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

www.reapower.eu

REAPower: Use of Desalination Brine for Power Production through Reverse Electrodialysis

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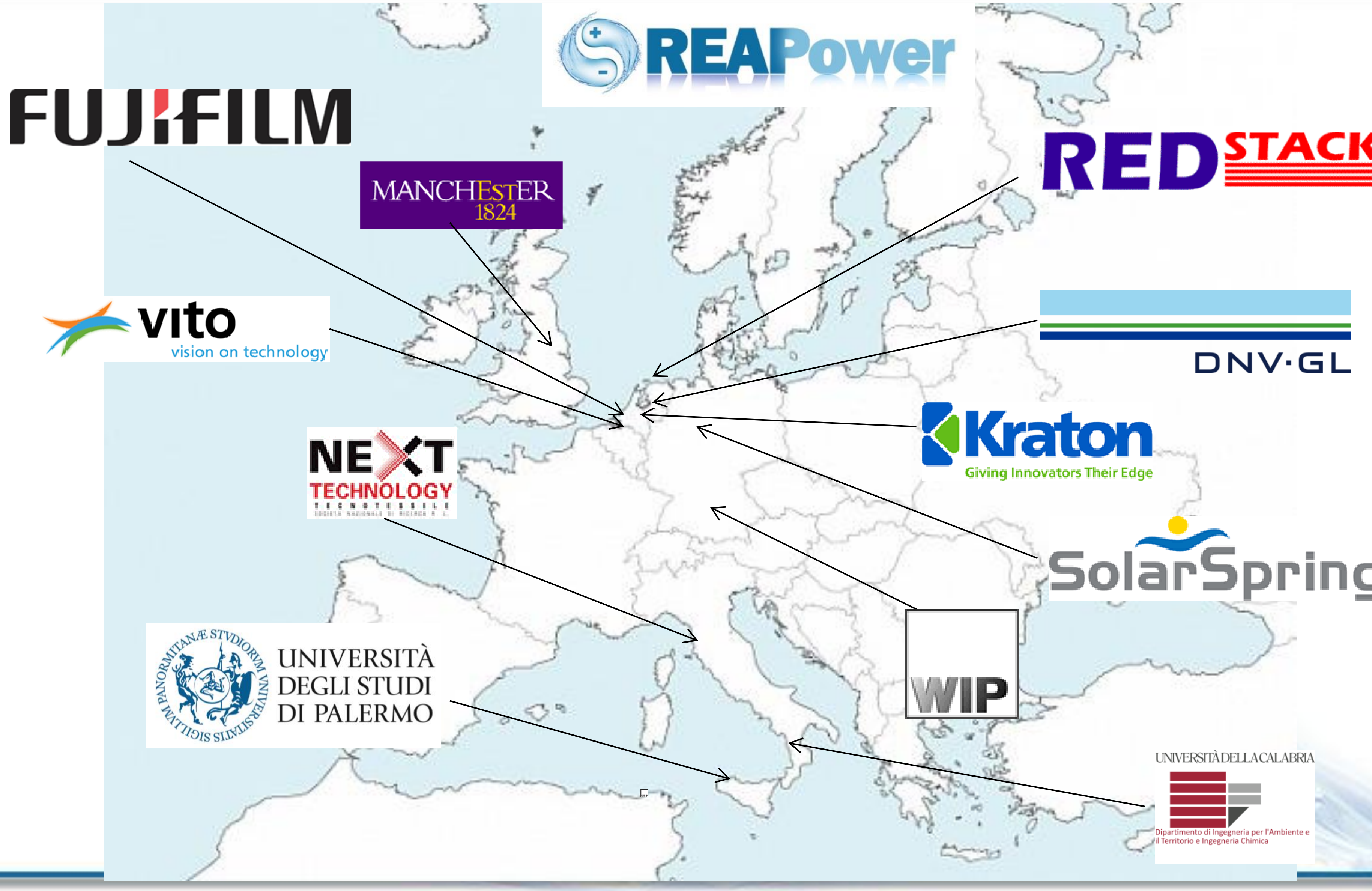
Second International Conference on Salinity Gradient Energy
10-12 September 2014, Leeuwarden (The Netherlands)

The REAPower Project

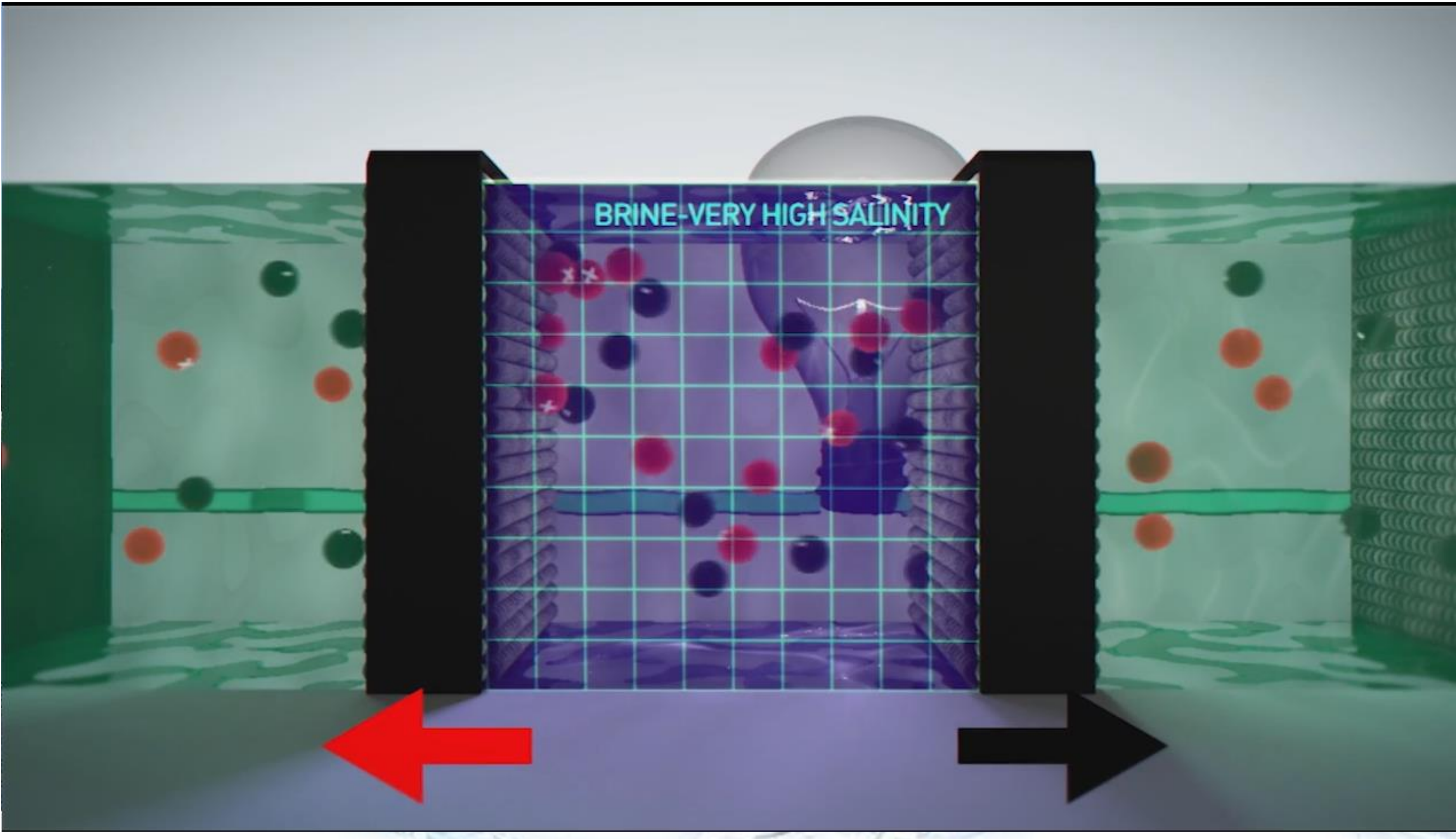
Main facts:

- "Reverse Electrodialysis for Alternative Power production"
- Cooperative project financed through the FP7 programme
- Starting date: 1 October 2010
- Closing date: 30 September 2014

The REAPower Project Consortium



The Reverse Electrodialysis technology



The REAPower Project

Potential Sources of brine

	Concentration of brine (g of salt/litre)	Volume of brine (m^3/day per plant)	Temperature
RO using brackish water	40 - 100	40,000 - 60,000	Ambient
RO using sea water	50 - 80	60,000 - 80,000	Ambient
Multi-stage flash distillation	40 - 50	60,000 - 70,000	5 - 8°C above ambient
Multi-effect distillation	40 - 50	8,000 - 10,000	5 - 8°C above ambient
Chlor-alkali process: Diluted brine	210 - 250	3,000 - 4,000	60 - 80°C
Glycerin to Epichlorohydrin (GTE) plant	200 - 230	1,500 - 2,000	over 60°C
Textile industry: Dyebath (cotton)	14 - 16	less than 100	60°C
Salt ponds	250 - 300	5,000 - 80,000	20 - 35°C
Oil refining	5 - 10	1,000 - 2,000	115 - 150°C
Metal Pickling	150 - 170	1,500 - 2,500	80 - 100°C
Garabogazköl Aylagy	300		Ambient

The REAPower Project Achievements

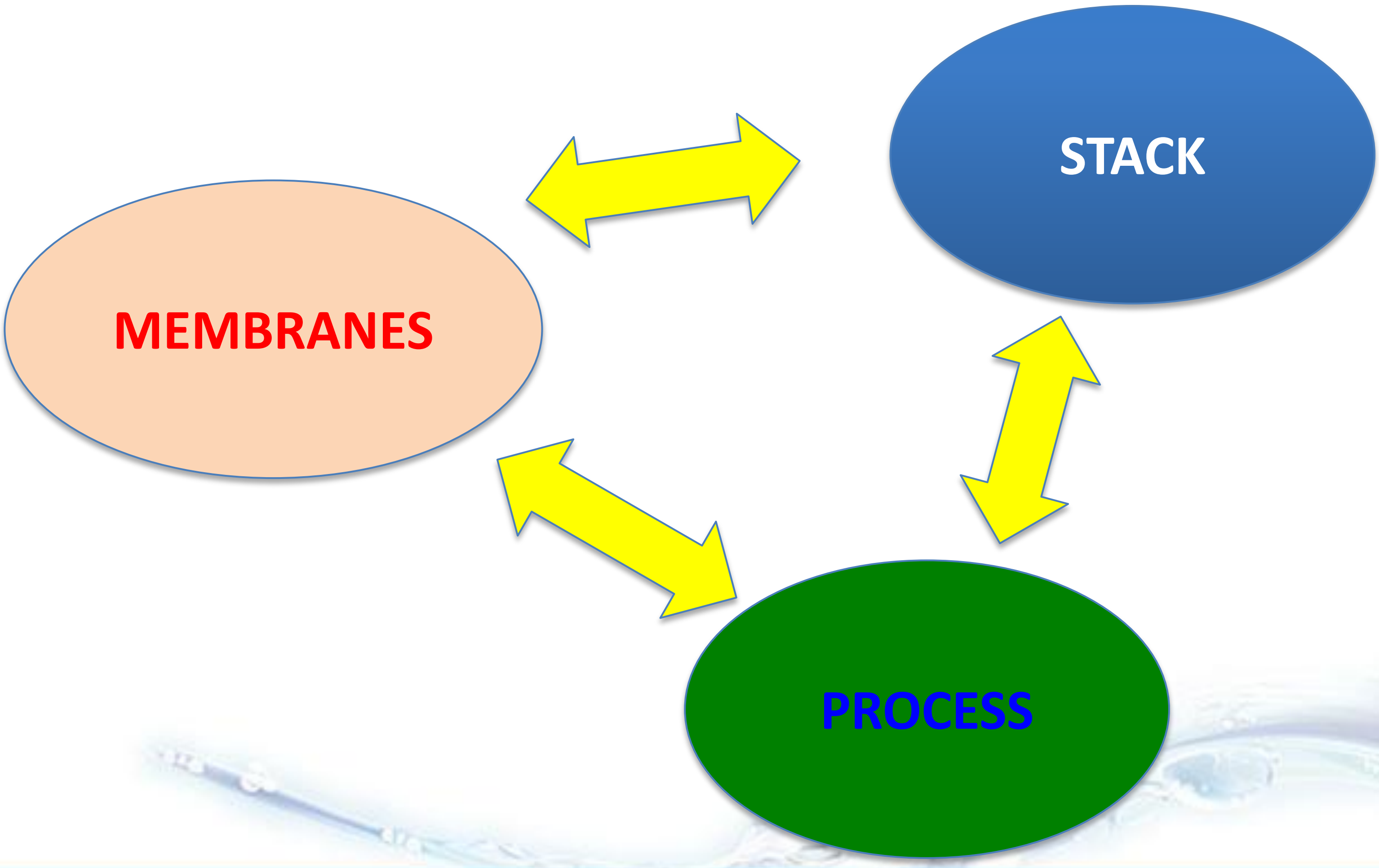
We have come a long way

- ✓ Tailor made membranes have been developed
- ✓ New stack design with higher performance
- ✓ Sophisticated modelling and process simulation
- ✓ 4 small and one larger lab stacks have been constructed and tested extensively
- ✓ Extensive lab testing - record power densities achieved and a lot learned about the factors that affect the performance

- ✓ Modelling and process simulation validated and improved
- ✓ Starting by a stack of 10x10 cm^2 with 50 cell pairs we scaled-up by a factor of 200 to a 44x44 cm^2 stack with 500 cell pairs
- ✓ We moved to a real environment and have been operating for over 6 months - without important problems but still learning a lot

First operating prototype in the world

Technological advances in RED process



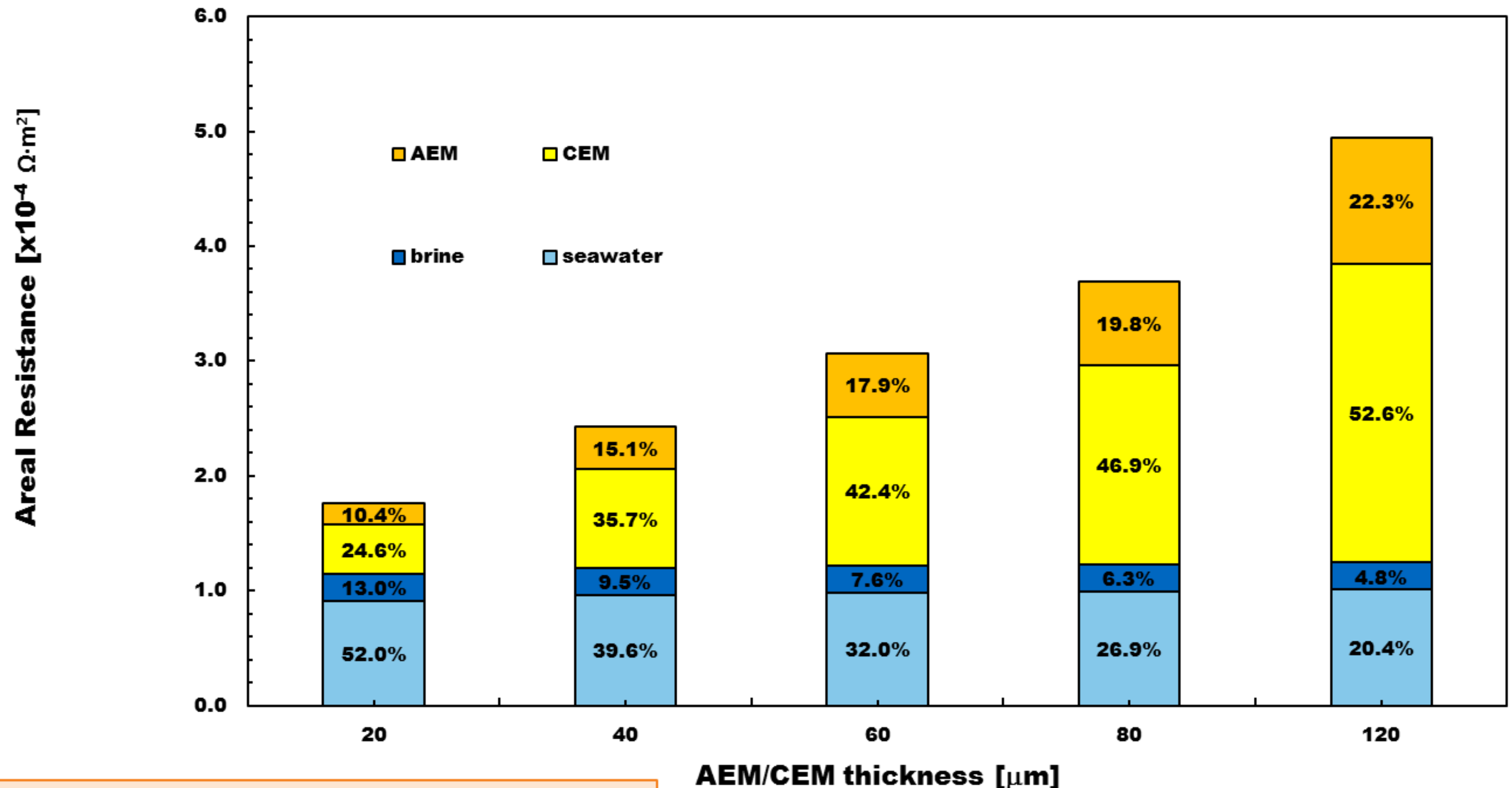
Improvements in membranes development

Reduced
membrane resistance

Increased
permselectivity

Improvements in membranes development

IEMs areal resistance



Influence of IEMs thickness on resistance of the system.

- Simulation of a 1000 cells stack assuming a linear decreasing of IEMs resistance with IEMs thickness.

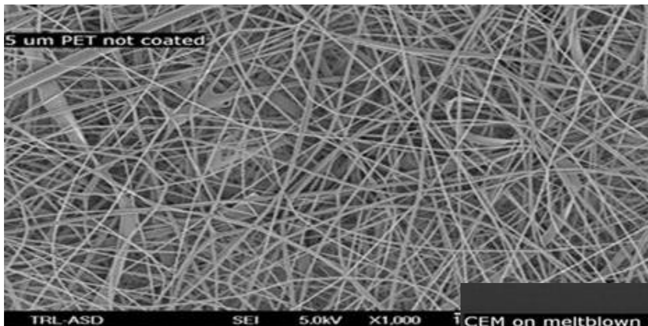
- α_{AEM} = 0.65, α_{CEM} = 0.90.

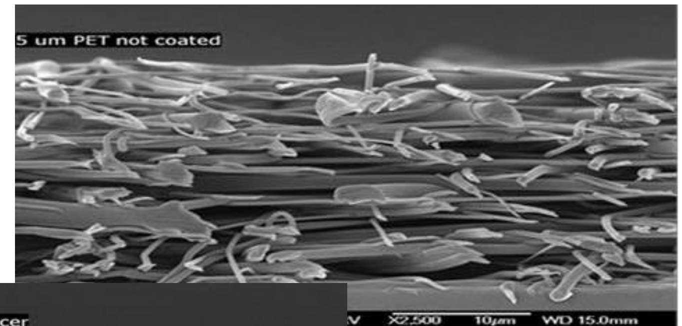
- spacer thickness of seawater/brine compartments d = 200 micron.

