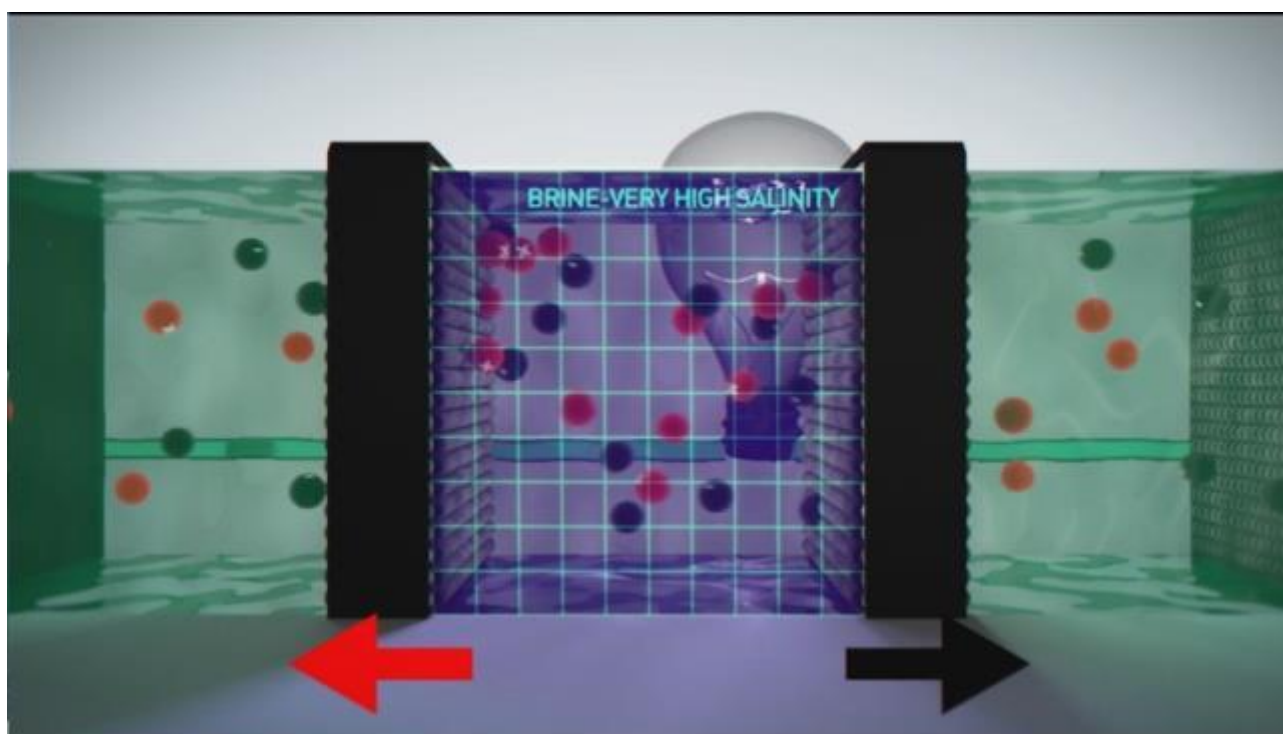




Reverse Electrodialysis Alternative Power Production  
Final Publishable Summary Report

# Electricity from Brine

## The future of Sustainable Energy



## Acknowledgements

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The consortium members are listed below and more information is available on [www.reapower.eu](http://www.reapower.eu)

You can also contact the project partners by e-mailing the project coordinator Michael Papapetrou on: [pmp@wip-munich.de](mailto:pmp@wip-munich.de)



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## Executive Summary

### Context and objectives

The project focuses on the salinity gradient power – reverse electrodialysis (SGP-RE) process. Members of the REAPower consortium had shown in scientific papers already before the start of the project that the performance of the process can be increased by an order of magnitude when brine and sea or brackish water are used for the creation of the salinity gradient rather than the current approach of seawater with fresh water. The main reason for the potential to increase the productivity is that this approach overcomes the limitation of the low overall conductivity dictated by the fresh water channels. The aim of the REAPower project was to explore how this new approach could be implemented in practice for enabling the SGP-RE technology to play an important role in the energy mix of the next decades.

### Main project results

Different membrane materials have been tested and new ones have been developed by the project partner FUJI, optimised for that specific application. They have been performing very well achieving very high power densities, never seen before in seawater vs. fresh water applications.

New stacks were developed by REDstack with important innovations compared to the traditional one. Full testing of the small lab-stack with different membranes and under different operating conditions has been performed by VITO with the support of UNIPA. The results were very positive and did give insights to the factors that affect the performance, providing input to the modelling, stack design and membrane development work. Power densities of over  $11\text{W/m}^2$  of cell pair have been measured, which is a very good result, several times higher compared to the fresh-water seawater approach.

On the basis of the CFD and the mathematical modelling of UNIPA, a process simulator has been developed allowing the prediction of the system behaviour for a wide range of inlet concentrations, flow rates and feed temperatures, providing a suitable predictive tool to support the design of a suitable system for each specific site.

The stack has been scaled up initially by a factor of 10 compared to the initial small lab-stacks. This larger lab-stack has also been fully tested in the lab by VITO, showing similar behaviour with the smaller stacks.

The good results in the lab and the ability to overcome practical challenges in scaling up the stacks has allowed us to take the big step and test the technology in a real environment. UNIPA, with support from REDstack and FUJI started the testing with natural solutions in a real environment. The installed system is more than 400 times larger than the one initially developed in the lab. The performance is still better compared to systems operating with seawater and fresh-water. However, the power densities achieved are lower than those achieved by the small stacks in the lab. The reduced productivity was expected because of the fast scale-up and the operation with real solutions that contain a mixture of salts, in some cases with very different behaviour compared to NaCl.

### Results and Impact

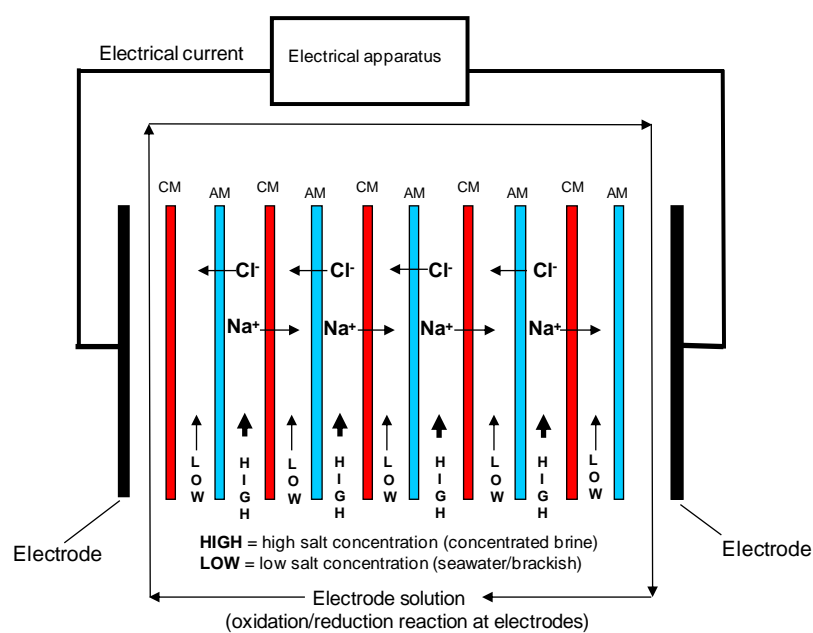
The project has achieved to operate the first system in the world to be producing power from brine in a real environment, with steady performance over a period of several months. The experience of scaling-up and moving to a real environment has offered many useful insights on practical issues that can guide future developments.

