Final report

Osmotic power generation from geothermal wells

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1.1 Project details

Project title	Osmotic power generation from geothermal wells
Project identification (program abbrev. and file)	Journal nr.: 64015-0008
Name of the programme which has funded the project	EUDP (smart grid og systemer)
Project managing company/institution (name and address)	Applied Biomimetic A/S, Nordborg Vej 81, DK 6430 Nordborg, Denmark
Project partners	Applied Biomimetic A/S, Aalborg University, Danfoss A/S, Sønderborg Fjernvarme, HOFOR
CVR (central business register)	27526160
Date for submission	

1.2 Short description of project objective and results

The project focused on demonstrating the feasibility of producing CO_2 free electricity from saline geothermal water using osmotic power technology. The main objectives for the project were:

- Design and construct a pilot plant for testing of osmotic power based on the technique pressure retarded osmosis (PRO)
- Use of the pilot plant to demonstrate that energy can be produced at a power density larger than 5 W/m^2 of membrane
- Show that the efficiency of the energy extraction can be increased by using a multistage setup
- Determine design criteria for osmotic membranes designed specifically for use in geothermal osmotic power
- Evaluate the potential for osmotic power at both Sønderborg and Amager geothermal plant
- Evaluate the long time performance and effect of salinity on osmotic power equipment

Overall, all the objectives have been successfully met in the project:

- A working prototype for an osmotic power plant was designed and inaugurated in April 2016.
- Power densities around 8 W/m^2 hollow fiber membrane have been achieved. This is equal to a power density of 75 W/m^2 flat sheet membrane (the type of membrane that the 5 W/m^2 membrane is based upon).
- By using two membranes in series instead of only one the energy production was increased with at least 48%.
- A collaboration with Japanese membrane manufacturer Toyobo has been established and used to develop a new high pressure osmotic power membrane.
- The pilot plant has been tested at the geothermal plants in both Sønderborg and Amager. The geothermal water on Amager has higher salinity (20wt%) and more energy (350W) was produced here compared to Sønderborg (255W) where the salinity is 16wt%.
- The geothermal water has been found not to affect the osmotic membrane and during inspection of the pump and turbine after a year of testing, only very limited corrosion was observed.
- Different pre-treatment technologies for feed water have been investigated and compared to optimise the process design.
- A survey of the different low salinity water sources in Sønderborg has been made.
- Three scientific papers have been published and the results have been presented at two conferences.
- Several articles about the project have been published in the media and many people (including Minister of Climate and Energy) have visited the plant.
- The project was awarded "Årets Ingeniørbedrift" by Engineering Weekly.

All together the project has been very promising. We have been able to confirm the energy potential and develop the PRO technology for extraction of this energy to a level where it is ready to be scaled up to full scale demonstration. It was expected that handling of the geothermal water could result in problems for membrane and equipment, but this has not been the case. Instead it has been the low salinity water that has had the biggest effect on the process, but treatment of these kinds of waters are well known from general water treatment applications where several commercial solutions are available.

1.3 Executive summary

Background

Osmotic power is a new energy technology based on using a membrane to harvest energy when two water streams of different salinity are mixed. This energy is completely CO_2 free. Prior to this work, pilot plants had investigated the use of seawater (3.5 wt% salinity) and desalination brine (6 wt% salinity), but these had not been found to be commercially viable. The team behind this project had identified geothermal water as an attractive possibility for osmotic power due to the high salinity of the water (10-30 wt%). This would allow use of standard components without direct need for new developments. Also, since the osmotic power could be viewed as an add-on to an existing investment, the investment could become increasingly interesting.

Project objective

In previous pilot studies, it had been estimated that a power density larger than 5 W/m^2 membrane was required for osmotic power to be cost efficient. The main objective of the EUDP project was therefore:

Investigate if osmotic energy can be produced from geothermal water at a power density larger than 5 W/m^2 flat sheet membrane

The project had several other objectives, some of which were:

- Design and construct a working pilot plant using standard commercial components
- Show that energy extraction can be increased by using a multi-stage setup
- Evaulate the potential for osmotic power at the geothermal plants at Sønderborg and Amager
- Collect data required for a full-scale demonstration plant.

Project results

Overall the project has been very successful and met all the objectives that were outlined in the scope. Most importantly

Energy could be produced at larger than 7 W/m^2 hollow fiber membrane theoretically equal to 75 W/m^2 flat sheet membrane

Next to this:

- A working pilot plant was designed and constructed. It is the first of its kind in the world and has created a lot of attention.
- Energy production could be increased with 48% by using a multi-stage setup with two membranes in series instead of a single membrane.
- A new commercial osmotic membrane has been developed together with Japanese membrane partner Toyobo. During the project a collaboration with Toyobo was established and this allowed for development of commercial scale membranes instead of lab scale.
- Using nanofiltration as pretreatment of the low salinity water and sand filtration as pretreament of the geothermal water it was possible to obtain a stable production with no noticeable decrease in production during a week's testing.
- After one year of operation, no noticeable corrosion was observed in the pumps and turbine.
- More energy can be extracted from the geothermal water on Amager. Here 350W could be produced in stage 1 compared to 255W in Sønderborg – expected due to the higher salt concentration in the geo-thermal water
- Based on the results from the pilot a 2-stage setup in Sønderborg diluting the geothermal water from 16 to 7% a full scale osmotic power plant can produce 0.8MW (gross). In the original EUDP application we estimated a gross energy production of 1 MW for the same dilution showing a good correlation between the estimates and the actual obtained results.
- Different sources of feed water have been analyzed and investigated for use in an osmotic power plant and different pre-treatment technologies have been evaluated. This has allowed for a selection of the most promising setup for a full scale demonstration unit
- 3 scientific papers have been published.

Conclusion & perspectives

The EUDP project has shown that energy can be produced from geothermal water at power densities larger than 5 W/m^2 membrane using standard off the shelves industrial components and has in this way confirmed the hypothesis going into the project. Furthermore, using standard water treatment techniques such as sand filtration and nanofiltration, we have been able to overcome fouling issues and obtain a stable process.

The next step in the development of the technology will be to scale up from pilot to full scale demonstration where full size equipment parts can be applied and full automation reached. This will allow SaltPower to gain the necessary data to demonstrate the feasibility and gains of the process to customers.

1.4 Project objectives

The overall objective for the project was to investigate if it was possible to achieve an energy production larger than 5 W/m^2 of membrane. Prior to this project, the Norwegian energy company Statkraft had investigated the use of osmotic power technology for energy production based on seawater. They found that in order to make the process cost effective, they had to be able to achieve a power density >5 W/m^2. Using seawater this was not possible and they had to abandon the technology. Compared to seawater, geothermal water can have salinities that are 3 to 10 times higher, and it was therefore assumed that this would allow for reaching power densities >5 W/m^2. This was the underlying hypothesis for the project. The plan was to build two automated pilot plants which were going to be tested at the geothermal plants in Sønderborg and Amager. In the end, we constructed one semi-automated pilot plant (see more further down), which was primarily operated in Sønderborg. This did not change the outcome of the project and we were able to meet all the project milestones. Only the construction phase suffered a small (2 month) delay, but we were able to catch up again during the testing phase.

According to the project plan, the project was set to begin 1/7-2015. In reality the start of the project was delayed and the official kick-off meeting was held on 12/8-2015. This meant that all milestones were pushed one month compared to the original Gantt diagram.

The project consisted of a total of 9 work packages (not including WP0. Project Management) and each of the WPs dealt with different project objectives, which will be covered in more detail in the following.

WP1: Designing and constructing the pilot plant

The objective in WP1 was to design and construct a working pilot plant that could be used to test osmotic power technology used together with geothermal heat production. The objective was met, but the time plan was delayed two months according to the original plan due to changes in the design and construction phase.

As part of this work, a control software had to be developed and the required level of pre-treatment of both the feed water and the geothermal water had to be determined. Osmotic power from high salinity sources is a completely new technology and no prior knowledge for installations larger than lab scale were available. The pilot unit was therefore going to be the first of its kind, which meant that there were many unknowns.

In the project plan three milestones were inserted to cover the design (M2) and construction (M3.1 and M3.2). The design was planned to be finished in October 2015 and this deadline was met, when the working group decided on the final design at the end of September. Construction were planned to take place in two stages. First a single stage pilot plant should be constructed to allow for verification of the overall hypothesis of the project. The deadline for this was February 2016. Secondly, a multi-stage pilot plant should be constructed to allow for testing of the hypothesis that use of a multi-stage approach would allow for a higher yield. The deadline for this was July 2016. However, due to two incidents, the construction phase became delayed.

- The intended supplier of osmotic membranes underwent bankruptcy and we had to find a new membrane supplier.
- The conclusion from the design phase was that an external contractor should be hired to construct the pilot unit. Meetings with several contractors were held, but this became too expensive. Thus, this approach was abandoned and it was decided to construct the pilot plant by ourselves.

Due to this, the construction of the pilot plant was finished in April 2016 rather than February.

During the design and construction phases, it was also decided to keep the pilot unit semi-automatic. The original plan was to have the plant fully automated, but this was not feasible due to two reasons: The complexity of operation and the maintenance at the geothermal plants.

Since we were working with a completely new technology, we found that it was necessary to have an operator present to make required changes and modifications in the process and to

handle alarms and unforeseen problems. Also, a fully automated plant required more expensive components and control software. Therefore, we decided to keep the pilot plant at a semi-automated level.
During the project different kinds of maintenance were scheduled for the hosting geothermal plants. In Sønderborg, it was decided to clean the injection well and on Amager, lead was discovered in the geothermal water, which delayed a scheduled maintenance. Therefore, it was not practical for the SaltPower unit to extract water directly from the geothermal plant. This would result in large periodes with no experimental activity. To adapt to these challenges we established a large reservoir of geothermal water in Sønderborg, which could be used for testing even when the geothermal plant was not in operation. Testing on Amager was planned so that it was aligned with the maintenance. This also, meant that the primary part of the testing occurred in Sønderborg and therefore we decided not to construct two pilot plants, but instead modify the existing pilot plant to be able to test both the single stage and multi stage operation. Doing this, it was possible to meet the deadline for testing of multi-stage operation.

WP2: Verifying the 5 W/m^2 hypothesis
The aim of WP2 was to investigate the hypothesis that the high salinity of the geothermal water would be enough to achieve a power density >5W/m^2. Results from the pilot plant were to be compared to laboratory results, where a range of commercial osmotic membranes were to be scanned for use as osmotic power membranes.
WP2 also functioned as a “go/no go” milestone in the project depending on whether the 5 W/m^2 could be obtained or not (M4.1).
The deadline for M4.1 was May 2016, and even though the construction phase had been delayed 2 months, we were able to meet this deadline.

A second part of WP2 were verification of the calculated power potential in lab scale testing. The deadline for this verification was September 2015, and this deadline was also met. Lab scale testing continued throughout the Autumn of 2015 to collect sufficient data to allow for a scientific publication.

WP3: Increasing the energy production through a multi-stage setup
Modelling results prior to the EUDP project had indicated that more energy could be extracted if the osmotic power process was split into several stages placed in series where each step operated at different conditions. The objective of WP3 was to find a way to test this and evaluate how much energy could be increased. This was covered by M3.2, which had a deadline in September 2016.

As mentioned under WP1, the multi-stage process was tested by modifying the single stage setup. By doing this instead of constructing a separate pilot system for multi-stage testing we could meet the milestone already in July 2016 and at reduced costs.

WP4: Development of osmotic power membrane
One of the underlying arguments for going directly to EUDP and pilot scale testing rather than starting the project at a more fundamental level was that all of the individual components were commercially available. This was also the case for the osmotic power membrane, but because no membrane producer had specifically designed a membrane for use in geothermal osmotic power, there was room for optimisation of current membrane technology. The objectives in WP4 were therefore to determine the properties that an osmotic power membrane should possess to perform optimally in the osmotic power setup and use this optimised membranes in lab scale.

Membrane development was planned to take place during 2016, where lab scale membrane manufacturing was going to be made. This part of the project was modified due to new possibilities that arose during the project. After the intended membrane supplier went bankrupt, we had to find a new supplier. Here we discovered the Japanese membrane company Toyobo with whom we established a very fruitful collaboration. Toyobo supplied membranes to the project and based on the data that we send back to them, we developed a new membrane for osmotic power. Thus, instead of developing conceptual membranes in lab scale we went directly to pilot scale and were able to develop a new commercial product ready for use in a full scale demonstration plant.