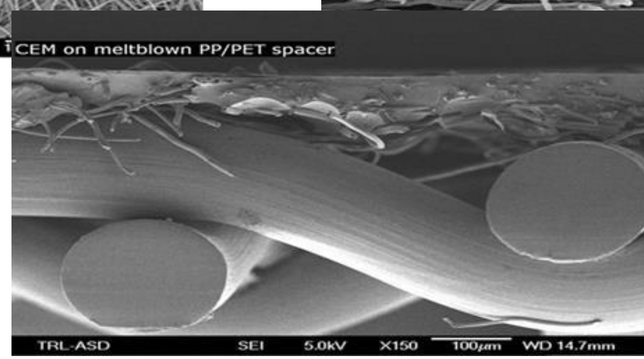
Source: A multi-scale model for the Reverse ElectroDialysis process with seawater and concentrated brines by M. Tedesco University Palermo

Improvements in membranes development

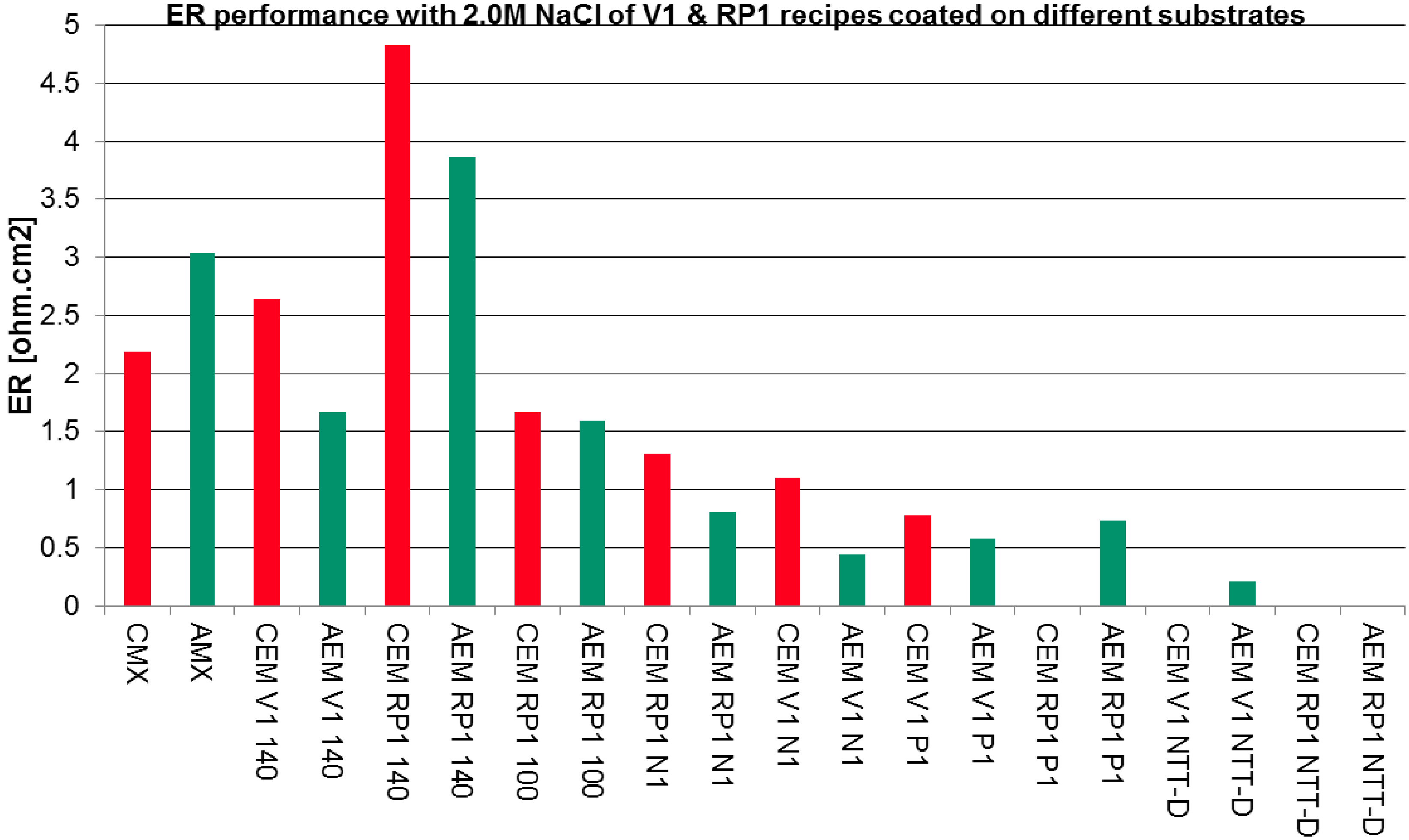
IEMs improved morphology and support







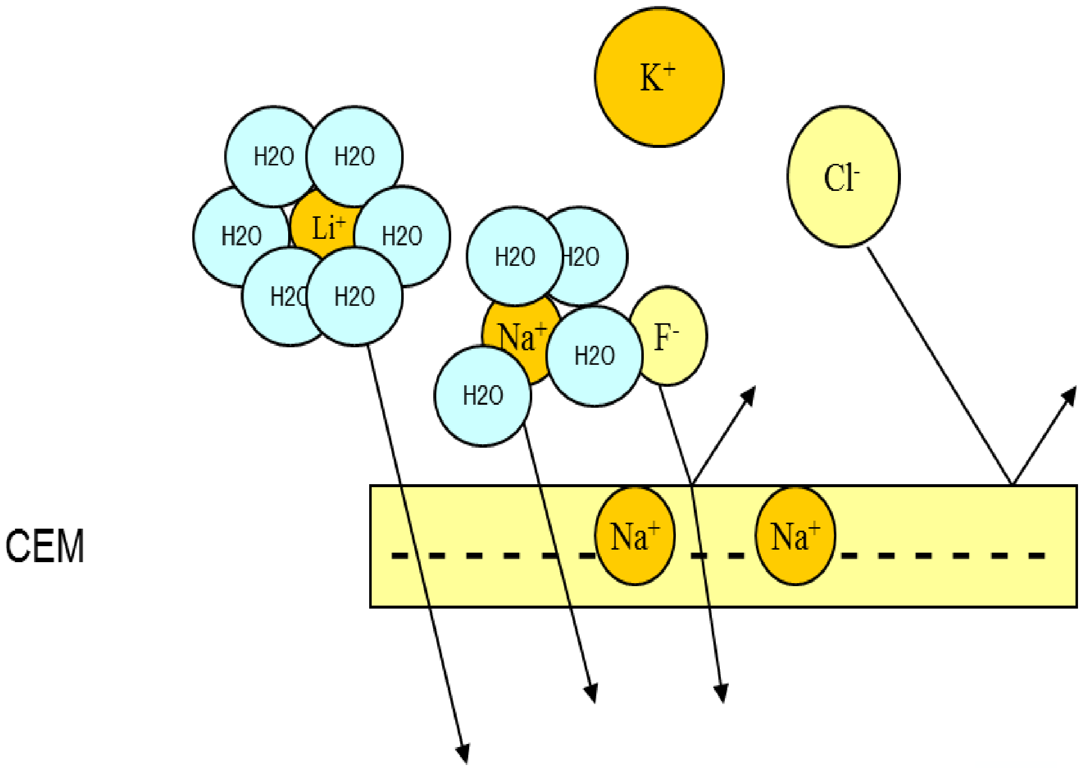
Improvements in membranes development



Thickness 150 - 140 - 110 - 76 - 66 - 50 micron

Improvements in membranes development

IEMs permselectivity: analysis of transport mechanisms



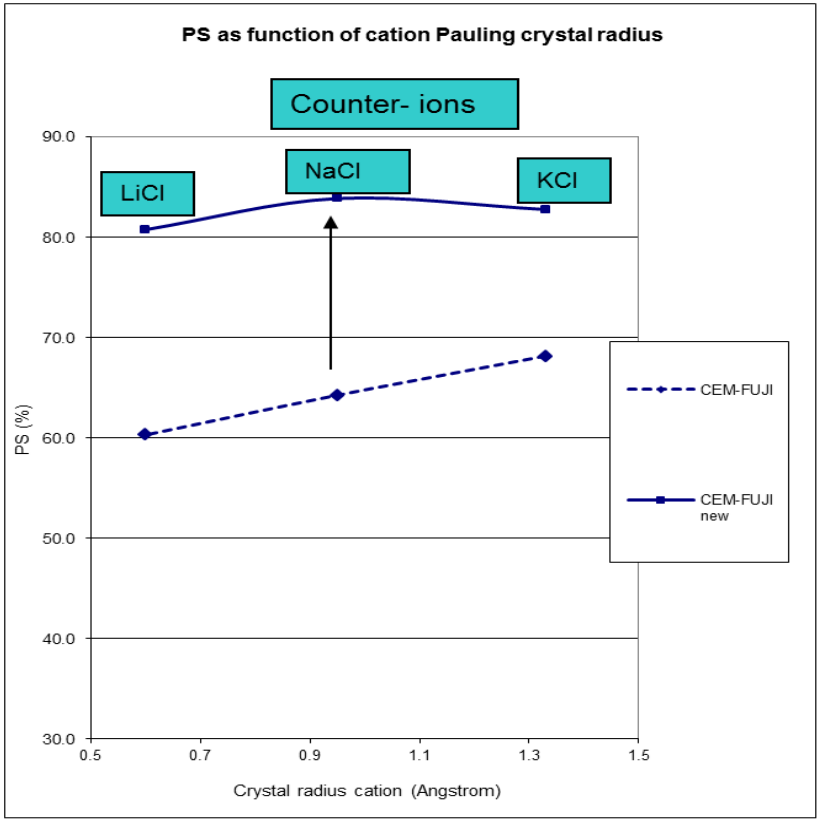
- Size exclusion ?

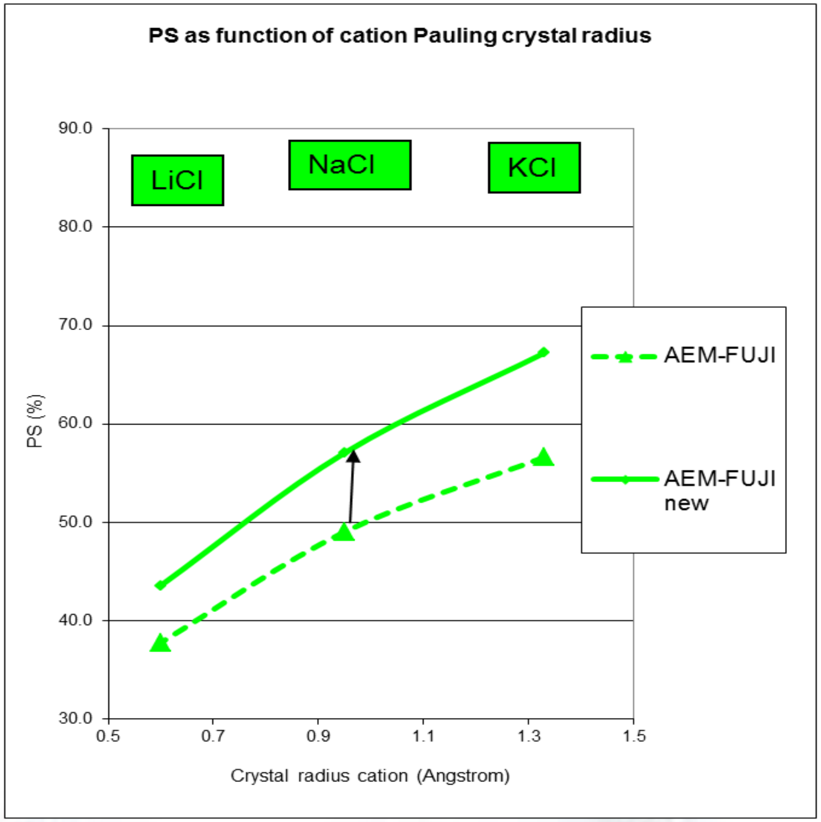
- Co-ion transport by counterions in membrane ?

- Water hydration shell of importance ?

Improvements in membranes development

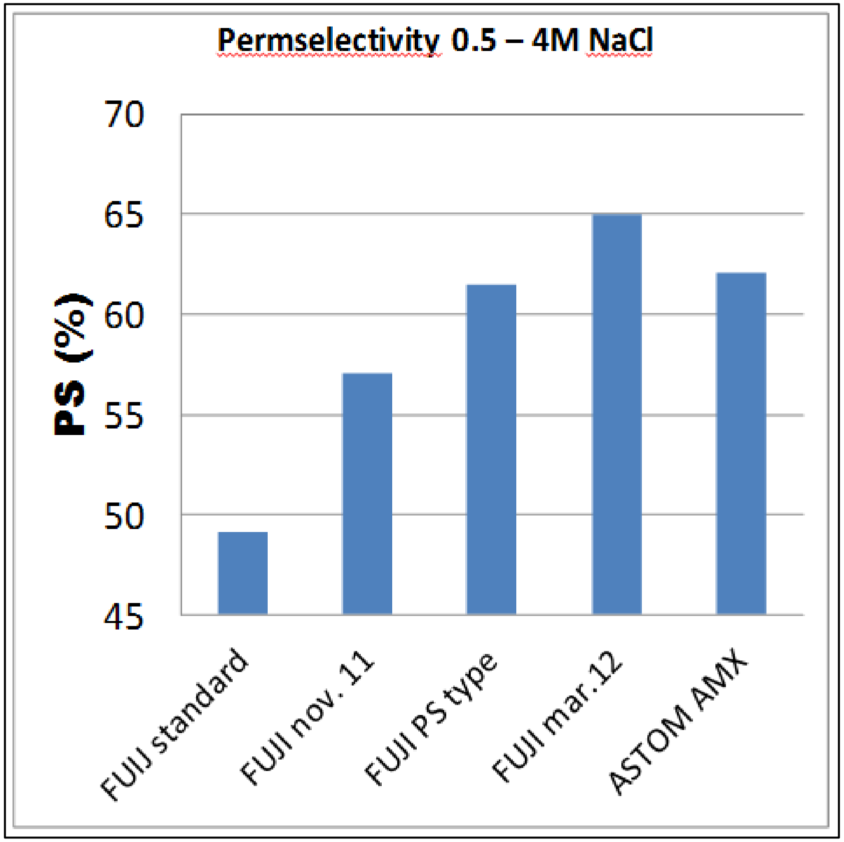
IEMs permselectivity: achievements

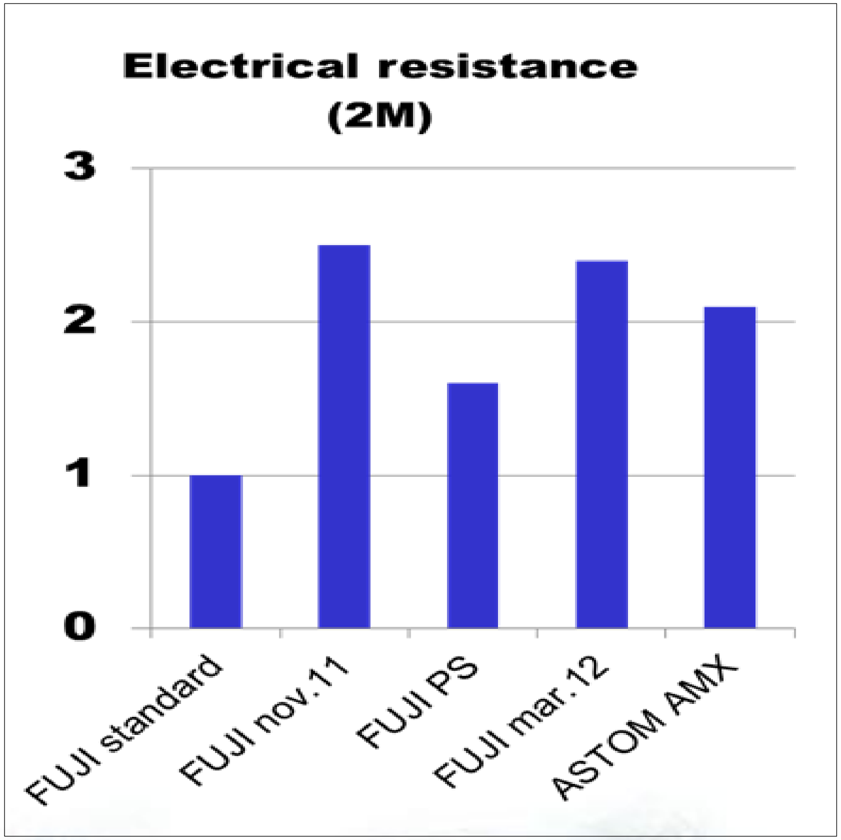




Improvements in membranes development

IEMs: Projects achievements





Electrochemical aspects and stack design

Redox couples selection

Investigated redox couples under different conditions:

- ✓ **$FeCl_3/FeCl_2$**
- ✓ **$K_3Fe(CN)_6/K_4Fe(CN)_6$**
- ✓ Fe(III)-EDTA/Fe(II)-EDTA

New **stack design**

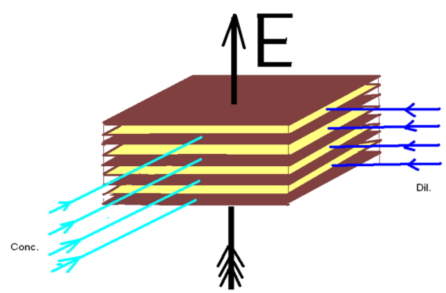
- ✓ Different **stacks** already designed, constructed and tested
- ✓ Currently available for the consortium

Advances in RED technology

RED Stack Development

- Lab stack: 10x10 cm2 , up to 50 cell pairs
- Large lab stack: 20x20 cm2, 100 cell pairs
- Pre-prototype stack: 22x22 cm2; 109 cells
- First prototype pilot stack: 44x44 cm2, 125 cell pairs
- Final prototype pilot stack: 44x44 cm2, 500 cells

200x



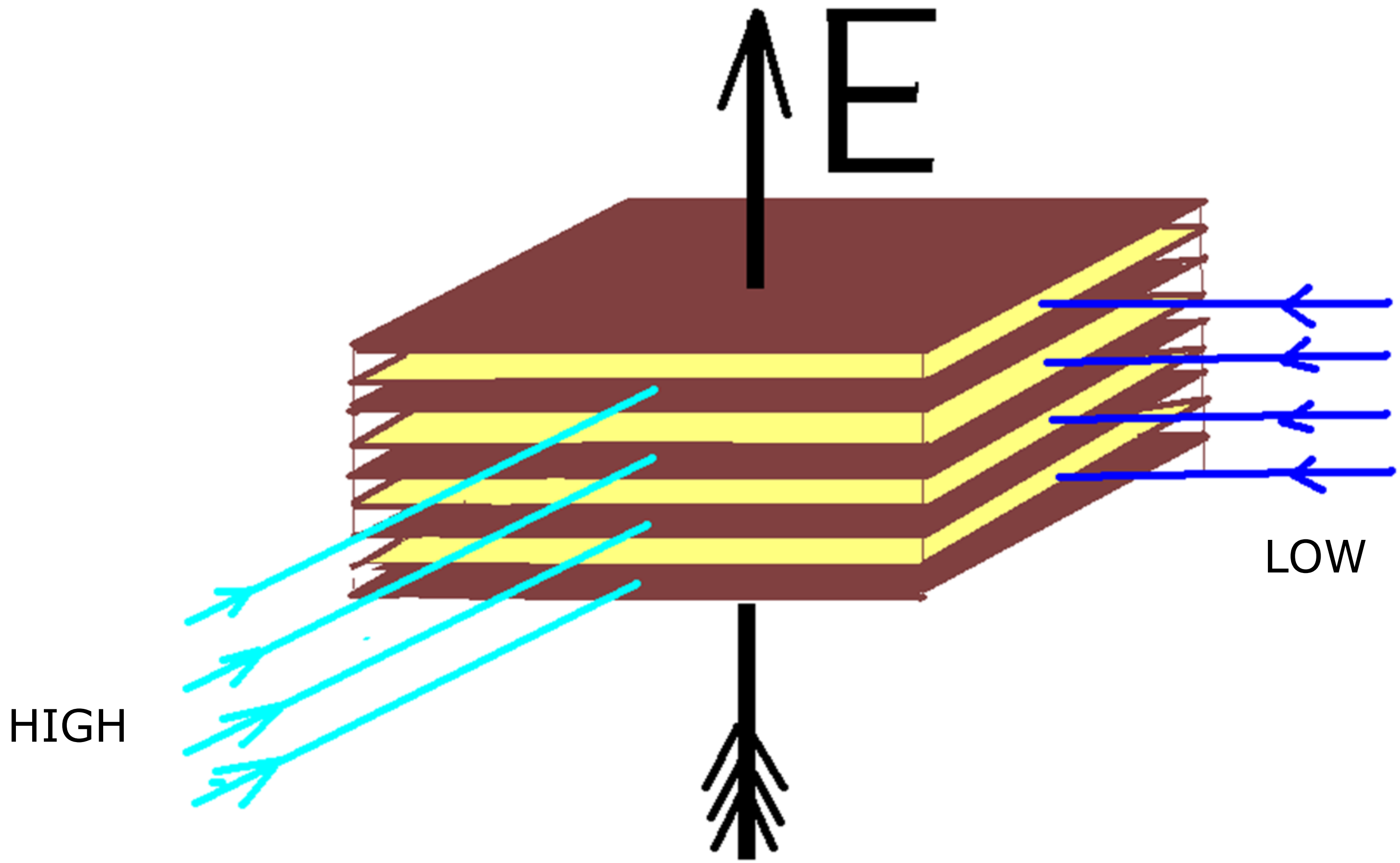
Advances in RED technology

Design goals and challenges

- Leak-free design
- Homogeneous flow distribution
- Minimise parasitic short-cut current losses
- Improving assembly process
- Robust design: Optimising materials and strength

