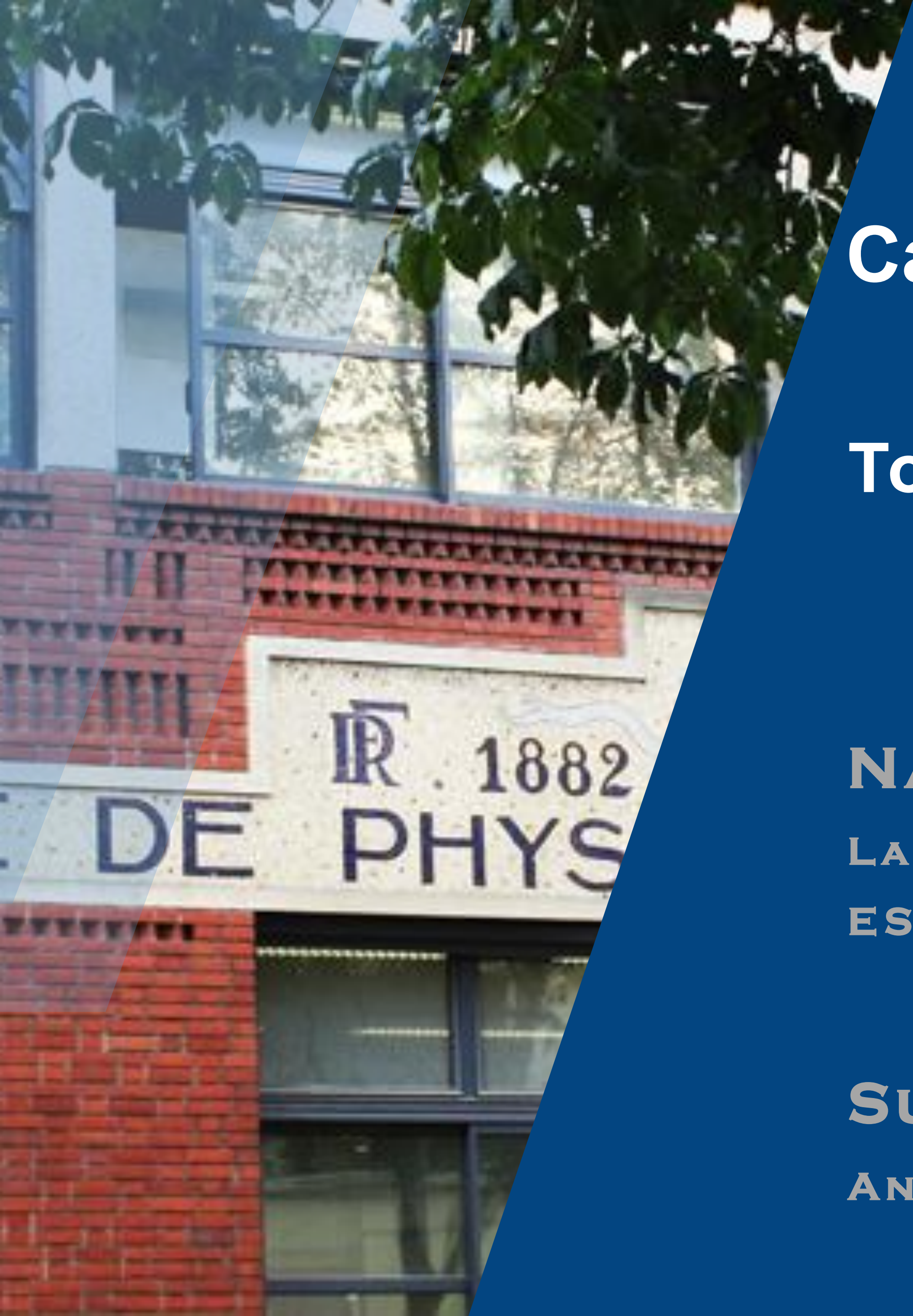

ESPCI PARIS | PSL

Capacitive reverse electrodialysis cells for osmotic energy harvesting:

Toward real brines and power enhancement

PH.D. DEFENSE **18/09/2024**

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OUTLINE

1 **Introduction**

Osmotic energy and its harvesting technologies

2 **Boosting strategy**

Towards power density amelioration

3 **Divalent ion mixing impact**

Towards real brine application

4 **pH gradient cell**

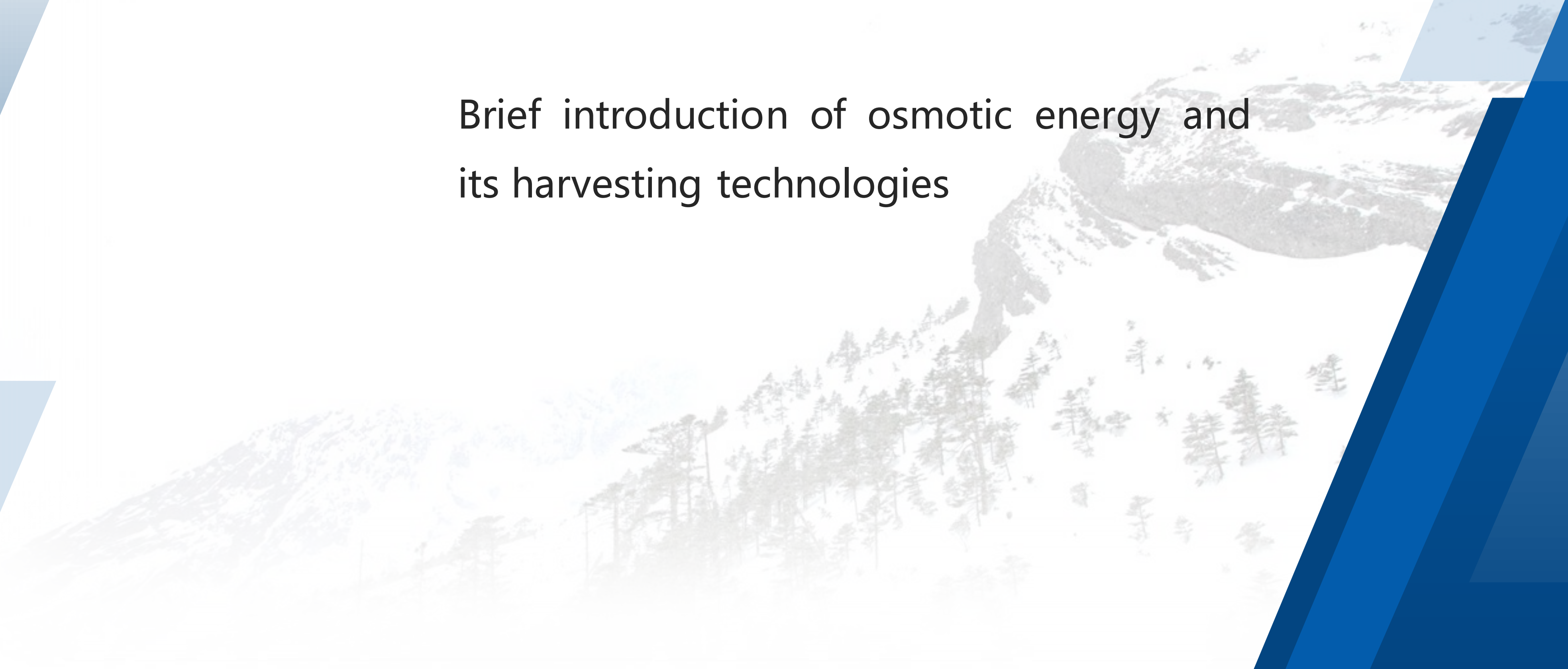
Towards pH based osmotic energy harvesting

5 **Conclusion and Perspectives**

01

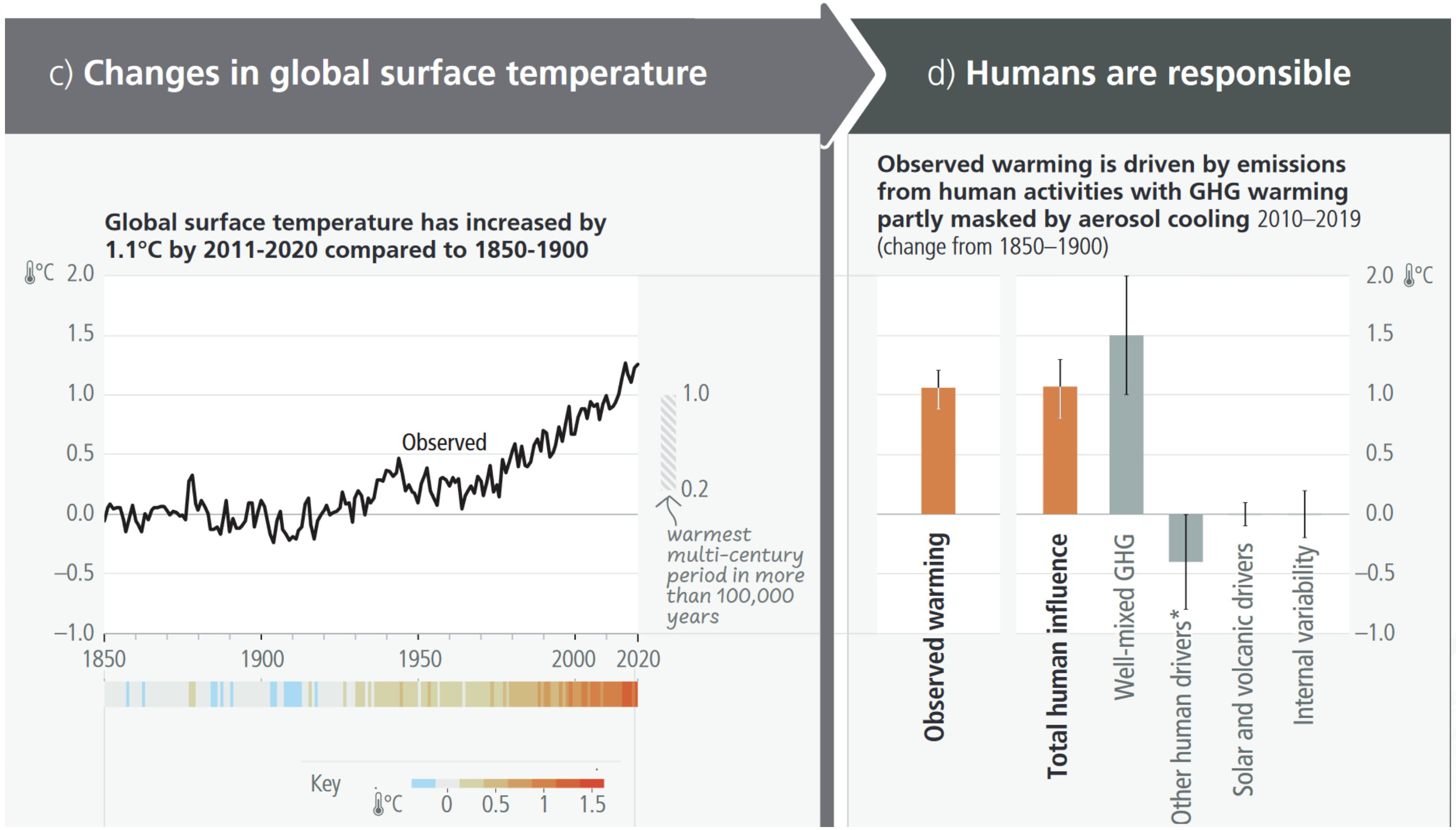
Introduction

Brief introduction of osmotic energy and its harvesting technologies



01.1 Global warming and energy crisis

Human activities are responsible for global warming

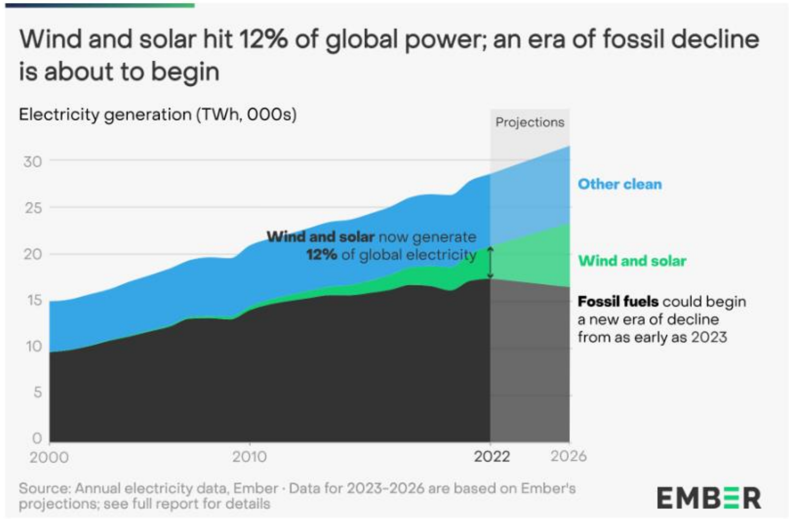

c) **Changes in global surface temperature**

Global surface temperature has increased by 1.1°C by 2011-2020 compared to 1850-1900

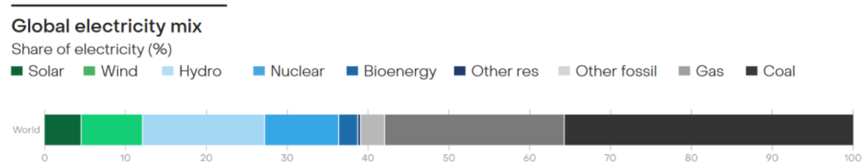
d) **Humans are responsible**

Observed warming is driven by emissions from human activities with GHG warming partly masked by aerosol cooling 2010–2019 (change from 1850–1900)

Energy transition


Wind and solar hit 12% of global power; an era of fossil decline is about to begin

Source: Annual electricity data, Ember · Data for 2023-2026 are based on Ember's projections; see full report for details


Global electricity mix

Share of electricity (%)

Sources: *IPCC 2023 report*

Ember Global Electricity Review 2023

01.1 Osmotic energy harvesting

Image Credit: Peter Bocklandt/Shutterstock.com

Osmotic Energy

The Gibbs free energy of mixing released by combining two solutions of different salinities.

Enormous potential

- **Considering all the sites**
  Estimation of 2.4 Terawatts
- **Considering easily accessible sites**
  Estimation of 0.1 Terawatts ~ 3% World electricity power

Blue Energy harvesting technologies

PRO
Pressure Retarded Osmosis

RED
Reverse Electrodialysis

Capmix
Capmixing

Sources: *Wu et al. Lab on a Chip 2023*
Wu et al. Nano Energy 2023

01.1 Osmotic energy harvesting

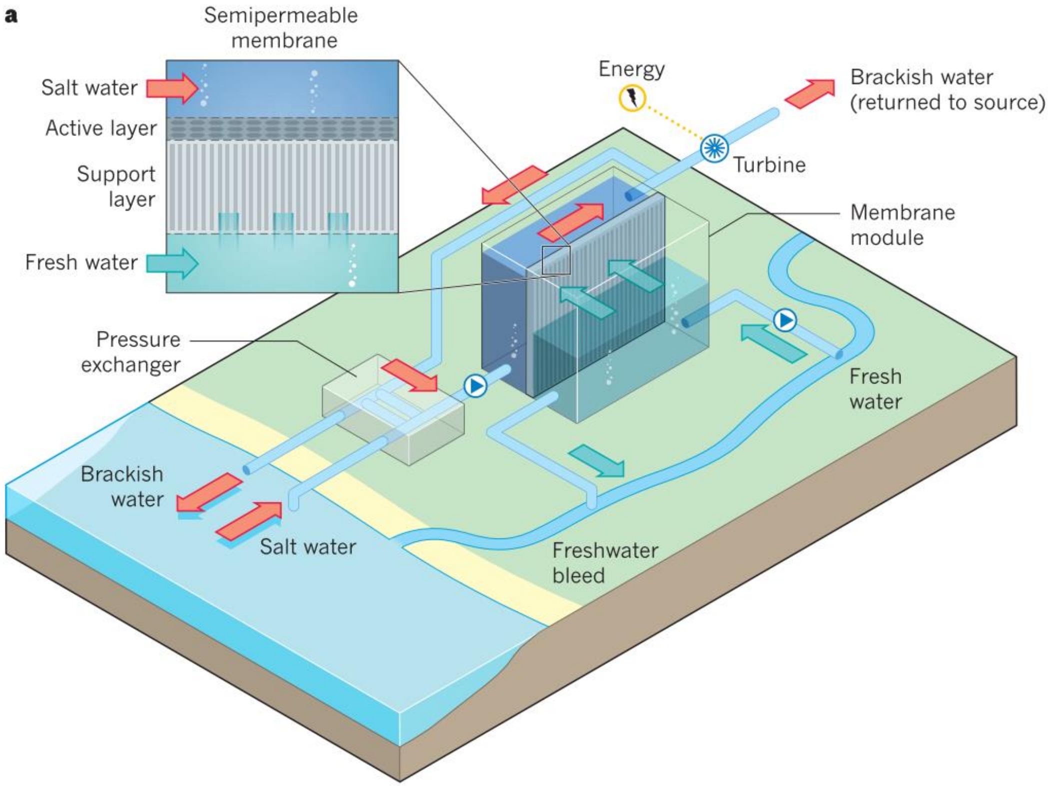


Figure 1 Energy harvesting procedure via PRO technologies

Sources: Logan, B. E. and M. Elimelech. Nature 2012

PRO Pressure retarded osmosis

Semipermeable membrane:

Free passage of water molecules

Block of passage of ions

Pressurization in salt water chamber:

Water flux from fresh water chamber to seawater chamber

Energy conversion by turbines:

Depressurization process by accessary installations (turbines)

Energy conversion from hydrostatic potential to electricity

State-of-art performance:

9 W.m^{-2} < 25 W.m^{-2} (Commercialization threshold)

High cost of accessory systems (turbines, pumps, and etc.)