WP5: Optimisation of process for energy production in Sønderborg
The objective of WP5 was to find the optimal operational conditions for the pilot plant in Sønderborg and investigate how the different parameters affected the process.

Process optimization was planned to take place from July to December 2016 and in general we followed the plan. Optimization of the operation of the SaltPower unit was done during this time period, but we also started to look at optimization of the pre-treatment systems. This work continued into 2017.

WP6: Long term performance and lifetime expectancy
The purpose of WP6 was to evaluate how energy production developed over time. From other membrane processes, fouling is known to be an issue resulting in the need for regular cleaning. Also, the high salinity of the geothermal water meant that corrosion of equipment was expected. However, no membrane or pump producers had experience with highly saline geothermal water, so the exact extend of the corrosion was unknown.

Since, the final pilot plant was not fully automated, it was not possible to obtain fully continuous operation. Instead, the pilot was operated several days in a row with the same operational conditions to estimate long term performance. The effect of the high salinity on the equipment was evaluated by visual inspection, while the effect on the membrane was evaluated by observation of the membrane performance.

WP7: Optimisation of process for energy production at Amagerværket
WP7 was similar to WP5, but here the objective was to optimise the process for the geothermal water found on Amager where the salinity is higher.
The original plan was to have a separate pilot plant in operation on Amagerværket, but since only one pilot unit was constructed, the same unit was used in Sønderborg and Amager. Also, during the final months of 2016 and the beginning of 2017, the geothermal plant on Amager was shut down for maintenance. In total this also meant that the pilot was in operation for 1 months on Amager compared to 9 months planned. However, based on the experiences from Sønderborg, we were able to quickly find optimal operating conditions and make a long term test. We also had the opportunity to test a new pre-treatment method for the geothermal water on Amager. Thus, in total we were able to collect the necessary data.

WP8: Evaluation of test results and profitability
The objective of WP8 was to collect the results and use these to provide a more accurate evaluation of the profitability of the addition of osmotic power to geothermal heat.
The objective in WP8 was covered by M4.3 and M5, both with deadlines at the end of the project. With the data that has been collected in the project it has been possible to design a full-scale demonstration plant and the from the energy production it has been possible to compare with the original estimates that formed the basis for the profitability evaluation.

WP9: Environmental impact
The current technology is based on discharging dilute geothermal water to the sea, which can have an environmental impact. The objective of WP9 was to investigate this to be able to obtain permission for later large-scale demonstration of the technology.

In the final pilot plant design, we did not directly discharge to the environment, so no direct observations could be made. To be able to evaluate the environmental impact of discharge, we therefore initiated a dialogue with the local authorities in Sønderborg, and had their geologists and biologists evaluate what requirements the diluted brine would have to live up to in order for it to be discharged. Back when the geothermal plants were established, discharge permits for the raw geothermal water had been made, which gave the authorities an informed basis to talk from.

1.5 Project results and dissemination of results

In the following we will go through the results of the project, to some extend following the structure laid out in section 1.4.

Design and construction of the pilot plant

First part of the project was focused on designing the pilot plant. Several meetings were held where the relevant project partners were invited to discuss how to best design the system to allow for the planned tests. Also, a consultant who had been working with Statkraft on designing their pilot plant was hired to assist with the design of the system. The final design plan can be seen in Figure 1.

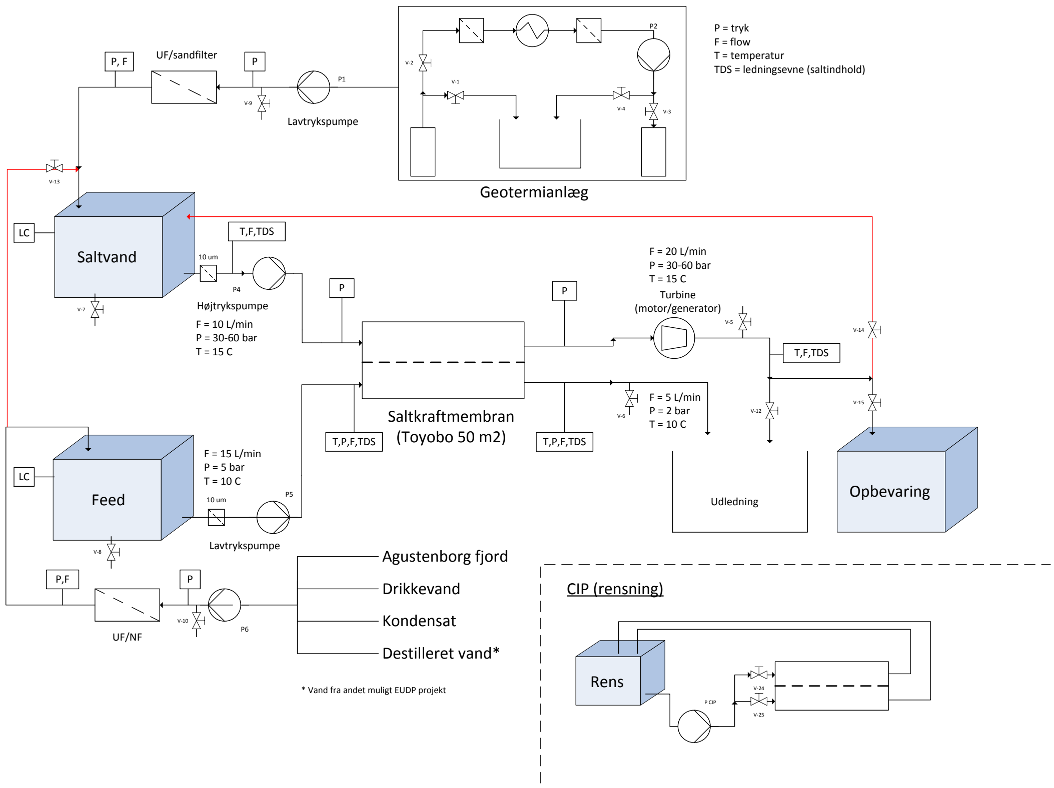

Figure 1 Design of the osmotic power pilot plant

The pilot was designed to operate with two holding tanks, which made it easy to integrate the SaltPower system with the geothermal plant.

One of the challenges for the systems was that both geothermal plants had to undergo maintenance and that they were taken out of operation during the warm season where the heat requirement was smaller. This meant that the plants were shut down for several months making it impossible for continuous operation of a SaltPower plant connected directly to the geothermal plant. To overcome this, we decided to use the large reservoir tank (gylletank) at the geothermal plant in Sønderborg, which is normally used by the geothermal plant to collect surplus geothermal water. This tank can hold several hundred-cubic meter of geothermal water, and by drawing water from here, the SaltPower unit could be kept in operation continuously. Given the size of the reservoir tank, we could also discharge dilute geothermal water back to the tank without any significant dilution. During our tests, we also observed near constant salinity in the geothermal water. The reservoir tank and placement of the SaltPower unit can be seen from Figure 2.

To test a multi-stage setup, a third collection tank was installed. This could be used to collect diluted geothermal water after one pass through the SaltPower system. Afterwards, this water could be pumped to the saltwater holding tank and used in a new experiment. In this way, the same membrane setup could be used to investigate single- and multi-stage operation of the pilot plant.

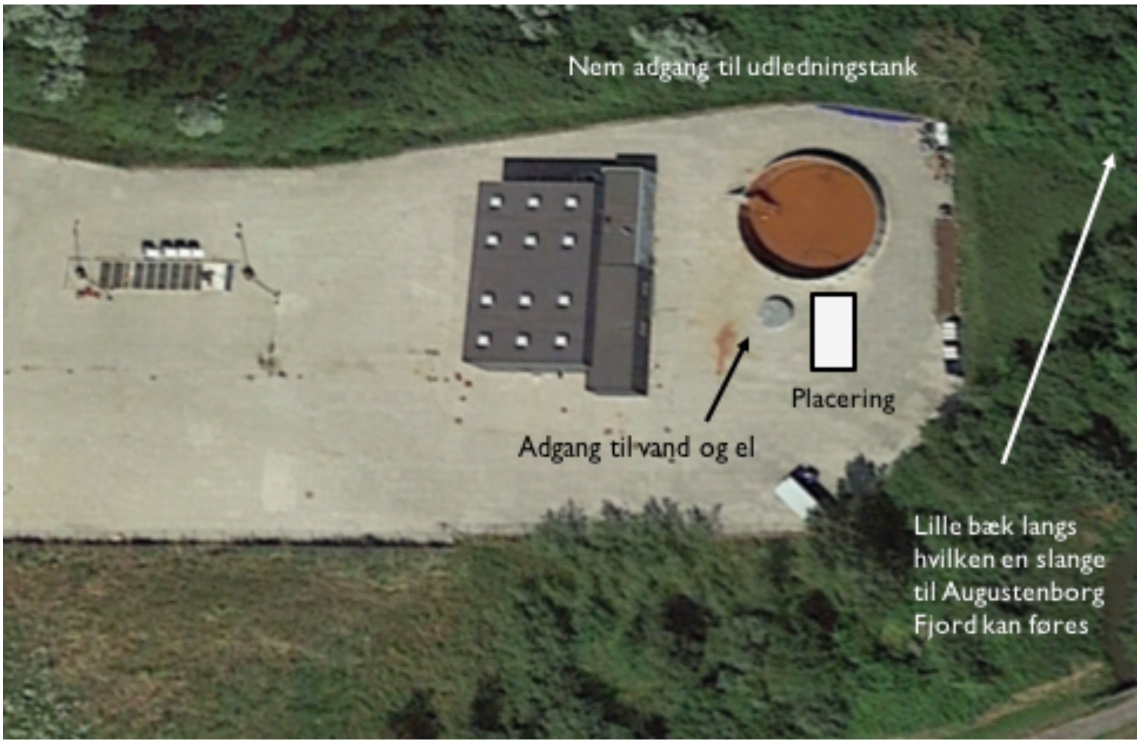

Figure 2 Overview of the geothermal plant in Sønderborg and the placement of the SaltPower pilot unit

The pilot plant was constructed in a 20 foot high-cube container, which was insulated and converted into a wet room laboratory, which could easily be hosed down in case of spillage of geothermal water. It also allowed for an operator to work during all kinds of weather. In Figure 3, pictures of the finished pilot plan can be seen. Equipment was placed on one side of the container while control equipment and a work bench was installed on the other side.

Figure 3 The finished pilot plant. To the left, the container can be seen with the in- and outlet manifold. In the background the reservoir tank can be seen. To the right, the interior of the container is shown. From left to right is seen: the sand filter, ion exchange softening, particle filtration, high pressure pump, osmotic membrane, and turbine.

The first part of the container handled the pre-treatment of the two water streams, while the osmotic power process was placed in the back of the container. This gave a very structured flow through the system, which made it easy for visitors to see and understand the process. In Figure 4, a picture the osmotic power process is shown. A Danfoss high pressure pump was used to pressurize the geothermal water and pump it into the membrane. Here it was distributed across the membrane fibers and due to the difference in osmotic pressure, water was drawn across the membrane and into the geothermal water. The increased volume of dilute geothermal water was then send to a turbine to be converted into energy. The turbine was also a Danfoss product, similar to the pump, but where the displacement mechanism ran opposite that of the pump and in this way produced energy rather than consuming it. The turbine was used to control pressure, by braking it partially. This created a back pressure that was used to set the pressure across the membrane.

Figure 4 The heart of the SaltPower process. From left to right is seen: The high-pressure pump, the osmotic membrane and the turbine.

Pump and turbine was both supplied by Danfoss. The grey boxes mounted on the wall are frequency converters used to control the pump and turbine. The Danfoss products are made of super duplex steel, which is a very corrosion resistant steel alloy making them ideal for operation on high salinity geothermal water. The membrane supplied by Toyobo is a hollow fiber membrane consisting of a large bundle of fibers with an inner diameter of 100 um. In order to protect the membrane during start up, a bypass loop was made.

One of the challenges for osmotic power from high salinity geothermal water compared to seawater was the membranes pressure resistance. In order to fully utilize the osmotic potential of the geothermal water, it is necessary to operate at high pressures, > 25 bar. The osmotic membranes from Toyobo are hollow fiber membranes with an inner diameter of 100 um. This make them ideal for high pressure osmotic power. In Figure 5, the water flow through the membrane is illustrated. The pressurized geothermal water flows on the outside of the fibers and because of the small diameter of the fibers these become self-supporting up to a certain pressure. Toyobo had previously operated the membranes at 30 bar.