# 1 Project context and objectives

## 1.1 Introduction

Salinity gradient power (SGP), also called “osmotic energy” is the chemical energy potential associated with the “controlled” mixing of two salt solutions at different concentrations. The concept of SGP is already known in the literature and was described for the first time in 1954 by Pattle<sup>1</sup>. There are two main techniques considered currently for recovering the osmotic energy of a system and convert it into a more exploitable form: pressure retarded osmosis (SGP-PRO) and reverse electro dialysis (SGP-RE). In the former, SGP is converted into mechanical energy and then to electrical energy by means of turbines using osmotic membranes, i.e. membranes allowing the passage of water and obstructing the passage of salts.

In the REAPower project we focused on reverse electro dialysis (see figure 1), where cation and anion conductive membranes are placed in an alternating way in order to produce diluate and concentrate compartments. The concentrate compartment (HIGH) is then filled with the high concentration salt solution while the diluate compartment (LOW) is filled with the low concentration salt solution. The salt concentration difference (salt gradient) between both compartments in the cell pair invokes a Nernst potential across the cell pair which causes an electrical current to flow through the electrical load connected to the electrodes.



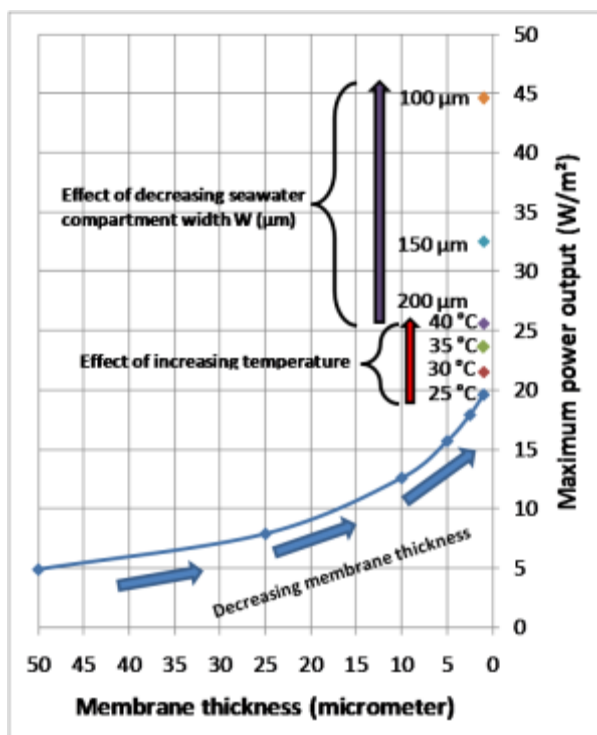
*Principle of reverse electro dialysis.*

<sup>1</sup> R.E. Pattle, Production of electric power by mixing fresh and salt water in the hydroelectric pile, Nature 174 (1954) 660.

## 1.2 The REAPower Concept

Up to recently research focused mainly on the combination of fresh water as the low concentration solution (LOW) and seawater as the high concentration solution (HIGH)<sup>2</sup>. However this approach has an important limitation: The electrical resistance within the LOW compartment filled with the fresh water (typical conductivity < 0.05 Sm<sup>-1</sup>) is very high when compared to the HIGH compartment filled with seawater (typical conductivity of 4.8 Sm<sup>-1</sup>). As a result the LOW compartment with the fresh water completely dictates the overall resistance of the cell pair. The LOW compartment resistance cannot be minimised by reducing its width, because of practical restrictions. This high resistance limits the power that can be extracted by the reverse electro dialysis method.

This restriction has led to the REAPower project and the idea of using sea or brackish water as the “low concentration” salt solution in combination with brine, a salt solution with a very high salt concentration. This offers a tremendous potential for the improvement of the electrical performance. Firstly, the conductivity in the “low salt concentration” compartment can be up to two orders of magnitude higher. As a result, the cell pair is no longer restricted by the resistance in its compartments and an optimization of the membrane and other elements with respect to their effect on the total resistance becomes of importance. It



is shown for example by model calculations<sup>3</sup> that decreasing the thickness of the membranes could result in very low total cell pair internal resistance, which allows producing much higher power outputs (W/m<sup>2</sup>) compared to the combination of seawater with fresh water. Other factors that can help to increase further the power output are: (a) to decrease the seawater compartment width and (b) to increase the feed water temperature. The effects of each parameter as calculated by Brauns [2009] are illustrated in Figure 2.

Effect of various parameters on the power output.

<sup>2</sup> See for example: J. Veerman, M. Saakes, S. J. Metz, G. J. Harmsen, Reverse electro dialysis: Performance of a stack with 50 cells on the mixing of sea and river water, *Journal of Membrane Science* 327 (2009) 136-144

<sup>3</sup> E. Brauns, Salinity gradient power by reverse electro dialysis: effect of model parameters on electrical power output, *Desalination* 237 (2009) 378–391

### **1.3 Project Objectives and Progress**

The aim of the REAPower project was to explore how this new approach could be implemented in practice for enabling the SGP-RE technology to play an important role in the energy mix of the next decades.

The following specific scientific and technological objectives were set at the beginning of the project:

- (i) Create materials and components tailored to the requirements of the process
- (ii) Optimise the design of the stack using a computer modelling tool
- (iii) Verify the model, and assess the developed system through tests on laboratory stacks
- (iv) Evaluate the overall system through tests on a prototype fed with real brine from a salt pond
- (v) Evaluate the results, analyse the economics, assess the environmental impacts and define the next necessary R&D activities for further development of the technology.

## 1.4 The Project Consortium

For achieving these objectives, a multidisciplinary consortium consisting of key players from the industry and academia were brought together to work across traditional boundaries, contributing to the establishment of a strong scientific and technical base for European science and technology in this emerging area of energy research:

Universities (UNIPA, UNIMAN and DICEM-UNICAL) and Research Institutes (VITO and NTT) that lead the research activities of the project

Industrial partners (FUJI and KRATON) that support the research with their extensive R&D departments and facilitate the fast up-scaling and up-take of the technology through membrane development.

Specialised SMEs (REDstack and Solar-Spring) that support with key components development and have the potential to market the new system

Consultancies (WIP and DNV GL) that provide professional research management, R&D planning and market analysis





## 2 Main project results

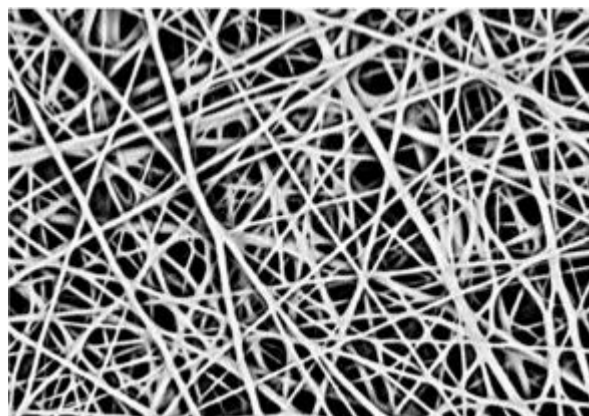
### 2.1 Ion exchange membranes

The ion exchange membranes have been identified as one of the most important elements that will dictate the potential impact of the technology, for two main reasons: Firstly, the ion exchange membrane characteristics and performance define the power density of the system and play a major role in the efficiency with which the salinity gradient can be converted to electricity. Secondly, the membranes have traditionally had the lions share on the overall system cost and as a result can affect its feasibility and competitiveness with other power technologies.

The project started with defining a set of target specifications, relating to the main characteristics of the membrane materials. More specifically the target areal membrane resistance was set to be  $1 \Omega \cdot \text{cm}^2$  at  $100 \mu\text{m}$  membrane thickness and the target permselectivity was set to be at least 60 %. It was also defined that the swelling and stability characteristics should be adequate for long-term efficient operation within a stack.

