2020

Full Scale Osmotic Power Generation from Geothermal Wells

EUDP REPORT

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Final report

1.1 Project details

Project title	Full Scale Osmotic Power Generation From Geothermal Wells
Project identification (program abbrev. and file)	Journalnr. 64017-0596
Name of the programme which has funded the project	Energy Efficiency
Project managing company/institution (name and address)	Applied Biomimetic (nu Saltkraft Aps), Østager 2, 6400 Sønderborg
Project partners	Saltkraft Aps, Aalborg Universitet, Sønderborg Fjernvarme, HGS, Danfoss A/S, Semco Maritime, Toyobo, Experimentarium, Universe
CVR (central business register)	25074297
Date for submission	June 11th 2020

1.2 Short description of project objective and results

English version

The project focused on demonstrating the osmotic power concept of Saltkraft Aps in large scale, using the same full scale components as would be used in a commercial system. The main objectives for the project were:

- To design and construct a full-scale demonstration system for osmotic power, built into a 40 ft container to make it mobile and flexible.
- Determine how the dilute geothermal water from the system could be handled without negatively affecting the operation of the geothermal installations.
- Develop measurement principles and select sensors required for autonomous operation of an osmotic power system.
- Develop and test membranes for operation at pressures up to 70 bar.
- Implement, test and evaluate the use of Danfoss pressure exchanger, iSave, in osmotic power.
- Develop a control system for full scale osmotic power systems.
- Create an overview of legislation concerning discharge of dilute saltwater and the technologies that allow for safe discharge.
- Demonstrate operation at three sites
- Assess the market potential for osmotic power in the European geothermal market.

Overall, the project goals have been successfully met although the project has experienced some changes:

- The demonstration system was put into operation at the geothermal plant in Sønderborg in February 2018.
- Tests were performed for three sites:
    1. Sønderborg geothermal water
    2. Discharge brine at Nouryon
    3. Raw brine at Nouryon
- Continuous and autonomous operation was achieved based on the control software and philosophy developed for the system.
- Full scale membranes capable of resisting pressure up to 80 bar were developed and tested
- The Danfoss iSave was tested and found to achieve slightly better pressure exchange efficiency compared to traditional use in desalination.
- An exhibition at Universe was made showcasing osmosis and osmotic power to a wide audience. The exhibition has gotten very positive feedback from visitors. Early in the project Experimentarium decided to step out of the project, and Universe carried the whole dissemination activity
- Several articles about the project has been published in the media.
- Saltkraft Aps has taken out several patents protecting the use of osmotic power technology for geothermal water and salt formations.
- Based on the results, Saltkraft Aps, has developed a commercial strategy and are now ready to start rolling out commercial units.

In total, the project has been very successful. We were able to scale up the technology concept from pilot to full scale demonstration and to use the results as a basis for commercial evaluation. The project was initially aimed at testing applications in the geothermal sector, but during the project the focus has changed to the salt industry where the conditions for osmotic power are even better. As such, the system was never tested at the geothermal plant in Copenhagen, but instead at Nouryon's salt factory in Mariager, Denmark.

Dansk version

Projektet fokuserede på at demonstrere Saltkraft Aps's koncept for osmotisk energi teknologi i stor skala, ved at bruge de samme komponenter, som bruges i et kommercielt system. De primære mål i projektet var:

- Designe og bygge et fuld skala demonstrations anlæg for osmotisk energi indbygget i en 40 fods container for at gøre anlægget mobilt og fleksibelt.
- Undersøge hvordan det fortyndede geotermivand kunne håndteres uden at påvirke geotermiværkets drift.
- Udvikle målprincipper og udvælge sensorer for at kunne automatisere det osmotiske anlæg.
- Udvikle og implementere membraner til tryk op til 70 bar
- Implementere, teste og evaluere brugen af Danfoss trykveksleren, iSave, til osmotisk energi.
- Udvikle et kontrol- og styresystem for fuldskala osmotiske systemer
- Skabe overblik over lovgivning vedr. udledning af saltvand og hvilke teknologier, der kan bruges til at skabe en sikker udledning.
- Demonstrere teknologien på tre lokaliteter.
- Vurdere markedspotentialet for osmotisk energi på det europæiske geotermimarked

Projektmålene er generelt blev nået på trods af, at der har været ændringer i projektet:

- Demonstrationsanlægget blev taget i drift på Sønderborg geotermi i februar 2018
- Tests blev udført på tre lokaliteter: Sønderborg geotermi, restbrine fra salt produktion og brine feltet i saltproduktion.
- Kontinuerlig automatiseret kørsel blev opnået baseret på den kontrolfilosofi og det styringssystem, der blev udviklet til systemet.
- Fuld skala membraner blev udviklet og testet op til 80 bar
- Danfoss iSave blev testet og fundet til at præstere bedre end forventet i forhold til den normale anvendelse i afsaltningsprocessen.
- En udstilling på Universe blev lavet, hvor publikum kunne se og høre om osmose og osmotisk energi. Udstillingen har fået positive tilbagemeldinger fra besøgende og Universe vil fortsætte med at køre udstillingen efter projektet er afsluttet. Experimentarium besluttede tidligt i projektet at udtræde.
- Adskillige artikler om projektet og teknologien er blevet publiceret i projektets periode.
- Saltkraft Aps har udtaget flere patenter, der beskytter brugen af osmotiske teknologi i forbindelse med geotermi og salt formationer.
- Baseret på resultaterne har Saltkraft Aps udviklet en kommerciel strategi og er nu klar til at begynde produktion af kommercielle systemer.

Total set har projektet været meget succesfuldt. Vi var i stand til at opskalere teknologien fra pilot til fuldskala demonstration og til at bruge resultaterne som basis for en vurdering af forretningspotentialet. Projektet fokuserede oprindeligt på anvendelser i forbindelse med geotermisektoren, men undervejs i projektet har fokus ændret sig til salt industrien, hvor betingelserne for osmotisk energi er endnu bedre. Derfor blev systemet aldrig afprøvet på det geotermiske anlæg i København, men i stedet for hos Nouryon's salt fabrik i Mariager, Danmark.