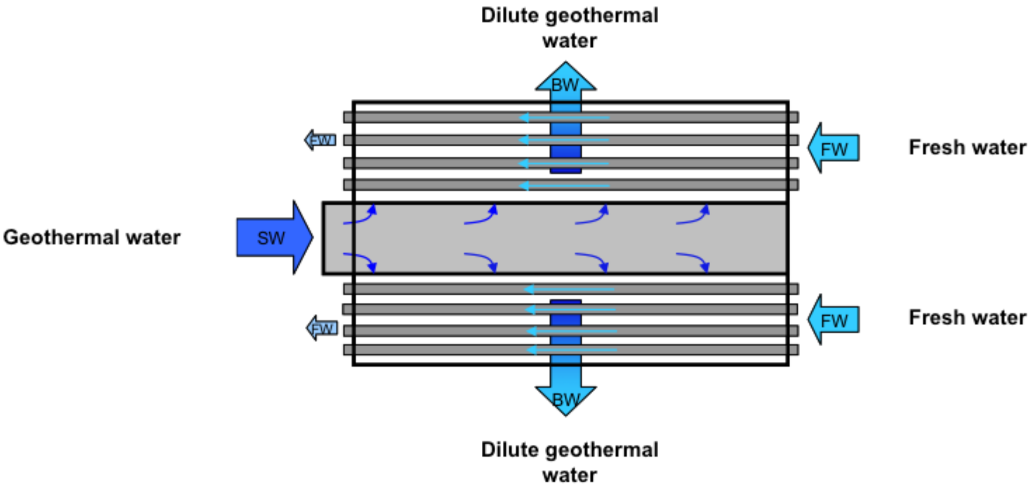

Figure 5 Schematic of the osmotic membrane technology from Toyobo. The fresh water flows in the hollow fiber lumen while saltwater flows around the fibers on the shell side of the membrane.

On a sunny day in April 2016, the pilot plant was officially inaugurated. Former EU climate commissioner Connie Hedegaard performed the official act of pressing the start button, which initiated energy production.

More than 100 guests witnessed the opening of the World's first geothermal osmotic power plant.

Figure 6 Connie Hedegaard inaugurates the SaltPower pilot plant.

Lab results

Laboratory tests where carried out in parallel with the design and construction of the pilot plant. Here six different commercial osmotic membranes were compared for high salinity osmotic power and the effect of salinity was investigated.

The fundamental transport parameters for osmotic membranes: Water permeability A, salt permeability B and structural coefficient S were determined for each of the membranes and their performance in SaltPower were compared at a synthetic 3 M NaCl solutions, which is close to the salinity observed in the geothermal water in Sønderborg.

Table 1 summaries the transport parameters for the membranes.

Table 1 Overview of membranes used in study with the data that has been made publically available by the producers and the data determined in this study. Column 4 and 5 are data from the producers, while columns 6, 7 and 8 are experimentally determined values. The values were determined as described in section 3.3. B values were determined at an applied pressure of 10 bar. S values were determined for the uncompressed membrane at an applied pressure of 0 bar. It was not possible to determine the parameters for the Aquaporin membrane since it was too fragile for the procedures used in this study.

Membrane	**Material**	**Producer**	**Water permeation at 1.0 M NaCl draw (LMH)**	**Reverse salt flux (g/L)**	**Water permeability, A (L m^{-2} h^{-1} bar^{-1})**	**Salt permeability, B (L m^{-2} h^{-1})**	**Structural coefficient, S (μm)**
HTI CTA	Cellulose acetate	Hydration Technology Innovation	-	-	0.42 +/- 0.06	0.29 +/- 0.05	1028
HTI spiral	Cellulose acetate	Hydration Technology Innovation	-	-	0.76 +/- 0.06	0.44 +/- 0.08	655
FTS CTA	Cellulose acetate	Fluid Technology Solutions	-	-	0.69 +/- 0.08	0.34 +/- 0.09	707
FTS TFC	Thin film composite	Fluid Technology Solutions	-	-	1.25 +/- 0.25	0.19	471
Porifera	Thin film composite	Porifera	33 ± 2 (FO) 58 ± 3 (PRO)	0.2 - 0.6	2.38 +/- 0.05	0.50 +/- 0.32	458
Aquaporin	Thin film composite	Aquaporin A/S	> 7 (FO)	< 2g/m^2/h	-	-	-

All commercially available osmotic membranes were collected and tested. At the beginning of the EUDP project, the most well established producers of osmotic membranes were HTI, but the company underwent bankruptcy. Out of this sprang a new company, FTS. Membranes from both were tested in this study. Membranes from the companies Porifera and Aquaporin were also tested. These are both of based on the thin film composite technology and relies on the addition of water transporting nanoparticles to improve membrane performance. It was not possible to test the membrane from Toyobo in laboratory scale since these are only available in large scale modules.

In Figure 7, the performance of the membranes is compared. Two parameters are important for an osmotic power membrane: It must produce a high water flux in order to generate a sufficiently high power density potential and it must be stable at high pressures in order to realize the power density potential. Several conclusions were reached in the study:

First of all, membranes of the TFC kind generally showed highest water flux, but were also more sensitive to increased pressure. This can be seen from the rapid decline in flux when pressure is increased. Also, the TFC membranes had a limited pressure stability. The cellulose based membranes (CTA) had a more pressure stable water flux and could be operated up to 70 bars, which was the maximum allowed pressure in the laboratory setup. This proved that operation at high pressures are possible with existing osmotic membranes and that one of the keys to designing high pressure membranes for osmotic power is the design of the membrane element and the support material. In these tests, a sintered steel plate was used to support the membrane, which gave it a very stable background to operate on.
A second important conclusion was that power densities significantly above 5 W/m^2 could be obtained. At a 3M salinity >30 W/m^2 could be produced.

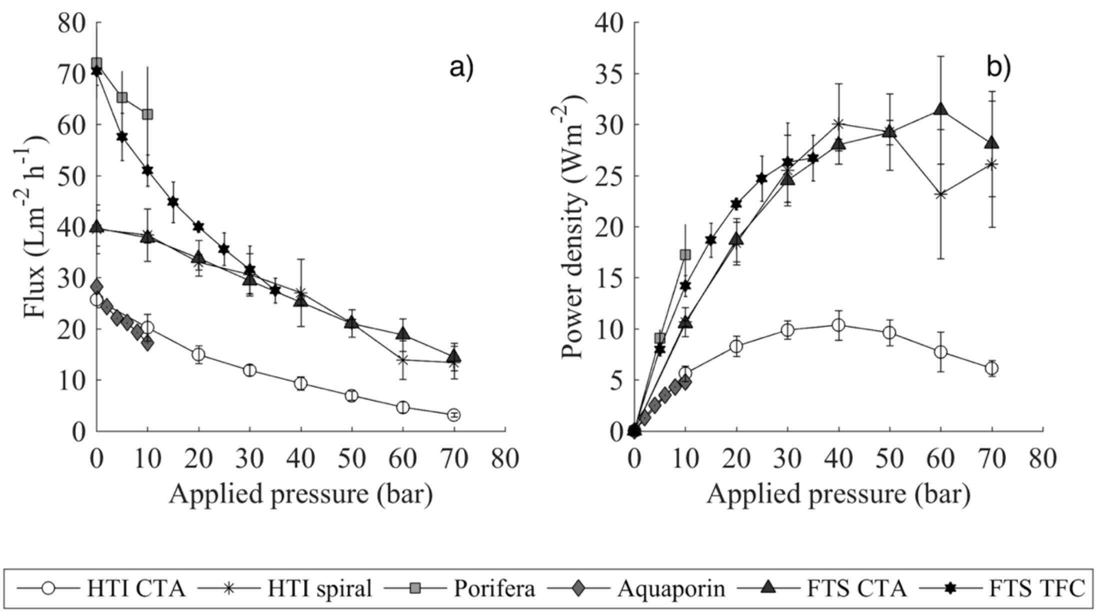

Figure 7 Observed flux and power density for the six commercial membranes investigated in the laboratory study.

One of the key ideas of the project was that increasing salinity would allow for higher power densities. A standard cellulose membrane (HTI CTA) was used in these tests. This was the same membrane employed by Statkraft in their work. The results are shown in Figure 8.

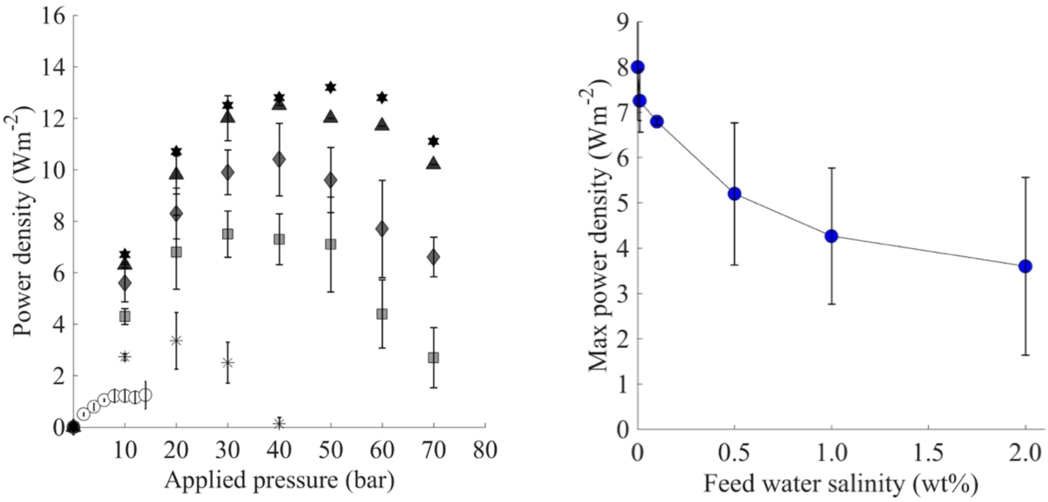

Figure 8 Investigation of the effect of draw and feed salinity. To the right draw salinity is investigated at 0.6, 1, 2, 3, 4 and 5M NaCl. Distilled water was used as feed. To the left a draw salinity of 3M is used to investigate the effect of increasing salinity in the feed water.

When employing seawater salinity (0.6M), a maximum power density of 1.5 W/m^2 could be produced, which is similar to the results reported by Statkraft. Increasing the salinity to 3M (similar to the salinity seen in the geothermal water in Sønderborg) gave a power density of 10.4 W/m^2. As such the power density increased with a factor of 7 while salinity increased with a factor of 5. In this sense, the hypothesis of surpassing 5 W/m^2 by using higher salinity solutions was confirmed.

The power density results can be compared to those calculated theoretically using the equations developed as part of the EUDP application. This is done in Figure 9.

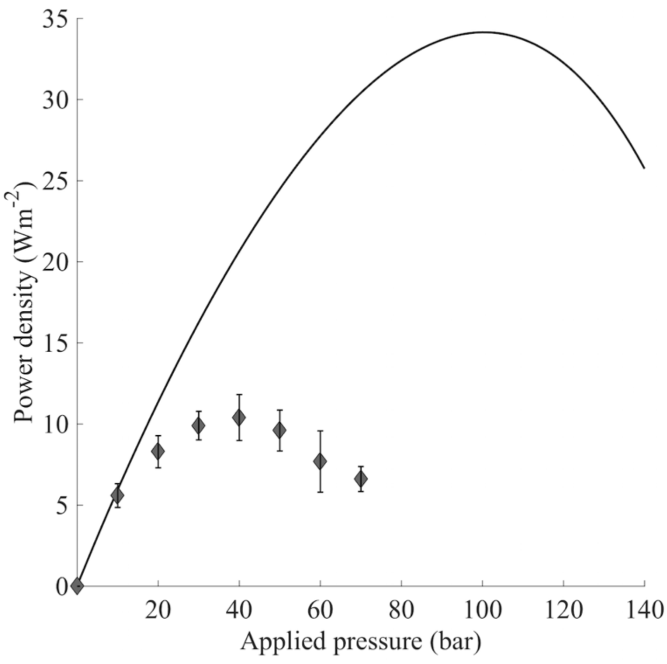

Figure 9 Modelling of power density. The values from Table 1 for HTI CTA membrane have been used to model the expected membrane performance. A mass transfer coefficient of 300 $Lm^{-2}h^{-1}$ has been used.

