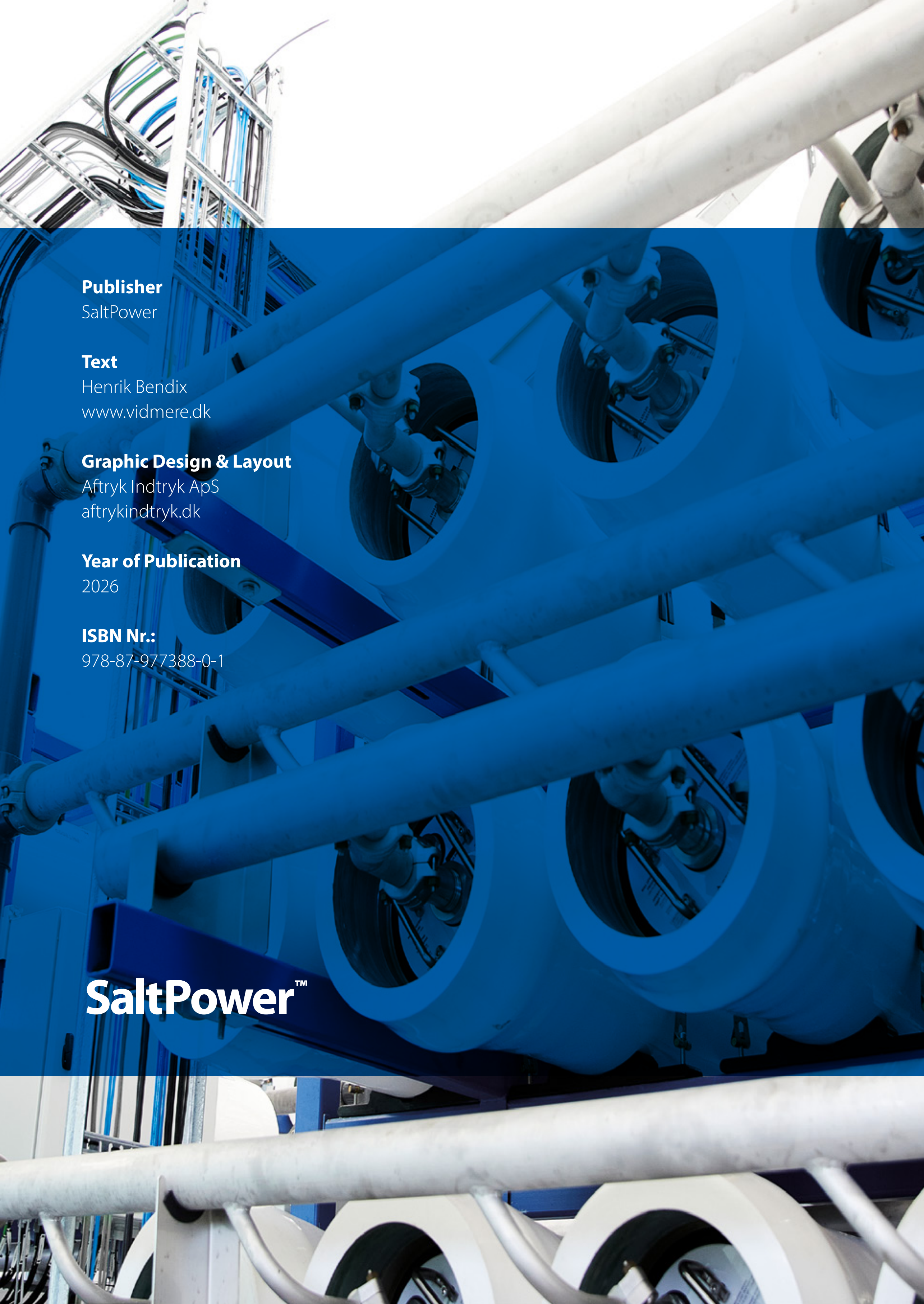
SaltPower

A story about salt, osmosis and green energy

SaltPower™



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Jørgen M. Clausen, Founder at SaltPower

Executive summary

This is the story of the most ambitious attempt to date to harness the substantial energy potential locked in the difference between the salt content of fresh water and salt water. With the technology pressure retarded osmosis (PRO), it is possible to convert the energy in the concentration difference into mechanical and then electrical energy. Osmosis delivers green energy, and unlike wind and solar, osmotic power is a stable and predictable energy source that can deliver energy independently of the weather.

On that basis, SaltPower was founded with the ambition of developing and commercialising osmosis-based energy production. From the outset, the focus was directed towards hypersaline water, such as is found in geothermal facilities and in the salt industry. In extremely salty water, the energy potential is significantly higher than in seawater.

Through an intense, focused effort, from theoretical studies and laboratory experiments to pilot and demonstration plants, SaltPower has documented that PRO technology can be brought to a level where it is relevant in practice. It is possible to extract energy from naturally occurring saline water streams, and a commercial plant has confirmed that the technology can be integrated into existing processes and deliver stable operation over an extended period.

In the salt industry in particular, the technology demonstrates its potential. Here, both concentrated brine and fresh water are available, and the energy produced can be used directly in the salt extraction process.

Working with PRO technology for more than 10 years has made the central technical challenges clear. The semi-permeable membranes, which are at the heart of the process, must be able to withstand high pressure and at the same time deliver a high water flux. In addition, even the smallest impurities in the water lead to fouling and reduced performance, which makes extensive pretreatment necessary, and that has major consequences for both operation and economics.

SaltPower has brought osmosis-based energy production a significant step closer to broad commercial use. The technology is not yet mature enough for large-scale implementation, but with further optimization of membranes and a focus on system design and process integration, the full potential may perhaps be realised in the future, so that PRO can contribute to the green transition.

A glass of salt water starts the journey

The story of SaltPower starts with a glass of water drawn up from a depth of 1.2 kilometres. Down there, the water is 48 degrees, and the heat can be utilised in the district heating system.

In 2015 the engineer, entrepreneur and former CEO of the Danfoss Group, Jørgen M. Clausen, visits the geothermal plant in Spang near Sønderborg, and there he is served water drawn up from a depth of 1.2 kilometres.

Jørgen M. Clausen sips the cooled water from the subsurface, and he notices how salty it is. The water contains 16 percent salt, 4.5 times as much as seawater. And it is here the idea strikes like a bolt from the blue: this very salty water must be able to be used for producing green energy.

He has already heard of a small Norwegian power plant that produces electricity by exploiting the difference in salt content between seawater and fresh water. When the two liquids are separated by a membrane that only allows water to pass, an osmotic pressure arises which can drive a turbine. Via a generator, the energy stored in the salt water can become sustainable electricity.

Osmosis is a process in which water moves through a semi-permeable membrane to equalize a concentration difference, and nature has shown the way.

When a plant is able to push up through a layer of asphalt, it is due to osmotic pressure.

Plant cells contain dissolved salts and sugars that cannot pass through the cell membrane. Water molecules, on the other hand, can cross the membrane and enter the cells. They do so in order to equalise the difference in the concentration of dissolved substances on either side of the membrane. This increases the pressure inside the cells to such an extent that a plant can even break through asphalt.

The osmotic pressure can become surprisingly large. In plant cells, the pressure can reach 20 bar, that is, 20 times the normal atmospheric pressure at sea level. That corresponds to the pressure from a water column 200 meters tall, or 10 times the pressure in a car tyre.

If you want something to move, for example to break through asphalt or set the blades of a turbine in motion, you need a force. Pressure is force per area, so pressure can be used to do mechanical work.

In other words, it is possible to release and exploit the energy bound up in the difference between the salt concentration in fresh water and salt water. It just requires that the natural osmotic force can be tamed.

The energy in salt water is predictable and stable

The amount of energy that can be extracted from osmosis is proportional to the difference in salinity. The saltier the water, the greater the energy potential. It therefore makes good sense to use the salty water from the subsurface for energy production or, even better, to use a saturated brine, where the salt makes up 26 percent of the solution's weight.

That insight prompts Jørgen M. Clausen to found the company SaltPower. The ambition is to kick-start a new Danish industrial adventure within renewable energy.

Opening of Geothermical test facility

Wind power has shown the way. In the late 1970s, enthusiasts experimented with turning the energy of the wind into electric current, and as a reaction to the oil crisis and the plans for nuclear power in Denmark, the Tvind school cooperative decided to build the world's largest wind turbine. The 54-metre-tall Tvind turbine was ready in 1978, and it demonstrated the great potential of wind power.

At the same time, a national research effort to develop wind energy was launched at the Risø research center, and an entirely new industry grew up. Today, Denmark is a leader within wind energy, and more than half of Denmark's electricity consumption is covered by wind turbines.

For Jørgen M. Clausen, the interest in renewable energy comes from his time as chairman of the board of Risø, and as CEO and later chairman of Danfoss, he made sure to put decarbonization at the heart of the worldwide group.

At the same time, he has always had an eye for new technologies that can advance the green transition, and now he sees great possibilities in osmotic power. He imagines osmotic power plants of megawatt size built wherever water with a high salt content is available.

An osmotic power plant can be constructed so that there are no emissions to the environment whatsoever. Compared to solar and wind power, osmotic power plants have a major advantage, namely that they can run around the clock independently of whether the sun is shining or the wind is blowing.

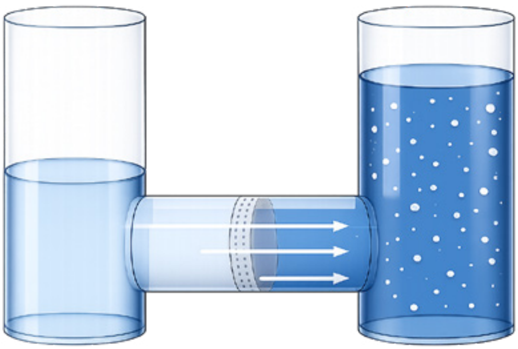
Much like nuclear power, osmosis can function as a baseload technology; a predictable and stable energy source. It only requires that there is access to two water streams with different salinities. For Jørgen M. Clausen, it is essential to investigate whether osmotic power can play a role in the energy supply.

'I had seen the wind turbine industry arise out of nothing. We could repeat that with salt power. That was the vision' as he puts it.

A pig's bladder put a physicist on the trail

That it is at all possible to extract energy from the difference in salinity (or more generally in water concentration) on the two sides of a membrane is due to nature's drive towards disorder.

If you have one vessel of fresh water and one of salt water, things are in order, but that order disappears if the two liquids are allowed to mix. Then you quickly end up with diluted salt water. In physics, one speaks of entropy, which is a measure of the amount of disorder or randomness in a system. The second law of thermodynamics tells us that the entropy in a closed system will always increase or remain constant. It can never decrease.



Fresh water **Concentrated brine**

Entropy of osmotic system

The explanation for the increasing entropy is to be found at the molecular level. In pure water, all the molecules are identical, and although they can move around among each other, there are limits to how many different ways they can arrange themselves. In salt water, there are many more possibilities, because the salt ions can place themselves in countless different ways between the water molecules.

This means that it is far more likely that the fresh water will mix with the salt water than that the two liquids will remain separate. In nature, systems move spontaneously towards the state that is most likely, where mixing is total, the thermodynamic equilibrium state with maximum entropy.

The microscopic explanation for osmosis came with statistical mechanics, which the Austrian physicist and philosopher Ludwig Boltzmann founded in the late 1800s. But the exploration of osmosis as a natural phenomenon goes all the way back to 1748, when the French priest and physicist Jean-Antoine Nollet discovered osmotic pressure somewhat by chance.

He had filled a bottle with ethanol, sealed it with a piece of pig's bladder and submerged it in a water bath. After 5-6 hours he finds, to his great surprise, that the pig's bladder has swelled up so much that it is close to bursting. When he pricks a hole in the bladder, ethanol sprays out.

He correctly concludes that water has passed through the bladder, so that an overpressure has built up inside the bottle. The little piece of bladder functions as a semi-permeable membrane that allows water molecules, but not the larger ethanol molecules, to pass.

In 1826, osmosis is studied more closely by the French physician Henri Dutrochet, who specifically investigates the great importance of osmosis for living organisms. He is also the one who names the effect.

Half a century later, the German chemist and plant physiologist Wilhelm Pfeffer develops accurate methods for measuring osmotic pressure. This quantification of the phenomenon paves the way for the Dutch chemist Jacobus Henricus van 't Hoff, who in 1887 establishes the theory behind osmosis within chemical thermodynamics.

Jacobus H. van 't Hoff arrives at a formula for the osmotic pressure: $\Pi = icRT$

where Π is the osmotic pressure, i is the dimensionless van 't Hoff factor (which is 2 for a salt solution, since salt dissociates into 2 ions), c is the molar concentration, R is the ideal gas constant, and T is the temperature in kelvin.

The formula only applies when the concentration of dissolved substance is so low that the solution can be regarded as ideal. At high salt concentrations, the relationship between concentration and osmotic pressure is no longer linear.

In 1901, van 't Hoff receives history's first Nobel Prize in chemistry for the discovery of the laws governing chemical reactions and the osmotic pressure.

To calculate the energy that is released by mixing fresh water and salt water, however, it is more practical to use the theoretical apparatus that, in the same period, is developed by the American physicist and chemist J. Willard Gibbs.

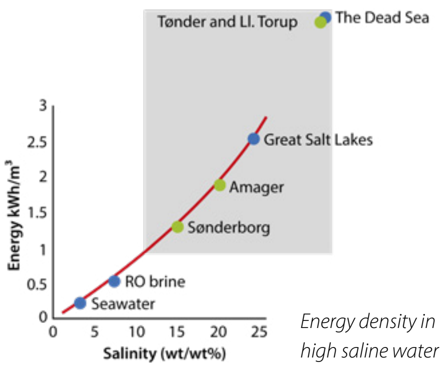
He lays the foundation for modern chemical thermodynamics, and it is still his formulas that are used today when one wants to calculate the energy potential in chemical reactions.
The formula for Gibbs free energy of mixing describes the change in free energy when two solutions are mixed. With it, one can calculate

NaCl	Osmotic pressure	NaCl	Osmotic pressure
(g/l)	(bar)	(g/l)	(bar)
310	406	150	143
300	385	140	131
290	365	130	120
280	345	120	109
270	326	110	98.1
260	307	100	87.7
250	290	90	77.7
240	272	80	68.1
230	256	70	58.7
220	240	60	49.6
210	225	50	40.8
200	210	40	32.2
190	195	30	23.9
180	182	20	15.7
170	168	10	7.78
160	156	0	0.00

The osmotic pressure rises with the salt concentration. A saturated brine gives an osmotic pressure of more than 400 bar. That corresponds to the pressure from a four-kilometer-tall water column.

how much energy is released when fresh water is mixed with salt water[1].