01.1 Osmotic energy harvesting

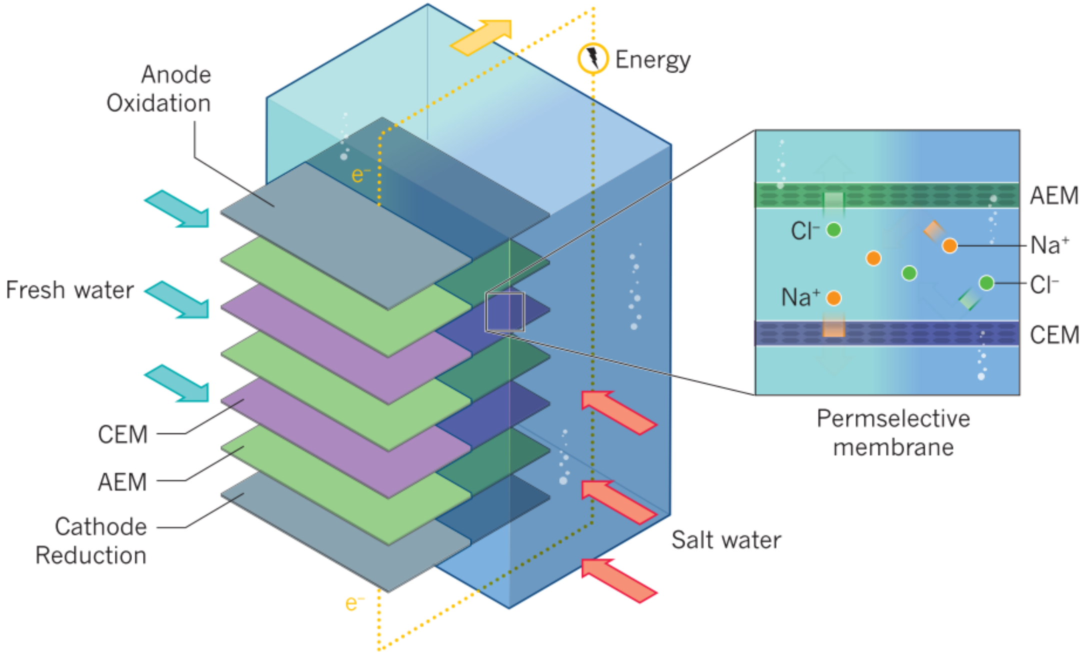


Figure 2 Working principle of energy harvesting by RED

Sources: Logan, B. E. and M. Elimelech. Nature 2012

RED Reverse Electrodialysis

Ion-exchange membrane:

Free passage of counter-ions

Block of passage of co-ions and water molecules

Directional ion flux through membranes:

Directional ion flux under osmotic effects through membranes

Ion flux from saltwater chamber to freshwater chamber

Stacks of CEM and AEM enable the voltage addition

Energy conversion by redox reactions:

Conversion of ionic flux towards electric flux by redox reactions

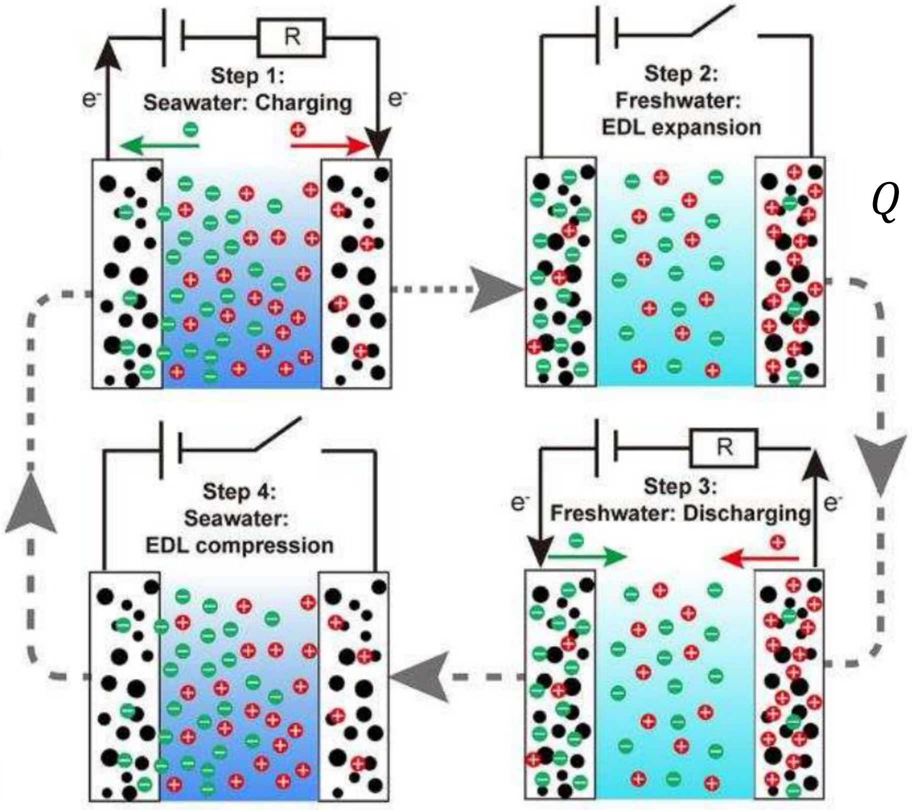
Energy conversion from osmotic potential to electricity

State-of-art performance:

Pilot-scale RED plant 0.5 W.m^{-2}

Toxic electrolytes and overpotential problems

01.1 Osmotic energy harvesting



$$Q = C.U$$

Figure 3 The 4-step energy harvesting via CDLE

Sources: Zou et al. Energy Reports 2022

Capmix

Capmixing

CDLE **(capacitive energy extraction based on double layer expansion)**

4-step process using capacitive electrodes:

Step1 Seawater compartment + electrode charging

Step2 Conversion into freshwater + EDL expansion

Step3 Freshwater compartment + electrode discharging

Step4 Conversion into seawater + EDL compression

Capacitive currents:

Conversion of ionic flux towards electronic flux by capacitive electrodes

Advantages:

Suppression of redox reaction related problems

Low cost of carbon based capacitive electrodes

State-of-art performance:

Power density ~0.1 $W.m^{-2}$

01.2 Capacitive RED (CRED)

Comparison

PRO
Pressure Retarded Osmosis

Highest power density
High cost of accessory systems

RED
Reverse Electrodialysis

High power density
Redox reaction related problems (toxic electrolytes; overpotential problems; environmental impact)

Capmix
Capmixing

Low cost; No redox reactions
Low power density

Combining RED system with capacitive electrodes:

Wonderful combination at the crossroad of RED and Capmixing : previous thesis work of Dr. Brahmi Youcef

RED
High power density
Redox reaction problems

Capmix
Low cost; No reaction
Low power density

Capacitive RED cell

- ✓ **Ion-exchange membranes ('RED')**
  - Directional ionic flux creation under osmotic effect
  - Possibility of using stacks
- ✓ **Capacitive electrodes ('Capmixing')**
  - Capacitive electrodes charging by ion adsorption
  - Avoidance of hazardous redox reactions

Sources: *Y. Brahmi and A. Colin. Energy Conversion and Management 2022*

01.2 Capacitive RED (CRED)

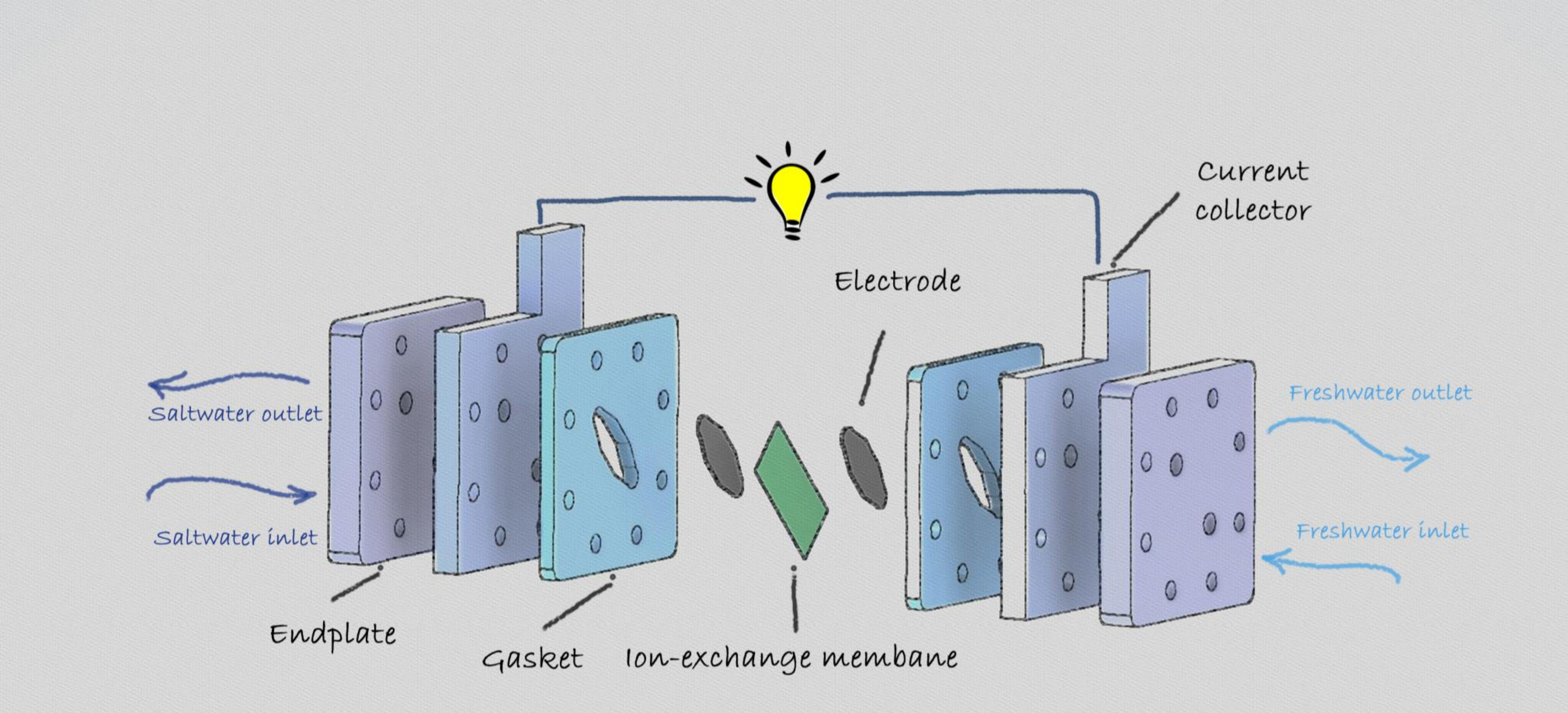


Figure 4 The design of the CRED assembly

Sources: Y. Brahmi and A. Colin. Energy Conversion and Management 2022

01.2 Capacitive RED (CRED)

Working principle

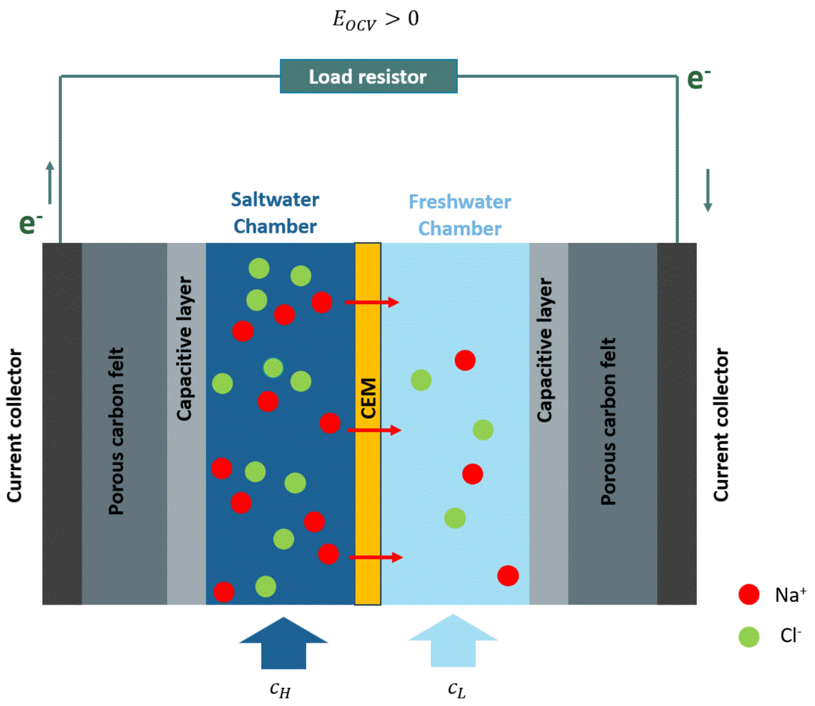


Figure 5 The working principle of the CRED system

Image Credit: Youcef Brahmi, Thesis 2021

Ion-exchange membrane CEM:

Free passage of cations (Na^+)

Block of passage of anions (Cl^-) and water molecules

Directional ionic flux:

Directional ionic flux under osmotic effects through membranes

Ion flux from saltwater chamber to freshwater chamber

OCV further enhanced by capacitive electrodes:

$$E_{ocv} = E_{mem} + E_{elec}$$

Capacitive electrodes:

Conversion of ionic flux towards electronic flux by ion adsorption

A blocking type electrode without redox reactions

01.2 Capacitive RED (CRED)

Working principle

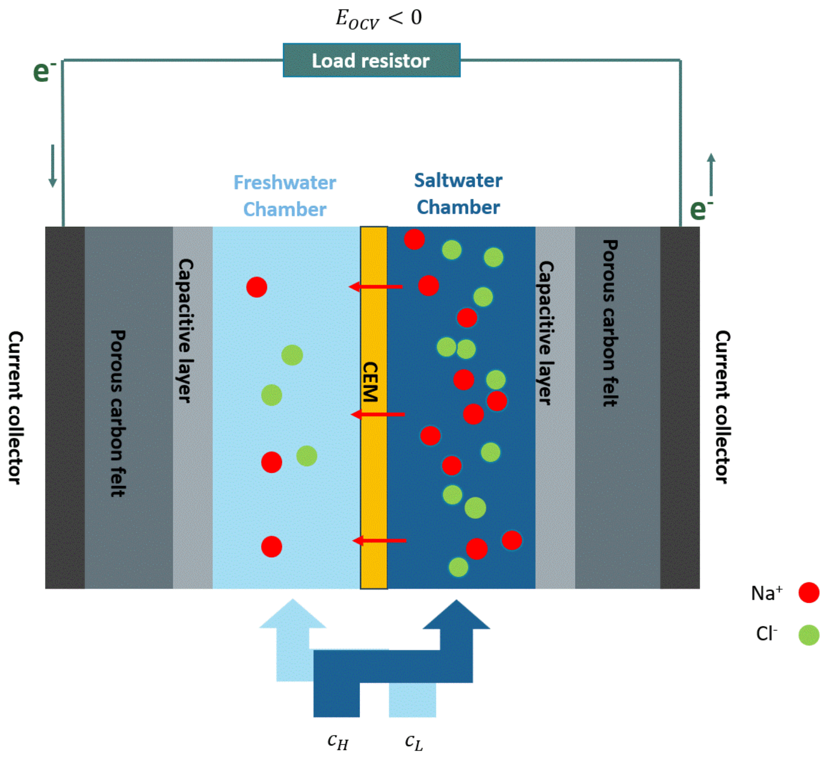


Figure 5 The working principle of CRED system

Image Credit: Youcef Brahmi, Thesis 2021

Capacitive current decay:

Ionic flux will be slowed down and eventually reaches a saturation regime

Blocking electrodes requires concentration reversal to deblock this state

Chamber switch to deblock saturation regime:

Necessity of water chamber switch to deblock the saturation

Creation of alternating periodic capacitive currents

01.2 Capacitive RED (CRED)

Power density measurement

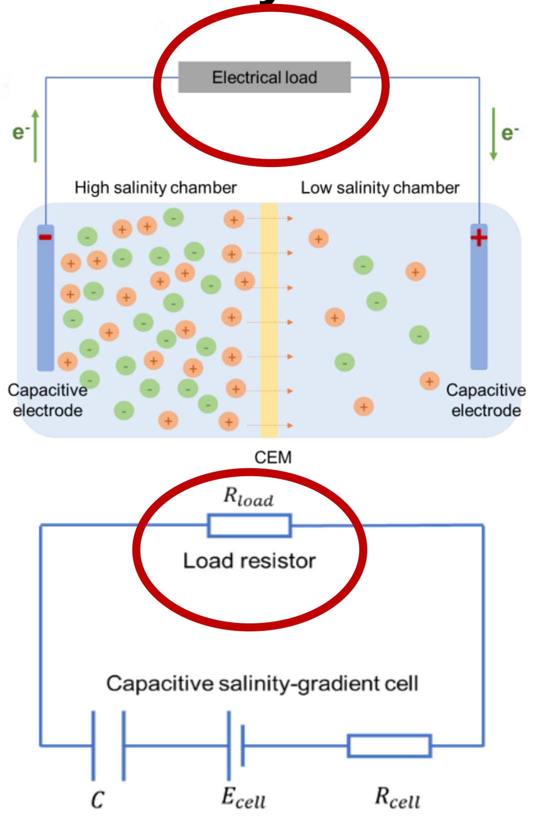


Figure 6 Direct connection of the resistor to the CRED system for power density measurement

Cell-Resistor circuit

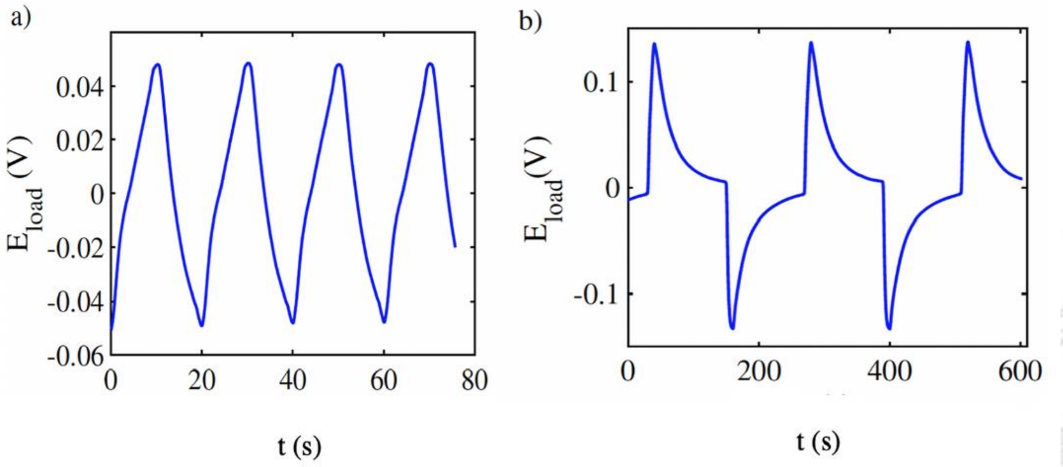
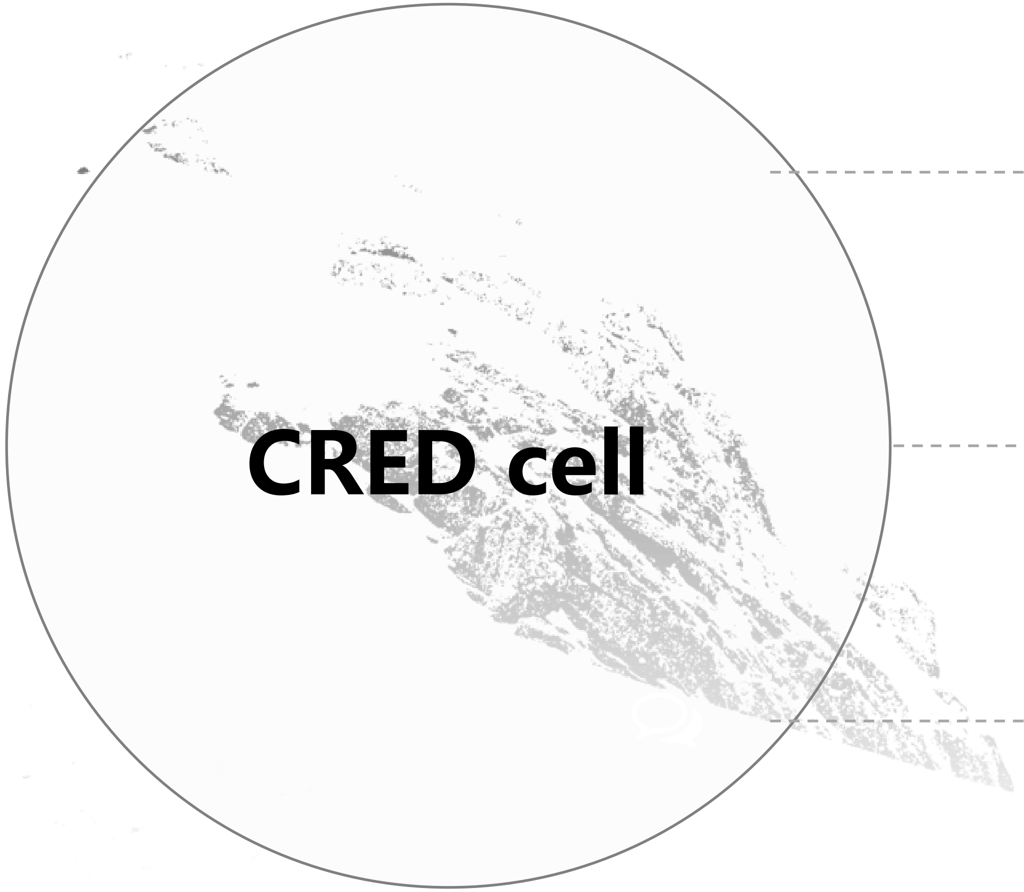


Figure 7 Resistor voltage measurement curves as a function of time for different resistance.

$$P_{nb} = \frac{1}{S.T}\int_0^T \frac{E_R(t)^2}{R_{load}}\,dt$$

Sources: *Brahmi, Y.; Colin, A. Energy Convers. Manag. 2022*

Summary



01 CRED:
Reverse electrodialysis + Capacitive electrodes

02 Alternating periodic output (switching)

03 Direct connection to resistor for power density measurement

04 Power density amelioration ?

05 Lack of study in real world solutions ?

06 Generalization in other forms of osmotic energy ?

01.3 Thesis objective

Objective:

Investigate the fundamental mechanism of the CRED system, aiming to enhance its energy performance and broaden its range of applications.

Towards Power density amelioration

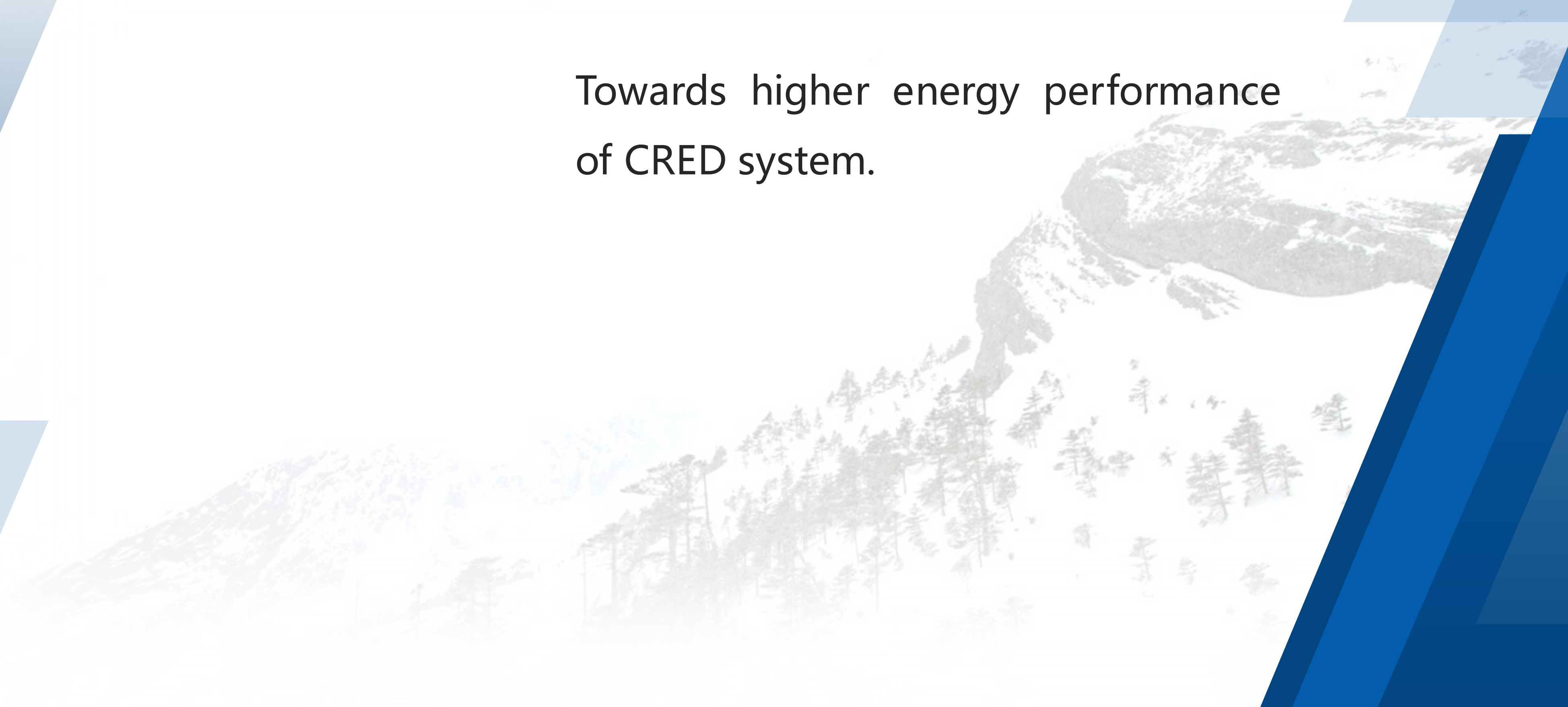
Towards Real brines

Towards pH gradient based osmotic energy harvesting

02

Boosting strategy

Towards higher energy performance of CRED system.



02.1 Preamble

E_{ocv} ↗

Membrane selectivity
Optimized electrode
Salinity gradient
...

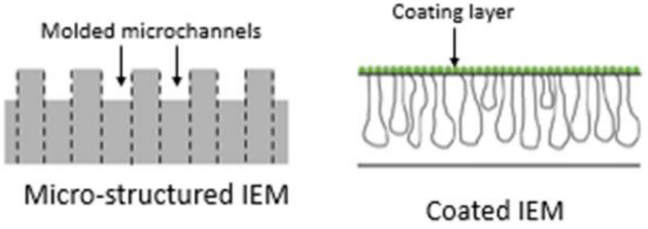
$$P_{max} = \frac{E_{ocv}^2}{4R_{cell}}$$

R_{cell} ↘

Freshwater chamber
Membrane resistance
Polarization effect
...

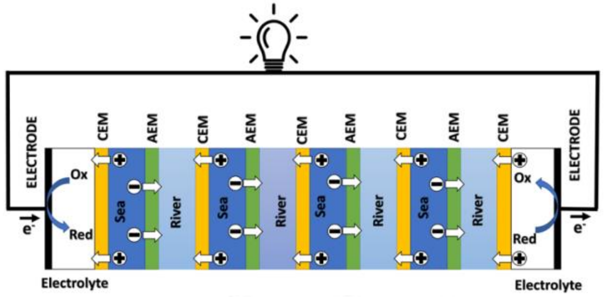
Membrane Design

Abidin et al. Desalination 2022



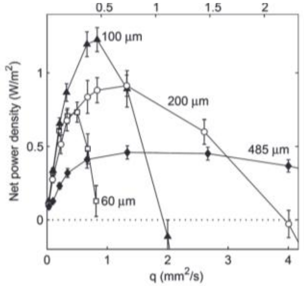
RED stacking

Wu et al. Lab on a Chip 2023



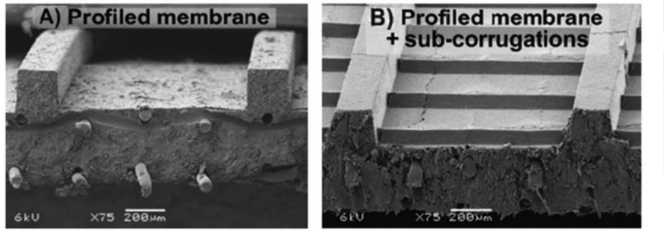
Inter-distance optimization

Vermaas et al. Environmental Science & Technology 2011



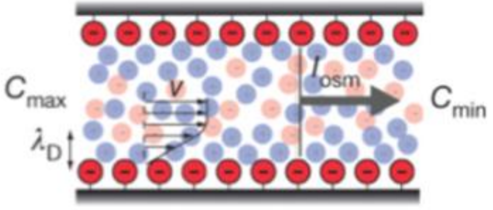
Local mixing

Vermaas et al. Journal of Membrane Science 2011



Nanopore RED

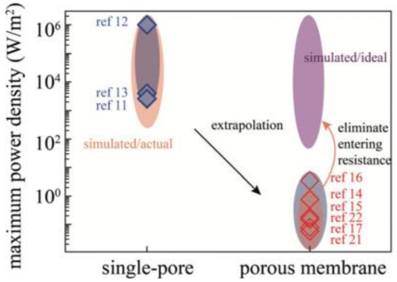
Siria et al. Nature 2013



Diffusio-osmotic streaming current

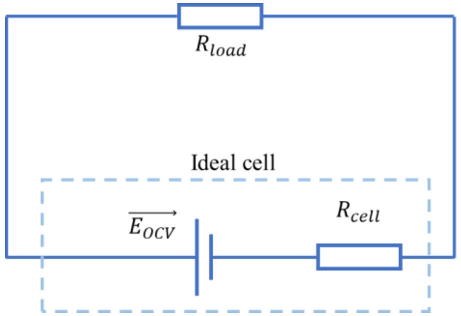
Scale up difficulty

Gao et al. Small 2019



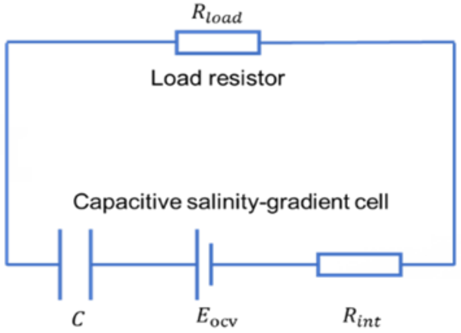
02.1 Preamble

Ideal cell equivalent circuit



$$P_{max} = \frac{E_{ocv}^2}{4R_{cell}}$$

CRED cell equivalent circuit



$$P_{Capa} \sim 60\%\ P_{max}$$

Objective:

- Power density enhancement of capacitive cells
- Optimization of the collection of an ionic current and its transformation into an electric current using a capacitive electrode.

Boosting Principle

Sources: Y. Brahmi and A. Colin. Energy Conversion and Management 2022

02.2 Boosting strategy - Principles

Cell-Booster-Resistor circuit

Boosting system:

An alternating voltage power supply synchronized to the switching period of the salinity-gradient cell.