Executive summary

Background

Up to this project, Saltkraft Aps, had tested the osmotic power concept in EUDP project nr 64015-0008. Here a pilot system using a single 5” Toyobo membrane (50 m^2 membrane area) had been tested for different types of saltwater, primarily geothermal water. The results from these tests were very promising, as they showed that it was possible to achieve much higher energy densities compared to previous attempts to commercialise osmotic power for seawater. The most prominent of these had been the work carried out by Statkraft in Norway, using seawater, but also the Mega Ton project in Japan where desalination brine was tested. None of these resulted in commercial osmotic power systems. However, it had not been possible to test the full scale 10” membranes that would form the basis for a commercial system, and several key components had also not been tested. Most importantly, the pressure exchanger had not been implemented in the concept, and the pilot was only designed for manual operation, not continuous.

Project objective

In this project the goal was to take the technology one step closer to commercialization and the main objective was therefore to:

> *Scale up the osmotic power concept using all the components a full scale system would use and demonstrate continuous power production at three different applications*

The project had several other objectives some of which were:

- Design and construct a mobile full-scale demonstration system based on the results of the previous EUDP project
- Develop and/or test new components, incl. new high-pressure membranes, the iSave pressure exchanger and sensors, together with a control system
- Prepare an overview of legislation and the effects of discharge of saltwater
- Determine how to couple osmotic power to geothermal heat production
- Present the technology to a wide audience through a popular scientific exhibition.
- Assess the market potential for osmotic power in Europe.

1.3 Project objectives

The overall goal for the project was to demonstrate continuous operation of the osmotic power technology in full scale at three different locations.

Prior to this project, Saltkraft Aps had tested the novel idea of coupling osmotic power to high salinity geothermal water. This work formed the basis of EUDP project nr 64015-0008. By exploiting the high salinity of the geothermal water, it was possible to produce power significantly more compact than from seawater or desalination brine, and a power density > 5 W/m^2 was obtained. However, here it was primarily the membrane operation that was tested and evaluated. In order to approach a commercial level, it was necessary to scale up on all fronts to allow for testing of full-size components and to test continuous operation. Also, as osmotic power is relatively unknown as a source of clean power, it was necessary to better communicate the potential and mechanics of the technology.

In order to achieve the overall goal of the project, a project plan of a total of eight work packages (WPs) were put together.

WP1: Project management
The objective of WP1 was to ensure that the project objectives were met within the budget and time frame of the project as well as to facilitate communication with EUDP.

WP2: Construction of full scale demonstration plant
The objective of WP2 was to design, construct and commission a full scale osmotic power demonstration system. Semco Maritime and Saltkraft Aps were the main partners.

The WP consisted of four primary tasks

- Task 2.1: Design and scale up of 20-40 m^3 full scale plant
- Task 2.2: Building plant
- Task 2.3: Factory test
- Task 2.4: Commissioning

Expected results:

- A fully functioning containerised osmotic power plant that could be setup at geothermal plants
- Knowledge on how to design and build large scale osmotic power plants
- Exact estimate for the costs of an osmotic power plant

WP3: Handling of dilute geothermal water
In order to avoid damage to the geothermal installations as well as the geothermal reservoir itself, it was necessary to evaluate the effects of coupling a large scale osmotic power system to the geothermal plant. Also, a strategy of how to handle the dilute geothermal water had to be developed to ensure that the tests could be performed even if the evaluation on the effects on the reservoir would be inconclusive.

The WP consisted of three primary tasks:

- Task 3.1: Evaluate the effect of injecting dilute geothermal water
- Task 3.2: Evaluate the effect of extracting more water than is reinjected
- Task 3.3: Design brine recovery system for implementation with the SaltPower unit.

Expected results:

- Damages to geothermal wells are avoided
- Improved knowledge of the impact of SaltPower technology on a geothermal reservoir.

WP4: Product development

The objective of the WP was to develop the products required to move from pilot to demonstration scale. Membranes had to be scaled up from 5” to 10”, sensors had to be chosen to facilitate continuous operation, the Danfoss iSave pressure exchanger had to be implemented in the design and a control philosophy had to be designed.

The WP included Saltkraft, Danfoss, Toyobo and Semco Maritime and consisted of four tasks:

- Task 4.1: Sensors for measurements
- Task 4.2: Membrane development
- Task 4.3: Danfoss iSave pressure exchanger
- Task 4.4: Development of control system

Expected results

- Identification of improved sensors for monitoring and controlling the SaltPower process
- Development of membranes and pressure vessels for testing at 50 bar on large scale
- Successful implementation of the Danfoss iSave in the SaltPower process.
- Development and implementation of a control system that allows for fully automated operation and cleaning in the demonstration unit.

WP5: Environmental impacts of brine discharge and associated legislation

Environmentally safe discharge of brine resulting from the process is very important for a widespread commercial use of the technology. The objective of the WP was to collect knowledge from other processes that discharge saltwater to the environment, primarily the desalination industry, and to engage with local authorities to gain insights into the relevant legislation on the area.

The WP was led by Saltkraft and consisted of two tasks:

- Task 5.1: Legislative overview
- Task 5.2: Measures to reduce environmental impacts of brine discharge

Expected results:

- Mapping of the legislative demands regarding discharge of dilute geothermal water to relevant sinks.
- Identification of the measures that must be taken to limit the environmental impact during discharge to the relevant sinks.

WP6: Demonstration and testing

The objective of the WP was to determine optimal operational parameters for the SaltPower system at the different testing locations and to then achieve stable operation to allow for continuous production of power to document the feasibility of the process.

