UNIVERSITÀ DEGLI STUDI DI PALERMO
Dipartimento di Ingegneria Chimica, Gestionale, Informatica, Meccanica (DICGIM)

REAPower

European Desalination Society

# *Reverse Electrodialysis Process: Analysis of Optimal Conditions for Process Scale-up*

Michele Tedesco

P. Mazzola, A. Tamburini, G. Micale,

I. D. L. Bogle, M. Papapetrou, A. Cipollina

Desalination for the Environment, Clean Water and Energy
Cyprus, 11 -15 May 2014

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# Outline

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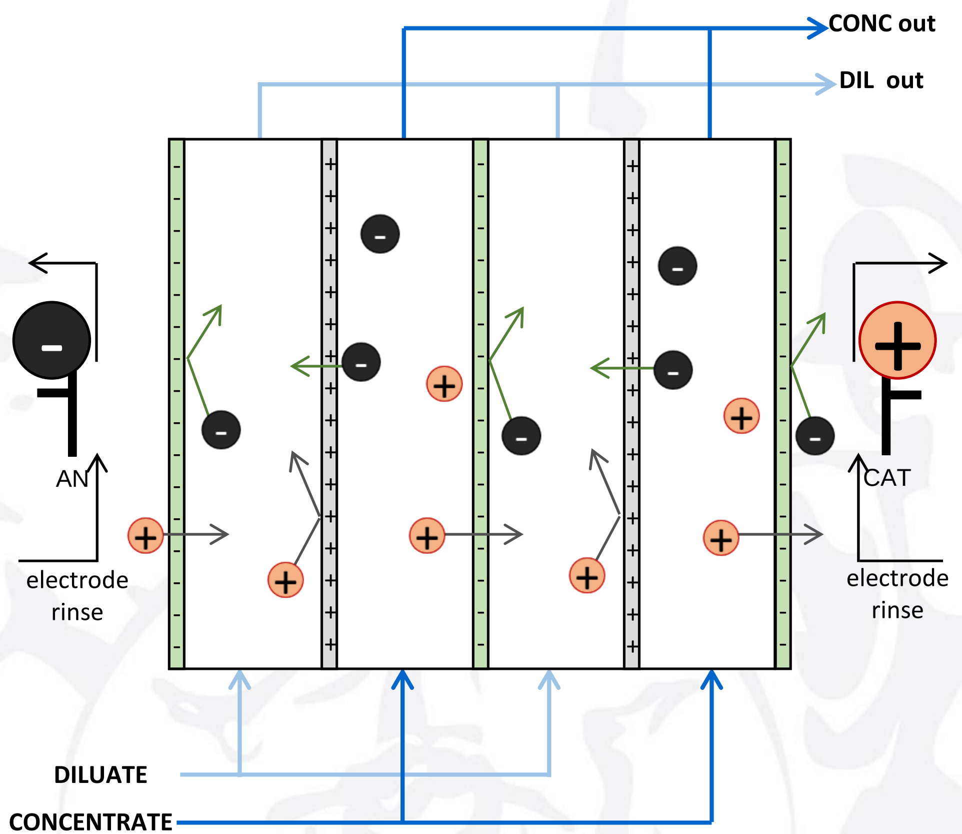
  - Exploring the optimal operating conditions
  - Simulation of large-scale pilot
  - Process simulation for a 3 RED units plant
- **Conclusions**

# Principle of Reverse Electrodialysis

**direct conversion of**

SALINITY GRADIENT ENERGY → **ELECTRICITY**

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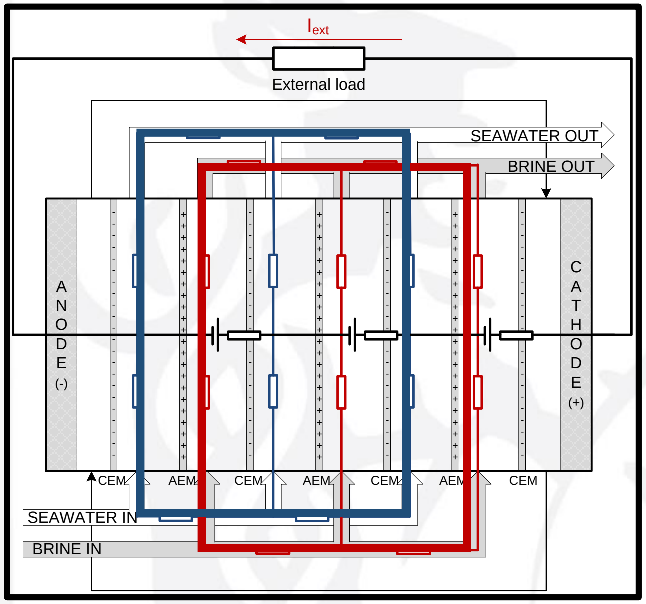
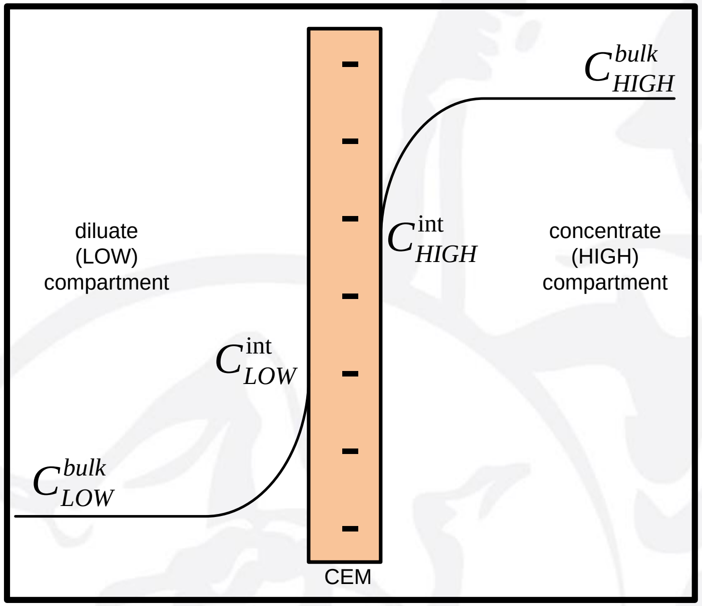
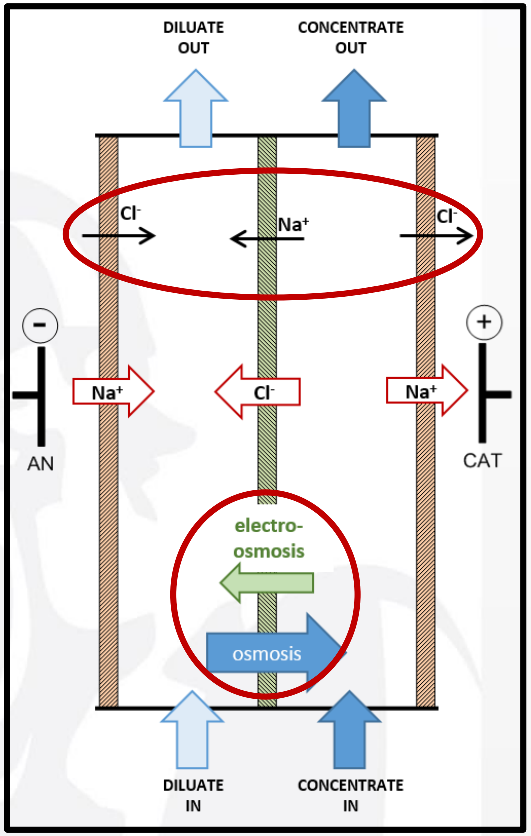
# Non-ideal phenomena

- *non-ideal IEMs permselectivity*
- *Solvent transport through IEMs*
- *Concentration polarisation phenomena*
- *Parasitic currents*