The permselectivity of available reverse electrodialysis when operating at the REAPower conditions (with very concentrated brine versus seawater) was identified as one of the main challenges the project had to deal with. The project partner FUJI focused its work on this aspect and through important innovations managed to develop improved membrane material increasing the Cation Exchange Membrane (CEM) permselectivity to 84% and the Anion Exchange Membrane (AEM) to 65%<sup>4</sup>. Further improvement seemed to be hardly possible due to the fact that  $\text{Cl}^-$  is a bigger ion than  $\text{Na}^+$ . As a consequence, the co-ion  $\text{Na}^+$  can more easily transfer the AEM, resulting in lower permselectivity values.

The developed membranes have been used at several laboratory stacks and at the prototype operating with natural streams, as will be described in the following sections. They have been performing very well achieving very high power densities, never seen before in seawater vs. fresh water applications. The membrane composition is continuously adapted and improved, based on the feedback received from the detailed testing performed under various operating conditions.



*PU nanofibres that have been tested as a support structure of ion exchange membranes*

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<sup>4</sup> between 0.5M (sea) and 4M NaCl (brine)

Also there has been a lot of work aiming to produce thinner membranes that would allow increasing even further the conductivity of the stack, leading to higher performance. As the FUJI ion exchange membranes have been using support structures, the main idea was to use nanofibres for creating thin support structures for the membranes. This approach has provided mixed results, with the main challenge being the adhesion strength and the extent to which it could withstand the forces created by the membrane swelling. A lot has been learned from this process that was led by NTT resulting to important innovations in the area of nanofibres with several potential applications (i.e. Filtration, Membrane for sportswear application, sound absorption textiles, reinforcement etc.). For the ion exchange membranes, it has been decided to study further the option of further improvements in the membrane compositions that could lead to membrane films that would not require support structures. This work is on-going.

## 2.2 Reverse electrodialysis stack

For the design of the reverse electrodialysis stack, several experiments have been performed by REDstack under REAPower conditions, highlighting some points for improvement against the “conventional” design. The experience gained during the experiments and previous practical experience with handling and building of the stack, as well as stacking the membrane pile and positioning it inside the stack, has been incorporated in the REAPower adopted design. And with the input from the modelling work that will be described in the next sections this led to a list of 45 points describing the functionalities and boundary conditions/limitations of the new stack.

The final stack design for REAPower had important innovations compared to the traditional one and improved performance. A stack making workshop took place at the offices of REDstack in Sneek, The Netherlands on the 21st of June 2012. The project partners formed four teams and each of them constructed a stack with support from the REDstack personnel, based on the new stack design. In total four lab-stacks have been constructed that were used by the partners over the following months for testing the performance and evaluating different components.



*Stack making workshop in Sneek, The Netherlands (21 June 2012)*

Another important innovation that was developed by REAPower was the concept of the replaceable membrane-pile. As it was recognised that handling of thin membranes would be difficult, it was decided that the membranes would have to be glued together creating a leak-free membrane pile, which cannot be dismantled anymore. For that purpose, an evaluation of several adhesives was performed, shortlisting and testing three adhesives that give promising results for good performance when gluing the membranes.

### **2.3 Redox processes and electrode materials**

Numerous redox processes and electrode materials have been studied by the project partner UNIPA in order to select some processes/electrodes characterized by high chemical and electrochemical stability, fast electrochemical reaction of the redox couple, no poisoning of electrodes and membranes, low cost and absence or minimization of waste water treatment requirements.

In the first stage a detailed study of the state of the art was carried out, investigating a large number of processes used in numerous fields such as: water electrolysis, chlorine production, electrodialysis, reverse electrodialysis, investigation of electrodes properties, redox catalysis, redox flow batteries, etc. to select more promising redox processes and electrodes: The following redox systems were selected for the experimental investigation:  $\text{FeCl}_2/\text{FeCl}_3$ -graphite electrodes,  $\text{Fe(II)EDTA}/\text{Fe(III)EDTA}$  - graphite or DSA electrodes, Hexacyanoferrate(II)/Hexacyanoferrate(III) - graphite or DSA electrodes, water/ $\text{Na}_2\text{SO}_4$ ,- DSA- $\text{O}_2$  and Ni electrodes, water/ $\text{NaCl}$  - DSA- $\text{Cl}_2$  and Ni electrodes;

Various electrochemical cells were assembled in UNIPA (cell for electro analytical experiments, undivided and three-compartment cells for electrolysis) while a small stack of 10 cell pairs was provided by REDstack with accessories. Electroanalytical experiments, long term electrolysis, experiments in three-compartment cells and in a stack allowed to evaluate advantages and disadvantages of each couple and to select the more suitable systems for the project:  $\text{FeCl}_2/\text{FeCl}_3$  at low pH and the  $\text{H}_2\text{O}/\text{Na}_2\text{SO}_4$  redox systems.

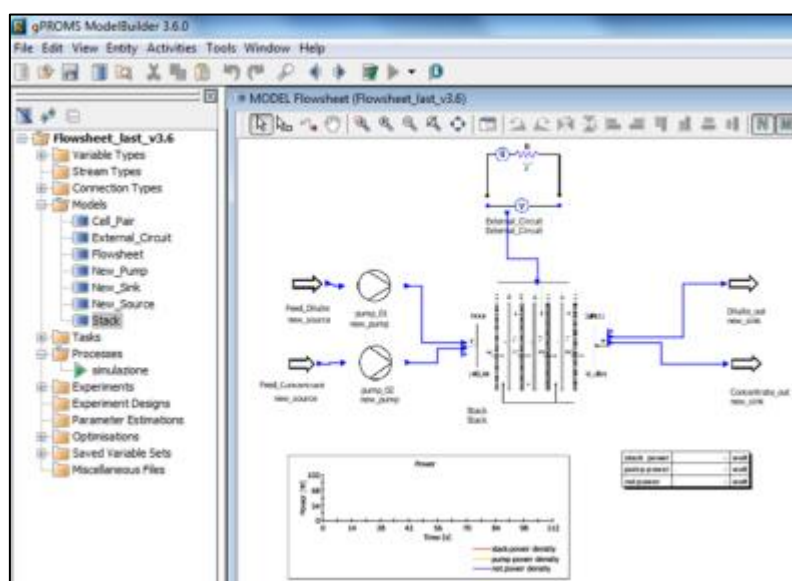
UNIPA performed detailed tests for further assessing the selected redox couples, concluding that  $\text{FeCl}_2/\text{FeCl}_3$  is a suitable redox couple for RED applications. The  $\text{H}_2\text{O}/\text{Na}_2\text{SO}_4$  system presents some relevant drawbacks including the problem of the acidification of diluted and concentrated solutions flowing inside the stack. The possible utilization of this system by circulating the same solution in cathode and anode compartments could avoid strong pH gradients but has to be carefully realized to avoid any risk of possible formation of hydrogen-oxygen explosive mixtures.

## 2.4 Multi-scale modelling and process simulation

UNIPA has studied the effects of spacer-filled channel geometry on the performance of the system via Computational Fluid Dynamics (CFD). CFD simulations were carried out, using the ANSYS CFX® software, to assess the influence of different parameters on the global process efficiency, such as the choice of spacer material and morphology, and the optimization of feed and blow-down distribution systems. Both a unit cell approach and a full-length channel approach were adopted to investigate the effect of the different choices on the fluid flow along the channel. The results of this work have provided input for the stack geometry and the selection of the spacers to be used, the design of the feed distributor and the discharging collector. Operational parameters were also addressed like the effect of flow velocity on the net power density and the significance of the concentration polarisation phenomena.

At the same time, the basic principles of the operation of the stack have been mathematically modelled by the implementation of a single cell-pair model. A reference literature work has been considered as a starting point and from this a novel and comprehensive cell-pair model has been developed and validated for the more complex case of REAPower process conditions. Chemical and electrochemical properties of the solutions have been estimated by purposely-selected thermodynamics equations, which allow good predicting capabilities up to solution concentrations of 5 M and more. Minor phenomena often neglected in other literature works, such as osmotic and electro-osmotic flux through the membranes, have been also considered and their effect on the overall efficiency evaluated.