The WP was led by Saltkraft, and incl. Sønderborg Fjernvarme, HGS and Semco Maritime, and consisted of four tasks:

- Task 6.1: Finding optimal operational parameters for the plant
- Taks 6.2: Commissioning of full scale plant.
- Task 6.3: Continuous operation
- Task 6.4: Data collection, treatment and conclusions

Expected results:

- Continuous production of power at three different locations has been demonstrated
- The knowledge required to operate a full scale osmotic power plant has been collected
- Optimal operational parameters have been identified

WP7: Towards commercial exploitation

The objective of the WP was to use the results from the previous WPs to evaluate the power potential for each of the sites and use this to assess the full market potential in Europe. The expectation was that power potential would follow salinity of the water, and therefore, by knowing the power production from sites with different salinities and comparing this to the salinities found in the market, the market potential could be estimated. The WP consisted of four tasks:

- Task 7.1: Characterization of conditions site 1
- Task 7.2: Characterization of conditions site 2
- Task 7.3: Characterization of conditions site 3
- Task 7.4: Mapping of salinities in Europe to understand market potential

Expected results

- Cost analysis for a full scale osmotic power plant at the sites of the project
- A precise overview of the salinities in European geothermal plants
- An estimate for the commercial potential of SaltPower technology in Europe

WP8: Dissemination

The objective of the WP was to disseminate the knowledge gathered in the project to the scientific community as well as the wider audience. The WP consisted of four tasks:

- Task 8.1: Mass and energy balances for a full scale PRO plant
- Task 8.2: Modelling of the PRO process
- Task 8.3: Dissemination at Experimentarium – development of activity
- Task 8.4: Dissemination at Experimentarium – running the activity

Expected results

- Development of a model for the system that predicts performance at different locations
- The collected data has been used to get an improved understanding of the osmotic power process and how this is influenced by going from lab to full scale.

1.4 Project results and dissemination of results

Sometimes pictures say more than words, see Figure 1. The project succeeded in constructing the World's first large scale osmotic power plant and to test it out on three different locations.

Figure 1: Photos of the demonstration system

WP2: Construction of full scale demonstration plant

A 40 ft mobile demonstration system for osmotic power was successfully designed and constructed. The overall design vision was to limit the size to a 40 ft container, and then filling it with as much osmotic power equipment as possible, while maintaining flexibility for operation on multiple sites. One of the main challenges was to match pretreatment capacity to the capacity of the osmotic power system, and this required an iterative process.

It was decided to go with nanofiltration (NF) as the pretreatment technology for the low salinity side. The previous EUDP project had shown that with NF all types of feed waters could be safely used in the PRO system, although not always necessary. The use of NF limited the use of feed water to waters with relatively low salinity, but to be able to also use test these types of waters, the system was designed with a parallel feed water input.
Sand filtration was chosen for pretreatment of the high salinity water. This was based on the results from the previous EUDP project and to have the capability of removing dissolved iron, of which especially the geothermal water in Sønderborg was known to have a high content of.

The osmotic power system was designed as a two PRO step with a high pressure and low pressure step, to test out different membranes.
The system was designed with onboard pre-treatment systems, CIP system and a resistor block to deposit the produced power.

The system was completed partly in February 2018 where it was brought in operation at the geothermal system in Sønderborg. However, based on the learnings in the project, it was continuously updated to match the requirements.

WP3: Handling of dilute geothermal water
In order to ensure that the demonstration unit could be coupled to a geothermal plant without risking damage to the geothermal plant or the geothermal reservoir a number of actions were taken:

- The supply of geothermal water was solely controlled by the geothermal plant. This was to avoid that hard starts and stops in the demonstration unit could damage the geothermal installation. Instead the geothermal plant operator could open and close the supply of geothermal water at the rate that was deemed safe for the geothermal plant.
- Sensors to monitor oxygen and salinity of the dilute geothermal water was added to the demonstration unit. This ensured control that the water coming from the demonstration system to the geothermal system was free of oxygen and the salinity measurement made it possible to distinguish between whether the water was dilute geothermal water or another fluid.
- A general risk assessment was made where Sønderborg Fjernvarme was involved.

In parallel to this, an external consultant was hired to evaluate the effect of extracting water from the geothermal reservoir. The report can be found as Appendix 2, and found that the amounts of geothermal water extracted in this project would not affect the total reservoir volume and hereby the reservoir pressure.

The investigation of the effects on the geothermal reservoir formed the basis for an application to Energistyrelsen for extraction of geothermal water for electricity generation, which resulted in a permit.

Based on these findings, it was decided to start operation without reinjecting dilute geothermal water back into the reservoir. This also meant that Task 3.3, was not initiated, as it was possible to operate the demonstration system by extracting geothermal water, diluting it and discharging it through the discharge system present at the geothermal installation.

No effects on any of the installations that the demonstration unit was connected to were observed.

WP4: Product development
As part of the design for the demonstration system, sensors had to be chosen that could endure the harsh environment and allow the control system to operate the system autonomously. The biggest challenge was for the salinity measurement on the high salinity side of the system, where it proved difficult to get accurate online measurements. Measuring flow also proved to be challenging, but it was possible to find a solution.
In general, most of the sensors were found to have an acceptable efficiency and precision and it was possible to fullfill the goal of the project.

With the sensors, it was possible to develop a completely automated system. The demonstration system was able to start up with only little assistance from an operator and to maintain a stable operation autonomously without the need of an operator to be present. Also, in the case of an accident, the system was designed to shut down into a safe mode automatically. This happened once during testing at one of the locations, where access to incoming water was suddenly lost. In this case the system was able to go into safe mode on its own. Also, the control system was extended with a data logging system, that allowed the operator to monitor and control the system from afar.

Prior to this project, a pressure exchanger had not been tested out within the scope of the SaltPower concept. For this project, Danfoss developed a new iSave pressure exchanger, iSave 21+, which was implemented in both PRO stages in the demonstration system.
The iSave was found to operate without any problems and to operate at an efficiency of 96%, which was higher than expected for the application. The exact reason for the better performance is unknown, but it is possible that the higher viscosity of brine compared to seawater allows for a more efficient transfer of energy.