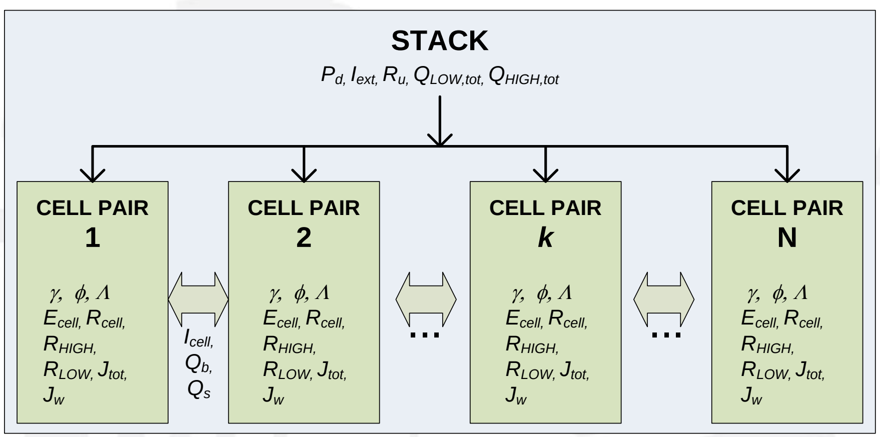



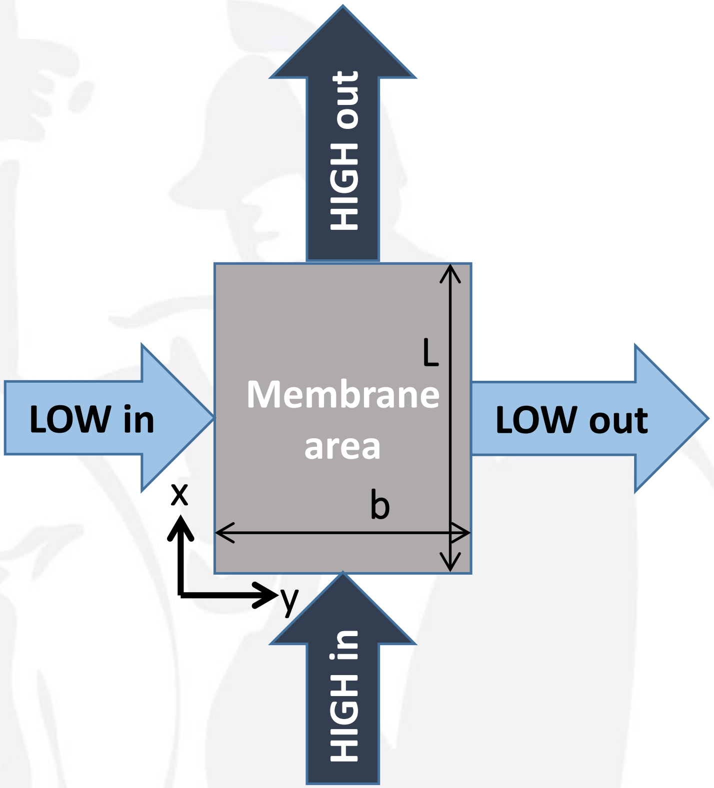
# Focus of the work

**GOAL:**

Development of a **simulator for RED Process** using **sea/brackish water** and **brine** as feed solutions

**Multi-Scale Modelling Approach:**

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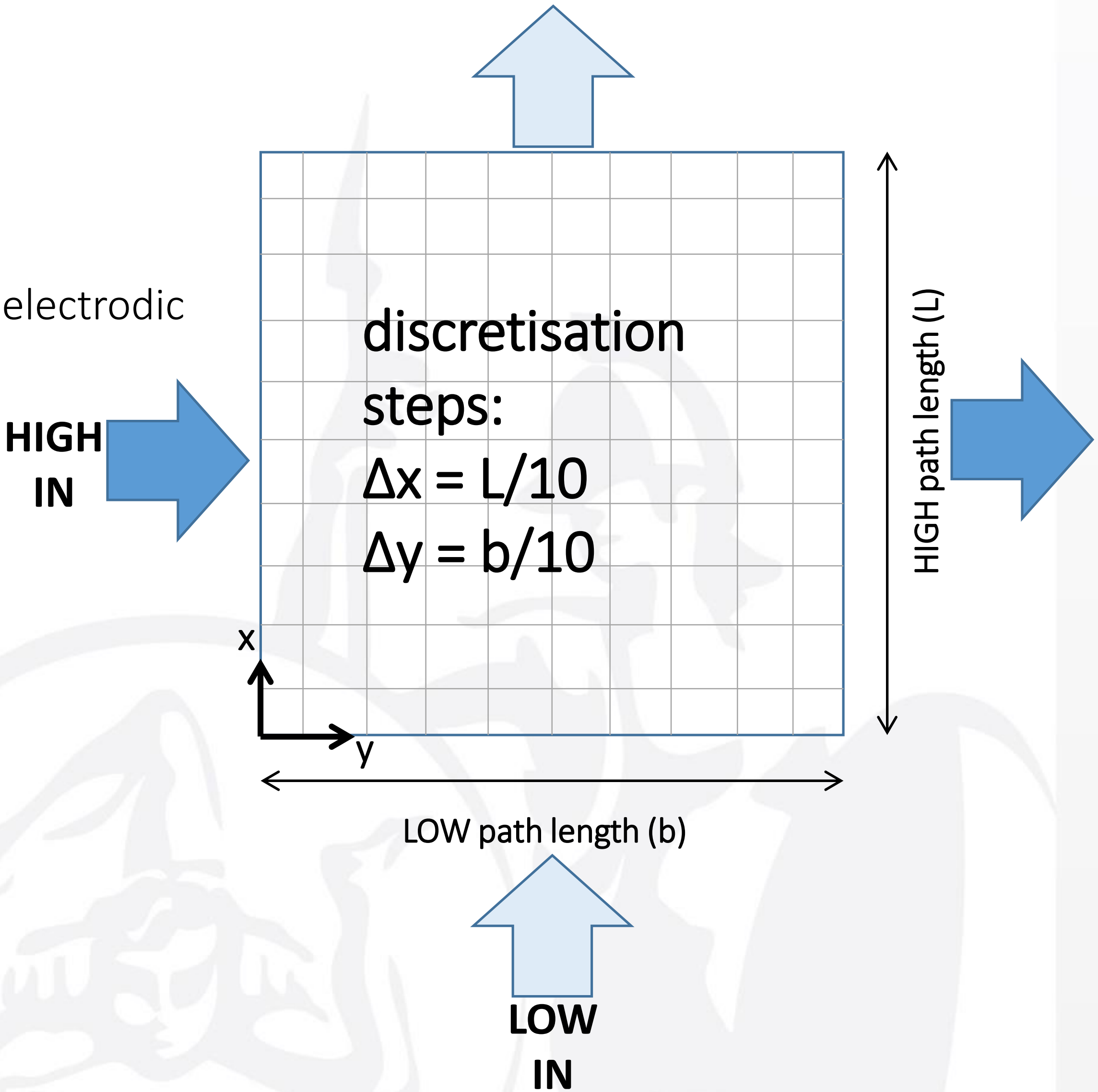
# Model assumptions

- ✓ 2D model
- ✓ **pure NaCl** aqueous solutions
- ✓ **negligible parasitic currents** for electrodic solution

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# Governing equations

- solutions properties
  - Activity and osmotic coefficients
  - Equivalent conductivity
  - Density
  - Viscosity

- Electric variables
  - Cell pair voltage
  - Solutions and membranes resistance
  - Parasitic currents in manifolds

- Transport eq. through membranes
  - Salt transport
  - Solvent transport

- Mass balance and polarisation phenomena

- Response variables
  - Gross power

$$P = I_{ext}^2 \, R_u$$

  - Pumping power

$$P_{pump} = \frac{\Delta P_{HIGH} \, Q_{HIGH}^{tot} + \Delta P_{LOW} \, Q_{LOW}^{tot}}{\eta_p}$$

  - Gross Power density

$$P_d = \frac{1}{N} \left( \frac{I_{ext}}{A} \right)^2 R_u$$

  - Net Power density

$$P_{d,net} = P_d - \frac{P_{pump}}{N \, A}$$

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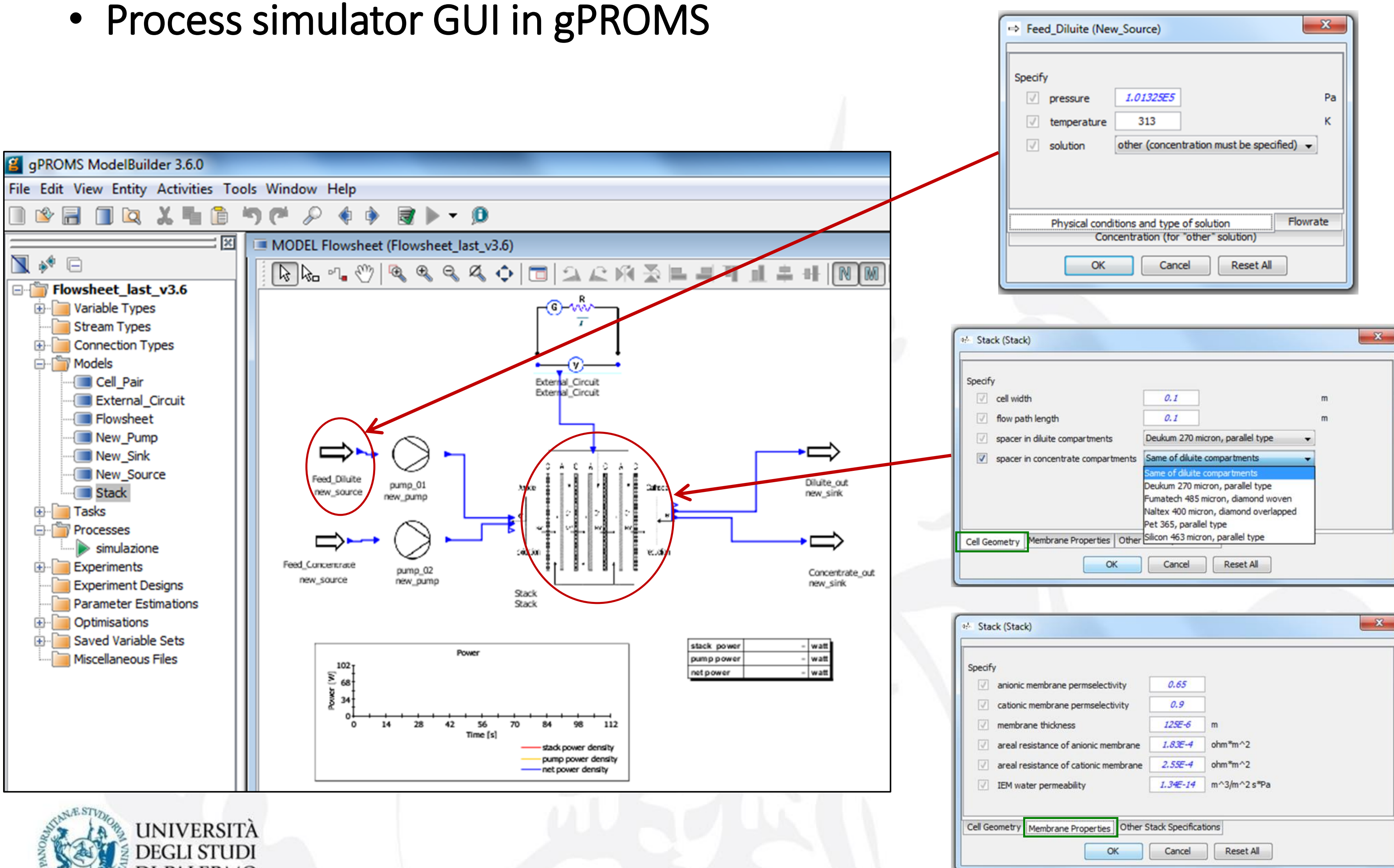
M. Tedesco, A. Cipollina, A. Tamburini, I. D. L. Bogle, and G. Micale, ***"A simulation tool for analysis and design of Reverse Electrodialysis using concentrated brines"***, Chemical Engineering Research & Design, accepted for publication (2014).