Here it can be seen that we were unable to fully utilize the potential of the membrane. The reason for this was investigated as part of the study. Here it was found that the membrane transport parameters change with increased pressure. There are three fundamental membrane transport parameters: A (water permeability), B (salt permeability) and S (structural coefficient. Can be thought of as the membrane resistance). In order to improve power performance A should be high, while B and S should be low. By measuring these parameters at different pressures we found that A was constant while B and S increased. Increasing the pressure thus reduced the membrane performance. A second reason for the lower power density was the flow conditions. These were far from ideal because of the use of sintered steel plate as the feed spacer. This only allowed for a low flow rate on the feed side and the laminar flow conditions led to enhanced concentration polarization. Based on these findings we concluded that an optimal membrane for osmotic power should:

- Have a high water permeability
- Minimize increases in B and S when pressure is increased
- Stabilize the membrane while still allowing for sufficient flow on both feed and draw side of the membrane.

Power density tests in pilot container

The first experiments were carried out to determine whether the geothermal water would allow for power densities higher than 5 W/m^2 of membrane as had been seen in the laboratory. Therefore, standard experiments were performed in which the applied pressure were increased up to the maximum recommended pressure for the membrane.

Power density is determined by measuring the obtained flux, J_w, through the membrane at a given applied pressure, ΔP. Flux is theoretically linked to the osmotic pressure, $\Delta\pi$, of the solution and the applied pressure via the following equation.

$$J_w = A \cdot (\Delta\pi - \Delta P)$$
(1)

When flux has been measured, power density can be calculated as follows.

$$P_d = J_w \Delta P$$
(2)

Membrane	Toyobo 5” PRO3
Active area	60.2 m^2
Outer diameter	200 um
Inner diameter	100 um
Draw	Sønderborg geothermal water
Feed	Groundwater
Draw flow	6.6 L/min
Temperature	20 C
Salinity	145 g/L (165 mS/cm)
Pretreatment of draw	Sand filtration
Pretreatment of feed	Ion exchange

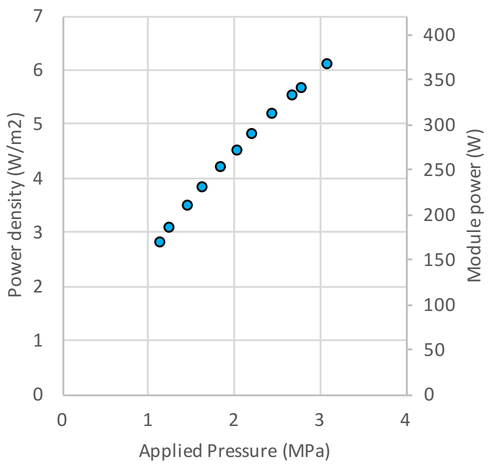

Figure 10 Results from power density test in Sønderborg

In Figure 7, the results from the power density test can be seen. As expected, the obtained power density increased with the applied pressure. The maximum recommended pressure from the manufacturer was 30 bar. At this pressure, a power density of 6.1 W/m2 was obtained, equal to a total power production of 370 W. Thus, with this the primary objective of the project was met.

At this point, it is fitting with a further comment on the power density results. Power density is a measure of the amount of energy that can be produced per surface area membrane. In the original work by Statkraft, where the 5 W/m^2 goal was put up, flat sheet membranes were used and in this project we have used hollow fibers as outlined during the design section. Using hollow fibers makes calculation of the power density more complex. For instance,

the surface area can be calculated based on both the outer and the inner diameter of the fibers. If the inner diameter is used to calculate the membrane area, the surface area will be half of that based on the outer diameter. Accordingly, power density will be double as high. Arguments can be made in favor of both, but in these calculations we have chosen to use the outer diameter (and thus be conservative).
A second point to be made about hollow fibers, are their high packing density, measured as the number of square meter membrane that can be packed into a given volume. Compared to a commercial flat sheet osmotic membrane of similar size, the Toyobo hollow fiber membrane can pack about 10 times more membrane area in the same volume, see Table 1.

Table 1 Comparison of flat sheet and hollow fiber membranes. Data from a flat sheet osmotic membrane in a spiral wound configuration from FTS technology is used to represent flat sheet membranes. Data from the Toyobo 5" PRO3 membrane is used to represent hollow fiber membranes.

Membrane type		*Flat sheet (spiral wound)*	*Hollow fiber*
Producer		FTS	Toyobo
Length	mm	1016	680
Diameter	mm	201	127
Volume	m^3	$32 \cdot 10^{-3}$	$10.5 \cdot 10^{-3}$
Active surface area	m^2	21.5	60.2
Packing density	m^2/m^3	667	6989
HF/FS ratio		10.5	

Packing density is important since it influences the module power density. Power density is a measure that can be used to calculate the number of membrane elements that are required in order to produce a specific amount of power (e.g. number of membranes required to produce 1 MW). The lower the power density is, the higher is the number of membrane modules needed, which increases the capital expenses and the foot-print since the membrane plant becomes less compact. By packing more membrane area into each module the necessary number of modules can be reduced similar to increasing power density of the membrane material.

The 5 W/m^2 membrane was based on using flat sheet membranes. It is therefore interesting to calculate the power density that flat sheet membranes would need to achieve to reach the same modular power output as the Toyobo HF membrane. The theoretical power density achieved by a flat sheet spiral wound (SW) membrane can be calculated with the following equation.

$$P_{d,SW} = P_{d,HF} \cdot \frac{HF\ packing\ density}{SW\ packing\ density} \quad (3)$$

In Figure 8, the two power densities are compared. The figure shows what the power density would have been if the same membrane housing had contained a flat sheet membrane and produced the same modular power. Here we see, that flat sheet power densities >60 W/m^2 is achieved. The numbers are theoretical, but they show that by using HF membranes we get a very compact power production.

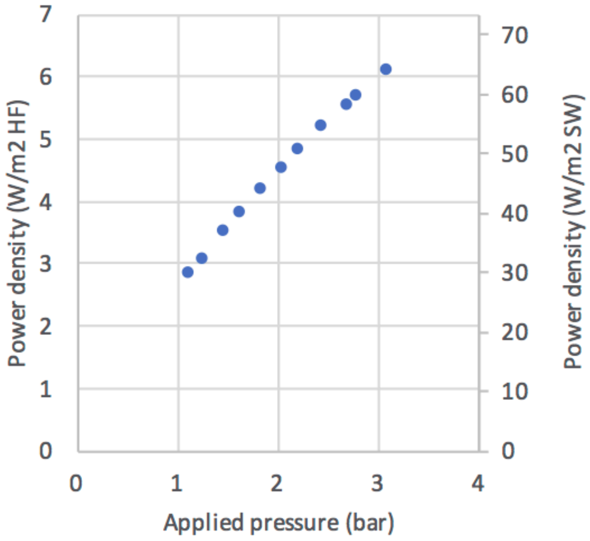

Figure 11 Comparison of power density for hollow fiber (HF) and flat sheet spiral wound (SW). The SW numbers have been calculated by assuming that the SW membrane was placed in the same housing as the HF membrane and then produced the same modular power

Based on these findings we can therefore conclude that:

- Using geothermal water allows for production of power at a power density > 5 W/m^2
- Hollow fiber membranes are the most promising membrane type for high salinity power production. Their self-supporting structure allows for high pressure resistance and they offer a very compact power production.

Modelling

Based on the results from Sønderborg, we investigated if the performance could be modelled. Therefore, we determined the apparent membrane permeability, A, see equation 1.

$$A = \frac{J_w}{\Delta\pi - \Delta P}$$
(4)

Where the average osmotic pressure and applied pressure was calculated as the logarithmic mean between in- and outlet.

$$\Delta\pi - \Delta P = \left(\frac{\pi_{D,In} - \pi_{D,Out}}{ln\left(\frac{\pi_{D,In}}{\pi_{D,Out}}\right)} - \frac{\pi_{F,In} - \pi_{F,Out}}{ln\left(\frac{\pi_{F,In}}{\pi_{F,Out}}\right)} \right) - \left(\frac{P_{D,In} - P_{D,Out}}{ln\left(\frac{P_{D,In}}{P_{D,Out}}\right)} - \frac{P_{F,In} - P_{F,Out}}{ln\left(\frac{P_{F,In}}{P_{F,Out}}\right)} \right)$$
(5)

Osmotic pressure was calculated from salinity via a fitted plot, where x is concentration in g/L (correction for units is required) and t the temperature in degree Celsius.

$$\pi = 0.098 \cdot (0.0085x^3 + 0.0425x^2 + 8.1625x) \cdot \frac{273 + t}{298}$$
(6)

As seen in Figure 9, it was possible to accurately describe the measured power production via this simplified approach. The model is not complete since it does not account for changes in important parameters such as concentration polarization, but it can nevertheless be used to evaluate the process. One of the immediate conclusions from the modelling was that power density could be further increased by operating the membrane at higher pressures.

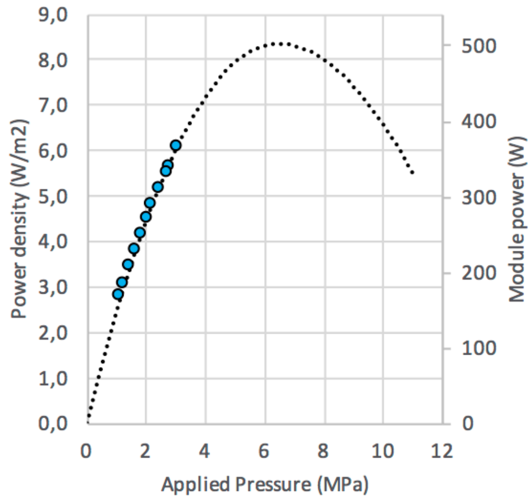

Figure 12 Modelling of power density results based on tests with geothermal water from Sønderborg. A was determined to $3{\cdot}10^{-13} \pm 0.06\ m^3m^{-2}Pa^{-1}s^{-1}$ at a draw flow rate of 6.6 L/min and a salinity of 14 wt%.

Operating conditions – optimizing performance

In osmotic power, some of the most important (controllable) parameters that can influence the process are:

- Draw flow rate
- Feed flow rate
- Applied pressure

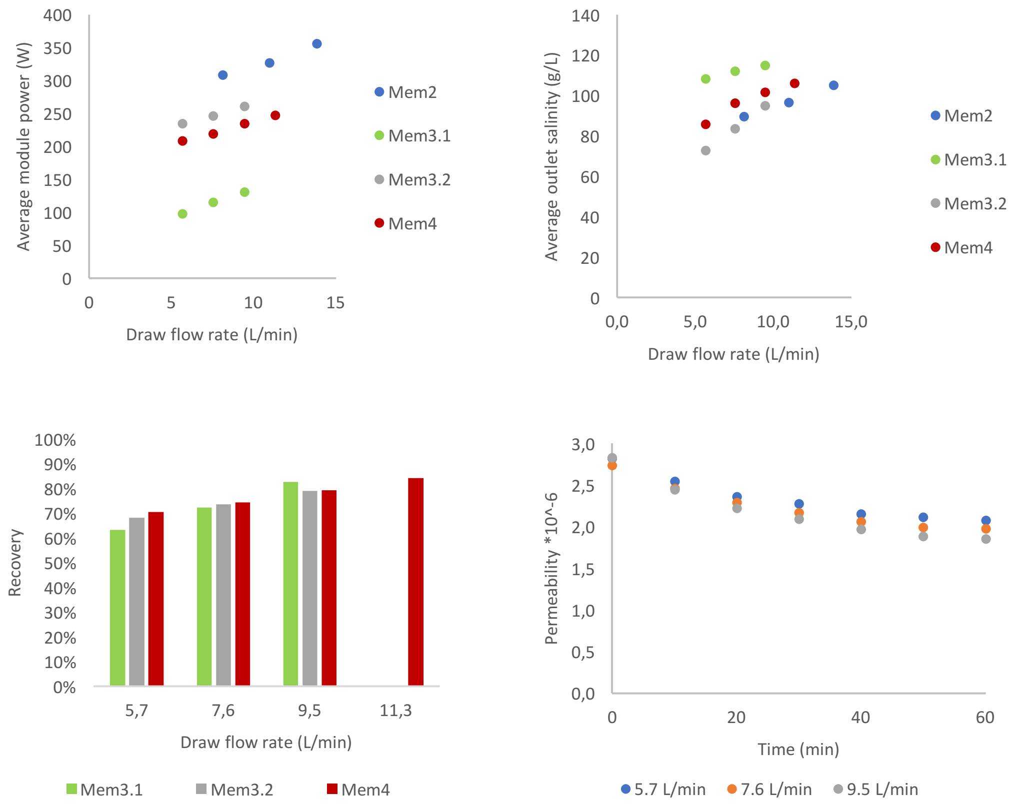

Figure 13 Effect of draw flow rate investigated with four membranes. Permeability is given in $cm^3/cm^2/(kgf/cm^2)/s$. Average data are values collected over the span of one hour.