In the previous project, Toyobo had developed a new type of membrane, H3K, that could go to higher pressures compared to the first generation of osmotic membranes, that were limited to 30 bars. The membranes had been made in a 5" pilot version and tested at pressures up to 50 bar, but were in this project scaled up to 10", which is the size of Toyobo's commercial line of membranes for desalination.
The membranes were successfully tested at pressures up to 70 bar, which was higher than the previous target of 50 bar. Higher pressure is a key to improved performance as it increase power density of the membranes and allows for extraction of a larger proportion of the mixing energy.
Toyobo managed to develop a second generation of high pressure membranes capable of going to 80 bar. The membranes were tested, but it was not possible to get long term testing within the time frame of the project.

WP5: Environmental impacts of brine discharge and associated legislation
In order to evaluate the environmental impacts several actions have been taken:

- Obtainment of discharge permit of geothermal water in Sønderborg
- Obtainment of discharge permit of saturated saltwater in Ll Torup
- Overview of handling of concentrated brine in the desalination industry

Sønderborg
For the Sønderborg case, an application was filed to the local authorities for obtaining a discharge permit for the testing of the demonstration unit at the geothermal plant in Sønderborg. The application is attached as Appendix 4.
The case applied for was to extract 10 m^3/h of geothermal water, mix and dilute it in the PRO system with treated groundwater to a concentration of around 5% and discharge it to Als Sund through the existing pipeline at the geothermal plant. This meant that the saline wastewater was not discharged through the wastewater treatment plant, but around it.
The main concerns faced during the application process related to:

- Nutrient content (primarily N and P)
- Salinity of wastewater
- Presence of heavy metals
- Oxygen content

Since the diluted geothermal water was not discharged through the wastewater treatment plant, it did not undergo biological treatment in which N and P could be removed. Therefore, the was a strong focus on the presence of these components in the saltwater. For the geothermal water in Sønderborg, N was present as ammonium, but for the current testing phase, it was not deemed a problem. No or very little P was present in the geothermal water.

The salinity of the wastewater was also a focus point. The organisms facilitating the biological treatment at wastewater treatment plants are adapted to freshwater conditions and discharge of large amounts of saline water could disrupt the workings of the microbiological community. A second aspect of the salinity was the density difference with the water body it was discharged into. As density increase with salinity, high salinity water will tend to sink and flow along the bottom of the discharge area where it could interrupt bottom dwellers. Since the dilute saltwater was not discharged through the wastewater treatment plant, it had no effect on the microbiology. Also, the discharge pipe was situated next to the regular wastewater discharge pipe, where it mixed with the ordinary wastewater. Since the volume of dilute saltwater was much lower than the wastewater, there was no effect on the surrounding water salinity.

Heavy metals can be an issue when underground brines are discharged as they might have had time to reach equilibrium with the formation rock from which rare heavy metals might be released. In the case of Sønderborg there was not found any issues with heavy metals.

Finally, oxygen content can be an important parameter. In waterways as those found in Denmark, where the ecology is stressed due to nutrient load from wastewater treatment plants and agriculture, eutrophication can be a returning phenomenon. This leads to oxygen depletion, which can seriously affect especially bottom dwelling creatures in the water systems. Discharging a dilute saltwater with low oxygen content could due to the density difference lead to a lowering a the oxygen concentration at the bottom of the water system. This was not found to be an issue in Sønderborg. The volume of dilute saltwater was relatively small compared to the total volume of water flowing in and out of Als Sund and the tests were planned to take place in the autumn and winter months, where storms help increase mixing an brings fresh oxygen to the bottom.

In total there was no problem in obtaining a discharge permit for Sønderborg. The most serious potential limitation for a large scale installation was evaluated to be the presence of ammonium in the geothermal water. Ammonium is typically removed biologically, but because of the high salinity traditional biology cannot be applied.

Ll Torup

In Ll Torup saturated saltwater was stored in a salt formation used for gas storage. Previously the saltwater had been discharged to Limfjorden, but this had been stopped. Despite a detailed investigation, it was not possible to find the exact technical reasoning behind the termination of the discharge, and SaltPower initiated a process to see if a discharge permit could be obtained.

The saltwater would be discharged to the part of Limfjorden known as Lovns Bredning, which is both classified as a Natura 2000 area and covered by the bird and habitat directive, see Figure 2. Since much of the Danish water systems are classified as Natura 2000, it was evaluated to be a good case to evaluate the effect of saltwater from pure salt formations.

Compared to the geothermal water case in Sønderborg, the saltwater from the salt dome was largely concentrated seawater, which meant that the primary effect would be from density differences.

To investigate potential effects, the consulting engineering company COWI was hired to make an analysis of the effect of the discharge. They performed a Natura screening, using a box plot technique to evaluate the effect of the discharge on concentrations in relevant water bodies. This screening found that there would be no increase in the concentration of nutrients, heavy metals and suspended matter and that the increased flow of water during the operation of the osmotic power system would actually decrease the concentration of the heavy metal copper, which already today exceeds the allowed concentration in the water phase. In total the report concluded that it without any scientific doubt was unlikely that the discharge would affect the Natura 2000 area.

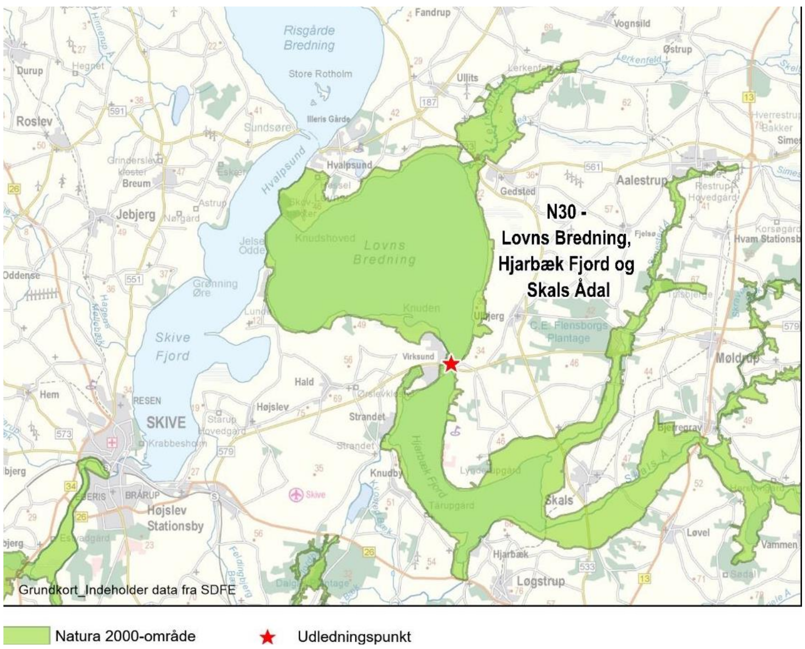

Figure 2 Overview of the part of Limfjorden next to the salt formations in Ll Torup