After implementing the cell-pair model on a higher hierarchical level model using gPROMS® software, predictions have been compared with experimental data purposely collected at the FUJIFILM laboratories by UNIPA staff, thus starting the model validation procedure. The influence of several parameters on the process performance has been assessed. In order to extend the modelling approach potentials, COMSOL Multiphysics® software was used to perform hybrid simulations of the behaviour of single cell-pairs, with the aim of coupling in one simulation tool the modelling of fluid flow behaviour and mass (and ions) transport through membranes and channels. In spite of its simplifying approach, the developed COMSOL model can simulate correctly the trend of both concentration and voltage profiles inside the system, highlighting the possibility of addressing several aspects of the process at the same time.

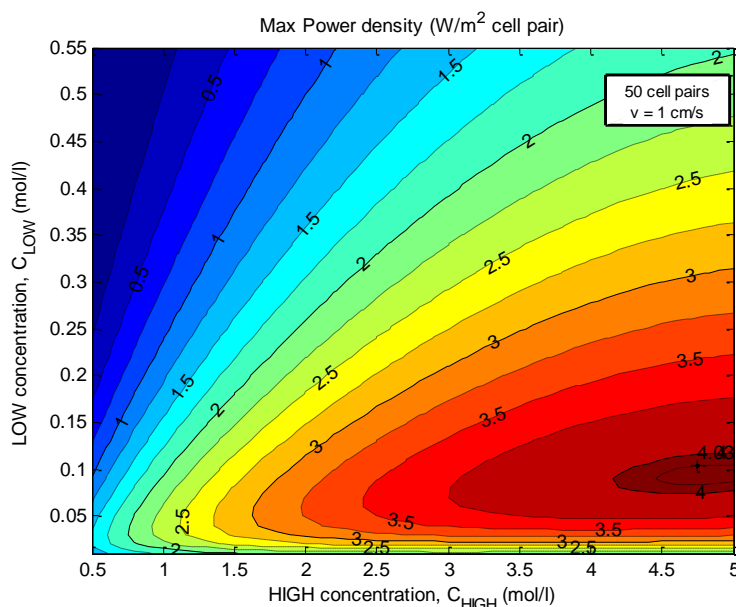


Graphical User Interface (GUI) of the implemented flowsheet on gPROMS 3.5.3.

All that work was used to develop a process simulator for performing operation performance analysis and design of pilot plants. For this reason, the gPROMS Model Builder was purposely selected as modelling tool: this software allows the numerical solution of user-defined equations, providing also a built-in flowsheeting environment, as similar as other commercial flowsheeting software in process system engineering. Therefore, the model developed in the activities described above has been finally implemented within gPROMS environment to build the process simulator, allowing the development of a user-friendly interface as shown in the figure below. In particular, the flowsheet for the main section of the prototype plant has been implemented: this section includes the stack, as well as two feed pumps for salt solutions and the electrical connection of the system to an external load.

As any commercial flowsheeting software, the user can select each of the system elements to specify input data before running simulations. After the development of the process simulator, the proposed model has been calibrated on experimental results collected during the testing of the stacks, described in the following sections. A parametric variation study was afterwards carried out to understand the effect of input conditions (flow rates, inlet concentration) on the tuning parameters: finally, the calibrated model has been used as a predictive modelling tool to simulate different situations for the lab-scale system, in terms of solutions properties (flow rates, concentration, temperature), as well as stack geometry (membrane size, number of cells).

The developed process simulator allowed predicting the experimental behaviour for a wide range of inlet concentrations, flow rates and feed temperatures, providing a suitable predictive tool for further investigations. For instance, the best conditions in terms of salt concentration were identified for enhancing the power generation as indicated in the following figure, i.e. the use of brackish water (0.7-0.9 M NaCl) and brine (4.5-5 M NaCl).



*Effect of LOW/HIGH inlet concentration on maximum power density. Simulations of a 50 cell pairs stack (10x10 cm<sup>2</sup>) equipped with Fujifilm membranes, 270  $\mu$ m woven spacers; feed flow velocity inside channels: 1 cm/s.  $T=20^{\circ}$ C. Contours show max power density (W/m<sup>2</sup>).*



## 2.5 System testing in the lab

Full testing of the lab-stack with different membranes and under different operating conditions has been performed by VITO with the support of UNIPA. A large amount of data has been collected from the lab-stack tests. Over 100 full tests have been completed testing different membranes at various temperatures, salinity gradients, flow rates etc. Similar tests have also been performed with a second generation lab-stack, which was 10 times larger than the first one and the main results have been confirmed.

The performance of the stacks was very encouraging and has provided insights to the factors that affect the performance. The testing results gave also input to the modelling and membrane development work. Power densities of over  $11\text{W/m}^2$  of cell pair have been measured, which is a very good result, several times higher



*The lab stack is tested at the lab of VITO and is used to operate a radio during the visit of the REAPower team and the EC representatives.*

compared to the fresh-water seawater approach and among the highest power densities ever measured in reverse electrodialysis.

In parallel to these activities, UNICAL have performed tests in their own labs to improve the understanding of the effect that the real feed composition will have on the process. More specifically, the evaluation covered the effect of monovalent and multivalent ions ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$  and  $\text{HCO}^-$ ) individually present in NaCl solutions, as well as their combination according to the composition of seawater and brine in the site of the project's pilot installation in the Ettore Infersa saltworks (Trapani, Sicily). The evaluation was carried out by measurement of gross power density and voltage on a lab stack. The results have shown that the most important impact is caused by the presence of  $\text{Mg}^{2+}$ , which increased significantly the resistance of the stack and decreased both the OCV and the power density. Other experiments carried out by VITO and UNIPA have confirmed the important impact of  $\text{Mg}^{2+}$  on the performance of the system.

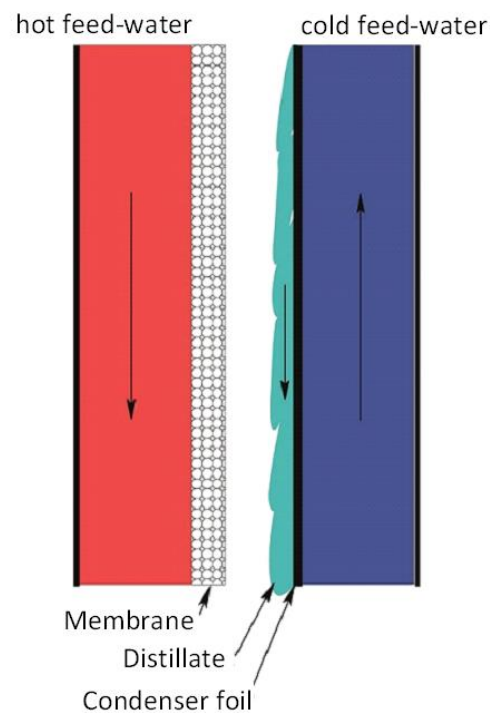
## 2.6 Membrane Distillation

The membrane distillation (MD) technology has also been studied in the project as a means of further concentrating available brine streams, with salinity that is not high enough to power the process. The project partner SSP does develop membrane distillation systems and adapted them for the specific case of REAPower.

First an adapted spiral-wound MD prototype was developed and tested, showing promising results in terms of higher productivity and efficiency as well as lower selectivity. However, the 2<sup>nd</sup> spiral-wound prototype could not be tested due to a defective distillate channel causing leakages. After that it was agreed that the greatest benefit for the joined operation of MD and RED would be reached in the project through using a module design that would be better scalable and a solution for the sealing problem could be found faster. SSP proposed to shift the focus to the plate module design, which was expected to be more suitable for these purposes and a better scalable solution for the Air Gap channel setup.