# Process simulator

- Process simulator GUI in gPROMS

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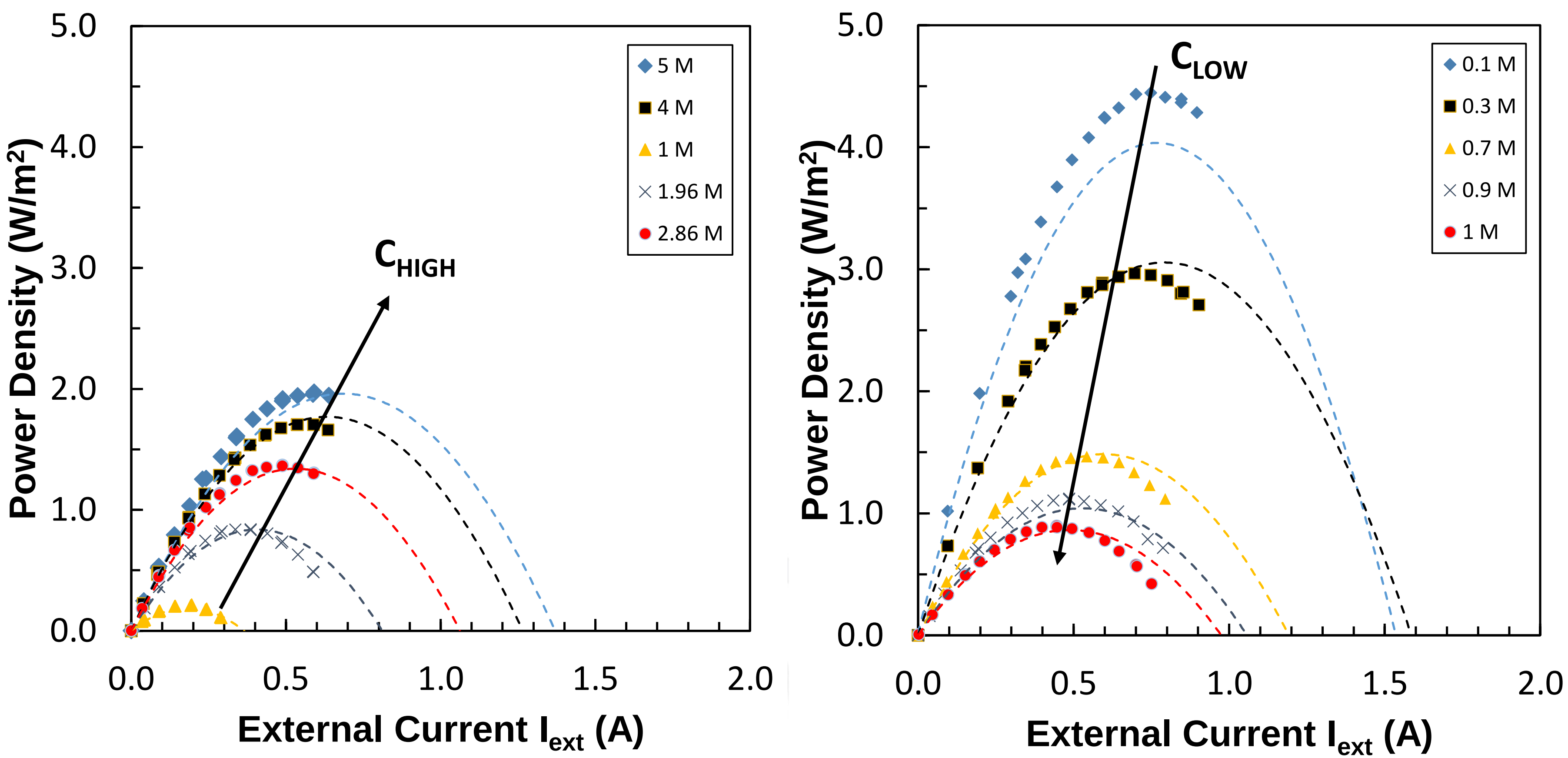
# Validation on a lab-scale unit




Experimental (points) and simulated (lines) data for a 50-cells stack equipped with Fujifilm membranes, Deukum 270 μm spacers; feed flow velocity: 1 cm/s; T=20°C. Experimental data collected at VITO (Belgium).

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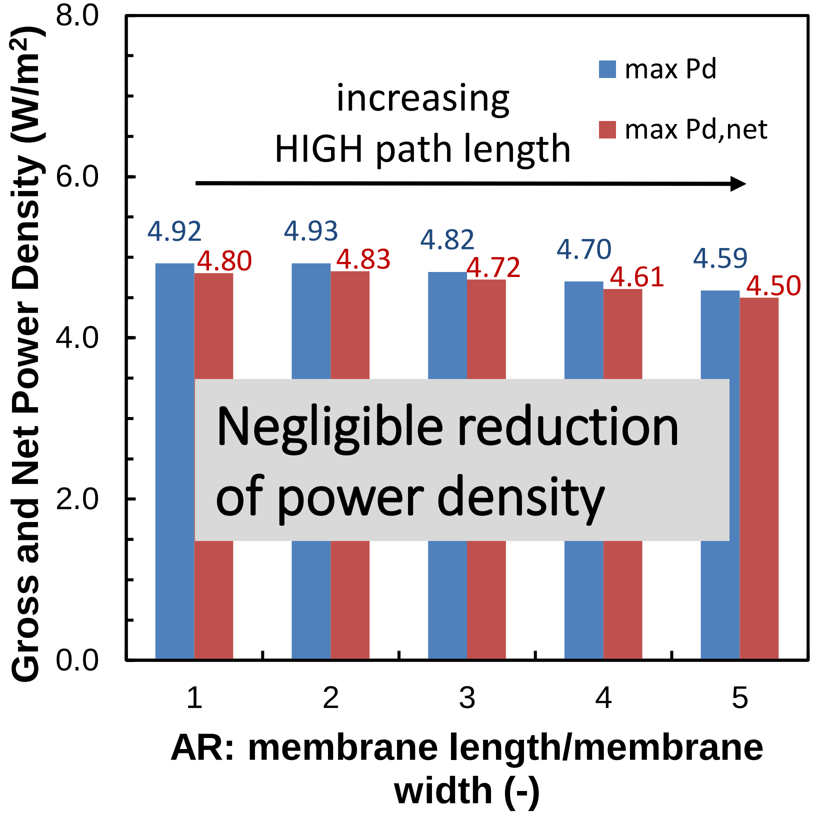
# Different path length for diluate/concentrate (1/2)

- **Effect of Aspect Ratio on Power Density**

$$Aspect\ Ratio\ (AR) = \frac{HIGH\ path\ length\ (L)}{LOW\ path\ length\ (b)}$$

| Aspect ratio (AR) | Membrane size (b x L) |
|---|---|
| 1 | 20x20 |
| 2 | 20x40 |
| 3 | 20x60 |
| 4 | 20x80 |
| 5 | 20x100 |