For every cubic metre of seawater that is mixed with a cubic metre of fresh water, around 2 megajoules (0.56 kWh) is released. That corresponds to the calorific value of 60–70 grams of coal. The energy potential rises with salt concentration, so for saturated brine, the figure is more than twenty times as big.



Energy density in high saline water

New membranes can be used for desalination

With the theoretical foundation in place, it becomes easier to understand the importance of osmosis in biology, both in plants and animals.

Without osmosis, our kidneys, for example, would not work. But the industrial exploitation of osmosis is slow to arrive, primarily because it is difficult to fabricate durable membranes that can both withstand high pressure and let water flow through.

In 1959, the chemical engineers Sidney Loeb and Srinivasa Sourirajan from UCLA in the USA succeed in developing membranes that can be used for reverse osmosis on an industrial scale. The aim of the research is to produce drinking water from seawater in a cheaper and more efficient way.

In osmosis, the natural osmotic pressure drives water through a membrane, so that it ends up on the side of the membrane where the water concentration is lowest, for example because there is dissolved salt in the water. The salt water is thereby diluted.

But if the osmotic pressure on the salt-water side is overcome, the process can run the opposite way, so that the pure water passes through the membrane from the salt-water side to the fresh-water side. This is called reverse osmosis and is used, among other things, for desalination.

Seawater gives an osmotic pressure of about 27 bar, so for reverse osmosis the membranes must be able to withstand a pressure that is even higher. It costs energy to make natural osmosis run backwards, but it can be worth the price where clean drinking water is in short supply.

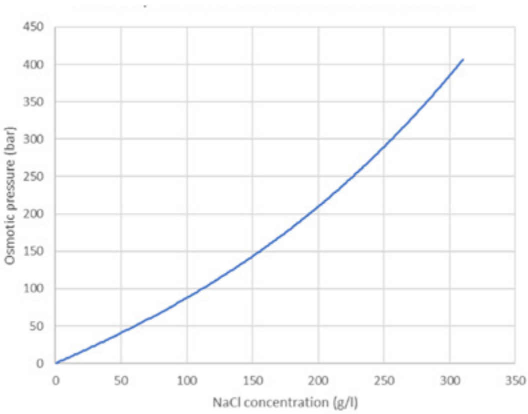
Then as now, the technological challenge was to create a solid membrane that can withstand a very high pressure while at the same time letting a great deal of water – and only water – pass through. A thick membrane can withstand the pressure, but it quickly becomes so dense that the water flow is blocked, and then you are no better off

For Loeb and Sourirajan, the breakthrough comes with the manufacture of asymmetric cellulose acetate membranes. They are asymmetric because they consist of two very different structures of the same polymer material, namely an ultra-thin surface layer that rejects salt but lets water pass, and a thicker, porous substructure that ensures mechanical stability.

Reverse osmosis (RO) with the new generation of membranes makes seawater desalination far cheaper than it has previously been. And they can be used not only in desalination plants, but also in wastewater treatment and in the food industry.

The method is energy-intensive, because it is about overcoming the natural osmotic pressure. In separating fresh water from salt water, one must work against nature's drive towards disorder, and that requires energy. But then it also makes sense that one can extract energy from the reverse of reverse osmosis, that is, by letting fresh water flow together with salt water.

Counter-pressure makes it possible to extract energy from salt water



Osmotic pressure vs. NaCl salinity

The American biologist Richard S. Norman makes this clear in the Science article 'Water Salination: A Source of Energy', which is published on 25 October 1974[2].

He imagines osmotic power plants everywhere fresh water from rivers meets the salty water of the sea. For example, he calculates that a power plant placed at the mouth of the Mississippi River could deliver 1000 megawatts, if 10 percent of the flow is utilised with an efficiency of 25 percent.

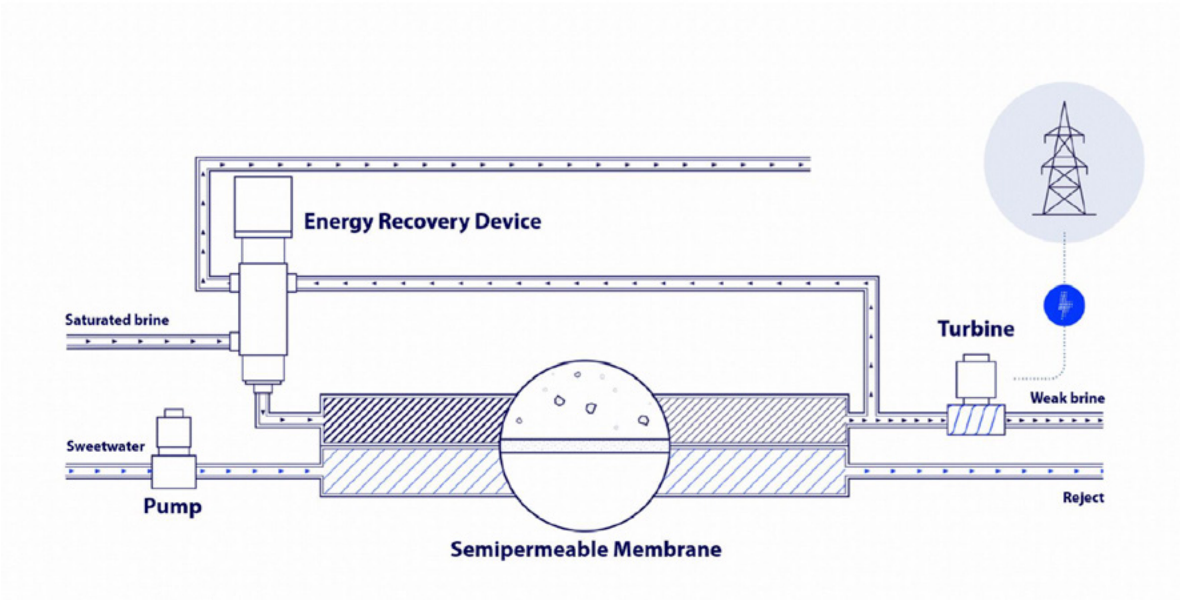
In practical terms, he envisages how the osmotic pressure lifts fresh water, which via a membrane mixes with salt water, high up. From there it can fall and drive a turbine in the same way as in hydroelectric power plants.

The following year, the American-Israeli Sidney Loeb points out that the economics of osmotic power plants becomes much better if, instead of ordinary seawater, one uses the hypersaline water (water with a higher salt content than seawater) from salt lakes such as the Dead Sea in the Middle East or the Great Salt Lake in Utah. The osmotic pressure rises with the salt content, and today the salt content is as high as 34 percent in the Dead Sea (NaCL and other dissolved salts), almost ten times the salt content of seawater.

Sidney Loeb also points to the possibility of using concentrated brine from salt extraction at salt domes. He concludes his comment in Science with the sentence 'In anticipation of such future utility, I propose the term 'pressure retarded osmosis' for the osmotic process utilized.'[3]

Pressure retarded osmosis (PRO) is a method for extracting energy from osmosis, which Sidney Loeb applies for a patent on. He was granted the patent in the USA on 16 September 1975[4].
In two scientific articles published in the Journal of Membrane Science in 1976[5,6], he elaborates on the technology behind PRO, and he describes experiments with concentrated brine.

When the osmotic pressure causes fresh water to flow spontaneously into salt water through a semi-permeable membrane, two different things can happen. If the salt water is in a rigid, closed container, the water flow will cause the pressure on the salt-water side to rise until it equals the osmotic pressure, and then the process stops. But in the opposite case, the volume of water on the salt-water side increases.



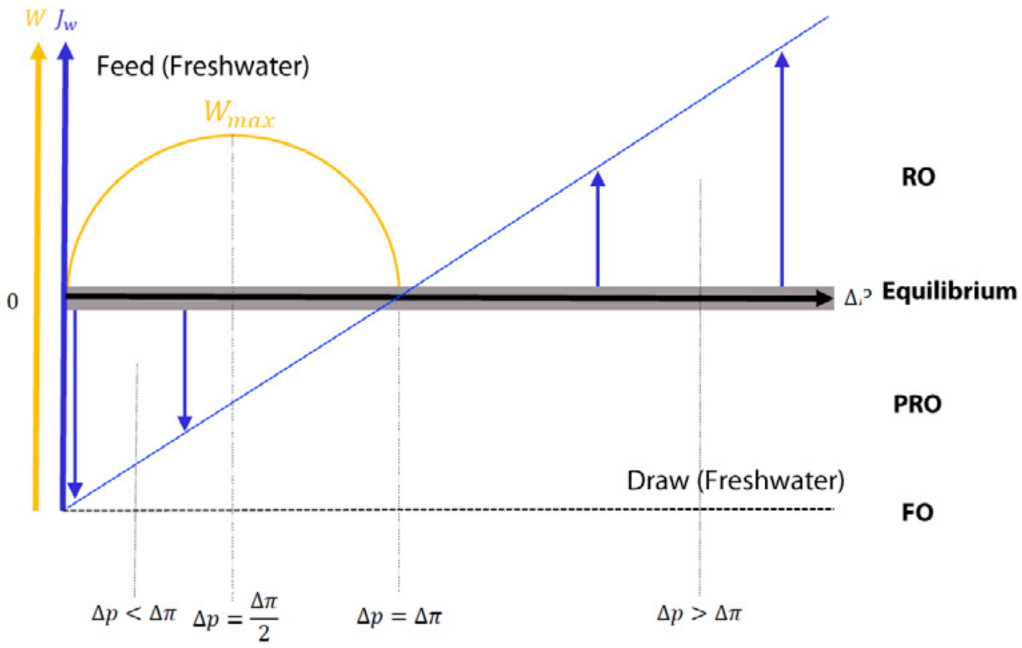
This volume increase can be exploited if the salt water is under pressure. This of course requires that the applied pressure is less than the osmotic pressure, because otherwise the result is energy-consuming reverse osmosis.

In a PRO power plant, a counter-pressure is applied to the salt-water side, and this brakes or retards the natural, osmotic water flow. Since the osmotic pressure is larger, the volume of the pressurised salt water increases, and the extra volume under pressure drives a turbine which, via a generator, can generate electric current.

The water that passes through the membrane – the permeate – will perform mechanical work corresponding to the pressure on the salt-water side times the volume change. At least if the pressure is held constant (constant pressure retarded osmosis, C-PRO).

Without the counter-pressure, the water would flow freely through the membrane, and the volume on the salt-water side would increase maximally. But in that case, the released energy is not exploited. Conversely, it is also of no use to apply a pressure to the salt water that is equal to the osmotic pressure.

Then the water flow comes to a halt. The osmotic pressure can in fact be understood as the counter-pressure one must apply to the salt-water side in order to stop the inflow of fresh water.



In theory, the highest energy density in a PRO process is obtained when the pressure on the salt-water side is half of the osmotic pressure Π. Without counter-pressure, the water flow is maximized, but then there is no pressure to drive a turbine.

A PRO plant for producing green energy thus requires two water streams with different salinities – a draw solution with high salinity which, via osmosis, 'pulls' the water through the membrane, and a feed solution with low salinity.

In addition, an efficient semi-permeable membrane that can withstand the high pressure is needed, along with pumps with associated piping and fittings to maintain and regulate the pressure on the salt-water side and to deliver a steady stream of fresh water that can pass through the membranes, as well as a turbine and a generator to convert the hydraulic energy into electric energy.

Outside the laboratory, it will also typically be necessary to pre-treat both the fresh water and the salt water before it meets the membrane. Particles such as sand and clay, organic material from dead animals and plants, microorganisms as well as minerals such as calcium carbonate and silica that can form deposits must be removed as well as possible. Otherwise the membrane will quickly become fouled, so that the water flow is hindered or completely blocked.

[1] *Theoretical framework for energy analysis of hypersaline pres sure retarded osmosis*

[2] *Norman, R. S., 'Water salination: a source of energy ' Science 186:4161 (1974), DOI: 10.1126/science.186.4161.350*

[3] *Loeb S., 'Osmotic power plants', Science 189:4203 (1975). DOI: 10.1126/science.189.4203.654*

[4] *Method and apparatus for generating power utilizing pressure-retarded-osmosis. Patent US3906250A.*

[5] *Loeb S., 'Production of energy from concentrated brines by pressure-retarded osmosis : I. Preliminary technical and economic correlations', J. Membr. Sci. (1976), DOI: 10.1016/S0376-7388(00)82257-7*

[6] *Loeb S. et al., 'Production of energy from concentrated brines by pressure-retarded osmosis : II. Experimental results and projected energy costs', J. Membr. Sci. (1976), DOI: 10.1016/S0376-7388(00)82271-1*

Norway and Japan build prototypes

Energy production depends on how rapidly the fresh water passes through the membranes. If the flux is too low too much membrane area is needed which would become cost prohibitive.

In the second half of the 1970s, Sidney Loeb and other researchers conducted various experiments with PRO. The technical and economic analyses generally show that PRO works, but as a report from the US Department of Energy summarises, better and cheaper membranes are needed if the economics are to make sense[7].

Energy production depends on how rapidly the fresh water passes through the membranes. If the flux is too low too much membrane area is needed which would become cost prohibitive. For a couple of decades, osmotic power did not attract much attention, but in 1997 the Norwegian, state-owned energy company Statkraft began to take an interest in the technology. From 2001 to 2004, Statkraft coordinates the EU project 'The Salinity Power Project'[8], which aims to test and develop membranes and membrane modules for use in PRO plants.

