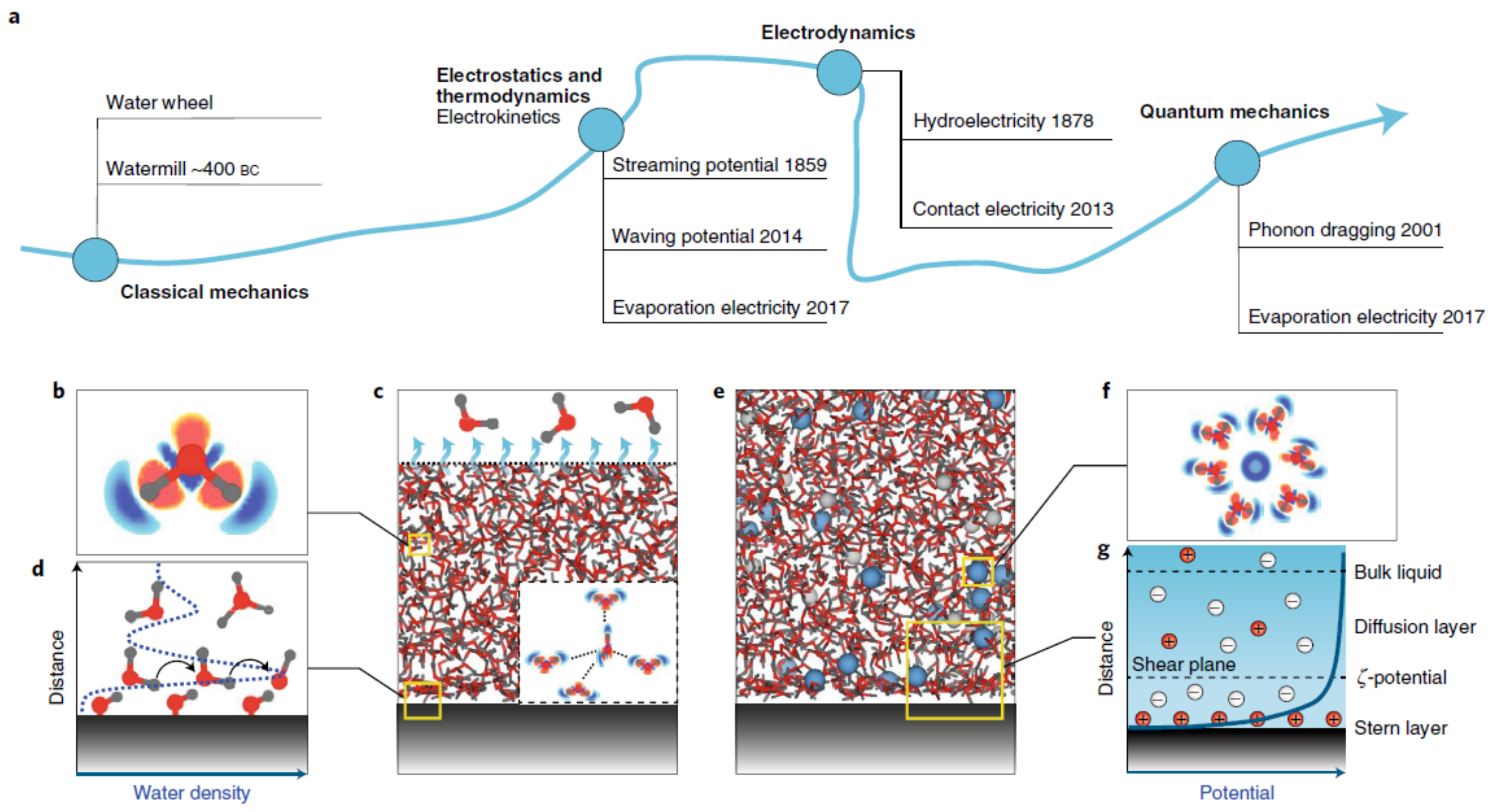
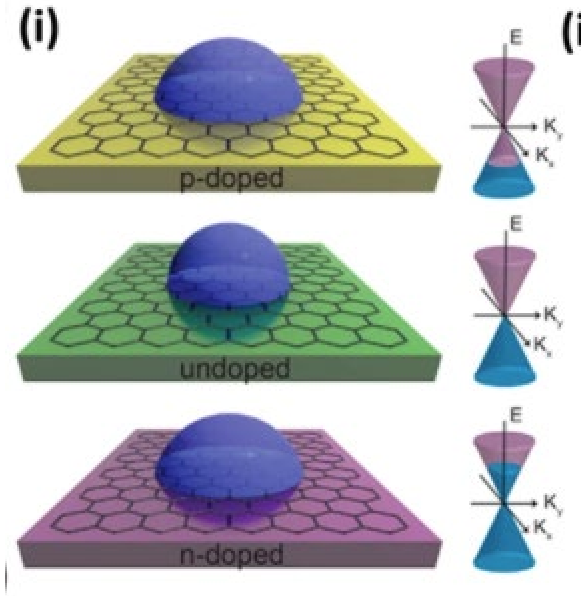


