UNIVERSITÀ DEGLI STUDI DI PALERMO
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REAPower

Ion Exchange Membranes for Salinity Gradient Power production from brines: the REAPower project

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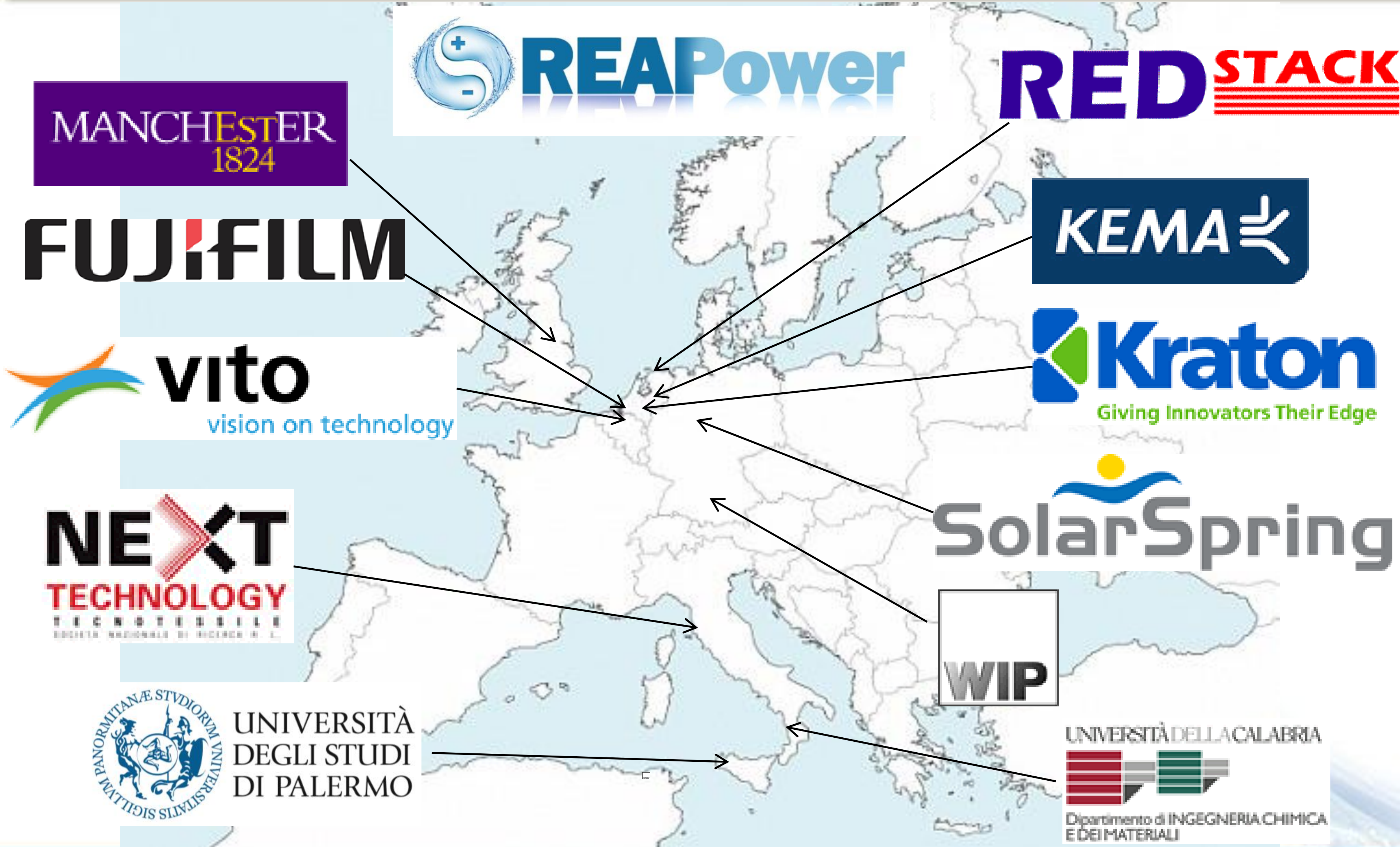
The REAPower Project

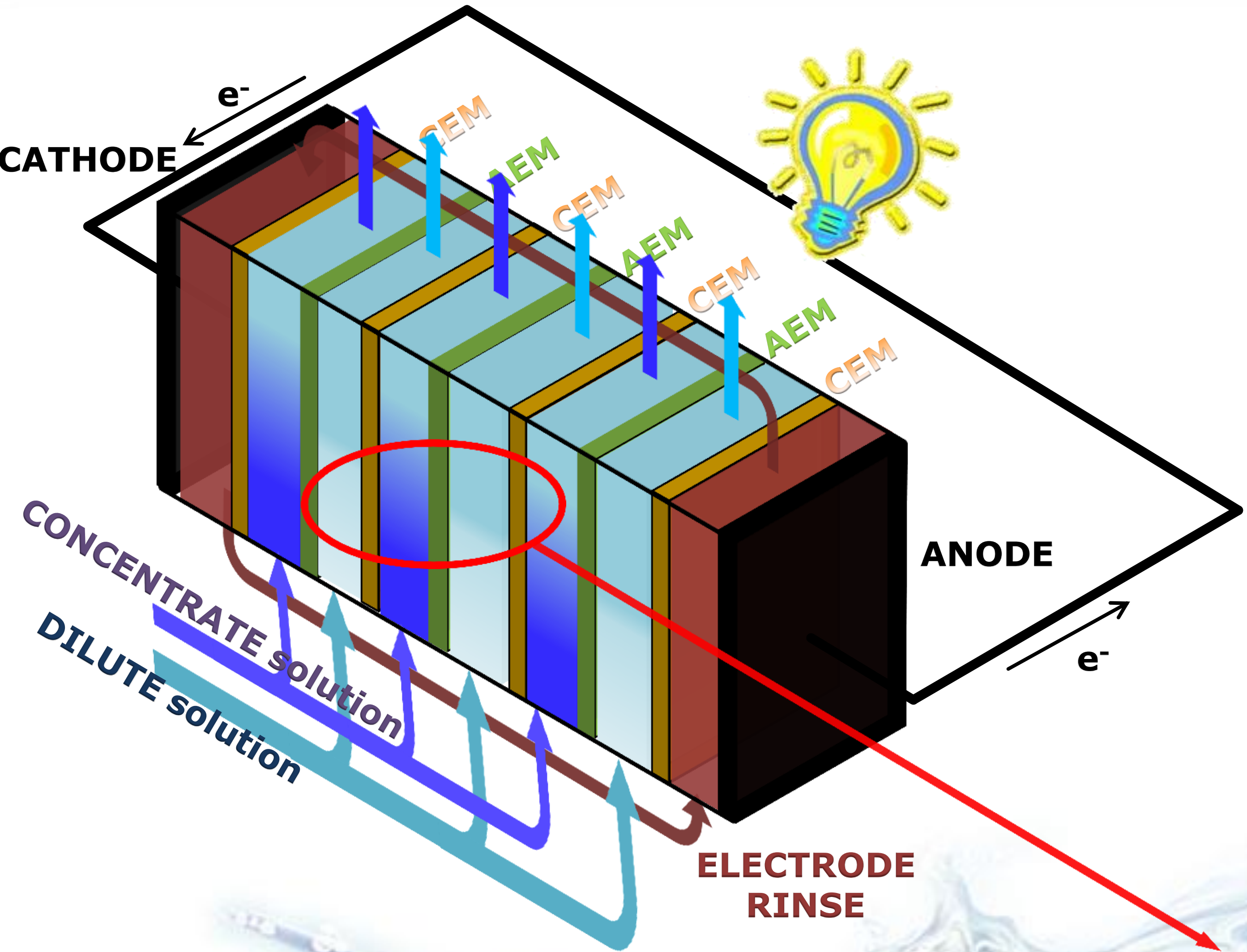
Main facts:

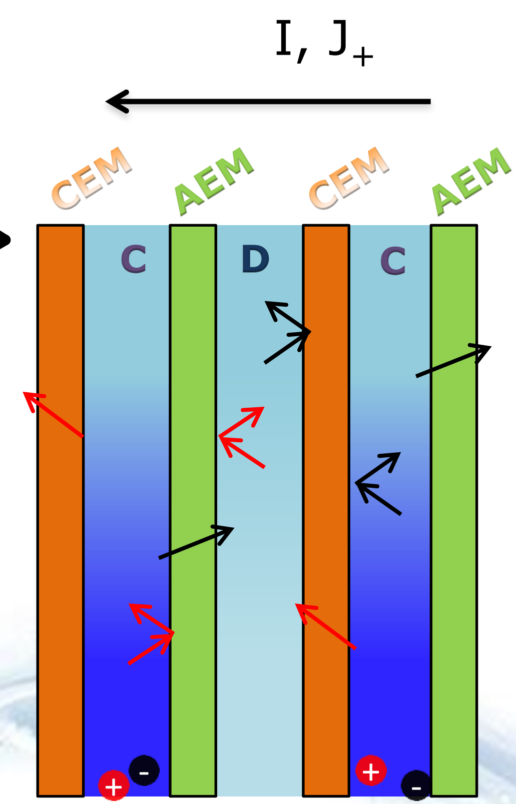
- Project acronym: “Reverse Electrodialysis for Alternative Power production”
- Cooperative project financed through the FP7 programme
- Starting date: 1 October 2010
- Closing date: 30 September 2014

The REAPower Project Consortium



The Reverse Electrodialysis technology





The REAPower Project

The idea…

to produce energy from salinity gradients generated by sea/brackish water and ultra-concentrated brines

Technological benefits for the SGP-RE process

new potentials for the exploitation of brines

The REAPower Project

Technological basic concepts . . .

i) Seawater (≈30-35 g/lt) in the LOW conc. compartment and concentrated brine (≈ 300 g/lt) in the HIGH conc. compartment dramatically reduce the electrical resistance in all battery compartments

ii) As a result: an ultra-low overall internal resistance within the SGP-RE battery cell-pairs can be achieved . . . especially with the introduction of thinner membranes

iii) Thus, the ultra-low internal resistance will significantly promote a higher power density of the SGP-RE battery.

The REAPower Project

Technological barriers. . .

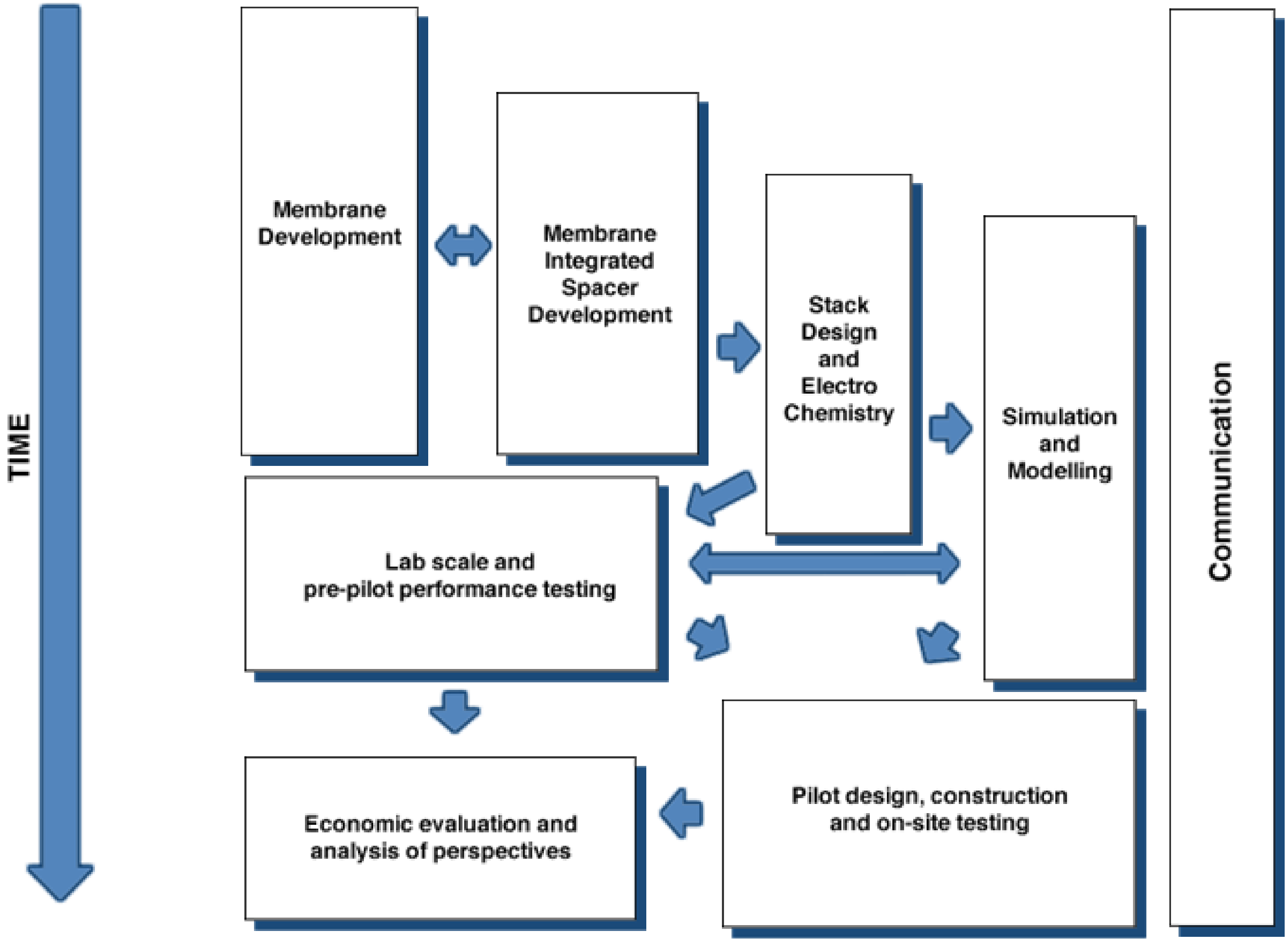
Effect of salinity on permselectivity	Solution strategy →	Improve IEMs formulation/preparation
High fouling and scaling potentials	Solution strategy →	Adequate pre-treatments for seawater and brine
Still low power density	Solution strategy →	Thin IEMs & optimised spacer geometry
Limited quantity of brine	Solution strategy →	Increase “fuel efficiency” and regeneration strategies

The REAPower Project

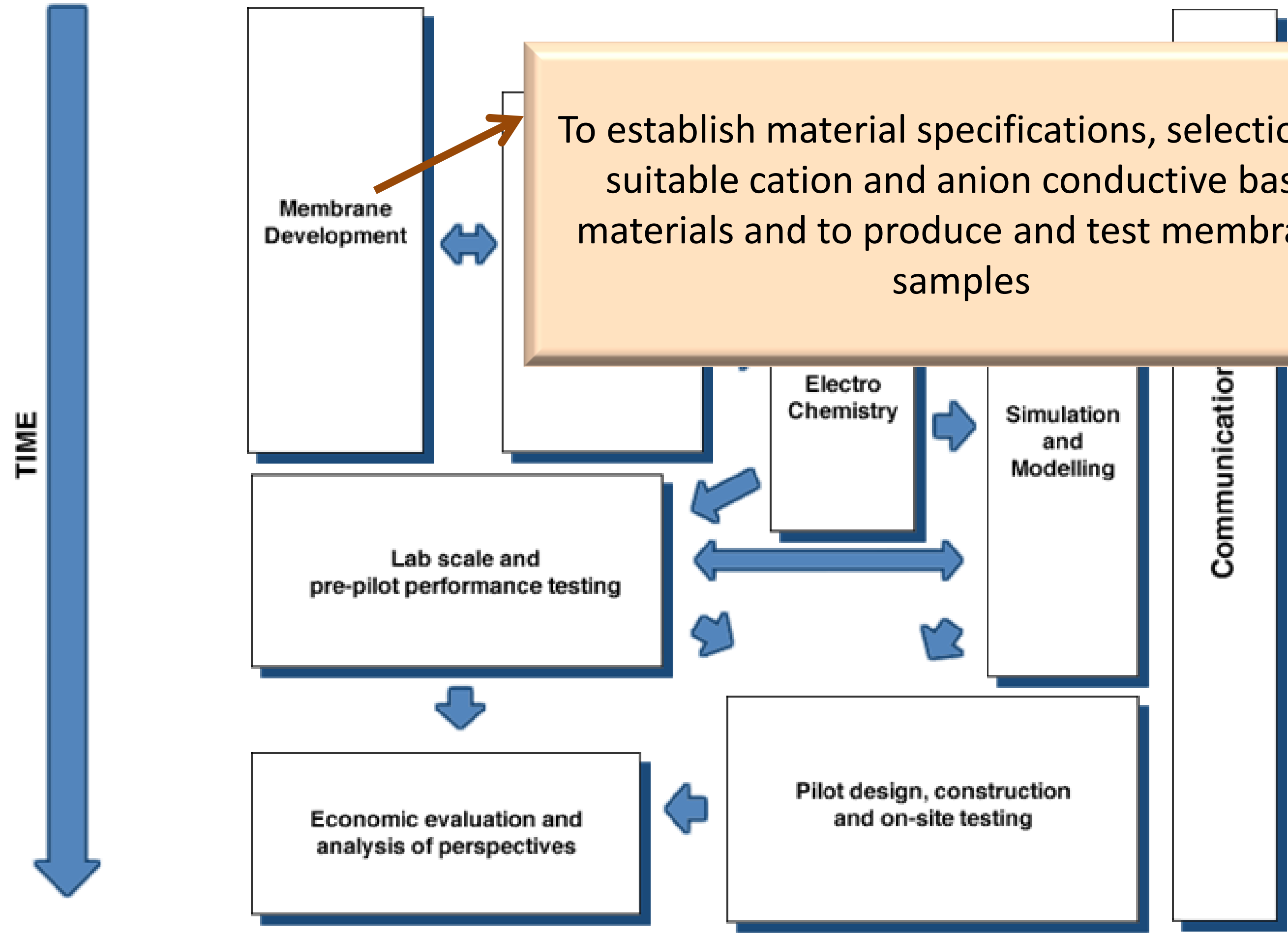
The Objectives. . .