### AGMD Process



*Images of the airgap module testing rack (from left to right: module rack, feed tank and hydraulics)*

Many technical challenges in the production of plate MD modules were overcome and a prototype was successfully tested, confirming the results achieved with the 1 prototype. It has been shown that the option of using MD to further concentrate brine from a reverse osmosis desalination system is particularly interesting, as additional potable water can be produced, while the concentrated brine can be used in an SGP-RE system, giving back a large part of the electricity required by the reverse osmosis system. The



developed MD system has also other possible applications as a part of zero liquid discharge desalination facilities, in industrial waste water treatment and material recovery.

The power production of the SGP-RE process increases the efficiency of the overall water production process and therefore increases the overall economic efficiency of the desalination system. The application that appears most suited is the combination of the MD-RED plant setup with RO plants which are the state of the art technology for large scale water desalination. This combination would additionally save investment costs by utilising a shared pre-treatment unit as well as feed and brine infrastructures.

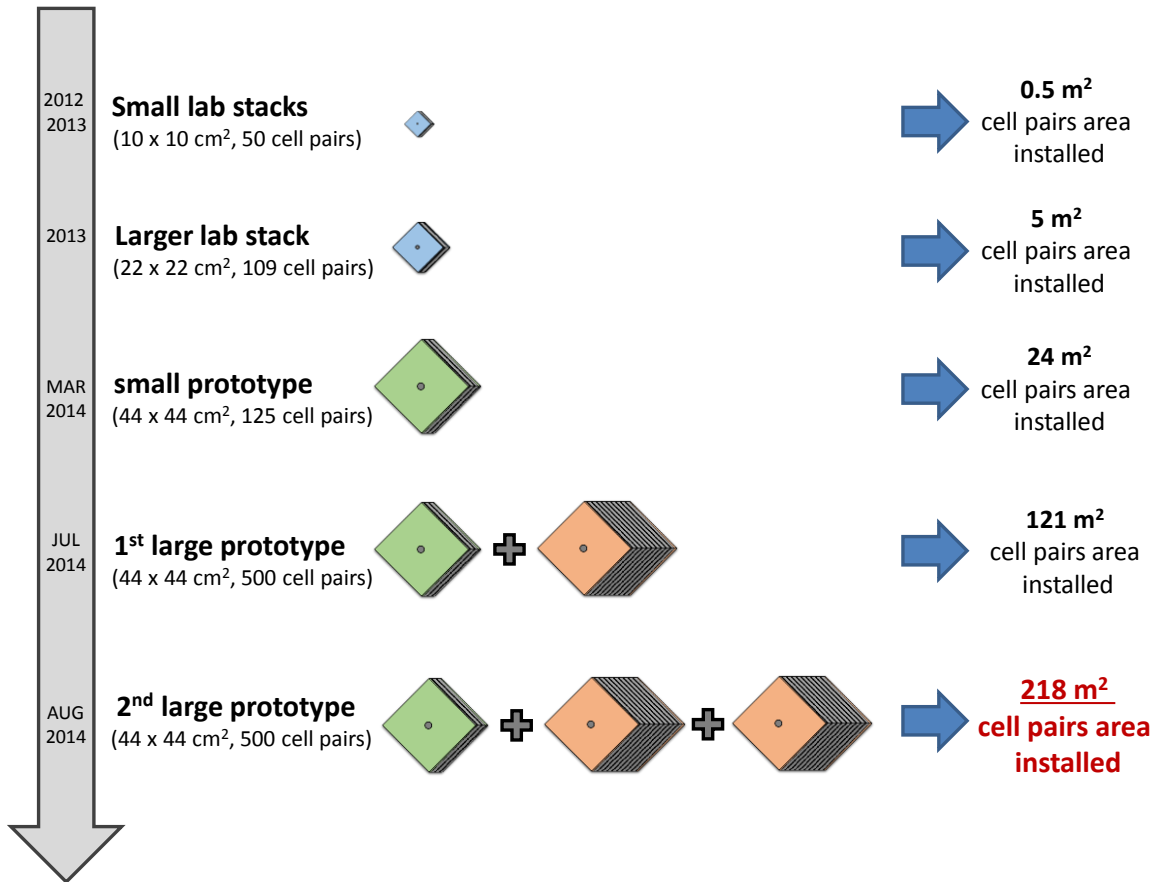
## 2.7 *Prototype system tests*

The good results in the lab and the ability to overcome practical challenges in scaling up the stacks has allowed us to take the big step and test the technology in a real environment. UNIPA, with support from REDstack and FUJI started the testing with natural solutions in a real environment in March 2014, only 3.5 years after the start of the project, when the whole concept was still at its infancy. The installation site is the Ettore-Infersa saltworks in Marsala (Trapani, Sicily), which provides access to natural streams of both solutions required for power production: sea or brackish water as dilute solution and brine from the saltworks as concentrated solution.



*The installation site is the Ettore-Infersa saltworks in Marsala (Trapani, Sicily)*

The installed system is more than 400 times larger than the one initially developed in the lab. The performance is still better compared to systems operating with seawater and fresh-water. However, the power densities achieved are lower than those achieved by the small stacks in the lab. The reduced productivity was expected because of the fast scale-up and the operation with real solutions that contain a mixture of salts, in some cases with very different behaviour compared to NaCl. Based on these results there was further work in the lab by UNICAL, UNIPA and VITO as described in the previous sections, which identified which ions are those that mostly affect its performance providing input for future improvements in the membranes and the stacks for performing even better with natural streams in a real environment.



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*The fast scale-up of the reverse electro dialysis stack within the REAPower project*

## **2.8 Assessment of environmental impacts**

DNV GL together with WIP carried out a study on the potential environmental impacts, both positive and negative, associated with Salinity Gradient Power – Reverse Electrodialysis (SGP-RE) technology. The key areas analysed are the intake of feedwater, the discharge of wastewater, infrastructure and the positive impacts of installing a SGP-RE unit.

With respect to the intake of water, feedwater may be subject to mechanical, chemical and thermal stress. Consequently the microorganisms suspended in this water may be depleted, with a knock-on effect on the marine ecology from which they were taken. Although it is not known which type of stress has the biggest impact on microorganisms, problems are likely to be more severe if pre-heating of the water is undertaken (to improve the power output of the SGP-RE unit) or chlorination is applied (to reduce fouling problems).

The discharge of wastewater will have varying degrees of negative impact depending on a multitude of location-specific factors. The salinity of the wastewater will most likely be higher than that of the receiving water which can lead to a change in the marine ecology as organisms may be intolerant to the new conditions (or conversely able to flourish). Based on where the brine stream necessary for the SGP-RE process is procured from, the temperature and chemical composition of the water will also potentially impact the receiving water. If pre-heating of feedwater is carried out then this will worsen the situation although it could be possible to alleviate such a problem through recuperating heat from the discharge stream and using it to pre-heat the incoming water. Accidental leakage of the electrode rinse solution presents a possibility which should be avoided. Depending on the electrode rinse solution used consequences can be more or less severe.

The characteristics of the receiving water also play an important role in determining to what extent the discharge of wastewater negatively impacts the environment. Exposed, open-sea locations are considered less susceptible to being negatively impacted as they are able to dilute and disperse the discharged wastewater more easily than enclosed shallow sites.

In general the infrastructure aspect of SGP-RE technology is not expected to pose too many issues. In terms of operation, noise is limited to that generated by the pumps (which can be insulated if deemed a problem), and given that the technology can be housed within most types of buildings without any special requirements it is unlikely that there will be any objections on visual grounds. There may be negative impacts on the environment during the initial construction of the facility where installation of intake and discharge pipes may cause an initial disturbance of the seabed, but this is unlikely to be too severe. Probably the most problematic issue is that the cross-linked membranes used in the installation cannot be recycled – and hence incineration must be performed in a suitable facility that can monitor the emissions and treat them for avoiding any impacts on the environment.

