From Nano Innovation to Macro Application in Blue Energy

NanoInnovation 2020
Advanced Materials and Technologies for Sustainability
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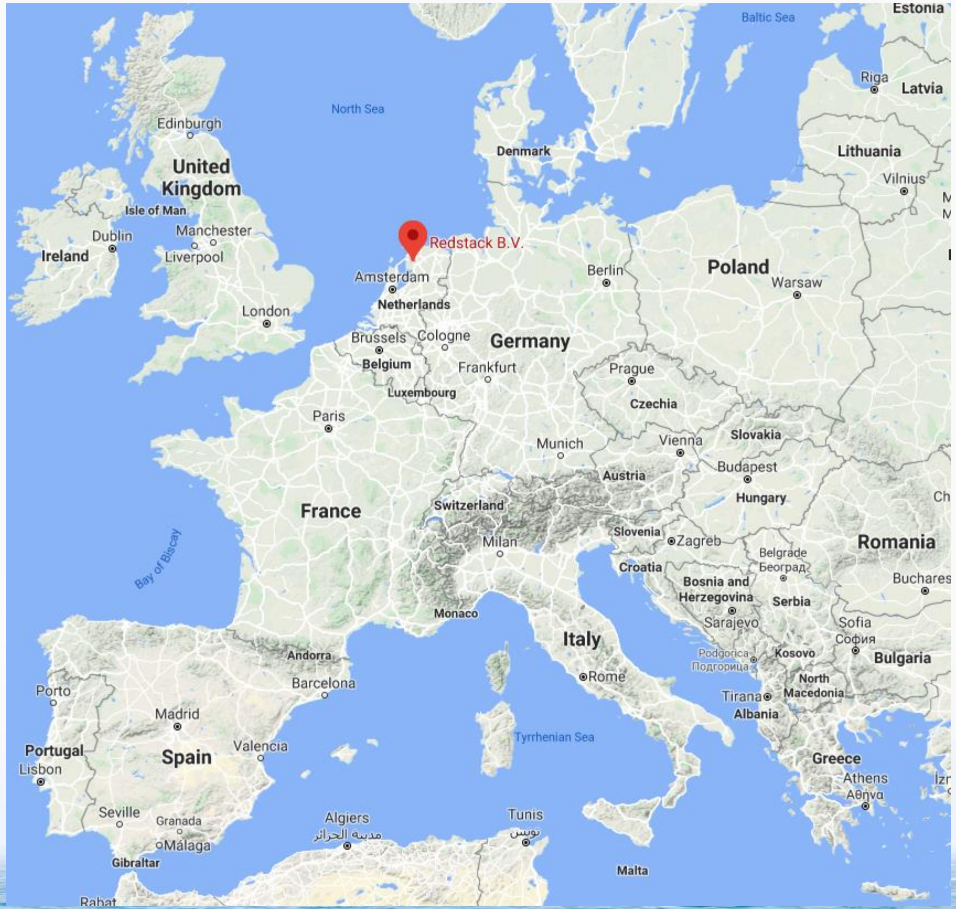
REDstack

How did we start:

- Founded in 2005
- Founded as single purpose company; to develop, up-scale and commercialize the Blue Energy technology.
- Spin-off company from Wetsus, European Centre of Excellence in Sustainable Water Technology



REDstack

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Who we are:

- Privately help company
- Dedicated team of 12 FTE
- Close cooperation with several institutes, universities and companies
- Involved in several research projects. Funded regional, national or by the EC.