1. Define and optimise materials and components tailored to the requirements of the technology
2. Optimise the design of the SGP-RE cell pairs and stack using computer modelling tools;
3. Validate the model and assess the developed materials, components and design by laboratory stack tests;
4. Evaluate and improve the system performance through tests on a prototype fed with real brine;
5. Analyse the “economics” and assess the perspectives
6. Define the next R&D steps

Project workplan

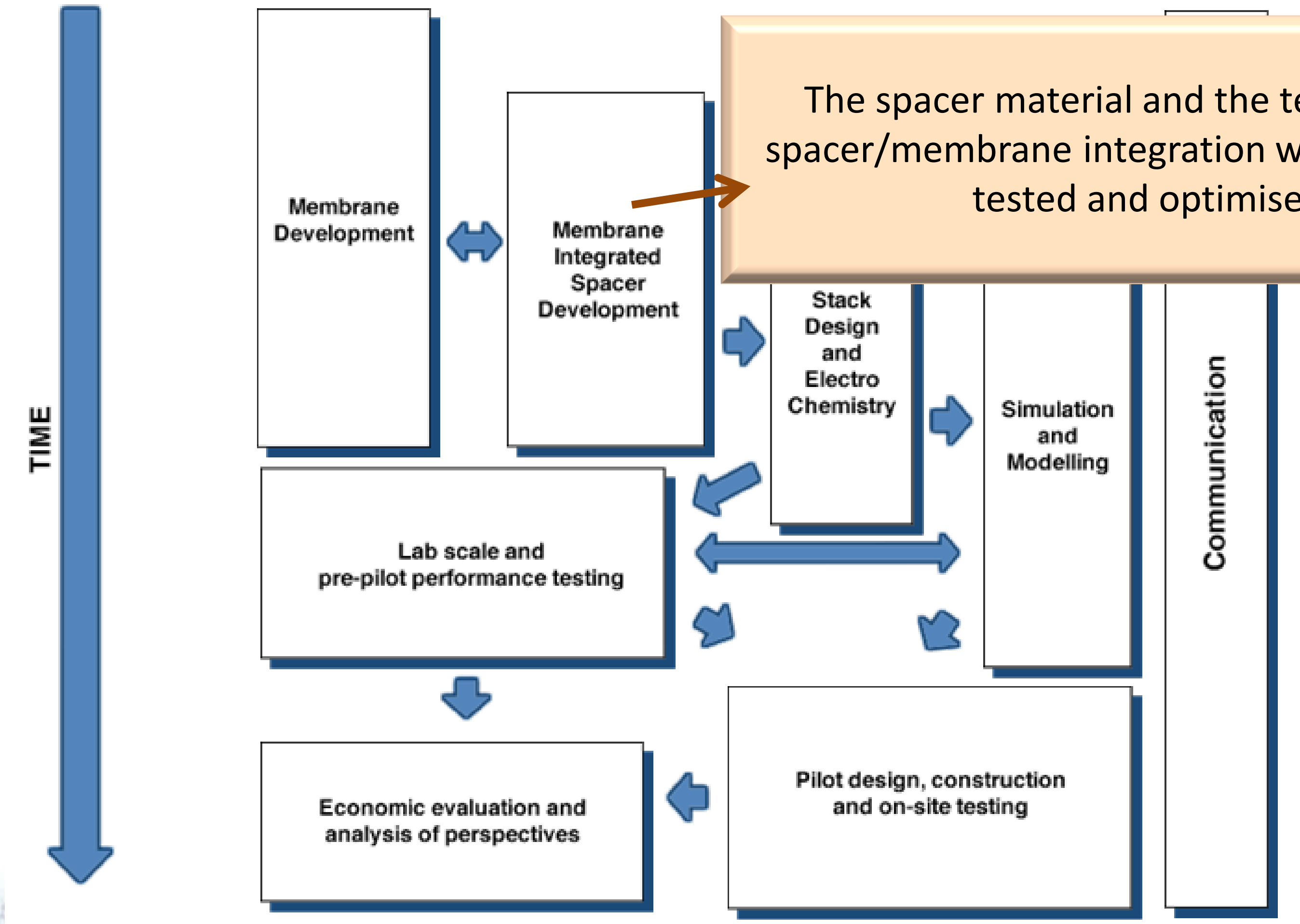


WP2. Membrane Development



To establish material specifications, selection of suitable cation and anion conductive base materials and to produce and test membrane samples

WP3. Membrane Integrated Spacer Development



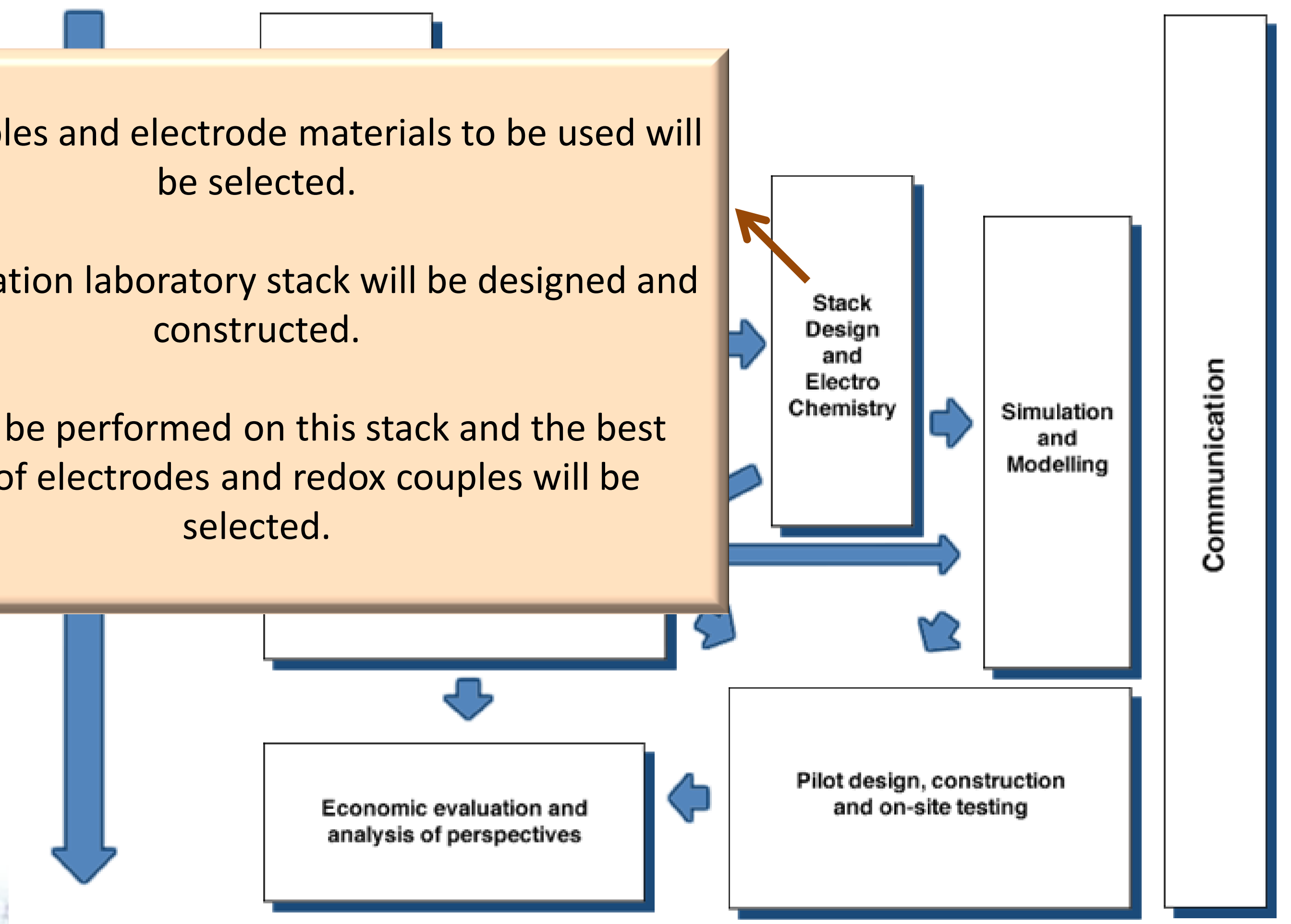
The spacer material and the technique for spacer/membrane integration will be selected, tested and optimised.

WP4. Electrochemical engineering/stack design

Redox couples and electrode materials to be used will be selected.

First generation laboratory stack will be designed and constructed.

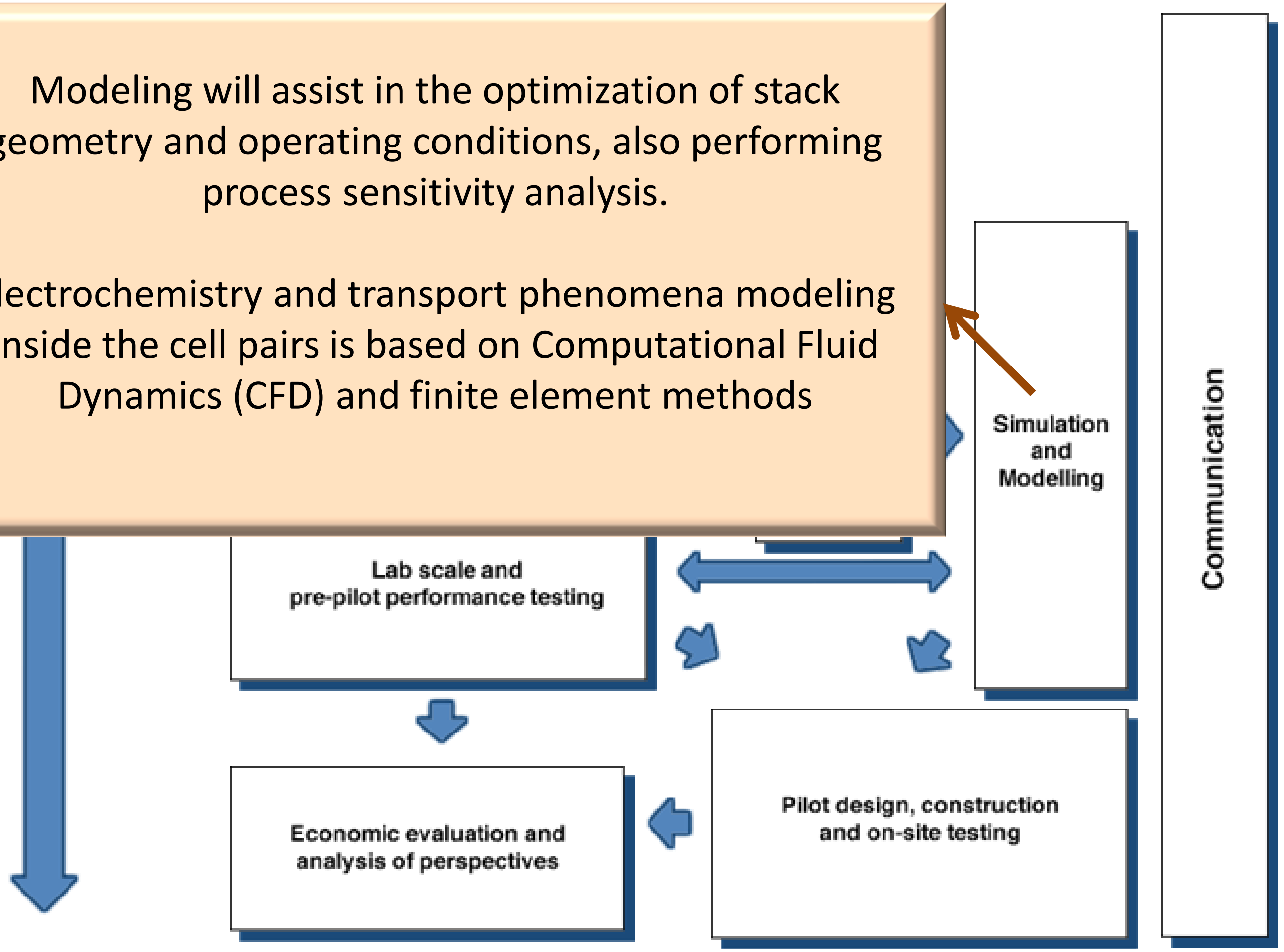
Tests will be performed on this stack and the best couple of electrodes and redox couples will be selected.



WP5. Process simulation

Modeling will assist in the optimization of stack geometry and operating conditions, also performing process sensitivity analysis.

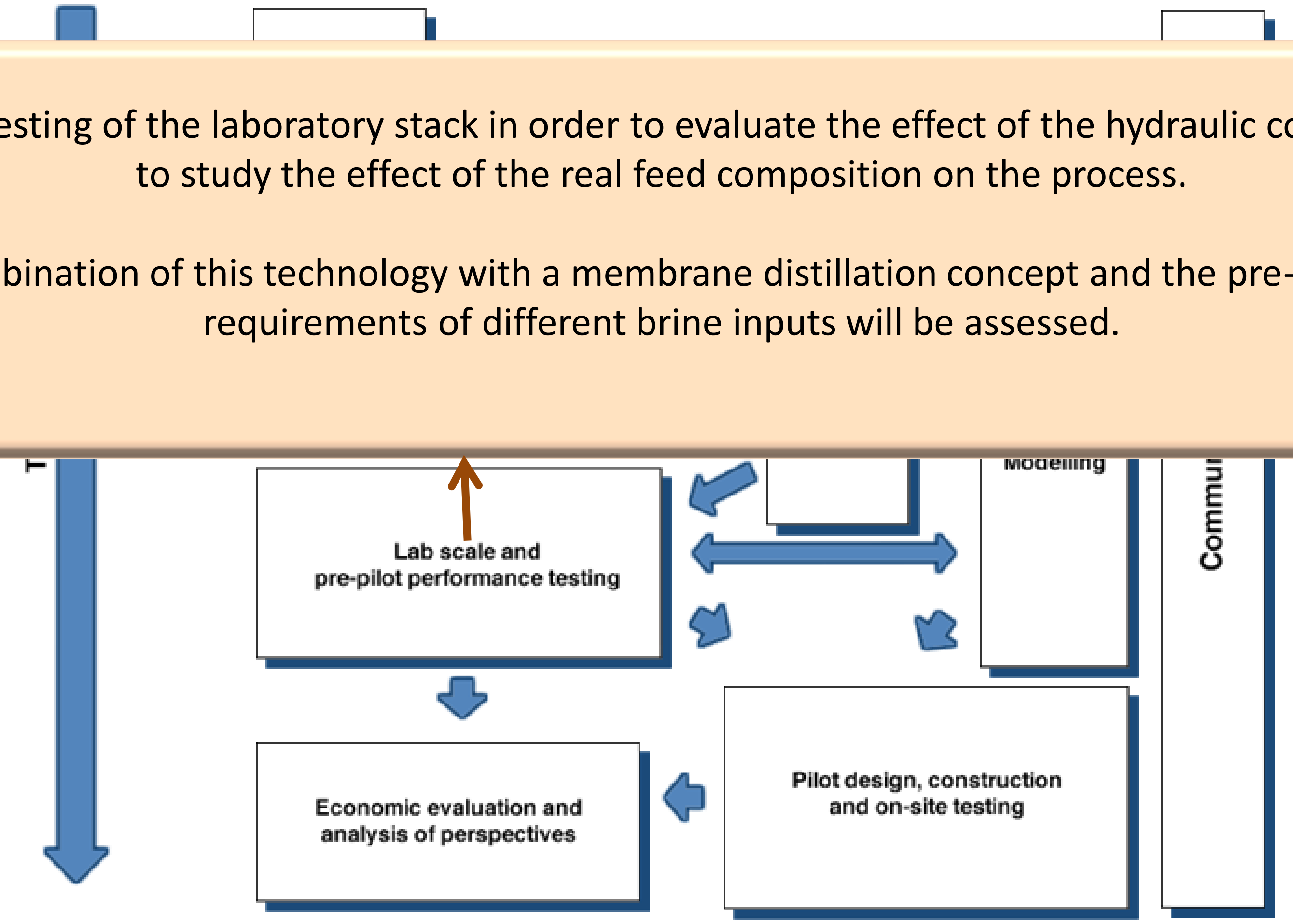
Electrochemistry and transport phenomena modeling inside the cell pairs is based on Computational Fluid Dynamics (CFD) and finite element methods