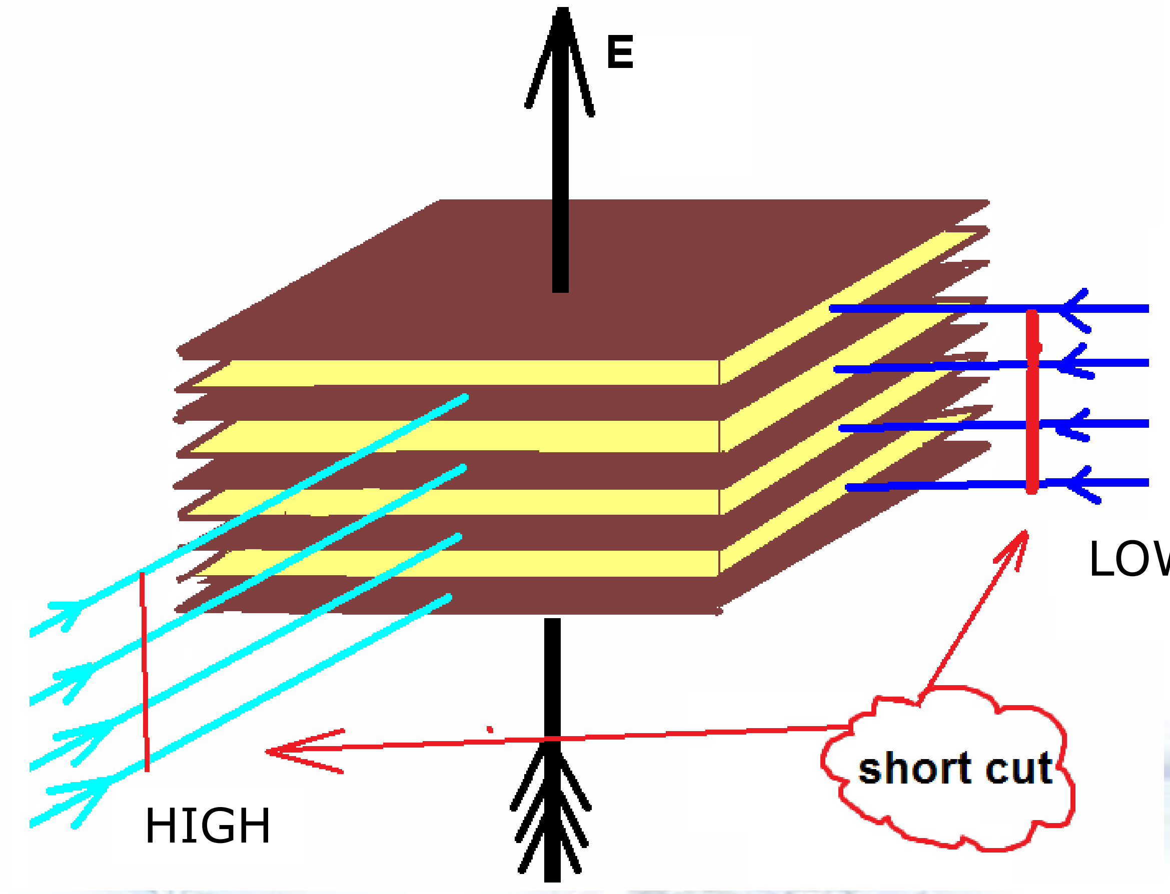
Advances in RED technology

- **Principles of REDstack's Cross-flow Stack**



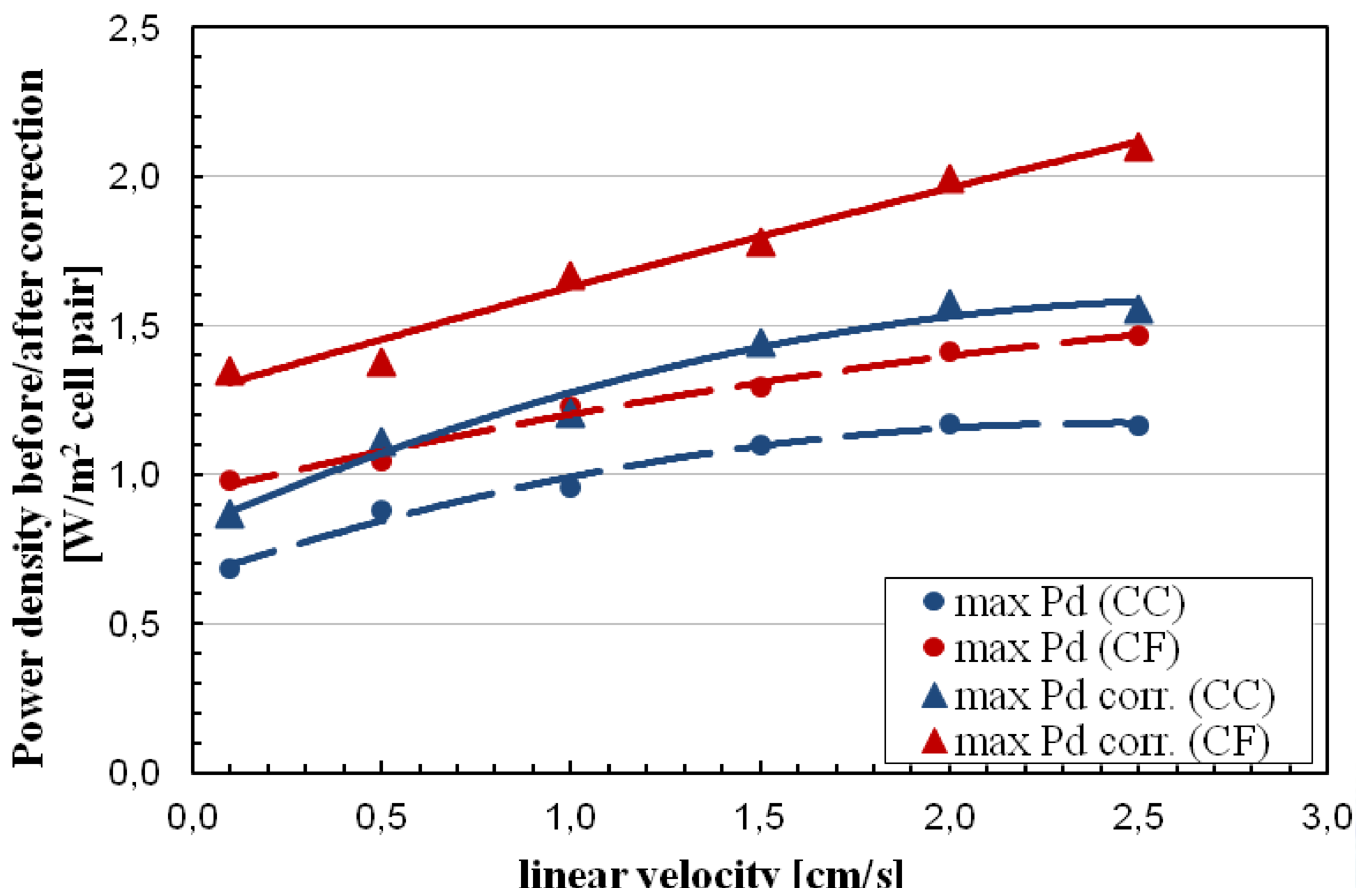
Advances in RED technology

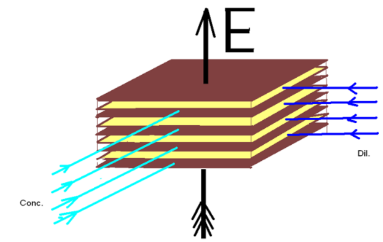
- Principles of REDstack's Cross-flow Stack



Advances in RED technology

Performance Lab Cross-Flow Stack

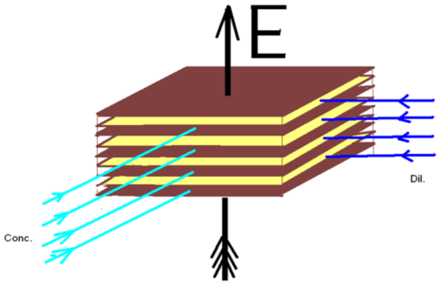




The power density of conventional co-current stack and cross-flow stack using 300 micron spacers.

The REAPower Prototype

Final result: 44x44 cm^2 pilot stacks with 500 cells

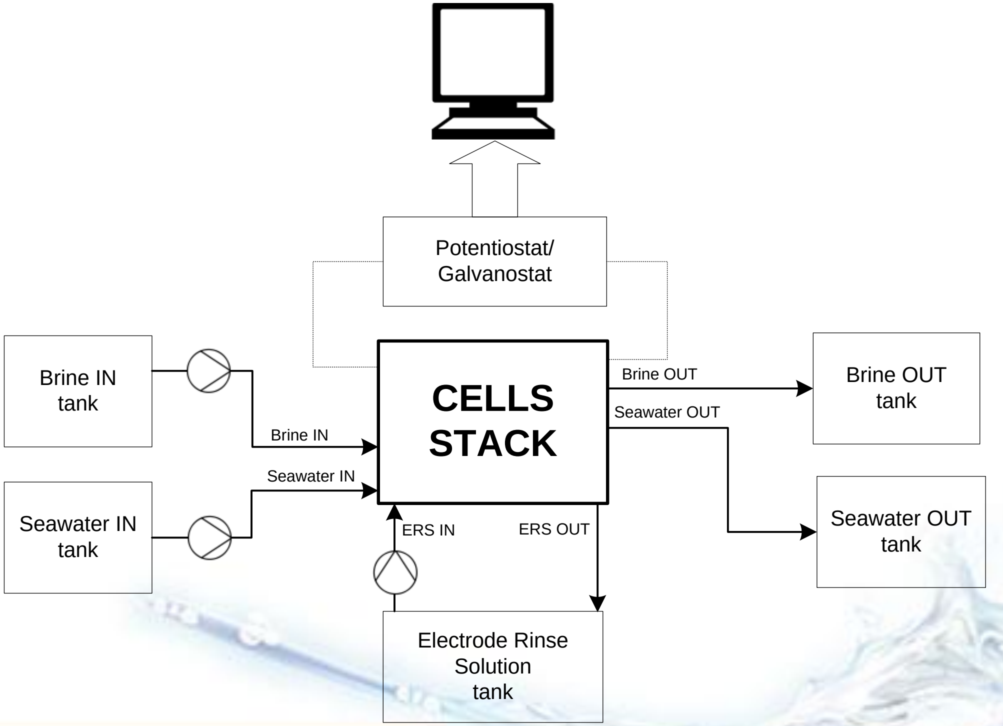


Laboratory Experimental investigation

Experimental investigation on a lab-scale unit

Experimental conditions investigated:

- ✓ fluid velocity (0.1 – 4 cm/s)
- ✓ feed temperature (20 – 40 °C)
- ✓ concentration of redox couple (0.1 – 0.3 M of $K_3Fe(CN)_6/K_4Fe(CN)_6$)
- ✓ salt concentration of dilute solution from 0.1M to 0.55M
- ✓ salt concentration of concentrate solution from 0.5M to 5M



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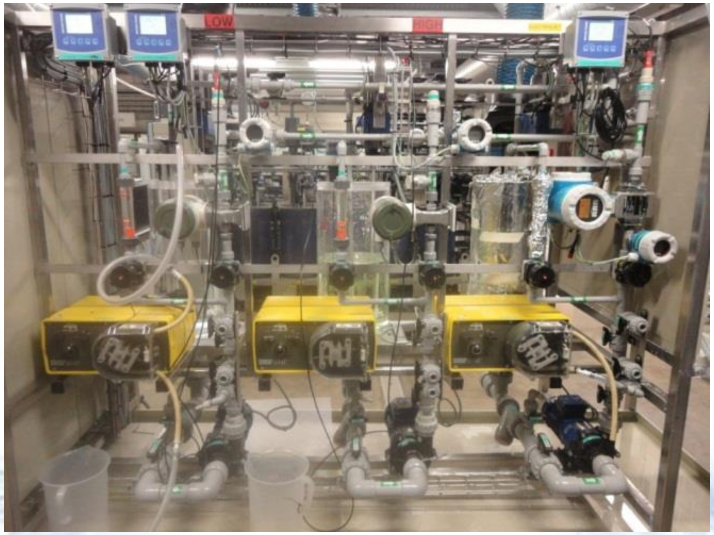
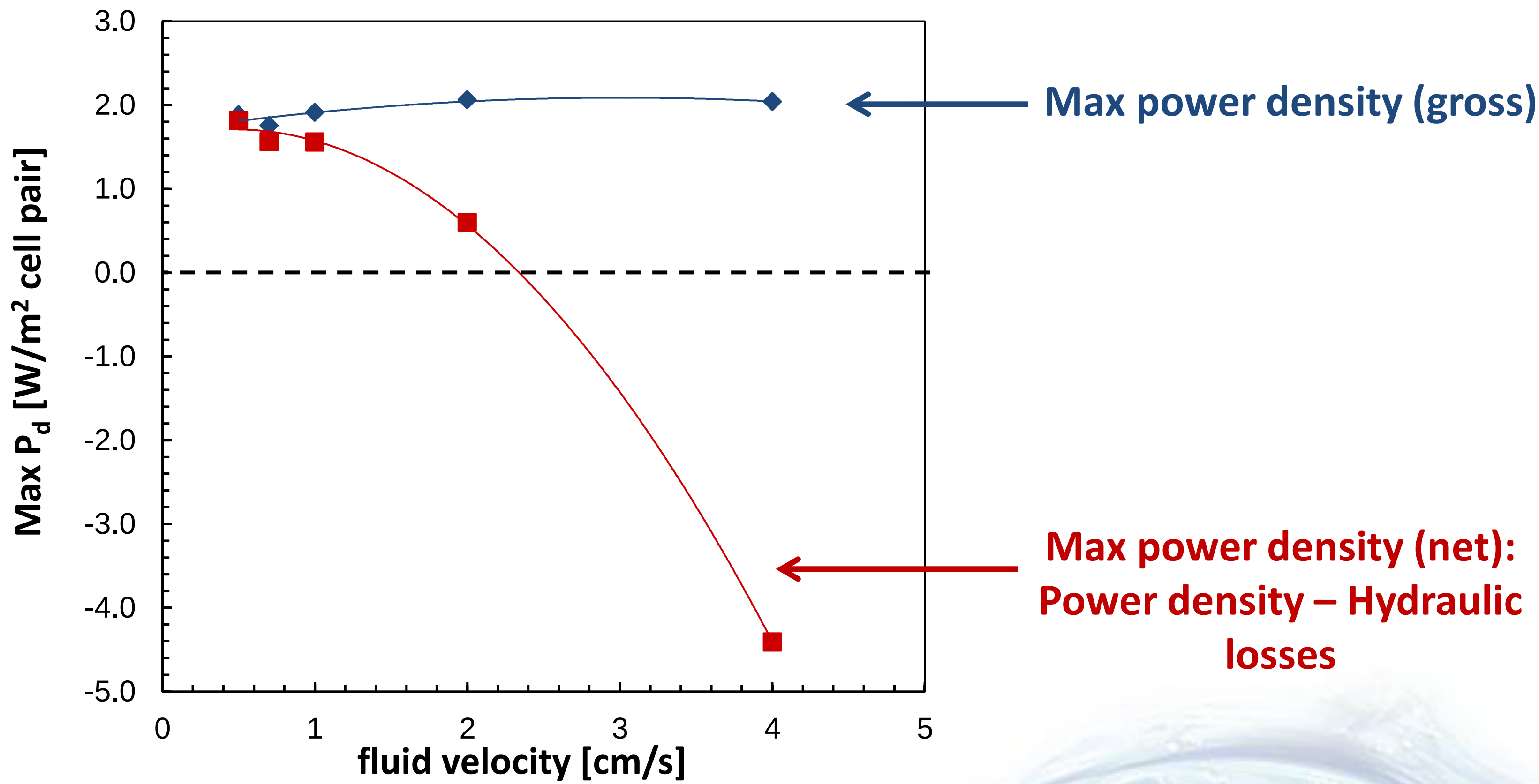


Experimental investigation on a lab-scale unit

Effect of fluid velocity on power output

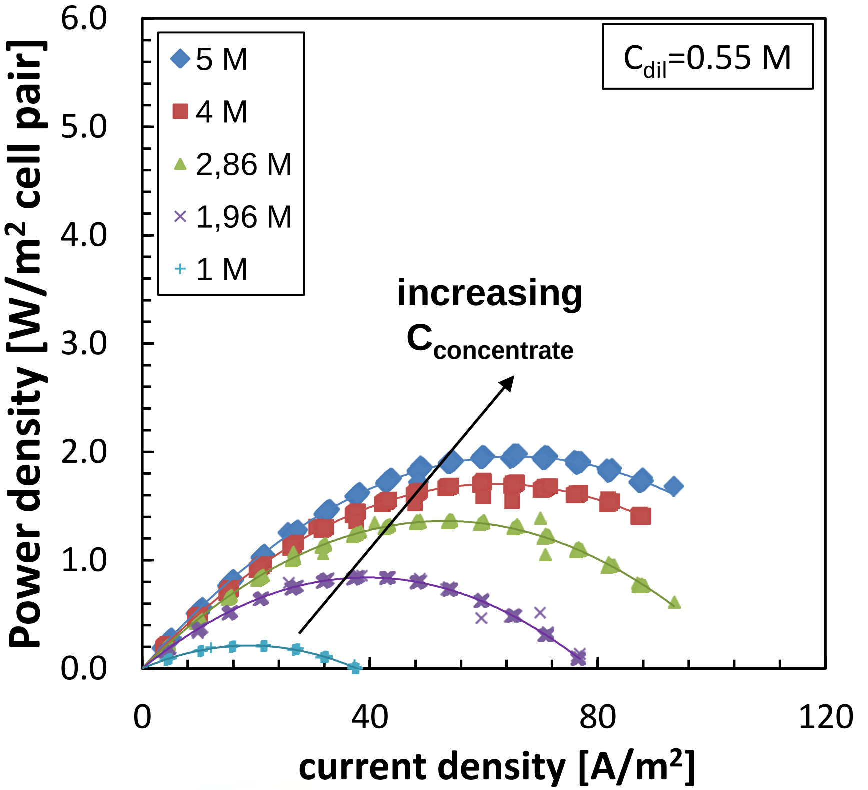


Stack equipped with 50 cell pairs, Fujifilm membranes, Deukum 270 μm spacers .Brine solution: 5 M NaCl, seawater: 0.5 M NaCl. T=20° C. Electrode rinse solution: 0.1 M $K_3Fe(CN)_6$ / $K_4Fe(CN)_6 \cdot 3H_2O$ + 2.5 M NaCl.