Highlighted results from tests with varying draw flow rate can be seen in Figure 13. In general, increasing draw flow rate lead to increased power production from the membrane. This was due to a lower degree of dilution of the geothermal water, which produced a higher osmotic pressure in the membrane. Since the feed water flow was operated at constant value, a larger proportion of the feed water was utilized, registered as a higher feed recovery. Higher draw flow rate thus seems to improve performance, but the reality is not as straight forward. The increasing power production comes at the expense of having to move larger quantities of water through the system, which makes efficiency losses in pumps and turbines more significant. Also, pressure loss increases. Going from 8.3 to 14 L/min increased the pressure loss from 2.1 to 4.1 bar. Increasing feed recovery may also increase the risk of scaling as low soluble species in the feed water is more concentrated.

One of the expected results would be to see an increased permeability. The over permeability calculated with equation 4 contains concentration polarization on the draw side of the membrane. It was expected that higher draw flow rates would produce more turbulent conditions, which could suppress the concentration boundary layer. However, this was not observed, since initial permeability was found to be independent on the draw flow rate. This indicates that concentration polarization on the draw side plays a minor role in the overall mass transport.

Feed flow rate was tested in different settings. In general, the feed flow was found not to affect the power output significantly as long as sufficient fresh water could be supplied to the membrane. The feed flow varied linearly with the feed pressure as seen in Figure 14. During plant operation it was decided to operate between 2 and 4 bar in order to supply sufficient water. The exact pressure depended on the type of membrane and the draw salinity.

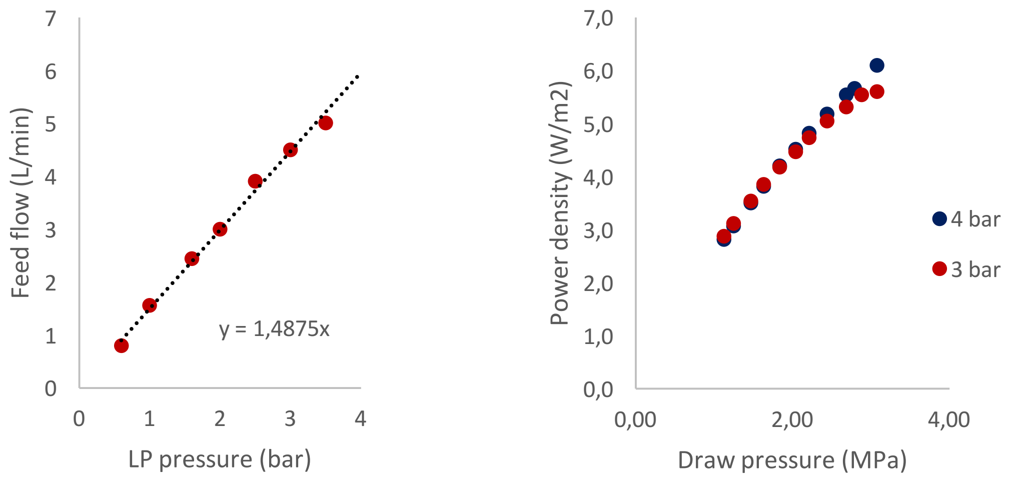

Figure 14 Optimizing feed conditions. The PRO3 membrane was used in these tests.

As was seen from the modelling, there was a potential for increasing pressure above the recommended 30 bar. In Figure 15 it can be seen that it was not possible to further improve the gain much by increasing the pressure. The obtained power plateaued between 40 and 50 bar and at 60 bar it dropped significantly indicating damage to the membrane. A closer inspection revealed that the increased pressure lowered the observed permeability, and that at 60 bar the membrane selectivity was also compromised as a larger degree of salt diffusing through the membrane was observed. The optimum pressure for the PRO3 membrane was therefore set at 30 bar.

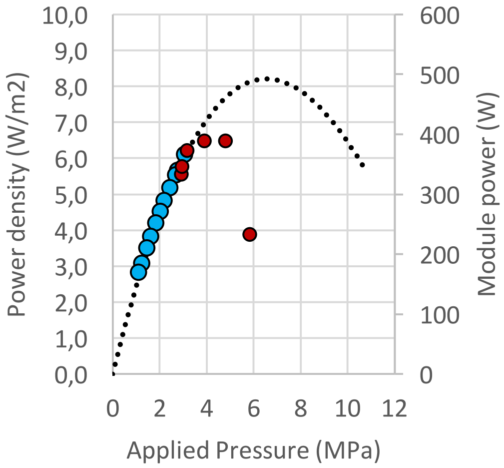

Figure 15 Effect of increasing pressure for PRO3 membrane.

Choice of membrane

In the project, three membranes were tested:

- PRO3
- PRO4
- H3K

The PRO3 and PRO4 were the originally available osmotic membranes from Toyobo, while H3K was developed during the project in order to reach higher pressures.

The PRO3 and PRO4 membrane was found to give similar power densities, but due to the larger membrane surface area ($60m^2$ vs $50m^2$), PRO3 could produce a more power per module.

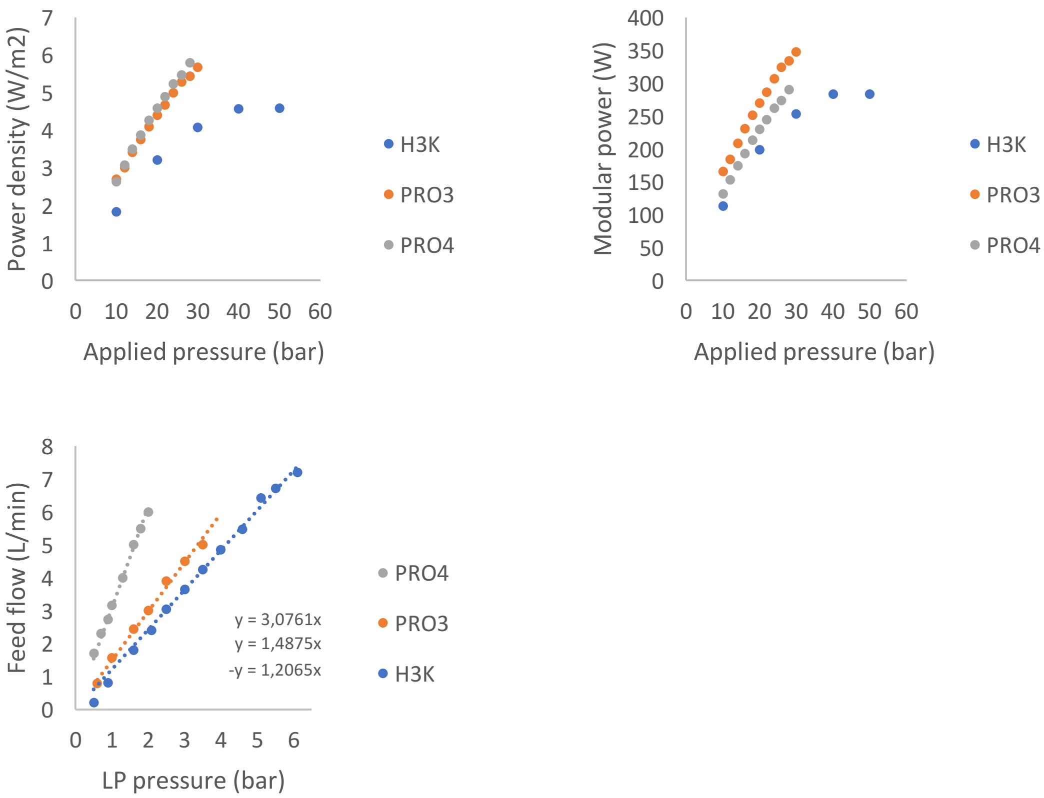

Figure 16 Comparison of osmotic membranes tested in pilot plant

The fibers in the PRO3 membrane had a smaller dimensions compared to PRO4 (OD/ID (um): 200/100 vs 240/120) and due to the larger inner diameter, it was possible to operate the PRO4 membrane at half the feed pressure of the PRO3 membrane.

The H3K membrane had lower power performance, but displayed higher pressure resistance. In the tests, it was possible to operate it up to 50 bar. This was the upper limit of the pressure vessel, but tests at the factory in Japan indicated that the membrane could be stable up to at least 70 bar.

The difference in the membrane behavior meant that they had optimum operating conditions PRO4 and PRO3 are most suitable for lower salinities, where a high permeability is required in order to obtain sufficient power production, while the H3K membrane is most suitable for high salinity where high pressure resistance is required in order to maximize power production.

Long term operation and fouling
One of the challenges that became clear early in the project was the long time stability of the energy generation. As seen in Figure 17, power production decreased over time. Initially, it was thought that this was due to equilibrium reactions approaching a steady state, but the membrane was found to never reach a steady level. Also, although the power production increased when the membrane system was shut down and then restarted, the starting point would be lower compared to the previous run. Therefore concluded that fouling was affecting the membrane performance.

The decrease was found to fit well to a logarithmic plot, although a more thorough theoretical modelling of fouling processes is required in order to fully establish if this model can explain long term performance. If the trend from Figure 17 is used to extrapolate the performance a membrane starting with a power production of 370 W (6.2 W/m^2) would decrease to 236 W (3.9 W/m^2) in the course of a year. This is a rather significant power loss and a series of experiments were conducted in order to investigate if fouling could be limited or avoided.

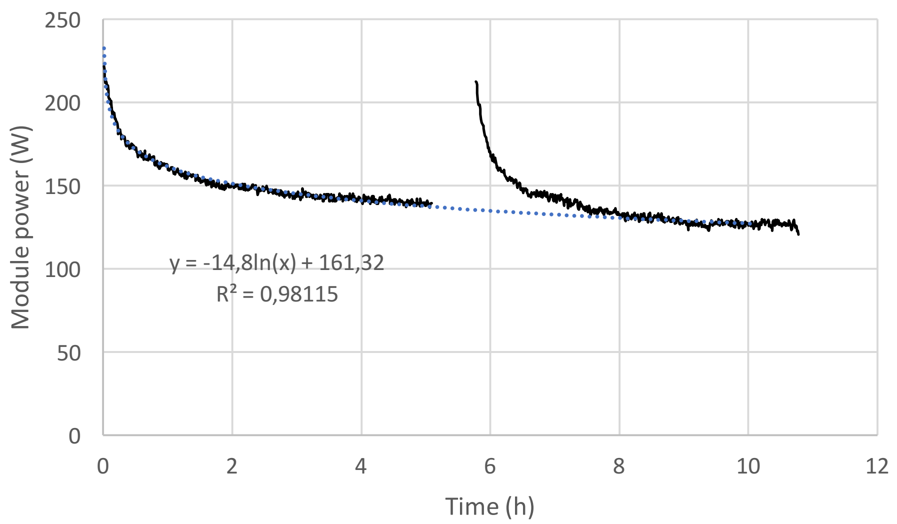

Figure 17 Long term performance of PRO3 membrane in Sønderborg. Feed water: softened groundwater, geothermal water pretreatment: sand filtration

The initial assumption was that the power loss was caused by fouling on the draw side. The high content of iron in the geothermal water meant that iron colloids might be present in the draw water after the sand filter and these could foul the membrane and lower performance.

This was similar to the observations from the pilot work of Statkraft, where deposition of iron on the membrane surface had been observed. Different strategies were attempted to improve draw pretreatment as seen in Figure 18. These were:

- Intermittent wash
- Citric acid cleaning
- Improved pre-filtration

If the fouling was caused by particles clogging the membrane pores, it was possible that fouling could be alleviated by washing the membrane during operation. We used fresh water, but in a final SaltPower plant, clean saltwater could also be used to sustain energy production. However, washing was found not to remove fouling. Power production was initially higher than before washing, but this was due to removal of salts contributing the concentration polarization in the membrane.

Iron colloids and other inorganic foulants can often be removed with citric acid cleaning. From the results in Figure 18, cleaning seemed promising and it was possible to recreate the original performance of the membrane. However, later experiments showed that this was not the case.