Fig. 1 | Fundamental theories of water energy harvesting and water–solid interactions. **a**, An evolutionary overview of the fundamental theories, from classical mechanics, thermodynamics and electrostatics, and electrodynamics, to quantum mechanics. Electrokinetics is a more specific theory for the corresponding electric phenomena, founded on thermodynamics and electrostatics. The timeline follows the shape of the Yellow River. Important advances of harvesting principles pertaining to each theory are listed. **b**, A water molecule is polarized owing to electron transfer from hydrogen to oxygen (from blue to red). **c**, Illustration of bulk water on a solid surface. In bulk water, each water molecule attracts four neighbours arranged in a tetrahedral coordination via hydrogen bonding (inset). The molecule is evaporated near the water surface when its hydrogen bonds are broken. **d**, Illustration of proton transport (indicated by curved tail arrows) near a solid surface terminated with hydroxyl groups. The dotted blue line is a typical water density profile near a solid surface. **e**, Ions dominate the interaction between aqueous solution and solid. The cations and anions are illustrated by blue and grey balls, respectively. **f**, Each ion is hydrated by attracting six water molecules. **g**, An electric double layer forms at the solution–solid interface, consisting of Stern layer and diffusion layer. The boundary between the diffusion and Stern layers is the shear plane, at which the potential is called the zeta potential. The blue line gives the electric potential profile near the interface.