A discharge permit was obtained demonstrating that even the most protected areas, the osmotic power technology can be safely used.

Experiences from the desalination industry
In the desalination process seawater, 3,5% salinity, is concentrated to 6-7% salinity and discharged back into the ocean. Thus, in these areas there is a continuous large scale discharge of concentrated saltwater to the sea. These concentrations would be similar to those for an osmotic power plant and the desalination industry was therefore found to be a good place to search for relevant experiences.

Typically, desalination brine is either mixed with cooling water from nearby power stations or discharged through mixing systems such as those seen in Figure 3. Here the brine is pumped out through a diffuser system to ensure rapid mixing with the surrounding seawater.

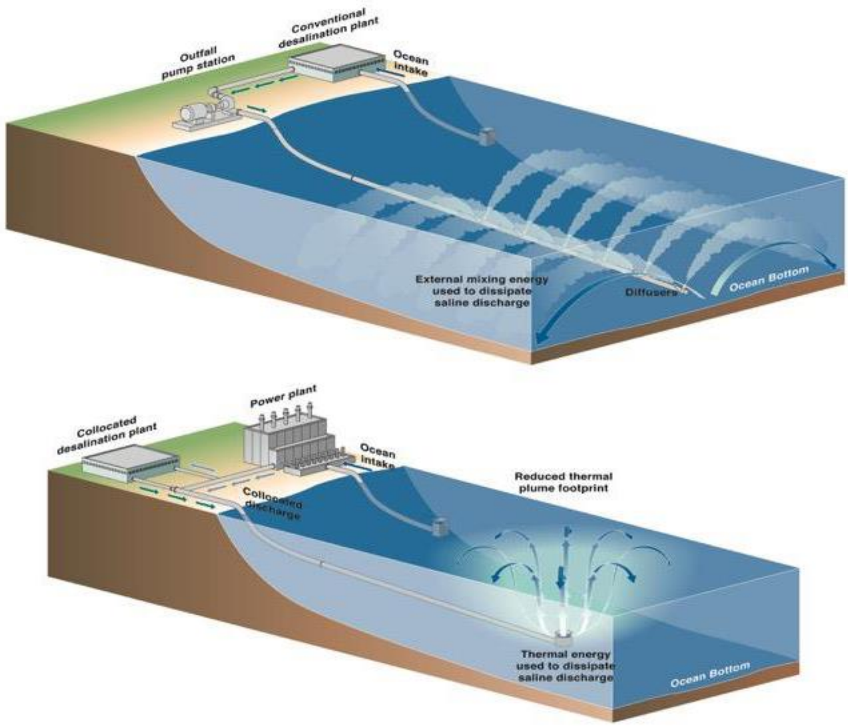

Figure 3 Illustration of discharge systems used in desalination

The primary effect is on benthic organisms, that is organisms living on the seafloor and who are relatively immobile. These can be sensitive to the local increase in concentration. Studies from several desalination plants show that the zones with a local increase in concentration are relatively small, giving a reduced area of effect. Another worry is the effect on sensitive ecosystems such a corals, but this is primarily in the cases where special chemicals are being used in the desalination process, which is no longer state of the art in desalination.

The discharge of brine with elevated salinity and temperature does naturally affect the local environment as it alters the specific conditions in the vicinity of the discharge system. However, it might not be for the worse and some organisms are found to thrive under these conditions as the photograph in Figure 4 shows.

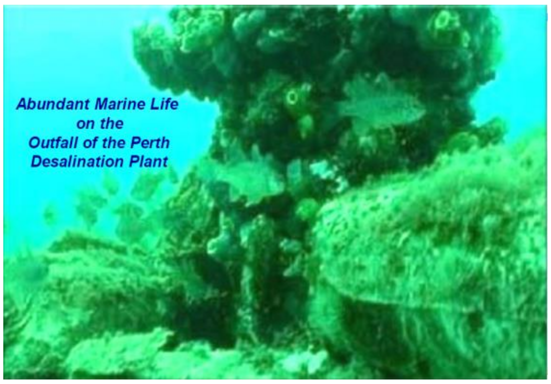

Figure 4 Photos from discharge pipe at a desalination plant. Borrowed from presentation from IWA in Dubai 2019

Also, as part of the evaluation of the total potential a calculation was made to evaluate what the effect of using large scale osmotic power would be on the ocean salinity. In this calculation it was estimate how much osmotic power would be required to cover the World's electricity consumption until the year 2100 and assuming that all osmotic power came from operation on salt domes. For such a scenario, not including the added freshwater from melt off at the poles and mountain glaciers, it was found that the global salinity would barely change going from 3.5% to 3.50008%. This is of course a simplified calculation, but it illustrates that potential for osmotic power to change the world's energy systems without affecting the environment.

WP6: Demonstration and testing

The demonstration system was tested at three locations. Initially, the plan was to test at Sønderborg geothermal plant, Amager geothermal plant and a third – potentially international – location that could be decided during the project.

In the end testing was carried out at Sønderborg geothermal plant, but not at Amager. The geothermal plant on Amager was never in operation during the project period. It had to undergo major repair and renovation and it was decided from HGS not to pursue geothermal heat further and instead start talks with private developers.

