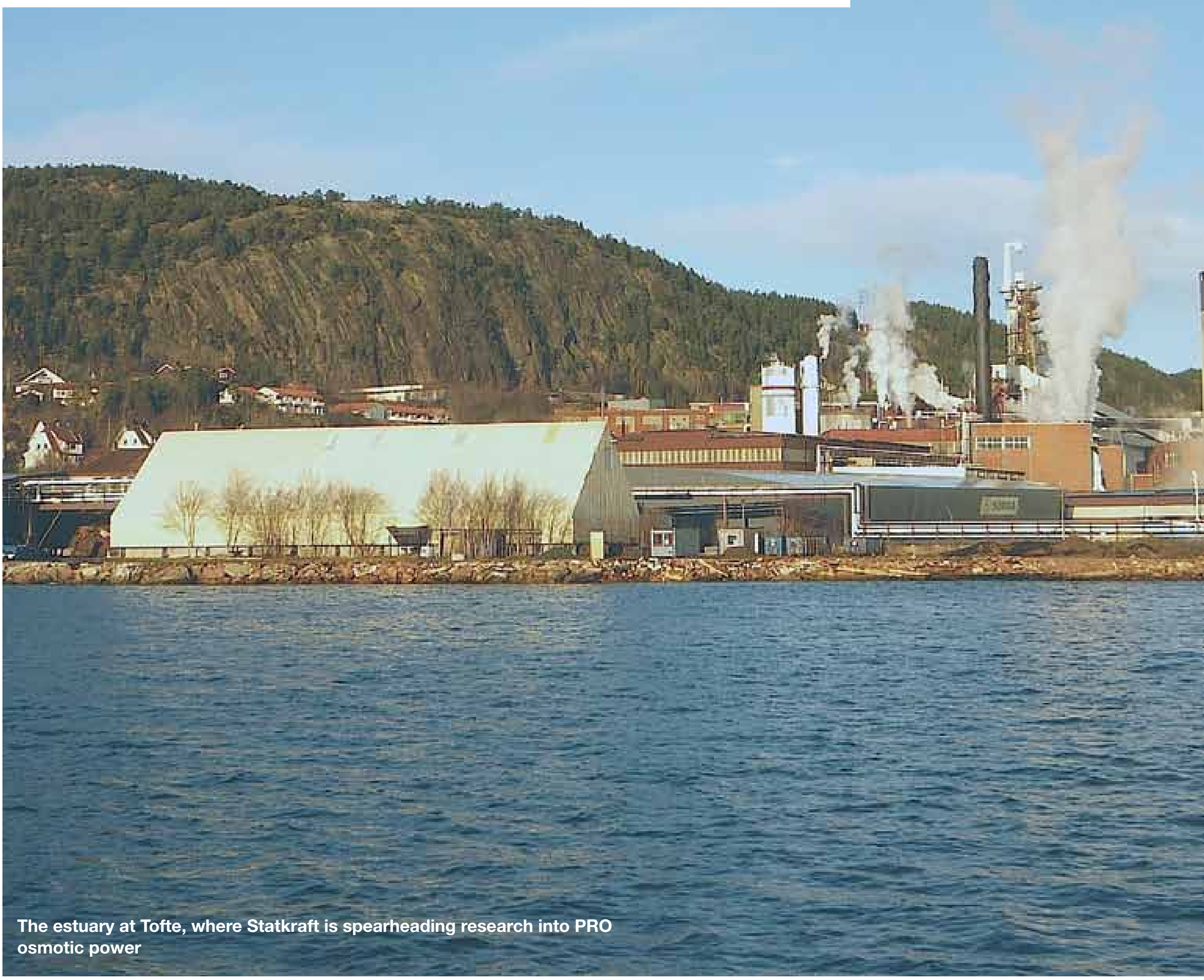
POWERING UP USING OSMOSIS

MEMBRANES MOVING AHEAD ON THE SALINITY GRADIENT

If you're overlooking an estuary, you'd never guess that vast amounts of energy are flowing into the sea. But what if you place a thin and strong membrane between the fresh and brackish water? Then it might be possible to tap so much energy that tens of thousands of households can be provided with electricity. At least, that is the goal of Dutch and Norwegian researchers, as they seek to make osmotic power commercially viable, as **Tseard Zoethout** reports.