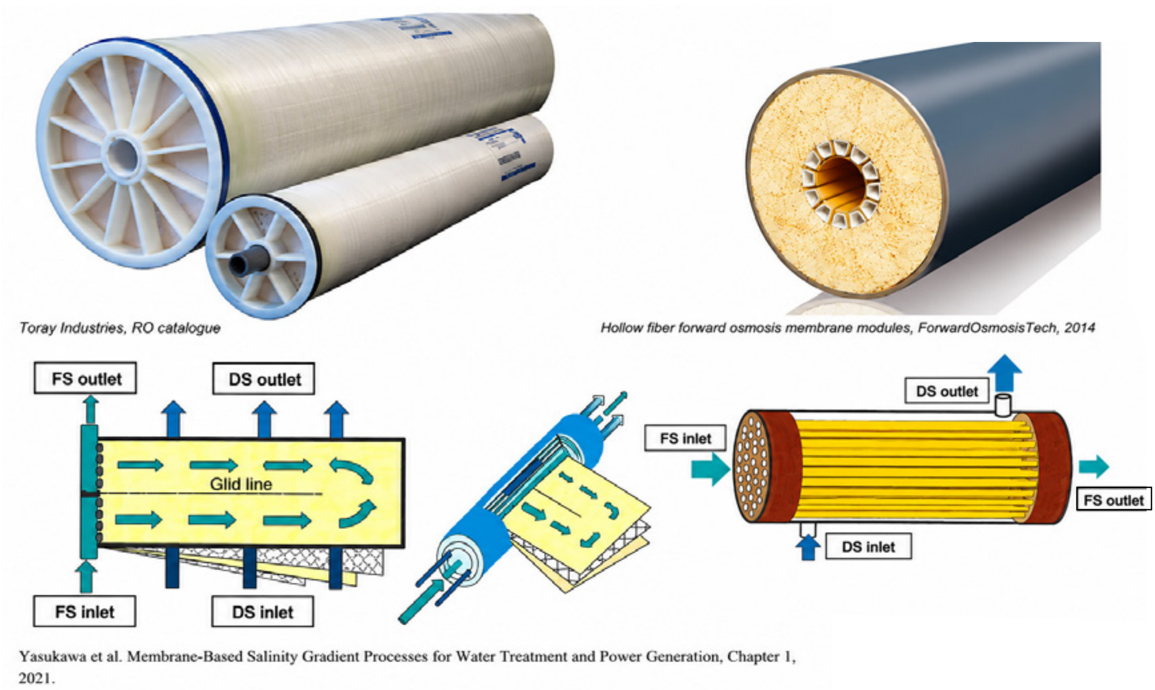
The results are promising enough that Statkraft continues to work on the technology, and on 24 November 2009 a pilot plant is inaugurated at Hurum on the Oslo fjord in Norway. Here, fresh water from a river flows down into the salt water of the fjord, and the difference in salt content is utilised to produce electricity in what is referred to as the world's first osmotic power plant.

In osmosis plants, membrane modules in the form of pressure vessels are used, typically made of fibreglass. In the vessel, membranes are distributed in a way that maximises the membrane area. There are two main types, namely spiral wound modules and hollow fibre modules.

In a spiral wound PRO module, the fresh water is sent into a central tube and from there out into 'envelopes' of flat membrane sheets that are glued together back to back on three sides. Several 'envelopes' are wound around the central, perforated tube. The salt water is sent into one end of the module and flows around the membrane envelopes. On both the fresh-water and the salt-water side, structures called spacers keep the membranes apart, so that the water can flow freely and reach every part of the module.

The fresh water passes through the membranes and increases the volume of water on the salt-water side. When the salt water has passed all the way through the membrane module, it has been diluted and has increased its volume, and from there it is sent towards the turbine.

The membranes in a spiral wound module are typically made of thin-film composite (TFC), which was developed during the 1970s. Here the membrane consists of an ultra-thin layer of polyamide that rejects salt but let water pass, combined with a porous layer of thermoplastic (often polysulfone) and a coarser and thicker



Spiral-wound modules (left) and Hollow fiber modules (right)

layer of non-woven polyester for mechanical support.

In hollow fibre PRO modules, the membranes are instead shaped as very thin tubes or fibres of asymmetric cellulose triacetate. The fresh water runs inside the thin fibres and is drawn across the membrane by the salt water, which flows outside the fibres. Tens of thousands of fibres with a very large total surface area fill the module.

Statkraft ends up using the spiral wound architecture, where the fresh water passes through approximately 2,000 square metres of membrane distributed across 66 modules, each eight inches (20 cm) in diameter and one metre in length.

The target for the Norwegian project is a power output of 10 kW, but it never reaches more than 2–4 kW, enough to drive one or two electric kettles.

As part of the project, the global energy potential for osmotic power is calculated at around 1650 TWh per year. By comparison, global electricity consumption is close to 30,000 TWh (2025).

[7] *Lonsdale, H. K. et al.,'Membrane research for salinity gradient energy production. Final report', Osti.gov, DOI: 10.2172/6749667*

[8] *The Salinity Project Group: 'The Salinity Power Project: Power production from the osmotic pressure difference between fresh water and sea water - final report', The European Commission, 2004.*

The membranes must be efficient

The Norwegian calculations show that a PRO plant can only become economically viable if the membrane delivers a power (pressure times water flux) that exceeds 4–6 watts per square metre of membrane[9].

This quantity, called power density, determines the size of the entire PRO plant – the fewer square metres of membrane needed, the more compact the plant can be. A large part of the capital expenditure (CapEx) will go to the membranes, so their efficiency is decisive for the economics.

If the applied pressure on the salt-water side is, for example, 70 bar, equal to 7,000,000 pascals, then every second, 0.714 millilitres of fresh water must pass through each square metre of membrane in order to achieve a power of 5 watts, since:

$$7 \cdot 10^6 \text{ Pa} \cdot 7.14 \cdot 10^{-7} \text{ m}^3/\text{s} = 5 \text{ W}$$

That corresponds to a flux of just over 2.5 litres per square metre per hour. That may sound modest, but it is not easy to fabricate a membrane that is strong enough to withstand the high pressure while at the same time letting so much water pass through, while keeping the salt out.

The 5 W/m^2 is the hydraulic power per area at the membrane. The mechanical energy cannot be converted to electric energy without a loss of 15–20 percent, so after the turbine and generator there may only be 4 W/m^2 left. Of this, some goes to pressurising the salt water and ensuring a stable flow of fresh water.

The systems for pre-treating the water will also typically require a considerable amount of energy.

Three years after start-up, on 20 December 2012, the Norwegian pilot project is shut down. It did not succeed in coming close to the desired power density of 5 W/m^2. Instead, the power density lies around 1 W/m^2 (one watt for each of the 2,000 square metres of membrane, equal to a total output of 2 kW), which can never be economically viable. The technology works, but it is commercially immature.

In the literature, the 5 W/m^2 is often given as a rule of thumb for when a PRO plant can become economically interesting, but of course the economics depends on many factors other than the amount of water that passes through the membranes.

The price of the membranes plays a large role, as do the costs of pre-treating the water. The need for pre-treatment depends on where the water comes from. On the fresh-water side, there is, for example, a great difference between river water and groundwater, and on the salt-water side, water from geothermal wells or from solution mining is easier to clean than seawater.

With the results from Statkraft's pilot plant, it becomes clear that it is difficult to make osmotic power plants that use seawater competitive, particularly in light of ever cheaper electricity from solar and wind. But the interest in PRO does not disappear, because the technology may still make sense in niches where one has access to water with a higher salinity than seawater.

In 2010, the Japanese research project Mega-ton Water System starts, with the aim of developing new technologies for future, large desalination plants that use reverse osmosis to desalinate one million cubic metres of seawater per day. Here it is decided to investigate whether PRO can play a role in making the desalination plants less energy-intensive. Such a hybrid system is called SWRO-PRO (Sea Water Reverse Osmosis – Pressure Retarded Osmosis).

When seawater is desalinated with reverse osmosis, the result is drinking water on one side of the membrane and salt water with a salt content of 5–7 percent on the other. In a two-stage desalination plant, the salt content can rise to around 9 percent.

The concentrated salt water can be utilised in a PRO plant, but it only makes sense if water with low salt content is available. Here seawater could be one option, but even better is to use treated wastewater. As a side benefit, the concentrated salt water from the desalination plant gets diluted before it is discharged into the sea, where it could otherwise disturb marine ecosystems.

In a prototype PRO plant operating for one year in the Japanese city of Fukuoka, a membrane power density of up to 13.3 W/m^2 is achieved. Here, cellulose triacetate (CTA) membranes in hollow fiber modules are used. CTA is a better membrane material than cellulose acetate (CA), because it is more chemically and mechanically stable and has better strength[10].

In a smaller plant in the laboratory, 17.1 W/m^2 is achieved by using pure drinking water and water with 7 percent salt. The conclusion is that a PRO plant can reduce the energy consumption for SWRO by 10 percent, and that the high figures for the membranes' efficiency pave the way for commercial PRO plants[11]. South Korean studies point in the same direction[12].

9 *Gerstandt. K. et al., 'Membrane processes in energy supply for an osmotic power plant', Desalination 224 (2008), DOI: 10.1016/j.desal.2007.02.080*

10 *Kurihara, M. et al., 'Role of pressure-retarded osmosis (PRO) in the mega-ton water project', Desalin. Water Treat. 57(55), 2016,*
DOI: 10.1080/19443994.2016.1168582

11 *Kurihara, M. & Takeuchi, H., 'SWRO-PRO System in 'Mega-ton Water System' for Energy Reduction and Low Environmental Impact', Water 10(1) (2018), DOI: 10.3390/w10010048*

12 *Chung, K. et al., 'Investigation into design parameters in seawater reverse osmosis (SWRO) and pressure retarded osmosis (PRO) hybrid desalination process: a semi-pilot scale study', Desalin. Water Treat. 57(51), 2016, DOI: 10.1080/19443994.2016.1152644*

High salt concentration means more energy

In Denmark, Jørgen M. Clausen decides to investigate the potential of osmotic power.

The starting point is concentrated salt water like that which can be found deep in the subsurface in Denmark and many other places. Initially, the interest is directed at the salt water brought up at geothermal facilities.

In geothermal energy, the heat from the interior of the Earth is exploited. In places like Denmark without volcanic activity, this is done by pumping warm water up from sandstone reservoirs, which lie at more than 800 metres depth. Via heat exchangers, the heat from the water, which has temperatures from 30 °C to 90 °C, can be utilised in district heating systems.

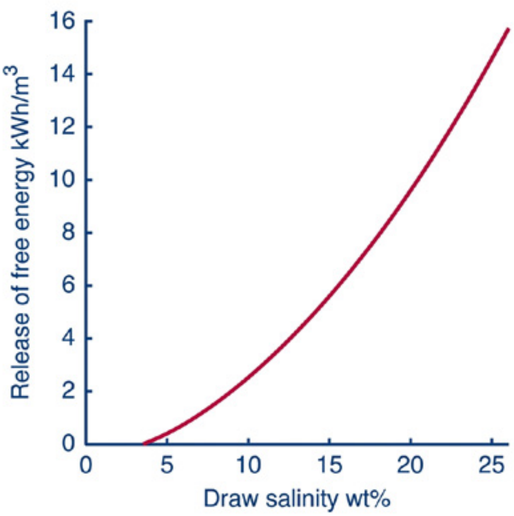
The sandstone layers were deposited more than 100 million years ago, and the water in the porous rock is ancient seawater. Through the many millions of years, minerals have dissolved into the water and made it much saltier.

The question is whether the high salinity can make osmotic power plants profitable. That is what Jørgen M. Clausen wants to find out, and first of all he contacts researchers from Aalborg University's Department of Chemistry and Bioscience in Esbjerg. They calculate how much energy can theoretically be extracted from osmosis depending on the salt concentration, all the way up to saturated brine at 26 percent salt.

The researchers find, not surprisingly, that the highest salt concentrations give the most energy.

The results are presented in a scientific article in the journal Chemical Engineering Science[13] and later form part of a larger review article in the journal Desalination[14].

The thermodynamic calculations show that 15.7 kWh is released for every cubic metre of saturated brine that is mixed with fresh water, so that the result is water with the same salinity as seawater. The energy is there; the question is just how much of it can be exploited, and how it can best be done.



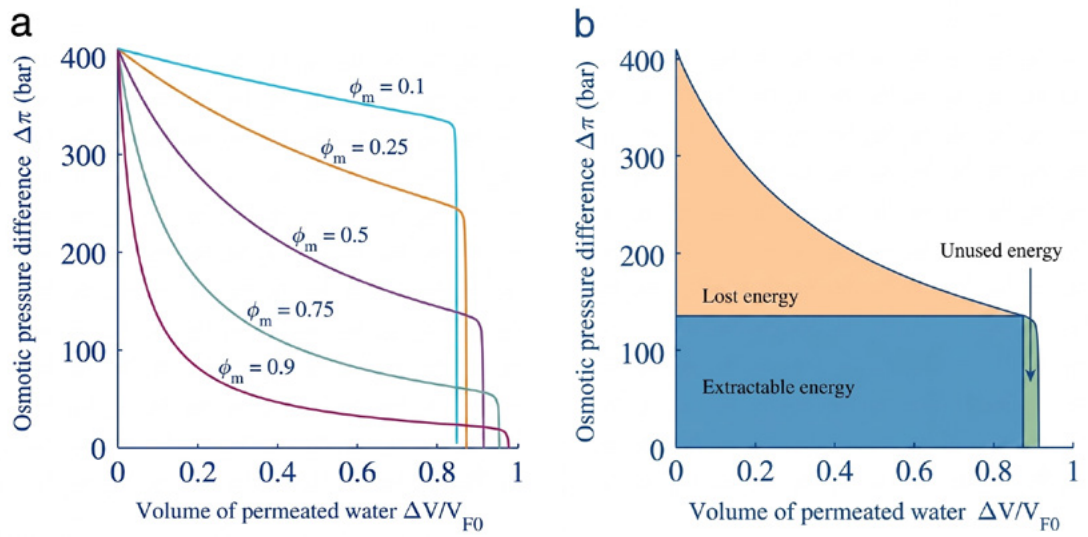
Gibbs free energy in saturated brine

In practice, there are limits to how large a fraction of the released energy, the Gibbs free energy of mixing, can be exploited with PRO. Only with a reversible PRO process, which would take an infinitely long time, could all the energy be harvested[15].