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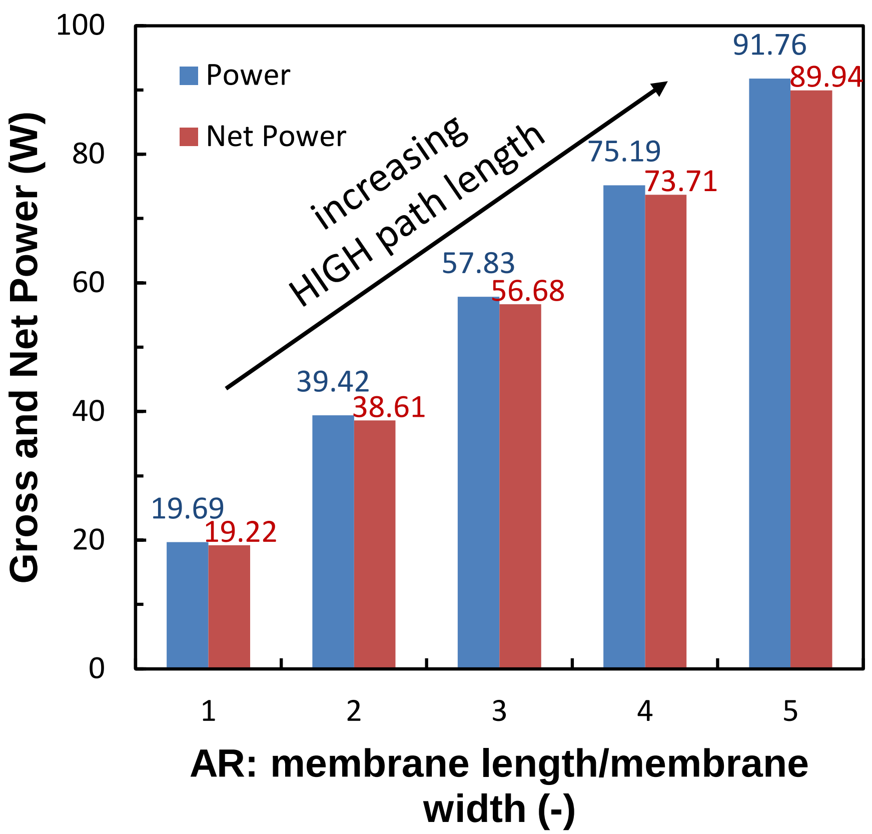
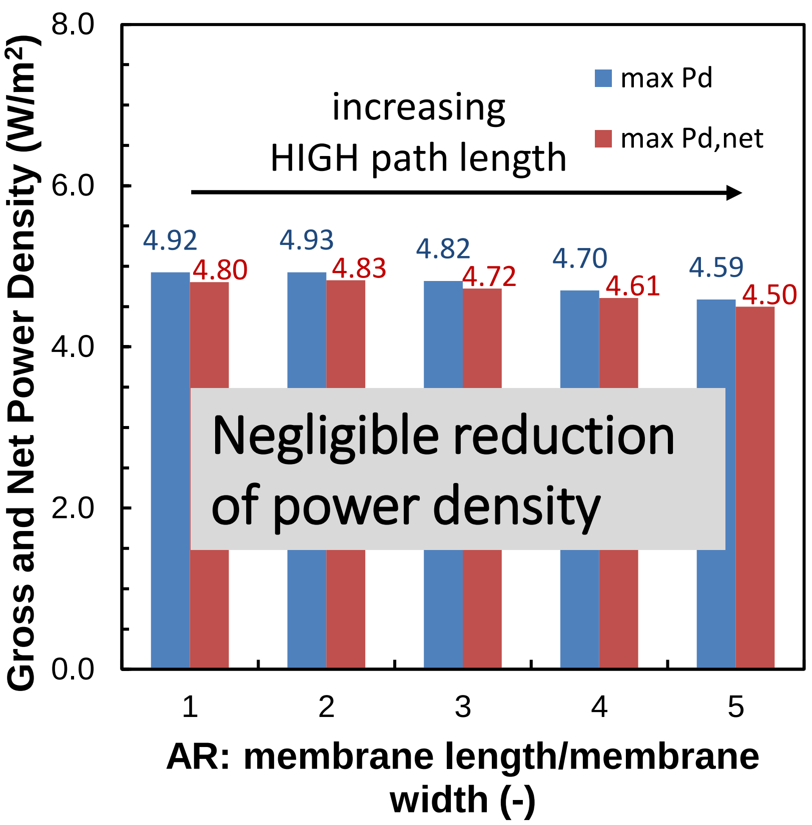
Simulations of a 100-cells stack equipped with Fujifilm membranes, **270 μm** spacers; $C_{LOW}$ = 0.1 M; $C_{HIGH}$ = 5 M; $v_{HIGH} = v_{LOW}$ = 1 cm/s; **membrane width: b = 20 cm**; T=30°C.

# Different path length for diluate/concentrate (2/2)

- Effect of Aspect Ratio on Power output

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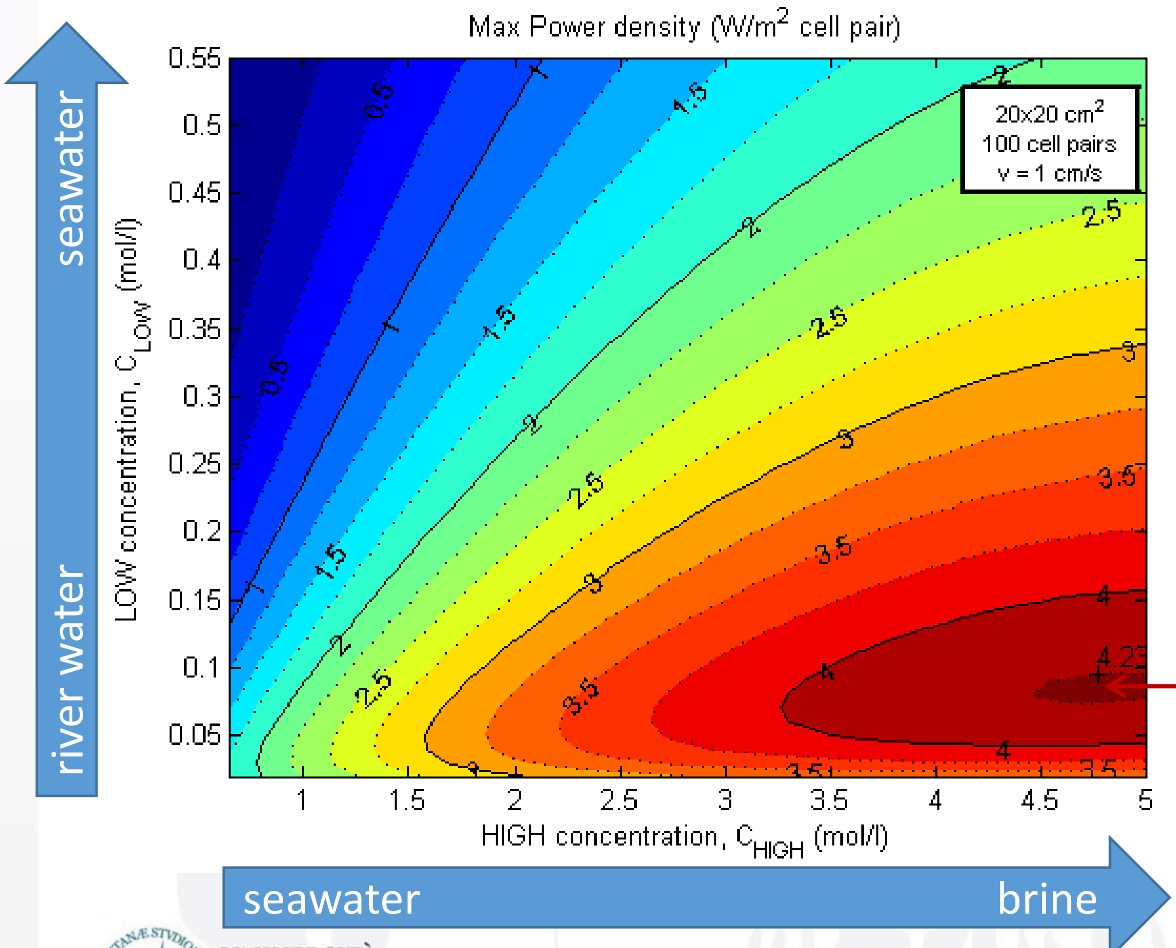
Simulations of a 100-cells stack equipped with Fujifilm membranes, **270 μm** spacers; $C_{LOW}$ = 0.1 M; $C_{HIGH}$ = 5 M; $v_{HIGH}$ = $v_{LOW}$ = 1 cm/s; **membrane width: b = 20 cm**; T=30°C.