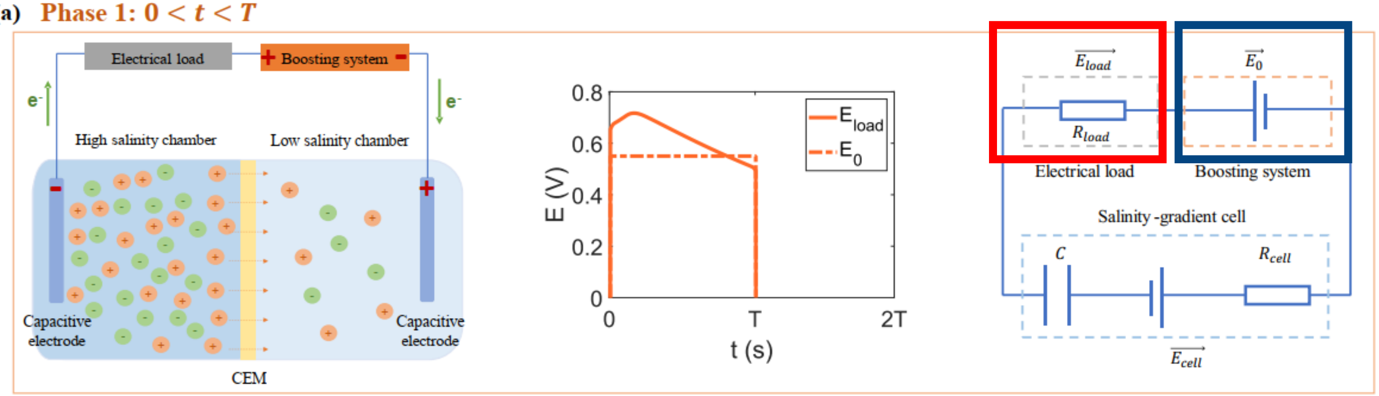
Net power density calculation:

$$P_{b-gross} = \frac{1}{S.T}\int_0^T \frac{E_R(t)^2}{R}\,dt$$

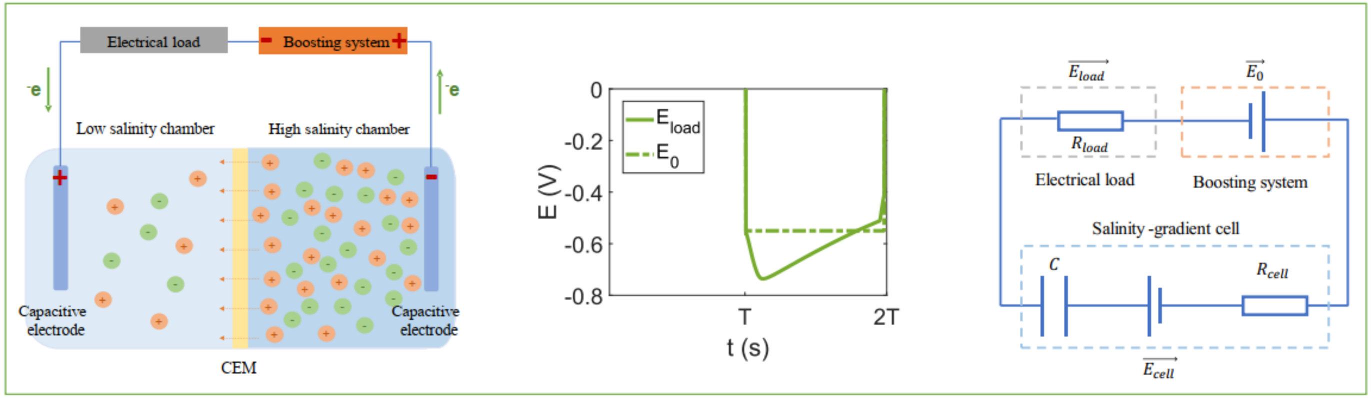
$$P_{b-boost} = \frac{1}{S.T}\int_0^T E_0(t).I(t)\,dt$$

$$P_{b-net} = P_{b-gross} - P_{b-boost}$$

(a) Phase 1: $0 < t < T$



(b) Phase 2: $T < t < 2T$



Sources: *Wu et al. Environmental Science & Technology 2023*

02.2 Boosting strategy - Principles

$$P_{b-net} = P_{b-gross} - P_{b-boost}$$

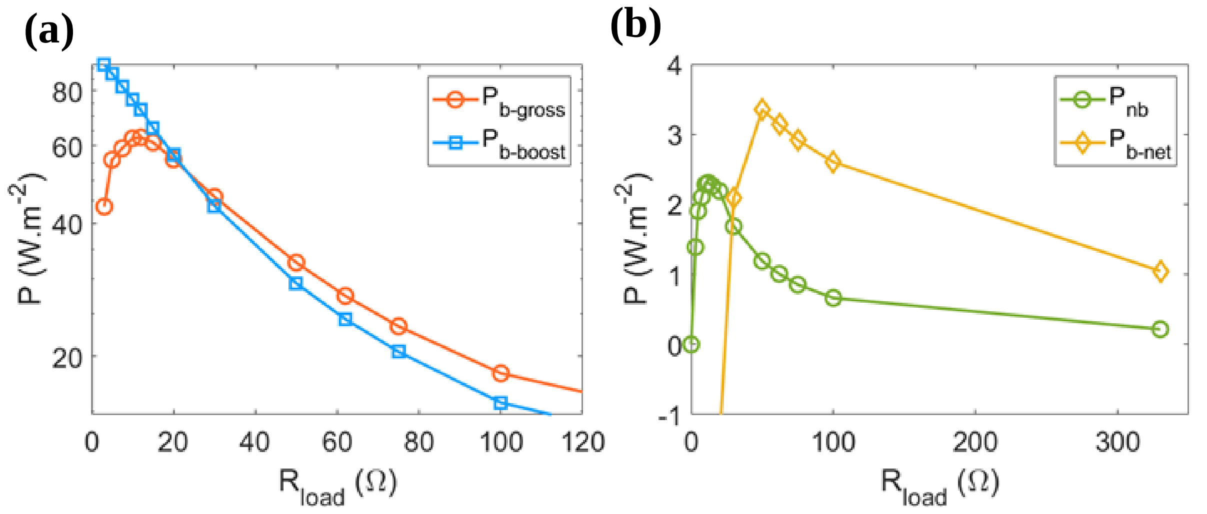


Figure 8 Salinity gradient of 0.17 mol.L^{-1} and 5.17 mol.L^{-1}, flow rate of 10 mL/min, switching period of 45s, cation exchange membrane of Nafion 117 and boosting voltage of 0.8V. The chronovoltammetric measurement of E_{load} illustrated in (a) is for load resistance of 50 Ω.

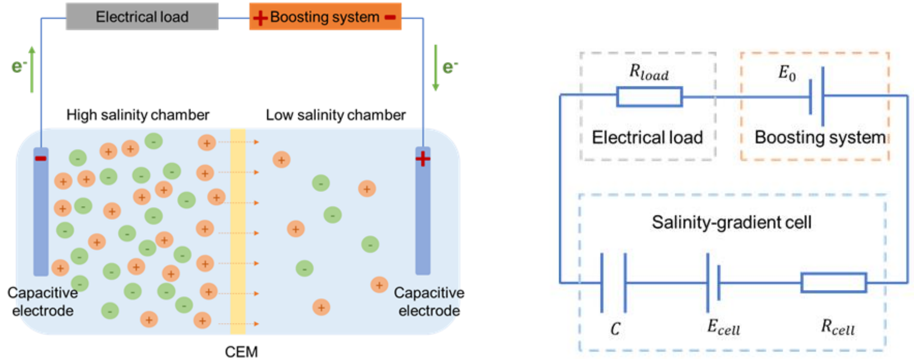
P_{nb} Non-boosting Power density	P_{b-net} Boosting power density	Gain
3.29 W.m^{-2}	5.26 W.m^{-2}	**59.8%**

Sources: *Wu et al. Environmental Science & Technology 2023*

02.3 Boosting strategy - Models

Theoretical models by equivalent R-C circuits

Cell-Booster-Resistor circuit



$$(R_{load}+R_{cell})I(t)+\frac{q(t)}{C}=E_{mem}(t)+E_c(t)+\ E_0(t)$$

$$P_{th}=\frac{1}{S.T}\int_0^T I(t)^2\ R\ dt$$

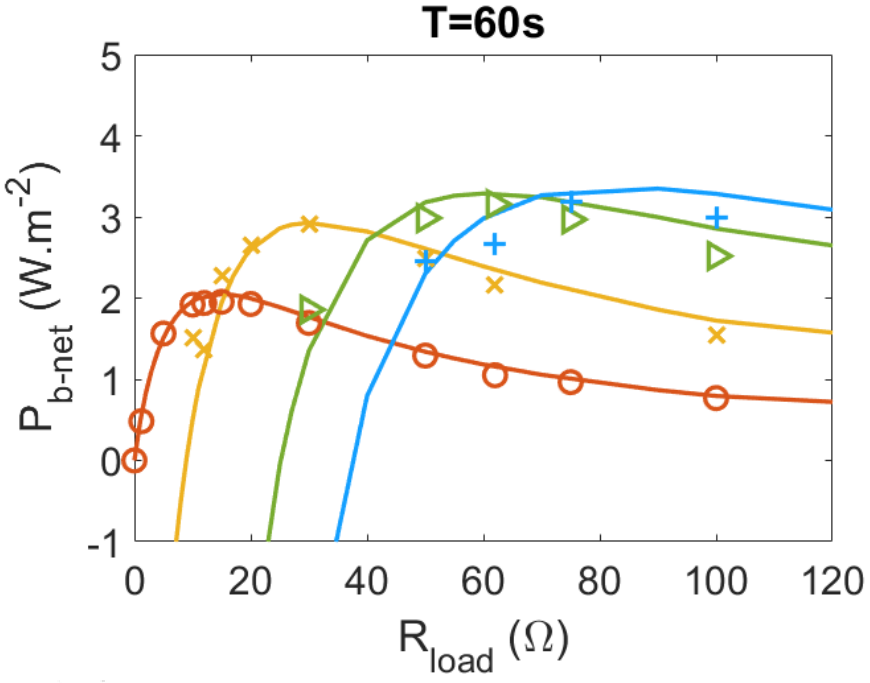
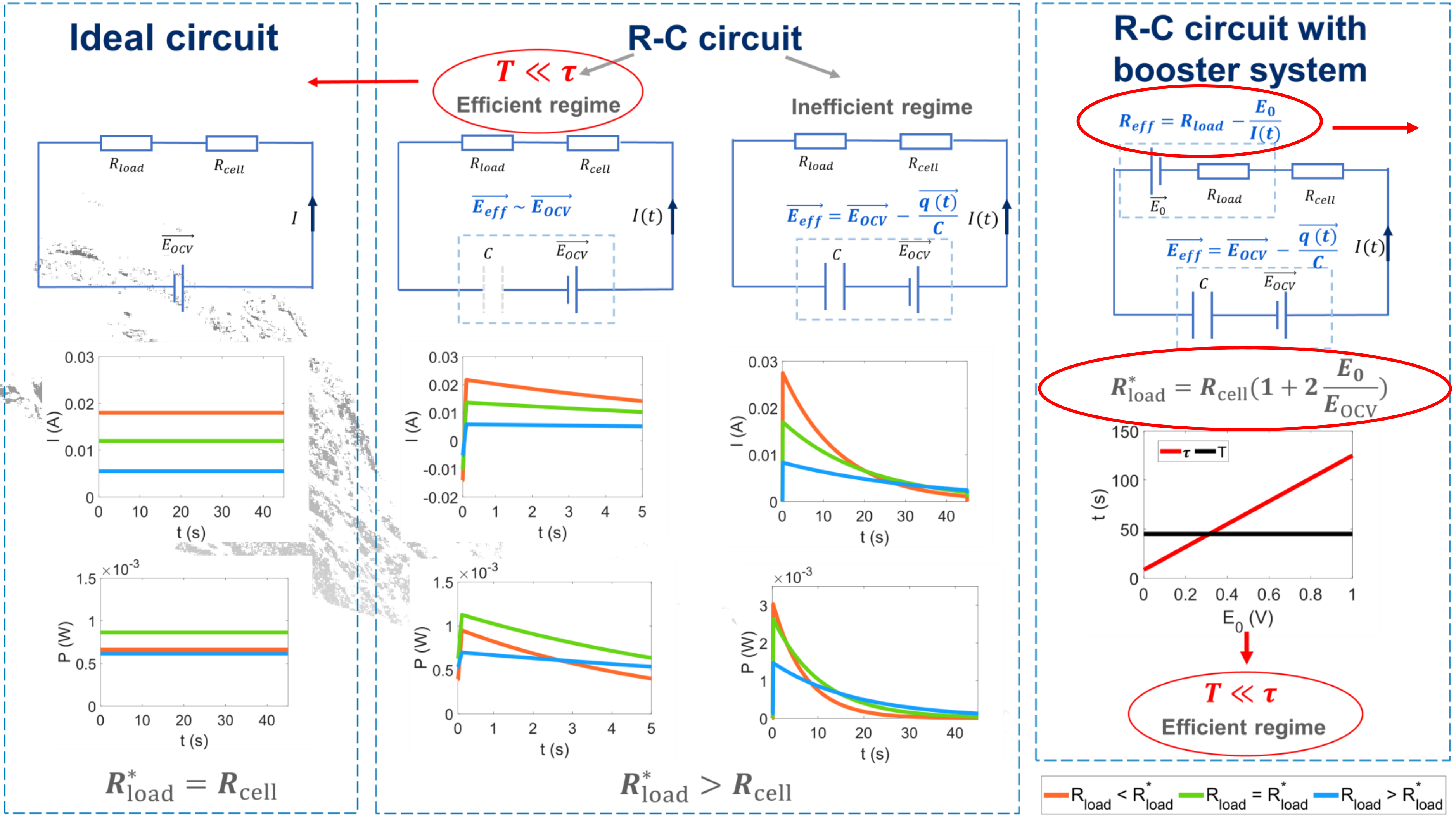


Figure 9 Comparison between theoretical model prediction and experimental data of the cell-resistor circuit and cell-booster-resistor circuit. Salinity gradient of 0.17 mol.L^{-1} and 5.17 mol.L^{-1}, flow rate of 10 mL/min, switching period of 60s, cation exchange membrane of Nafion 117 , and various boosting voltages.

Sources: *Wu et al. Environmental Science & Technology 2023*

02.4 Boosting strategy - Mechanism



$$\frac{E_{OCV}^2}{4R_{cell}}$$

Sources: *Wu et al. Environmental Science & Technology 2023*

02 Summary

Boosting principle

01 Boosting system: electrical signal in phase with switching period

02 Maximum net power density of 5.2 W/m^2 reaching over 90% of P_{max}

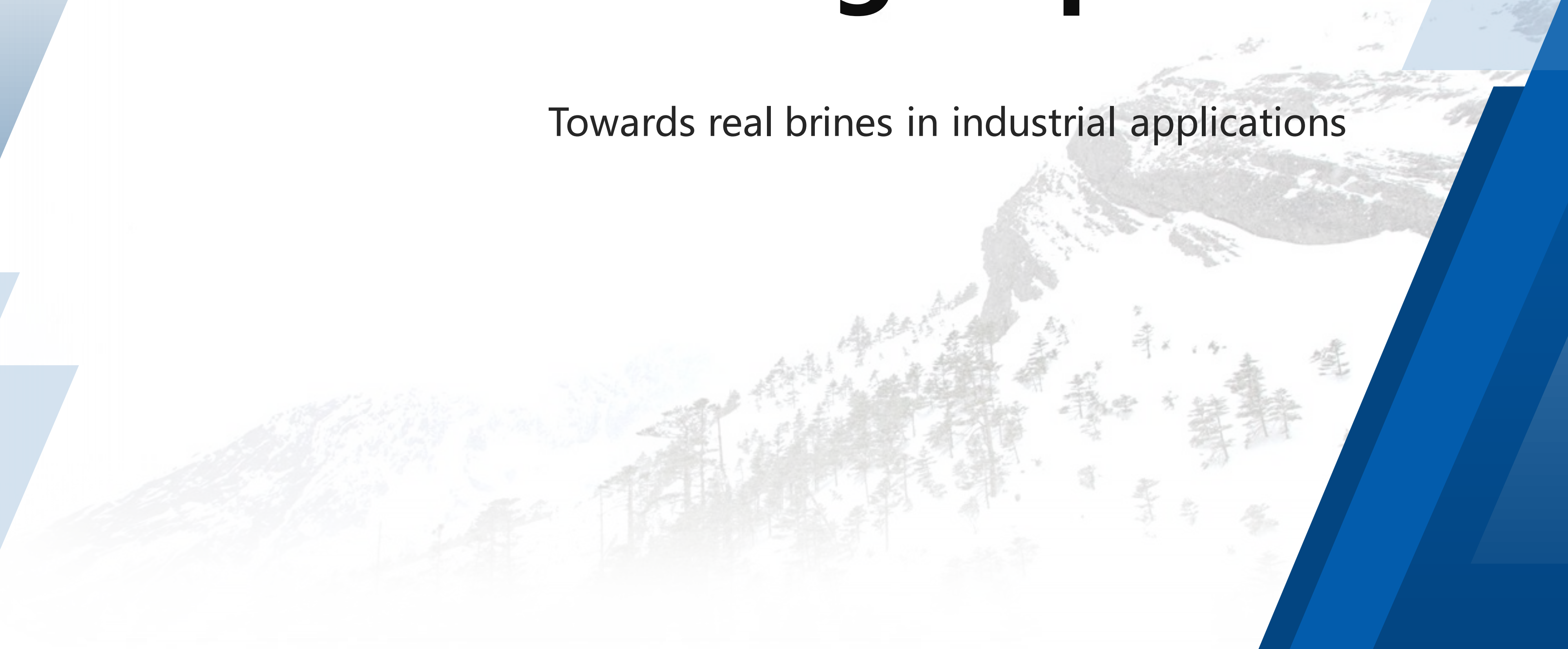
03 Agreement between experimental data and theoretical model