It is the difference in osmotic pressure that drives the process, but as the fresh water passes through the membrane, the salt water becomes diluted, so the osmotic pressure difference falls. If one is to exploit all the energy, the hydraulic counter-pressure must be constantly adjusted downward, so that it is at all times infinitely close to the osmotic pressure, and only an infinitely small amount of water passes through the membrane at a time. The process continues until the final equilibrium. Only in that way the total amount of energy can be exploited.

But in real PRO plants, the pressure on the salt-water side is held constant, and therefore some of the energy is inevitably wasted. Only the part of the energy that corresponds to the counter-pressure times the change in volume can be exploited.

One can say that one pays a thermodynamic price to obtain a real flow that can drive a turbine. In addition, the osmotic pressure difference will at some point become smaller than the counter-pressure, and then the flow through the membrane stops. The counter-pressure means that the osmosis stops before the salt concentration is the same on both sides of the membrane, and therefore there is energy that is not exploited.



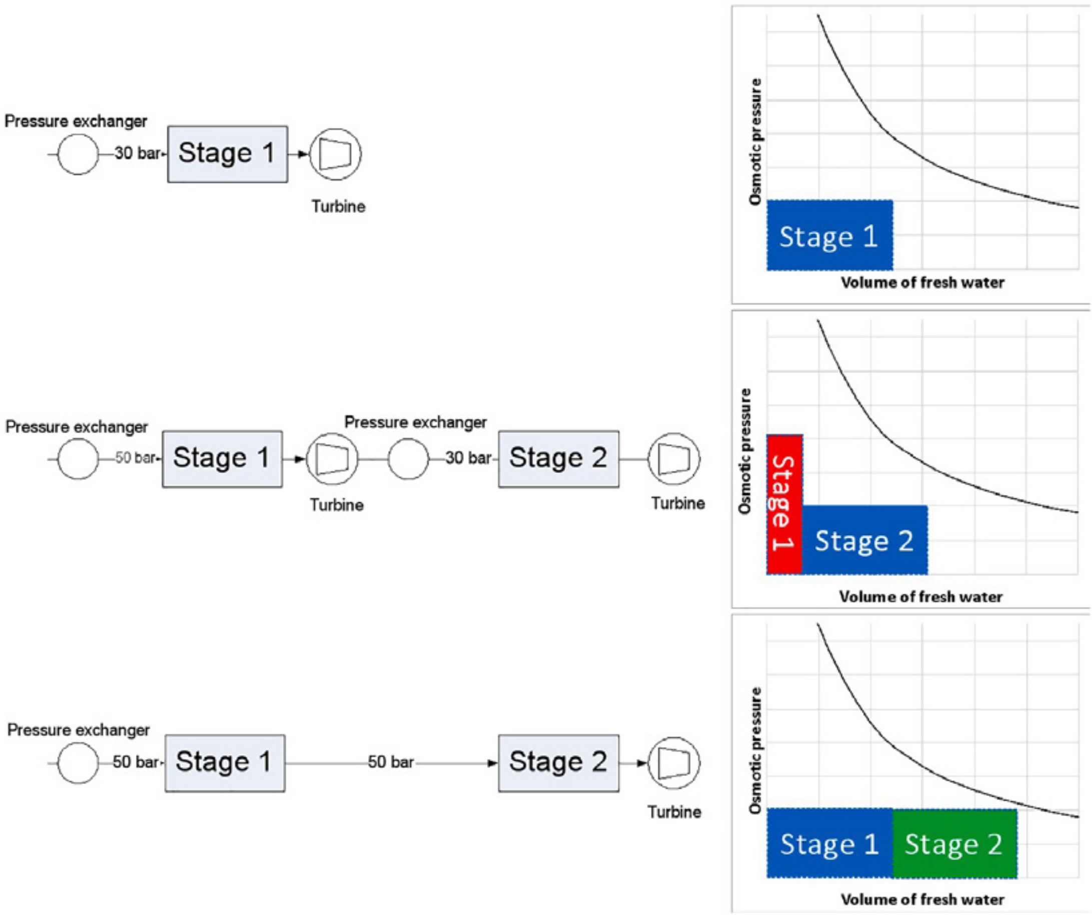
PRO working curves. To the left (a) the osmotic pressure is plotted as a function of the fraction of the feed (0.01 wt% salinity) that permeates over in the draw (26 wt% salinity) for different mixing ratios. At low mixing ratios, when the feed to draw ratio is low, the osmotic pressure difference changes slowly because the draw concentration is only slightly diluted. At high mixing ratios, the draw is diluted more quickly and the osmotic pressure difference drops faster. To the right (b), the working curve for a mixing ratio of 0.5 has been split into three areas indicating the extractable energy, the lost energy and the unused energy when the extractable energy is maximized.

The loss can be minimised by adding more stages to the PRO process, so that the diluted salt water from the first stage becomes the next stage's salt water and so on. The osmotic pressure falls with the salt concentration, so the pressure on the salt water must be lowered at each stage.

By having several PRO systems connected in series, more energy can be extracted from the process, but the costs of membranes, pumps and piping also rise. There are limits to how many stages it pays to implement, since the energy yield falls with each stage.

The researchers' calculations show, incidentally, that the power density can reach as high as 143 W/m^2 for saturated brine drawing fresh water across the membrane, but then the pressure on the salt-water side must be 209 bar. No usable semi-permeable membranes can withstand such a high pressure.

Realistically, for the time being, one has to use membranes that can withstand at most 70–80 bar. This sets yet another limit to how much of the potential energy in osmosis can be exploited, but in theory it should still be easy to exceed 5 W/m^2 with concentrated brine.



Single- and multi-stage designs for the PRO plant. Graphs depict the osmotic pressure as a function of the volume of fresh water added. Boxes show the higher energy recovery for the various stages.

Membranes are tested at Aalborg University

Theory confirms that PRO with hypersaline water has the potential to become a new, green energy source, and Jørgen M. Clausen decides to invest in investigations of the technology's potential in practice.

To back up the theoretical calculations and to test commercial membranes, a small PRO rig is built at Aalborg University in Esbjerg. The small proof-of-concept rig, which is roughly the size of a desk, makes it possible to test different types of commercial membranes at pressures up to 70 bar in the laboratory. Tests are done with salt solutions at various concentrations.

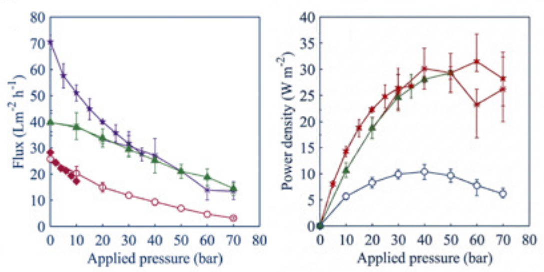
No membranes have been developed specifically for PRO at high salinities and high pressure, so the researchers have to use whatever forward osmosis (FO) membranes they can find that were made for other purposes, for example wastewater treatment.

In the first round, small pieces (approx. 20 cm^2) of five different membranes are tested, and the experiments show that cellulose triacetate (CTA) membranes best withstand pressures up to 70 bar. Another type of membrane made of thin-film composite (TFC) shows good water flow, but withstands at most 40 bar.

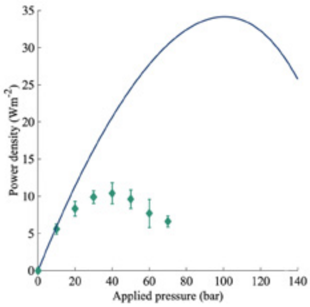
A third type of membrane based on aquaporins – proteins that let water pass through the cell wall of living organisms – fails at 10 bar, as salt passes through at higher pressures.

The conclusion is that the PRO process can proceed at up to 70 bar with commercially available CTA membranes, and that the power density can exceed 30 W/m^2 at high salinity. But the experiments also show that the power density at high salinity is lower than expected based on the membranes' specifications. The difference is attributed to compression of the membrane and higher salt permeation at high pressure. The results are presented in an article in Desalination[16].

In the following years, the small rig is upgraded and modified, and it serves as a system for rapid tests of membranes. It is given the name µCell.



Observed flux and power density for the six commercial membranes investigated in the laboratory study.
Six different membrane types are tested in the laboratory at pressures up to 70 bar. The CTA membranes are the most promising.



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–2h–1 has been used.

[13] *Madsen, H. T. et al.,'Theoretical framework for energy analysis of hypersaline pressure retarded osmosis', Chem. Eng. Sci., 139 (2016), DOI: 10.1016/j.ces.2015.09.018*

[14] *Bajraktari, N. et al., 'Pressure retarded osmosis from hypersaline sources — A review', Desalination, 413 (2017), DOI: 10.1016/j.desal.2017.02.017*

[15] *Yip, N. Y. & Elimelech, M.: 'Thermodynamic and Energy Efficiency Analysis of Power Generation from Natural Salinity Gradients by Pressure Retarded Osmosis', Environ. Sci. Technol. 46(9) (2012), DOI: 10.1021/es300060m*

[16] *Madsen, H. T. et al., 'Pressure retarded osmosis from hypersaline solutions: Investigating commercial FO membranes at high pressures', Desalination, 420 (2017), DOI: 10.1016/j.desal.2017.06.028*

Pilot project moves the technology out of the laboratory

The theoretical calculations and the ongoing results in the laboratory whet the appetite, and it is decided to launch a project with the purpose of designing and building a PRO pilot plant.

It is to demonstrate that the power density can exceed 5 W/m^2 using salt water from geothermal wells.

The project 'Osmotic Power generation from geothermal wells' receives a grant from the Danish public support scheme EUDP (Energy Technology Development and Demonstration Programme), which supports new energy technology that can contribute to meeting Denmark's targets for energy and climate. The budget is DKK 9.88 million (EUR 1.32 million), of which DKK 5.86 million is granted by EUDP.

On 12 August 2015, the kick-off meeting takes place for the SaltPower project, which is led by Applied Biomimetic A/S (as SaltKraft ApS and SaltPower Holding ApS only join later), and Aalborg University, Danfoss A/S, Sønderborg Fjernvarme and the Copenhagen-area utility HOFOR are the partners.

The plan is to use the most promising membrane from the laboratory experiments in the pilot plant, but the American membrane manufacturer goes bankrupt, and instead contact is made with the Japanese company Toyobo, which produces CTA membranes in hollow fiber modules.

Test unit 1 for real scale simulation

Toyobo PRO3 is an 88 cm long module that is five inches (12.7 cm) in diameter, and which can withstand pressures of up to 30 bar. It contains 60 square metres of membrane distributed across 143,000 fibres, each of which has an inner diameter of 100 micrometres and an outer diameter of 200 micrometres. A similar module called PRO4 is also tested. Here the fibres are slightly larger in diameter, which makes it easier for the fresh water to flow through, so that the pressure can be lowered. In return, there is only room for 50 square metres of membrane.

During the project, Toyobo also custom-designs the module H3K, which can go up to 70 bar and which is the first PRO module that can withstand such high pressures. In the project, it is tested up to 50 bar.

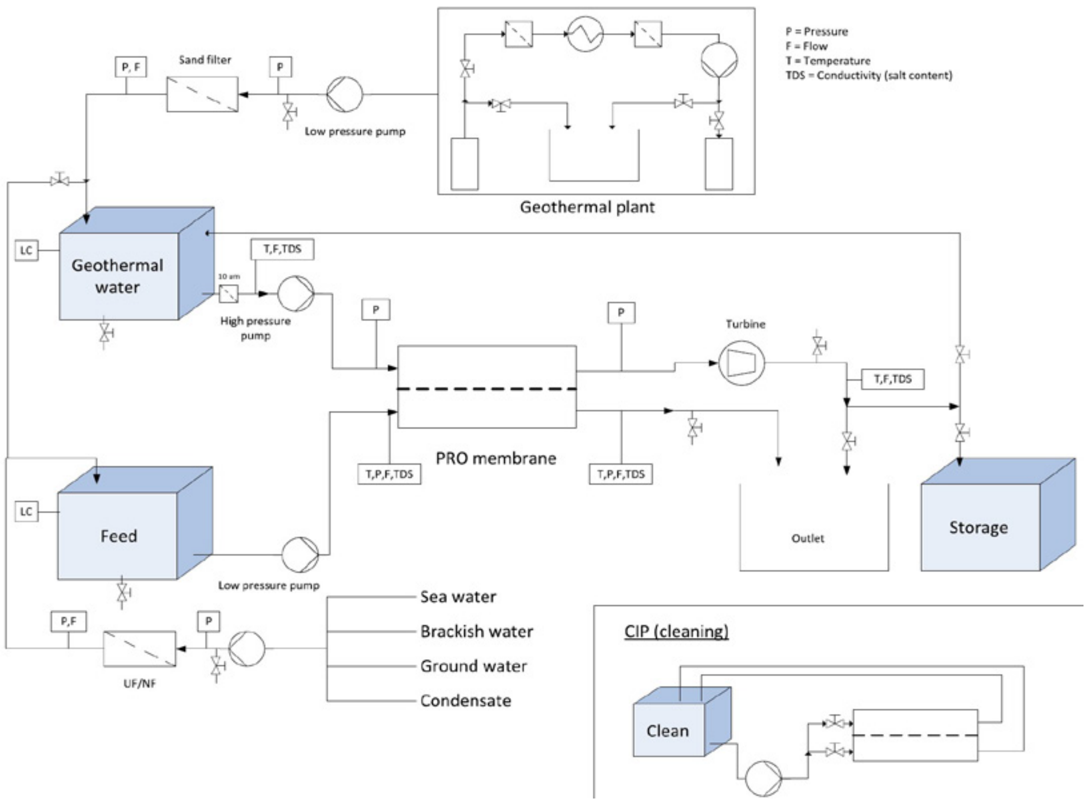
Hollow fiber modules can withstand the very high pressures required for PRO with hypersaline water, but they also have the advantage that the membranes can be packed extremely dense – 7,000 square metres of membrane per cubic metre. That is about 10 times more dense than in spiral wound modules, so with the hollow fiber geometry, osmotic power plants would require less space.