The estuary at Tofte, where Statkraft is spearheading research into PRO osmotic power

Last century osmotic power was no more than a pipe dream for researchers but in the past five years all that has changed. In November 2009 Norwegian utility company Statkraft launched a 1–2 kW prototype plant in Tofte, south of Oslo, while REDstack, a spin-off of Dutch R&D company Wetsus, is scaling up its 5 kW pilot at the salt refinery in Harlingen to a 50 kW demonstration plant halfway up the country's Afsluitdijk causeway.

With rapidly improving advances in membrane technologies, its huge potential is beginning to come to light. According to Wetsus, Dutch coastlines and rivers hold somewhere in excess of 18 TWh of potential generating capacity, enough to power 1 million households. Meanwhile in Norway, estimates suggest the technology could generate some 12 TWh annually from the country's fjords.

By its very nature, osmotic power's development potential seems far larger than that of tidal energy, as any place where fresh and salt water meet – from the Rhine and the Danube to the Mississippi and Yellow River – a constant flow of electricity can be generated without the risk of disturbance from heat waves, rain or lack of wind. Moreover, osmotic power barely impacts potentially fragile ecosystems because engineers can easily house the installations in the basement of a building where it will work silently and, thanks to the (electro) chemical process, with almost no moving parts.

OLD THEORY GETS 21ST CENTURY MAKEOVER

Despite recent advances the theoretical foundation of osmotic power is almost a century and a half old. In 1885 Nobel prize winning Dutch chemist Jacob van 't Hoff proved that thermodynamic laws apply not only to gases. He showed that in a semi-permeable membrane only the liquid, not the dissolved particle, can pass – a phenomenon he called osmotic pressure. Two world wars passed before Richard Pattle, in a 1954 *Nature* paper, suggested using the pressure between seawater and river water to generate electrical power.

He estimated the potential salinity power of average ocean salinity and annual river discharges to be between 1.4 and 2.6 TW/year. For almost twenty years, his dialytic battery remained a theoretical exercise with power density of $0.05/m^2$.

At the end of the 1950s Sidney Loeb and Srinivasa Sourirajan, two chemical engineers working on their PhD thesis at the University of California, Los Angeles, took Pattle's research a step further. Using synthetic membranes and high-pressure pumps, Loeb and Sourirajan managed to reverse osmotic pressure and pump fresh water from seawater, a principle that continues to underlie the seawater desalination process.

In 1972 Israel's Negev Institute for Research in Beersheba invited Loeb to pump water from deep beneath the desert and filter it through membrane purification. A new breakthrough followed. Loeb came up with the idea of separating a water tank into two parts using a semi-permeable membrane in which the osmotic process would pull fresh water to salty water, increasing the pressure to about 12 atmospheres before activating a small turbine. But Loeb, who died in December 2008, couldn't put his invention, pressure retarded osmosis (PRO) as he had dubbed it, into practice. Forty years ago synthetic membranes were simply not cheap or thin enough, or sufficiently durable to resist the operating pressures required.

MEMBRANE DURABILITY HITS GENERATION POINT

According to Thor Torsen and Torleif Holt from Norwegian state R&D company Sintef, who have been credited with bringing new life to Loeb's idea, present-day membranes are now durable enough for PRO installations to generate electricity. Backed up by thorough calculations, some 15 years ago they persuaded Statkraft to carry out a feasibility study for commercial exploitation of osmotic power.