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Blue Energy

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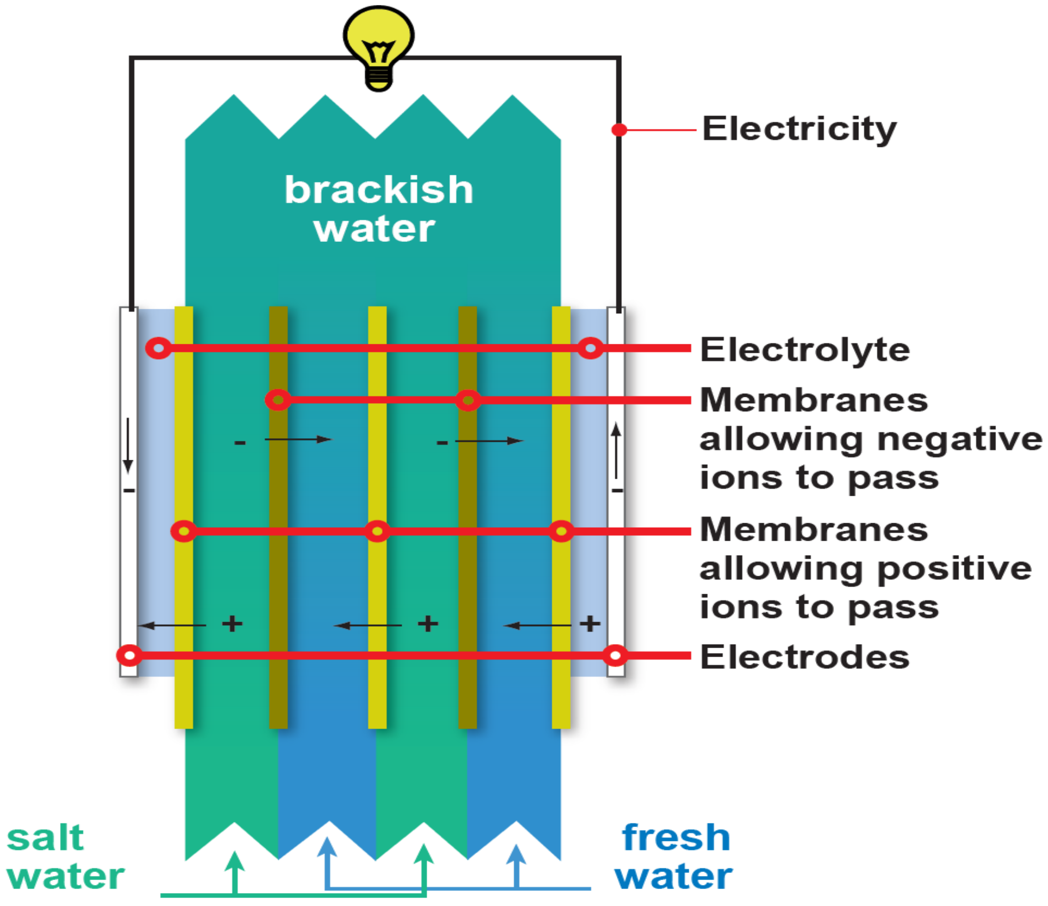
Characteristics of the technology:

- Energy harvested from the mixing of fresh and salt water.
- Fully sustainable, no CO_2 or other GHG emissions
- No back-up required; Blue Energy can function as a baseload.



Blue Energy

Salinity Gradient Power is based on the Gibbs free energy of mixing:

$$\Delta G = \Delta H - T\Delta S$$

Enthalpy (ΔH) Entropy (ΔS)

Since there is no change in Enthalpy, energy is coming from the change in Entropy:

$$\Delta G = -T\,\Delta S$$

$$\Delta S = S_b - (S_s + S_r)$$

Entropy being calculated by:

$$S = -N\,R \sum_i (x_i \ln(x_i))$$

Blue Energy

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How to harvest the energy, the molar free energy is:

$$\mu_i = \mu_i^0 + \vartheta_i \, \Delta P + RT \, ln(x_i) + |z_i| \, F \, \Delta\varphi$$

- **Free energy under standard conditions**
- **Change in pressure**
- **Chemical potential**
- **Change in electrical potential**

Pressure Retarded Osmosis = conversion into pressure
Reversed ElectroDialysis = conversion into <u>electrical potential</u>

Blue Energy

So, for an equilibrium between two NaCl solution this means:

$$\frac{RT}{|Z_{Na}|F}\ln\left(x_{Na,c}\right) + \frac{RT}{|Z_{Cl}|F}\ln(x_{Cl,c}) = \frac{RT}{|Z_{Na}|F}\ln\left(x_{Na,d}\right) + \frac{RT}{|Z_{Cl}|F}\ln(x_{Cl,d}) + \Delta\varphi$$

And with:

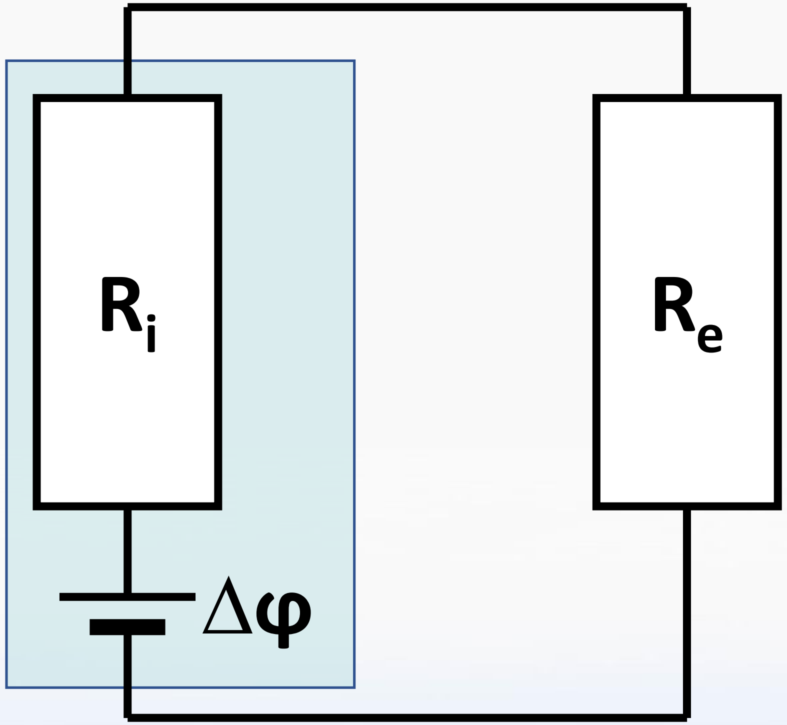
$$x_{Na} = x_{Cl} = x \quad ; \quad |Z_{Na}| = |Z_{Cl}| = 1$$

It gives the Nernst-equation:

$$\Delta\varphi = \frac{2RT}{F}\ln\left(\frac{x_c}{x_d}\right)$$

Blue Energy

Simplified electrical circuit:



$$I = \frac{U}{R} = \frac{\Delta\varphi}{R_i + R_e}$$

$$P_e = I^2 \, R_e$$

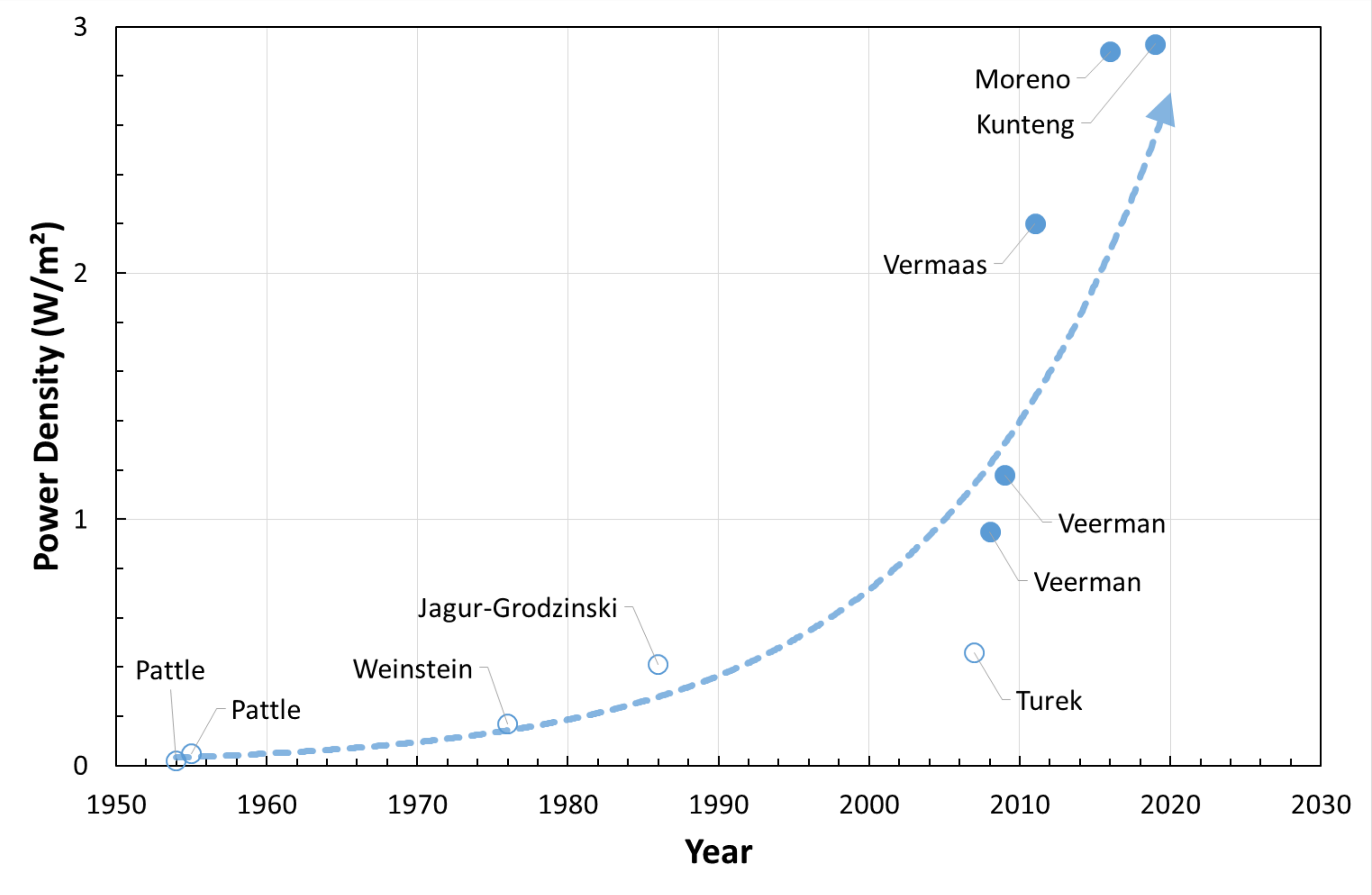
$$P_e = \left(\frac{\Delta\varphi}{R_i + R_e}\right)^2 R_e$$