Installation in a container makes the plant mobile

The pilot plant is built around a membrane module and installed in a 20-foot container, so that it can be moved around – like a mobile laboratory. It is semi-automatic and requires constant staffing.

To begin with, it is placed at Sønderborg Geotermi, and on 29 April 2016 the plant is inaugurated. Former EU Climate Commissioner Connie Hedegaard starts the osmotic energy production in the presence of 120 invited guests.

The geothermal plant in Sønderborg delivers hypersaline water from the subsurface (about 15% salt), which is used as draw solution.
A high-pressure pump (Danfoss APP 0.6) pumps the salt water into the membrane module, while a smaller centrifugal pump ensures a steady flow of fresh water (local groundwater). The fresh water only needs enough pressure to overcome the pressure loss in the membrane module (2 to 4 bar).



The pilot plant is to show that PRO technology works at high salinity. Both fresh water and salt water must be thoroughly filtered before they are pumped into the membrane module, which is the heart of the system.

The goal is not to produce electricity for the grid, but to test the technology, so another high-pressure pump (Danfoss APP 0.8) plays the role of turbine. When the flow of fresh water is opened, one can clearly hear how the pump speeds up violently (from 5–600 to 1400 revolutions per minute), because the fresh water is drawn across to the salt-water side of the membrane and increases the water volume.

It is clear that osmosis is producing energy. At a pressure of 30 bar, the power density is measured at just over 6 W/m^2 using the commercially available hollow fiber modules Toyobo PRO3 and PRO4. For PRO3, the total output of the module reaches 370 watts.

With the salt water from the geothermal plant in Sønderborg, the newly developed H3K module gives a lower power density at pressures up to 30 bar, but in return it can withstand higher pressures.

The technology works. The question now is whether it also works in the longer term, that is, whether the energy production is stable, and whether higher salinity gives the expected yield.

A patent is filed on energy extraction from the warm, geothermal salt water[17]

Pre-treatment of the water is crucial

Early in the project, it becomes clear how much effective pre-treatment of both salt water and fresh water matters. The performance drops noticeably within a few hours of operation. The membranes appear to foul. Initially, suspicion falls on scaling from the salt water, for example in the form of small iron particles (iron colloids, ochre) that settle in the membranes and lower the performance.

Fouling of membranes

The salt water is pre-treated by being run through a sand filter that catches particles and iron. In addition, a 3 µm nominal and later a 10 µm absolute particle filter is mounted upstream of the high-pressure pump.

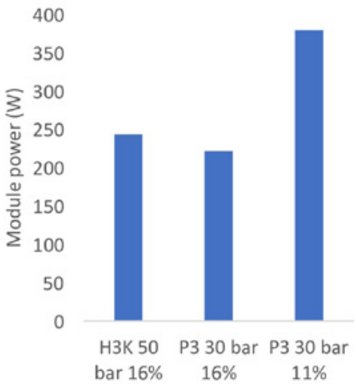
But it turns out that the fresh water is the major culprit. This is revealed when a membrane is sent to Toyobo in Japan for analysis. The analysis shows that the thin membrane fibres are fouled internally by carbonates and silicates. The fresh water requires more thorough pre-treatment than softening (ion exchange) and ultrafiltration.

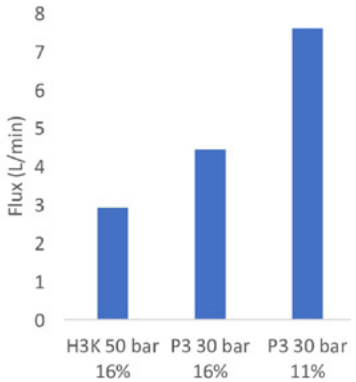
SaltPower commits to nanofiltration, which, unlike ultrafiltration, can remove most minerals from the fresh water. Nanofiltration seems to solve the problem of fouling of the membrane fibres. An NF270 element retains most of the calcium and magnesium, but a finer NF90 element is needed to also filter out silicon.

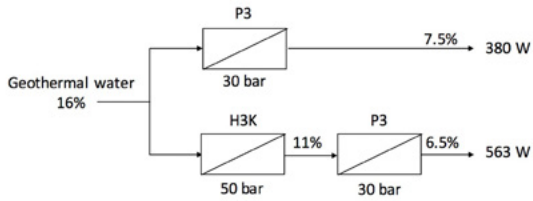
This unfortunately also means that the pre-treatment becomes energy-intensive, since the fresh water has to be passed through the nanofiltration system. Whereas the PRO process itself has an efficiency of 72 percent, the efficiency drops to 40 percent for the entire system including the pre-treatment. But these are figures that can be improved through optimisations.

In Sønderborg it is also investigated whether multiple stages in the PRO process make sense. Using a single PRO3 module at 30 bar, about 35 percent of the potential osmotic energy is extracted, but if the process is first run through an H3K module at 50 bar and then the diluted salt water is sent to a PRO3 module at 30 bar, 46 percent of the energy can be extracted. It is also possible to increase the amount of extracted energy by using two H3K modules connected in series at 50 bar.

Power single stage vs. power multi stanges







In March 2017, the plant is moved to the geothermal facility on Amager, where the water has a higher salinity of 19–20%. Here a power density of up to 9 W/m^2 is achieved.

The plant can run reasonably stably for hours at a time with an energy production of about 350 watts for an H3K module at a salt-water pressure of 50 bar. With the osmosis, the salt water is diluted to 12% salt.

The conclusion of the pilot project is that it is possible to extract the osmotic energy from geothermal water so efficiently that PRO technology is ready to be scaled up to a full-scale demonstration plant. This is set out in the final report to EUDP and in an article in the journal Energy Conversion and Management[19].

Both the membranes, the high-pressure pump and the turbine seem to be able to withstand the hypersaline geothermal water, but it is absolutely necessary to thoroughly pre-treat the fresh water that is to pass through the membranes. Otherwise the membranes will quickly become fouled. Readers of the trade journal Ingeniøren vote the pilot project the Danish engineering achievement of the year in 2016.[20]

[17] *Power generation process', US 201816630121A*

[18] *'Osmotic power generation from geothermal wells', EUDP 64015-0008*

[19] *Madsen, H. T. et al., 'Combined geothermal heat and pressure retarded osmosis as a new green power system', Energy Convers. Manag., 226 (2020), DOI: 10.1016/j.enconman. 2020.113504*

[20] *'Saltkraft kåret som årets danske ingeniørbedrift', Ingeniøren (2016)*

Demonstration plant paves the way for commercialisation

A new project is launched, called 'Full Scale Osmotic Power Generation from Geothermal Wells'[21].

The idea is to scale up the pilot plant to a larger plant with all the components needed in a full-scale PRO plant, and to demonstrate continuous operation of the plant in various settings.

In addition to designing and constructing a demonstration plant in a 40-foot container, which can be moved around in Denmark and abroad, the project aims to:

- develop a control and management system so that the plant becomes fully automatic.
- develop and test membranes at pressures of up to 70 bar.
- implement, test and evaluate the use of pressure exchangers.
- determine how a PRO plant can best be implemented at a geothermal facility and how effluents are best handled.
- demonstrate the technology at three locations.
- assess the market potential for osmotic energy in the European geothermal market.

The project receives a budget of DKK 20 million (EUR 2.68 million), of which half is granted by EUDP. It also receives support from Innovation Fund Denmark, which grants DKK 3.5 million via the Innobooster programme.

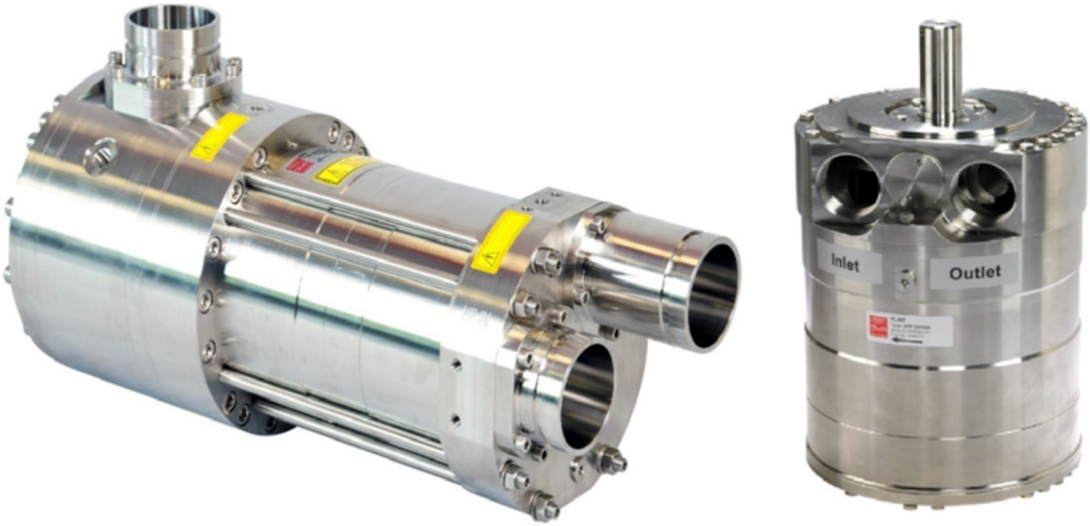
Among the partners is the engineering firm SEMCO Maritime, which is responsible for the actual construction of the plant.

The demonstration plant is built as a two-stage PRO plant. The first stage is to run at high salinity and a pressure of 70 bar, after which a turbine harvests part of the energy. The diluted salt water is sent on to a second stage at 30 bar and another turbine.

The Toyobo hollow fiber membrane modules have a diameter of 10 inches, double that of the prototype, and they are 1.3 metres in length. There are several hundred square metres of membrane in each module. Four modules are used in the first stage and six in the second.

Each stage is equipped with a Danfoss iSave 21+ pressure exchanger (also called Energy Recovery Device, abbreviated ERD), which can improve the energy efficiency. With an ERD, the pressure from the water leaving the PRO system can be reused to pressurise the salt water going into the membrane.

This requires the water flow after the membrane to be split in two. The turbine receives an amount of water corresponding to what the osmosis



Danfoss iSave + APP (pump) & MPP (turbine)

sends through the membrane. The rest is sent to the ERD, so that the pressure can be reused with a very high efficiency of about 96 percent. Since the loss of energy is far lower in an ERD than in a turbine, generator and high-pressure pump, it seems obvious to use an ERD to pressurise the incoming salt water.

In contrast to the prototype plant, there is now room for water pre-treatment inside the container – a nanofiltration system for the fresh water and sand filtration for the salt water.

The demonstration plant is first set up at the geothermal facility in Sønderborg, where the first tests take place from February 2018. Here the PRO plant is not fully built, and it never enters actual operation. It does not run fully automatically, and only the second stage with diluted salt water and a salt-water pressure of 30 bar is tested. This delivers about 4 kW.

In Sønderborg, the geothermal facility has operational problems, which complicates further tests. The original plan is subsequently to test the plant at the geothermal facility on Amager, but here there are also problems with operation, and at SaltPower a better idea emerges. The focus shifts from geothermal to the salt industry, more specifically salt extraction by solution mining.

[21] *'Full Scale Osmotic Power Generation from Geothermal Wells.' EUDP 64017-0596.*

PRO delivers energy for salt production

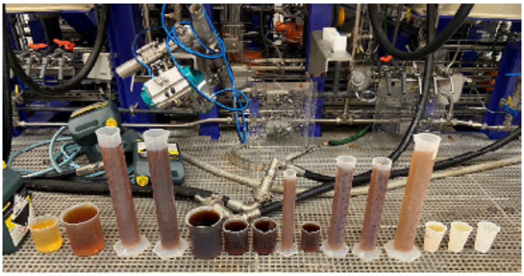
If you drill one and a half kilometres down into the subsurface south-west of the village of Hvornum near Hobro, you reach an underground salt mountain that is three km in diameter and four km deep. This salt dome (also called a salt diapir) was formed by evaporation of seawater about 250 million years ago, and it contains about 30 billion tonnes of salt.

From here, salt is extracted by pumping water down so that the salt dissolves in the water. The saturated brine is pressed up to the surface and evaporated, so that the salt precipitates out. Ever since 1966, the company Dansk Salt has been extracting salt in this way. Via a pipeline, the brine is sent to Scandinavia's only salt factory at Mariager Fjord, and more than 600,000 tonnes of salt are produced annually. The production is being expanded so that it will reach one million tonnes annually.

For SaltPower, this form of salt extraction is interesting because there is access to concentrated brine with as much as 26 percent salt (by weight). Here is an obvious application for SaltPower's PRO technology, which can deliver green energy to the energy-intensive salt production. Dansk Salt can save money and gain a better sustainability profile, and the salt producer (at the time owned by Nouryon) is on board with the idea.

The salt factory has a residual product in the form of brine that is left over after the salt production. This residual brine can be utilised in a PRO plant.

The demonstration plant is moved to Dansk Salt in Mariager, and with a flow of 4–5 cubic metres of salt water per hour, more than 10 kW is produced at the first-stage turbine, roughly as expected.



Hydrolisation of CTA at high pH

The membranes cannot tolerate alkaline water

But suddenly the power plummets. This time the problem is not fouling of the fibres, but rather that the residual brine from the salt production is so alkaline that it destroys the cellulose triacetate membranes. Dansk Salt uses the alkaline sodium hydroxide ($NaOH$) to make impurities precipitate from the brine, but in the PRO plant the membranes begin to disintegrate at the high pH, so that holes appear in the thin membrane fibres.

The solution could be to add acid, but that would mean a significant additional cost. Instead, SaltPower tries with cleaned brine from the salt dome rather than the residual brine. On the fresh-water side, distilled water is used instead of groundwater, because in the evaporation of salt at the salt factory, large quantities of distillate are produced which, due to their high purity, are an obvious choice for use in the PRO plant.