In terms of positive impacts, when comparing to a ‘Business as Usual’ situation there are two notable benefits of utilizing SGP-RE technology. The first, similar to other clean energy technologies, is that there are no harmful greenhouse gases being emitted. Hence assuming the energy generated by SGP-RE is consumed instead of energy generated by conventional fossil-fuelled generation there is an environmental benefit. Secondly, in many cases the SGP-RE unit will procure brine from a site already producing brine as a waste output. By utilizing this waste output as an input for SGP-RE, the wastewater that is eventually discharged from the SGP-RE process is of a lower salinity (and hence results in less environmental damage) than if the brine stream had been directly output into the receiving water.

## 2.9 Economic Analysis

DNV GL together with WIP investigated the economic feasibility behind applying Salinity Gradient Power – Reverse Electrodialysis (SGP-RE) within a number of different contexts. Three case studies were chosen which exemplify the broad range of possibilities open for this technology.

The first case study, a reverse osmosis desalination plant was identified to be one of the more promising applications, especially when the SGP-RE unit is combined with a membrane distillation system which further concentrates the large volume of wastewater brine output from the desalination plant. The second case study explores a slightly more alternative application of SGP-RE technology – operating within a closed-loop system and using heat to regenerate artificial brine solutions. The final case study explores the economics of SGP-RE at salt ponds – a natural choice given the pilot projects location at the salt works in Sicily.

The evaluation of the case studies is based largely on two financial key performance indicators (KPIs) which are output from an economic model: the Levelised Cost of Electricity (LCOE) and the Net Present Value (NPV). Both sensitivity analyses and Monte Carlo simulations are used in order to analyse the results of the case studies.

### Case study: Reverse Osmosis Desalination Plant

In this case study we examine a case study based on a specific reverse osmosis desalination plant in Barcelona. Before utilising the wastewater from the desalination plant, a membrane distillation system is used to increase the salinity of the brine further. It is expected that by using the membrane distillation system (MDS), the value of the extra fresh water produced will offset the initial cost of the system. The desalination plant disposes 250,000 m<sup>3</sup> of brine at a salinity of 60 g/kg, and it is calculated that the MDS can convert this into 10,411 m<sup>3</sup>/h of potable water and 12,500 m<sup>3</sup>/h of brine at a salinity of 300 g/kg. The payback period of the MDS based on the extra revenue generated by the additional potable water is in the region of 6-10 years depending on the heat source used to power the membrane distillation process (six years for operation with waste heat and ten with solar thermal heat generation).

Looking at the results for the desalination case study, the base case LCOE value is 10.5 cents/kWh. We see that if the cost of membranes approached its higher value (with all other parameters held at their base value), the LCOE would begin to get less competitive (although an LCOE of around 15 cents/kWh is not terrible). The Monte Carlo results support the economics of this business case further. The average simulation value gives an LCOE of 13.2 cents/kWh. On the basis of 1000 simulations the results give a probability of 100% that the LCOE would be less than an LCOE of 20 cents/kWh. The NPV of the project is calculated to be 46 million EUR – such a high value being naturally down to the large scale of this project.

### Case study: Closed Loop System

In closed loop-mode, instead of procuring brine from sources such as desalination plants, artificial saline solutions are used as the working fluids (i.e. solvent with an appropriate amount of salt added to reach the desired salinity). Once the artificial solutions have been used in the SGP-RE system, they are heated in the regeneration stage. In doing so the solutions which were diluted in the SGP-RE stage are once again concentrated by evaporating water, ready for recirculation back into system. Essentially this process converts low grade heat to electricity.

In this case study it was assumed that heat was acquired cost-free from a specific biogas plant in Germany. The results for this appear to be very positive, with a much lower base case LCOE. The variability in the regeneration system investment costs and membrane pair specific power give the biggest deviations in the sensitivity analysis. Looking at the Monte Carlo results the LCOE values arising from the simulations are in a much narrower range, with 100% of all cases giving an LCOE of less than 7 cents/kWh. Combined with a positive NPV result of 390.7 kEUR it seems that the electricity generated by such a closed-loop system would be competitive and offer a good business case.

### Case study: Saltworks

Given that many saltworks and mines in Europe have stopped operations due to the low price of salt, being able to find an alternative revenue stream for the brine through use in SGP-RE process may be an interesting option for salt production facilities. The REAPower pilot project at the salt works in Sicily utilises brine with brackish water – which offers a greater energy potential than using seawater as the low concentration solution.

SGP-RE operation is expected to be seasonal for weather conditions like those at the REAPower site, reducing the full load hours of the system. Using the brine for electricity production implies that the diluted output solution from the SGP-RE system would need to be evaporated again to regenerate the brine stream for salt production – and this can only be done in warm months. This means that although incorporating SGP-RE technology does not imply discontinuing salt production – extra time and therefore costs may be incurred due to having produce salt from a more dilute solution.

The sensitivity analysis shows a base case LCOE value of 13.8 cents/kWh, and the Monte Carlo results give an average value of 17.4 cents/kWh. Considering that an LCOE between 4 to 20 cents/kWh would be deemed acceptable, it is a promising result. Although it is more expensive than the desalination case study, or the closed-loop system, it is a good result given that the full-load hours of the system are much lower than the other case studies.

The fact that brackish water as opposed to sea water is used implying a higher brine potential energy and membrane pair specific power compensates for the reduced full load hours. The NPV is also positive at 21.9 kEUR – not as large as the other case studies but this is unsurprising given the smaller scale of such a site.

All three case studies show promising results in terms of their levelised cost of electricity and net present value. Provided SGP-RE technology can be scaled up in coming years, then numbers similar to those summarised in the table below should be achievable.

Case Study	Base Case LCOE (cents/kWh)	Monte Carlo LCOE (cents/kWh)	(Base Case) NPV (kEUR)
Reverse Osmosis Desalination Plant	10.5	13.2	46,309
Closed loop system	2.7	3.6	390.7
Salt ponds	13.8	17.4	21.9

## 3 Potential Impact

### 3.1 Perspectives of the technology

#### 3.1.1 Availability of Brine

The project team studied the availability of brine sources that could power the reverse electro dialysis system in order to identify where the technology could be applied in order to drive the further development and highlight the potential impact. A variety of industrial, commercial, and other activities where brine is available, often as a waste product, were analysed. For the different activities which are identified as being potentially suitable sources of brine, issues regarding the concentration, volume, purity and temperature of the brine stream are looked into. Possible synergies with the host location for SGP-RE installations are also explored – e.g. avoidance of brine disposal costs or minimizing environmental impact.

Based on the results of the modelling and laboratory work, the ideal brine conditions have been identified as follows:

*Salinity:* This should be as high as possible, in any case salinities over 200 g/l are preferred. Regarding the salts, the presence of multivalent ions should preferably be avoided.

*Temperature:* Higher temperatures are preferred. SGP-RE can operate well at around 20 °C, but anything above that up to 40 °C helps increase the productivity of the process. We have not tested higher temperatures, but in literature it has been shown that productivity continues to increase at least up to 60 °C.

*Flow rates:* Flow rates of at least 500 m<sup>3</sup>/day should be present. Otherwise the potential output of the SGP-RE system would be only a few kilowatts and would probably not be worth considering.

Here, a synopsis of all options examined is provided:

**Desalination:** The brine streams from current plants do not have high enough salinities. However, the flow rates are very high, making them a potentially promising option if it is feasible to concentrate the brine further and pay for that process with the extra fresh water produced from the concentration. As part of the REAPower project we have focused on the membrane distillation technology for concentrating the Reverse Osmosis desalination brines and the results look promising. The focus now should be on the feasibility of scaling up this process to match industrial scale desalination plants.