$$\eta_{energy} = \frac{I^2 \, R_e}{I^2 \, R_e + I^2 \, R_i} = \frac{R_e}{R_e + R_i}$$

Blue Energy

Important performance parameters

- Power density
- Energy efficiency



J. Moreno, S. Grasman, R. van Engelen, K. Nijmeijer, Upscaling Reverse Electrodialysis, Envir. Sci. & Tech. 52 (2018) 10856-10863

Blue Energy

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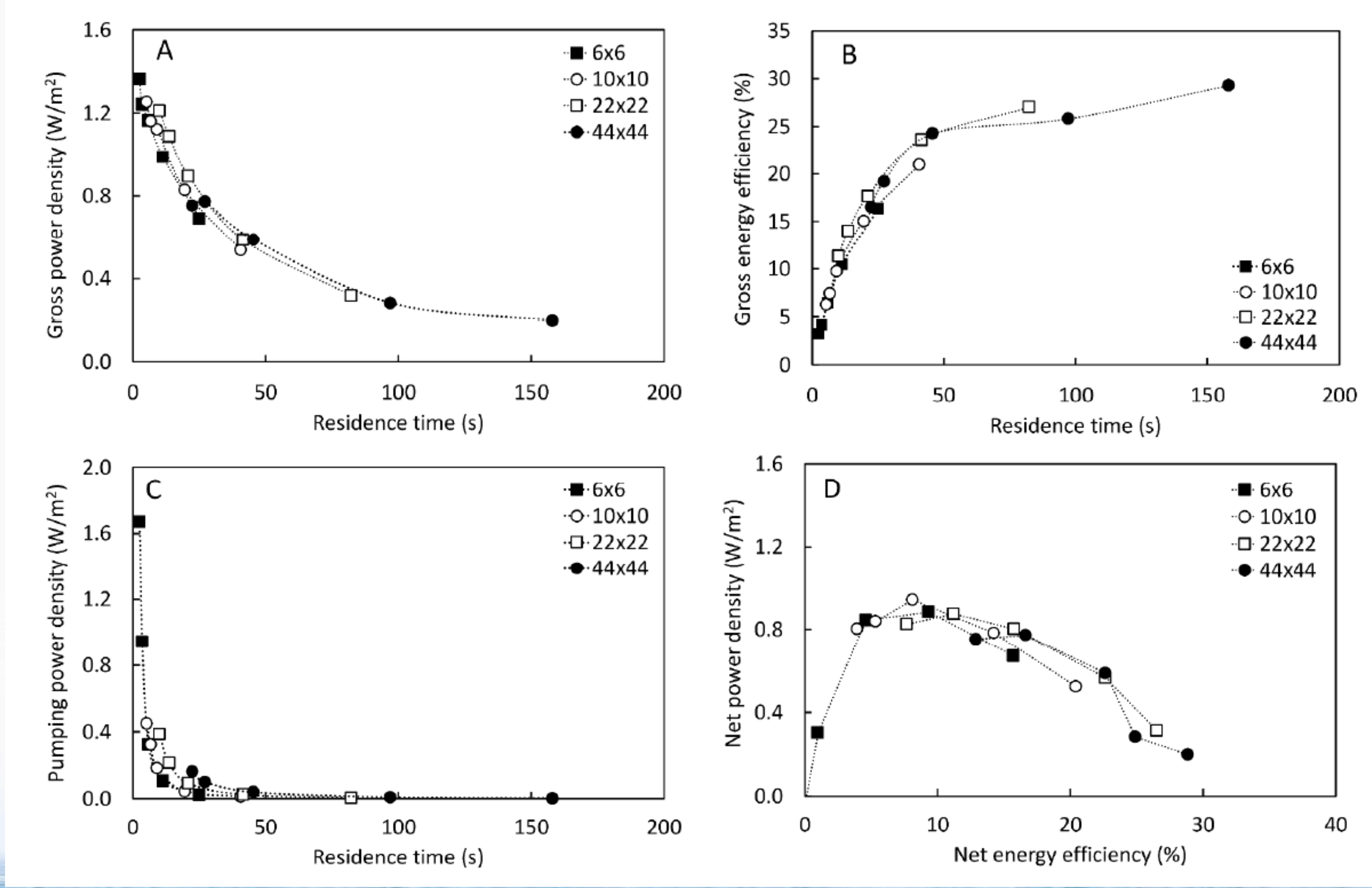