04 Underlying mechanism

03

Divalent ion mixing impact

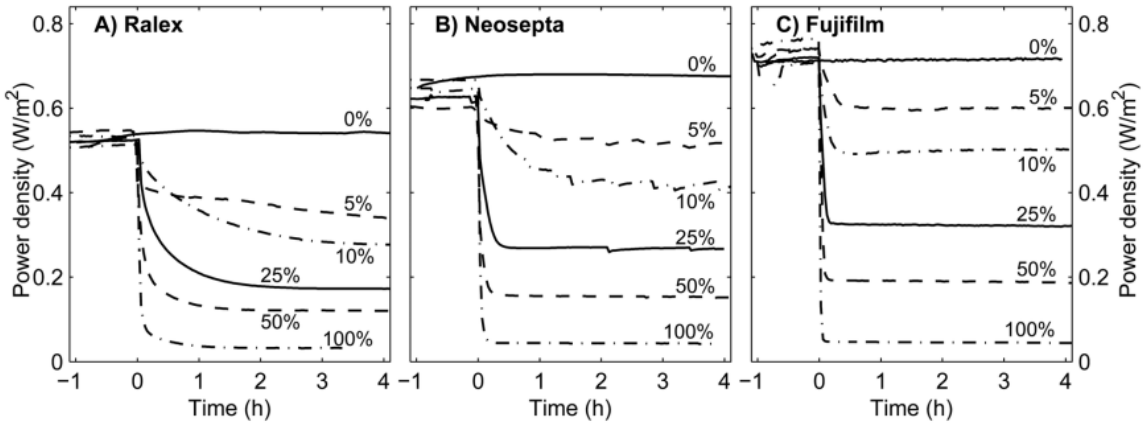
Towards real brines in industrial applications



03.1 Preamble

Towards complex solutions:

Mixing complex multi-valance ions inside the solutions injected in **RED systems**



Detrimental power density loss due to complex ion mixing

Reported both at lab and industrial scale

RED: 75% power density drop (50% of divalent ions)

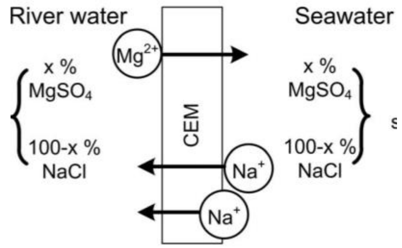
Sources: Vermaas et al. Energy & Environmental Science 2014
Veerman et al. Environmental Science & Technology 2010
Moreno et al. Journal of Membrane Science 2018
Tedesco et al. Journal of Membrane Science 2015

Uphill effect:

- Ion valence difference results in differed membrane voltage

$$E_m = \frac{\alpha RT}{z_i F} log \frac{a_{i,1}}{a_{i,2}} \qquad E_{m,monovalent} = 2E_{m,divalent}$$

- Emergence of a reversed transportation of multivalent ions against the concentration gradient



Membrane poisoning:

- Trapping of multivalent ions in the membrane
- It results in membrane selectivity decrease and electrical resistance increase.

02.1 Preamble

Current studies on CRED:

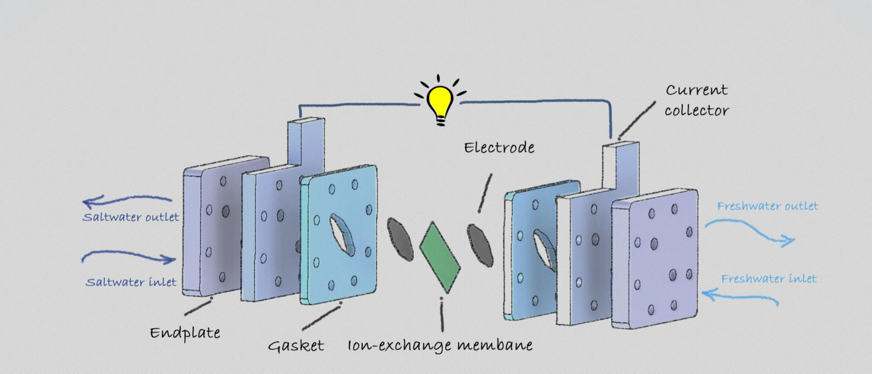
- System establishment and working principle
- Power density enhancement and mechanism
- **All studies are conducted using artificial NaCl solutions**

Objective

- Systematic study of CRED system performance under divalent ion mixing solutions
- Underlying mechanism analysis
- Economic analysis of CRED system towards industrial applications

03.2 Materials and methods

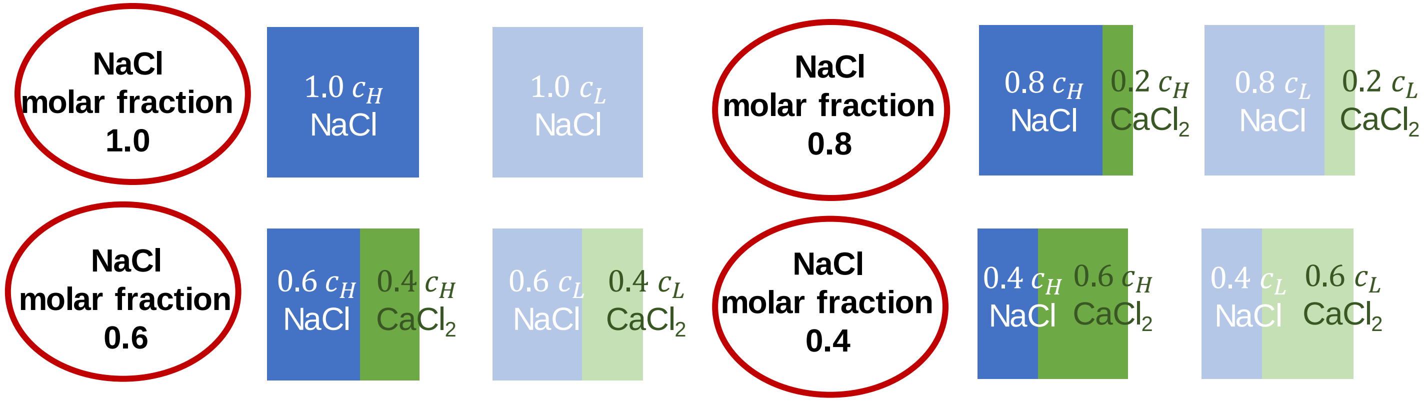
CRED Cell



Sources: Y. Brahmi and A. Colin. Energy Conversion and Management 2022

Complex ion mixing solutions

Mixture of monovalent ions (NaCl) with divalent ions ($CaCl_2$ or $MgCl_2$)



NaCl molar fraction 1.0
$1.0\ c_H$ NaCl
$1.0\ c_L$ NaCl

NaCl molar fraction 0.8
$0.8\ c_H$ NaCl $0.2\ c_H$ $CaCl_2$
$0.8\ c_L$ NaCl $0.2\ c_L$ $CaCl_2$

NaCl molar fraction 0.6
$0.6\ c_H$ NaCl $0.4\ c_H$ $CaCl_2$
$0.6\ c_L$ NaCl $0.4\ c_L$ $CaCl_2$

NaCl molar fraction 0.4
$0.4\ c_H$ NaCl $0.6\ c_H$ $CaCl_2$
$0.4\ c_L$ NaCl $0.6\ c_L$ $CaCl_2$

$$c_H = 0.171\ mol.L^{-1}\ or\ 0.513\ mol.L^{-1}\ or\ 1.711\ mol.L^{-1}$$
$$c_L = 0.017 mol.L^{-1}$$

Salinity ratio

$$\boldsymbol{Ra = 100\ or\ 30\ or\ 10}$$

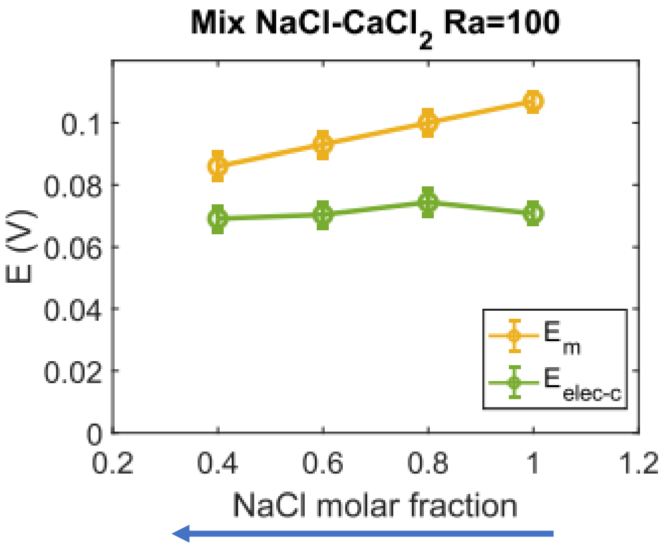
Electrochemical Characterizations

Cell voltage
E_m
E_{elec}

Power density

03.3 Experimental results

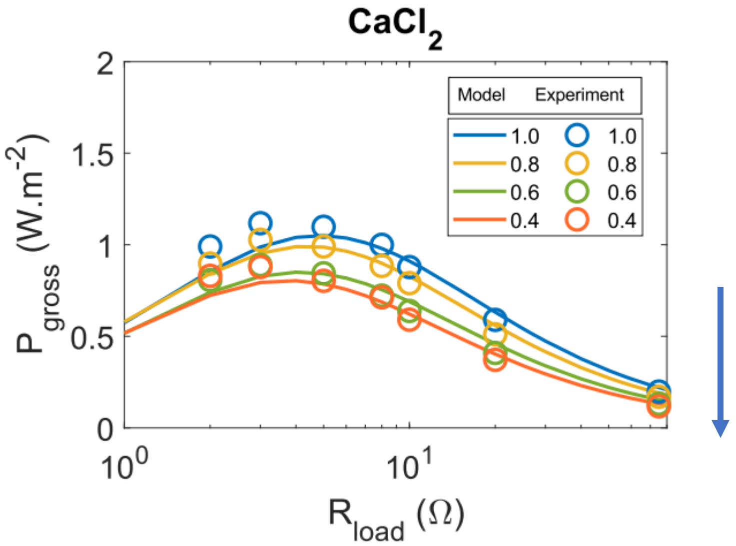
Cell voltage drop



E_m is severely influenced

E_{elec} remains stable

Power density drop



Smaller power density drop in CRED!

CRED: 34% power density drop

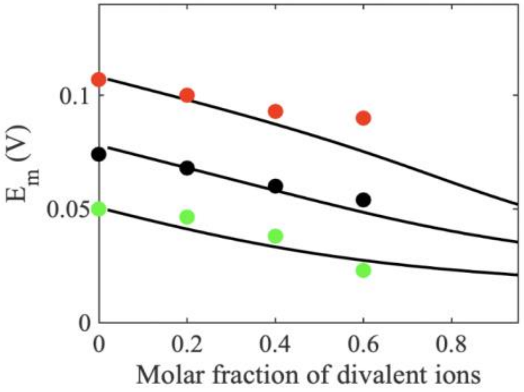
RED: 62% power density drop

Sources: *Wu et al. Scientific Reports 2024*

03.4 Mechanism

Uphill Effect

Theory V.S. Experiment



The uphill effect is enough to explain <u>the voltage drop</u> in CRED system

Membrane poisoning

Trapping of multivalent ions in membrane

↓

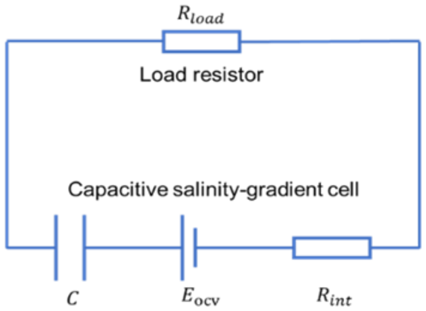
~~Selectivity drop~~

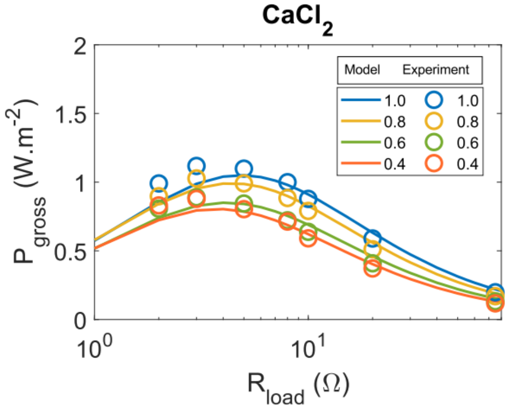
↓

~~Additional voltage drop~~

Suppression of Membrane poisoning by flow reversal in CRED system

Hidden mechanism?