Two additional sites were found both in relation to the salt industry:

- Discharge of waste brine
- Production of brine on the brine field

Both sites belonged to Nouryon, Dansk Salt, located in the vicinity of the city of Mariager.

The first test site was the geothermal plant in Sønderborg. Here the plant was setup in February 2018. The original plan had been to start commissioning in November 2017, but this was not feasible. As such the first part of the testing period was commissioning and start up of the different sub-systems.

First the NF and sandfilter systems were brought into operation and it was verified that they could live up to the required design parameters.

Next the two iSaves and turbines with the frequency converters (VLTs) were brought online. This required additional work in order to get configuration between the VLTs and the hardware working.

During the commissioning phase, a number of issues were detected, some of which were:

- The system had been designed with a closed buffer tank in front of the PRO system to more easily connect the PRO systems to the geothermal installation. However, it was found that it was difficult to contain the level and pressure in this tank, and visible deformations were observed. To solve the issue, a new tank was designed and installed.
- During operation, the system would shut down spontaneously. It was found that the culprit was the discharge pipe, where residual water from both the PRO system, the NF system and the sandfilters were discharged through. As part of the back flush operation of the sand filters, the air flow in pipe changed the pressure and meant that

the non-return valve connecting the NF system to the discharge pipe could not open. This resulted in an automatic shut down of the NF system followed by the rest of the system. Once identified the design error was easily corrected.

Due to issues like these, commissioning was not completed at the Sønderborg, meaning that automatic operation was not attempted and the high pressure membranes were not brought into operation.
Still it was decided to run the system manually using stage 2. The performance of stage 1 was simulated by premixing freshwater and geothermal water before sending the diluted geothermal water to stage 2 operating at 30 bar. Even though only manual operation was reached, it was possible to demonstrate continuous stable generation of about 4kW with the second stage, see Figure 5

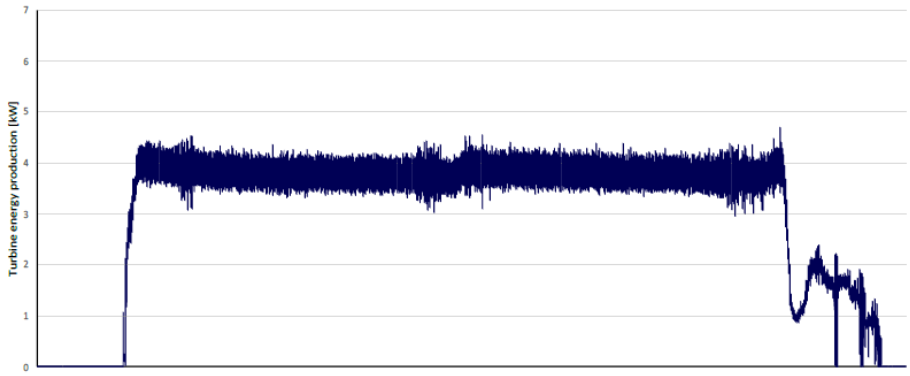

Figure 5 Data from power production of the second stage during operation in Sønderborg

The second test site was the discharge of waste brine at Nouryon, Dansk Salt. After production of salt, a residual stream of saturated saltwater is left and discharged. In this project, we tested the use of the demonstration unit to utilize this waste stream for energy production.

The system was setup and commissioned to the conditions at the salt factory and brought into operation. The initial tests were very promising. With an in flow of 4-5 m3/h saturated brine, we were able to generate >10 kW at the turbine in stage 1, following the predicted energy production, see Figure 6. However, after the initial phase a sudden decrease in performance was observed. This was found to be due to water chemistry affecting the membranes. Different approaches were attempted to solve the issue, but the final conclusion was that only change of membrane material would be a feasible solution.

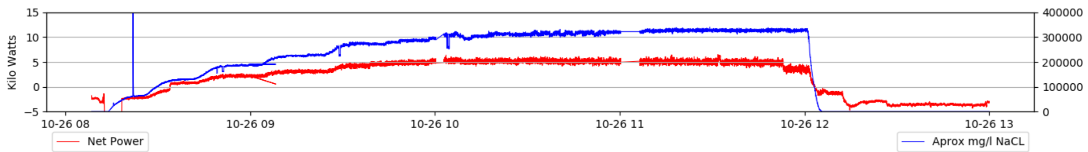

Figure 6 Data from one of the tests at Nouryon

The third and final application tested was the implementation into the brine field operation. This application was tested by using raw brine at the salt factory and using this the system commissioning could be completed. The automation software was completed and autonomous operation was demonstrated. By the end of the project, more than 1000h of continuous operation had been demonstrated laying the groundwork for commercial exploitation of the results.

WP7: Towards commercial exploitation
An important outcome of this project was that a change in the go to market strategy for osmotic power. At the beginning of the project, the target market was geothermal installations, as they provided access to a widespread source of high concentrated saltwater that was already extracted from the subsurface, but at the end focus had shifted to the salt industry. Compared to geothermal installations, the salt industry offered higher concentrations (always saturated) more uniform saltwater composition, access to freshwater sources and discharge permits in place. Thus, the SaltPower systems could be implemented much more easily here. Finally, the salt industry is also more mature and established throughout the world.

A closer look at the salt industry shows that it makes use of three methods for salt extraction:

1. Solar evaporation
2. Rock salt
3. Vacuum salt (solution mining)

The oldest technology is solar evaporation, where seawater is pumped into large shallow ponds from where water can slowly evaporate. This process has been in use for much of history and is still being used in many places around the world. It is not however, state of the art as the salt is less pure from what can be obtained from other sources, and it is slowly being replaced by especially vacuum salt. For SaltPower solar salt can be used, since it produces a waste brine called the bitterns, that is discharged back into the ocean. The disadvantage here is the access to a suitable freshwater source, and the best options are either local wastewater, river water or seawater.
Rock salt is simply mined directly from the subsurface through excavation. It is excavated and used directly in its solid form. Since the salt is never transformed to a dissolved state, it is not suitable for application in a SaltPower system.
Vacuum salt is the most promising application for SaltPower. Here water is injected into the subsurface to dissolve salt.