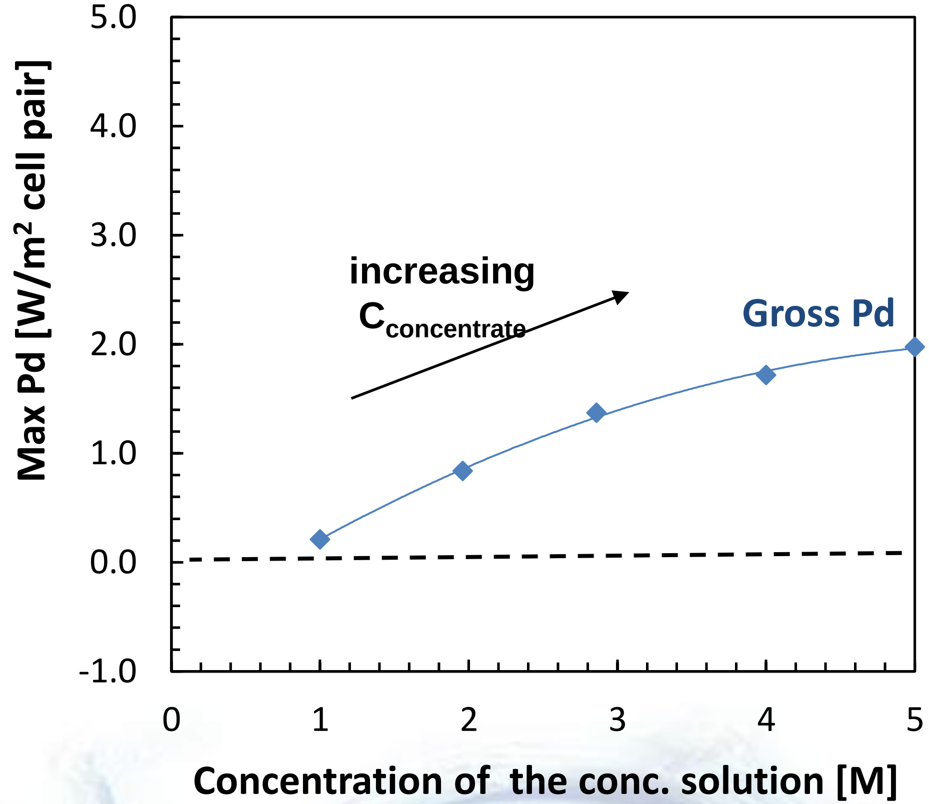
Experimental investigation on a lab-scale unit

Effect of the concentration of the concentrated solution (1 ÷ 5 M)

Power density vs. current density



Maximum power density vs. C_{conc}

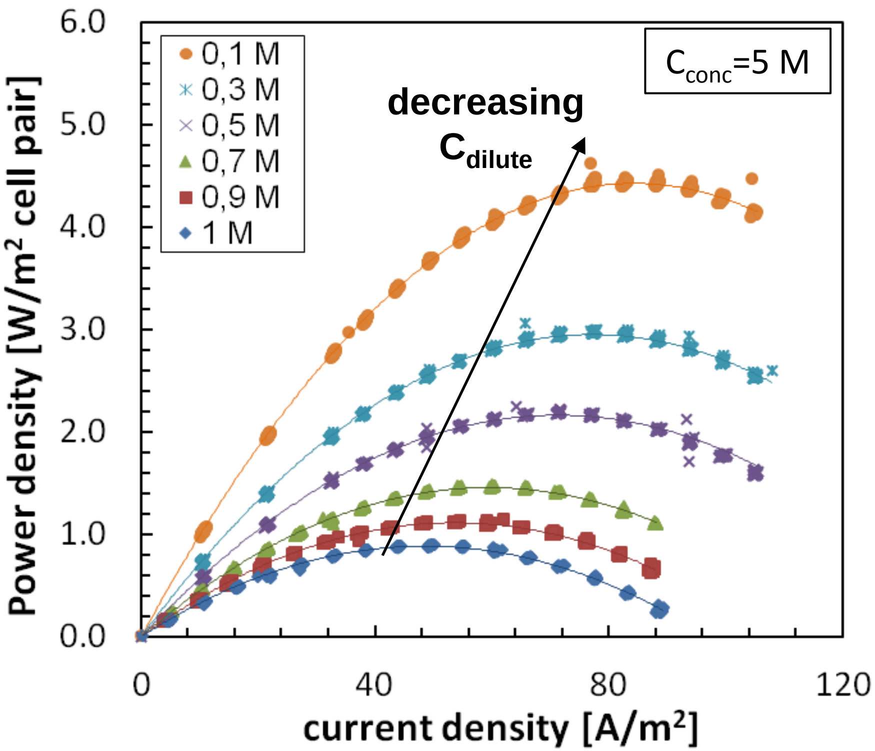


Stack equipped with 50 cell pairs, Fujifilm membranes, Deukum 270 µm spacers . Seawater: 0.55 M NaCl. T=20° C. Fluid velocity: 1 cm/s. Electrode rinse solution: 0.1 M $K_3Fe(CN)_6$ / $K_4Fe(CN)_6 \cdot 3H_2O$ + 2.5 M NaCl.

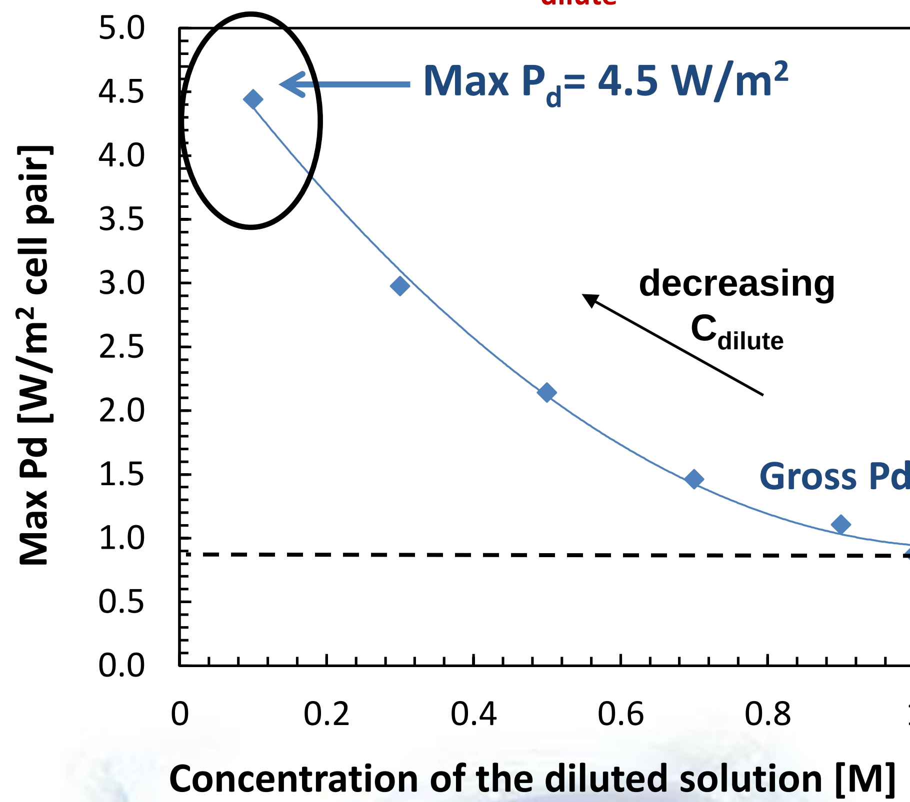
Experimental investigation on a lab-scale unit

Effect of the concentration of the diluted solution (0.1 ÷ 1 M)

Power density vs. current density



Maximum power density vs. C_{dilute}

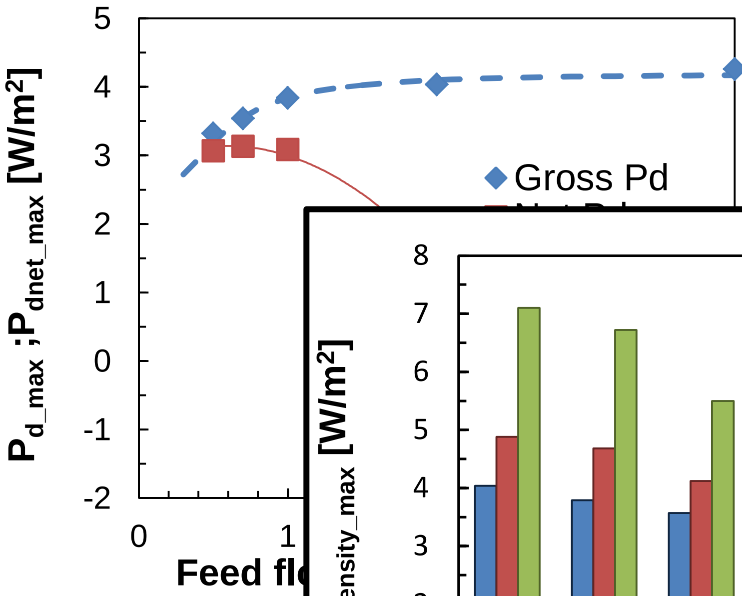


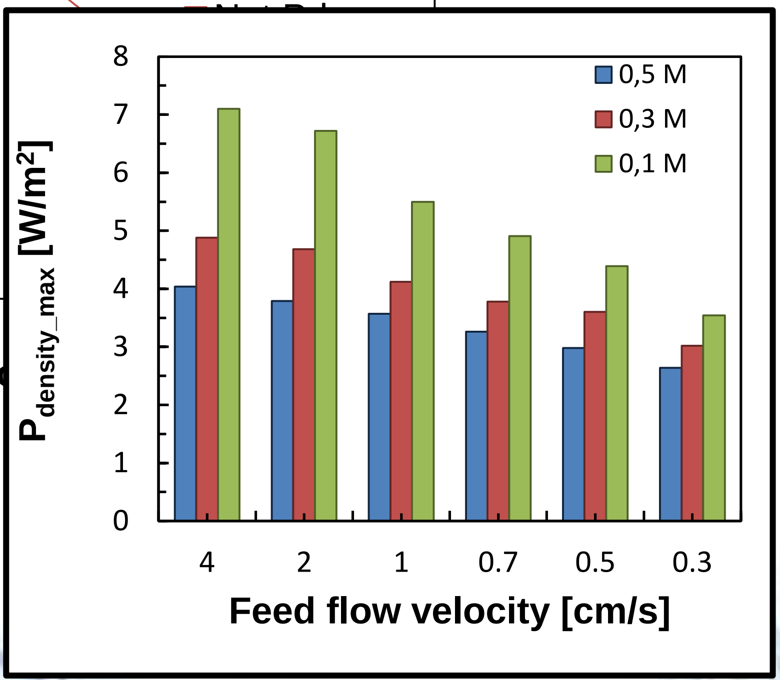
Stack equipped with 50 cell pairs, Fujifilm membranes, Deukum 270 µm spacers . Brine: 5 M NaCl. T=20° C. Fluid velocity: 1 cm/s. Electrode rinse solution: 0.1 M $K_3Fe(CN)_6$ / $K_4Fe(CN)_6 \cdot 3H_2O$ + 2.5 M NaCl.

Experimental investigation on a lab-scale unit

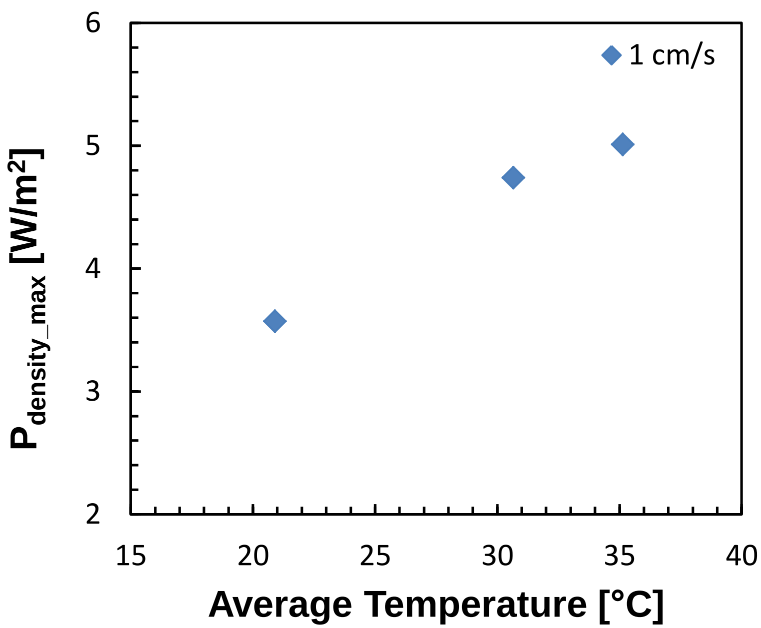
Change in membranes: 20-30 μm thin membranes

Influence of flow velcoity





Influence of Temperature



Influence of diluate concentration

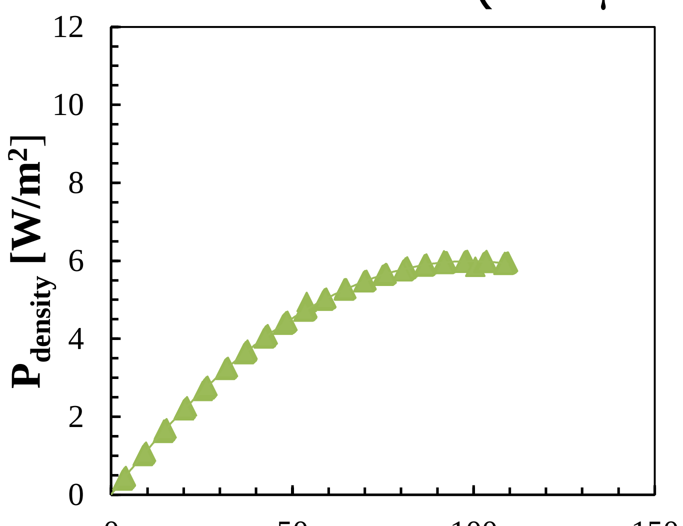
50 cell pairs - FAS – 20/FKS – 20 Fumatech membranes [thickness 20-30 µm] - Deukum spacers [thickness 270 µm] - Brine 5 M, seawater 0,1÷0,5 M - Electrode rinse solution [($K_3Fe(CN)_6$ 0,1 M, $K_4Fe(CN)_6 \cdot 3H_2O$ 0,3M; NaCl 2,5M), flow rate 30l/h].

Experimental investigation on a lab-scale unit

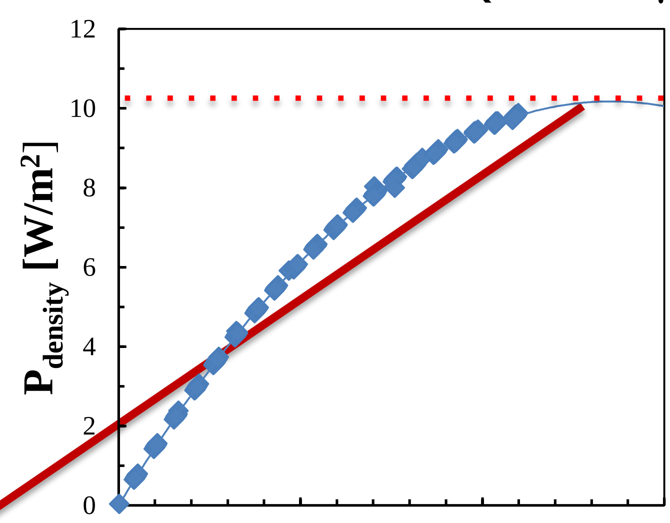
MAX power output conditions:

4cm/s, T = 40°C & brackish water diluate (0.1M)

Thick membranes (120μm)



Thin membranes (20-30μm)



Power density above **15 W/m²** can be expected with larger number of cell pairs, i.e. reducing the effect of **blank resistance**

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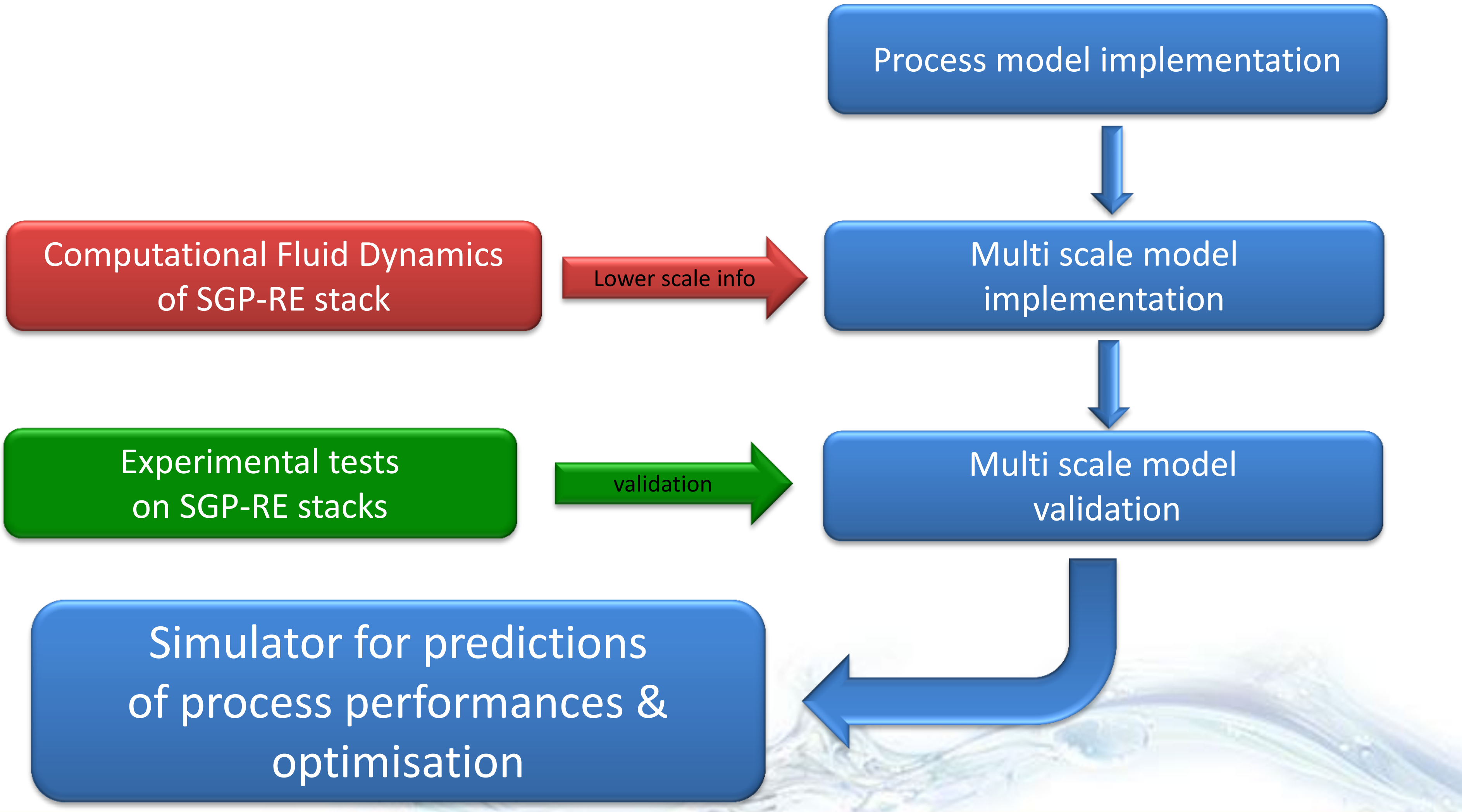
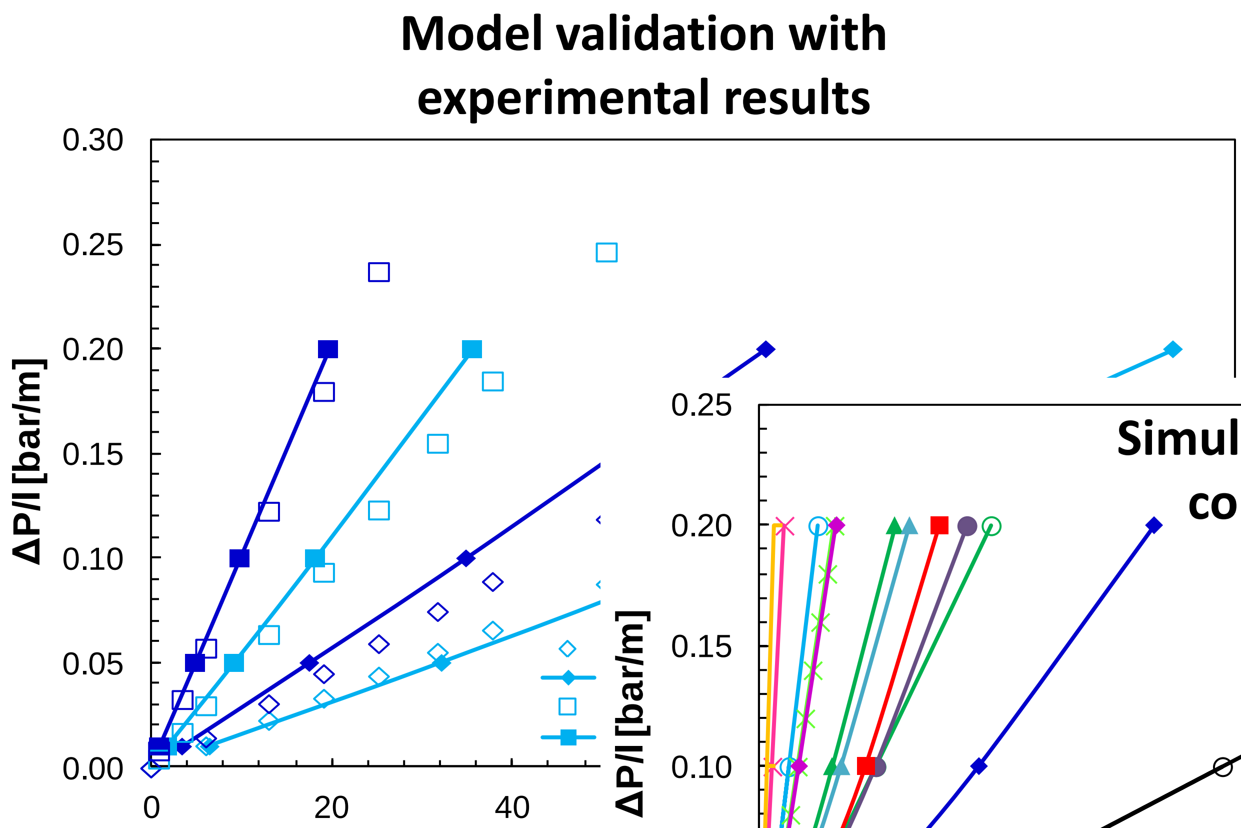
Modelling activities
and
process simulations