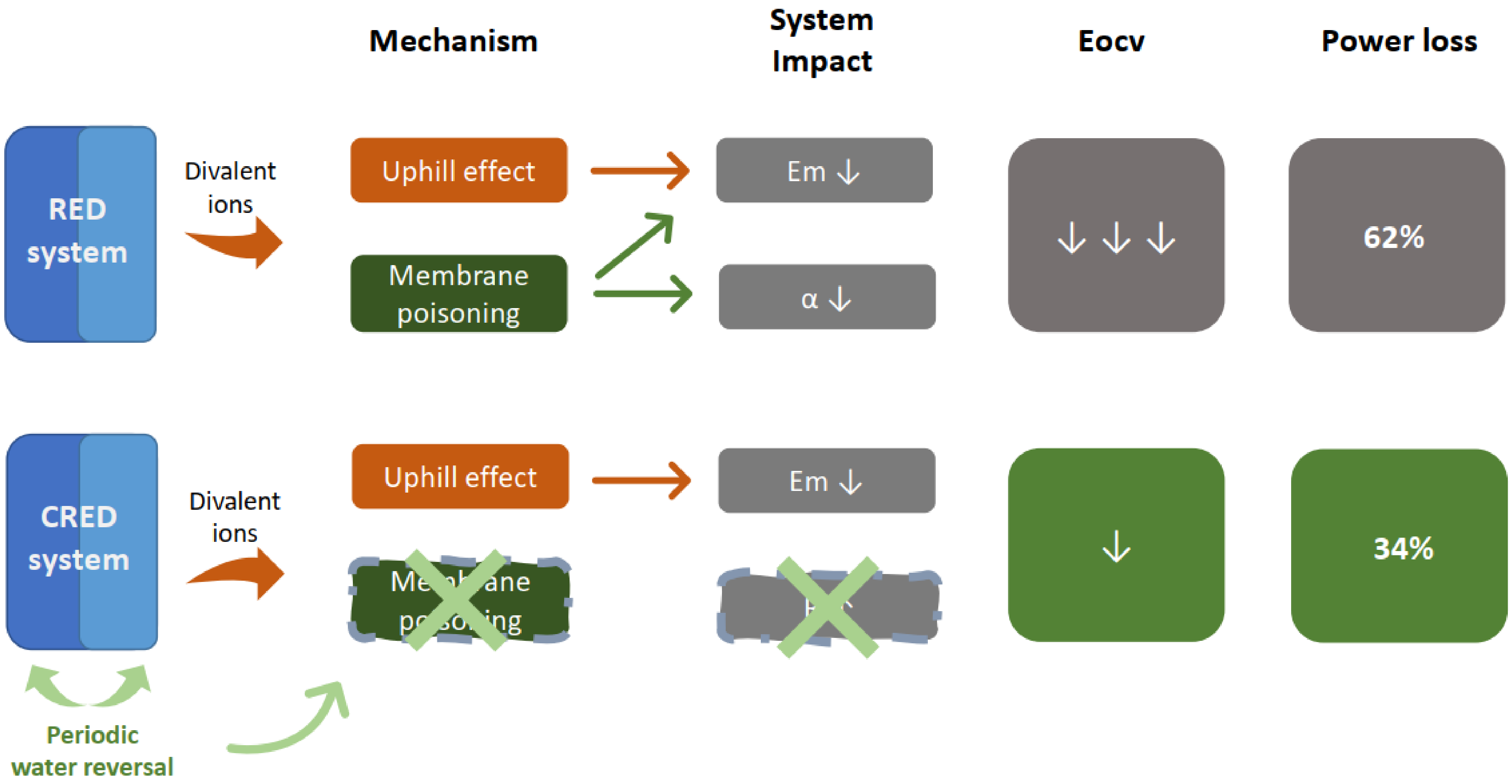


Voltage drop is sufficient to explain the <u>power density drop</u>

<u>Sources</u>: Vermaas et al. Energy & Environmental Science 2014

<u>Sources:</u> *Wu et al. Scientific Reports 2024*

03.4 Mechanism



Mechanism

System Impact

Eocv

Power loss

RED system

Divalent ions

Uphill effect → Em ↓

Membrane poisoning → Em ↓, α ↓

↓ ↓ ↓

62%

CRED system

Divalent ions

Uphill effect → Em ↓

~~Membrane poisoning~~

↓

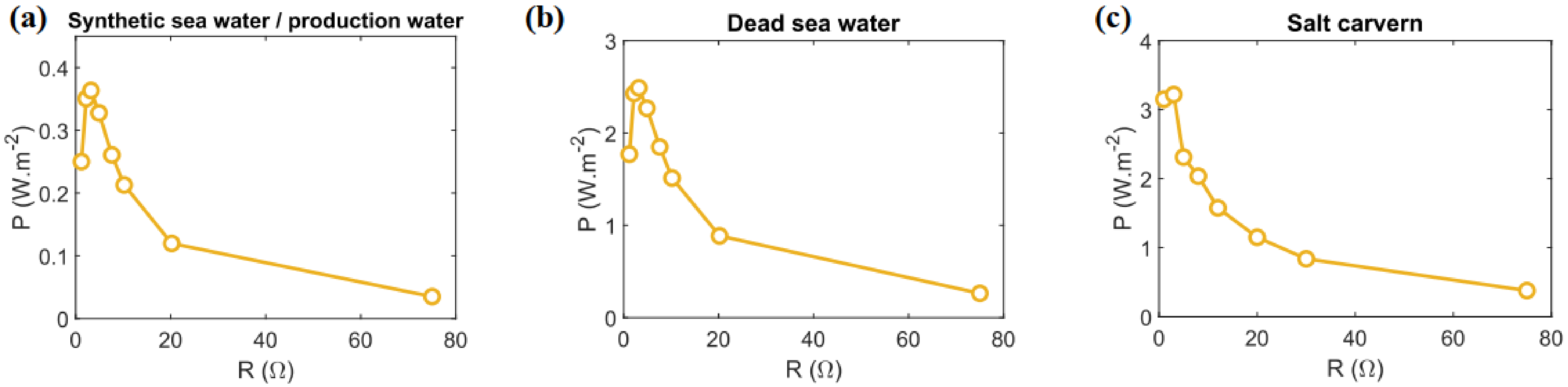
34%

Periodic water reversal

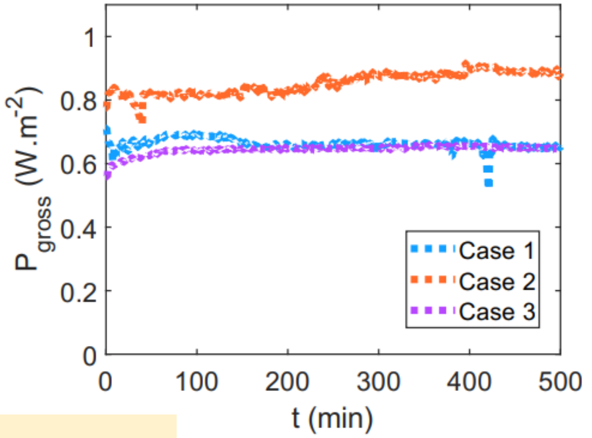
Sources: *Wu et al. Scientific Reports 2024*

03.5 Towards Real solutions

Real solution measurements



Long operation measurements



Case 1: Artificial NaCl (80%) - CaCl2(20%) mixed solution; Nafion 117

Case 2: Production water; Nafion 117

Case 3: Artificial NaCl (40%) - CaCl2 (60%) mixed solution; Fumasep FS720

The power density variation after 8h of operation is **within 6%**.

Sources: *Wu et al. Scientific Reports 2024*

03.6 Economic analysis

Analysis hypothesis:

RED membrane surface of 100 000 m2

Membrane lifetime is 7 years

Production runs 8000 hours per year

Annual exploitation cost estimated as 9% of the construction cost

Post scenario:

River water-Sea water mixing case.

RED system with a power of 2 W.m^{-2}

Membrane price at 2 euros per m^{2}

__Sources__: Post et al. Journal of Membrane Science 2009

A scenario:

Great salt lake with treated wastewater

Supplementary valves for water reversal

Suppression of filtration cost

CRED system with a power of 3.2 W.m^{-2}

Membrane price at 60 euros per m^{2}

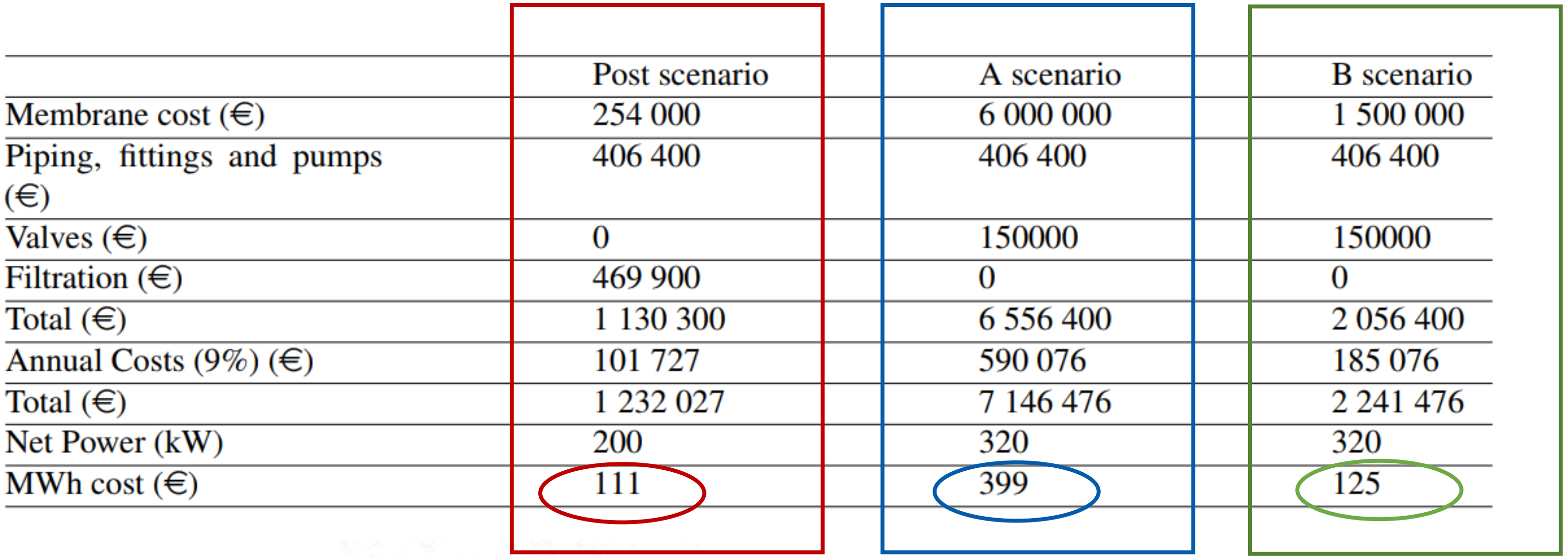
Current sPEEK membrane cost

B scenario:

Membrane price at 15 euros per m2

Future sPEEK membrane cost estimation

***__Sources:__** Wu et al. Scientific Reports 2024*



	Post scenario	A scenario	B scenario
Membrane cost (€)	254 000	6 000 000	1 500 000
Piping, fittings and pumps (€)	406 400	406 400	406 400
Valves (€)	0	150000	150000
Filtration (€)	469 900	0	0
Total (€)	1 130 300	6 556 400	2 056 400
Annual Costs (9%) (€)	101 727	590 076	185 076
Total (€)	1 232 027	7 146 476	2 241 476
Net Power (kW)	200	320	320
MWh cost (€)	111	399	125

Solar Energy: 40 euros per MWh

Wind off shore: 120 euros per MWh

03 Summary

Divalent ion mixing

01 Divalent ion mixing results in cell voltage and power density drop in CRED system.

02 Uphill effect is responsible for the drop.

03 Membrane poisoning is suppressed by water chamber reversal in CRED system

04 It is worthy of further developing CRED system according to economic analysis

04

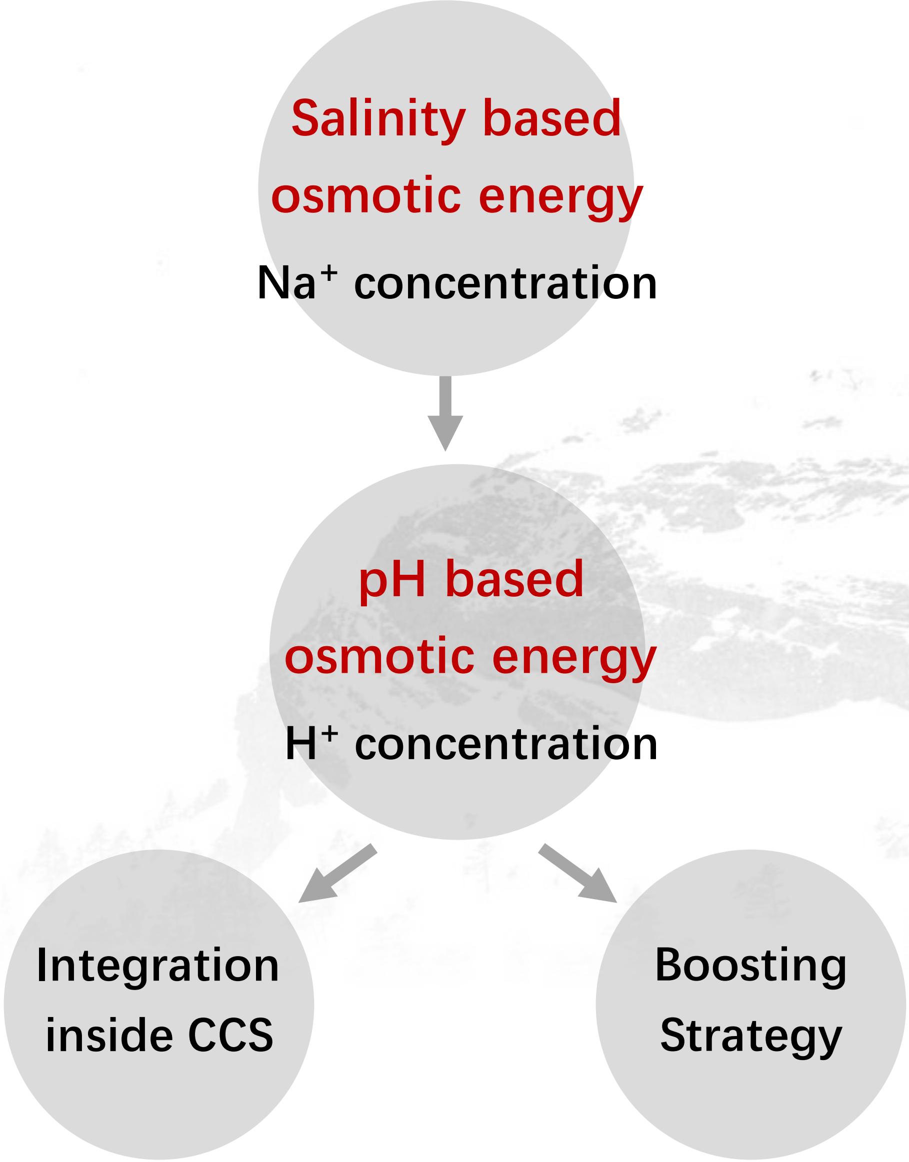
pH gradient cell

Towards pH gradient based osmotic energy harvesting

04.1 Preamble

Objective:

- Generalization towards pH gradient based osmotic energy harvesting system
- Integration inside the carbon capturing & storage (CCS) process
- Energy performance increase by boosting strategy



Salinity based osmotic energy

Na^+ concentration

pH based osmotic energy

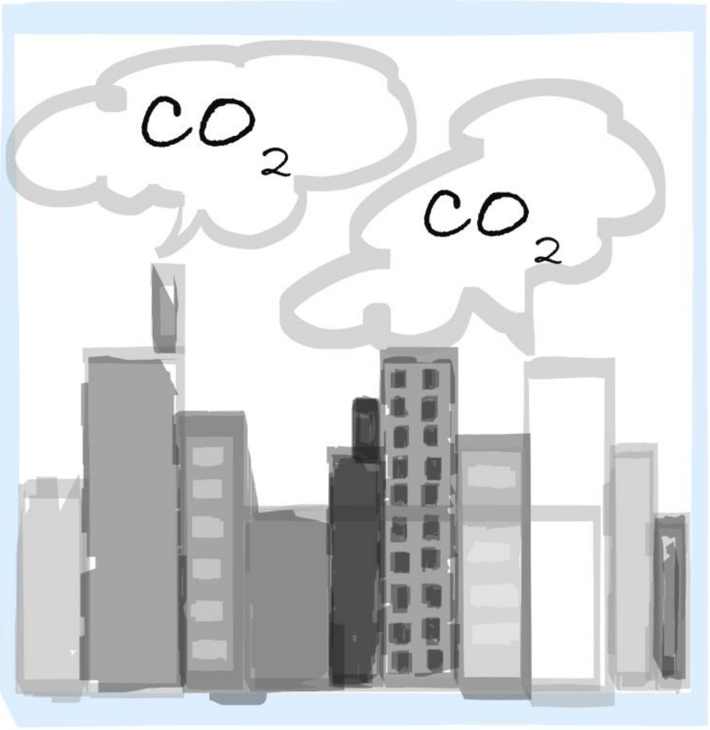
H^+ concentration

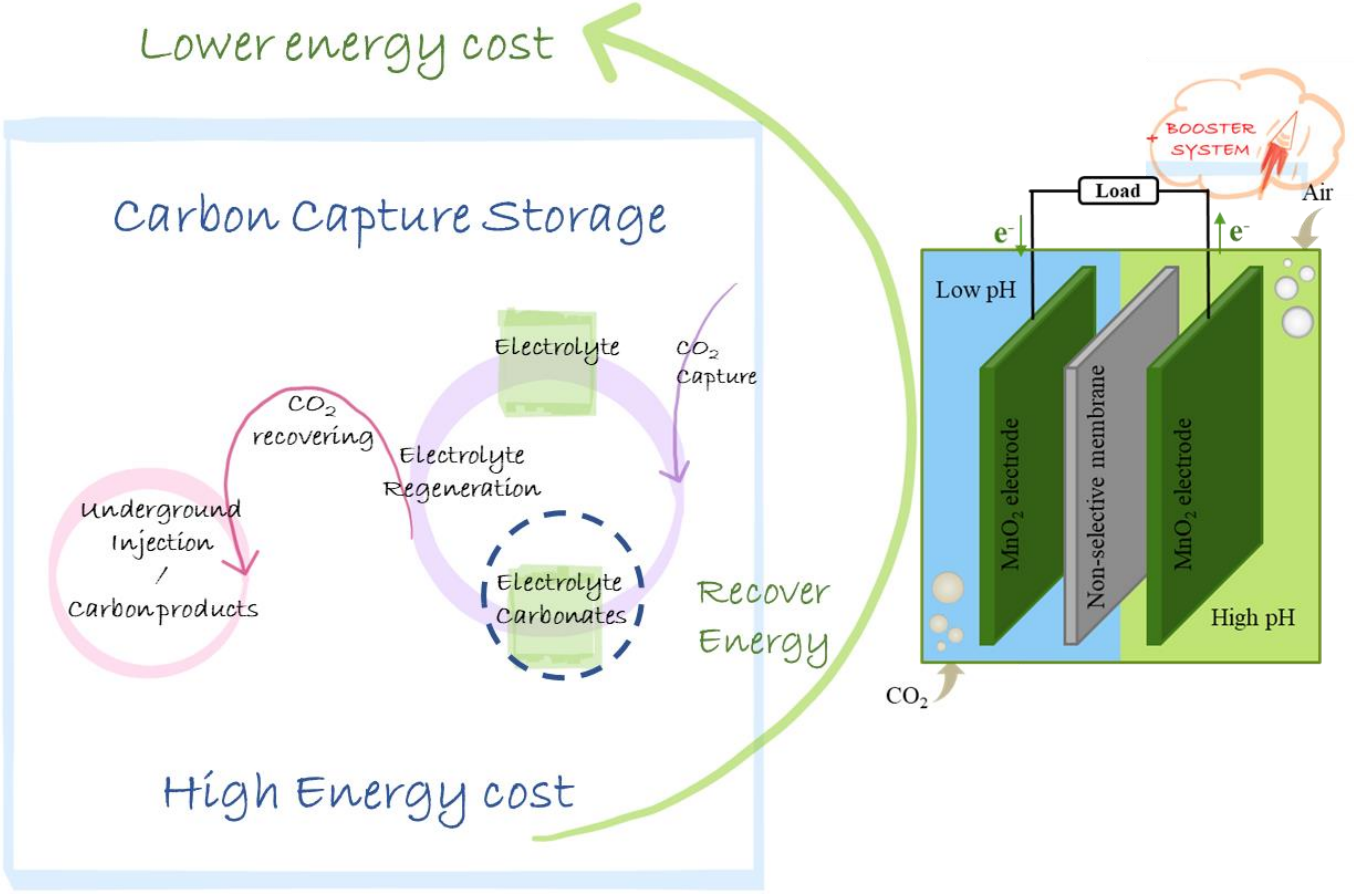
Integration inside CCS

Boosting Strategy

04.2 Osmotic energy source in CCS

CO_2 Capture & Storage (CCS)