**Chlor-alkali process:** The brine after use in the cells, has still suitably high salinities, high flow rates and very high temperature and purity. What has to be more carefully assessed is how the SGP-RE installation would affect the process as this brine is normally recirculated.

**Epichlorohydrin production plants:** When glycerin is used as a raw material, which is very common in all modern plants, the brine streams are very suitable, with high concentrations and temperatures and adequate flow rates. In this case it would have to be further examined how the presence of several impurities in the brine would affect the SGP-RE system performance.

**Textile industry:** Typical flow rates and salinities do not seem to be high enough to justify an SGP-RE system. Still, the wastewater could be treated with a view of reusing the freshwater in the process, which is a trend especially in modern plants located in areas with water stress. In such cases the salinity of the effluent would be higher and an SGP-RE system could be considered.

**Salt production facilities:** There is brine with suitable salinity and flow rate, while the temperatures are usually high-enough making them an interesting option. There are two elements that must be carefully

considered though. Firstly, the very concentrated brine is not available all year round and this has to be taken into account in the assessment of this opportunity. Secondly, the concentrated brine is not a waste stream, but is used in the main salt production process and the compatibility with the SGP-RE process has to be further investigated.

**Oil refining:** There are high amounts of brine, with high temperatures, but the salinities are not high enough. If this brine is treated for further concentration it could become more interesting. Also the oil drilling process involves large amounts of brine with salinities that could be high. This option could be also potentially interesting; however the effect of the impurities in the brine on the ion exchange membranes performance would have to be further examined.

**Metal pickling:** There is an adequate amount of brine produced at relatively high concentrations and high temperatures. However the main salt is Calcium Chloride and the ion exchange membranes do not operate well with bivalent ions like calcium.

**Salt Caverns:** They do involve large amounts of brine, which has to be diluted before disposal. So SGP-RE could offer an advantage by facilitating disposal while generating electricity. However, the salt cavern leaching happens only over a period of few years, which would not be enough to pay back the installation. One option would be to relocate the unit next to the salt cavern. In any case the salt composition and the involved flow rates would have to be examined before a more detailed assessment of this opportunity can be carried out.

**Naturally occurring sources:** The naturally occurring Garabogazköl Aylagy pond has very high salinities and is a very large water body. In this case the possible impurities and the sustainability of the process would have to be further examined. Also the Dead Sea, even if it has slightly lower salinities and is smaller than Garabogazköl Aylagy is still an interesting option, especially if the Dead Sea-Red Sea project goes ahead.

**Alternative options:** Another interesting application of the developed technology that was considered in this report was for pre-treatment of seawater with reverse electrodialysis, where the low salinity solution would be treated wastewater. The salinity difference in this case would not be that high, limiting the potential to generate electricity. However, here the electricity generation would not be the main focus, as this process would turn the seawater into brackish water without any energy requirements, but offering some electricity generation instead. Also the option to operate a closed-loop system with artificial solutions has high potential as the salt and the operating conditions can be defined for maximising productivity. In this case, low temperature heat would be required to regenerate the salinity difference, essentially converting low temperature heat to electricity.



## **3.2 Wider Impact of the project and exploitation of the results**

### **3.2.1 Wider Impact**

Salinity Gradient Power is a very promising energy technology and as such it has attracted the interest of companies and research institutes that have invested considerable time and resources looking into possible exploitation of the huge energy content of the salinity gradient between seawater and fresh water. The REAPower project explored a new path that had been so far been addressed only theoretically in scientific publications. The use of sea or brackish water as the low salinity solution and very concentrated brine as the high salinity is a highly innovative novel technology for electricity generation that offers the opportunity to have a very competitive power generation technology.

The 4 years of REAPower have resulted in the development of the main materials, components and tools, while lot of theoretical and practical information has been collected and new knowledge created allowing their further development to increase productivity and reduce costs leading the system to achieve its full potential as a competitive electricity generation technology.

The project has achieved to operate the first system in the world to be producing power from brine in a real environment. Most importantly, everything has ran smoothly and the real brines have not created any fouling or other problem as we have observed steady performance over a period of several months.

The experience of scaling-up and moving to a real environment has offered many useful insights on practical issues that can guide future developments. A positive experience from operating in a real site was that even though it is a natural reserve and protected area, the system has not created any environmental problems and has been very well accepted by the site owners and the local stakeholders.

The multidisciplinary consortium that brings together key players from the industry and the academic world will continue working together across traditional boundaries. An R&D roadmap has been developed, where the plan for further research and innovation actions has been outlined for the different partners, leading to a system that can enter the market in the next 5 to 10 years.

### **3.2.2 Exploitation foreground**

Overall the project produced significant results, which have the potential to be commercially exploited. In this section are outlined the main results that have commercialisation potential and their envisaged route to the market:

The one group of the most important project results have to do with the **Reverse Electrodialysis Stack**. They are related to issues like a new stack design and wet membrane gluing and there are 7 patent applications that have been filed as a result. The commercial exploitation of these results is driven by the project partner REDstack that is an SME that was established to design and constructs stacks for reverse electrodialysis applications in power production. The stack in principle is ready for the market, but real commercial potential will develop once the overall system costs are driven further down by following the R&D roadmap. The wet membrane gluing concept was developed by the project partner FUJIFILM that was responsible for membrane development. The gluing concept allows easier development of leak-free stacks and as such it is expected to be jointly exploited by FUJI and REDstack. Both the new stack design and the wet membrane gluing have the potential to be used also in other fields outside reverse electrodialysis for power generation, like electrodialysis, desalination and water softening applications.

The second group of the most important project results relates directly to the **Ion Exchange Membranes**. The new membranes that were developed show very good performance in high salinities, while some new compositions allow production of such membranes that can be much thinner and still robust enough for the required application. Overall 3 new patent applications were filed in relation to these innovations. The commercial exploitation of these results is driven by the project partner FUJIFILM that developed these membranes and is also responsible for production and sales. Similarly to the stacks, these membranes could also have other applications in water treatment of the chemical industry, some of which are very close to commercialisation.

The third main group of important project results relates to **membrane distillation** for high salinity applications. First it was shown how promising is the concept of using Membrane Distillation on the brine of Reverse Osmosis plants for additional freshwater production, with the resulting very high salinity brine used in a Reverse Electrodialysis system generating electricity that could partly power the reverse osmosis plant (RO+MD+RED). Then, the project partner Solar Spring optimised and scaled-up their plate module is an important step for allowing the promising RO+MD+RED concept to be realised. The project partner Solar Spring is the entity that will bring the new MD for high salinity applications to the market – where the RO+MD+RED concept is implemented of course REDstack and FUJI would be involved providing stacks and membranes respectively as explained above. In addition, when the MD process would be powered by solar energy this would be licensed by the project partner VITO as it holds a relevant patent. In addition to the RO+MD+RED concept, the MD for high salinity innovation is very interesting for industrial wastewater treatment e.g. waste material recovery from passivation fluids of the metal industry, pre-concentration for ZLD systems and other hybrid applications like concentration of the draw solutions from FOMD systems

Finally, there are several other fields where project results led to innovations with important potential for commercial applications:

The project partner NTT developed methods to produce **nanofibres with improved adhesion** adhesion, with possible applications in enzyme immobilisation in green chemistry, microfiltration, air nanofiltration and thin sound absorption. NTT will explore which of these applications are most suitable and will further develop the developed method aiming to enter these markets either by offering a product or licensing the IP to interested parties.

The project partner UNIPA developed and tested a **microbial electrolyte process** for industrial water treatment and will explore options for further developing it and optimising it for specific industries where it might be more attractive. When the process is more developed and closer to the market, different commercialisation avenues will be explored.

Last but not least, UNIPA developed and verified **modelling and process simulation tools** for reverse electrodialysis that can be further used in research and commercial applications.

### 3.2.3 Impact on participating SMEs

Overall the project results help the participating SMEs to improve their competitiveness.