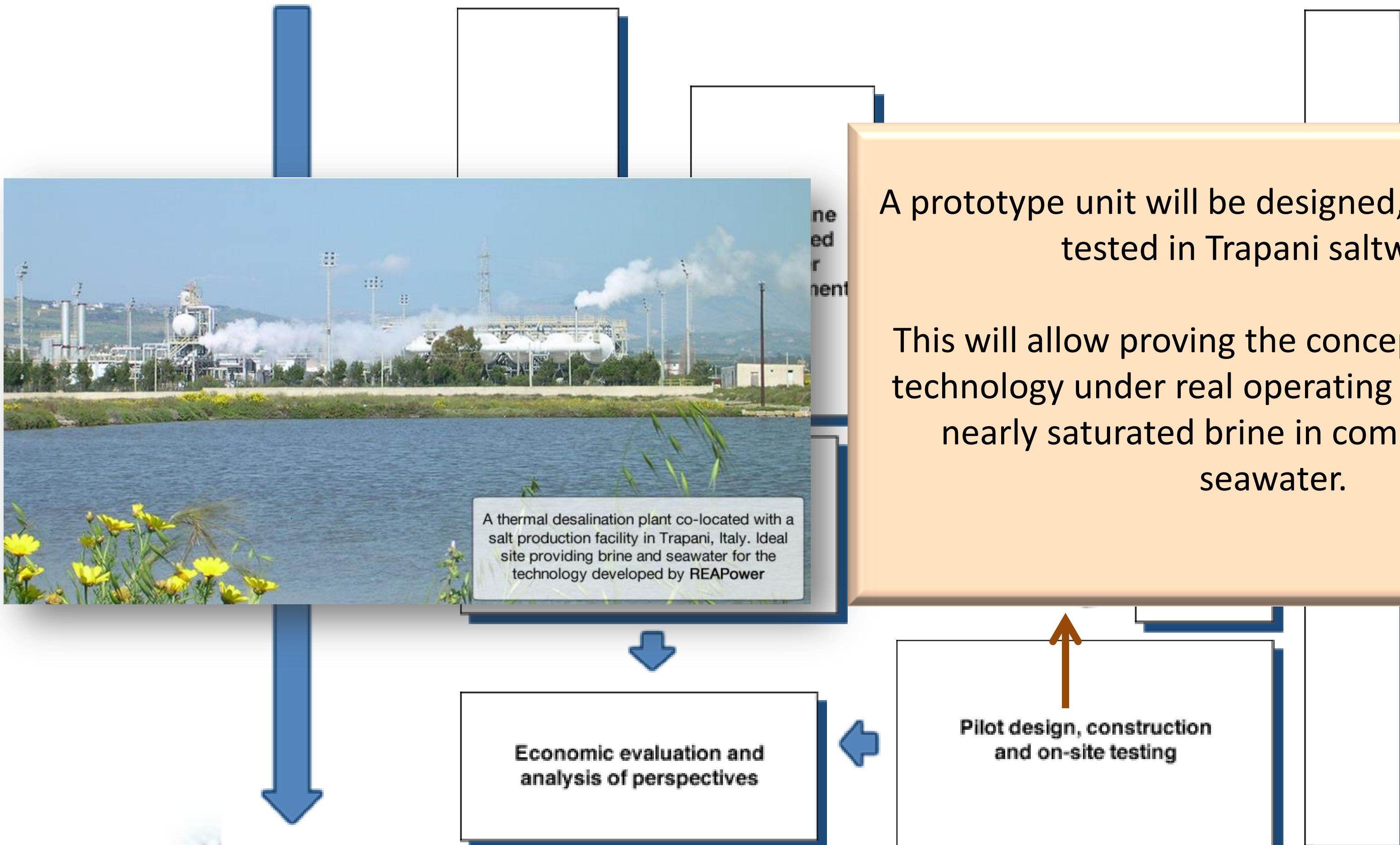
WP6. Lab-scale performance testing

Extensive testing of the laboratory stack in order to evaluate the effect of the hydraulic conditions and to study the effect of the real feed composition on the process.

The combination of this technology with a membrane distillation concept and the pre-treatment requirements of different brine inputs will be assessed.



WP7. Design, construction, testing of the prototype

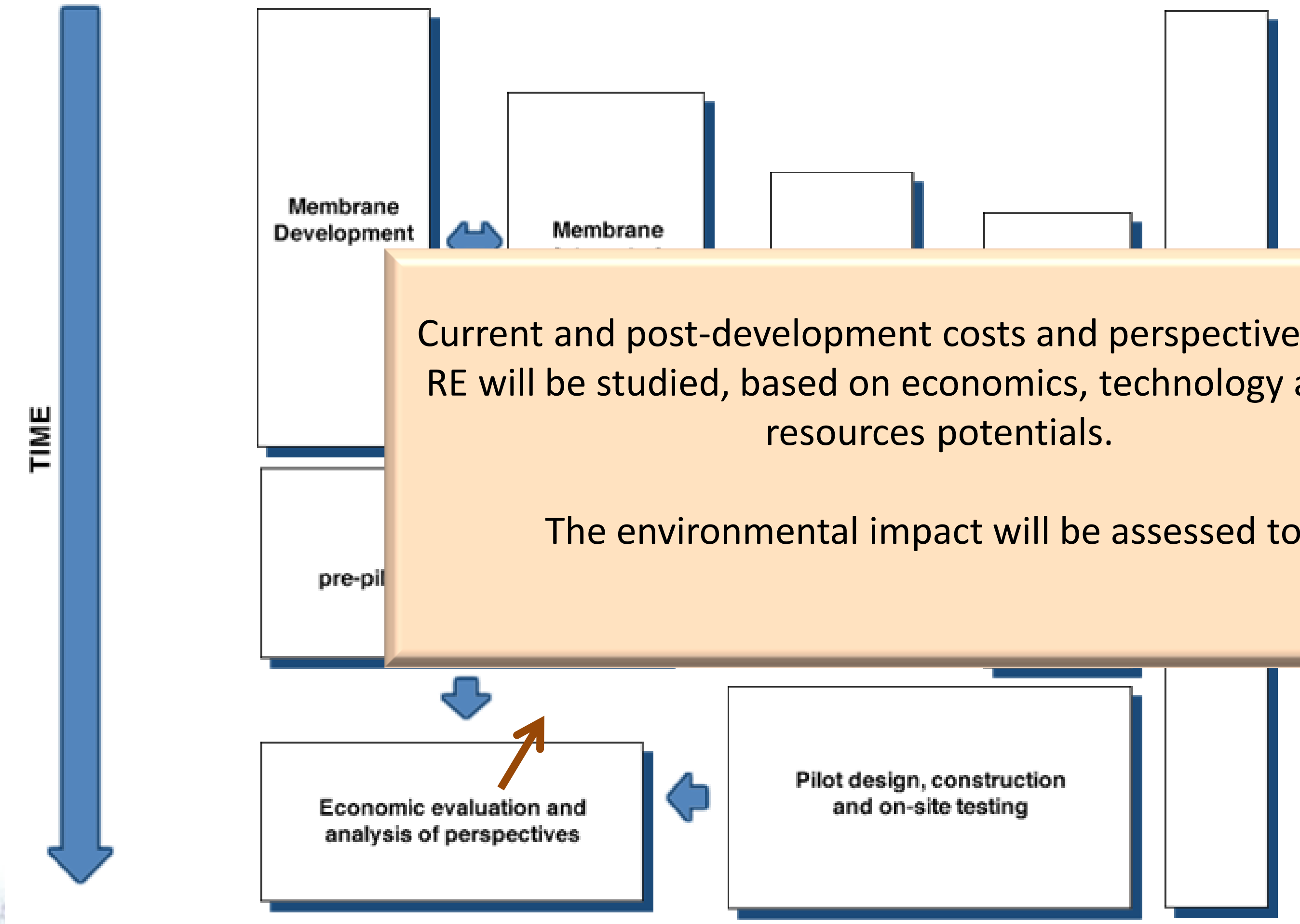


A thermal desalination plant co-located with a salt production facility in Trapani, Italy. Ideal site providing brine and seawater for the technology developed by REAPower

A prototype unit will be designed, constructed and tested in Trapani saltworks.

This will allow proving the concept of the SGP-RE technology under real operating conditions using nearly saturated brine in combination with seawater.

WP8. Economic evaluation/analysis of perspectives



Current and post-development costs and perspectives for SGP-RE will be studied, based on economics, technology and brine resources potentials.

The environmental impact will be assessed too.

Membranes performance enhancements

Increased permselectivity → Permselectivity has achieved values between **65 and 90%** when **in contact with** almost saturated **brine**

Reduced membrane resistance → Membrane specific resistance has been reduced to values around 1.5-2.5 $\Omega \cdot cm^2$ aiming at a 3-5 folds reduction in the next months

Redox couples and stack design

Redox couples selection

Several redox couples have been tested under different conditions, finding the most promising for the SGP-RE prototype: $FeCl_3/FeCl_2$; Water/Na_2SO_4; $[Fe(CN)_6]^{3-}/[Fe(CN)_6]^{4-}$

2 stack generations already designed and tested

Two different stack geometries have been already designed, constructed and tested and are now available for the consortium

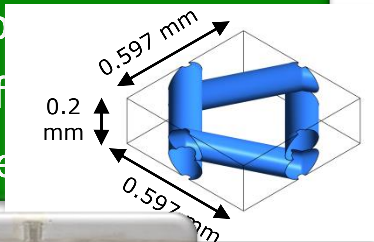
IEM-integrated Spacer & Fluid Dynamics optimisation

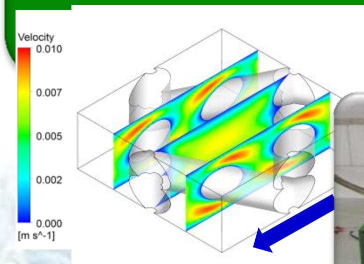
Membrane Integrated Spacer

→ Tests are being performed for the preparation of **Membrane Integrated Spacers**, aiming at membrane thickness in the range **10-20 μm**

Choice of spacer thickness and geometry

→ **CFD simulations** have been carried out along with exp characterisation of dif and ge

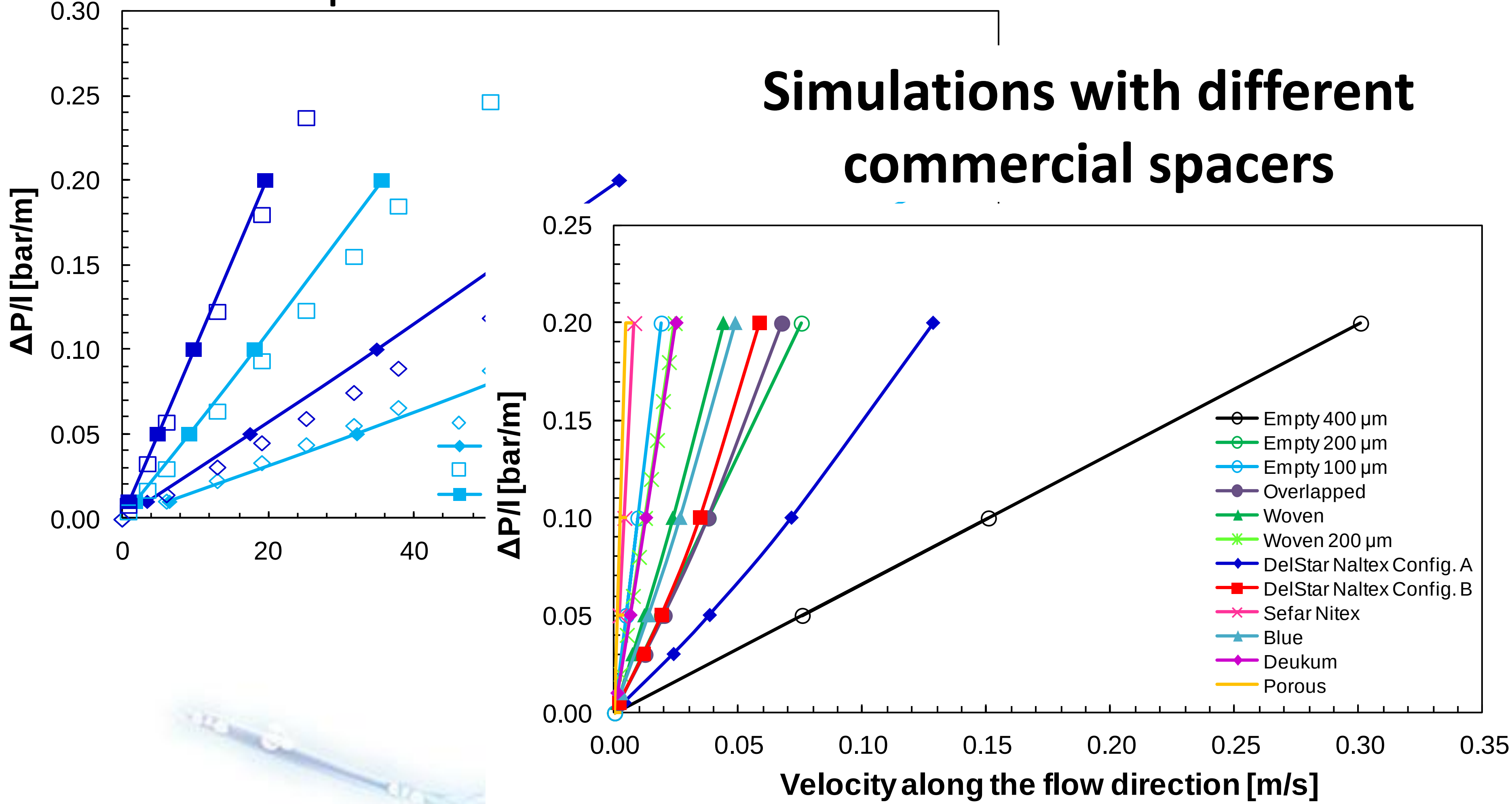




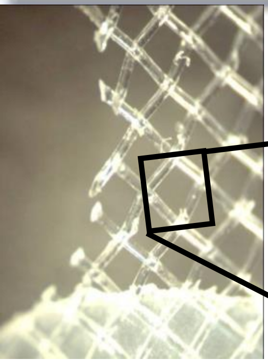
CFD Modelling: prediction of pressure drops

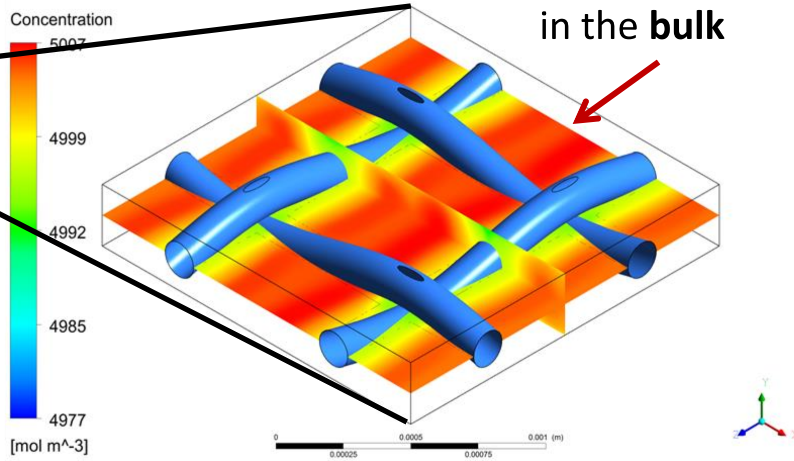
Model validation with experimental results

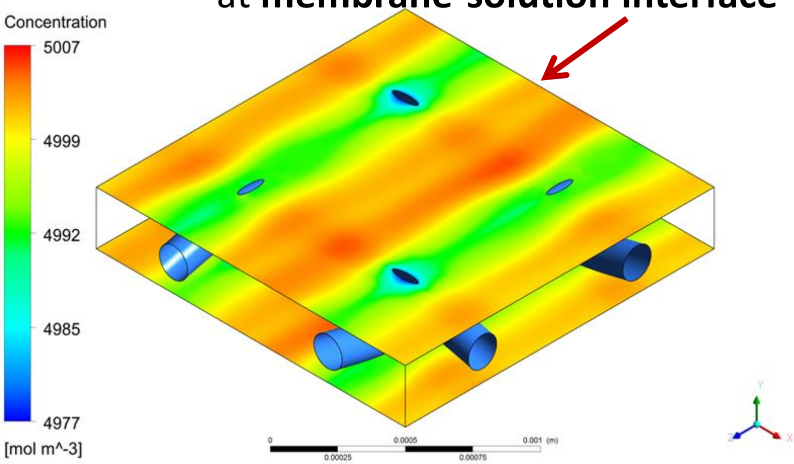
Simulations with different commercial spacers