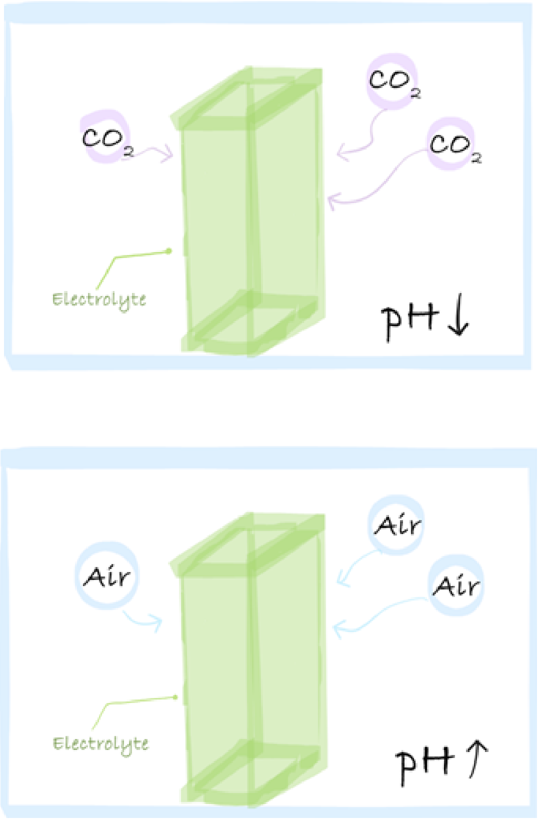


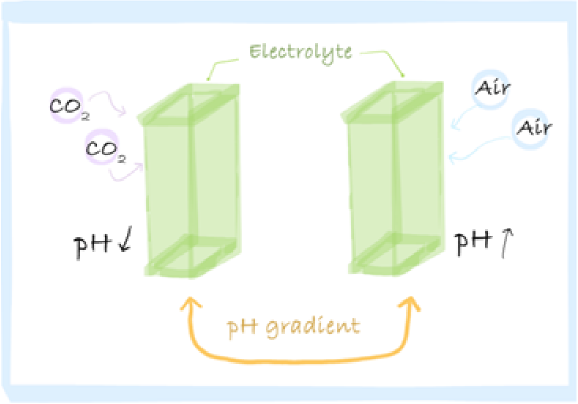


Sources: Alaba et al. International Journal of Precision Engineering and Manufacturing-Green Technology 2021
Garcia et al. Journal of Environmental Chemical Engineering 2022
Hamelers et al. Environmental Science & Technology Letters 2014

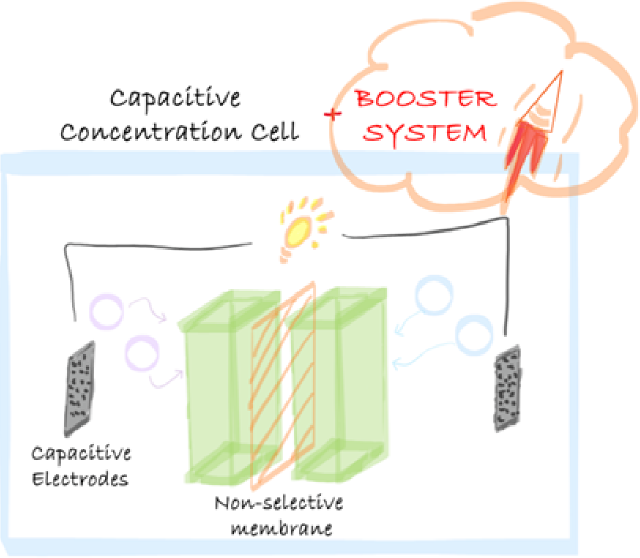
04.2 Osmotic energy source in CCS

CO_2 Capture → **Energy source** → **Electricity**



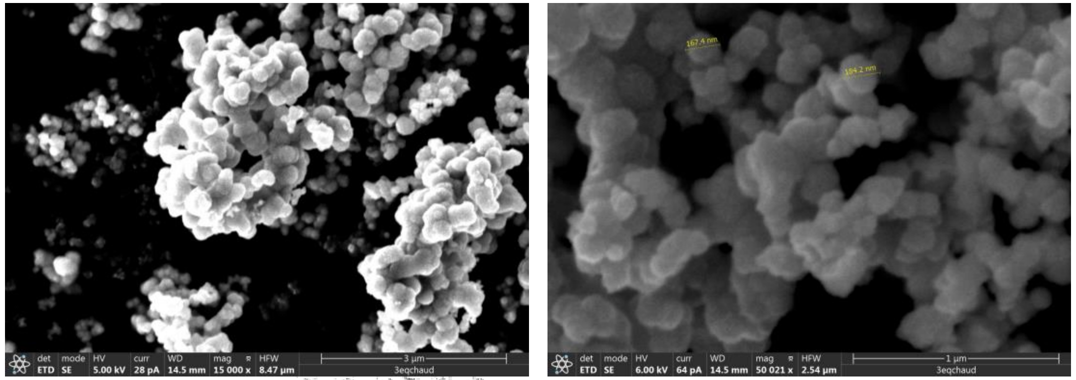


ENERGY SOURCE



ELECTRICITY PRODUCTION

04.3 pH gradient cell for energy harvesting



MnO_2 Carbon Nanotubes PVDF NMP

Capacitive layer

+ Carbon cloth (current collector)

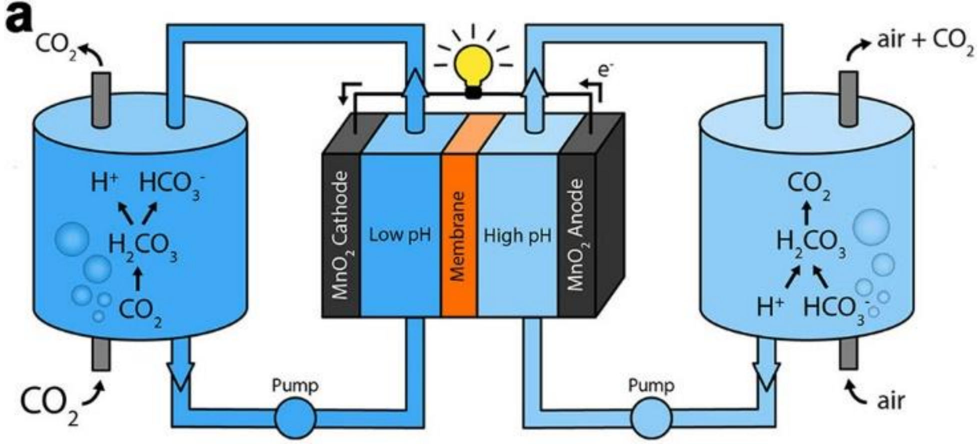


Figure 10 pH gradient based energy harvesting system.

Osmotic energy source:

CO_2 gas capturing in carbonate solutions

$NaHCO_3$ (1 M, pH = 7.8) vs. Na_2CO_3 (0.5 M, pH = 11. 7)

pH gradient based system:

Non-selective membrane is used to prevent direct solution mixing

MnO_2 electrodes present prior selectivity for protons H^+

Sources: Kim et al. Environmental Science & Technology Letters 2017

04.4 Energy performance

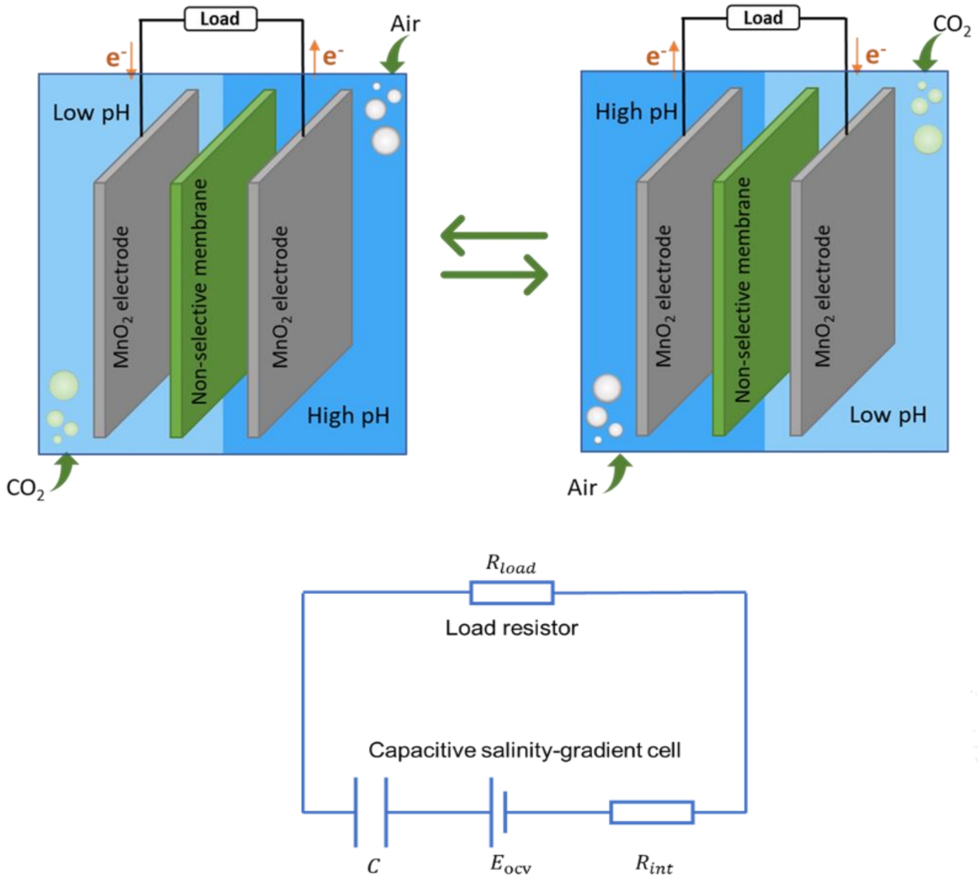
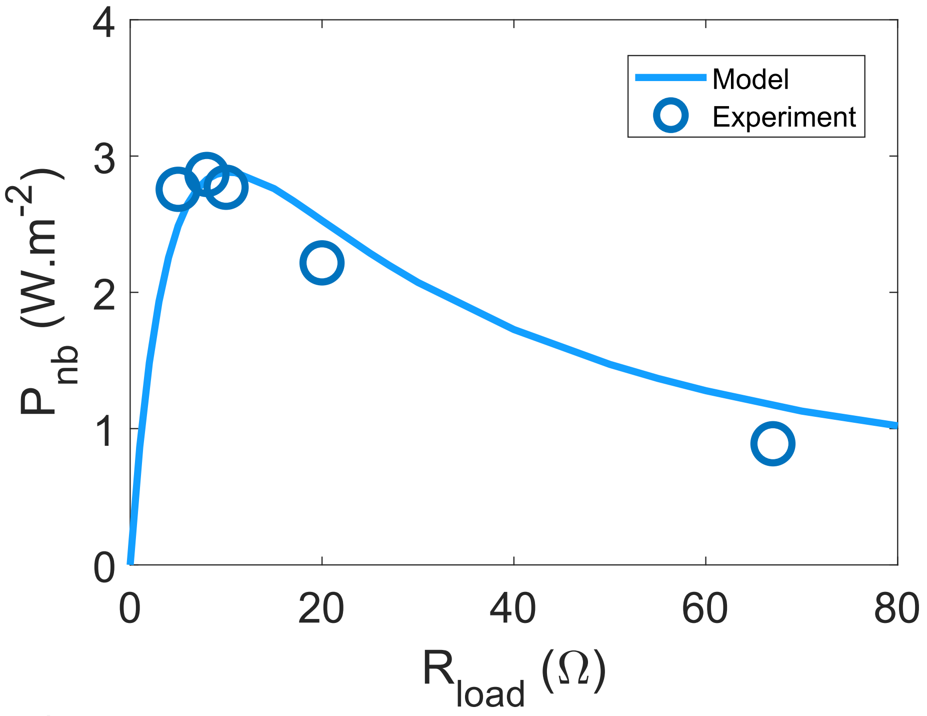


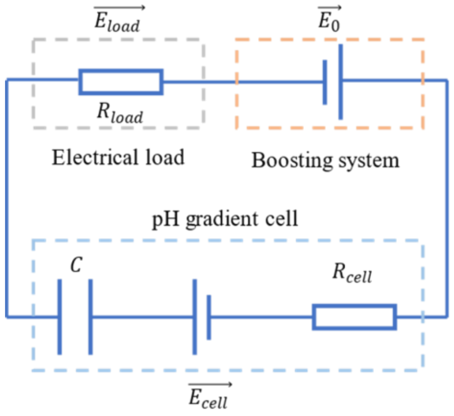
Figure 11 pH gradient based energy harvesting system coupled with a booster system.

Sources: *Wu et al. In Preparation*



Energy performance matched with capacitive equivalent circuit

04.4 Energy performance under boosting strategy

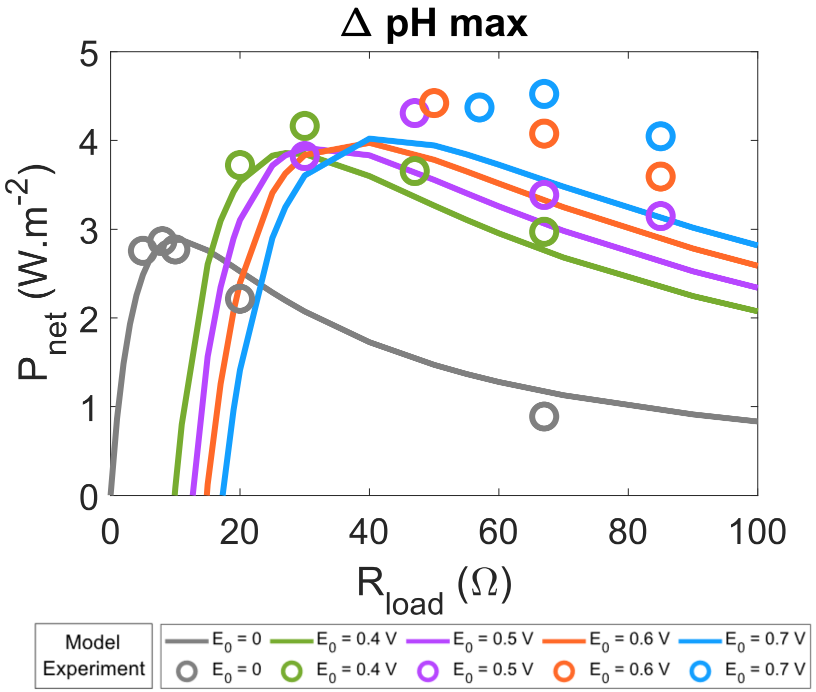


Net power density calculation:

$$P_{b-gross} = \frac{1}{S.T}\int_0^T \frac{E_R(t)^2}{R}\,dt$$

$$P_{b-boost} = \frac{1}{S.T}\int_0^T E_0(t).I(t)\,dt$$

$$P_{b-net} = P_{b-gross} - P_{b-boost}$$



Boosting principle works!

MAX: 4.52 W.m^{-2}

But BAD prediction of equivalent circuit

Sources: *Wu et al. In Preparation*

04.5 Mechanism discussion

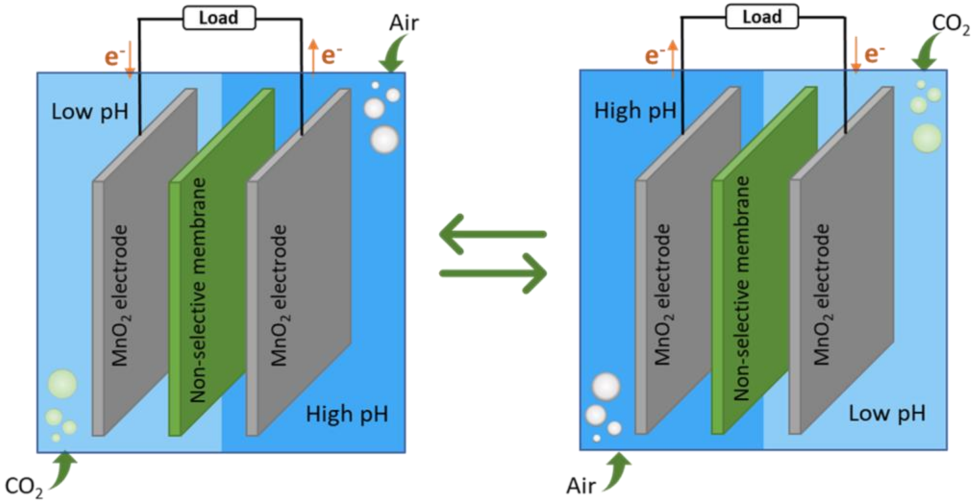


Figure 12 pH gradient based energy harvesting system.