In the original setup, a combination of sand filtration and 3 um (nominel) filter was used as draw pretreatment. In order to improve pretreatment, we installed a 10 um (absolute) filter after these. This would remove any particles larger than 10 um. At first this seemed to improve the process, since it was possible to stabilize membrane performance by intermittent washing, but longer experiments showed that fouling continued to affect the process.

It was also observed that leaving the membrane standing after washing with fresh water could deteriorate the membrane performance as it would start out at significantly lower levels compared to the previous operational period.

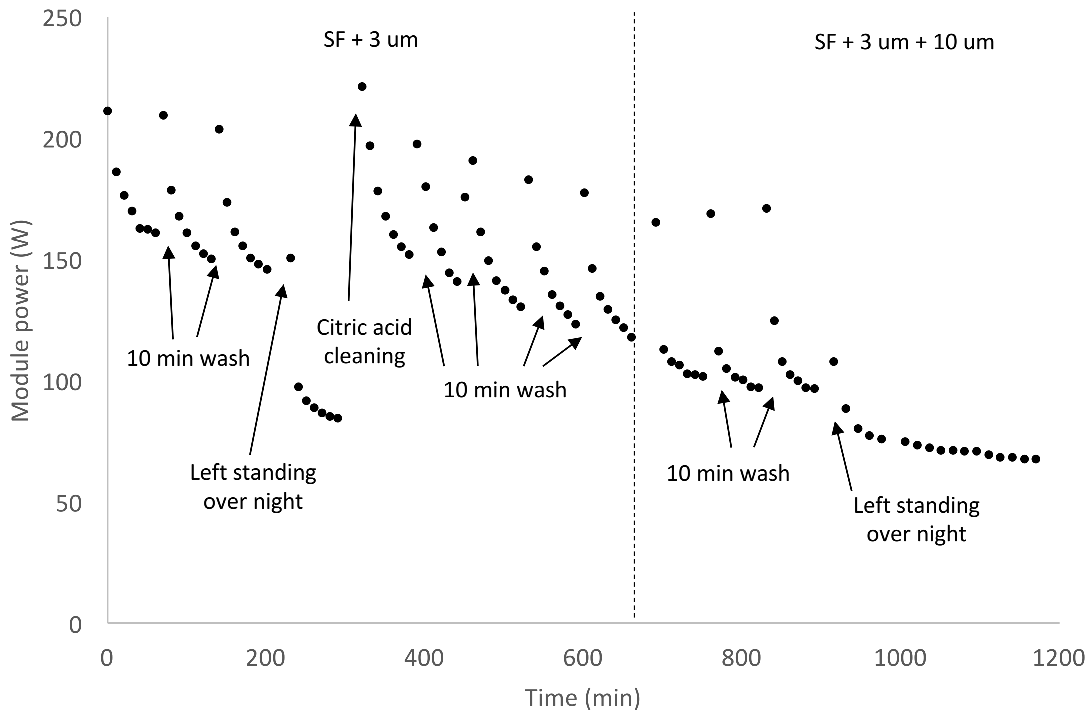

Figure 18 Effect of different draw pretreatment and operational strategies.

Further pretreatment of the draw would be complicated due to the high salinity of the water, and therefore we decided to send a membrane to autopsy in Japan to determine the nature of the fouling.

Figure 19: Pictures from the inspection of fouled membrane. At the top the outside of the membrane (the draw side) is seen, and at the bottom pictures from the draw distribution tube can be seen.

This inspection showed no visual deposits on the draw side of the membrane that could explain the observed decrease in membrane performance. However, it was observed that the fibers were harder in one end of the membrane (near feed outlet), and flow rate measurement in the fibers showed that these had become clogged. To investigate this more closely, the membrane was dismantled and the fibers cut open. Analysis with inductively coupled plasma spectroscopy was used to determine the content of the fouling. This analysis showed low amounts of iron, the suspected issue, and high amounts of calcium and silicium.

In total, the membrane analysis showed that the fouling problem was not on the draw side of the membrane as suspected, but on the feed side, in the fibers. This changed the strategy for obtaining a stable energy production to focus more on feed water pretreatment. However, it was still possible that fouling was caused by reverse flux of Ca and Si ions from the geothermal water to the feed water where these could become concentrated and precipitate out.

Table 2 ICP analysis of fouled fibers from osmotic membrane. Numbers represents mg/kg (fiber). Outer, middle and inner refers to where in the membrane the fibers were sampled from.

	Al	Ca	Cu	Fe	K	Mg	Na	Zn	Si
Outer	3.3	1200	2.0	8.5	2.2	7.6	75	2.3	3600
Middle	1.9	690	1.5	5.4	1.0	4.6	48	2.3	1600
Inner	2.7	760	2.8	11	1.3	11	58	2.7	3500

Cleaning

Fouling is a very common issue in membrane processes, but if appropriate cleaning can be used to regenerate the membrane performance it is manageable. Based on the findings in the autopsy, citric acid was attempted as a means for cleaning the membrane. Citric acid is commonly used in membrane cleaning since it both lowers the pH and can complex bind metal ions and keep them from precipitating.

To evaluate the effect of cleaning we measured the feed flow in the fibers before and after. As can be seen in Figure 20, use of the membrane had resulted in loss of flow through the fibers. First a citric acid solution was recirculated through the fibers for 30 minutes, after which the flow was measured again. This only increased the flow slightly. A second round of citric acid cleaning was performed where citric acid was also recirculated on the shell side of the membrane, but this also only resulted in a minor recovery of flow rate. After a longer period of operation the membrane was cleaned again. This time citric acid was recirculated through both fibers and shell side of the membrane for 30 minutes and then left standing in citric acid over night. This had a more significant effect on flow rate, which was improved with 41%. However, only 29% of the lost flow rate could be recovered.

One of the reasons for this is that fibers that are completely plugged may be very difficult to clean with acid. If the fibers are completely plugged the acid will have a small contact surface with the precipitate, which makes it impractical to clean the membrane completely. Therefore, either a high frequency of cleaning intervals was needed to avoid complete blockage or precipitation in the fibers had to be avoided completely.

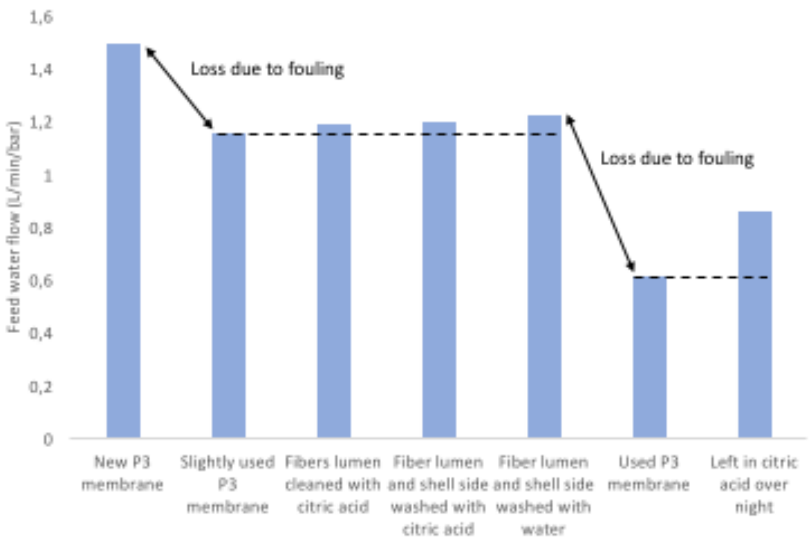

Figure 20 Effect of cleaning

Understanding the fouling process

Experiments with lower salinity (8.5%) had indicated that it was possible to obtain a stable process. Here no permanent loss of permeability was observed over the course of one hour. Together with the results from the autopsy, this indicated that fouling was caused by a feed recovery that was too high. At high feed recoveries, the feed water becomes increasingly concentrated and this could lead to supersaturation of low soluble species such as calcium carbonate. This created a further challenge unique for the Toyobo membranes. As previously described, the Toyobo membranes generates a radial draw flow, which is perpendicular to the feed flow. In traditional counter current membrane designs, the overall feed recovery would be the same as the feed recovery of each individual fiber. But, in a radial design, the inner fibers would be exposed to a higher draw concentration compared to the outer fibers. Therefore, the inner fibers would experience a higher feed recovery compared to the outer fibers and also higher than the overall observed feed recovery. If the feed recovery in the inner fibers lead to supersaturation of the feed water precipitation would occur in the fiber lumen and the inner fibers would eventually become fully plugged. This would make the next layer of fibers the innermost fibers, and the precipitation process could continue here. An observer would see this as a wave of precipitation going from the inner fibers towards the outer fibers until the entire membrane module had become plugged. Such a model described very well the observed decrease in performance that had been observed. Together with Toyobo we developed a mathematical model showing that in extreme cases, the inner fibers might completely dry up due to the high osmotic potential of the geothermal water.

In order to determine where the fouling was originating from, a new series of experiments were devised:

- Pure salt water and pure fresh water
- Pure salt water and real fresh water
- Real salt water and pure fresh water
- Real salt water and real fresh water

The first experiment was carried out at Toyobo's facility in Japan, and here stable conditions were achieved. Next we aimed to replicate the findings in Denmark and therefore a nano-filtration system was acquired and raw sodium chloride was used to make pure salt solutions.

Stable energy production is usually not obtained immediately. Several factors can lead to an initial decrease in power production. Some of the most important of these are membrane compaction and salt transport equilibrium. However, we needed to determined the effect quickly. Firstly, we could only prepare relatively small volumes of pure salt water and secondly, if the membrane was damaged we had to know quickly. Therefore we compared the four different scenarios with respect to the normalized decrease in power production.

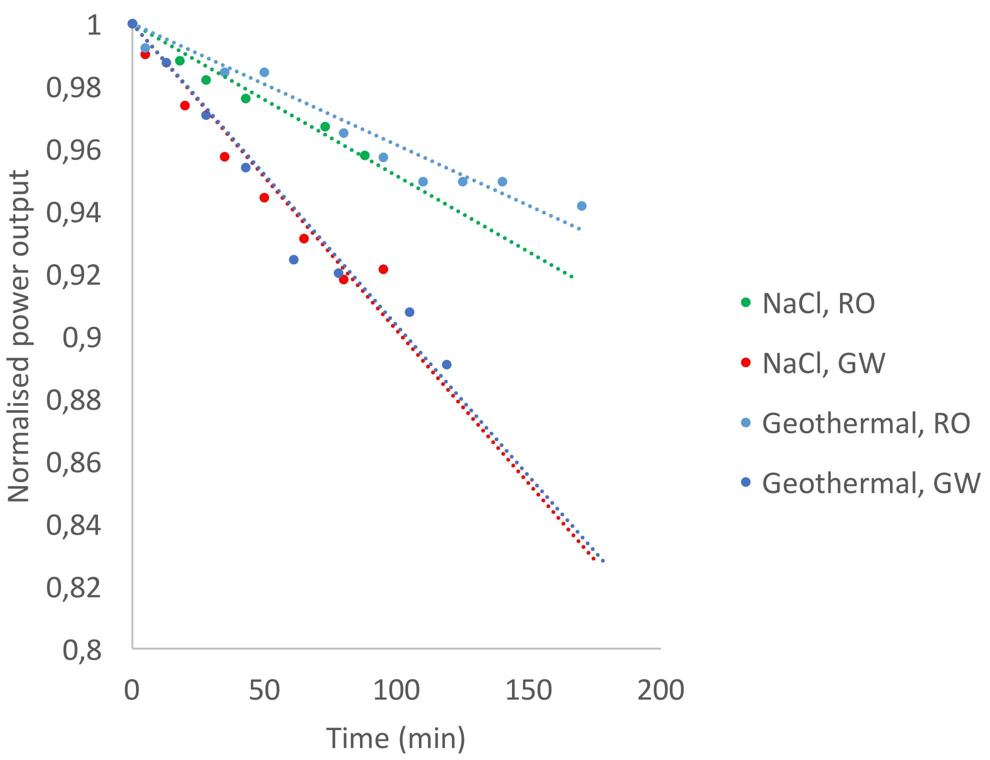

Figure 21 Determination of fouling. In these tests a newly developed high pressure membrane (H3K) was used. RO = groundwater filtered with the NF90 membrane. GW = softened groundwater. NaCl = pure salt water.