Under these ideal conditions, the plant runs stably for 2000 hours in early 2021. It only stops briefly due to maintenance work at the salt factory.

Salt producers using solution mining are the perfect match for PRO technology. Both brine and fresh water are available, and the extracted energy can be used to pressurise the water that is to be pressed down into the salt dome to dissolve the salt.

The waste products of the PRO process, the diluted salt water and the fresh water that does not pass through the membranes, can be pumped down into the salt dome. This means there are no major challenges in obtaining permits for discharge to the marine environment.

The market is large

Salt domes are widespread, and solution mining is used to extract salt in many places in Europe and the rest of the world. There is therefore a quite large market.

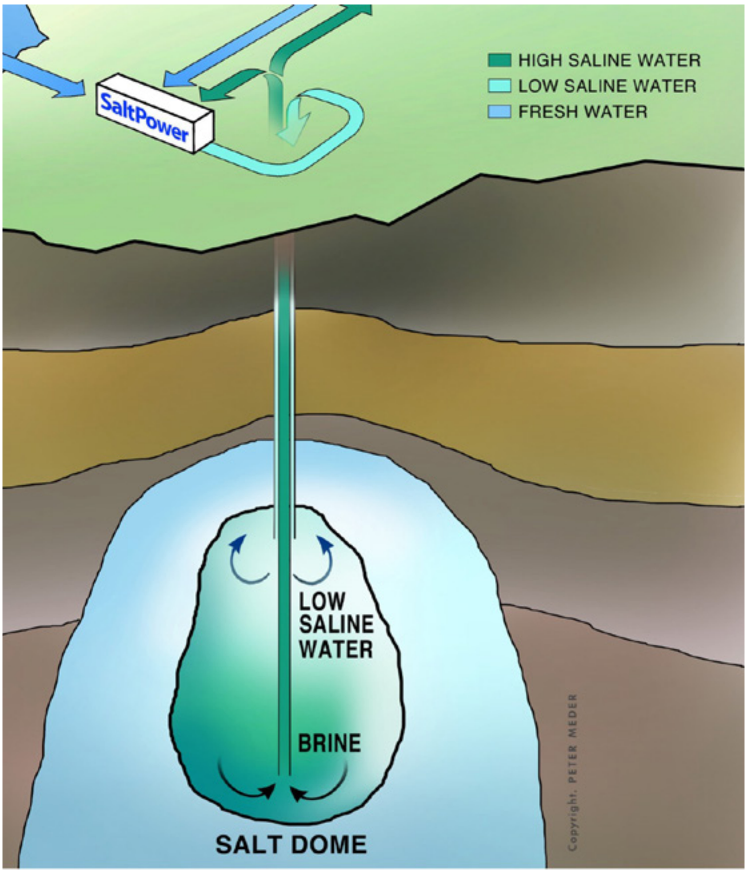
A cost analysis shows that the LCOE (Levelised Cost of Energy) for the demonstration plant is around EUR 50/MWh. That is more than the LCOE for onshore wind turbines and large solar energy plants, but in return the energy production from an osmotic power plant does not fluctuate and can run continuously regardless of wind strength and the amount of sunshine.

The results are so good that they pave the way for industrial plants, that is, a commercialisation of the technology.

But they also reveal that there is a need to lower the LCOE by energy-optimising the process and improving the membranes so that they let more fresh water through. Technologies and methods must also be developed for optimising pre-treatment of the water and for cleaning the membranes so that they do not become fouled.

The project also shows that the energy from the second stage with lower salinity and pressure only just covers the energy required to pressurise the fresh water and that is lost along the way in the turbine and generator. It is in the first stage at high pressure and high salinity that the energy must really be extracted.

In connection with the project, the PRO technology is communicated to visitors at the Universe Science Park experience centre on Als.



Solution mining with SaltPower osmotic pump

Test rig yields valuable experience

Before the work of designing and constructing a commercial plant can begin, there is a need to optimise the PRO process. Therefore a test setup, a test rig called Test Unit 1, is built at SaltPower in Sønderborg.

With the test system, SaltPower can carry out precise experiments with various membrane modules at full scale at varying pressures and salinities. Pre-treatment methods and control and management systems for ensuring continuous operation, including methods for cleaning the modules at regular intervals, can also be tested.

The project receives support from EUDP under the name 'Control methods and components for high salinity power and harsh environments'[22]. The budget is DKK 15.28 million (EUR 2.04 million), of which DKK 7.88 million is granted by EUDP.

SaltPower makes contact with the Israeli water treatment company IDE Technologies regarding the use of PRO with the hypersaline water from the Dead Sea. IDE has extensive experience with RO modules and has developed new methods for cleaning them, and the question is whether the methods can also be used for PRO plants at very high salinities.

IDE becomes a partner on the project together with Semco Maritime, which is responsible for the construction, as well as Dansk Salt (now owned by Nobian) and Sønderborg Fjernvarme.

The construction of the test plant is delayed by the COVID-19 pandemic, but in November 2020 it is ready in Sønderborg. In March 2021 it becomes fully operational, and the experiments begin.

In the meantime, SaltPower has entered into an agreement with Dansk Salt for the erection of a commercial plant at the salt extraction facility near Hobro. In connection with this, the organisation is expanded, so that SaltPower becomes less dependent on external resources.

The focus is now on the development of techniques and technologies that can be used in commercial osmotic power plants for the salt industry. Worldwide, about 110 million tonnes of salt are produced by solution mining each year, so the market is quite large.

Salt production is energy-intensive. Water must be pressed down to the salt dome so that the salt dissolves and the saturated brine is pressed up, and the evaporation process also costs a lot of energy. The salt industry wants to be less CO_2-heavy, and here SaltPower can help.

Talks with representatives from the salt industry suggest that there is interest in the technology, which can also be used when salt domes are to be emptied to create salt caverns for storing hydrogen produced with green energy.

To begin with, the test plant is used to test hollow fibre membranes, and 135 different experiments are performed with seven membrane modules. The experiments last from a few hours to 160 hours.

The membranes differ in that the fibres have different inner diameters. A larger inner diameter, for example 135 or 105 micrometres instead of 90, makes it possible to lower the fresh-water pressure, because the water can more easily flow through the fibres. In return, there are fewer square metres of membrane per module.

Pulse flow is tested

With the experiments, SaltPower attempts, among other things, to find out whether precipitation of minerals in the membranes can be prevented by controlling the flow of water. IDE Technologies holds a patent on a method to minimise fouling of RO membranes by letting the water flow pulse instead of flowing steadily [23, 24]

The method is called pulse flow, and the experiments are to show whether pulse flow can also be used for PRO. The idea is that the minerals in the water do not have time to precipitate in the membrane when the amount of water is constantly changing. The minerals are then flushed out of the system to a greater extent with the residual fresh water, the membranes' efficiency is improved, and their lifetime is extended.

Pulse flow may also reduce the amount of fresh water that does not pass through the membrane but is instead needed to flush out minerals. The hope is also that the method makes it possible to dispense with the energy-intensive nanofiltration pre-treatment of the fresh water.

The conclusion is that pulse flow works, but unfortunately not well enough to prevent the membranes' performance from falling over time. It is difficult to completely prevent the membranes from becoming fouled as minerals (not least silicates) from the fresh water are concentrated and precipitate in the membranes' porous layer.

Accumulation of carbonates in the membrane also creates another problem, namely that the pH value slowly rises, and that is something cellulose triacetate membranes cannot tolerate.

It is clear that, pulse flow or no, very thorough softening and filtration of the fresh water will be necessary before it reaches the membranes.

The membranes must be flushed clean regularly

Even the most thorough pre-treatment cannot completely prevent the accumulation of minerals, and SaltPower becomes aware of another challenge that lowers the osmotic pressure difference across the membrane.

No membranes are perfect, so a small amount of salt seeps in from the salt-water side and settles in the membrane's porous support layer. This results in so-called internal concentration polarisation (ICP), which means that the difference in salinity between the two water streams on either side of the active membrane layer becomes smaller. The osmotic pressure difference falls by more than 10 percent, and this hurts the flux.

SaltPower concludes that some of the problems with mineral accumulation and ICP can be alleviated by regular back-flushing, where fresh water is pressed through the membrane from the side where there is normally salt water. The water flow is then reversed, so that salts and other minerals are forced out of the porous membrane layer in a process called backflush. The membranes last much longer if they are maintained with backflush at intervals of a few hours.

Another aim of the test setup is to find out whether it is possible to use commercially available spiral wound RO modules for the PRO process at high salinities.

Thin-film composite (TFC) membranes are not as pH-sensitive as cellulose triacetate membranes, and they let more water pass through. These membranes therefore have the potential to be less delicate, require less maintenance and make PRO more efficient.

In the search for spiral wound TFC membrane modules that could potentially be used for PRO, SaltPower contacts every known supplier, but only one is willing to supply them. However, this membrane only worked up to 40 bar, and only for five minutes, before it ceased to function.

It is not immediately possible to find a new membrane that performs better than the hollow fiber membranes that have been used so far. But SaltPower continues its efforts to develop membranes that are optimised for PRO.

The results are presented at scientific conferences at home and abroad, including at Euromembrane 2021 in Copenhagen, Denmark, Euromembrane 2022 in Sorrento, Italy and ICOM 2023 in Chiba, Japan. In connection with the project, five patent applications are filed. [25, 26, 27, 28, 29]

[22] *'Control methods and components for high salinity power and harsh environments', EUDP 64019-0102*

[23] *'Forward osmotic and water hammer method of membrane cleaning', US Patent 10005040B2*

[24] *Liberman et al., 'Pulse Flow RO - The new RO technology for waste and brackish water applications', Desalination (479), 2020, DOI: 10.1016/j.desal.2020.114336*

[25] *'Anti-scalant process for an osmotic unit', US20240375057A1*

[26] *'Pressure retarded osmosis module', US20240375053A1*

[27] *'Osmotic solution mining', US12239940B2*

[28] *'Solvation entropy engine', US12398703B2*

[29] *'Brine saturator', US20230184230A1*

The hunt for better membranes is on

Hollow fiber cellulose triacetate membranes are developed for use in the RO industry.

They can be used for PRO, but are not ideal. The various experiments at SaltPower have shown that they are very sensitive to fouling, they cannot tolerate high pH values, and they cause a high pressure drop on the fresh-water side.

SaltPower therefore wants to investigate the possibilities of developing new membranes with accompanying membrane modules that are optimised for PRO. The membranes must have high water permeability and good salt rejection, and at the same time they must be mechanically stable at a very high pressure of up to 200 bar in order to optimise power output.

In collaboration with the Department of Chemical Engineering at the Technical University of Denmark (DTU) and Danfoss High Pressure Pumps, SaltPower launches a research project called 'High Pressure Membranes for next generation innovative green energy and water technologies' (Hi-PreM).

The three-year project starts in 2021 and is supported by Innovation Fund Denmark, which grants DKK 26.2 million out of a total budget of DKK 37.5 million (EUR 5 million)[30].

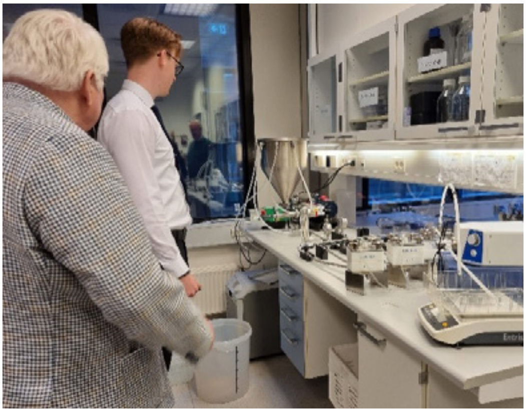
SaltPower builds a new test rig called Hi-Lab, where membrane modules can be tested at ultra-high pressures of up to 200 bar.

At Danfoss, the engineers set about developing high-pressure pumps, energy recovery units and turbines optimised for brine at very high pressure.

HiLab for testing high pressure modules

In connection with the project, researchers from DTU develop new, advanced computer models for how water and salt behave in and around the membranes. With methods for modelling the fluid dynamics (computational fluid dynamics, CFD) in three dimensions, it is possible to develop a virtual laboratory where various membrane modules can be tested on the computer. [31]

The researchers at DTU Chemical Engineering and SaltPower experiment with chemically modifying membranes so that they become more durable and let more water pass, while they reject the accumulation of salts and other minerals. They take their starting point in existing thin-film composite membranes, which do not have problems with high pH and are not as easily fouled.



DTU kemi

Laboratory experiments show that it is possible to improve commercial TFC membranes so that they get better water permeability and greater mechanical strength. In the long term, the results may lead to better membranes for PRO. [32, 33, 34, 35.]

SaltPower begins to experiment with using flat sheet modules, in a PRO module for the first time. The design is inspired by plate heat exchangers, where a stack of heat-conducting metal plates is clamped together in a frame in such a way that thin channels are formed between them. Through these run alternating cold and hot water, and patterns in the plates create turbulence that optimises the transfer of heat between the water streams.

The idea is to optimise the design for PRO. The metal plate between the fresh water and the salt water is provided with holes, and a semi-permeable TFC membrane is laid on top.

Then the fresh water can find its way to the salt-water side driven by the osmotic pressure.

Cassette based plate and frame module

But SaltPower has difficulty getting the technology to work, and it is still a challenge to find TFC membranes that can withstand very high pressure. The company has no other choice than to continue using the hollow fiber cellulose triacetate membranes, which have proved able to withstand a pressure of 70–80 bar – despite the many challenges associated with them.