CFD Modelling: prediction of polarisation phenomena

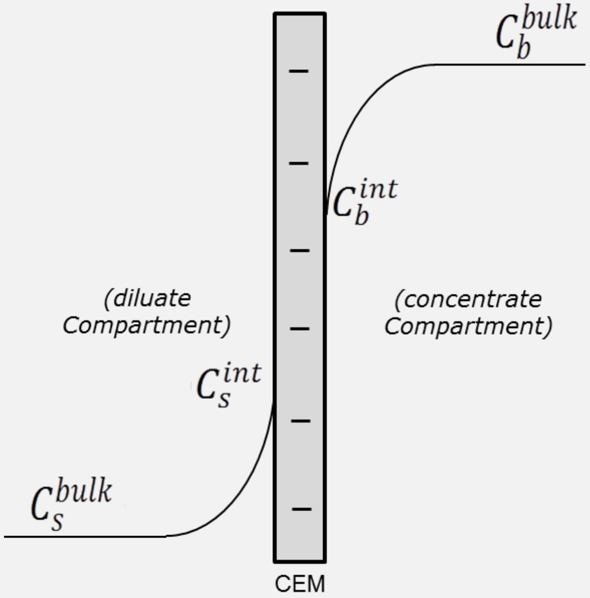






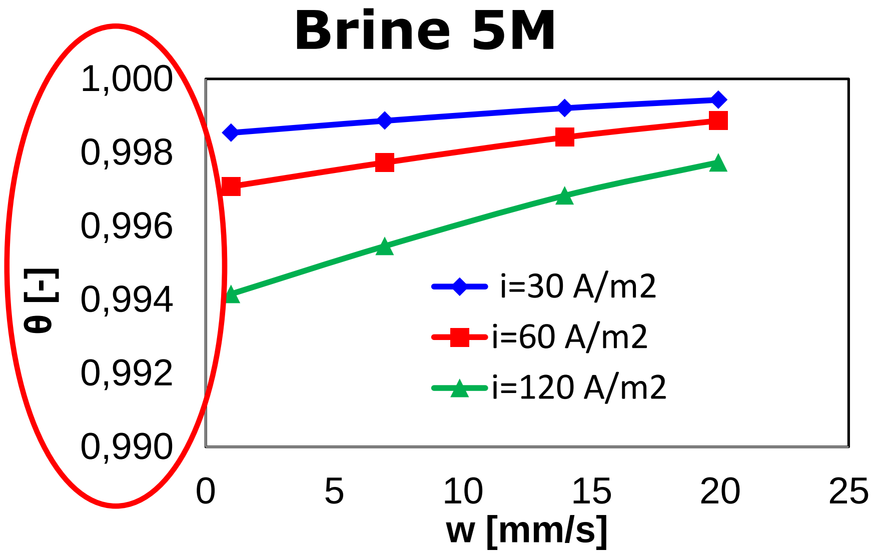
Polarisation Coefficients:

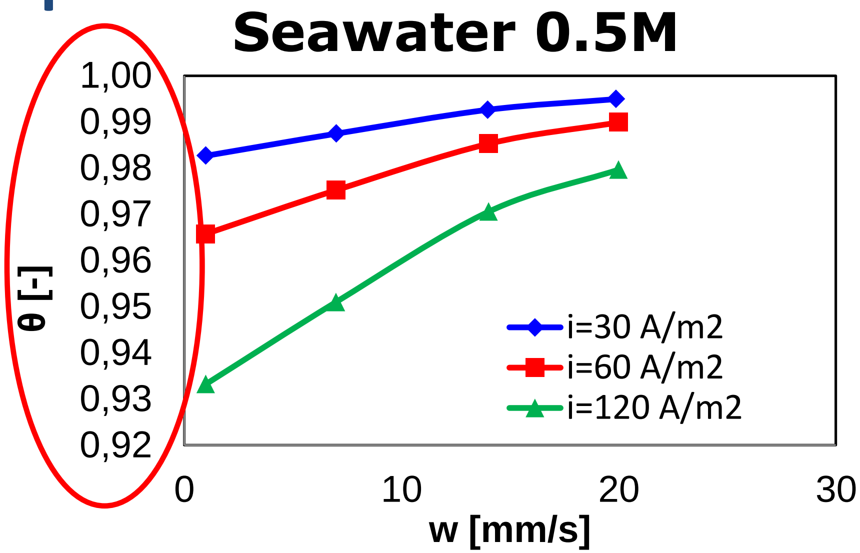
$$\begin{cases} \vartheta_b = \dfrac{C_b^{int}}{C_b^{bulk}} \\ \vartheta_s = \dfrac{C_s^{bulk}}{C_s^{int}} \end{cases}$$

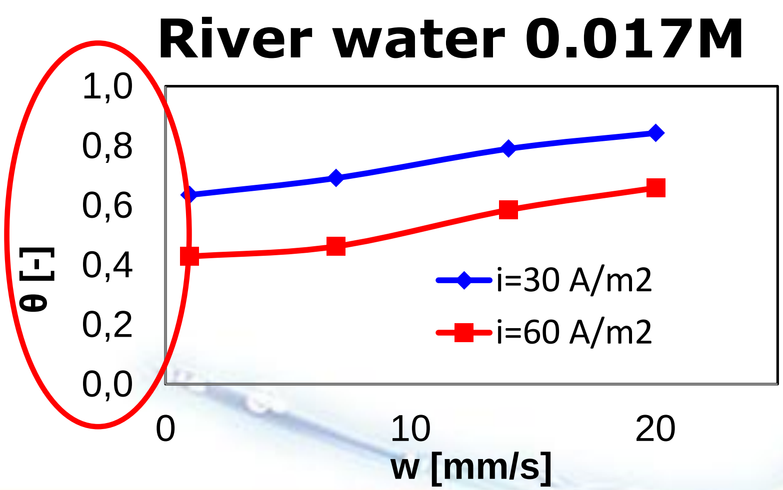


CFD Modelling: prediction of polarisation phenomena

Polarization factor for Deukum spacer-filled channels



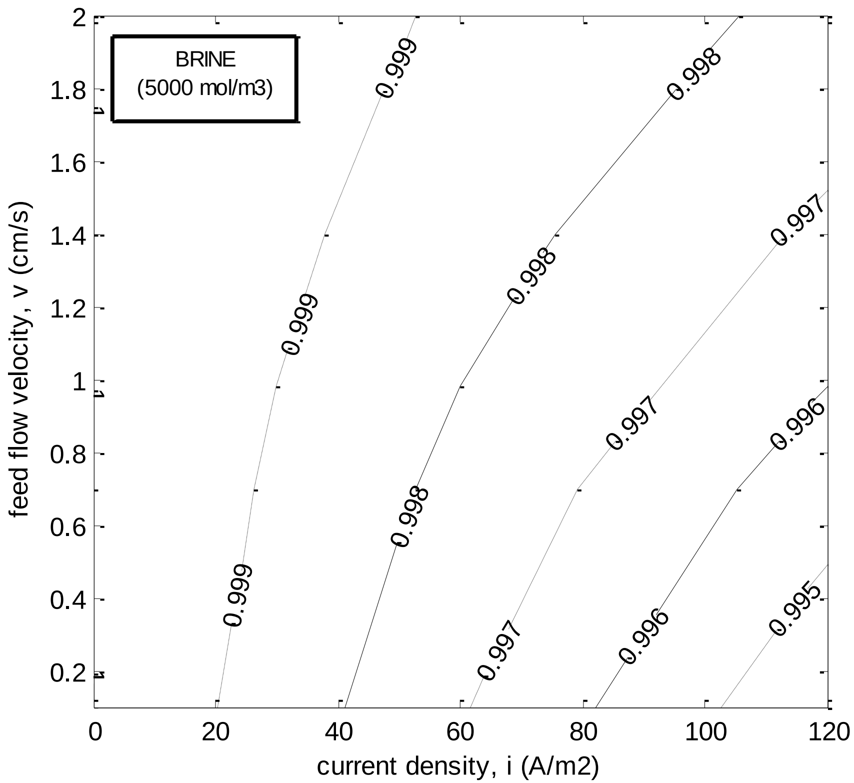


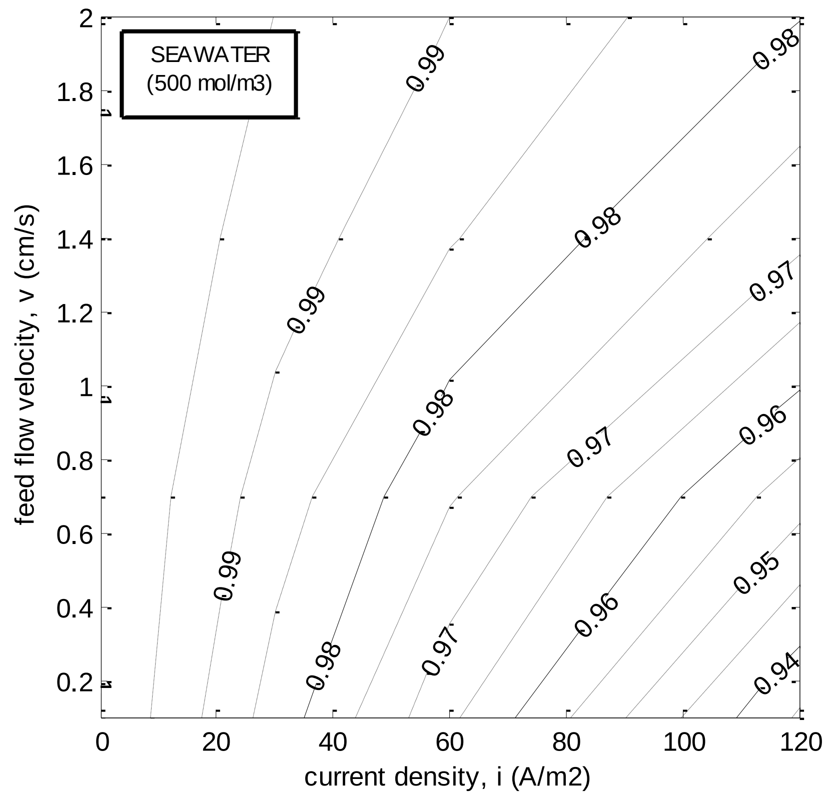


- Very high *θ* values predicted for brine and seawater, lower for river water. If C↑, θ↑
- The higher *i*, the lower the *θ* value, but this dependence is crucial only for river water
- Higher *w* corresponds to an enhanced mixing. If *w*↑, *θ*↑

CFD Modelling: prediction of polarisation phenomena

Polarization factor for Deukum spacer-filled channels

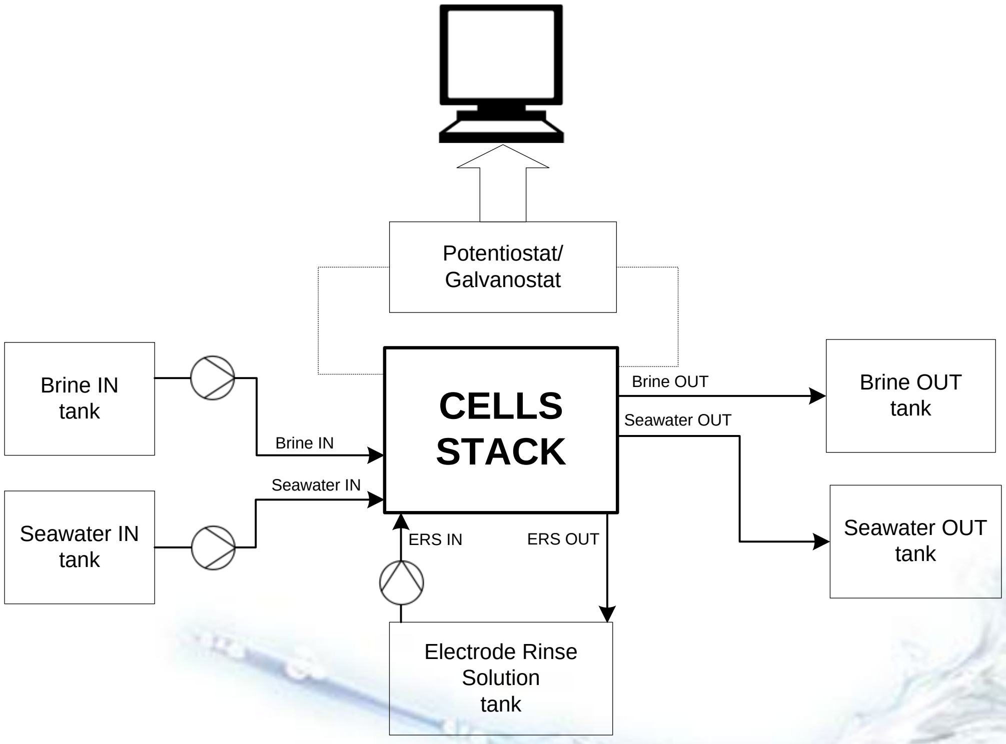




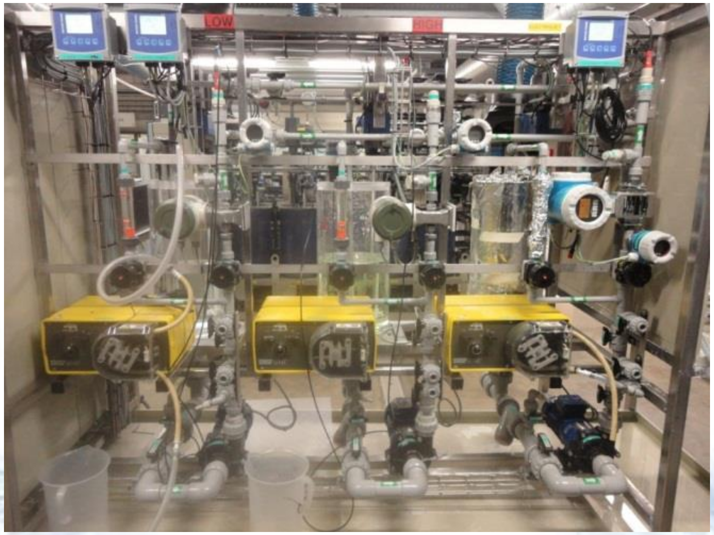
Example: Effect of current density and fluid velocity on polarization coefficients.
Model predictions from CFD simulations with 280 µm polyamide woven spacer (Deukum GmbH, Germany).

Experiments on the “second generation” stack

An extended experimental campaign has been (and is currently being) carried out at VITO laboratories to investigate the performance of a novel design SGP-RE stack under REAPower conditions

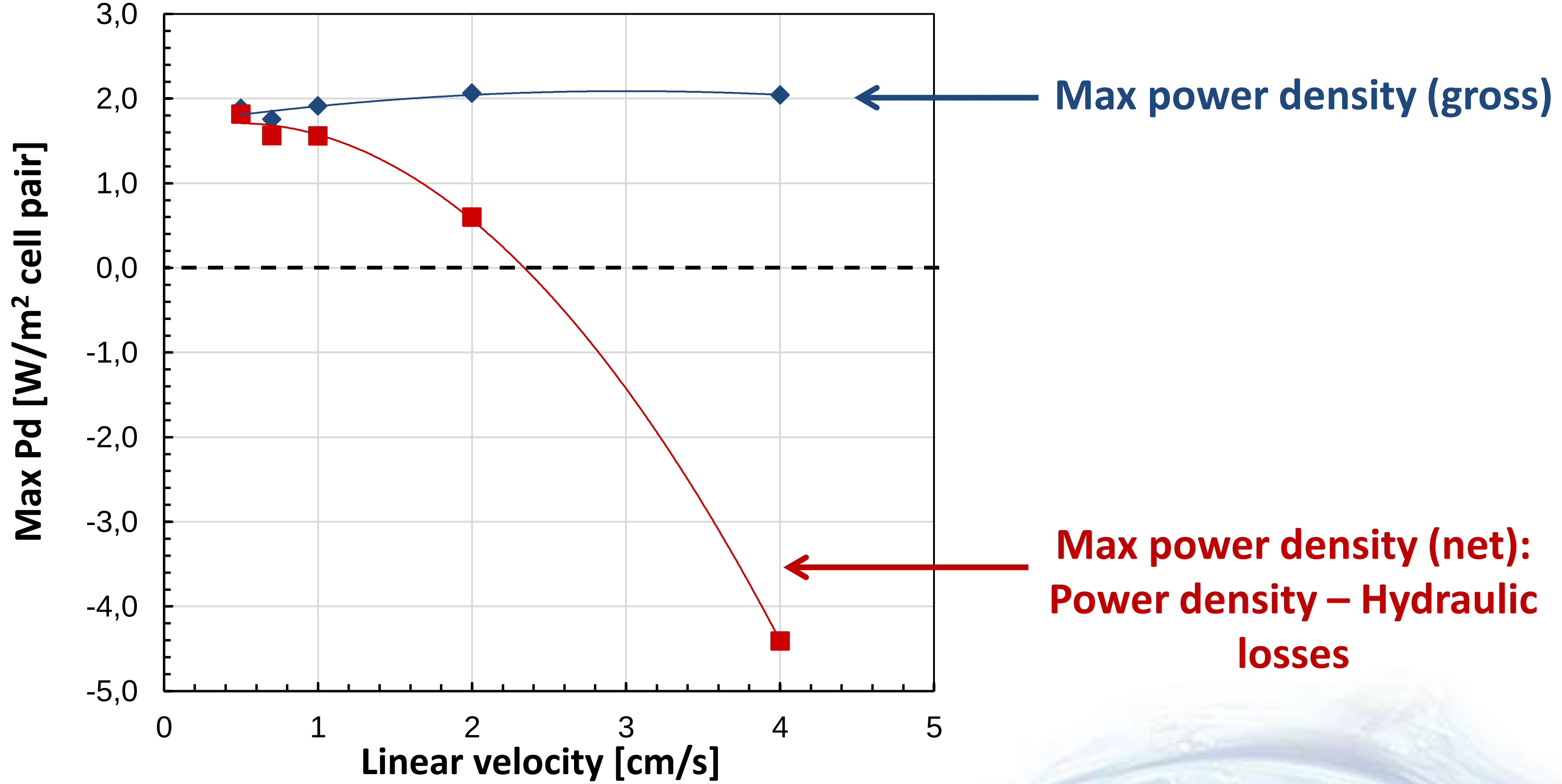


vito
vision on technology



Experiments on the "second generation" stack

Effect of feed flow linear velocity

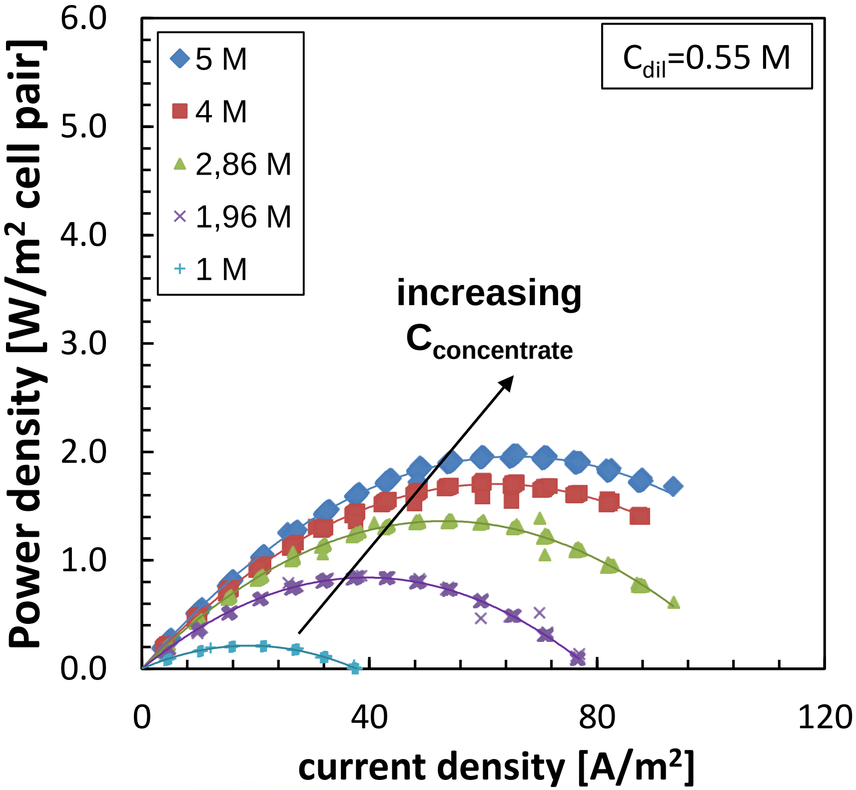


50 cell pairs - 80050 (CEM) and 80045 (AEM) membranes [thickness 120µm] - Deukum spacers [thickness 270 µm] - Brine 5 M, seawater 0,5 M - Electrode rinse solution [($K_3Fe(CN)_6$ 0,1 M, $K_4Fe(CN)_6 \cdot 3H_2O$ 0,1M; NaCl 2,5M) –conductivity 204 mS/cm – flow rate 30l/h].