# Exploring the optimal operating conditions (1/3)

- **Effect of salt concentration**

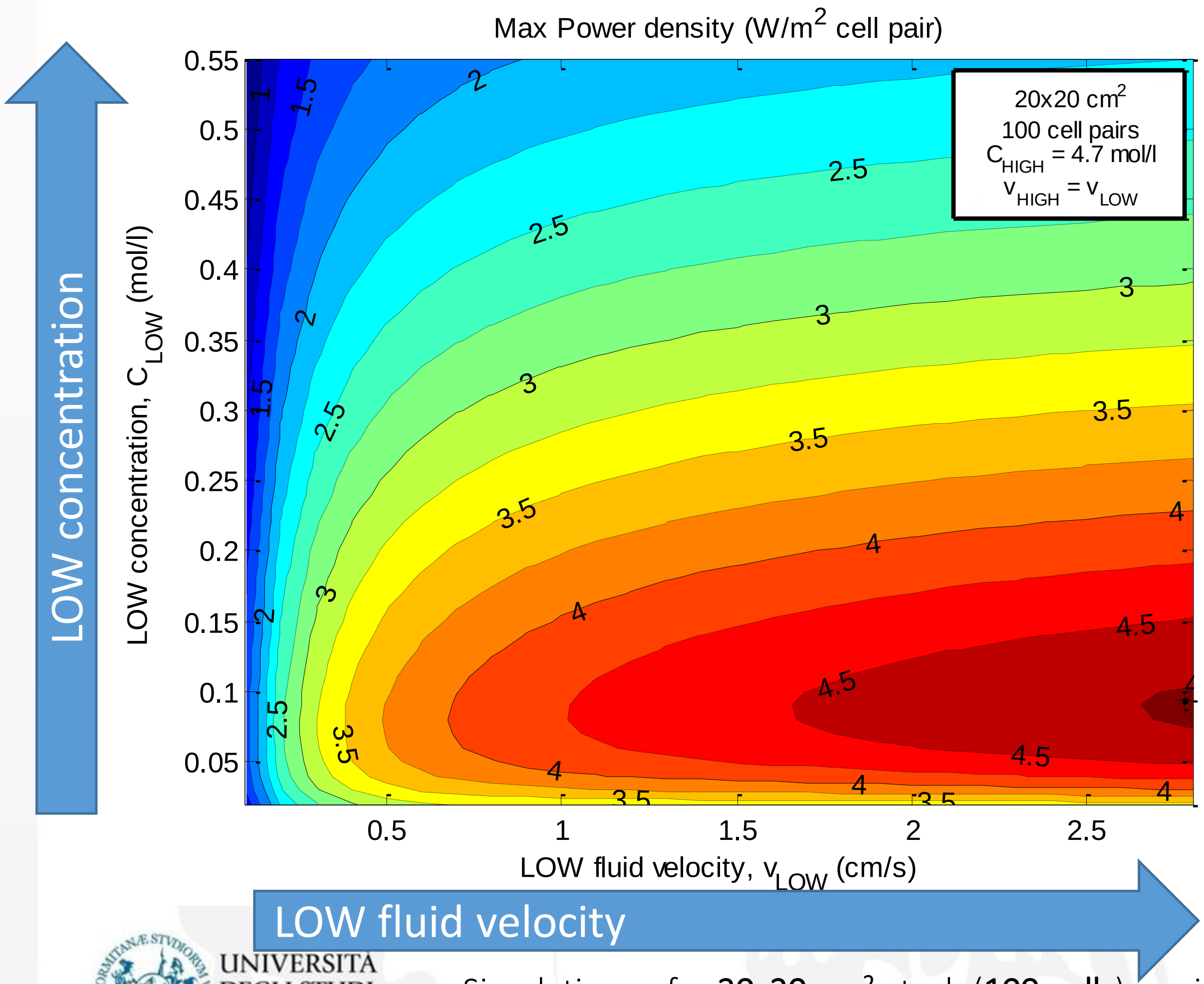



BEST conditions:
brackish water (0.07 – 0.1 M)
+ brine (4.5 – 5 M)

Simulations of a **20x20 cm²** stack (**100-cells**) equipped with Fujifilm membranes, **270 µm** spacers; feed flow velocity: 1 cm/s; T=20°C.

# Exploring the optimal operating conditions (2/3)

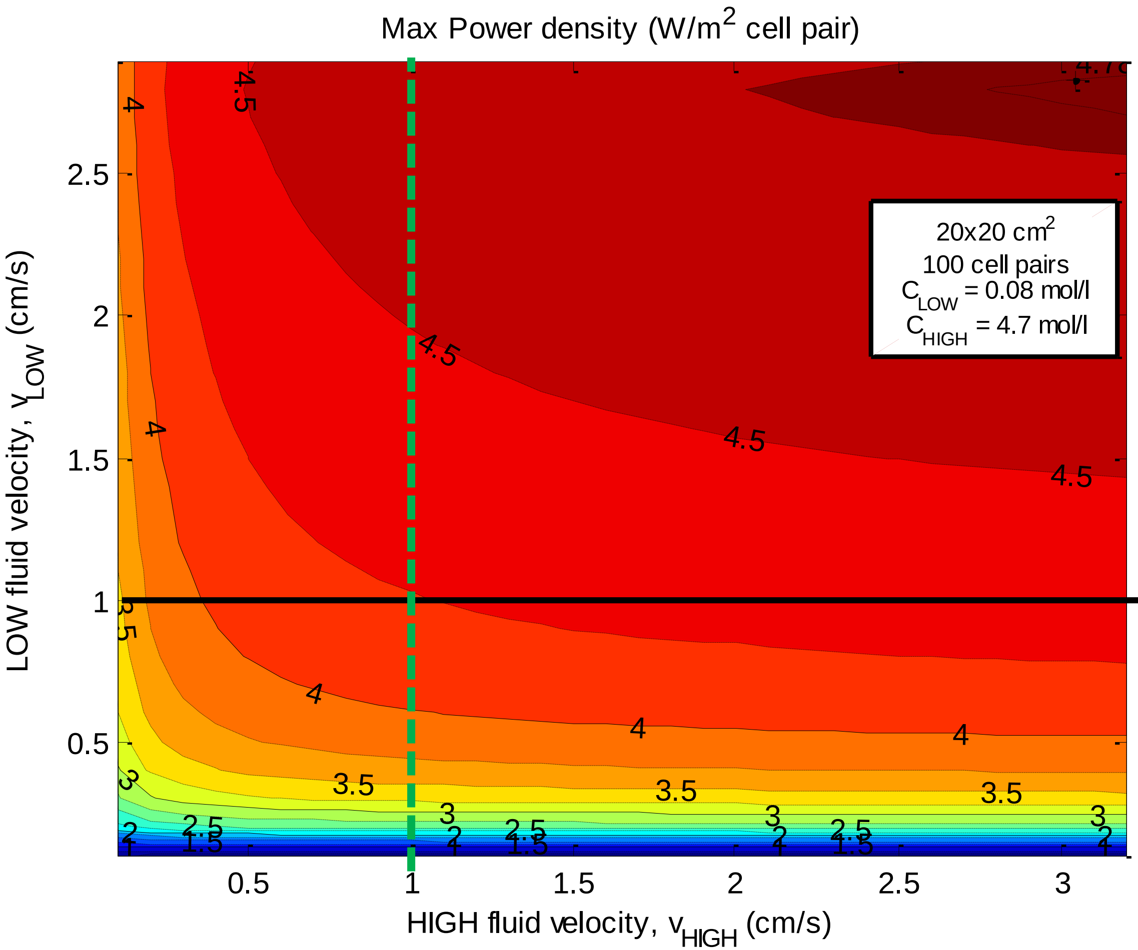
- **Effect of concentration/flow rate for diluate**

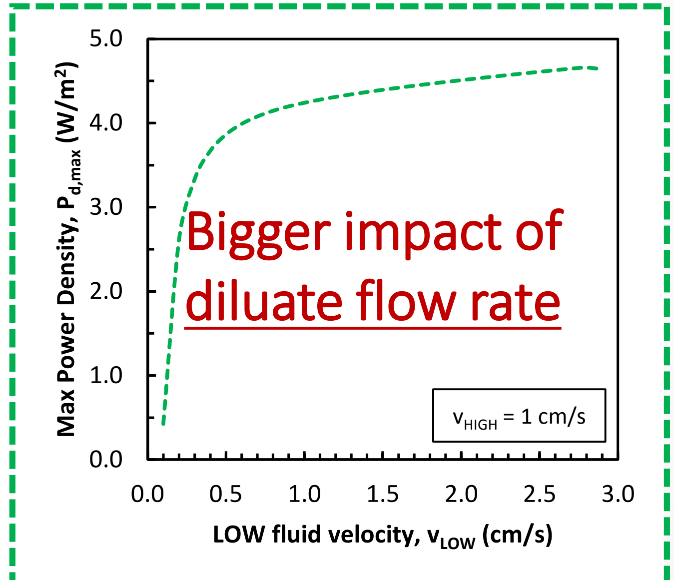


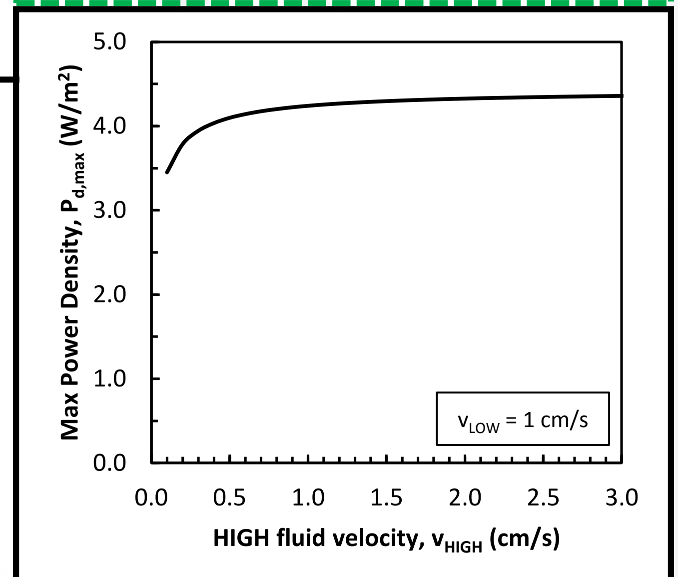

Simulations of a **20x20 cm²** stack (**100-cells**) equipped with Fujifilm membranes, **270 µm** spacers; $C_{HIGH}$ = 4.7 M; $v_{HIGH} = v_{LOW}$; T=20°C.