REDstack has further strengthened its position as the global leader in reverse electrodialysis stack design and construction for power applications because:

- The new design is 25% more efficient

- By making the big stacks for the pilot, the biggest stacks REDstack ever made, REDstack improved its stack building expertise
- REDstack gained important experience and a clear marketing advantage by constructing the first stacks globally to be generating electricity in a real environment.
- Initially REDstack was mostly focused on the opportunity to generate electricity from the salinity gradient between sea and fresh water. With REAPower the potential for new markets has opened, like using the brine from desalination plants, salt production facilities and other industries
- Also the more efficient stacks and membranes make it possible to enter markets like ED for desalination

Solar Spring also strengthened its position in the very competitive Membrane Distillation market by improving the performance and scale-up prospects of its MD system. This will lead to improved competitiveness and possibility to enter the market for applications like seawater desalination and brine treatment, which can also be combined with the reverse electrodialysis application developed within REAPower. The large size MD module and flexibility of the plate and frame design makes the MD very interesting also for industrial wastewater treatment. Very promising applications are e.g. waste material recovery from passivation fluids of the metal industry, pre-concentration for ZLD systems and other hybrid applications like concentration of the draw solutions from FOMD systems.

### 3.2.4 Regulatory and Market Issues

Looking ahead at the commercialisation of the main system developed within REAPower, it will be necessary to deal also with the framework conditions. The right regulatory and market conditions that will allow the technology to enter the market need to be developed.

One main issue is the availability of some kind of support scheme that will help the technology take-off during the early stage when the costs are still not at their lowest level and the investors still see a high technological risk. This support could be in the form of a feed-in tariff, investment subsidy or tax exemptions, depending on the country, similar to the support schemes that were used successfully for solar and wind energy when these technologies were at their earlier development stages.

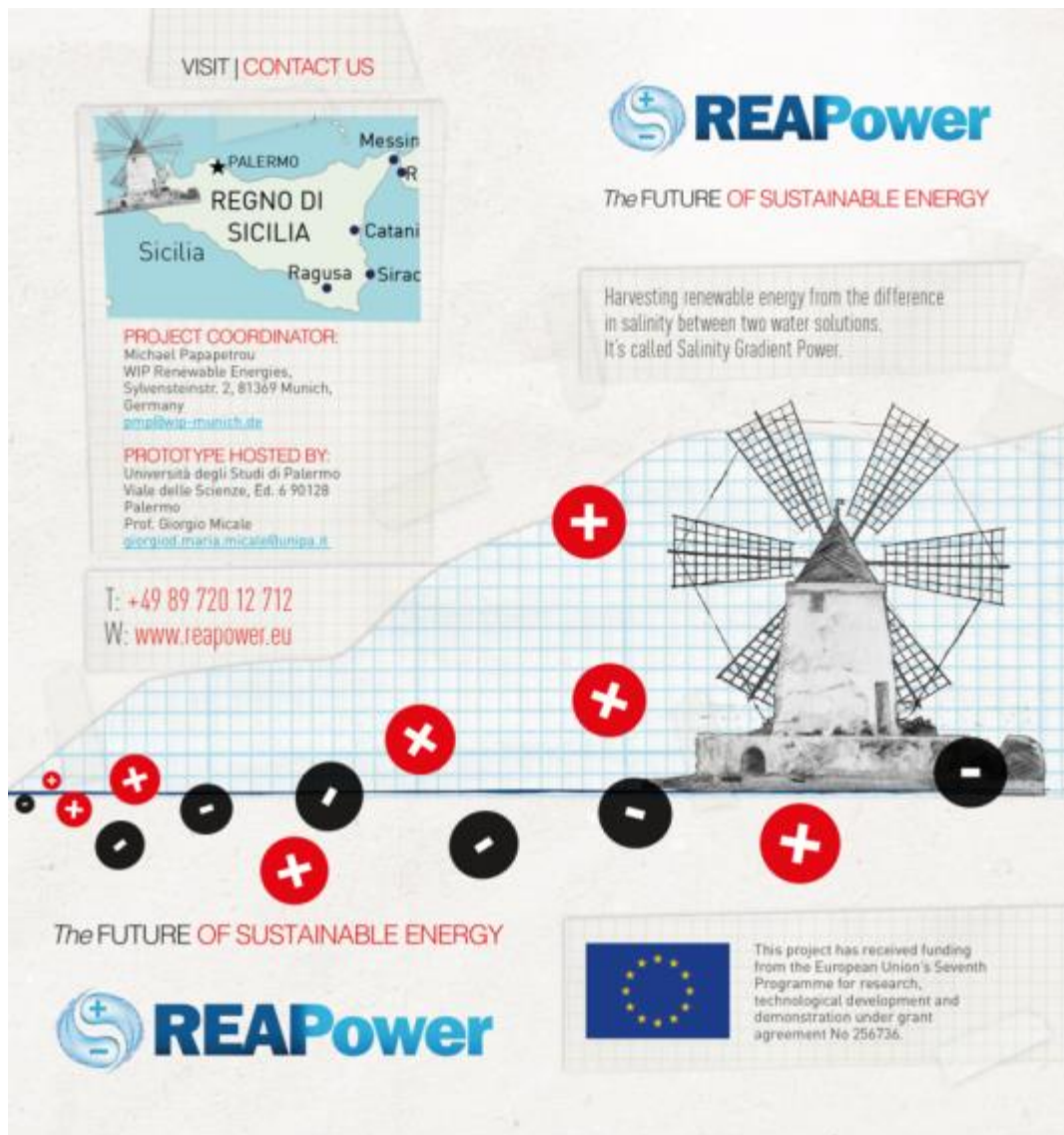
Other important issues that need to be addressed have to do with permits, both regarding environmental impacts and the connection with the grid. The developed technology is not expected to have any important challenges with these two aspects, however, as the personnel at the authorities that will have to deal with the first installations will not be familiar with the technology, it is expected that delays and requests for information will arise, increasing the cost for the first project developers. Concerted effort from an early stage could help accelerating the learning process and standardization of these issues.

For fast and efficient progress, cooperation with all actors active in salinity gradient power in Europe and globally is required and coordination at least on EU level for harmonised conditions among the various Member States.

### 3.3 Main Dissemination Activities

The [project website](#) has been used as the main communication tool with the wider public. It has been updated regularly with the latest publications and news. Every opportunity is used to make the website known to target groups placing links in relevant websites publications and articles. During the project lifetime there have been around 8,000 visits, a good figure for a research project.

The project has also developed leaflets, that were used by the partners in all events they attended to raise awareness about the project.



*Part of the project leaflet*

Project activities and results have been presented on international conferences and workshops through oral presentations, while in these and other relevant events the project partners have participated, distributed leaflets, networked promoting the project and gathered information from the latest developments in



relevant scientific fields. In total there has been participation in 25 external events, all of which are listed in the [event's section](#) of the project website, with a link to the presentation of the project where available:

In addition to that, REAPower organised its own event at the pilot plant site on the 30th of September 2014. Around 30 people attended the event and had the opportunity to see the system operating. REAPower also coorganised with the CapMix project and Wetsus the 2nd international Conference on Salinity Gradient Power. At this event, REAPower had a full hour to present and discuss its results, which were very well received. In addition, UNIPA personnel gave two separate presentations on specific results. The presentation by Michele Tedesco from the University of Palermo on the prototype plant performance analysis won the "Best Presentation Award".



Regarding publications, the project partners have 15 in total (13 in reviewed journals and 2 in conference proceedings) all of which are available on the [publications section](#) of the project website. There are currently more papers being prepared to be submitted presenting the latest results.

A professional [project video](#) was developed over the period February to August 2014, following the installation of the REAPower prototype system. The video was put on-line on the 18<sup>th</sup> of September 2014 and generated high interest with over 500 views in the first two months.