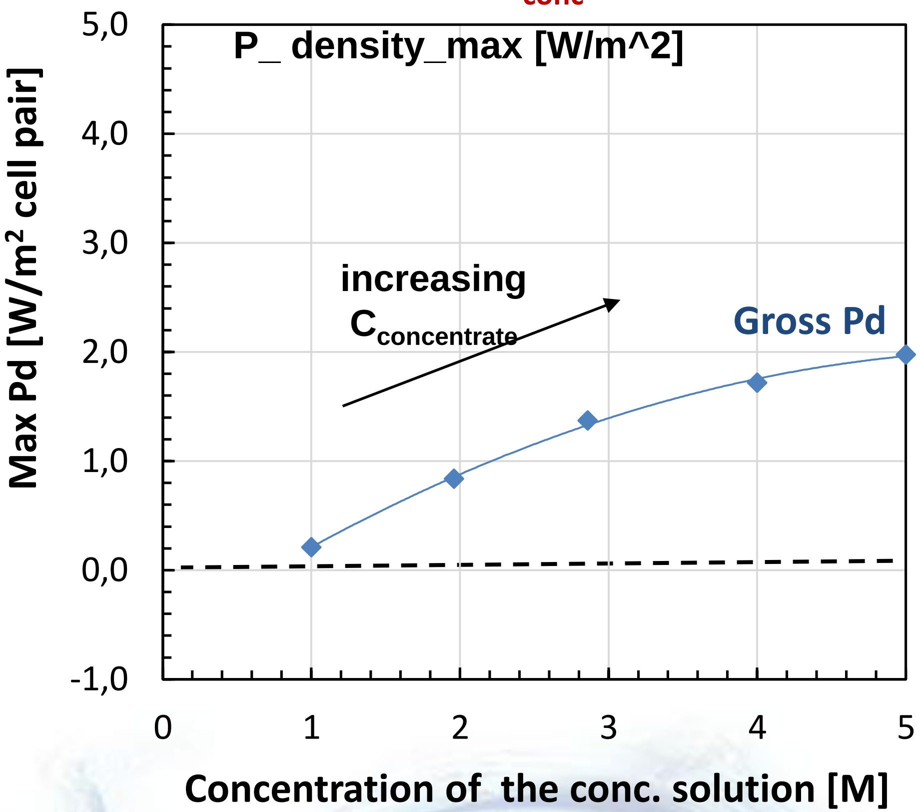
Experiments on the "second generation" stack

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

Power density vs. current density



Maximum power density vs. C_{conc}

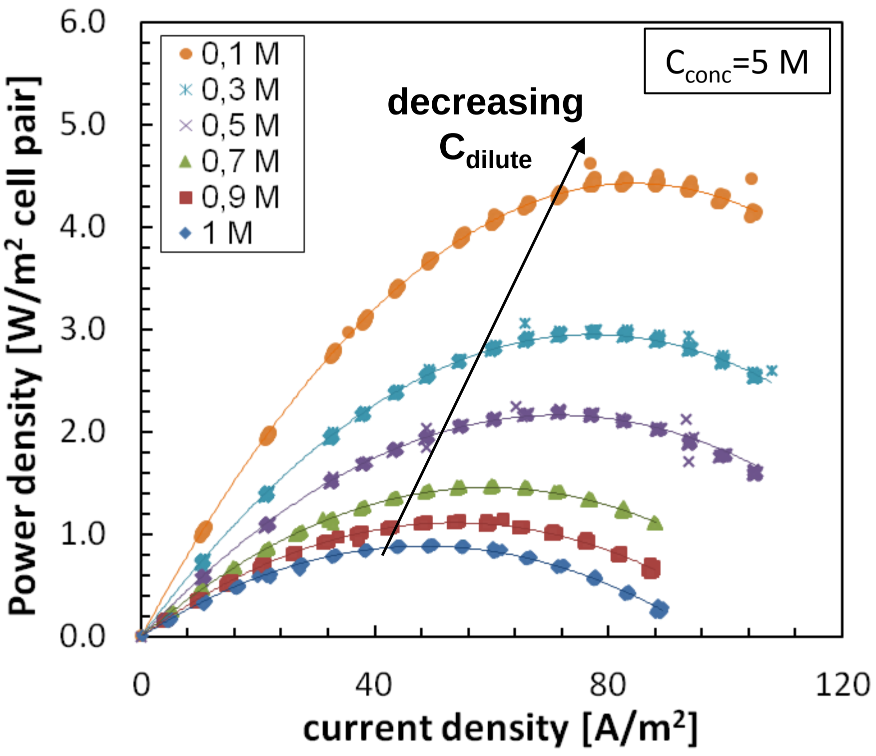


50 cell pairs - 80050 (CEM) and 80045 (AEM) membranes [thickness 120μm] - Deukum spacers [thickness 270 μm] - Brine 5 M [conductivity: 230 mS/cm – linear speed 1cm/s], seawater 0,1÷0,5 M [conductivity: 10,46÷84,4 mS/cm – linear speed 1cm/s] - Electrode rinse solution [($K_3Fe(CN)_6$ 0,1 M, $K_4Fe(CN)_6 \cdot 3H_2O$ 0,1M; NaCl 2,5M) –conductivity 204 mS/cm – flow rate 30l/h].

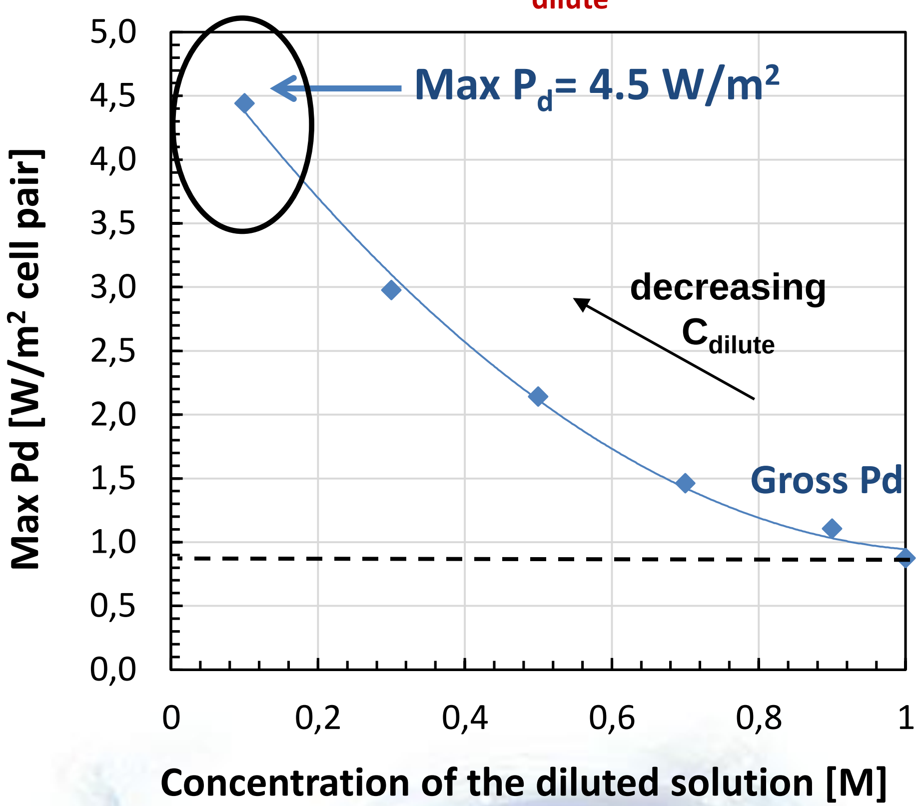
Experiments on the "second generation" stack

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

Power density vs. current density



Maximum power density vs. C_{dilute}

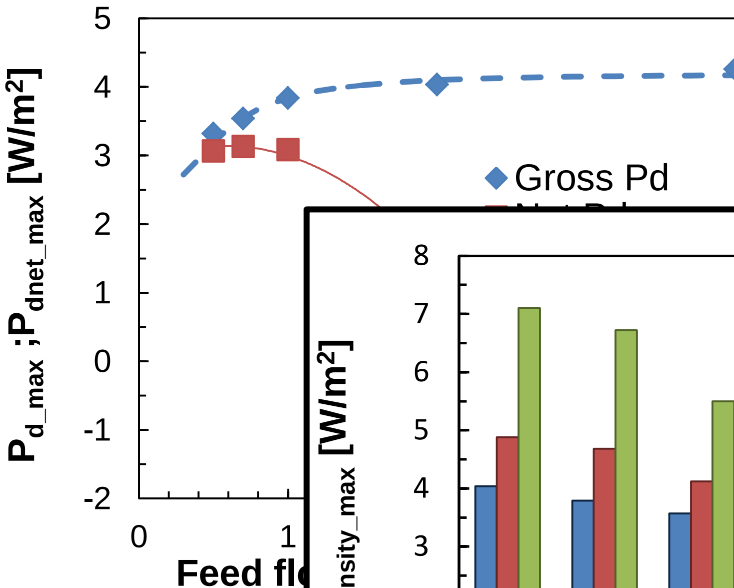


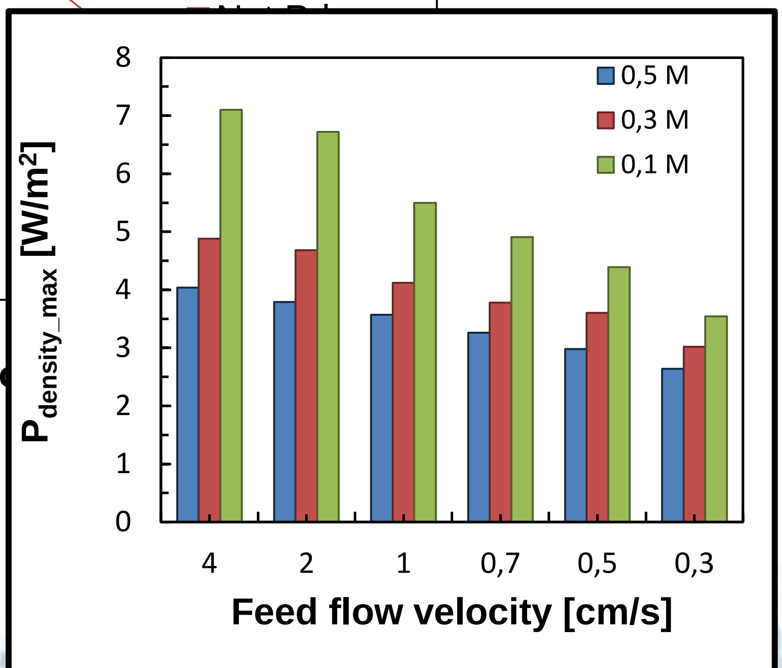
50 cell pairs - 80050 (CEM) and 80045 (AEM) membranes [thickness 120μm] - Deukum spacers [thickness 270 μm] - Brine 5 M [conductivity: 230 mS/cm – linear speed 1cm/s], seawater 0,1÷0,5 M [conductivity: 10,46÷84,4 mS/cm – linear speed 1cm/s] - Electrode rinse solution [($K_3Fe(CN)_6$ 0,1 M, $K_4Fe(CN)_6 \cdot 3H_2O$ 0,1M; NaCl 2,5M) –conductivity 204 mS/cm – flow rate 30l/h].

Experiments on the “second generation” stack

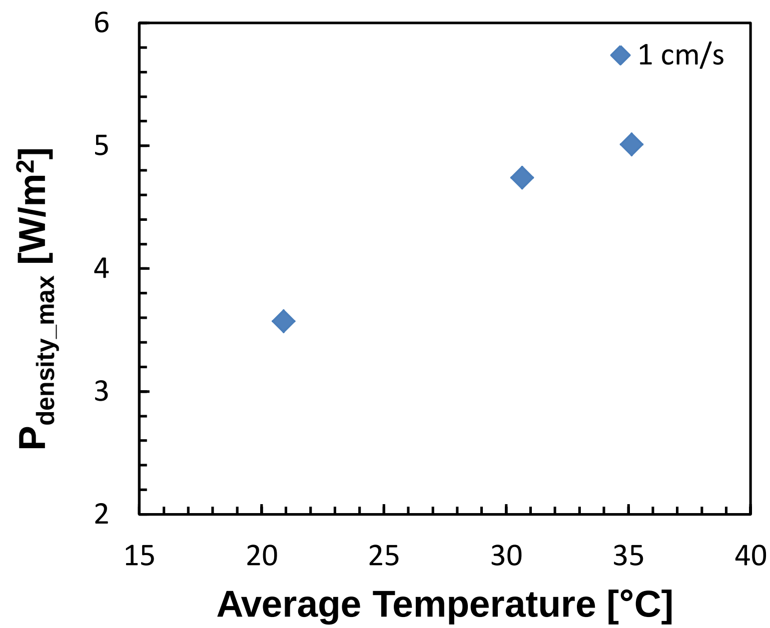
Change in membranes: 20-30 μm thin commercial membranes

Influence of flow velcoity





Influence of Temperature



Influence of diluate concentration

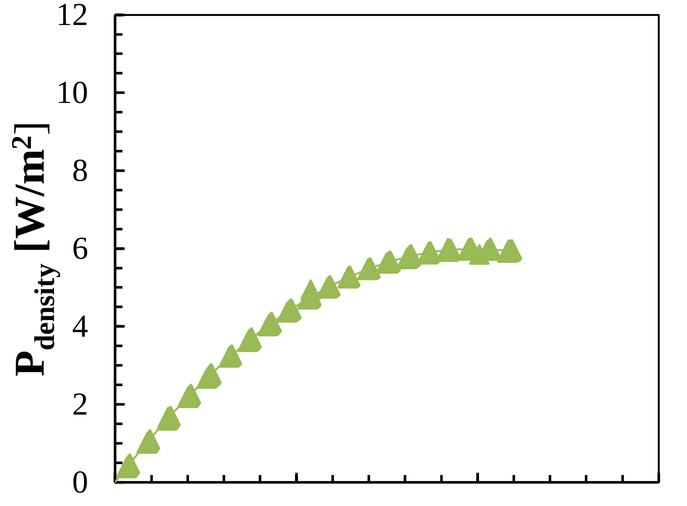
50 cell pairs - FAS – 20/FKS – 20 Fumatech membranes [thickness 20-30 μm] - Deukum spacers [thickness 270 μm] - Brine 5 M, seawater 0,1÷0,5 M - Electrode rinse solution [($K_3Fe(CN)_6$ 0,1 M, $K_4Fe(CN)_6 \cdot 3H_2O$ 0,3M; NaCl 2,5M), flow rate 30l/h].