# Exploring the optimal operating conditions (3/3)

- Influence of feed flow rates

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Simulations of a **20x20 cm²** stack (**100-cells**) equipped with Fujifilm membranes, 270 µm spacers; $C_{LOW}$ = 0.08 M; $C_{HIGH}$ = 4.7 M; T=20°C.

# Simulation of large-scale pilot (1/2)

| Scenario # | Stack size (cm) | cell pair Area | N° cell pairs | Notes |
|---|---|---|---|---|
| 1 | 22 x 22 | 0.05 $m^2$ | 100 | Reference case (small prototype) |
| 2 | 22 x 22 | 0.05 $m^2$ | 500 | Larger number of cell pairs |
| 3 | 44 x 44 | 0.20 $m^2$ | 500 | symmetrical stack |
| 4 | 22 x 88 | 0.20 $m^2$ | 500 | asymmetrical stack, AR = 4 |
| 5 | 44 x 88 | 0.44 $m^2$ | 500 | asymmetrical stack, AR = 2 |
| 6 | 22 x 88 | 0.20 $m^2$ | 500 | asymmetrical stack, different velocity ($v_{LOW}$ = 1 cm/s, $v_{HIGH}$ = 2 cm/s) |

Overall conditions:
- HIGH concentration: 5 M NaCl
- LOW concentration: 0.1 M NaCl
- Temperature : 30°C
- Fluid velocity: 1 cm/s (except for scenario # 6)

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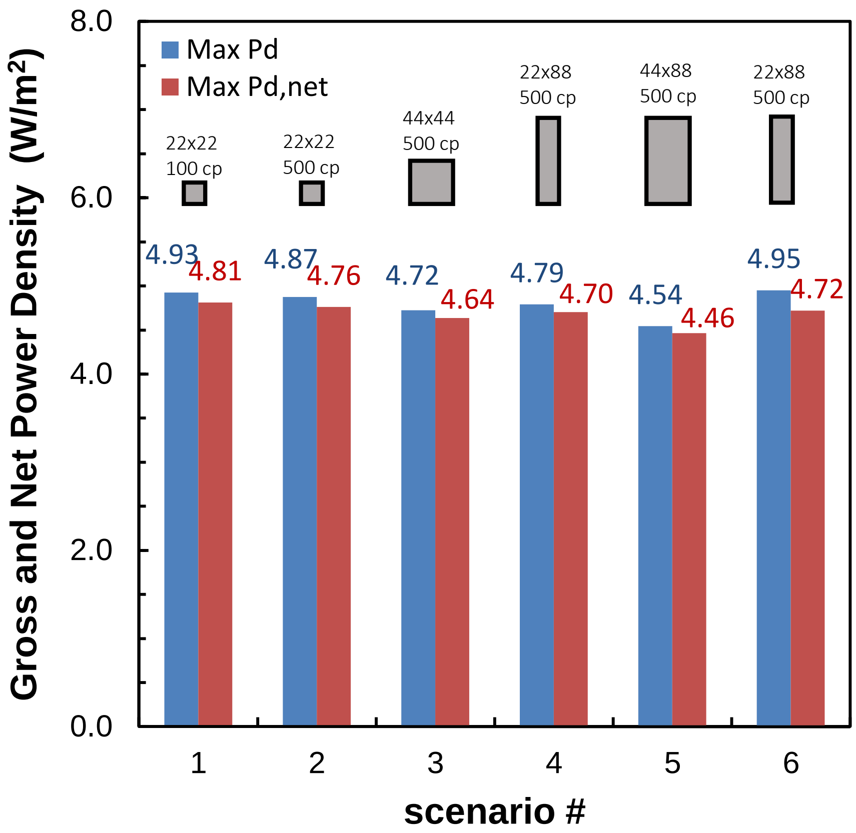
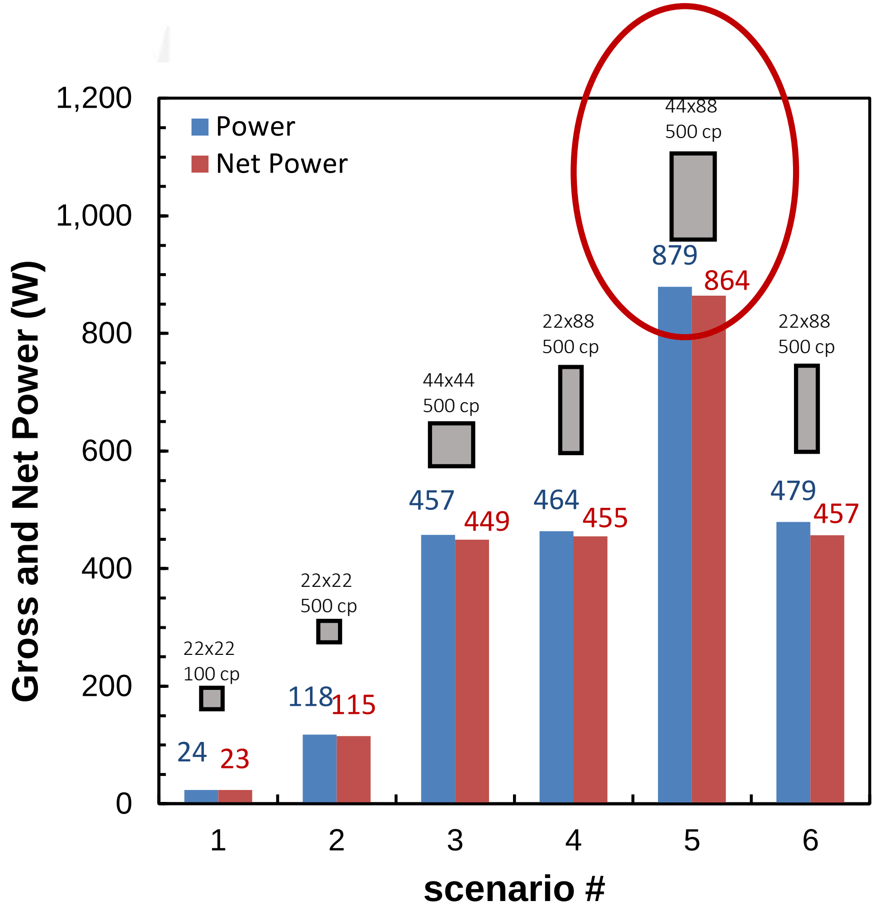
# Simulation of large-scale pilot (2/2)