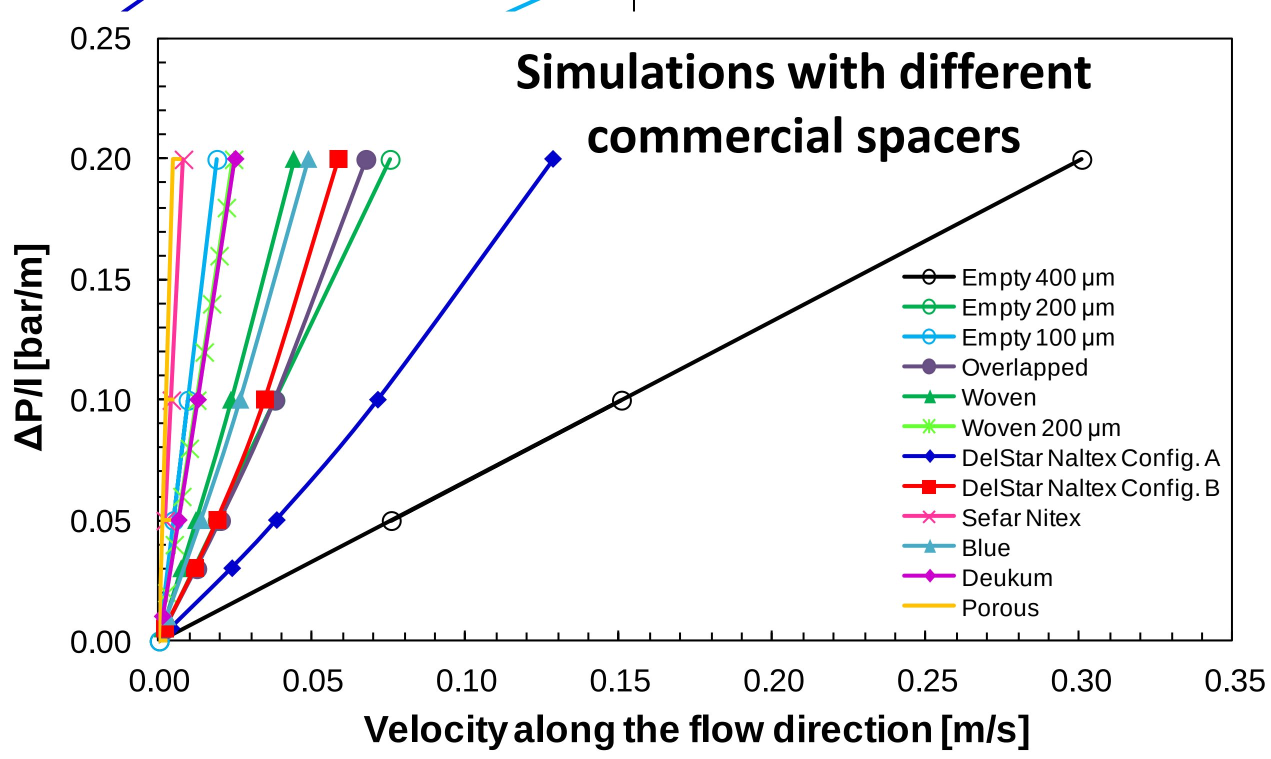
Modelling the RED process

Multi-Scale Modelling approach:

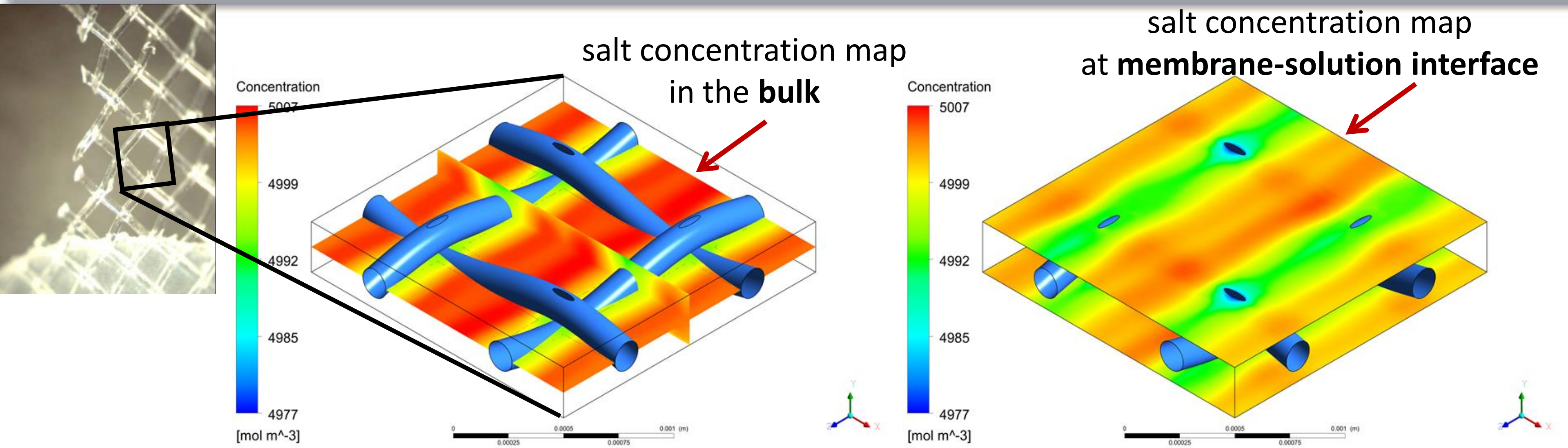


CFD Modelling: prediction of pressure drops



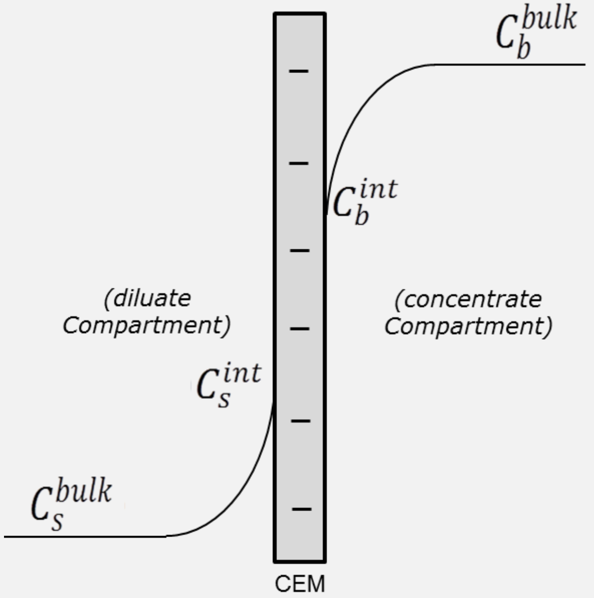


CFD Modelling: prediction of polarisation phenomena



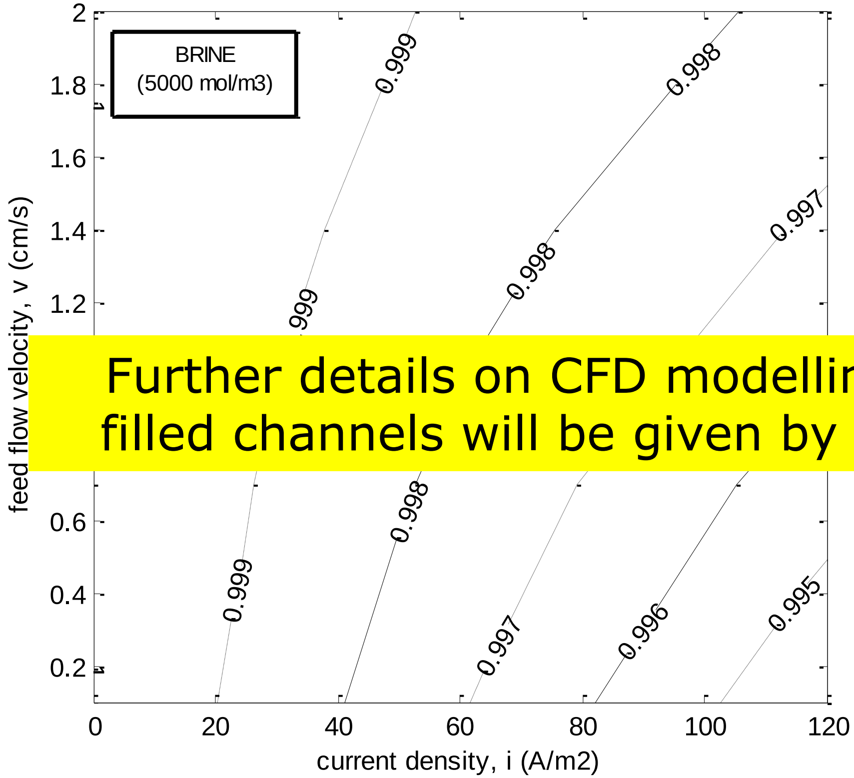
Polarisation Coefficients:

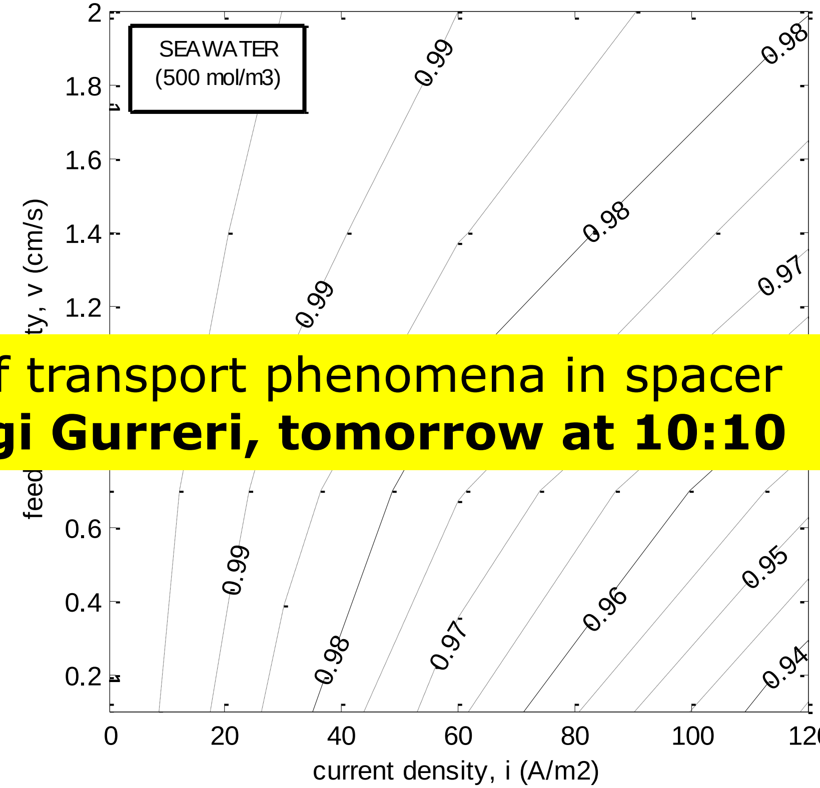
$$\begin{cases} \vartheta_b = \dfrac{C_b^{int}}{C_b^{bulk}} \\ \vartheta_s = \dfrac{C_s^{bulk}}{C_s^{int}} \end{cases}$$



CFD Modelling: prediction of polarisation phenomena

Polarization factor for Deukum spacer-filled channels





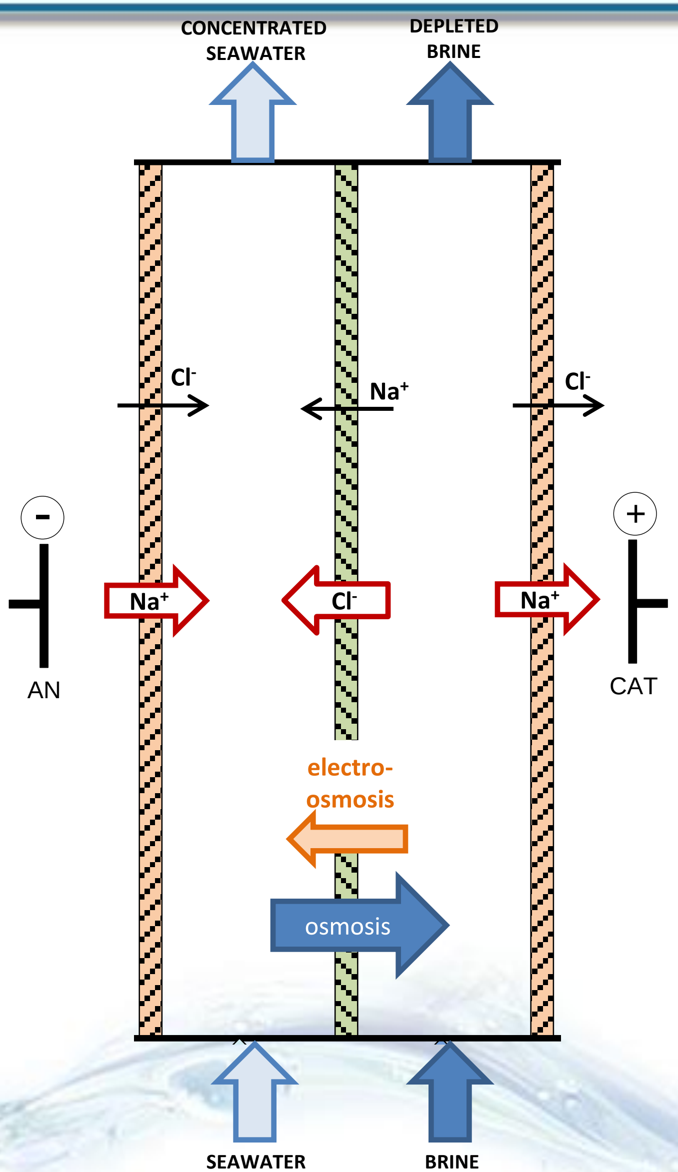
Further details on CFD modelling of transport phenomena in spacer filled channels will be given by **Luigi Gurreri, tomorrow at 10:10**

Example: Effect of current density and fluid velocity on polarization coefficients.
Model predictions from CFD simulations with 280 µm polyamide woven spacer (Deukum GmbH, Germany).