https://www.nature.com/articles/s41427-020-0203-1

Outlook – Energy Conversion Potential

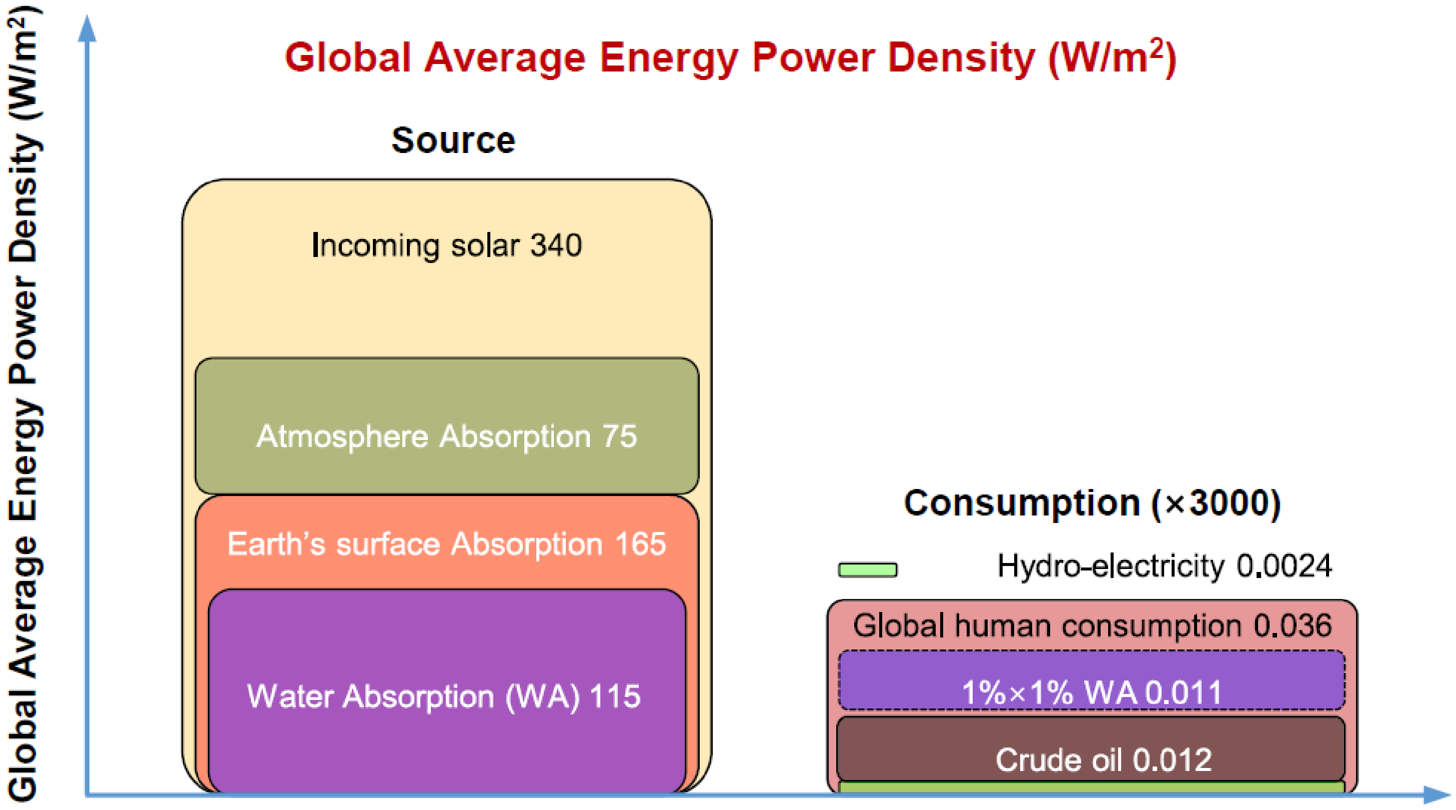


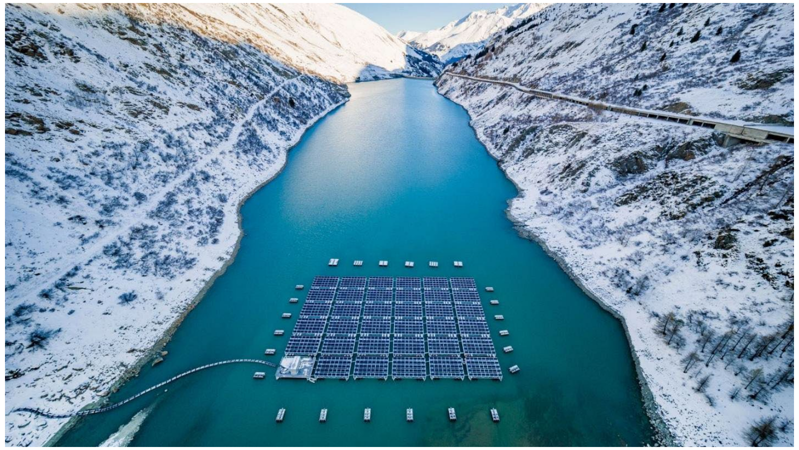
Figure 1. Global Energy Source and Consumption

The global average power density of energy source and human energy consumption (×3,000). Even if only 1% of the energy adsorbed by water can be utilized with an efficiency of 1%, it could provide nearly 1/3 of the global energy consumption by humans.