- Gross and Net Power density

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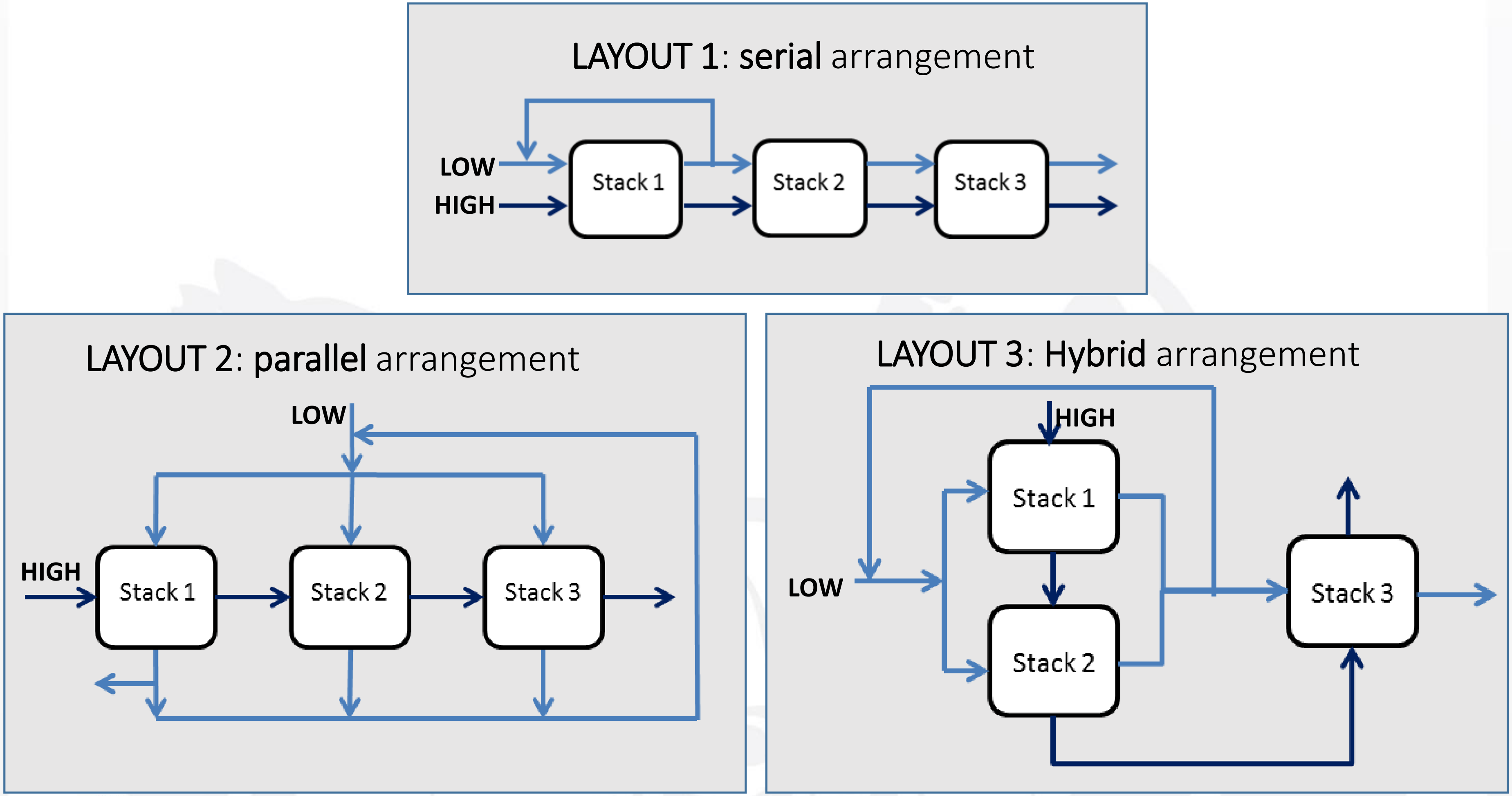
Simulations of stacks equipped with Fujifilm membranes, 270 μm spacers; $C_{LOW}$ = 0.1 M; $C_{HIGH}$ = 5 M; T=30°C.

# Process simulation for a 3 RED units plant (1/4)

- Investigated layouts

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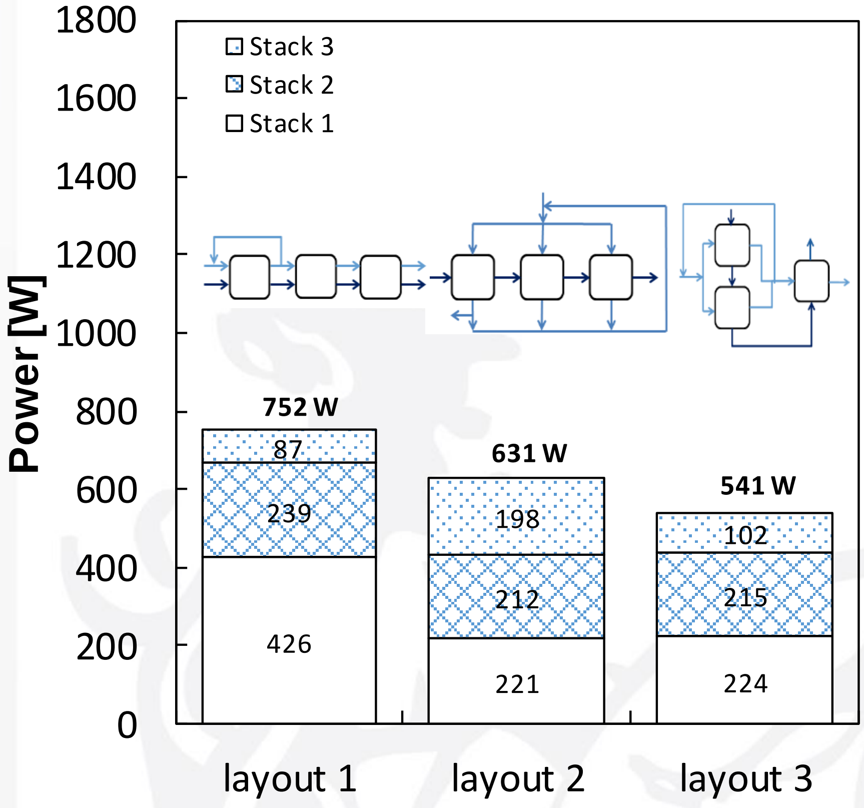
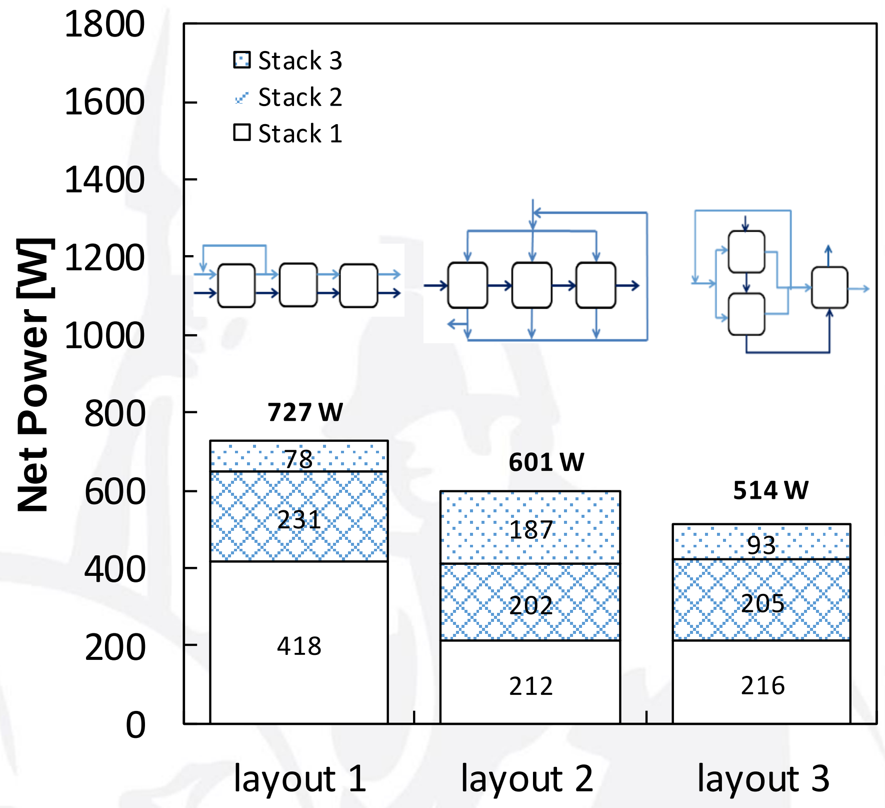
# Process simulation for a 3 RED units plant (2/4)