Experiments on the “second generation” stack

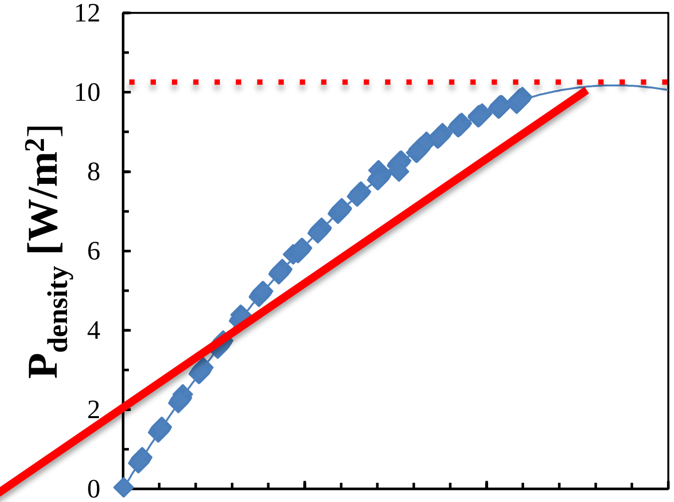
MAX power output conditions:

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

Thick membranes (120μm)

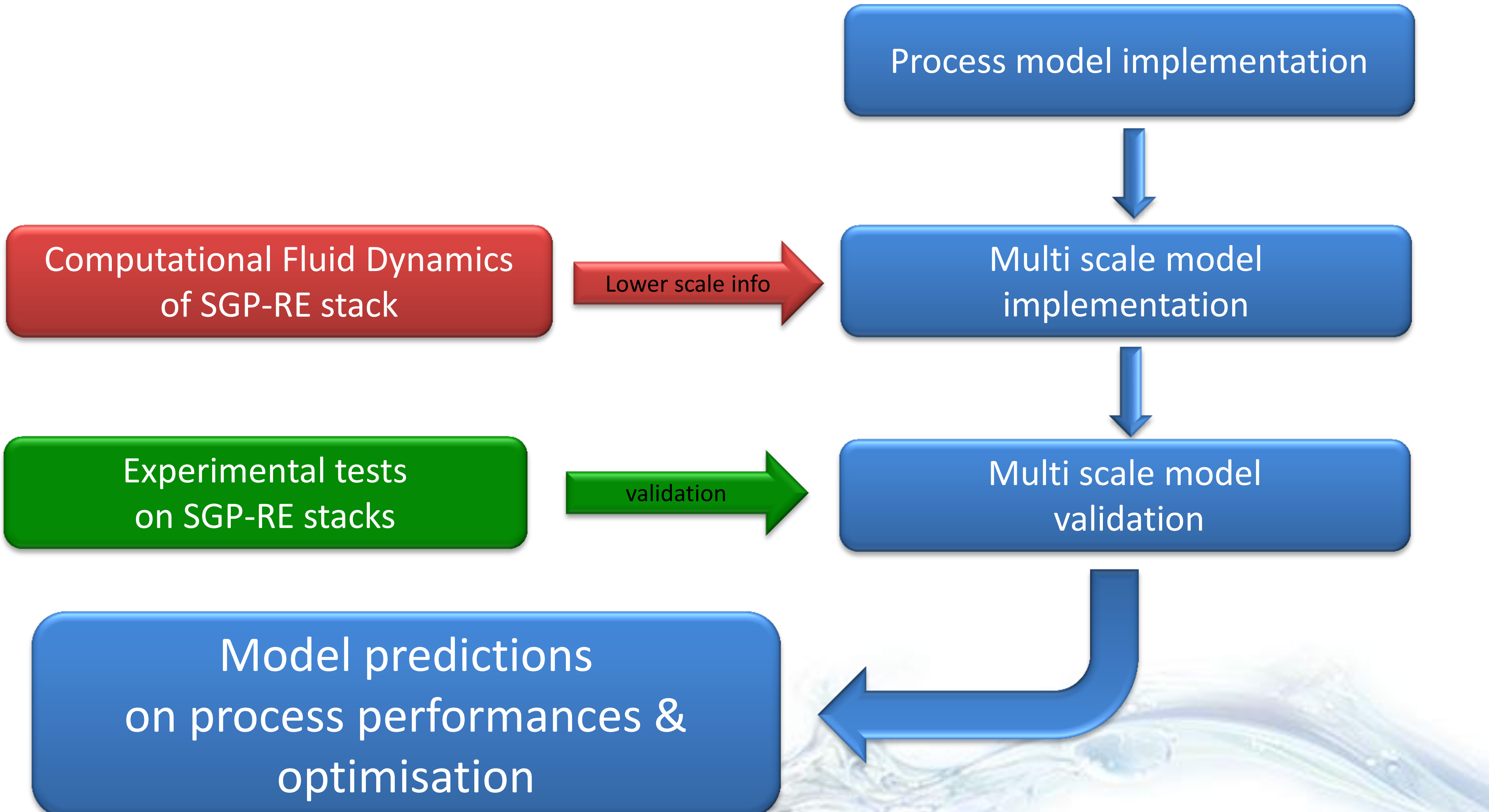


Thin membranes (20-30μm)



A power density between **15 and 20 W/m² can** be expected with larger number of cell pairs, which would reduce the effect of **blank resistance**

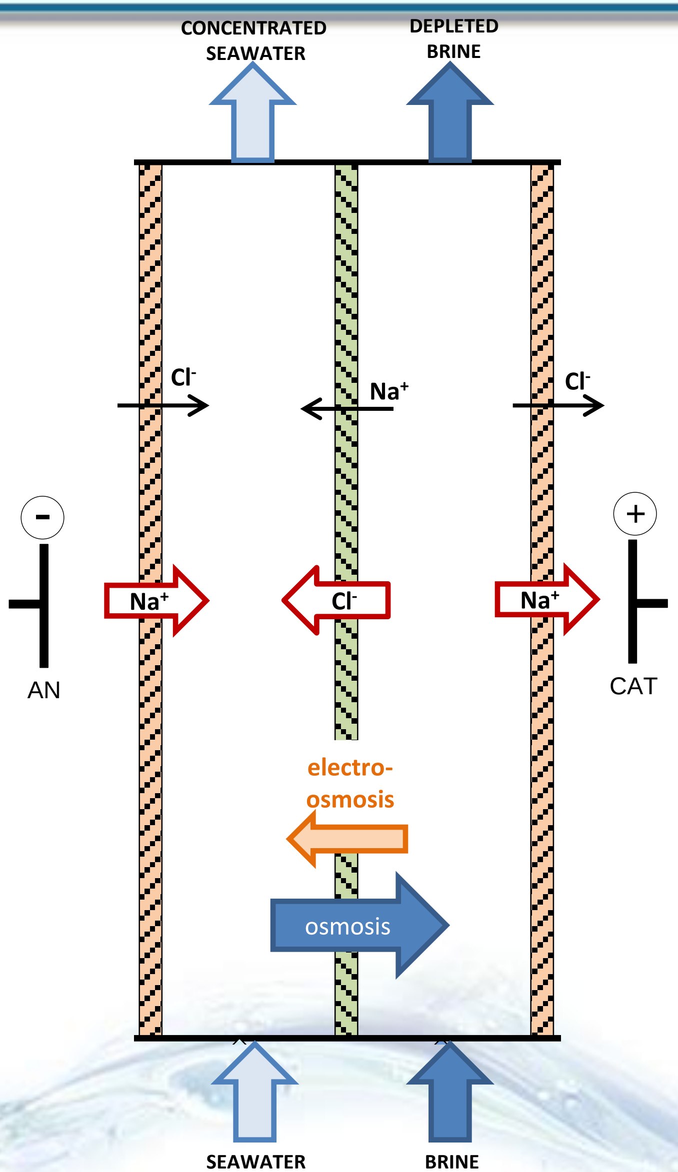
Multi-scale model implementation



Process Modelling Approach

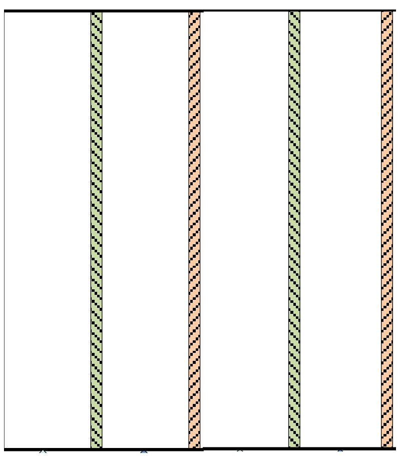
Low-hierarchy model (*cell pair*):

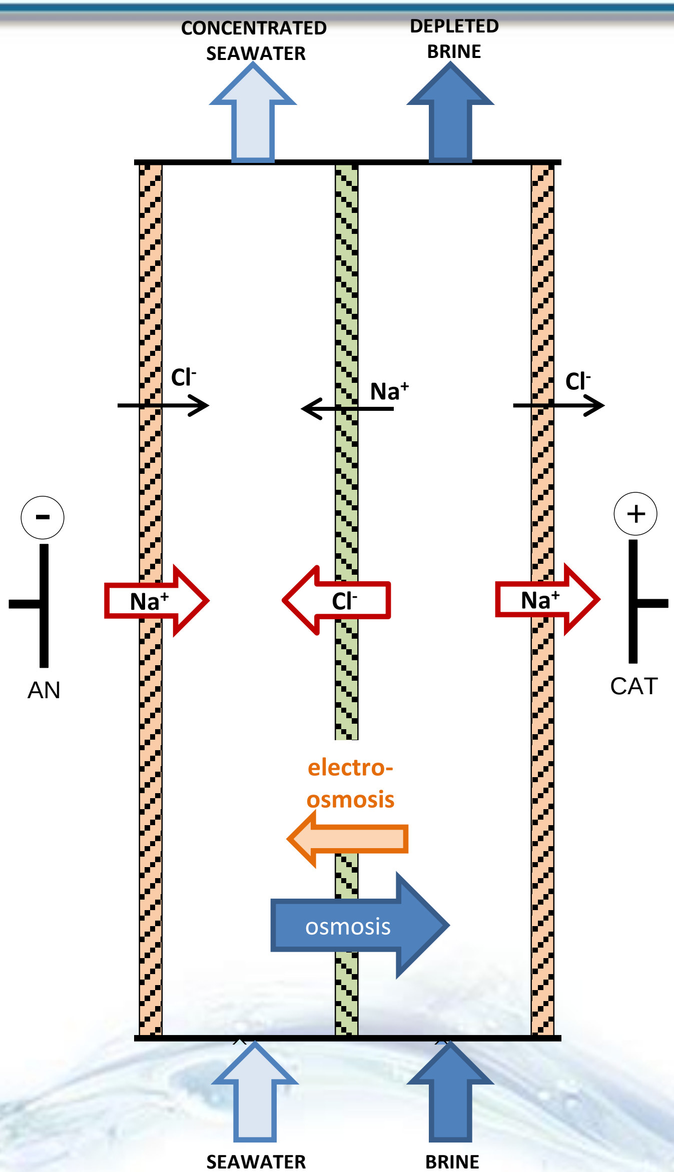
- thermodynamic properties of solutions
- electric variables
- salt transport (counter/co-ions)
- solvent transport (osmosis/electro-osmosis)
- polarization phenomena
- mass balance



Tedesco, M.; Cipollina, A; Tamburini, A.; van Baak, W.; Micale, G.; "Modelling the Reverse ElectroDialysis process with seawater and concentrated brines", *Desalination and Water Treatment*, vol. 49, pp. 404-424, 2012.

Process Modelling Approach





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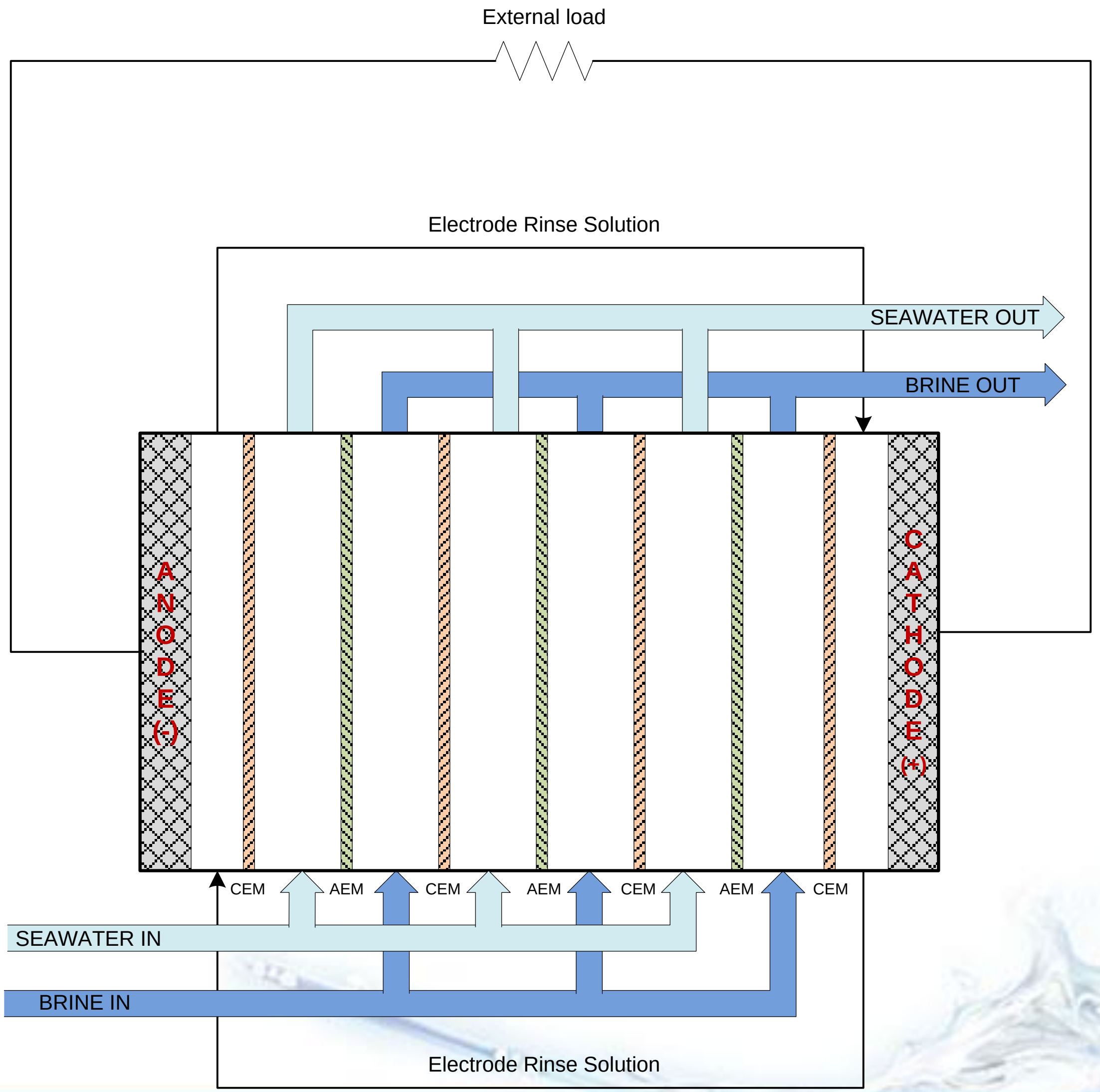
Process Modelling Approach

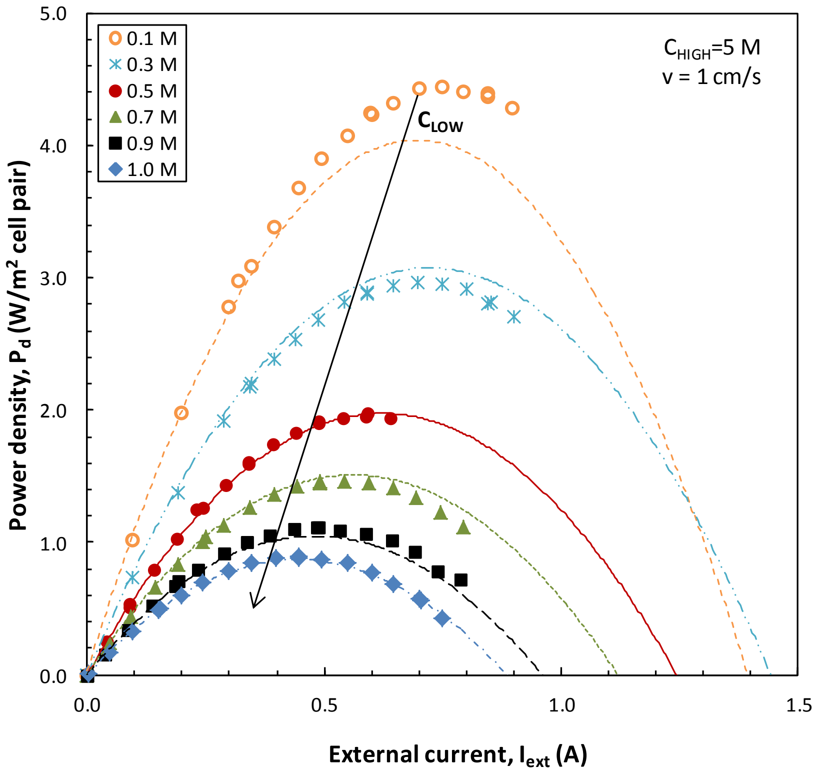


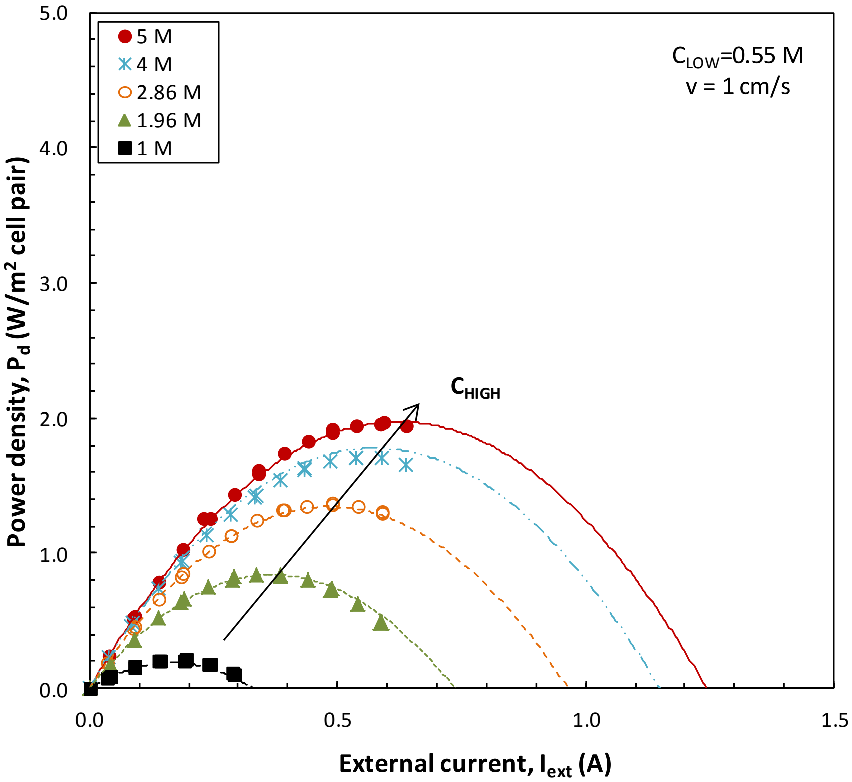
High-hierarchy model (*stack*):