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Blue Energy

Important performance parameters

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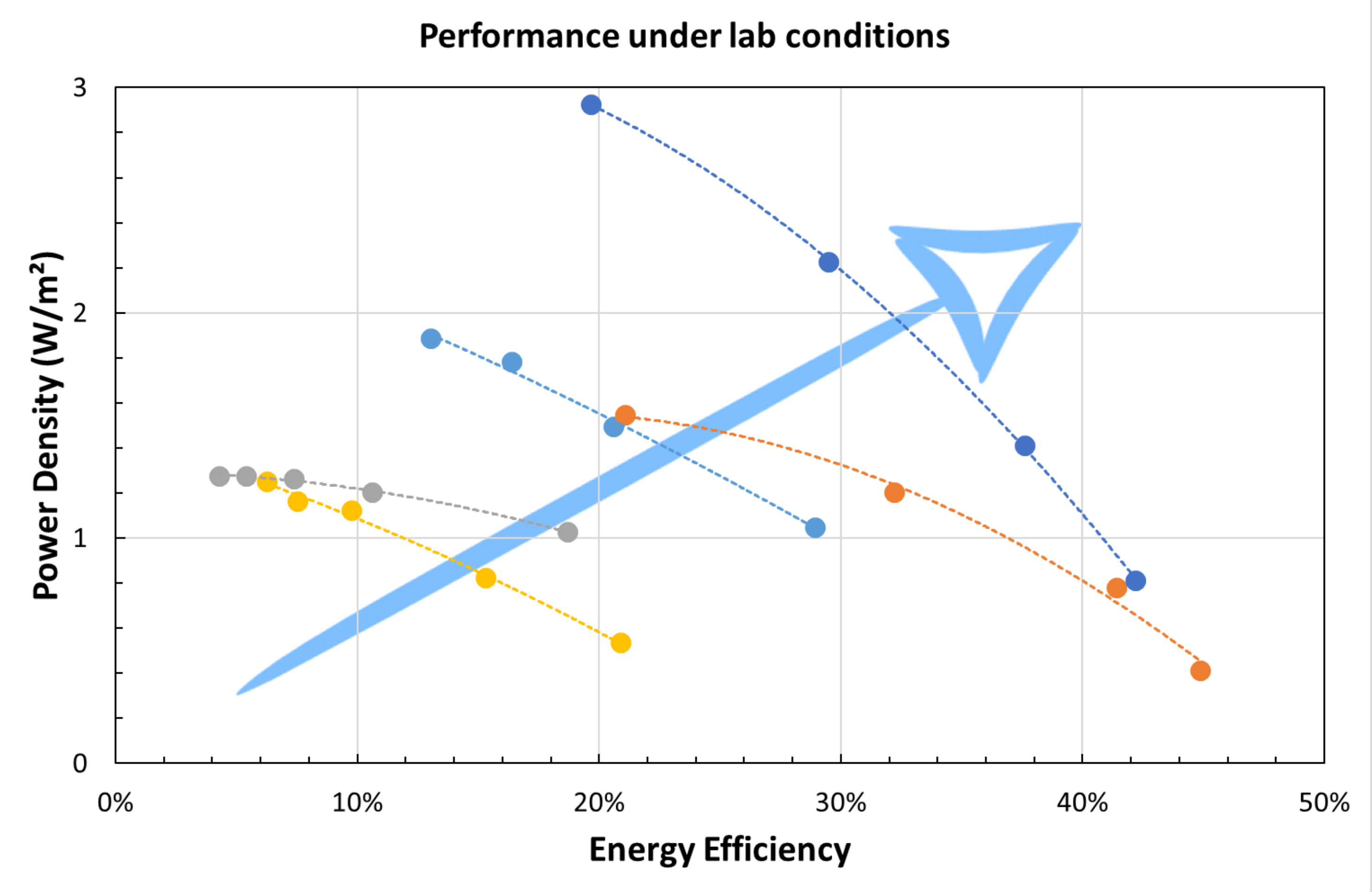