- Inlet diluate flow rate: <u>**20 l/min**</u>

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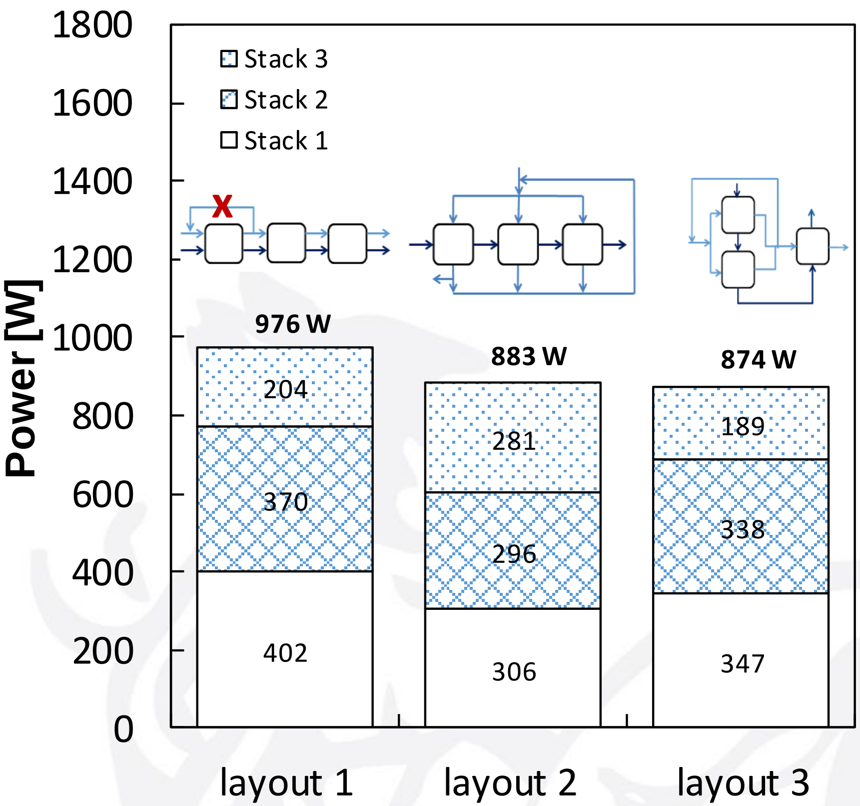
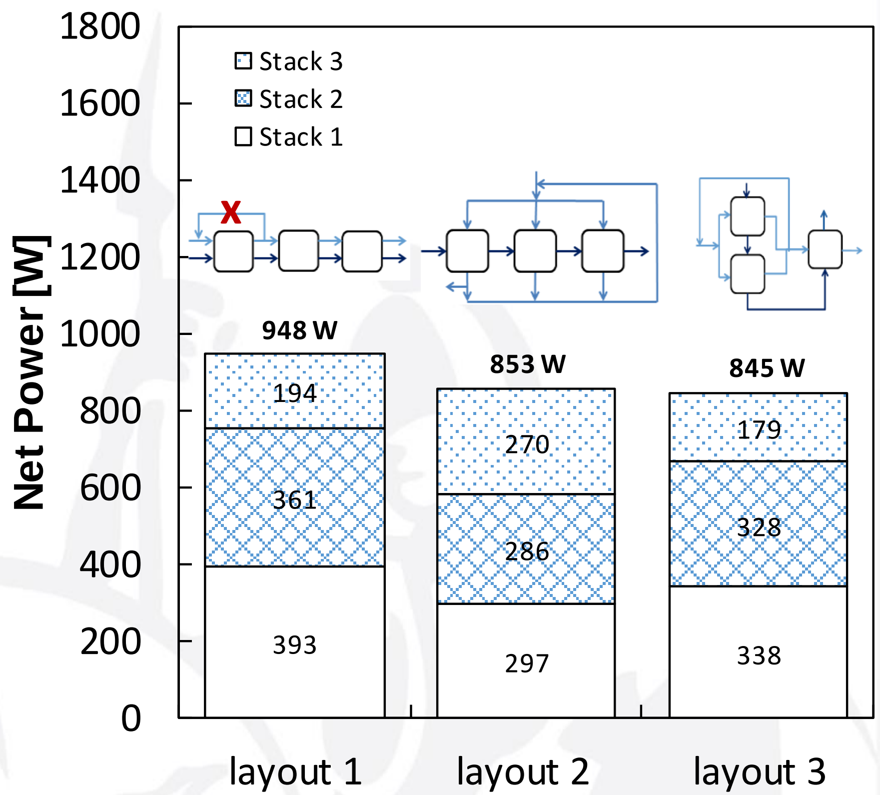
3 stacks (500 cells) equipped with Fujifilm membranes 44×44 cm, 270 μm woven spacers.
$C_{HIGH}$ = 5M; $Q_{HIGH}$ =29.4 lt/min; make-up of brackish water, **$Q_{MU}$ = 20 lt/min**, $C_{MU}$ = 0.03M

# Process simulation for a 3 RED units plant (3/4)

- Inlet diluate flow rate: **29.4 l/min**

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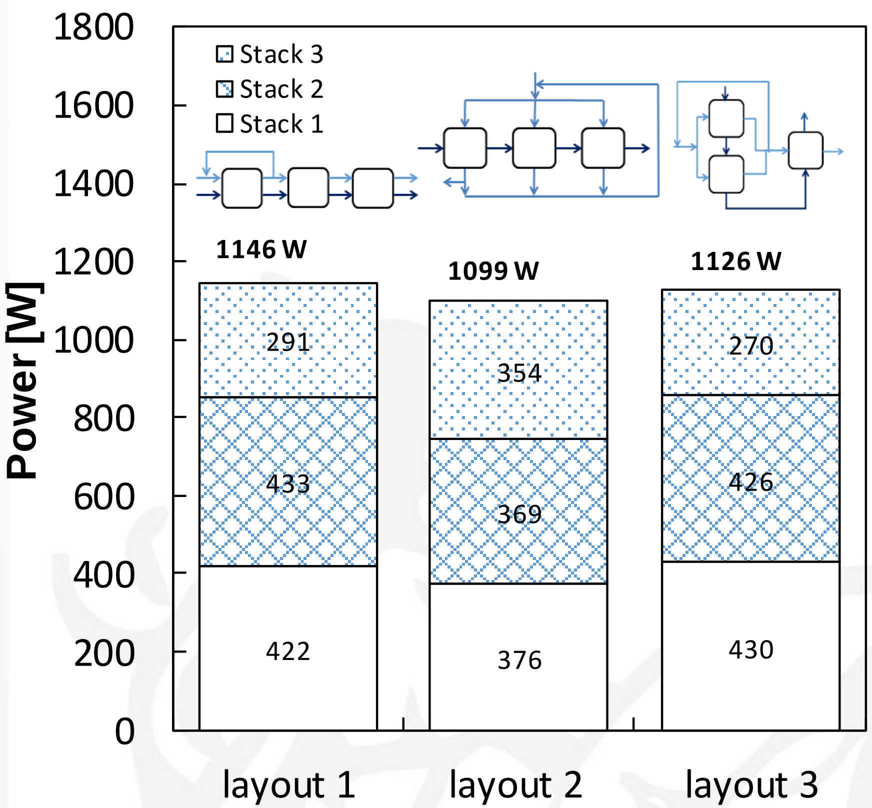
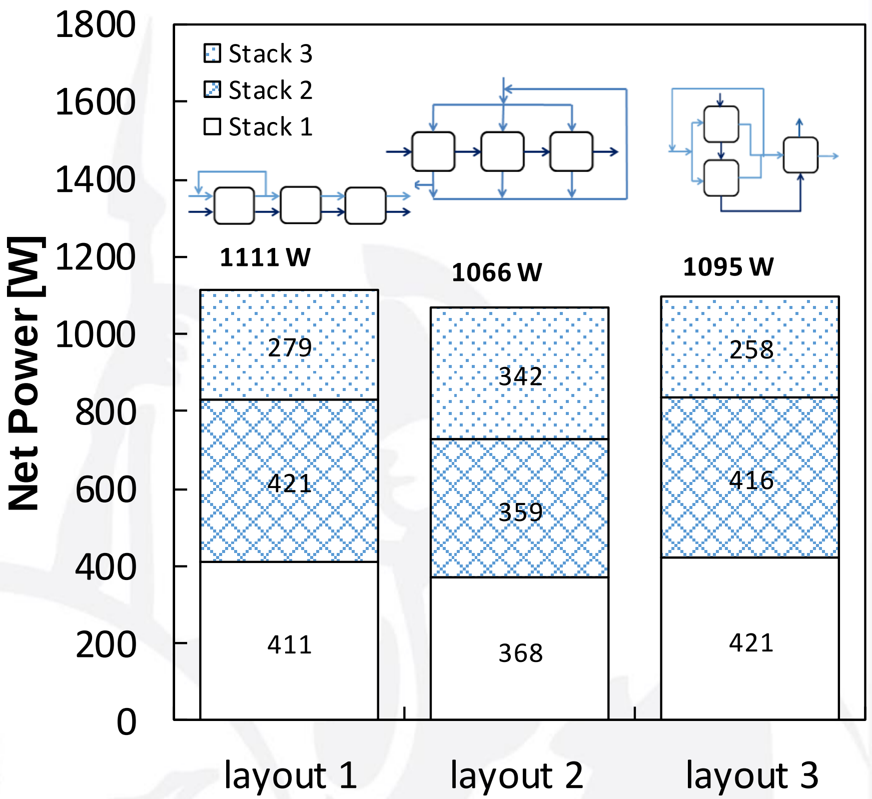
3 stacks (500 cells) equipped with Fujifilm membranes 44×44 cm and 270 µm woven spacers. $C_{HIGH}$ = 5M; $Q_{HIGH}$ =29.4 lt/min; make-up of brackish water, **$Q_{MU}$ = 29.4 lt/min**, $C_{MU}$ = 0.03M.

# Process simulation for a 3 RED units plant (4/4)

- Inlet diluate flow rate: **40 l/min**

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3 stacks (500 cells) equipped with Fujifilm membranes 44×44 cm and 270 μm woven spacers.
$C_{HIGH}$ = 5M; $Q_{HIGH}$ =29.4 lt/min; make-up of brackish water, **$Q_{MU}$ = 40 lt/min**, $C_{MU}$ = 0.03M.

# Conclusions

- ✓ A **Simulator** for **RED process** was developed
- ✓ Asymmetrical stack design (i.e. longer path for concentrate) increases process performance
- ✓ **brackish water flow rate/concentration** are key parameters for the process
- ✓ **Power output >1 kW** can be reached using 3 RED units (44x44 $cm^2$, 500 cell pairs)

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# Acknowledgments


REAPower

www.reapower.eu

Project title: *Reverse Electrodialysis Alternative Power Production*

Call identifier: FP7-ENERGY-2010-FET

(Future Emerging Technologies for Energy Applications)


# Next events on Salinity Gradient Power

INES Events

- 10-11 June 2014 Montreal (Canada)
- 23 June 2014 Brussels (Belgium)

CAPMIX Conference

- 10-12 September 2014 Leeuwarden (The Netherlands)

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Thank you
for your attention
EuroMed 2015
Desalination for Clean Water and Energy
Palermo, Italy, 10-14 May 2015
Michele Tedesco
michele.tedesco@unipa.it
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