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

Process Modelling validation

Model calibration with variable feed concentration

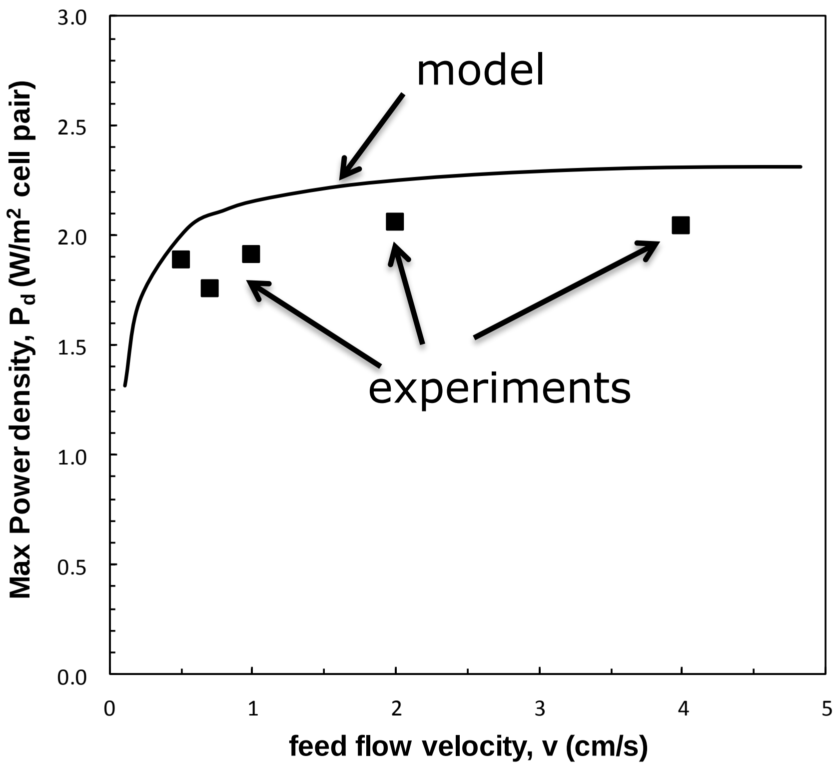


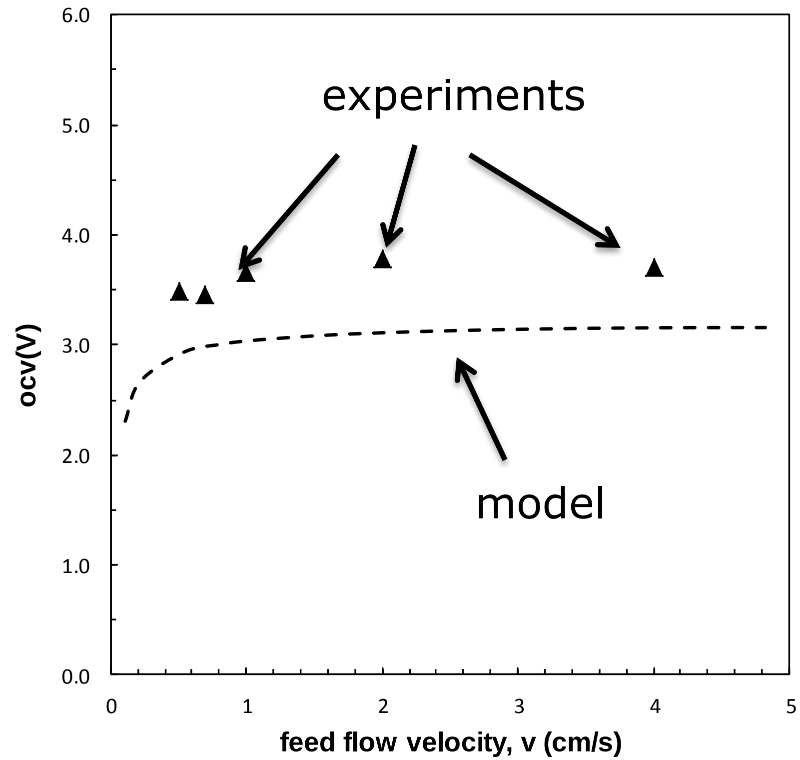


Experimental (points) and simulated (lines) data for a 50-cells stack equipped with Fujifilm membranes, Deukum 270 μm spacers; feed flow velocity: 1 cm/s; T=20° C. Blank resistance: 0.4 Ω.
Experimental data collected at VITO (Oct 2012).

Prediction of dependences

Influence of feed flow rate

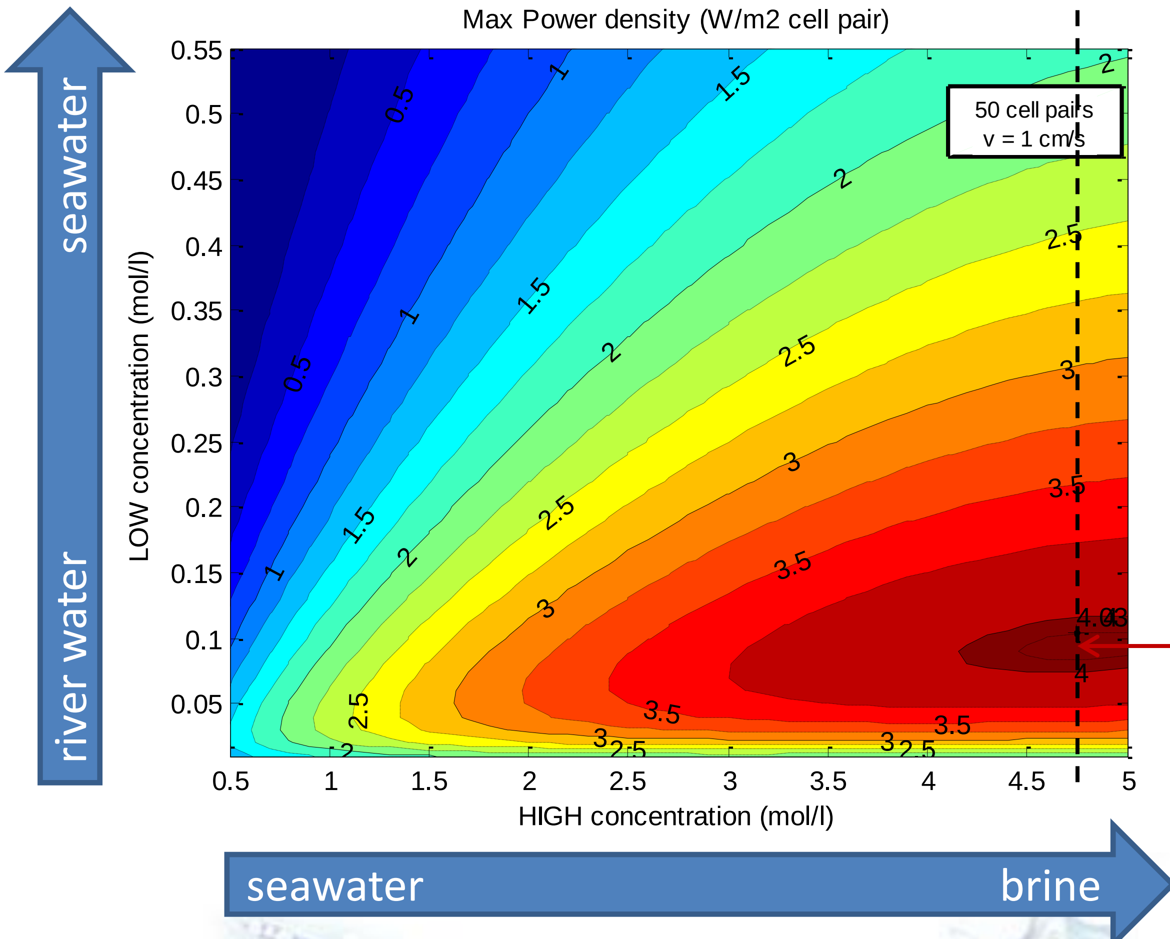




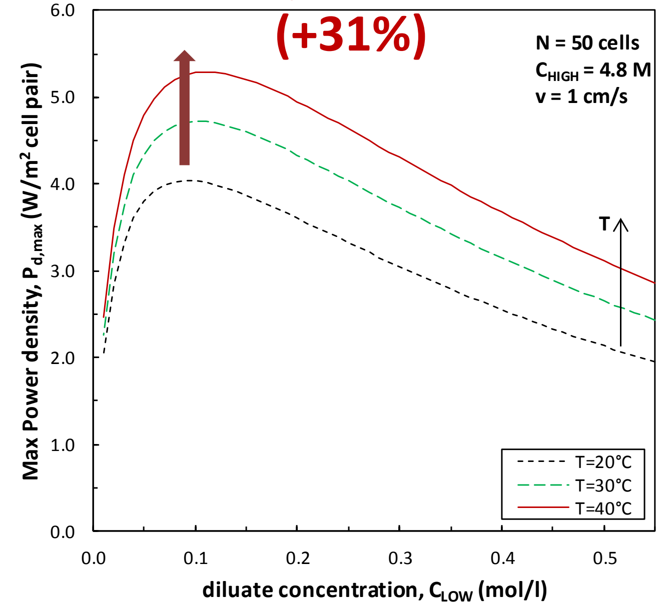
Experimental (points) and simulated (lines) data for a 50-cells stack equipped with Fujifilm membranes, Deukum 270 µm spacers. C_{HIGH}=5 M; C_{LOW}=0.5 M; T=20° C. Blank resistance: 0.4 Ω.
Experimental measurements collected at VITO (Mar-Apr 2013).

Prediction of dependences

Influence of feed T & conc.



Max P_d = 5.3 W/m²
(+31%)

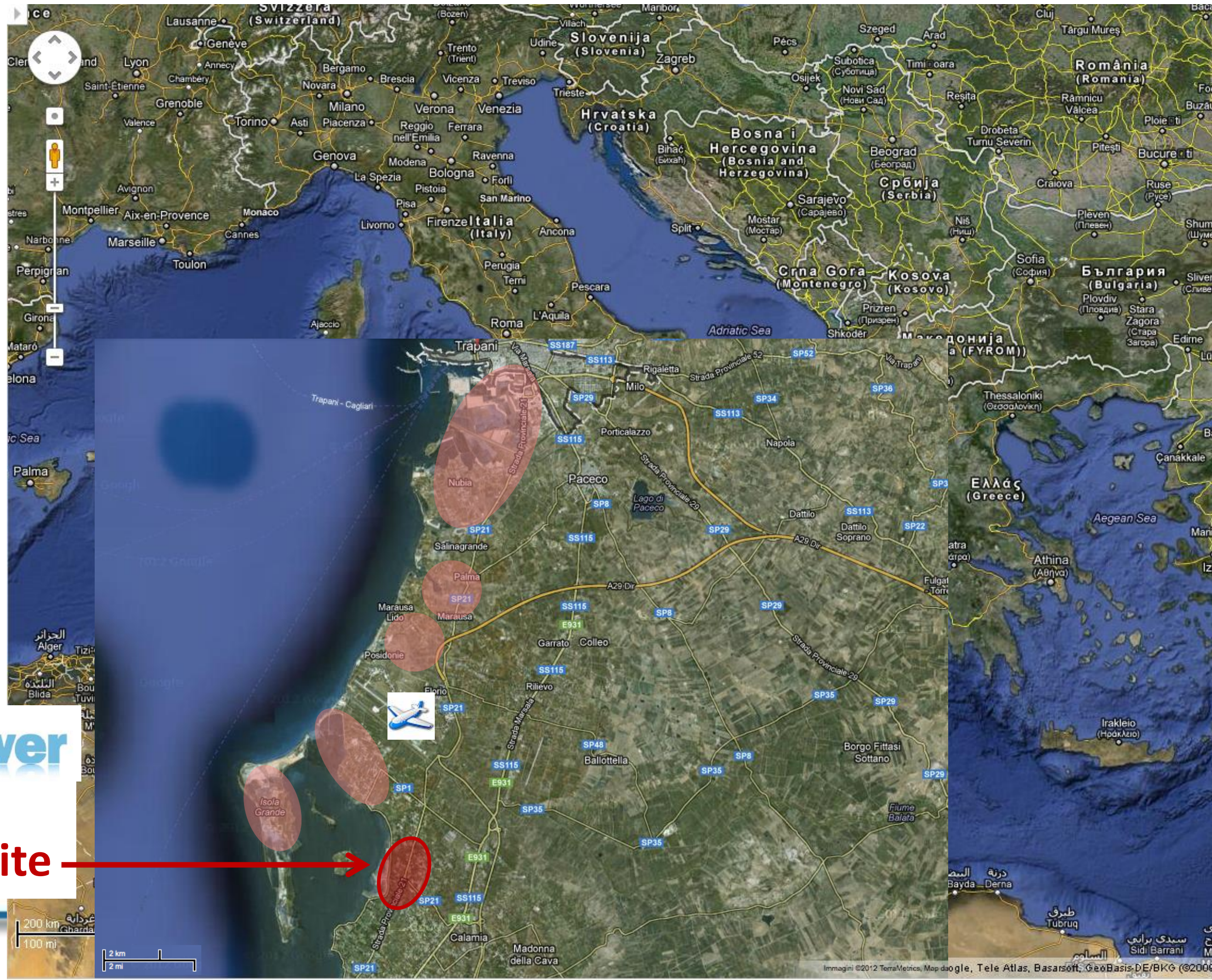


BEST conditions:
brackish water (0.05 – 0.1 M)
+ brine (4.5 – 5 M)

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

Which brines for the SGP-RE process?

Prototype installation site:
the singular framework of Trapani saltworks



Prototype installation site

Which brines for the SGP-RE process?

Prototype installation site: 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

- Seawater availability: unlimited;
- Brine availability: 10-15 m^3/h (much larger with feed-recycle);
- Brine concentration: variable between 250 and 320 gr/lt.