Since the turn of the millennium the pair have made made further scientific progress and published several widely acclaimed papers. Statkraft has also scaled up its experiments, first with a test facility at Sintef's headquarters in Trondheim, and then later with a small demonstration plant in the Sunndal fjord estuary, before launching a full-scale site in Tofte, at a former production unit of the adjacent Södra Cell pulp factory some 60 miles (96 km) southwest of Oslo.

Though the ability to produce energy from PRO has been proven, big challenges lie ahead. Whereas in the first series the membranes were unable to accumulate even 100 mW/m^2, the latest incarnations can generate more than 3 W/m^2 bringing the ultimate goal of 5 W/m^2 within sight. Multi-year prototype tests in Tofte, which started in November 2009, should show which membranes offer the best chance for a viable commercial osmotic plant. Researchers will also look at reducing energy losses from water transport.

'Efficiency has to increase two- to five-fold before this plant can be commercially viable', said Statkraft's vice president Stein Erik Skilhagen from the stern of the ferry transporting guests and international media to Tofte for the opening of the PRO plant. 'We are going to test different membranes of cellulose acetate and composites of different polymers since they will have to stand pressures of 12 atmospheres for at least six to 10 years. During testing, we are expecting to reach 5 W/m^2. When we are able to do that, we will scale up within two to three years.'

At present, the Tofte facility can only generate enough energy to power a coffee machine but within five years the utility hopes to have the world's first commercial osmotic plant in operation. As big as a football field, and with a membrane surface of 5 km, it will generate 25 MW, enough to provide electricity for 15,000 households. Post-2020, Statkraft predicts there will be dozens of plants in operation, generating 12 TWh, or 10% of Norwegian demand.

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Norway is an ideal location for rolling out the technology but it may face greater obstacles in warmer climes. In locations further south all kinds of biological processes are likely to see increases in the volume and variety of contaminants. The surface of thousands of square metres of membranes can quickly become contaminated by micro-organisms, reducing or even nullifying their power generating capacity. Additionally, pollution levels in most rivers outside of Norway are higher and the removal of suspended solids can have a serious impact on the efficiency of the technology.

After over six months of testing, Stein Erik Skilhagen sounds optimistic. 'It took a while before we knew how the whole system worked but, after monitoring, it seems it is within parameters and the core, the membranes, are well handled. Pre-treatment of seawater is good. The pressure exchanger functions well and the cellulose membranes have passed the proof of confidence. Power density of our osmotic prototype is now roughly 1 W/m^2. We will be happy to reach the lab results of 2 W/m^2 this year or the next.'

Nonetheless, the biggest challenge the technology faces is, and will remain, the performance of the fragile membranes. To maintain enough power, Statkraft has to clean them regularly with chlorine, a cleaning agent until recently in use at the paper mill, or by back flushing, reversing the whole system. 'Therefore we want to test other membranes in the near future and different ways to store them. One option is putting the membranes in spiral bound elements with some limitations to the speed of the water flows', said Skilhagen .

'Another option is storing them in hollow fibre, a proven technology that resembles the capillary of a plant or a tree and can withstand high pressures', he added.

THE DUTCH EYE 'BLUE ENERGY'

Dutch researchers at KEMA and Wetsus fear that the costs of bio-fouling removal in Norway will eventually prohibit the further development of PRO and have pinned their hopes on a completely different technology. Based upon experience from Israel, KEMA and building company VolkerWessels have developed a salinity gradient plant, activated by reverse electrodialysis (RED). KEMA dubbed their brainchild 'blue energy' and received the Dutch innovation award for their invention a couple of years later.

Blue energy is comparable with a common dialysis device in which, contrary to pressure-retarded osmosis, the ions in the salty water flow through the membranes rather than the water itself, simultaneously through one that allows positive ions and one that allows only negative ions to pass.

Since the biggest difference in salinity exists between brine and purified water, in 2005 the European Salt company (ESCO-salt) closed a deal with Wetsus, Harlingen Industries and Magneto Special Anodes, Schiedam, to test a 5 kW demonstration plant in Harlingen in the Netherlands, where ESCO mines common salt. According to Simon Grasman, project coordinator at REDstack, this form of blue energy is within three years of becoming cost-efficient for chemical industrial solutions.