Using data from the salt industry it was possible to map the potential of osmotic power from the salt industry in not only Europe but throughout the world. In Figure 7 a map of salt deposits in Europe, which closely coincides with places with salt production.

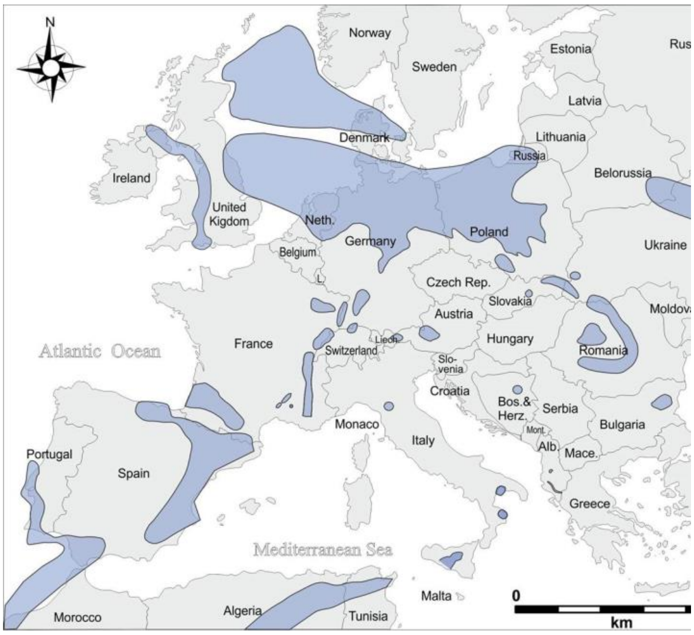

Figure 7 Salt formations in Europe

Based on the production data from the operation at Nouryon a levelized cost of energy (LCOE) analysis was made with inputs from Danfoss and Toyobo to estimate CAPEX of a full scale commercial system. The LCOE model was based on a present value method also used by Fraunhofer, which allowed for a direct comparison with other energy sources. This is shown in Figure 8. As can be seen, the current LCOE is estimated to be 50 EUR/MWh with a potential to go to 20 EUR/MWh by optimization of the technology. This makes SaltPower directly competitive with existing energy sources today. Large scale photovoltaics and on-shore wind can compete, but these need an energy storage option if they are to deliver power continuously, something which is not necessary for osmotic power.

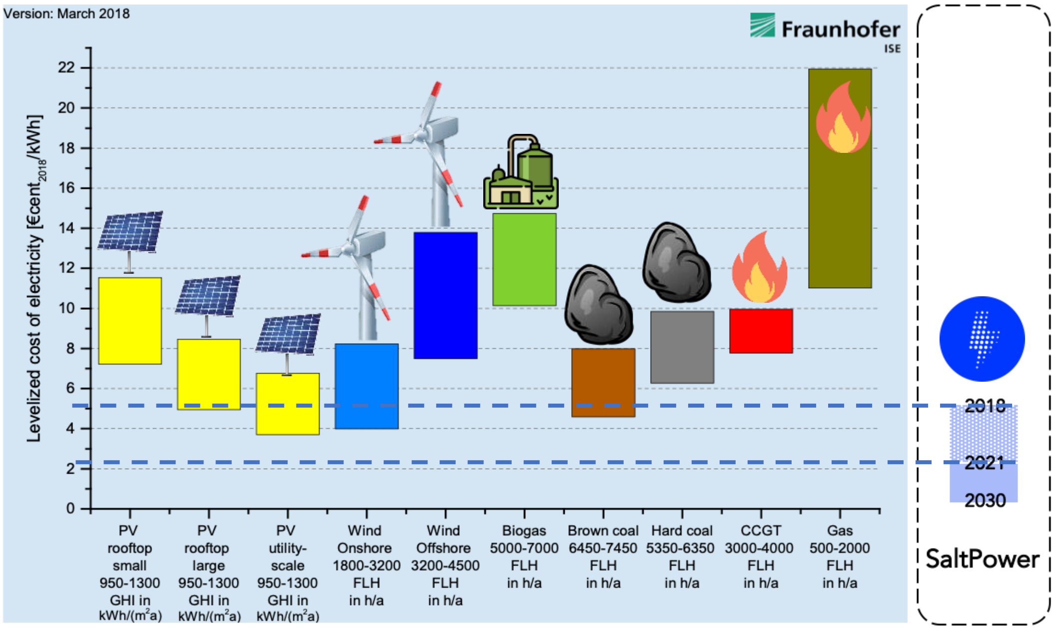

Figure 8 Comparison of LCOE for different energy sources

Finally, we can see a big potential for Denmark to take advantage of this use of the technology. Denmark is situated on top of the Zechstein formation, which means that there are many salt domes and salt formations available for utilization. Each one of these holds large quantities of energy. An average salt dome can contain up to 6000 TWh of energy, meaning that just four of these could cover the entire World's yearly electrical consumption.

WP8: Dissemination

There were two main activities in this WP – an exhibition on osmosis and osmotic power and modelling of the process, which could subsequently be presented in publications.
During the course of the project, one of the partners, Experimentarium, stepped out of the project and Universe and SaltPower took over the dissemination responsibility.

In the project an exhibition was created at Universe science park. The dissemination ran from May to October 2019 and is planned to continue in 2020, where it was active four hours per day with three to four live demonstration every day. On average 50 spectators were present for these demonstrations.

The science demo consisted of several small experiments. The experiments were carried out in the original pilot unit from the previous EUDP project, which had been modified to act of a demonstration facility with shelves, tables, materials etc.. The demonstration consisted of experiments for each of the different stages in the pilot unit: what is saltwater, the properties of saltwater, density, osmosis in a U-tube, the pumping principle and a generator model. The demonstration emphasised participation and discussion. Through the demonstration the story was told of how multiple technologies and science can be put together to create innovation.