J. Moreno, S. Grasman, R. van Engelen, K. Nijmeijer, Upscaling Reverse Electrodialysis, Envir. Sci. & Tech. 52 (2018) 10856-10863

Nano porous membranes

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Several types of nano porous membranes for Blue Energy have been reported:

- Boron Nitride (BNNT)
- molybdenum disulfide (MoS_2)
- Graphene Oxide Membranes (GOM)
- GO with Boron Nitride

LETTER

doi:10.1038/nature18593

Single-layer MoS_2 nan
generators

10^6 W/m^2

Jiandong Feng[1], Michael Graf[1], Ke Liu[1], Dmitry Ovchinnikov[2], Dumitru Dumcenco[2], Mohammad Heiranian[3], Vishal Nandigana[3], Narayana R. Aluru[3], Andras Kis[2] & Aleksandra Radenovic[1]

LETTER

doi:10.1038/nature11876

Giant osmotic energy … d in a
single transmembran … ube

10^3 W/m^2

Alessandro Siria[1], Philippe Poncharal[1], Anne-Laure Biance[1], Rémy Fulcrand[1], Xavier Blase[2], Stephen T. Purcell[1] & Lydéric Bocquet[1]

ACS NANO

www.acsnano.org

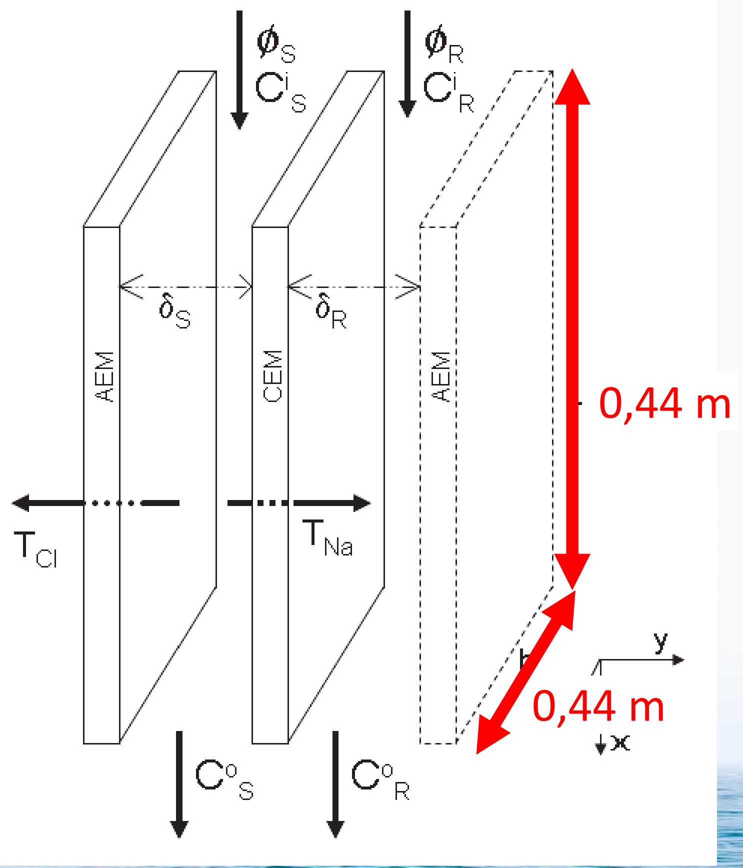
Tunable Anion-Selective Transport through
Monolayer Grap … ron
Nitride