'We are testing a new generation of membranes. Ordinary membranes from electrodialysis are less suited because of a too-high resistance', he said. 'The power density is too low. With Fujifilm, Tilburg and the support of our governmental agency, we're developing heterogeneous membranes that are thin as well as strong. Five years ago those membranes were more than half a millimetre. Now we aim at less than half this size. It's a fairly simple calculation: the thinner the membranes the lower the resistance will be and therefore the more power we can generate.'

According to Grasman, RED or the dialytic battery is on the verge of a breakthrough. He notes that although costs of available membranes are currently €30/m^2, this will decrease substantially while the power density of dialysis membranes, now at 1.2 W/m^2, is steadily on the rise. Grasman believes it won't be long before a maximum of 5 W and €5/m^2 will be achieved. By that stage 'overall costs for RED technology are approximately €8 cents/kWh, rather high when compared with energy from fossil resources, but substantially less than power from heavily subsidised large scale wind farms', he said.

Blue energy is far from being fully developed. Putting practical issues such as crooked stacks from excessive temperatures in the water inflow aside, Dutch research is now focused on substantially improving the performance of the system. Even so, in 2009 Piotr Dlugolecki of Twente University showed that the power density can quadruple by optimising the flow of water. To mix and evenly divide the brine and purified water, RED uses spacers, honeycomb-like structures between the positive and negative membranes.

But there's a problem. Currently available spacers cannot transport charged particles. A researcher, now working for Wetsus, has therefore developed conductive spacers that nullify this so-called shadow effect, doubling the power density. By further optimising mixture and the flow of water along the membranes, the researcher was also able to increase the power.

'We've taken [this] research a step further by thermal pressing profiles on the available heterogeneous membranes, having no need for spacers anymore', said Grasman. 'All sides of the membranes are now conductive to ion transport. On the downside, not using spacers anymore, we lost some turbulence but reasonably priced membranes with a power density of 2 W/m^2 more than compensate for that. Our goal of 5 W/m^2 is coming in sight.'

DUTCH OSMOTIC SUITABILITY QUESTIONED

Kees van den Ende, innovation manager at KEMA's energy knowledge centre and an early presence in the RED technology field, believes only a small proportion of Dutch rivers and even the IJsselmeer are suitable to generate osmotic energy.

'In theory, blue energy has the potential to generate 2.5 MJ, leading to an overall potential of 7000 MW in the Low Countries', he said. 'Although that's pretty impressive, one has to subtract losses due to fluctuating water flows, diminishing returns, shipping, anti-salinisation, drinking water and other societal limitations. After subtraction, our former national hydraulic laboratory (now Deltares) found out that not more than 500 MW for salinity gradient energy remains, depending on the location one is going to choose.'

One of the best locations is the Afsluitdijk, the 20 km dyke separating the salty North Sea from the less brackish IJsselmeer. Hopes are high to build a 200 MW osmotic power plant in its northern region before 2020. REDstack already has all the relevant permits for a 50 kW demonstration plant at Breezanddijk, though financing for the €3.5 million project has yet to be secured. Grasman says R&D will focus upon the effectiveness of the membranes and purification of the water flows. 'We will try different stacks – for instance new, heterogeneous membranes that capture ion conductivity in tiny, microscopic balls on the surface of the membrane, potentially reducing costs by a factor of two to five', he said.

To tackle bio-fouling REDstack has tested flow cells as well as pre-filtration. 'For over a year we've successfully used flow cells, simulating stacks or the throughput of the water for membranes for huge discharges. We only had to clean the cell, by reversing the flow, a couple of times. Another method is using the soil of the IJsselmeer as pre-filtration. The considerably lower discharge is more than compensated by the much bigger surface area', he concluded.

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REDstack aims for commercial osmotic energy within three years