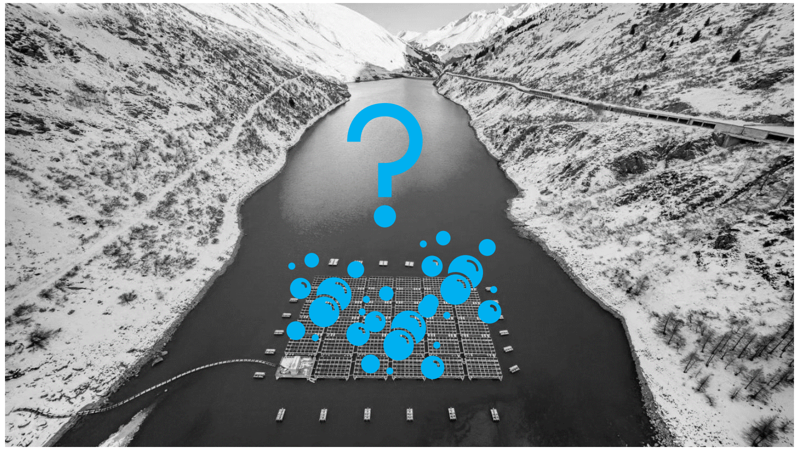
Outlook - Large-scale Utilities

Lac de Toules

Hydro-electric



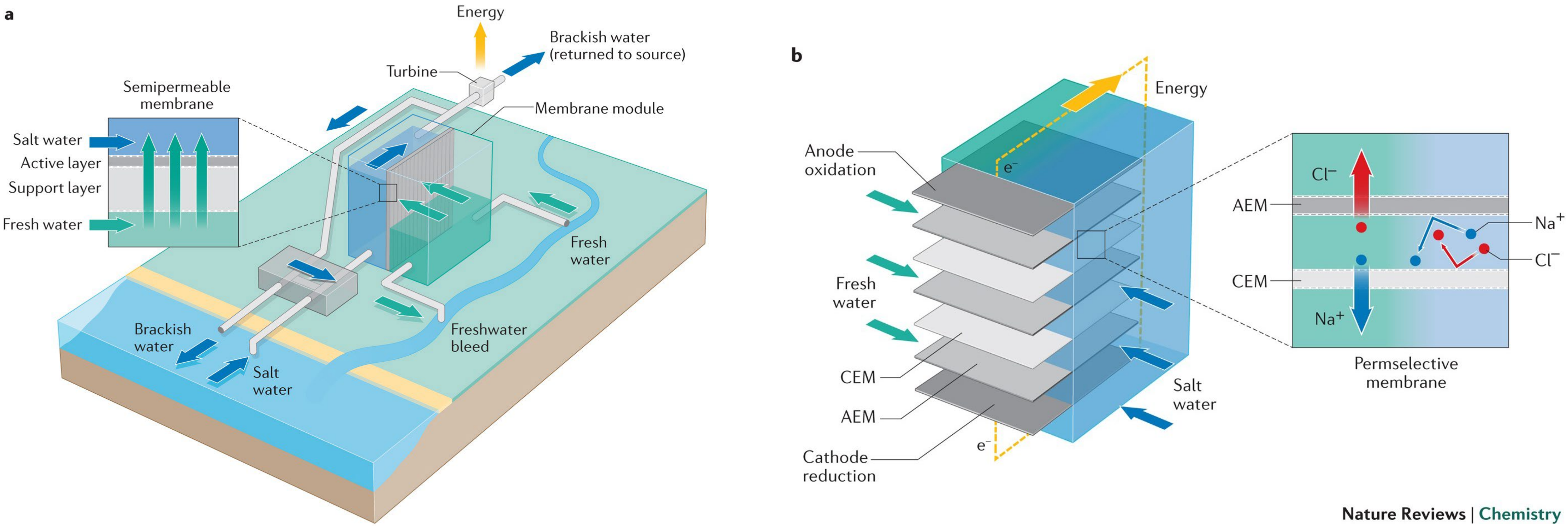
Photovoltaic



Hydrovoltaic

Getting the most energy out of water and making best use of water surfaces!