10^3 - 10^4 W/m^2

Mustafa Caglar, Inese Silkina, Bertram T. Brown, Alice L. Thorneywork, Oliver J. Burton, Vitaliy Babenko, Stephen Matthew Gilbert, Alex Zettl, Stephan Hofmann, and Ulrich F. Keyser*

Upscaling effects

Implications for upscaling, what does a power density of MW/m² mean for the process?



$$P = PD \cdot A_{membr.} = 387{,}000\ W$$

$$I = {}^{P}/_{U} = 7{,}744{,}000\ A$$

$$J = {}^{I}/_{F} = 80\ mol/s$$

$$\Delta C = C_{in} - C_{out} = 0.125\ mol/l$$

$$\emptyset = {}^{J}/_{\Delta C} = 642\ l/s$$

$$A_{channel} = b \cdot \delta_s = 0.0001\ m^2$$

$$v_{fluid} = {}^{\emptyset}/_{A_{channel}} = 5873\ m/s$$

$$\tau = {}^{v_{fluid}}/_{l} = 0.075\ mS$$

Upscaling effects

Is it realistic to upscale the performance based on the single pore measurements?

Single pore → Single membrane with multiple pores → Cell pair of CEM and AEM → Stack of multiple cell pairs

Upscaling effects

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Nano porous membranes with multiple pores:

- Anodic alumina
- Graphene oxide
- Silica nano particles
- Etc..

Structure:

- 1-, 2- or 3D Ion channels
- Diode membranes

Vertically-Oriented Graphene Oxi[...]

10 W/m²

High-Performance Osmotic Energy Conversion

Zhenkun Zhang[1], Wenhao Shen[2], Lingxin Lin[1], Mao Wang[2], Ning Li[1], Zhifeng Zheng[1], Feng Liu[2,3]*, and Liuxuan Cao[1]*

ELSEVIER

Contents lists available at Scie[...]

Nano Energy

2.5 W/m²

journal homepage: www.elsevier.com/locate/nanoen

Full paper

Engineered PES/SPES nanochannel membrane for salinity gradient power generation

Xiaodong Huang[a], Zhen Zhang[a], Xiang-Yu Kong[a], Yue Sun[a], Congcong Zhu[a,c], Pei Liu[a,c], Jinhui Pang[b,*], Lei Jiang[a,c], Liping Wen[a,c,**]

Upscaling effects

Effect of multiple pores:

- Increasing pore density → Decreasing current and potential
- Does this explain the difference?

Materials Chemistry Frontiers

ROYAL SOCIETY OF CHEMISTRY

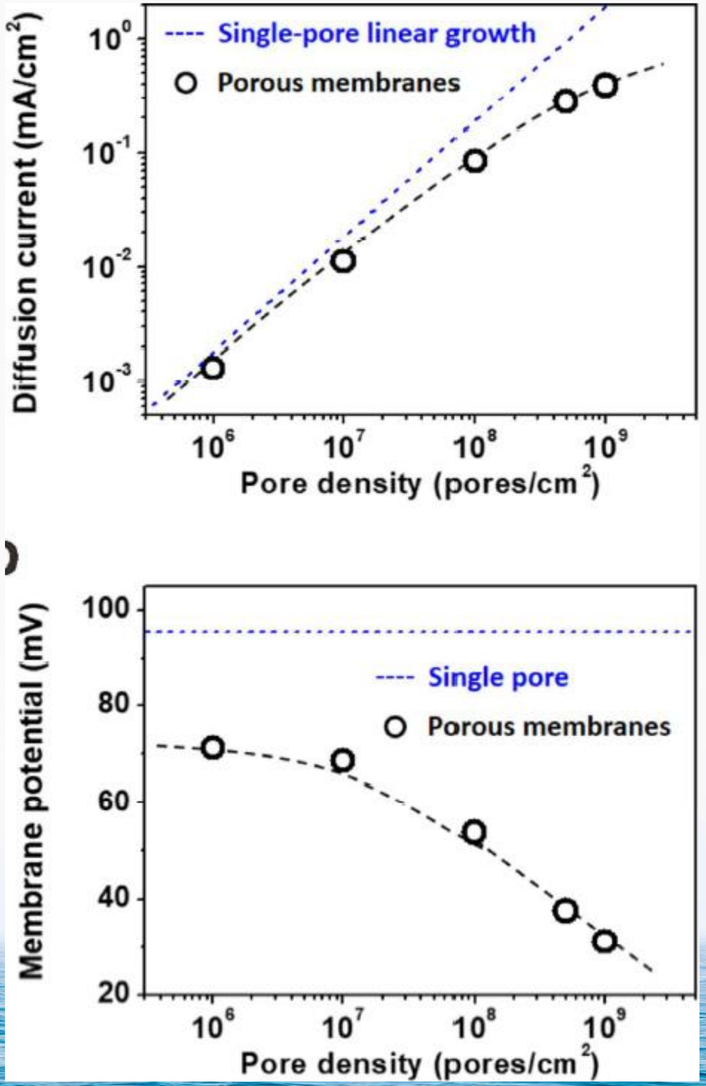
ARTICLE

A general strategy to simulate osmotic energy conversion in multi-pore nanofluidic systems