As seen in Figure 21, the type of freshwater had the biggest impact. Using pure saltwater and geothermal water resulted in similar decreases in energy production, which was significantly different from when groundwater was used instead of pure freshwater. There was also no significant difference between using pure saltwater and geothermal water when pure groundwater was used.

After this a long term experiment was performed with both softened groundwater and nano-filtrated groundwater as feed water, see Figure 22. Using softening of the groundwater was not sufficient and the power output kept decreasing. When shifting to nano-filtrated groundwater the power output was markedly increased and it was possible to reach stable production.

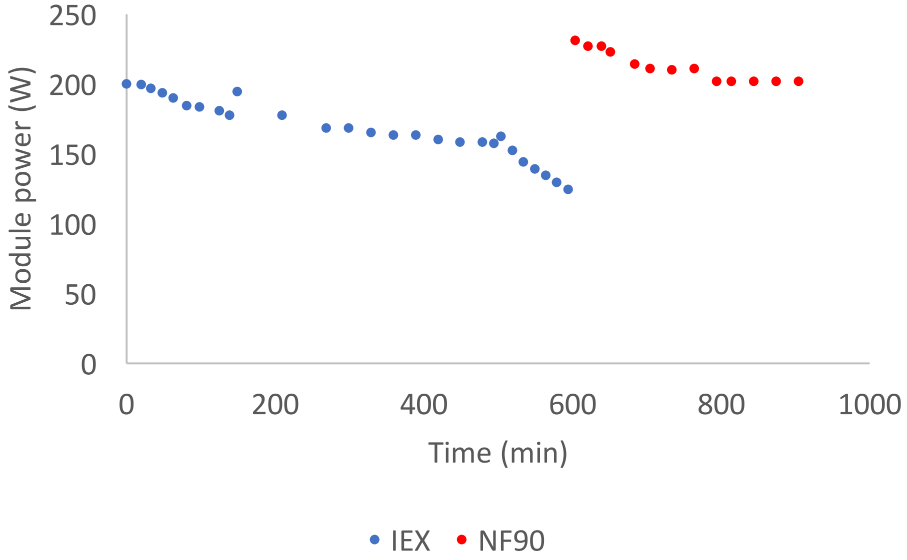

Figure 22 Effect of nanofiltration as feed pretreatment

These tests thus showed that the decrease was caused by fouling scaling inside the membrane fibers and that the scaling originated from the feed water. The geothermal water itself was not found to affect the process.

Feed water and pretreatment

In the final part of the project we investigated different pre-treatment technologies. Nanofiltration with the NF90 membrane was found to create stable energy production, but we were interested in evaluating whether other technologies could be used.

In Sønderborg three fresh water sources that could be used as feed water in the SaltPower process were identified: Tap water (groundwater), treated wastewater and condensate from CHP facilities. Table 3 gives an overview of the composition of these three waters. In order to evaluate their quality as feed waters, saturation indexes (SI) were determined for a number of different minerals of low solubility using the program PHREEQC.

These analyses revealed that condensate had the best composition. The water had a very low content of all ions and no minerals were as such close to saturation. However, condensate is only available in limited amounts in Sønderborg. Two sources deliver condensate. The waste incineration plant and a biomass fired CPH plant. In total these produced an average of 149 m^3/day, which is much lower than the 350 m^3/h flow rate of geothermal water. Groundwater and wastewater could be supplied in significantly larger amounts, but as the analyses show, they cannot be used directly. Both contain minerals that are above or close to saturation, which will therefore lead to precipitation in the osmotic membranes. Wastewater also contains organics (TSS) which can cause fouling. Finally, the similarities in composition between the groundwater and wastewater can be noted. This is because the wastewater is primarily made up of spent groundwater. During its way through the different system some water has been evaporated and some ions have been added to the water causing it to have slightly higher concentrations compared to groundwater.

Table 3 Potential feed water sources in Sønderborg. Concentrations are given in mg/L

	Tap water	Wastewater	Condensate
Na^+	28	70.6	1.3
K^+	7.3	22.4	0
Ca^{2+}	90.7	128.9	1.5
Mg^{2+}	10.7	10.3	0.2
Si	15	9.3	3.8
F^-	0.25	0.3	0
Cl^-	38.5	202.8	0
NO_2^-	-	6.1	0.4
NO_3^-	1.79	4.6	0.1
Br^-	0.09	0.5	0
SO_4^{2-}	21.3	52.4	0.1
pH	7.8	7.7	6
Alkalinity as HCO_3^-	350	369.1	4.3
Turbidity (NTU)	0.1	9.7	1.0
SDI	5.3	6.4	4.3
TDS	213.6	508.1	7.4
TSS	?	9.5	?
Total molar concentration (mM)	6	14.1	0.3
Estimated osmotic pressure (bar)	0.3	0.7	0.01
Flow (m^3/day)	?	13650	149
SI index (25 C)			
Anhydrite ($CaSO_4$)	-2.48	-2.03	-6.19
Aragonite ($CaCO_3$)	0.66	0.68	-4.6
Calcite($CaCO_3$)	0.8	0.82	-4.46
Chalcedony (SiO_2)	-0.04	-0.26	-0.65
Dolomite ($CaMg(CO_3)_2$)	1.02	0.9	-9.44
Flourite (CaF_2)	-2.19	-1.87	-5.03
Gypsum ($CaSO_4{:}2H_2O$)	-2.18	-1.73	-5.89
Quartz (SiO_2)	0.37	0.17	-0.13
SiO2(a)	-0.88	-1.1	-1.39
Talc ($Mg_3Si_4O_{10}(OH)_2$)	0.37	-1.29	-16.14

Tap water/groundwater had been the primary feed source in the project and therefore the first tests were made for this water. It was known that the NF membrane NF90 could produce feed water of sufficient quality, but it was decided to test a low pressure NF membrane NF270 as well as stand alone ion exchange for softening as potential alternatives.
As can be seen in Table 4, only NF90 was able to provide water with no scale risk. NF270 and IEX were capable of removing hardness ions, Ca and Mg, but could not remove silica, Si. Silica was thus the most likely compound causing the observed decrease in power production when using only softening as feed pretreatment. This was also an important result since it showed that the silica present in the water was not present as colloids, but rather as dissolved silica ions. Since other membrane technologies (ultrafiltration) would not be able to remove silica better than NF270, it was decided not to test further membranes. To use groundwater, removal efficiencies equal to that of the NF90 membrane would be necessary.

Table 4 Pretreatment of tap water in Sønderborg

	Tap water	IEX	IEX-NF270	IEX-NF90
Na^+	28	100	33	3.5
K^+	7.3	0.32	0.11	0
Ca^{2+}	90.7	0.16	0.1	0.07
Mg^{2+}	10.7	0	0	0
Si	15	15.5	13	1
F^-	0.25	0.23	0	0
Cl^-	38.5	32	17	2.2
NO_2^-	-	-	-	-
NO_3^-	1.79	0.4	1.1	0.37
Br^-	0.09	0.09	0.06	0
SO_4^{2-}	21.3	24	1.4	0.07
pH	7.8	7.8	7.4	6.7
Alkalinity as HCO_3^-	350	350	141.6	24.2
Turbidity (NTU)	0.1	NA	NA	NA
SDI	5.3	NA	NA	5.3
TDS	214	173	65.8	7.2
Total molar concentration (mM)	6	6.1	2.4	0.3
Estimated osmotic pressure (bar)	0.3	0.3	0.12	0.01
SI index (25 C)				
Anhydrite ($CaSO_4$)	-2.48	-5.06	-6.35	-7.69
Gypsum ($CaSO_4$:$2H_2O$)	-2.18	-4.76	-6.05	-7.39
Aragonite ($CaCO_3$)	0.66	-2.06	-2.94	-4.54
Calcite($CaCO_3$)	0.8	-1.92	-2.8	-4.39
Dolomite ($CaMg(CO_3)_2$)	1.02	-3.98	-5.54	-8.58
Flourite (CaF_2)	-2.19	-4.9	-6.31	-6.37
Chalcedony (SiO_2)	-0.04	-0.04	-0.11	-1.23
Quartz (SiO_2)	0.37	0.39	0.1	-0.8
SiO2(a)	-0.88	-0.88	-0.95	-2.07
Talc ($Mg_3Si_4O_{10}(OH)_2$)	0.37	-6.55	-8.93	-17.71

Due to the higher content of suspended solids in the wastewater, it was necessary with an additional pretreatment step before the nanofiltration. For this a ceramic ultrafiltration (UF) system from LiqTech was tested, see Figure 23.

Table 5 Pretreatment of treated wastewater from Sønderborg

	Wastewater	UF	UF-NF90
Na^+	70.6	78.8	11
K^+	22.4	21.7	3.0
Ca^{2+}	128.9	130.2	1.8
Mg^{2+}	10.3	9.7	0.3
Si	9.3	13.1	4.7
F^-	0.3	0.3	0
Cl^-	202.8	192.4	18.5
NO_2^-	6.1	4.8	0.5
NO_3^-	4.6	4.1	0.8
Br^-	0.5	0.6	0.0
SO_4^{2-}	52.4	48.7	0.1
pH	7.7	8	6.07
Alkalinity as HCO_3^-	369.1	368.3	11.2
Turbidity (NTU)	9.7	17.0	5.3
SDI	6.4	6.4	5.1
Time to filter 500 mL (s)	39	7.7	5.4
TDS	508.1	504	40.6
Total molar concentration (mM)	14.1	14.2	1.3
Estimated osmotic pressure (bar)	0.7	0.71	0.07
SI index (25 C)			
Anhydrite ($CaSO_4$)	-2.03	-2.06	-6.17
Gypsum ($CaSO_4{:}2H_2O$)	-1.73	-1.76	-5.86
Aragonite ($CaCO_3$)	0.68	0.97	-4.05
Calcite($CaCO_3$)	0.82	1.11	-3.91
Dolomite ($CaMg(CO_3)_2$)	0.9	1.45	-8.25
Flourite (CaF_2)	-1.87	-1.86	-5
Chalcedony (SiO_2)	-0.26	-0.12	-0.56
Quartz (SiO_2)	0.17	0.31	-0.13
SiO2(a)	-1.1	-0.95	-1.39
Talc ($Mg_3Si_4O_{10}(OH)_2$)	-1.29	1.01	-16.14

As predicted from the NF270 tests, the UF system did not remove silica. This could have been achieved if the silica was in the colloid form. UF is a technique that does not affect dissolved ions and the biggest change was in the removal of non-dissolved components. Although SDI did not change the filter ability did change though seen from the time required to filter 500 mL through a fresh SDI filter.
Ultrafiltration also improved the following filter ability on the NF90 membrane.

Table 6 Filtration performance of NF90 membrane

	Wastewater-UF-IEX	Tap water – IEX
Permeability (L/h/m2/bar)	9.5	8.0

Figure 23 Picture of the ceramic UF system from LiqTech

As a final feed water type, brackish water from the nearby Augustenborg Fjord were tested. The salinity was measured to be 2%, which was higher than expected (0.5-1%). In the testing phase, a high pressure membrane was used. This membrane had previously been used to operate on fouling groundwater and was as such not at peak performance. It was however, the membrane that was available at this time in the project. The results are shown in Figure 24. The higher salinity of the fjord water reduced the power output to around 50 W. This was half of the final power production in the previous series where the membrane had operated on softened groundwater. However, in comparison with the groundwater, the energy production quickly stabilized when using fjord water. It thus seems that stable energy production can be achieved by using fjord water. The actual power production must be evaluated with a fresh high pressure membrane.

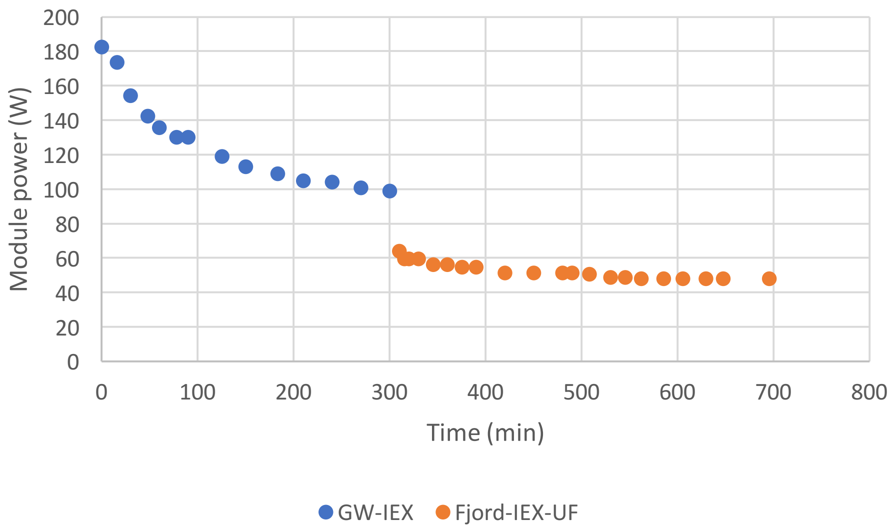

Figure 24 Use of Augustenborg fjord water as feed. A high pressure H3K membrane was used. This membrane was not fresh and had previously been exposed to fouling water.