[30] *IFD Grand Solutions 0224-00005B.*

[31] *Meisam, M. A. & Krühne, U., 'Computational Fluid Dynamics Modeling of Pressure-Retarded Osmosis: Towards a Virtual Lab for Osmotic-Driven Process Simulations', Membranes (14(11)), 2024, DOI: 10.3390/membranes14110236*

[32] *Malankowska, M. et al., 'Pressure Retarded Osmosis as a New Way for Sustainable Power Generation from Salinity Gradients', SSRN, 2023, DOI: 10.2139/ssrn.4363386*

[33] *Su, Z. et al., 'Comparison of 2D and 3D materials on membrane modification for improved pressure retarded osmosis (PRO) process', Chemical Engineering Science (285), 2024, DOI: 10.1016/j.ces.2023.119638*

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[35] *Malankowska, M. et al., 'Novel membrane modifications for pressure retarded osmosis as a new way for sustainable power generation from salinity gradients', Chemical Engineering Science (297), 2024, DOI: 10.1016/j.ces.2024.120221v*

SaltPower builds a commercial plant

Taught by the experiences from the demonstration plant and the test rig, SaltPower begins to design a commercial plant with a power output of 100 kW.

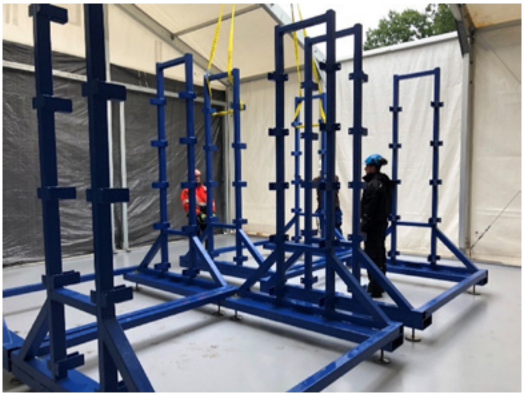
A number of employees are hired, so that the work on design, modelling and construction can be handled in-house.

The project is supported by a grant of EUR 2.4 million from Horizon 2020, the EU's framework programme for research and innovation, and is given the name 'Competitive and CO_2 Free Energy from Osmotic Power – Large Scale Deployment'.[36] The total budget is EUR 3.4 million.

The customer for the first commercial plant is Dansk Salt, part of the Nobian group. The plant is to be located at Hvornum near Hobro, where Nobian extracts salt from the subsurface. Nobian has a plan to become CO_2-neutral by 2040, and the PRO plant is to be part of the green transition.

In April 2020, SaltPower begins to design the large plant. Originally, the idea was to build a plant with four PRO stages and to use IDE's pulse flow technology, but taught by the experiences from the test rig, the design is changed. In addition, Nobian wants a larger plant than originally assumed, so a plan to make the plant modular and movable is abandoned.

In July 2022, a concrete foundation of 9 x 15 metres is poured, and a hall is erected with a soft roof that can be removed to ease the installation of the plant.



The site at Dansk Salt in an early phase of the comissioning

During autumn 2022 and spring 2023, the plant's components are delivered, and during summer 2023 it is assembled. Fresh water and brine with a salinity of 310 grams per litre are connected to the PRO plant, which is ready to run osmosis from September 2023.

In the following months, a long series of tests are carried out, and the process is continuously fine-tuned, so that the plant gets ever closer to being able to run continuously.

The PRO plant is built around 100 hollow fiber 10" membrane modules from Toyobo. They are 1.3 metres long and have a combined membrane area of 45,000 square metres.

To optimise the PRO process, it is decided to use two different membrane types. They differ in that the fibres have different inner diameters, namely 135 and 90 micrometres. Each of the 50 modules with 135 µm fibres contains 300 square metres of membrane, while the remaining 50 modules with 90 µm fibres each contain 600 square metres of membrane.

By placing the two blocks of membrane in series, the fresh-water pressure can be minimised. The fresh water passes first through the thicker fibres, where the fresh-water pressure does not need to be as high but the flux to the salt water is also not as high either, and then the diluted salt water is sent to the more efficient 90 µm modules. In this way, the plant has two stages, but with 70 bar on the salt-water side in both stages.

PRO replaces an electric pump

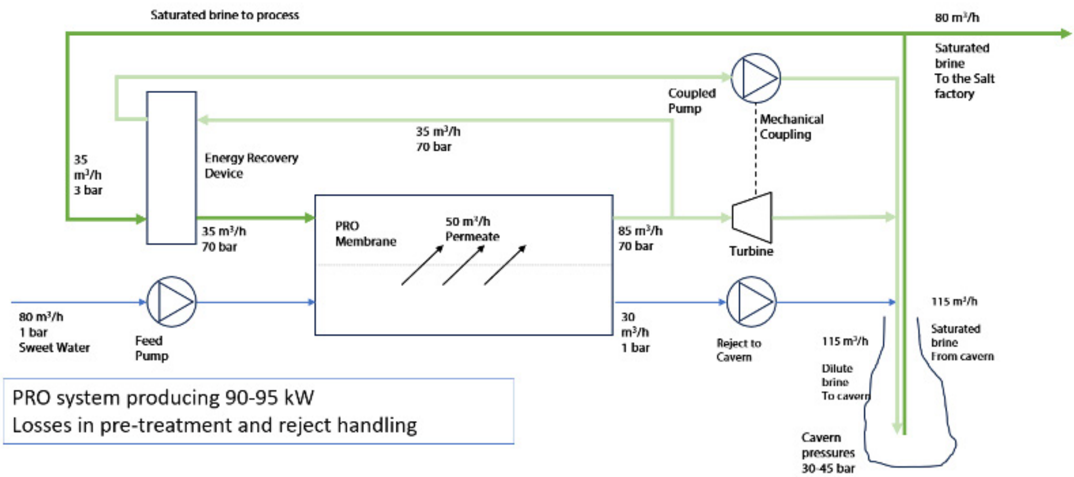
The industrial PRO plant is not to function as a classic power plant, but as an integrated part of the salt extraction process. The idea is to displace a large part of the electricity consumption for salt extraction by exploiting the osmotic pressure difference in two stages.

After pre-treatment, saturated brine and fresh water are sent into the membrane modules, where the osmosis causes the pressure to rise to 70 bar on the salt-water side. The diluted salt water meets a turbine connected to a generator, so that electric current is produced.

After the turbine, the pressure has dropped, and the remaining hydraulic energy is exploited to press the diluted salt water down into the salt dome.

In this way, the PRO plant can replace the electric pump that would otherwise pump fresh water down into the salt dome, and the electricity produced can be used for other purposes, such as other pumps in the system.

PFD of PRO system

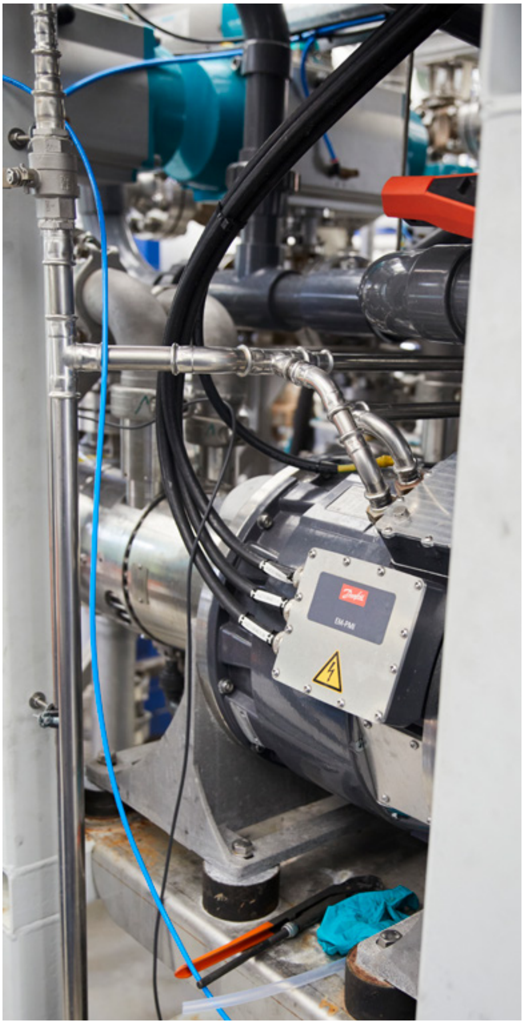


From one of Nobian's salt wells, the PRO plant receives about 35 cubic metres of saturated brine per hour – a small fraction of the brine that is brought up. Here it is pressurised to 70 bar by a Danfoss iSave 50 pressure exchanger. It is manufactured for the desalination industry, and like many of the other components in the commercial plant, it is made of super duplex stainless steel, which can withstand corrosion from the salty water.

The plant uses 80 m^3 of fresh water per hour, of which 50 m^3 passes through the membranes driven by the osmotic pressure difference. The result is 85 m^3 of diluted salt water at 70 bar, of which 35 m^3 is sent back to the pressure exchanger to pressurise the incoming brine. The rest drives a turbine, after which it is mixed with the 30 m^3 of fresh water that does not pass through the membranes.

Together with the diluted fresh water that has passed through the pressure exchanger – a total of 115 m^3 per hour – it is pressed down into the salt dome. There the water dissolves salt, and the process can start over.

For more details about the commercial plant.



Turbine Pump Unit

Pre-treatment requires energy

The PRO process itself gives a power output of about 90 kilowatts, but the pre-treatment of the water requires a considerable share of the energy. At the salt dome, distilled water is not available, as was the case at the salt factory at Mariager, so the PRO plant has to run on medium-hard groundwater (11 °dH).

Hard water can be treated with acid, which lowers the pH value, or with various antiscalants that prevent the precipitation of minerals. But the addition of chemicals will make the process more expensive, and even more important is the fact that they can change the chemistry in the salt dome.

For Nobian, it is absolutely crucial that the salt production is not disturbed by the PRO plant, and that the purity and salinity of the brine are not affected. The brine is used, among other things, for producing salt for foodstuffs and for the pharmaceutical industry, and it must be entirely pure.

To avoid the accumulation of silicates and carbonates in the membranes, it is also necessary to have a water purification system in the form of a large RO unit with 144 8-inch membranes (SUEZ AK-400 H). To press the fresh water through the RO unit, a considerable pressure of 7–8 bar is needed, which costs energy.

Still of piping in demonstration plant

For every 100 cubic metres of water that enters the RO unit, only 75 cubic metres is sent on to the PRO plant. The rest leaves as so-called reject, which contains the filtered-out substances. This reject is disposed of by pumping it down into the salt dome, which also costs energy. All in all, the energy costs associated with the pre-treatment come close to 50 kW, just over half of what is produced with PRO, but ongoing optimisations are bringing the loss further down.

The PRO plant is configured to run an automatic backflush every six hours, so that the membranes are flushed through. This means brief stops in operation and costs fresh water, but ensures stable performance of the membranes. They do not lose much efficiency, even over thousands of hours of operation.

In early 2025, the plant runs stably for hundreds of hours at a time, and thousands of cubic metres of water are pressed down into the salt dome. The PRO plant uses about 23 kW less than the pump Nobian would otherwise have used, and it is green energy. SaltPower is in conversation with several potential customers regarding the sale of further PRO plants, especially to the salt industry.

[36] *'Competitive and CO_2 Free Energy from Osmotic Power – Large Scale Deployment', European Commision, Horizon 2020 grant 954045, DOI: 10.3030/954045*

PRO is hard to make profitable

It gradually turns out that the brine also requires more thorough pre-treatment. A problem with gas accumulation in the brine stream is solved, but the brine also contains particles, which turn out to be a bigger challenge.

A 10 µm nominal filter proves insufficient to stop particles that wear on the pressure exchanger (the ERD unit). In addition, the filter quickly becomes clogged, so that it has to be cleaned with backflushing. This happens automatically, but each time brine is wasted.

In addition, SaltPower realises that the pressure exchanger does not yield as great an energy saving as expected when the entire process is analysed. The pressure exchanger is to pressurise the saturated brine using the pressure from the diluted salt water, but in the pressure exchange the two liquids become slightly mixed together. This means that the brine becomes a little less salty, so that some of the driving osmotic force is lost. The mixing loss must be taken into account when considering the use of an ERD for PRO. Calculations show that a high-pressure pump of the axial piston pump (APP) type can prove more efficient, all things considered.

SaltPower decides to rebuild the PRO plant so that the pressure exchanger is replaced with a high-pressure pump, and the design is simplified further by leaving out the turbine and generator. The plan now is for the PRO plant to more directly replace the electric high-pressure pump that Nobian uses to press water down into the salt dome, but without producing electric current. The pressure on the salt-water side in the PRO plant is to be lowered to the approximately 45 bar needed to press the diluted salt water down into the salt dome.

But the problem of particles in the brine still has to be solved. This can be done by installing a finer filter, for example a 5 µm absolute filter, but it will cost energy because there will be a significant pressure drop across the filter.

In the commercial plant, the power output is around 90 kW using 45,000 square metres of membrane, that is, 2 W/m^2. In laboratory experiments and in prototype PRO plants that only run briefly under ideal conditions, it is relatively easy to get the power density much higher, up to 5 W/m^2 but with prolonged operation using hollow fiber membranes, the efficiency is not satisfactory.

The osmotic pressure difference falls as the salt water passes through the module, because it is continuously diluted by the fresh water. The unavoidable concentration polarisation (ICP) caused by accumulation of salt in the membrane also lowers the osmotic pressure difference, so there is a long way from theory to practice.

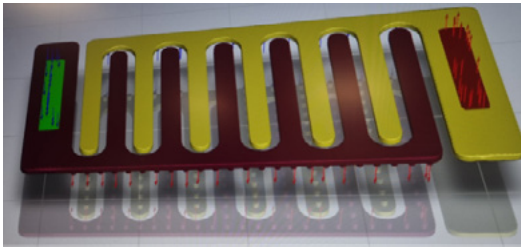
In addition, the salt water does not come into contact with the entire membrane surface throughout the module – there are dead zones that the salt water flows around. This is shown by CFD simulations.

The sensitivity to particles and pH as well as the need for a high fresh water pressure to pump the water through the thin fibres also argue against the use of hollow fiber modules for PRO. So does the price of the modules. The membranes alone cost about EUR 4,500 per module, and in addition there are EUR 2,000 per fibreglass pressure shell. SaltPower concludes that the low efficiency combined with a high price means that the hollow fiber architecture cannot be used for PRO with hypersaline water.