Received 00th January 20xx,
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

Feilong Xiao,[a,†] Danyan Ji,[b,†] Hao Li,[a] Jialiang Tang,[a] Yaping Feng,[b] Liping Ding,[c] Liuxuan Cao,[*a] Ning Li,[a] Lei Jiang,[b] and Wei Guo[*b]



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Upscaling effects

Cell pair of nano porous membranes:

- Graphene Oxide CEM and AEM

Materials Views
www.MaterialsViews.com

ADVANCED FUNCTIONAL MATERIALS
www.afm-journal.de

Osmotic Power Generation with Positively and Negatively Charged 2D Nanofluidic Membrane Pairs

Jinzhao Ji, Qian Kang, Yi Zhou, Yaping Feng, Xi Chen, Jinying Yuan, Wei Guo, Yen Wei, and Lei Jiang*

0.77 W/m²

Perspective

Optimization of cell pair configuration, assuming ideal membranes and no spacers.

- $R_{membr.} = 0\ \Omega \cdot cm^2$
- PS = 100%

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

ELSEVIER

Chemical Engineering Journal

Reverse electrodialysis: A validated process model for design and optimization

J. Veerman[a,b], M. Saakes[a], S.J. Metz[a,*], G.J. Harmsen[c]

Perspective

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Optimization of cell p
membranes and no s

- $R_{membr.} = 0\ \Omega\cdot cm^2$
- PS = 100%

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Contents lists ava

Chemical Eng

journal homepage: ww

Reverse electrodialysis: A validated pro

J. Veerman[a,b], M. Saakes[a], S.J. Metz[a,*], G.J. Harmse

Cell configuration spacer membranes		A, none, ideal	
Cell length (m)		0.001	1
α. Maximization of P_{d-net}			
Net power density	P_{d-net} (W/m^2)	60.2	6
Net river water yield	Z_{net} (kJ/m^3)	371	373
Flow ratio	Φ_S/Φ_R	2.8	2.8
Thickness seawater comp.	δ_S (µm)	19	185
Thickness river water comp.	δ_R (µm)	9	92
β. Maximization of $R_P{}^Z$			
Net power density	P_{d-net} (W/m^2)	51.6	5.2
Net river water yield	Z_{net} (kJ/m^3)	557	555
Flow ratio	Φ_S/Φ_R	2.4	2.4
Thickness seawater comp.	δ_S (µm)	23	232
Thickness river water comp.	δ_R (µm)	9	89

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Perspective

Optimization of cell p
membranes and no s

- $R_{membr.} = 0\ \Omega \cdot cm^2$
- PS = 100%

Cell configuration spacer membranes		B, real, ideal	
Cell length (m)		0.001	1
α. Maximization of P_{d-net}			
Net power density	P_{d-net} (W/m^2)	11.6	1.2
Net river water yield	Z_{net} (kJ/m^3)	373	373
Flow ratio	Φ_S/Φ_R	1.5	1.5
Thickness seawater comp.	δ_S (μm)	96	965
Thickness river water comp.	δ_R (μm)	48	478
β. Maximization of R_P^Z			
Net power density	P_{d-net} (W/m^2)	10	1
Net river water yield	Z_{net} (kJ/m^3)	555	554
Flow ratio	Φ_S/Φ_R	2.9	2.9
Thickness seawater comp.	δ_S (μm)	121	1200
Thickness river water comp.	δ_R (μm)	46	461

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Contents lists ava
Chemical Eng
journal homepage: wv

Reverse electrodialysis: A validated pro

J. Veerman [a,b], M. Saakes [a], S.J. Metz [a,*], G.J. Harmse

Perspective

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What can Nano contribute on a Macro scale?

Improve the efficiency?

- Influence of multivalent ions?
- Selectivity of the membrane?
- Water permeability?
- Ion selectivity?

Questions

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Thank you for your attention!