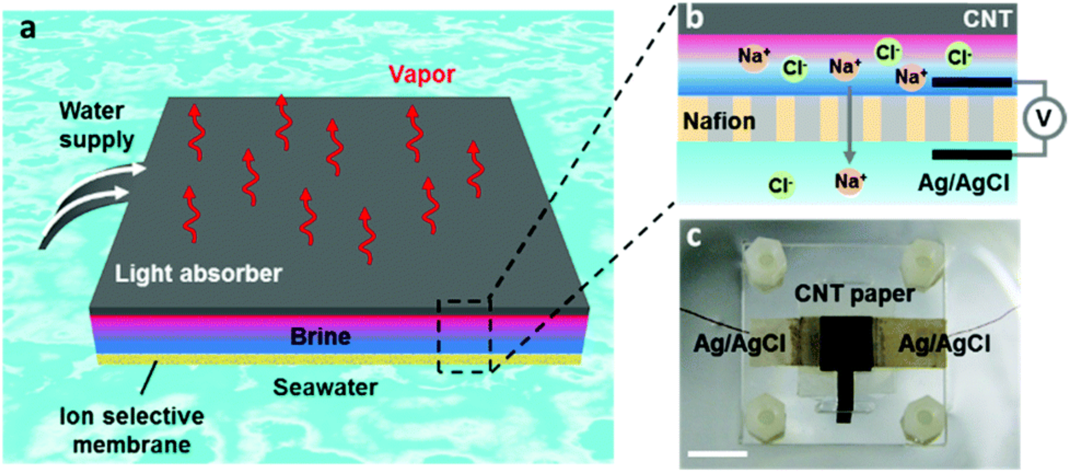
Outlook - Large-scale Utilities

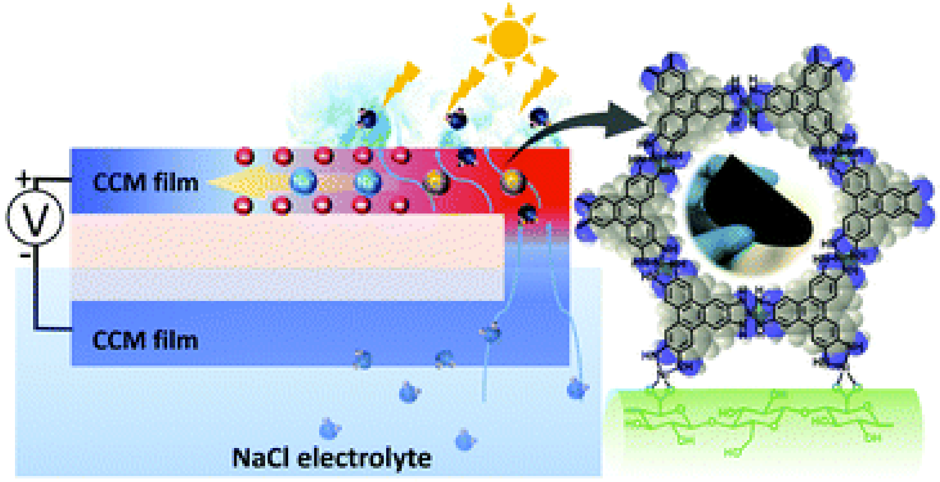


Getting the most energy out of water and making best use of water surfaces!

https://www.nature.com/articles/s41570-017-0091

Outlook - Portable devices





Combining solar purification/desalination with electricity production!

https://pubs.rsc.org/en/content/articlelanding/2017/EE/C7EE01804E#!divAbstract

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