Provisional Prototype features

-Total cell pair surface: from 4 to 125m^2 (2 stacks will be tested);

-Expected power density: > 5 W/m^2;

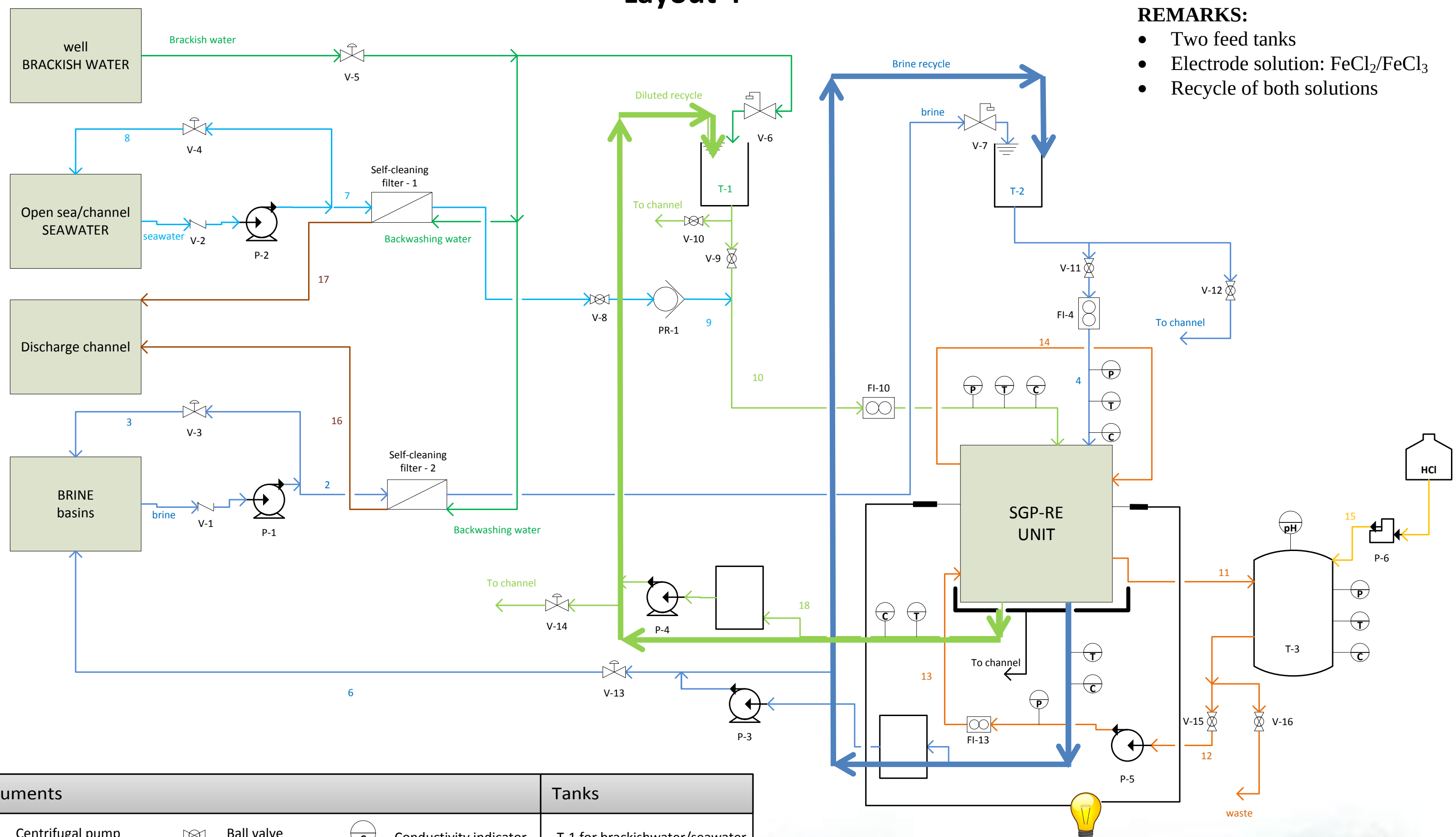
-Expected power output: from 20 to 600W

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			

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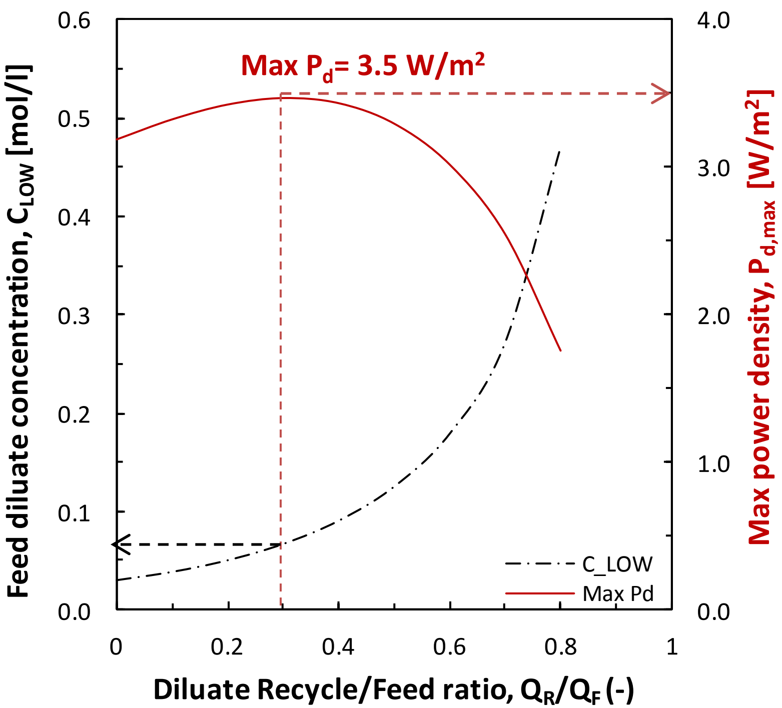
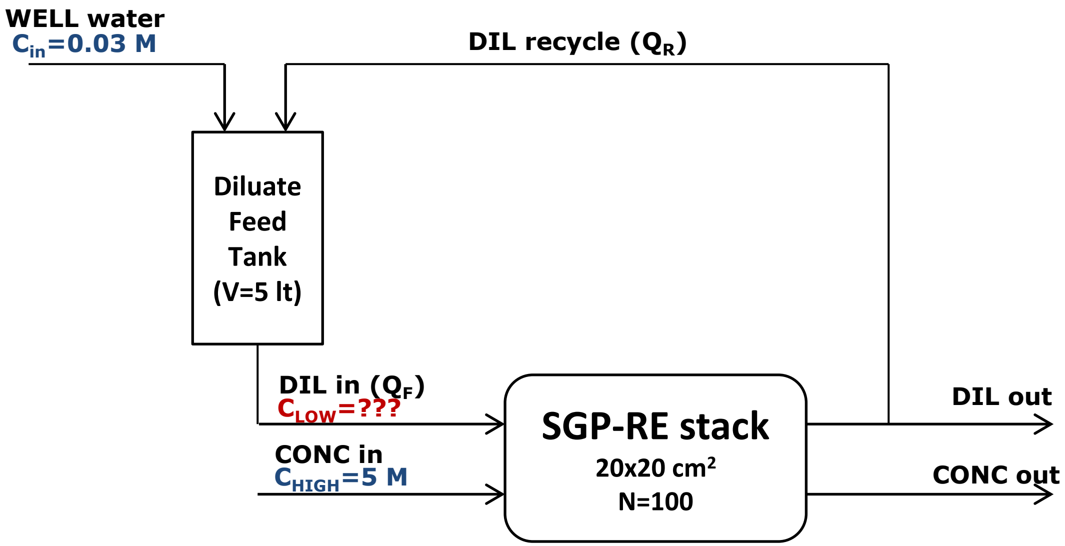
Scalici Claudio	WP7 Pilot Prototype
Installation site: Ettore-Infersa saltworks	24/05/2013

Simulation of Trapani prototype (2/3)

Investigate the optimal Recycle/Feed ratio for diluate

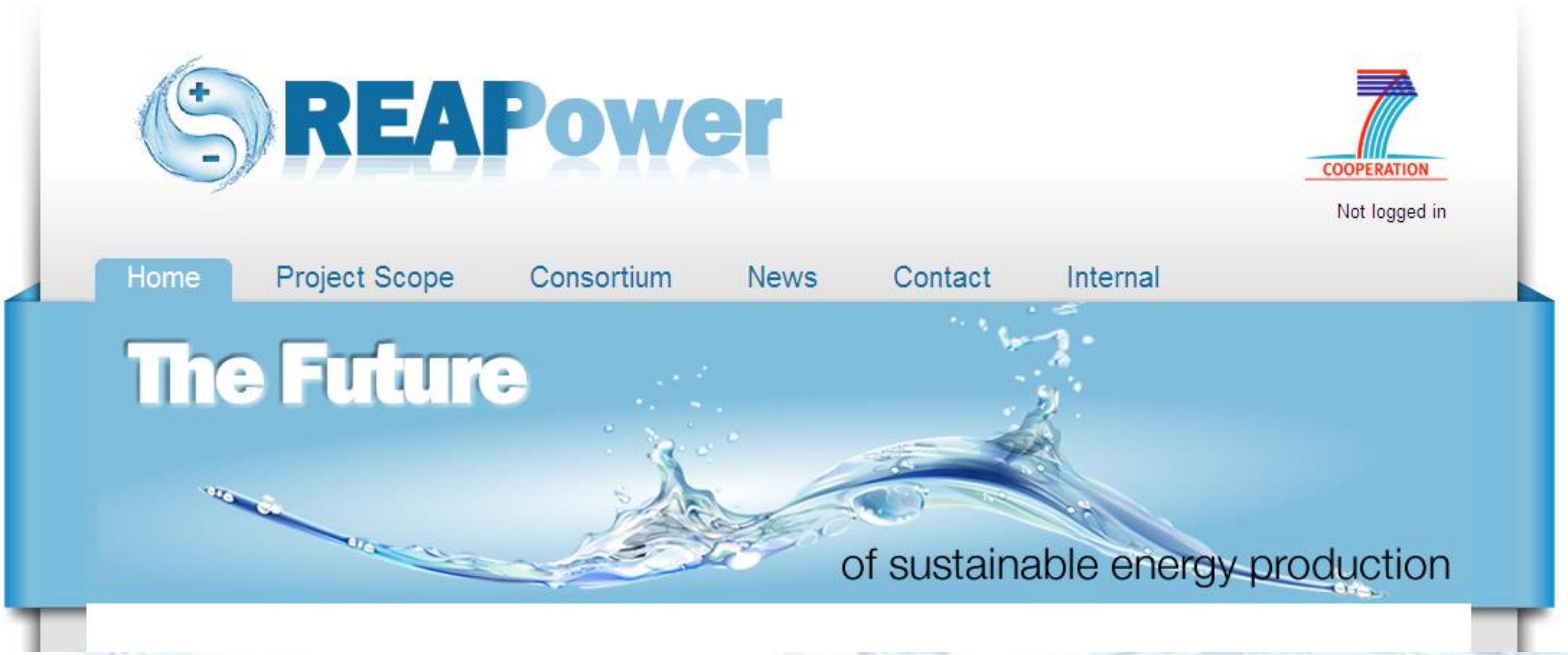




Simulations of a **20x20 cm²** stack equipped **100 cells**, Fujifilm membranes, Deukum spacers; feed flow velocity inside channels: 1 cm/s; T=20° C. C_{HIGH}= 5 M. Blank resistance: 0.4 Ω.

REAPower website

http://www.reapower.eu/



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Thank you for your attention

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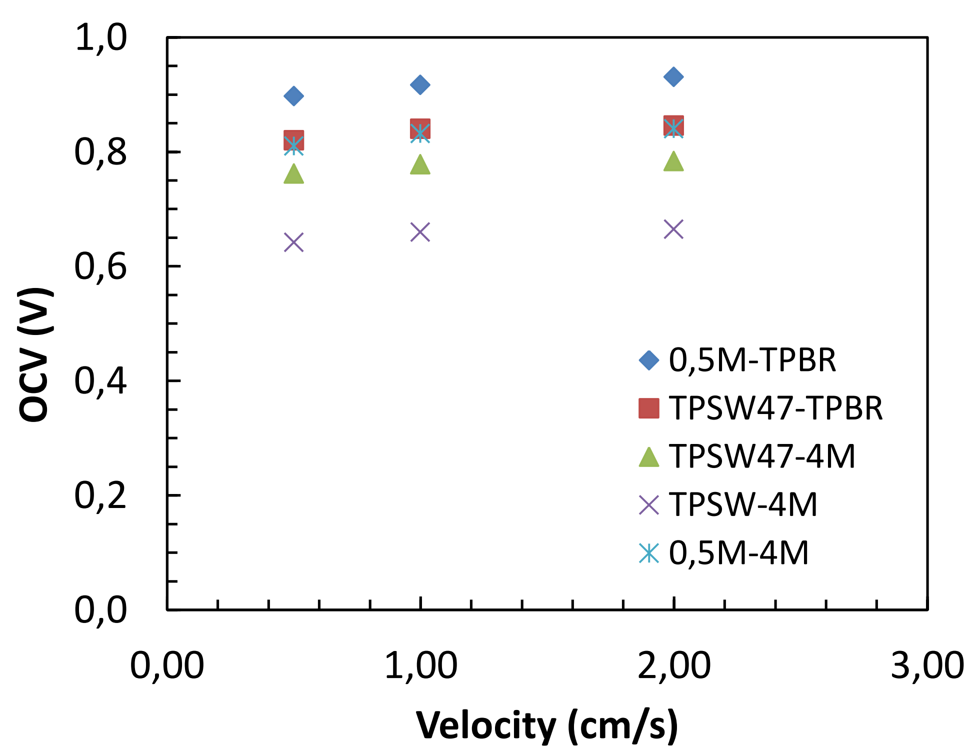
Back-up slides

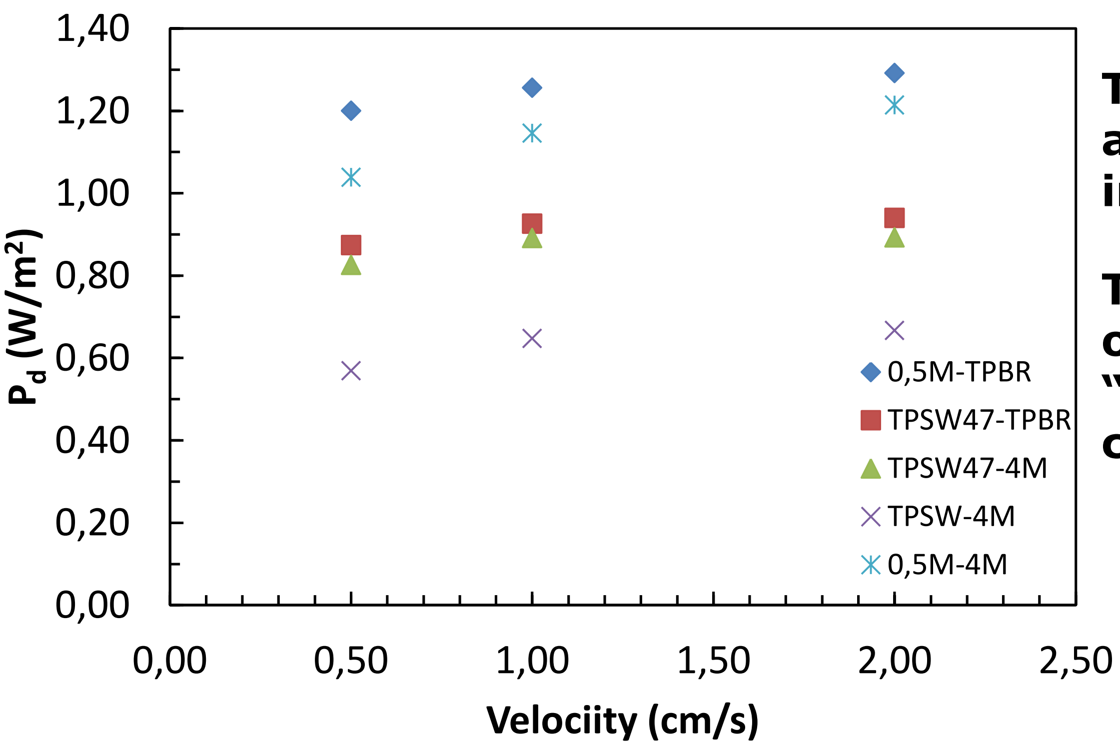
Influence of the use of real solutions on the power density

Name	Description	Conductivity [mS/cm]
0,5M	NaCl solution, 0.5M	47
4M	NaCl solution, 4M	228
TPSW	Seawater from Trapani	
TPBR	Brine from Trapani	
TPSW47	Seawater from Trapani dilu 0,5M solution conductivity	



Back-up slides

Influence of the use of real solutions on the power density

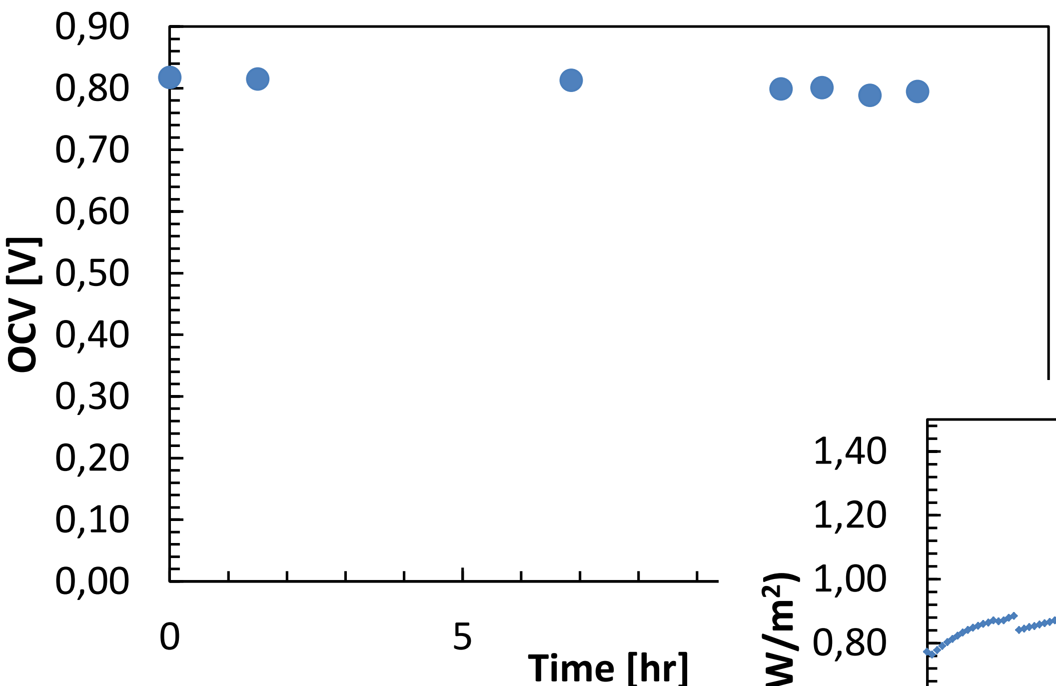


TP brine does not negatively affect the P_d, but a slight increase is observed;

TP SW significantly reduces the obtained P_d, even if "corrected" to the same conductivity as 0,5M solution;

Back-up slides

Long-run test with real solutions (13 hrs test)



No significant variations in the 13 hrs were observed…