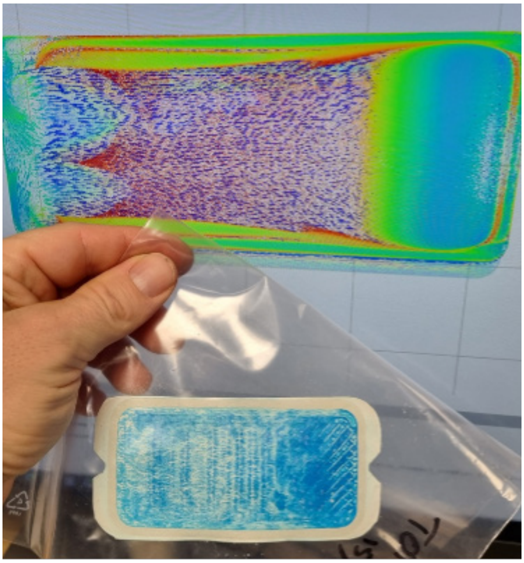
This becomes one of the aims of the project 'Breaking New Ground: Hyper-Salinity Gradient Membrane System for Osmotic Energy' (Hy-SaMOE), which receives a grant from Innovation Fund Denmark[37] of DKK 15.0 million out of a budget of DKK 20.6 million (EUR 2.76 million). Hy-SaMOE follows on from the Hi-PreM project, and the collaboration partners are the same, namely DTU Chemical Engineering and Danfoss High Pressure Pumps. The project is to run from 2025 to 2027.

New project to optimise membrane modules

In early 2025, the hope is still that it is possible to find new and better thin-film membranes that can withstand very high pressure and that can be packed tightly together. SaltPower wants to try to develop better membrane modules for the commercial PRO plant at Hobro.



3D Simulation Model

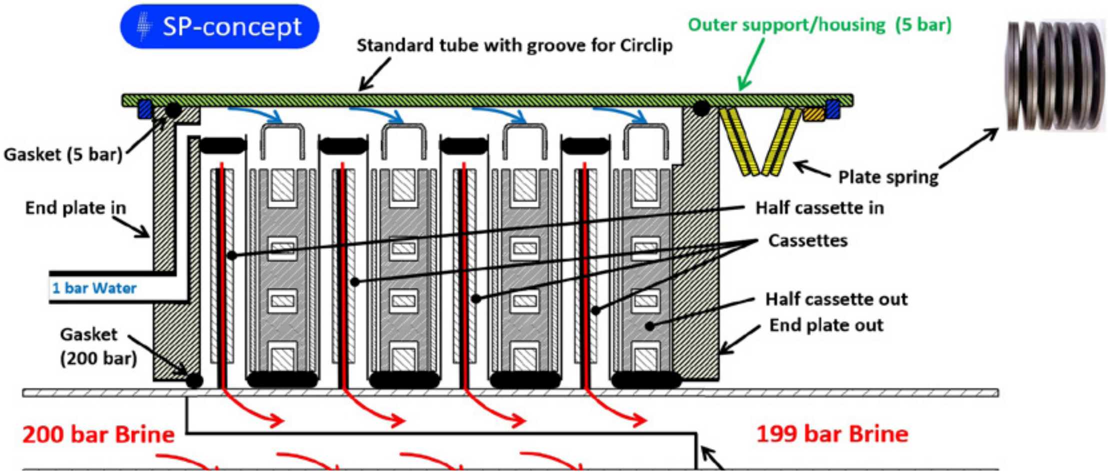


Stained Membrane and Simulation Result Comparison

3D Printed Spacer

Once again, the interest gathers around thin-film composite membranes in cassettes, which are continuously improved. SaltPower focuses, not least, on designing and 3D-printing spacers that control the flow of fresh water and ensure that it is distributed evenly across the entire surface of the membrane. At the same time, spacers can create turbulence that counteracts ICP.

The technology has the potential to solve some of the problems with the hollow fiber modules,



Cross-section of a potential design for a 200bar plate and frame solution

but it still requires that better membranes can be found. SaltPower has neither the expertise nor the financial resources to develop entirely new membrane types, and no usable commercially available TFC membranes can be found.

The ever better modelling tools also lead to an important realisation, namely that the pressure on the salt-water side does not necessarily have to be ultra-high to ensure the most optimal PRO operation.

In theory, the greatest possible power density is obtained from PRO with saturated brine at a salt-water pressure of about 200 bar – half of the osmotic pressure difference. But this requires perfect membranes, and in practice the osmotic pressure difference becomes smaller, because the salt water is quickly diluted, and because ICP plays a role. The higher the pressure, the more salt passes through the membrane's active layer, and then it lodges in the porous layer and lowers the osmotic pressure.

From a systems perspective, the benefit of ultra-high pressure above 110–120 bar is also doubtful, because the costs of components such as pumps, piping, fittings, valves and pressure vessels rise considerably.

But regardless of pressure, it gradually becomes clear that it is very difficult to make the PRO plant at Hobro economically sustainable. It produces green energy, but nowhere near enough for it to be cost-effective.

Even if it runs continuously and without problems, the capital expenditure (CAPEX) alone is so high that it will take at least a decade to earn the money back. And when operating expenses (OPEX) are also factored in, for example for ongoing replacement of valves and filters, the calculation does not add up at all.

PRO technology works on an industrial scale, but the economics do not add up. Even with better membranes, a techno-economic analysis from SaltPower shows that the LCOE from PRO at high pressure will remain well above the LCOE from the other green energy sources that PRO is up against.

Therefore, SaltPower decides to stop the ambitious energy project in January 2026 before the planned rebuilding work happens.

Year and week	Water in [m3]	Operation during PRO-mode Operation time [hours]	Energy using conventional pump [kWh]	Energy Saving [kWh]
2023	1711	19	1109	494
2024	36713	476	52591	10279
2025	25480	365	39465	6429
Total	**63904**	**859**	**93165**	**17203**

Water In [m3]	+	Brine In [m3]	=	To Cavern [m3]
63904		21993		89763

Energy savings over the years

By that point, the large PRO plant has pumped 90,000 cubic metres of water down into the salt dome. An electric pump would have used 93 MWh on the task, but the PRO plant saves Nobian more than 17 MWh.

SaltPower withdraws from the Hy-SaMOE project, which continues with the two remaining partners.

The small test setup µCell is donated to the Technical University of Denmark, while the two large test rigs Test Unit 1 and Hi-Lab are donated to Bochum University of Applied Sciences in Germany. There, research activities around PRO continue under Prof. Dr. Christine Kleffner, Chair of Sustainable Process Engineering.

The German researchers will use the test plants to try to identify and try out new application areas, with a particular focus on combining PRO with other innovative membrane processes in order to utilise resources energy-efficiently.
The commercial plant at Hobro is decommissioned, so that only the hall remains. Nobian can use that as a tool shed.

In the same spirit, SaltPower has released all patents filed in connection with the project. Rather than letting a decade of intellectual property sit unused, the company has made the entire portfolio freely available, so that future researchers and companies can build directly on SaltPower's work without legal barriers.

[37] *IFD Grand Solutions, 4355-00003A*

Experiments continue abroad

For now, PRO is finished in Denmark. But in Fukuoka in Japan, efforts to extract energy from salt water continue.

On 5 August 2025, a 110 kW PRO plant is inaugurated which uses brine from the Mamizupia desalination plant as well as wastewater from the local sewage treatment plant to produce electricity.

The residual product from the production of fresh water contains eight percent salt, and for environmental reasons it must, in any event, be diluted before it is discharged into the sea. That is what the PRO plant takes care of.

The plant, which cost EUR 3.8 million, is to go through a five-year test period during which it will be continuously optimised. At the time of writing, there are no public data on its operation. In the Netherlands, the company REDstack pursued attempting to extract energy from the salinity gradient between fresh water and salt water in a different way, namely with reverse electrodialysis (RED) – a kind of salt battery in which the chemical potential difference is converted directly into electric energy.

In RED, it is not fresh water that passes through membranes, but instead the ions of the salt water. They move through two different ion-selective membranes. Cation exchange membranes allow only the positively charged sodium ions to pass through to the fresh water, while anion exchange membranes allow only the negatively charged chloride ions to pass. In this way, a voltage difference is built up.

With hundreds of membrane pairs, between which fresh water and salt water flow alternately, the voltage difference can become substantial, and electrodes at the ends of the stack of membrane pairs ensure that the electric energy can be utilised.

Since 2014, a pilot plant on the Afsluitdijk causeway, which separates the fresh water of the large lake IJsselmeer from the salt water of the Wadden Sea, has functioned as a research and development platform. REDstack has ambitions to build a large demonstration plant, but the company faces many of the same challenges as SaltPower, including expensive and inefficient membranes and a need for thorough and energy-intensive pre-treatment of the water to avoid fouling of the membranes. The problems with fouling are not made smaller by the use of sea and lake water.

Other technologies for exploiting salinity gradients are also being researched. One example is ionic nano-osmotic diffusion (INOD) from the French company Sweetch Energy, which is attempting to develop extremely efficient nano-scale ion membranes. Another is capacitive mixing (CapMix), where the idea is to develop a kind of capacitor whose capacitance – and therefore the voltage difference between two electrodes – changes as one switches between salt water and fresh water.

Around the world, especially in Europe, researchers continue to investigate the possibilities of exploiting the large amount of energy that is released when salt water meets fresh water. They are not giving up, because the world needs more green energy.

Final words

In Denmark, it proved impossible to make PRO economically meaningful with the current membrane technology.

The people behind SaltPower are sad that a decade of intensive research and development has not been crowned with success. But at the same time, they are proud of what they have achieved.

No-one else in the world has attempted to extract energy from the meeting of saturated brine and fresh water, and certainly not on an industrial scale. Countless problems have been solved along the way, and in the end a commercial PRO plant produced green energy that displaced more polluting energy from the electricity grid.

The idea was good, just not good enough when it met the harsh economic reality. Now Jørgen M. Clausen hopes that others will one day pick up the baton and take up osmotic power.

Perhaps a breakthrough in membrane technology or new ideas for applications will breathe new life into PRO technology. Then the experience that SaltPower has gained, and which is described in this document, may perhaps be of help.

Jørgen M. Clausen gets the last word: 'Anyone can see that osmotic power is an interesting field of research, and we have shown that it is possible to extract energy from osmosis. One fine day it must be possible to make this form of renewable energy economically sustainable.'

Jørgen M. Clausen at SaltPower Hobro Pilot Plant

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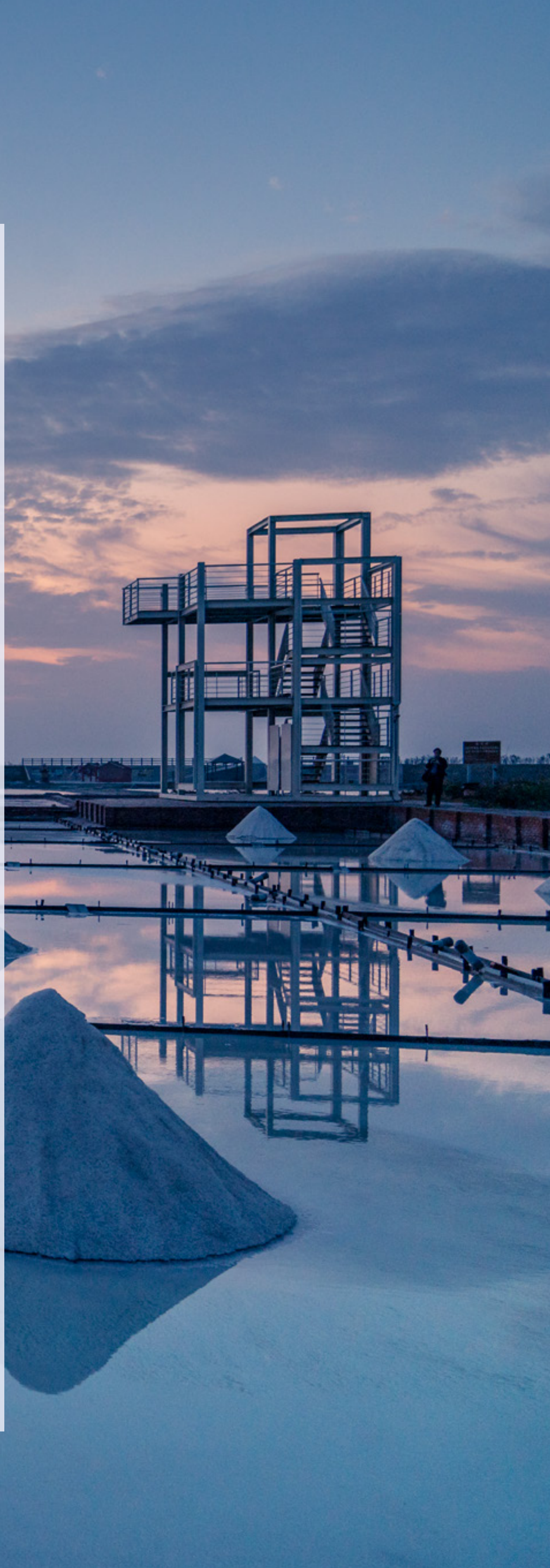

Appendix

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List of Patents

Patent Family Title	Representative Publication	Jurisdictions
Anti-scalant process for an osmotic unit	WO2023036943A1	United States, European Union, Australia, Israel, Canada, Great Britain
Brine saturator	WO2021239701A1	European Union, United States, Israel, Canada, Germany
Osmotic processes	WO2022129044A1	United States, European Union, Israel
Osmotic solution mining	WO2021165337A1	Brazil, United States, European Union, Israel, Australia, Canada, Mexico
Pressure retarded osmosis module	WO2023036944A1	United States, European Union, Israel, Great Britain
Pressure retarded osmosis system	EP4467809A1	India, United States, European Union
Pretreatment integration in pressure retarded osmosis	GB202414435D0	Great Britain
Solvation entropy engine	WO2021165338A1	Brazil, United States, European Union, Israel, Australia, India, Canada

For details on individual jurisdictions and legal status, please contact SaltPower.

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