Faradaic or Capacitive?

Is this a redox reaction governed faradaic process?

- Electrode related electrical potential well described by Nernst Equation
- **However, the system shows capacitive behavior**

Is this an ion-adsorption governed capacitive process?

- Established capacitive equivalent circuit
- Capacitive behavior verified by impedance characterization
- Well prediction of energy performance by RC circuit
- **However, the system presents a reversed electrical voltage**

Faradaic process with capacitive behavior:

- Unique behavior occurred in some materials: **Surface faradaic reactions**
- Redox reactions occurred mainly at the electrode surface
- It presents certain capacitive behavior

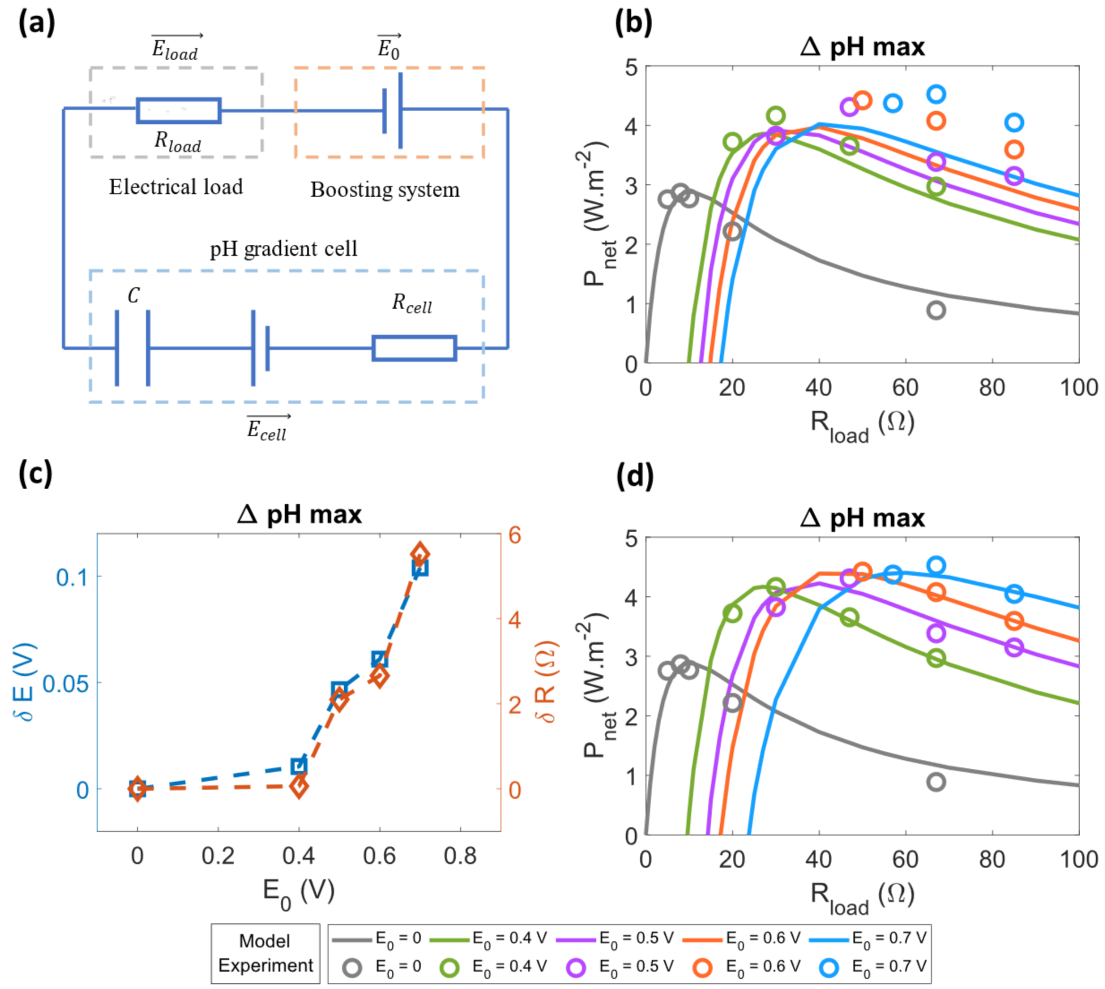
$$MnO_2 + H^+ + e^- = MnOOH_{(s)}$$

$$MnO_2 + HCO_3^- + 2e^- + 3H^+ = MnCO_{3(s)} + 2H_2O$$

Sources: Toupin et al. Chemistry of Materials 2004
Augustyn et al. Energy & Environmental Science 2014
Lee and Goodenough Journal of Solid State Chemistry 1999

***Sources:** Wu et al. In Preparation*

04.5 Mechanism discussion



Sources: *Wu et al. In Preparation*

Unexpected boosting result:

- Redox reaction leads to chemical composition variation
- Boosting amplifies such phenomenon
- Material composition variation leads to parameter variations in equivalent circuits
- Cell voltage E_{OCV} and cell inner resistance R_{cell}

Fitting correction:

- Use of two fitting parameters: δE and δR

$$E_{OCV-eff} = E_{OCV} + \delta E \qquad R_{cell-eff} = R_{cell} + \delta R$$

- Well accordance by adjusted capacitive equivalent circuit
- This occurred due to the material composition variation inside MnO_2 electrodes

Sources: Ferrell and Vosburgh Journal of The Electrochemical Society 1951
Johnson and Vosburgh Journal of The Electrochemical Society 1953
Conway Electrochimica Acta 1993

04 Summary

pH-gradient cell system

- 01 pH gradient based osmotic energy harvesting in CCS cycle
- 02 pH gradient cell composed of MnO_2 electrodes and non-selective membrane
- 03 Faradaic process with capacitive behavior
- 04 Max net power density of 4.5 W/m^2 under boosting strategy related to the chemical composition variation in electrodes

05

Conclusion & Perspectives

Some future work to be further developed

05.1 Conclusion

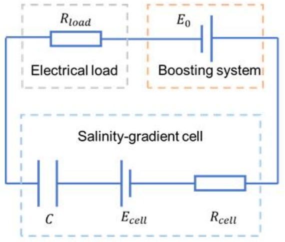
Thesis Objective:

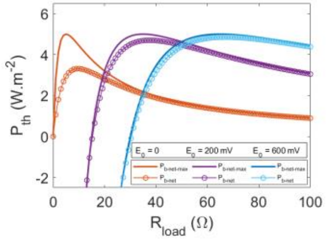
Investigate the fundamental mechanism of the CRED system, aiming to enhance its energy performance and broaden its range of applications.

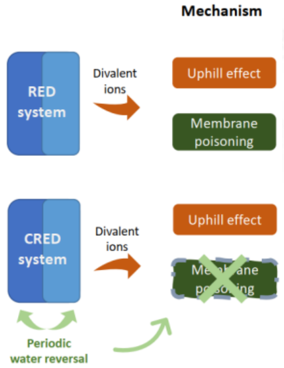
Towards
Power density
amelioration

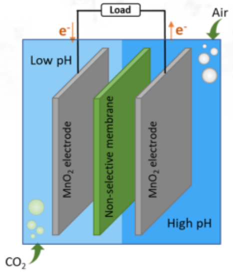
Towards
Real brines

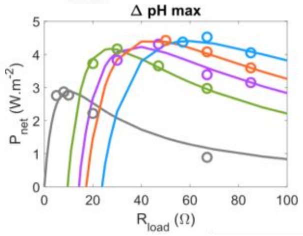
Towards
pH gradient based
osmotic energy
harvesting





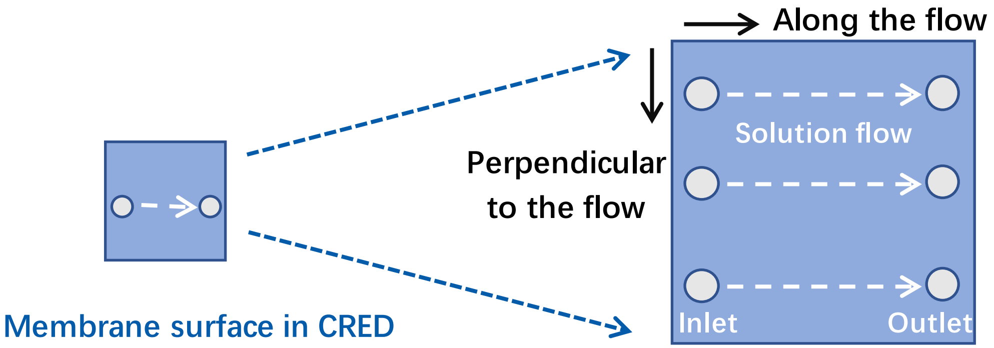






05.2 CRED system scale up

Surface area increase



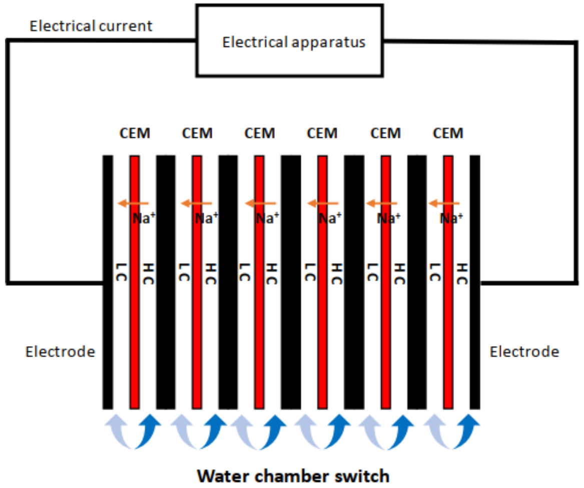
Along the flow:

- Increase of filling time for the entire system
- Impact on cell voltage and inner resistance due to the inhomogeneous ion concentration profile
- More efforts to fight against viscous dissipation

Perpendicular to the flow:

- Limited width related to lineic resistance of current collectors
- Structural design of co-flow or counter-flow

Stacking CRED in series



$$E_{OCV} = N.E_m + N.E_{elec}$$

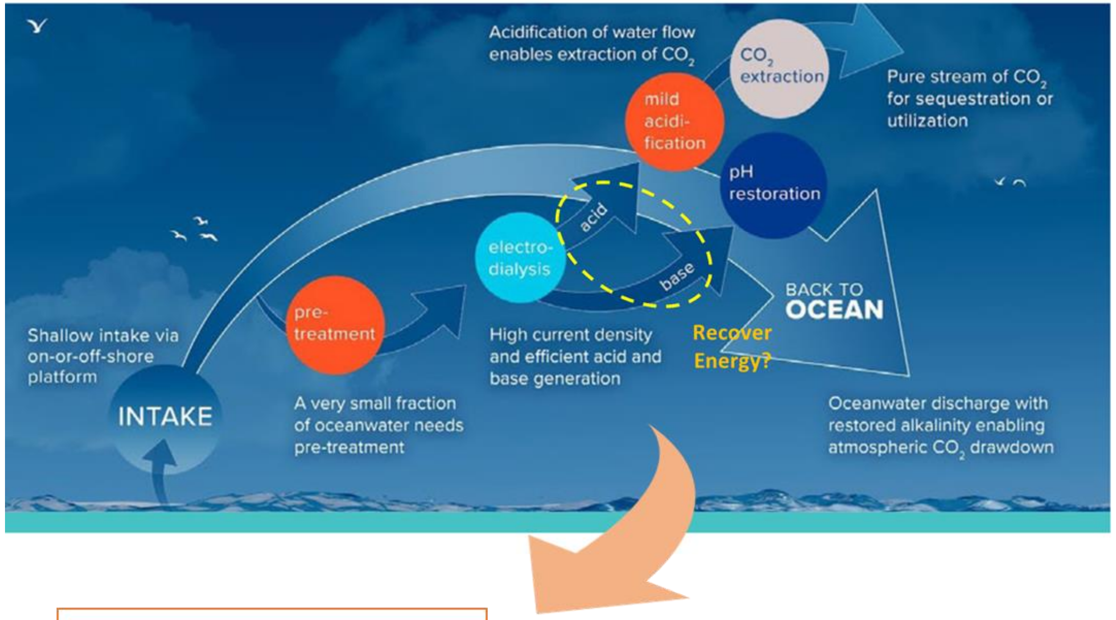
Stacking CRED units:

- Each unit comprises 1 CEM membrane with 2 capacitive electrodes
- Lower system cost compared with RED system stacking

05.3 pH gradient cell in DOC

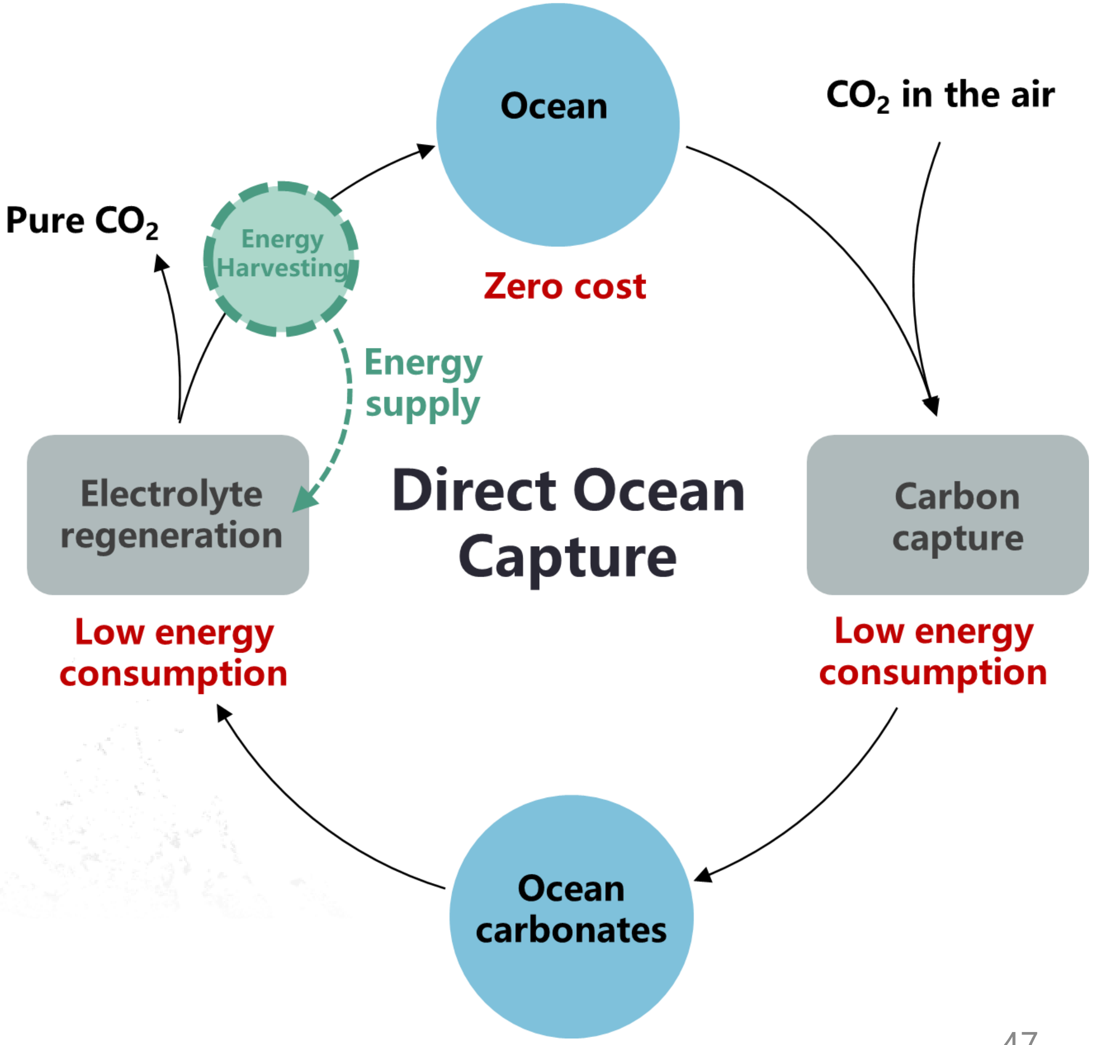
Direct Ocean Capture (DOC):

Direct removal of Carbon dioxide from oceanwater is a method of capturing dispersed CO_2.



pH gradient energy harvesting system

Image Credit: Captura



Ocean

Zero cost

CO_2 in the air

Pure CO_2

Energy Harvesting

Energy supply

Electrolyte regeneration

Low energy consumption

Direct Ocean Capture

Carbon capture

Low energy consumption

Ocean carbonates

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Pr. Véronique Balland
Pr. Mikhael Bechelany
Dr. Michael Levant

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Dr. Audric Jan

Thanks for your attention!

Any questions?