Amager
An important part of the project was testing geothermal water from Amager and in March 2017 the pilot plant was moved to Amager. The geothermal water at the geothermal plant on Amager has a higher salinity (19-20%) compared to Sønderborg (15-16%) and therefore a high pressure H3K membrane was used. As can be seen in Figure 25, high pressure membranes are required for Amager geothermal water. The maximum pressure obtainable with the membrane used in the study was 50 bar, but as seen in the Figure 25, going to higher pressures can allow for even higher energy productions. The energy stabilized at 350 W in which process the water was diluted from 20 to 12%.

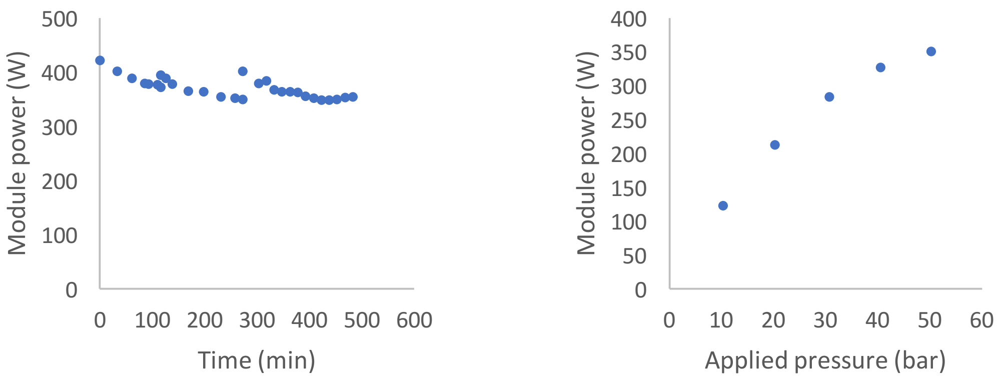

Figure 25 Stable power production at Amager geothermal plant. A high pressure H3K membrane was used, the feed was NF90 treated groundwater. Operating pressure was 50 bar.

Multi-stage setup
Another important objective in the project was to test the hypothesis that the total energy production could be increased by running the process as several stages in series instead of the traditional one stage setup. This hypothesis was tested and successfully confirmed in Sønderborg. The results are shown in Figure 26.
To test the hypothesis, we diluted the geothermal water in Sønderborg to the same degree but with two different setups as illustrated in Figure 26.

The plot of flux in Figure 26 shows that the same overall flux, or degree of dilution was obtained, with both setups. Due to the higher applied pressure (50 bar) and the lower permeability, the high pressure H3K membrane obtains a flux that is less than half of the flux for a P3 membrane operating on the raw geothermal water. If the diluted geothermal water coming from the H3K membrane is send to a P3 membrane operating at 30 bars the final degree of dilution will be the same. However, because the first part of the dilution was operated at 50 bar, the flux generated in this part of the process has a higher energy content. Thus, the total power production becomes higher (563 W) for a multi stage setup compared to a single stage (380 W). An increase of 48%.

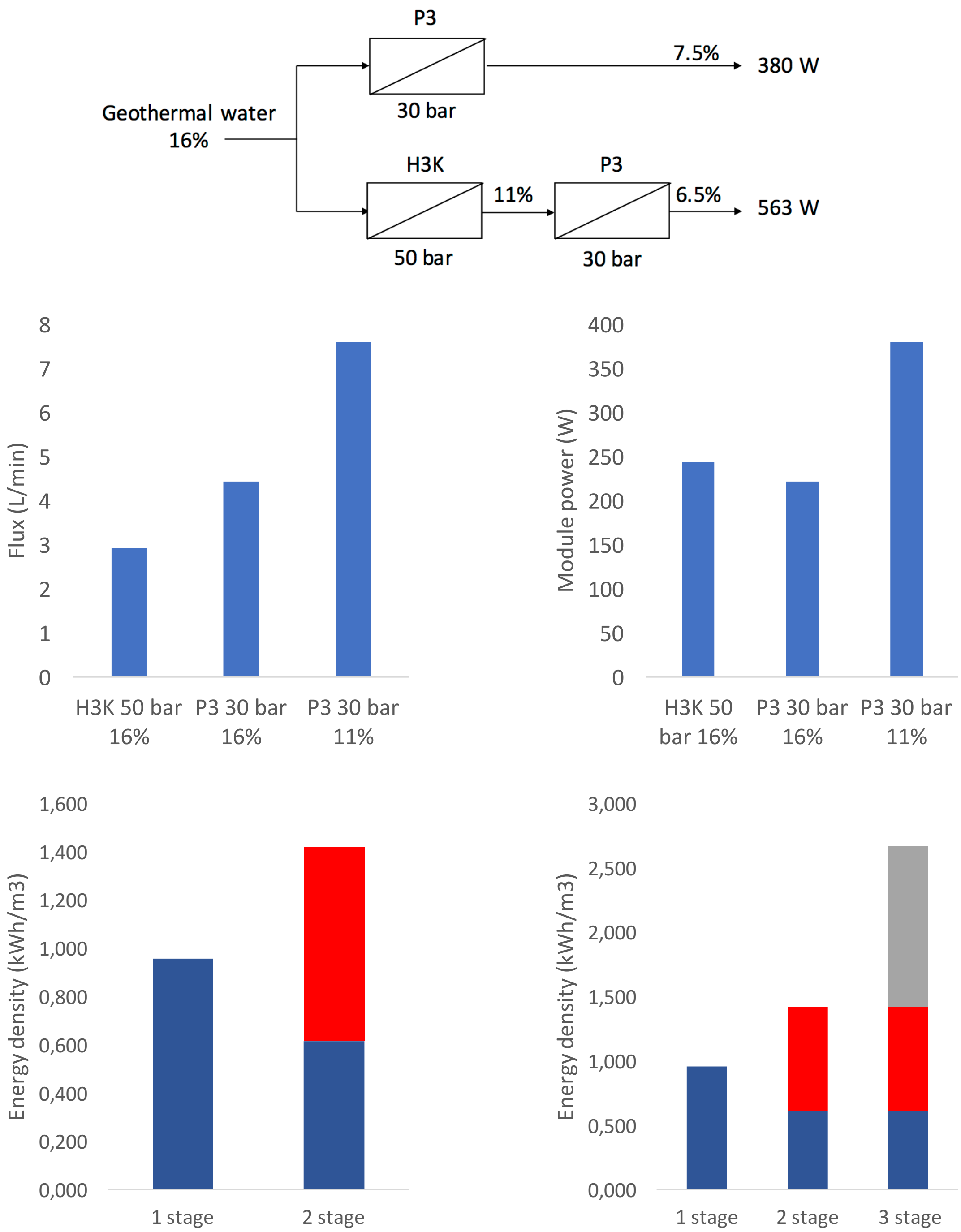

Figure 26 Multi-stage setup results

Energy potential

In the previous EUDP application we estimated the energy production from the geothermal plants. These are summarized in Table 7.

Table 7 Estimated energy production at Sønderborg geothermal plant

Conditions		
Geothermal flow rate	m^3/h	350
Geothermal salinity	%	15
Feed salinity	%	0.01
Mixing ratio		0.885
Energy production		
Mixing energy	kWh/m^3	8.4
Max energy extraction 1 stage	kWh/m^3	3.0
Energy with serial	kWh/m^3	5.7
Energy incl. efficiencies	kWh/m^3	2.8
Energy production	MW	1.0
Estimates		
PRO efficiency	%	70
System efficiency	%	70
Increase by serial setup	%	50

In the original energy estimate, we calculated with a dilution down to seawater concentration (mixing ratio of 0.885), while in the pilot tests we ran tests with dilutions down to 6% salinity (mixing ratio 0.6). The lower mixing ratio means that part of the energy in the geothermal water is not extracted. The water thus still carries power potential. In Table 8 the estimated numbers have been corrected for the new mixing ratio and are compared to the actual values obtained with the pilot unit.

Table 8 Comparison of estimated and actual energy production in pilot unit in Sønderborg

Conditions			
Geothermal flow rate	m^3/h	0.4	
Geothermal salinity	%	15	
Feed salinity	%	0.01	
Mixing ratio		0.6	
Energy production			
Mixing energy	kWh/m^3	3.7	
Max energy extraction 1 stage	kWh/m^3	2.1	1.0
Energy with serial	kWh/m^3	2.9	1.4
Energy incl. efficiencies	kWh/m^3	1.4	0.6
Energy production (for 350 m^3/h)	kW	494	199
Estimates			
PRO efficiency	%	70	72
System efficiency	%	70	40
Energy utilized by serial approach	%	50	17

The numbers show that the actual power production is close to the estimated values. Some of the underlying reasons for the differences are:

- Restriction to 50 bar with the membrane
- Use of more energy demanding feed pretreatment

The 5” membrane was restricted to a maximum pressure of 50 bar. With the larger 10” inch membrane pressures up to 70 bar can be reached. This will increase the energy extraction for a two stage plant from 1.4 to 1.8 kWh/m^3 geothermal water.
In the investigations with groundwater, we found that it was necessary to use nanofiltration to obtain stable flow. Without it the system efficiency increases to 72 % close to the estimated 70%.

Finally, it should be noted that we estimated that up to 50% of the energy that was not captured in a single stage dilution could be captured by using membranes in series. Using two membranes in series we were able to utilize 17%. This can be increased by applying additional stages in combination with a variation in the flow of the geothermal water.

In total, the numbers are lower than the original estimates, but much of the difference can be gained through additional optimization.

Other
After being in operation for 1 year, a maintenance check was made on the pumps and turbine to investigate how these had been affected by the high salinity of the geothermal water. Very limited corrosion was found, which exceeded the expectations of the project partners. During the testing of the pilot no measures were taken to try and limit corrosion. Immediately in front of the pump and turbine, the geothermal water was aerated in the sand filtration process, hereby creating oxidizing conditions to remove dissolved iron and manganese. To protect the pump and turbine, oxygen could have been removed after the sand filter, but this was not done in the current pilot. In a larger scale plant, it will thus be possible to lower the corrosion potential further. As a side note it should be noted, that this may be necessary to create reduced conditions again before reinjecting the dilute geothermal water to the reservoir. In total this results were positive with respect to the expected life time of the Salt-Power equipment.

1.6 Utilization of project results

The project partners were very satisfied with the results and have decided to scale up. A new demonstration plant is being projected which will be able to handle a flow of 10 m^3/h geothermal water compared to 0.4 m^3/h in the current pilot. The demonstration plant will be fully automated and containerised in a 40 foot container where new and larger membranes capable of being operated at pressures up to 70 bar will be used. This demonstration plant will give SaltPower the opportunity to demonstrate the technology at a commercially relevant scale.

1.7 Project conclusion and perspective

The EUDP project has shown that energy can be produced from geothermal water at power densities larger than 5 W/m^2 membrane using standard off the shelves industrial components and has in this way confirmed the hypothesis going into the project. Furthermore, using standard water treatment techniques such as sand filtration and nanofiltration, we have been able to overcome fouling issues and obtain a stable process.

The next step in the development of the technology will be to scale up from pilot to full scale demonstration where full size equipment parts can be applied and full automation reached. This will allow SaltPower to gain the necessary data to demonstrate the feasibility and gains of the process to customers.

The technology is developed for use with geothermal resources, but it can also be used for other high salinity sources. As part of the EUDP project a scientific review paper was published in which a number of high salinity sources were identified. Some of these are salt works where salt is produced from seawater through evaporation, hypersaline lakes such as the Dead Sea, Lake Urmia and the Great Salt Lakes. A theoretical study was made in collaboration with Texas Tech University on the potential of producing energy from lake Urmia, which showed that several hundred MW potentially can be produced in such schemes. Another interesting potential lies in using SaltPower technology for energy storage in a scheme where energy is used to concentrate a saline solution, from which energy can be released again via the SaltPower process.