Development/validation of a process simulator

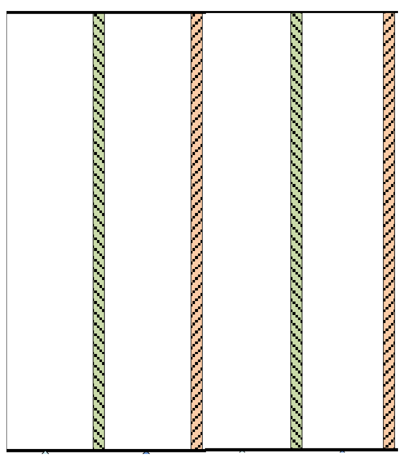
Low-hierarchy model (*cell pair*):

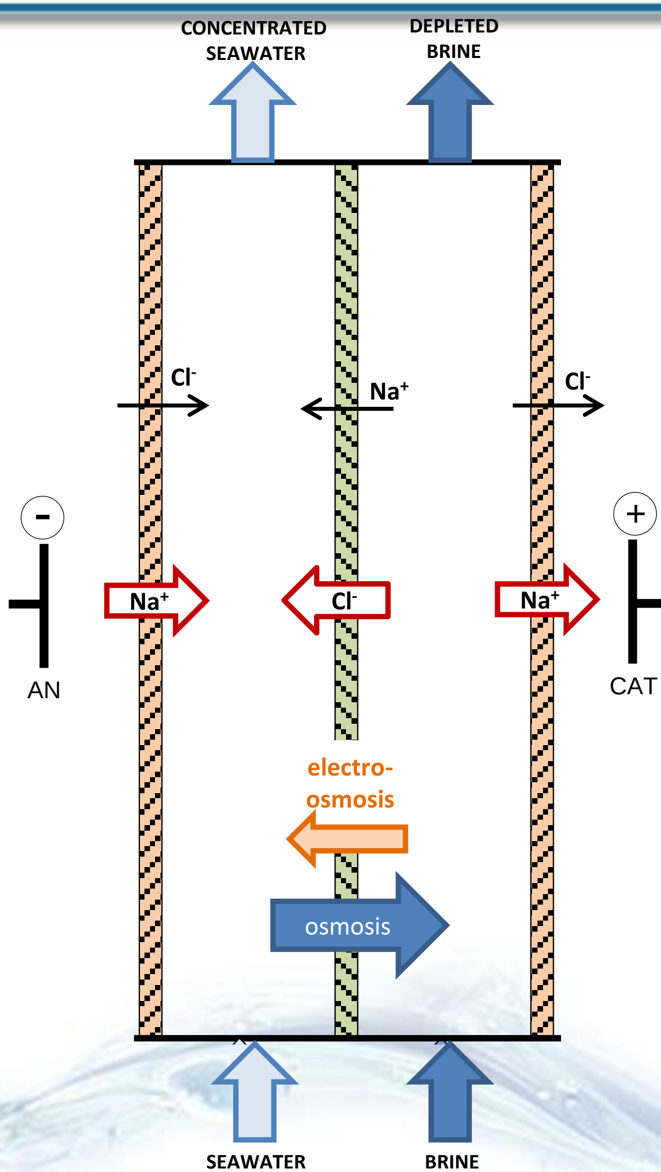
- thermodynamic properties of solutions
- electric variables
- salt transport (counter/co-ions)
- solvent transport (osmosis/electro-osmosis)
- polarization phenomena
- mass balance



Source: M. Tedesco *et al.*, *Desalination and Water Treatment*, vol. 49, pp. 404-424, 2012

Process Modelling Approach





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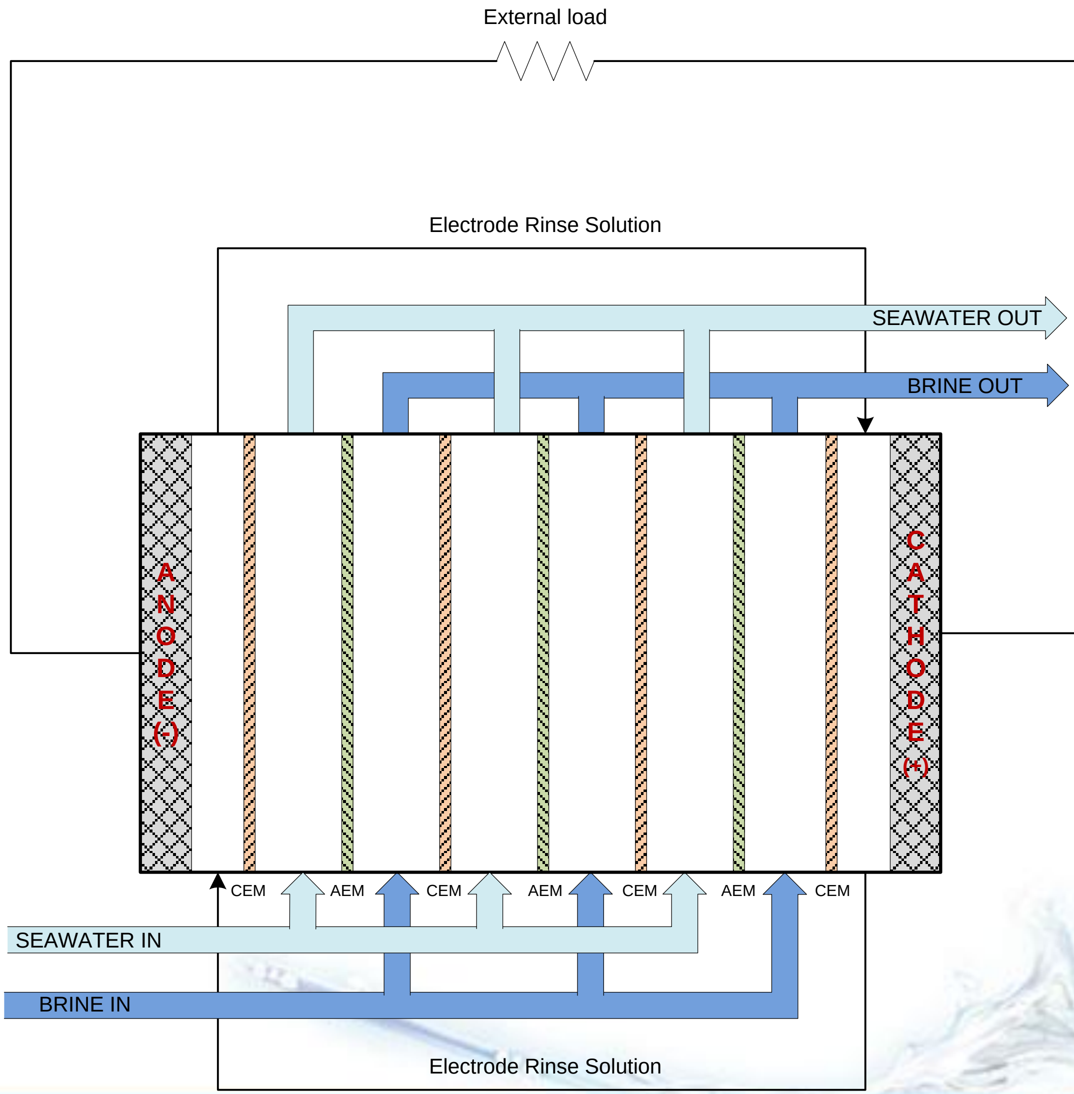
Process Modelling Approach

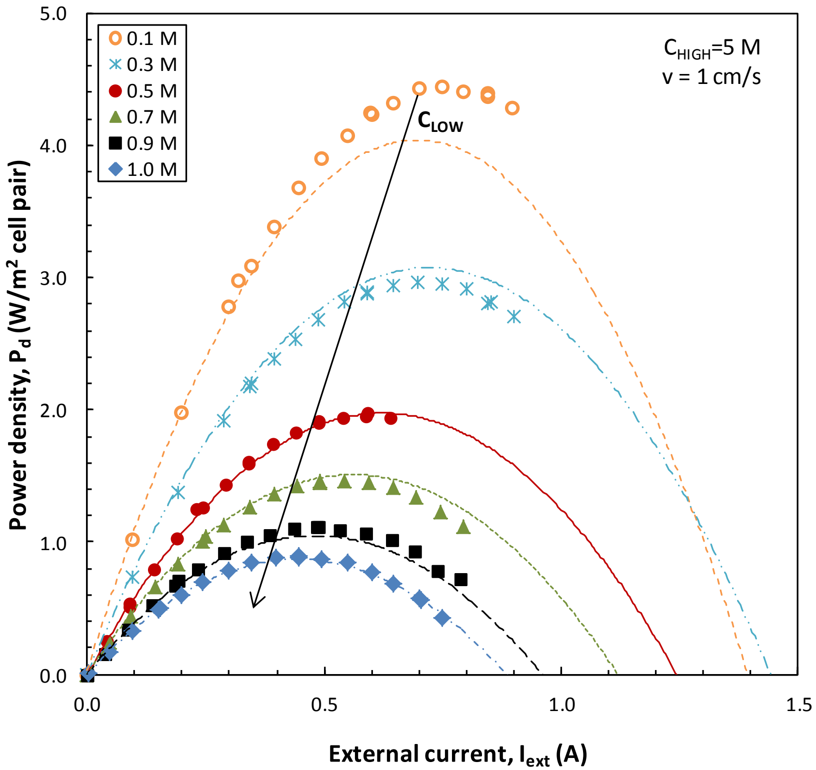


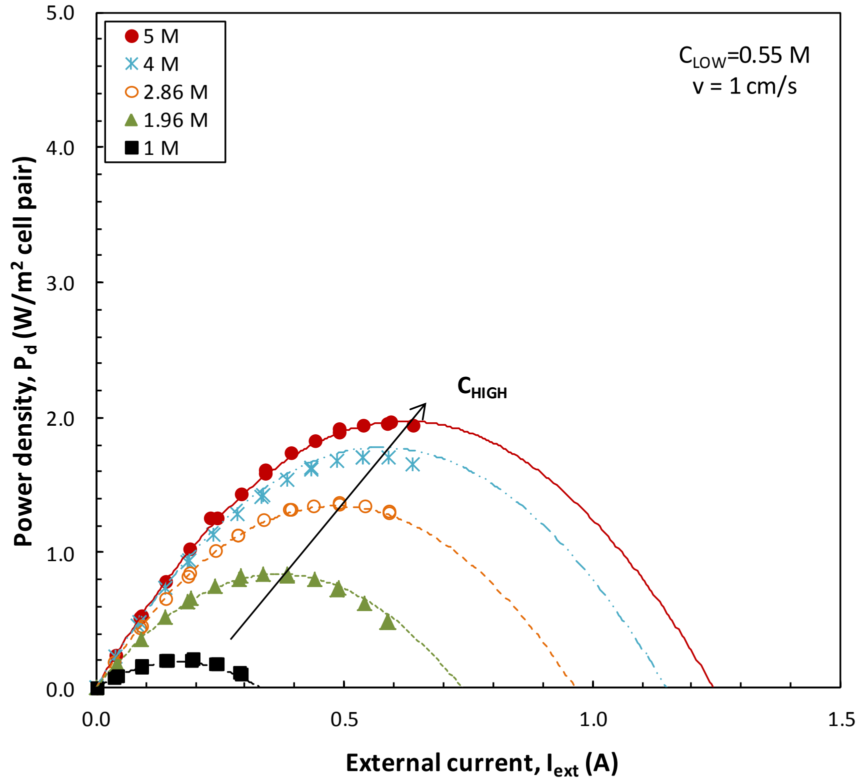
High-hierarchy model (*stack*):

- parasitic currents through manifolds
- stack resistance
- stack voltage
- Pressure drops
- power density (gross/net)

Process Modelling validation

Model calibration with variable feed concentration





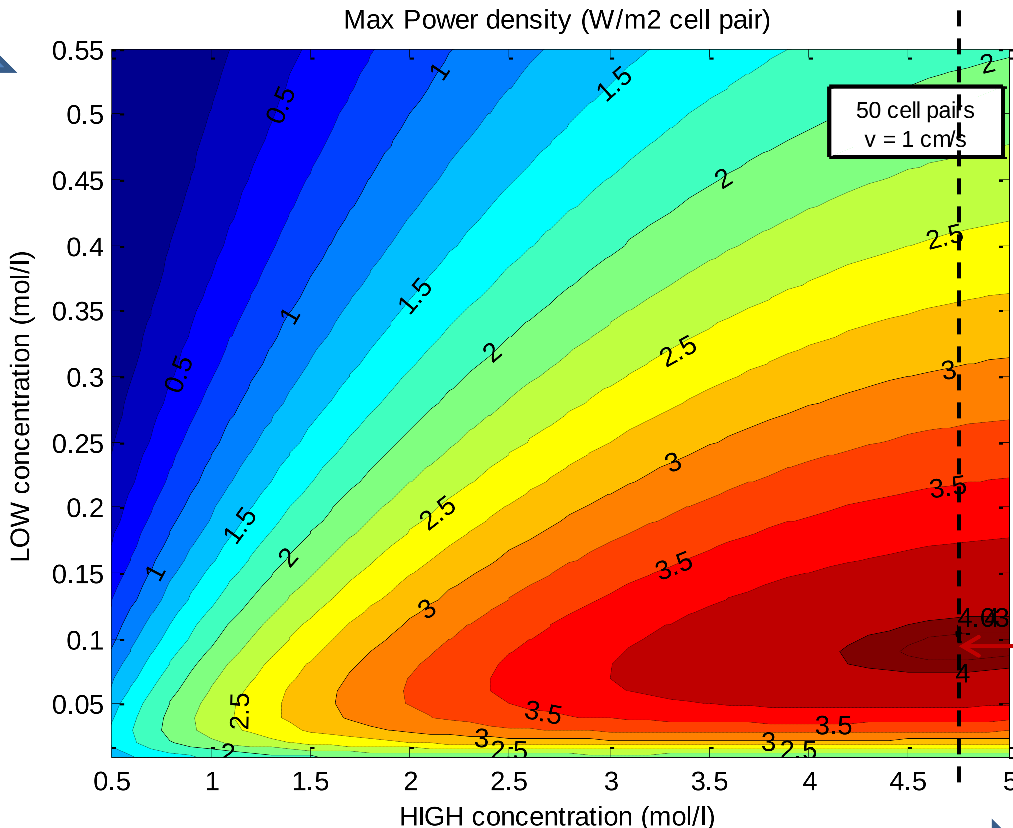
Experimental (points) and simulated (lines) data for a 50-cells stack equipped with Fujifilm membranes, Deukum 270 µm spacers; feed flow velocity: 1 cm/s; T=20° C. Blank resistance: 0.4 Ω.

Prediction of dependences

Influence of feed T & concentration

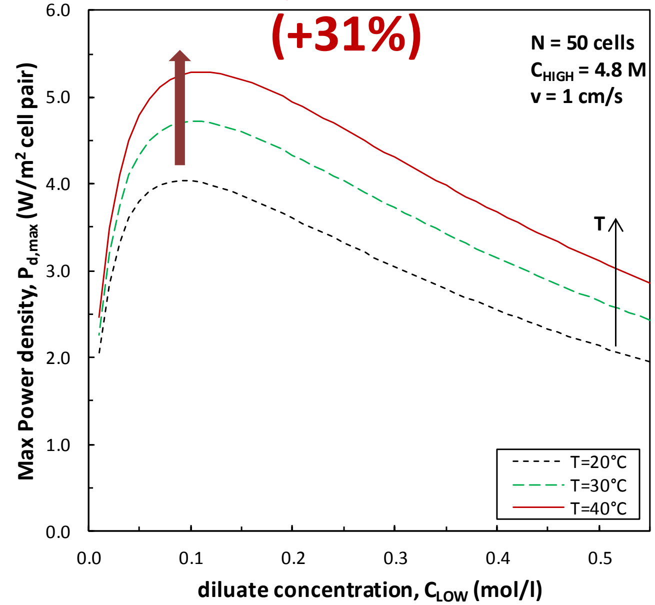
seawater

river water



seawater brine

Max P_d= 5.3 W/m^2 (+31%)

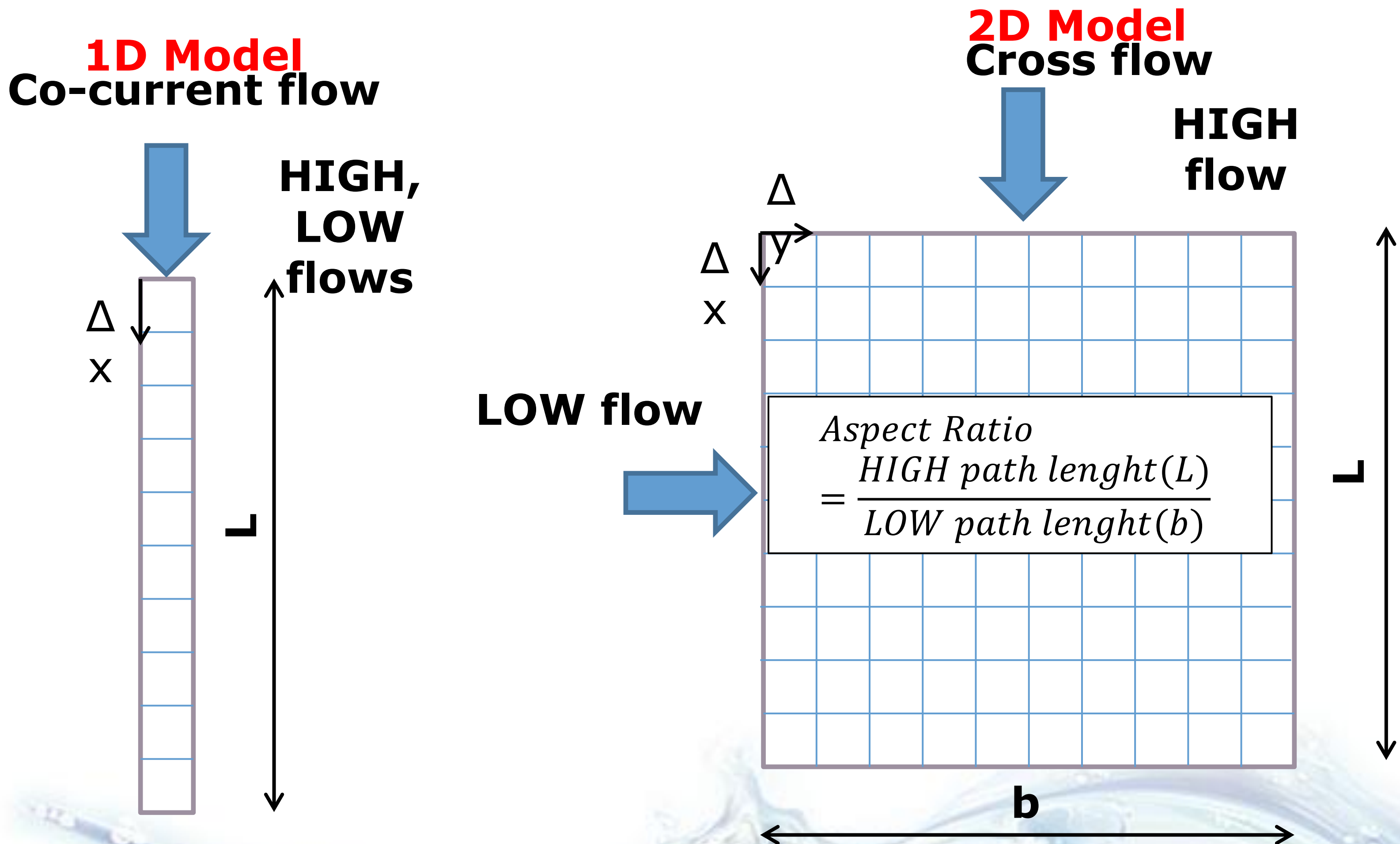


BEST conditions:
brackish water (0.05 – 0.1 M)
+ brine (4 – 5 M)

Simulations of a 50-cells stack equipped with Fujifilm membranes, Deukum spacers; fluid velocity inside channels: 1 cm/s; T=20° C. Blank resistance: 0.4 Ω.