Furthermore, a physical model disseminating the prototype during all opening hours of the science park was implemented. It too aimed at creating discussion with the park guides. Here it was possible for guests to experience and manipulate the different subprocesses in the osmotic power prototype. Focus was on how osmosis can be used to create energy by illustrating the different flows of water and seeing how osmosis could increase pressure. The guests could control each of the different elements themselves and experience how they work together. A number of extra valves were build into the prototype, to allow for mistakes to be made. Guests could pump water the wrong way and see that this did not lead to power generation. Only when the valves and pumps were operated in the correct manner, power would be created.

At Universe the dissemination was considered a big success. Especially the science demos were popular and it was found that especially the younger visitors found it very interesting to participate in the experiments. The older guests, parents, found the story about innovation to be the most interesting.

Dissemination is extended to 2020 by Universe. Selected photos can be seen in Figure 9.

At SaltPower different dissemination activites were initiated. A webpage was constructed that functioned as a platform for dissemination knowledge about osmosis and the project http://www.saltpower.net/. Part of this also include creating of content, for instance an animation showing the PRO process and a direct link to the demonstration unit allowing for live viewing of the energy production.
A second activity was video material. Two videos were made: An animated video and a video with real footage. The aim was to create videos that would allow people to understand how osmosis works and how salt can be turned into energy. Both videos will be uploaded to Youtube and be freely accessible.

Stories about the project was also published in different media, one example was a story published on Nouryons webpage, https://www.nouryon.com/news-and-events/features-overview/2019/producing-green-electricity-from-salt-in-denmark/

Finally, a number of scientific publications has been made in collaboration with Aalborg University. These are currently in the middle of the publication process and have two focus areas. Publishing test results and investigating the effect of injecting dilute brine into geothermal reservoirs.

For the modelling part of the process SaltPower was able to develop two tools:

- Membrane simulation tool
- Process modelling tool

The membrane modelling tool was build using a finite element (FEM) approach to simulate the performance of the Toyobo membranes and was validated against the results obtained with the demonstration system. Doing this, it was possible to achieve a high accuracy of the estimated membrane performance within +/- 5%.
To extend the simulated membrane performance to an estimation of the total plant performance, a process tool was developed which took efficiencies of system components into account. With this it was possible to accurately predict the performance of the demonstration system.

Figure 9 Photos from the exhibition and inauguration at Universe

1.5 Utilization of project results

The project results have laid the groundwork for taking the osmotic power concept to full scale level. Identification of the salt industry have resulted in a changed focus for SaltPower with the salt industry now being the primary market.
The tools developed in the project has allowed SaltPower to design full scale system and predict their performance. This will be used as part of the business development when engaging customers as well as to better evaluate the profitability of new applications.
During the project period SaltPower has taken out several new patents focused on the application of osmotic power technology to high salinity sources, both geothermal water and salt formations, which will make it very difficult for competitors to enter the market.

Semco Maritime has gained experience in the design and construction of osmotic power systems for high salinity water including how to operate these and component selection. This experience can be used as the next step in the business development at Semco.
At Aalborg University, the project has allowed to further strengthen the knowledge base within geothermal energy and osmotic membrane processes.

1.6 Project conclusion and perspective

Overall the project has been very successful. We were able to design and build the World's first full scale demonstration system based on PRO technology, and in this sense the project can be compared to those that enabled the construction of the first wind turbine and solar cell.

The demonstration system was tested at three sites and allowed the project consortium to conclude that although geothermal water can be used for osmotic power generation, the market with the lowest entry barrier is the salt industry. It is easier to implement the PRO systems here, there will be no new extraction or discharge meaning that all regulatory work is avoided and the value to customers can be immediate and significant as the industry has a very high energy consumption and a great need to move towards energy sources with low CO_2 emissions.

It was found that water can be extracted from geothermal reservoirs, but for long term operation it is necessary to balance the volumes extracted and injected. Because of the lower salinity of the diluted geothermal water, the geothermal reservoir will be affected, although the exact effect is not yet clearly understood. Injecting a dilute brine may help to increase flow pathways in the reservoir, which can be an advantage, but it is crucial to control the chemistry of the diluted water. Tests at Aalborg University showed that if oxygen is present together with iron, the reservoir can quickly clog to due formation of iron hydroxides.

The evaluation of discharge of dilute brine to water bodies showed that this can be achieved within the legal framework of the relevant EU directives, and lessons from the desalination industry shows that the effect on the local environment are very small and can even be beneficial if the discharge is handled properly. A study showed that discharging dilute saltwater into Limfjorden could even help to lower concentration of heavy metals in the water phase, creating a cleaner environment. However, especially the lessons from the case at Ll. Torup as well as ongoing discussions in the desalination industry shows that public resistance to any discharge can be significant, and that communication is crucial in order to avoid conflict.

The osmotic power concept and osmosis in general was successfully disseminated at Universe science park. An exhibition was created together with live demonstrations and the running of the activity will continue after the end of the project.

In total, the World is now one step closer to seeing osmotic power helping the transition to a CO_2 free future.
The next steps will be to scale up the results to a full scale commercial system.

In parallel to this, the further development of the technology will continue. In this project, we were able to setup a LCOE model for the osmotic power process, which allowed us to determine the most promising places for further improvements. These relates to the energy consumption on the feed water side and to the implementation of new membrane materials that allow for operation under high pH. These activities will continue in a new EUDP project.

Annex
Relevant links

http://www.saltpower.net/

https://www.energy-supply.dk/article/view/677601/dansk_saltteknologi_taet_pa_kommercialisering

https://jv.dk/artikel/danfoss-arving-vil-lave-varmt-saltvand-om-til-energi

https://universe.dk/da/parken/shows/saltpower

https://ctwatch.dk/nyheder/milj_teknik/article11635017.ece

https://aktuelnaturvidenskab.dk/fileadmin/Aktuel_Naturvidenskab/nr-4/AN4-2018-saltpower.pdf