Further model developments

2D model implementation



Prototype plant simulations outcomes

Analysed scenarious

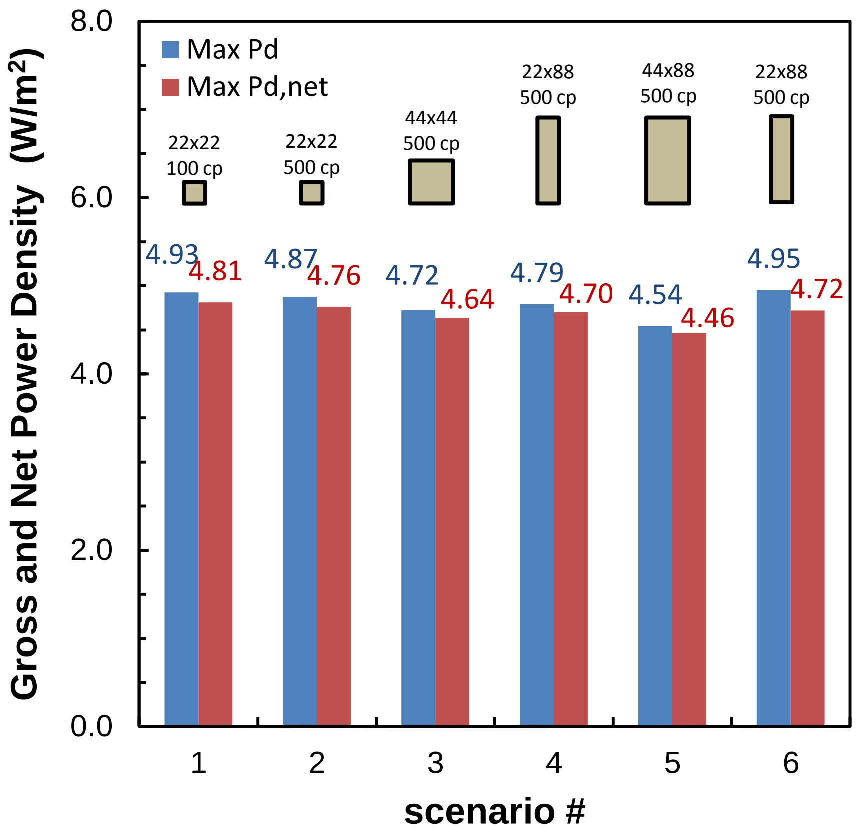
Scenario #	Stack size (cm)	N° cell pairs	Notes
1	22 X 22	100	Reference case (small prototype)
2	22 X 22	500	Larger number of cell pairs
3	44 X 44	500	symmetrical stack
4	22 X 88	500	asymmetrical stack, AR = 4
5	44 X 88	500	asymmetrical stack, AR = 2
6	22 x 88	500	asymmetrical stack, different velocity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

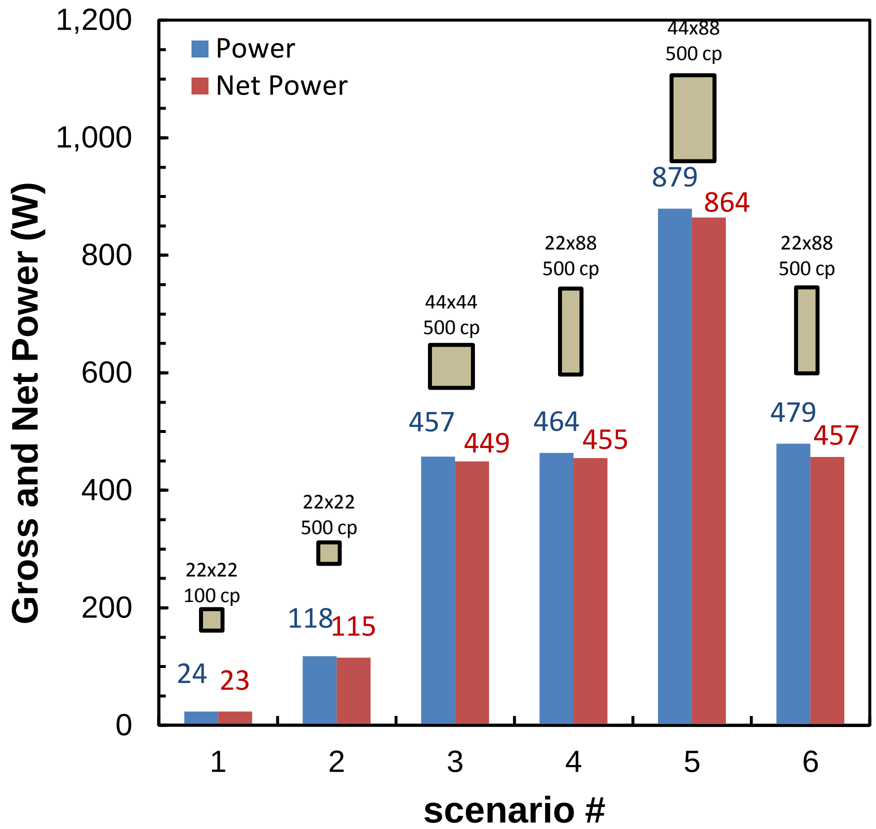
Operating conditions:

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

Prototype plant simulations outcomes

Gross and Net power density (*W/m² cell pair*)

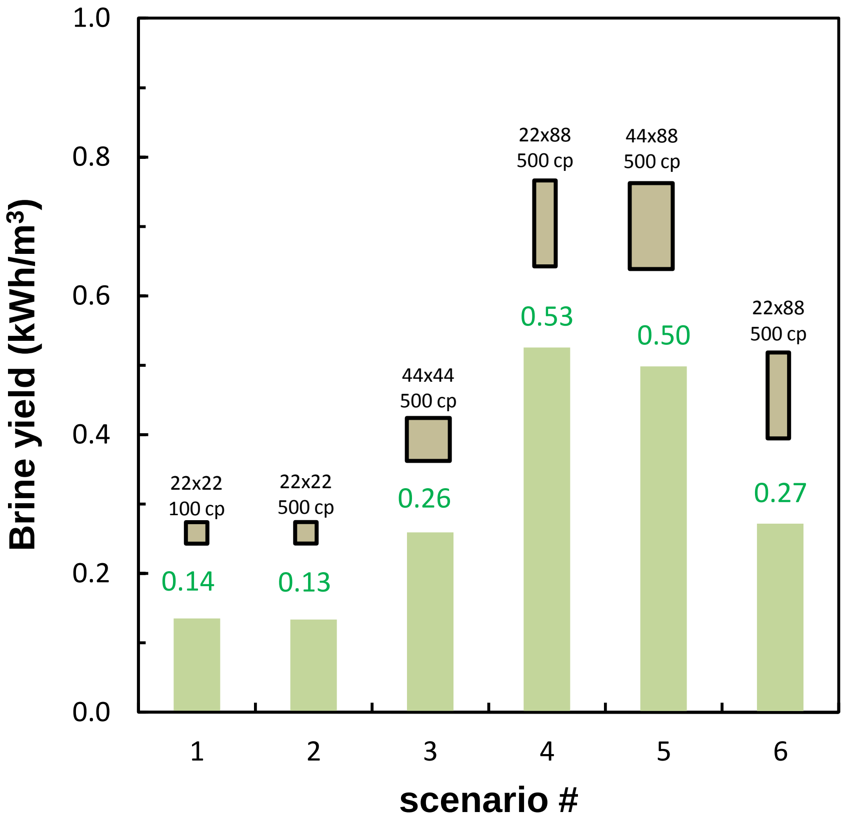




Simulations of stacks equipped with Fujifilm membranes, 270 µm woven spacers; C_{LOW} = 0.1 M; C_{HIGH} = 5 M; T=30° C.

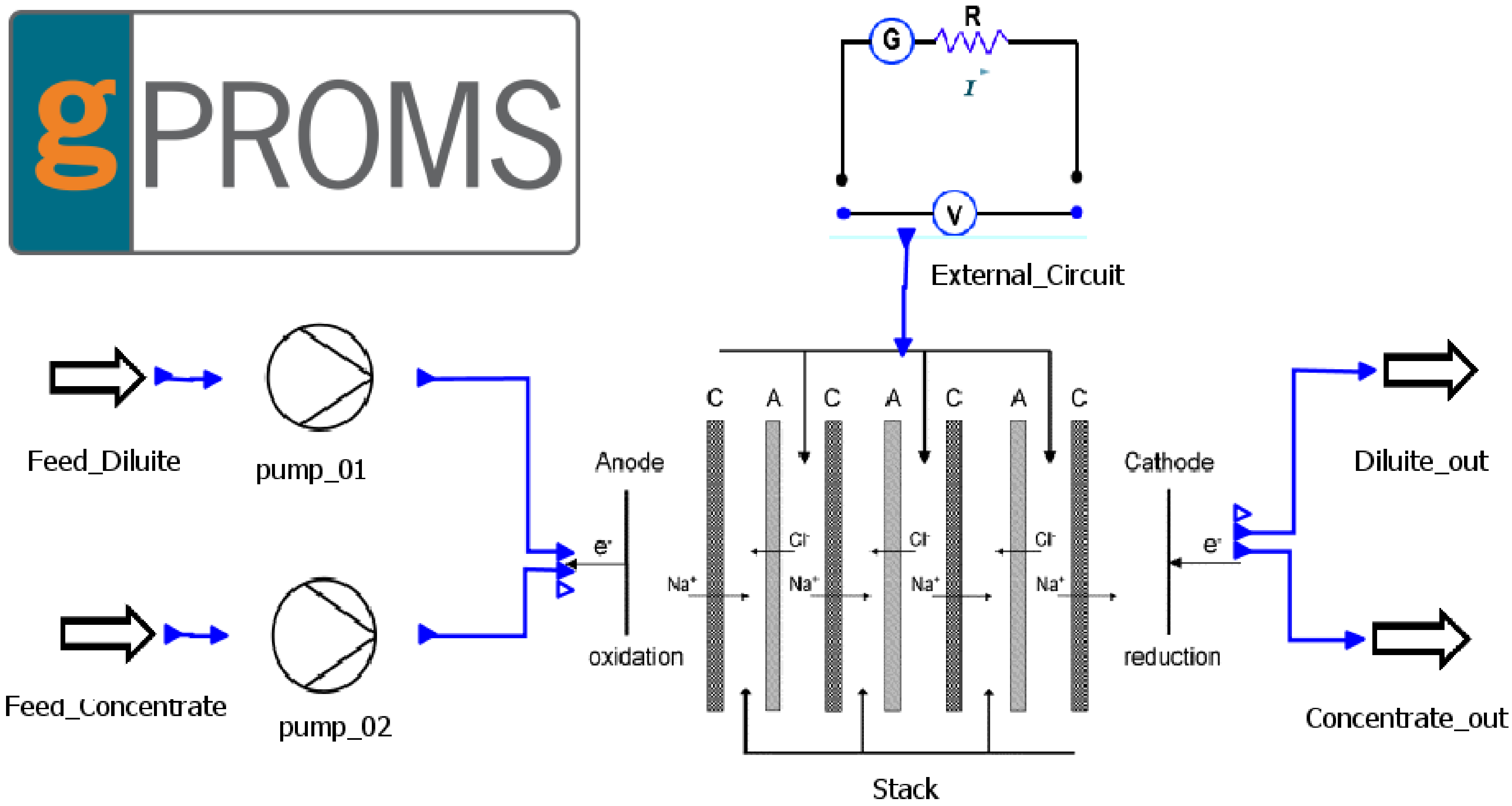
Prototype plant simulations outcomes

Process yield (k*Wh/m*^{3} *of brine*)

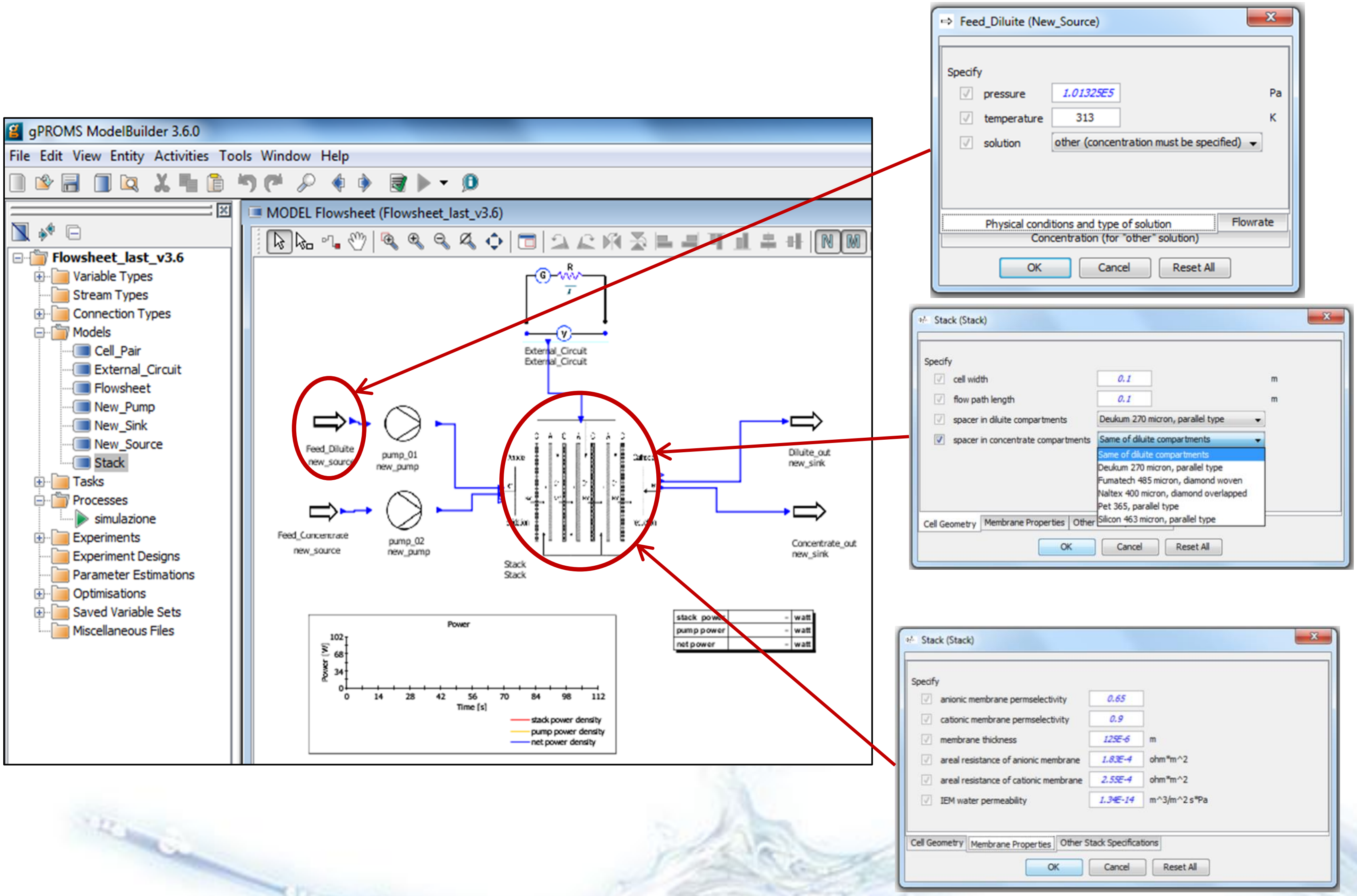


Simulations of stacks equipped with Fujifilm membranes, 270 µm woven spacers; C_{LOW} = 0.1 M; C_{HIGH} = 5 M; T=30° C.

Implementation of the prototype plant simulator

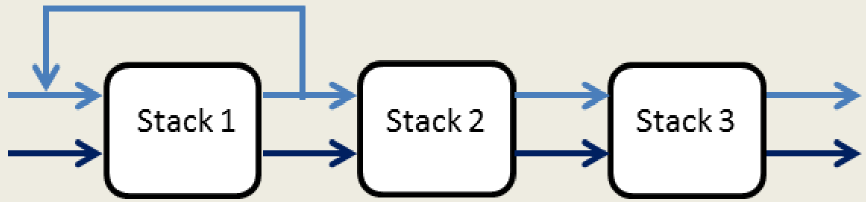


Implementation of the prototype plant simulator

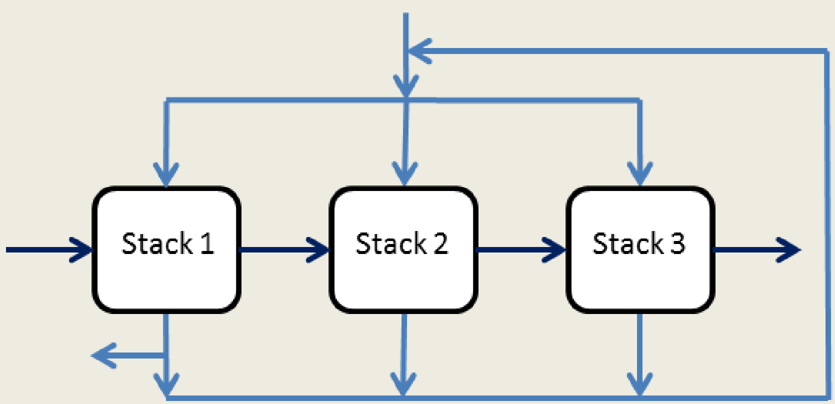


Analysis of plant layouts: stacks arrangement

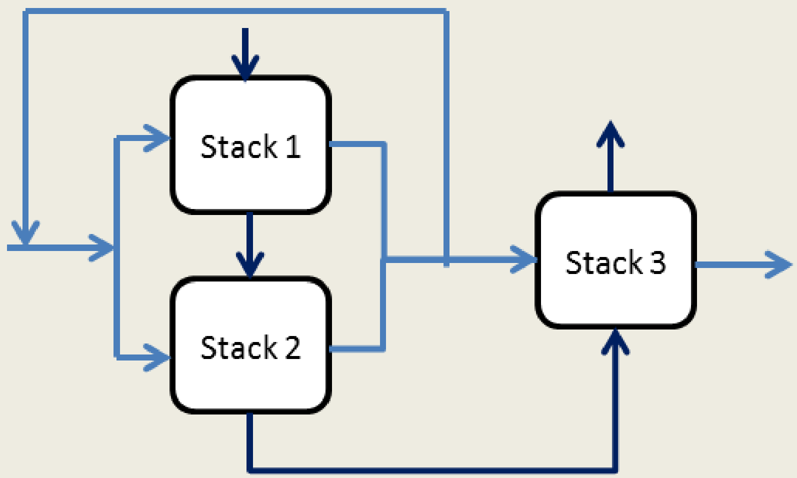
LAYOUT 1: serial arrangement



LAYOUT 2: parallel arrangement

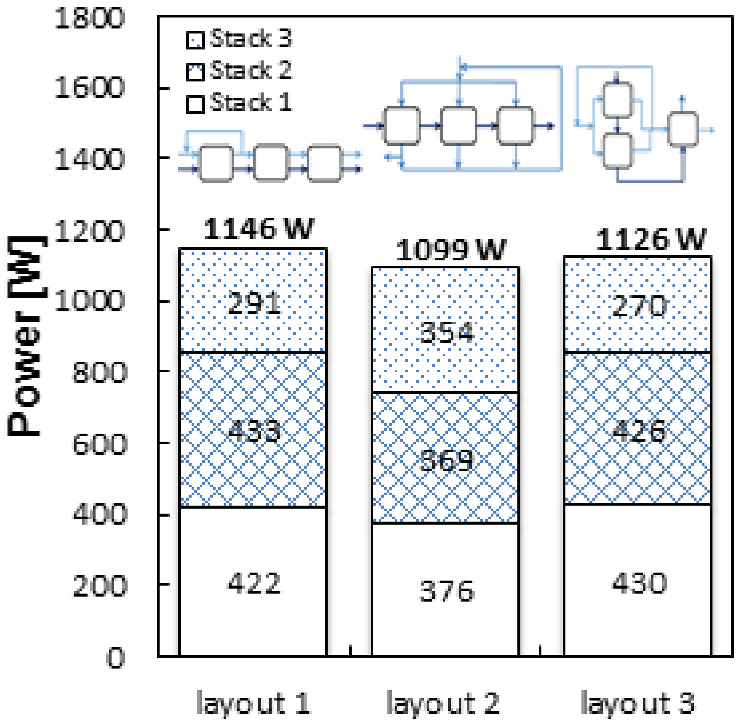


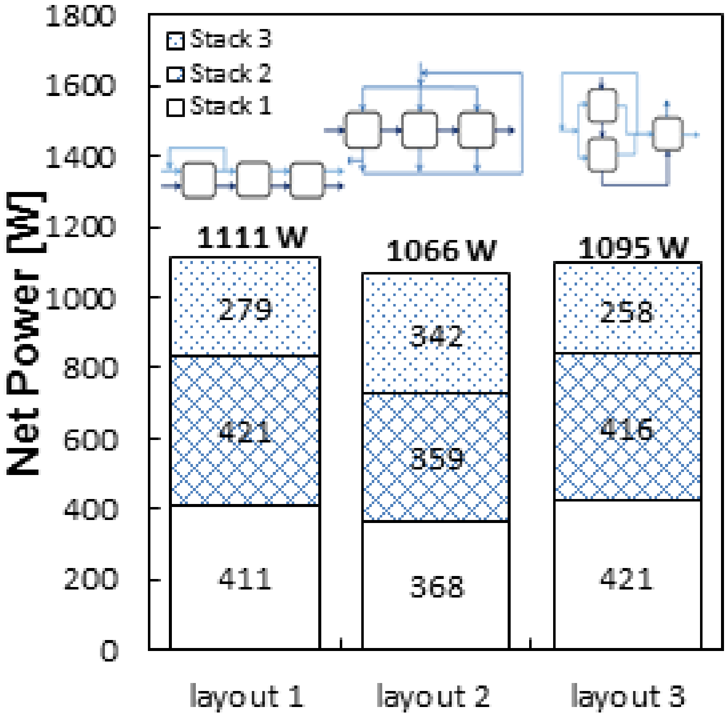
LAYOUT 3: hybrid serial-parallel



Analysis of plant layouts: simulation results

REAPower final **TARGET**: **1000 W**





Simulations of 3 stacks (500 cells) equipped with Fujifilm membranes 44×44 cm^2 and 270 µm woven spacers; C_{HIGH} = 5 M; Q_{HIGH} =29.4 lt/min; make-up of brackish water, Q_{MU} = 40 lt/min, C_{MU} = 0.03 M.

The REAPower prototype: installation, commissioning and testing

Project scheduling and units scaling-up

- **lab stack**
  (10x10cm^2 , 50 cell pairs)
- **large lab stack**
  (20x20 cm^2 x 100 cell pairs)

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Laboratory tests performed on lab-scale units

(Oct. 2012 – Dec. 2013)

- **Very small prototype stack**
  (22x22 cm^2, 109 cell pairs)
- **Small prototype stack**
  (44x44 cm^2 , 125 cell pairs)
- **Large prototype stack**
  (44x44 cm^2 , 500 cell pairs)
- **Final prototype system**
  (3 large prototype stacks)

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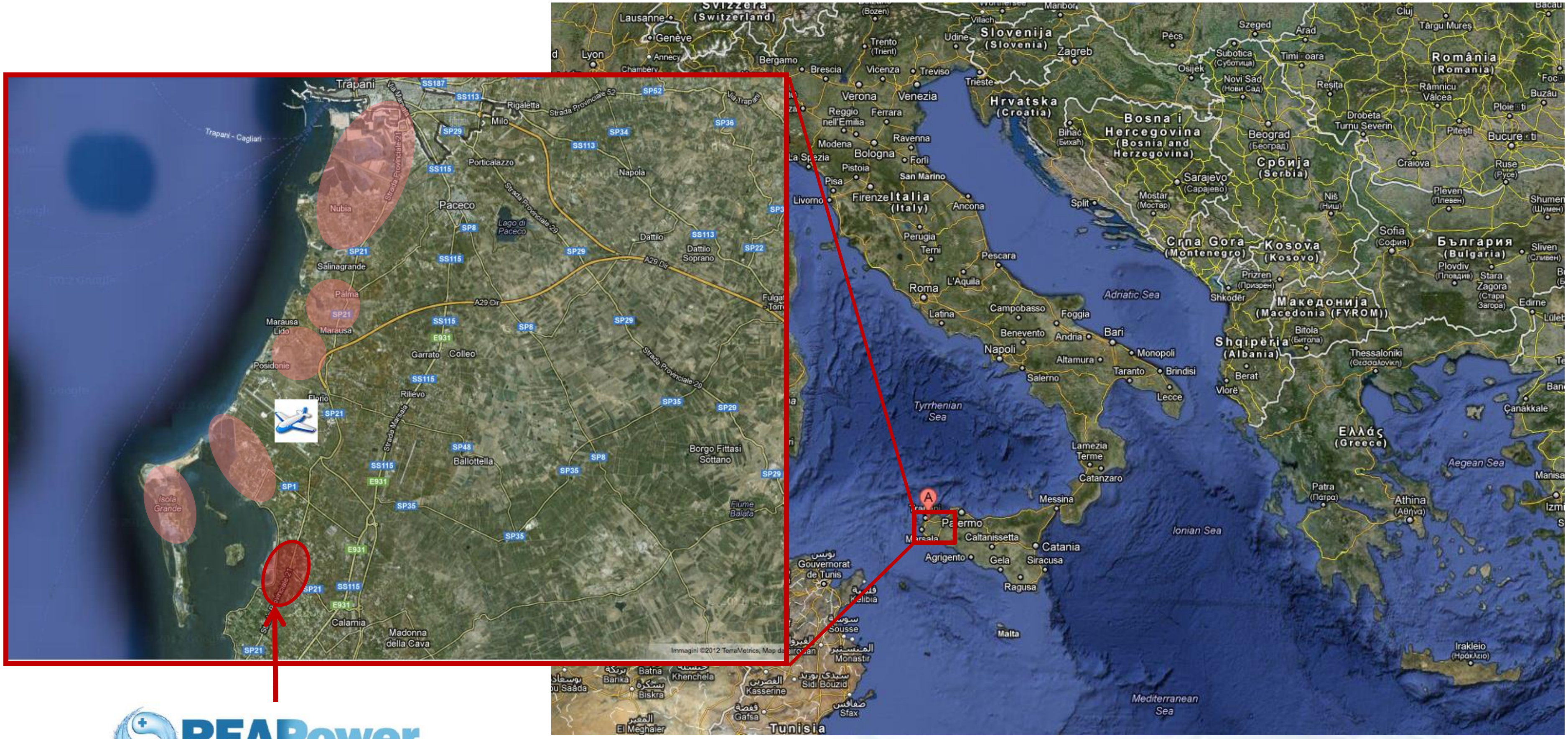
Prototype construction, installation and testing

(Sept. 2013 – Sept. 2014)

The REAPower prototype installation site

The singular framework of Trapani saltworks



REAPower

Prototype installation site

The REAPower prototype installation site

The "*Ettore-Infersa*" saltworks

Direct access to both saturated brine and seawater from open channels

Installation place within an old, restructured WINDMILL

Prototype installation: plant specifications

Site features

- Availability of both sea & brackish water;
- Brine availability: 10-15 m^3/h (larger with feed-recycle);
- Brine concentration: variable between 250 and 320 gr/lt.

Prototype features

- Total cell pair surface: from 5 to more than 200 m^2 (3 stacks under testing);
- Expected power density: > 3 W/m^2;
- Expected power output in real operating conditions: from 500 to 800W

Site preparation

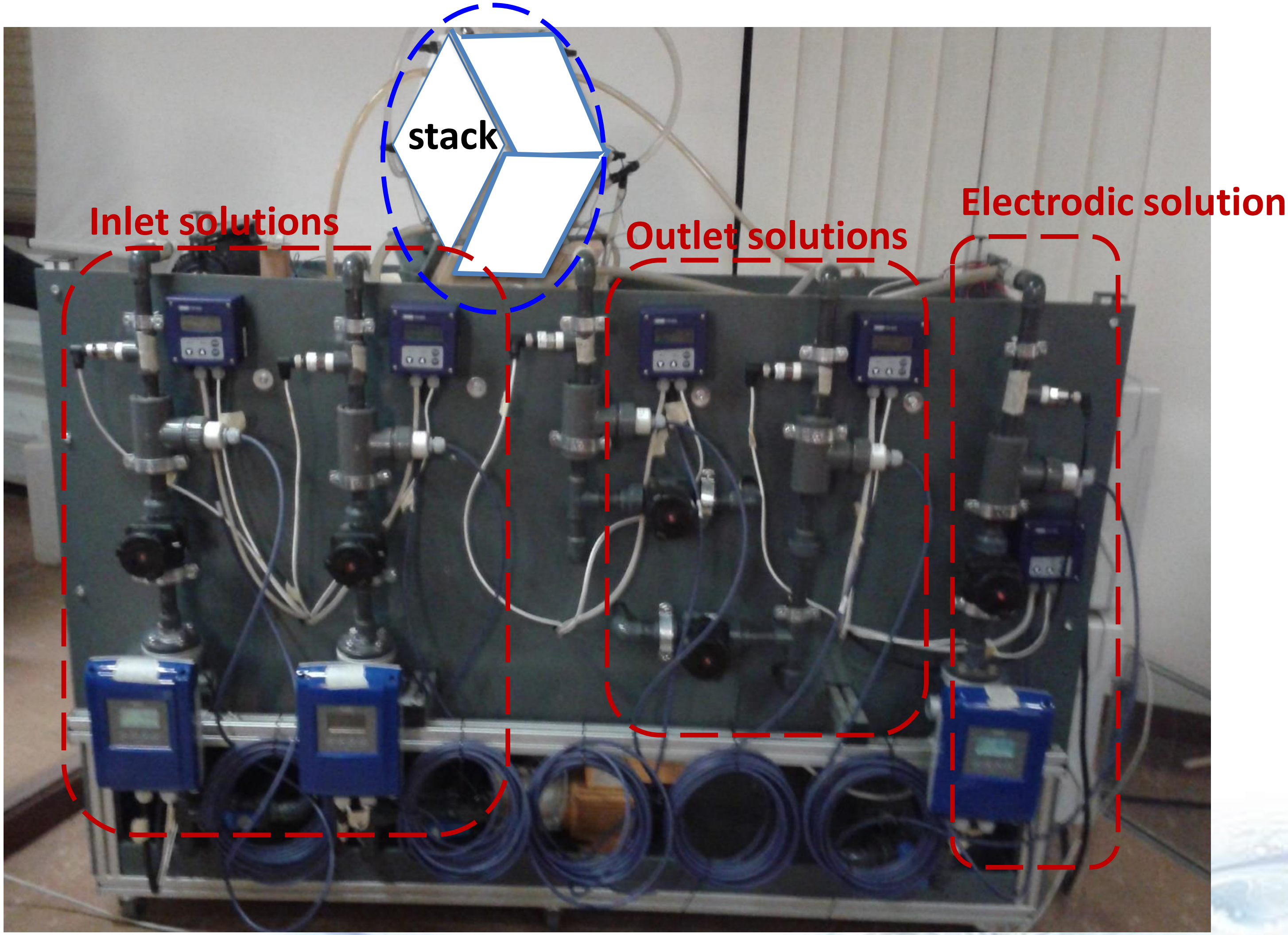
Site preparation, piping & auxiliary systems installation

(Dec. 2013 – Feb. 2014)

- ✓ About **1 km pipes** installed for the three feed solutions intakes
- ✓ **4 m³ tanks** adopted for buffering the availability of brackish water
- ✓ Cartridge filters as the only feed solutions pre-treatment
- ✓ Membrane or centrifugal pumps in techno-polymeric materials installed




Prototype test-rig and control system



(Jul. 2013 – Feb. 2014)

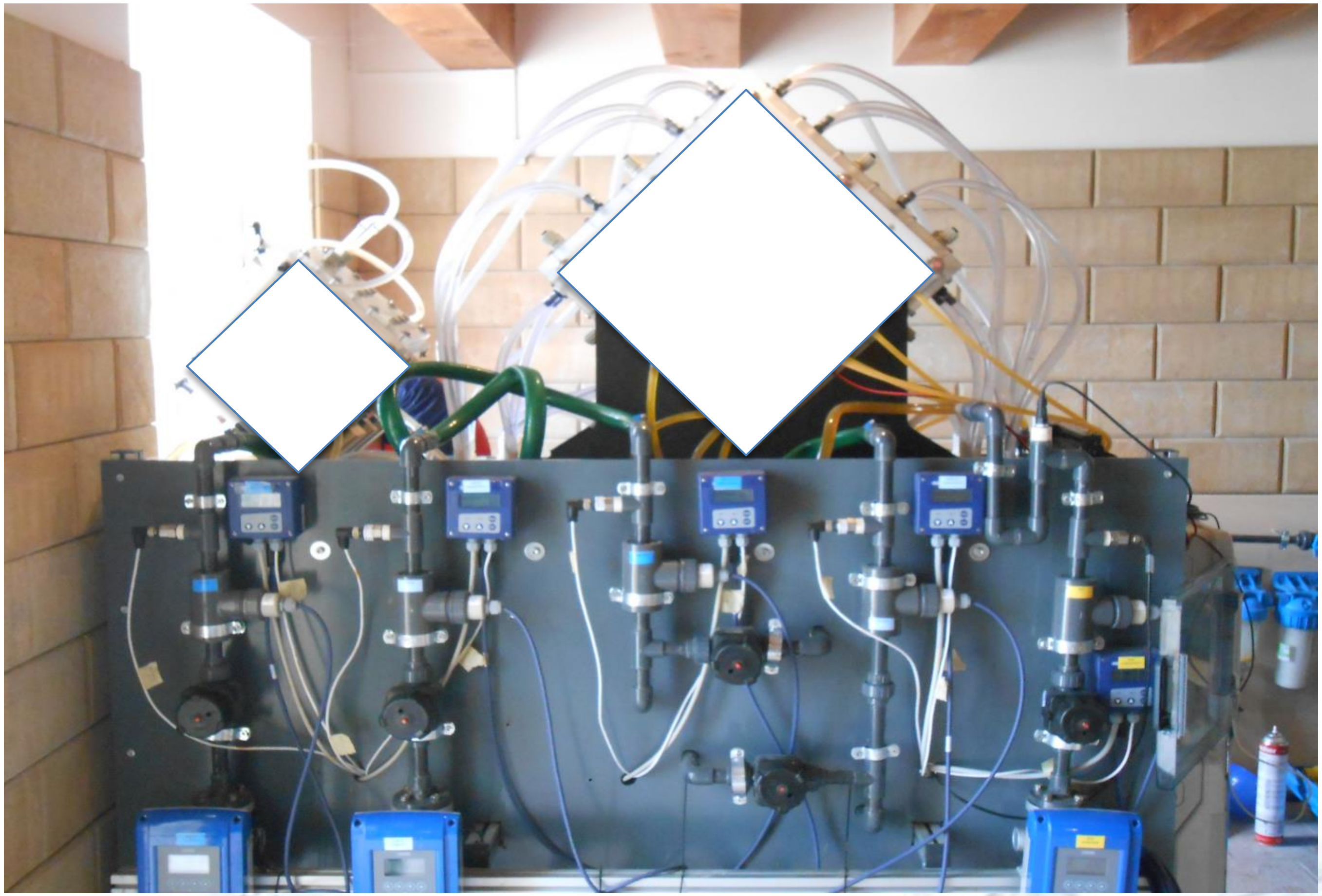
Prototype commissioning

First stack: 22x22 cm^2, 109 cell pairs

MARCH 2014

Prototype commissioning

Second stack: 44x44 cm^2, 125 cell pairs



APRIL 2014

Prototype operations and testing

Second stack: 44x44 cm², 125 cell pairs

Testing with natural and artificial solutions

April 2014 – August 2014

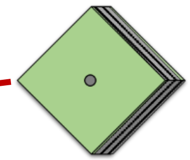
Feed streams	Conductivity [mS/cm]	Flow rate [lt/min]	Temperature [°C]	Power output [W]
Natural or artificial brine	180-230	4-16	25-30	40-60
Natural or artificial brackish water	1-6	4-16	22-25	

Further details on the REAPower prototype activities will be given by
Michele Tedesco, today at 15:10

Prototype scaling-up

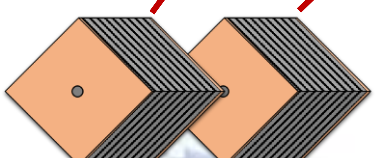
August 2014

small prototype
44 x 44 cm^2
125 cell pairs



Almost 220m^2 of cell pairs installed

System under testing



large prototypes
44 x 44 cm^2
500 cell pairs

REAPower workshop and prototype visiting

The REAPower pilot plant:

First installation in the world to generate electricity from brine

30th September 2014
Saline Ettore e Infersa, Marsala (TP)

WORKSHOP

To visit the pilot site, contact us:
andrea.cipollina@unipa.it

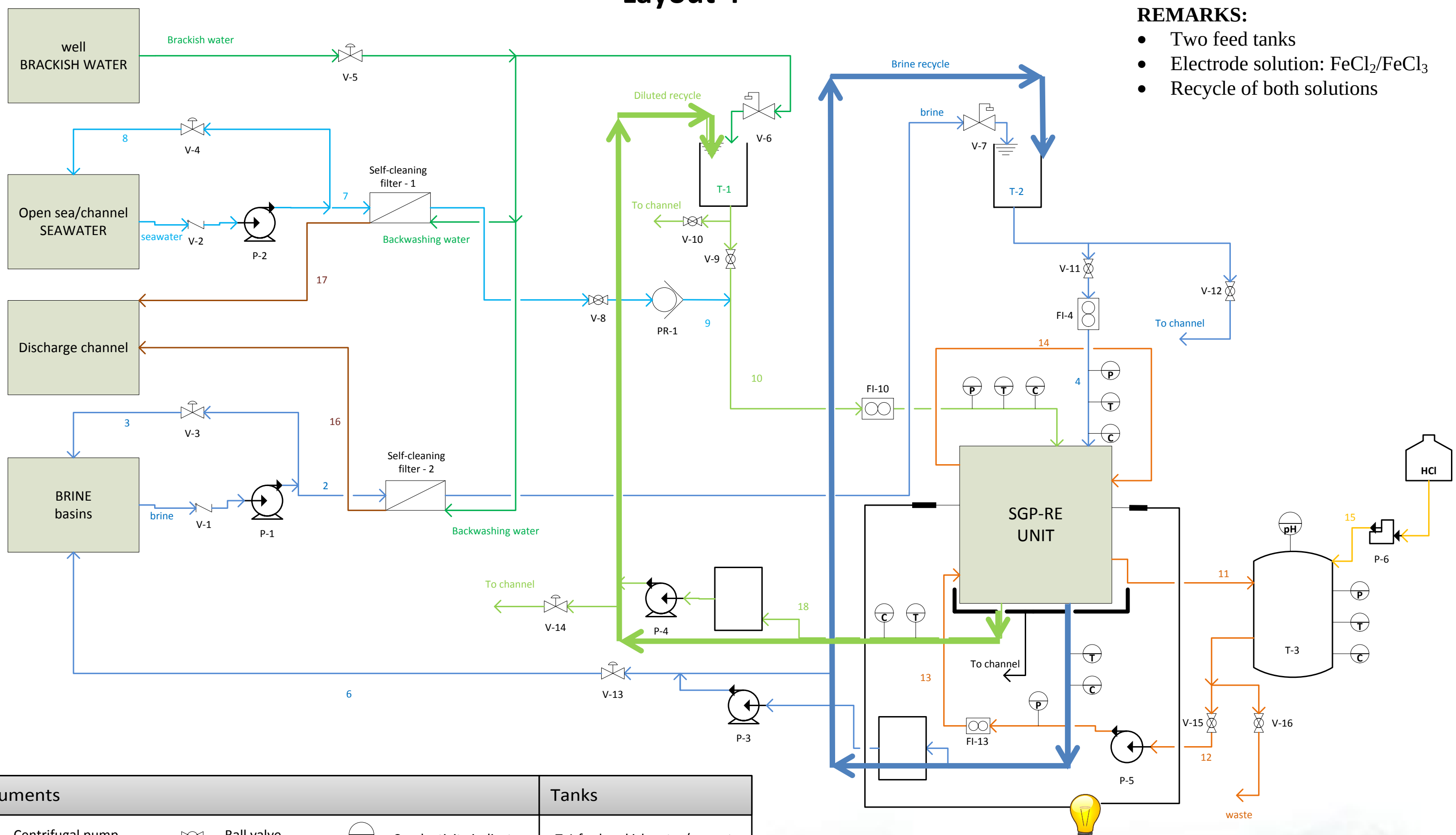
Thank you
for your attention

www.reapower.eu

Process Flow Diagram & recycle option

Layout 4

REMARKS:
- Two feed tanks
- Electrode solution: $FeCl_2/FeCl_3$
- Recycle of both solutions



Instruments			Tanks
Centrifugal pump	Ball valve	Conductivity indicator	T-1 for brackishwater/seawater
Rotary pump	Float valve	Temperature indicator	T-2 for brine
Proportioning pump	Flowmeter	Pressure reducer	T-3 for electrode solution
Check valve	pH indicator		
Membrane valve	Pressure indicator		

REAPower	UNIVERSITÀ DEGLI STUDI DI PALERMO
Scalici Claudio	WP7 Pilot Prototype
Installation site: Ettore-Infersa saltworks	24/05/2013

Thank you
for your attention

EuroMed 2015
Desalination for Clean Water and Energy
Palermo, Italy, 10-14 May 2015

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