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Osmotic power — a new, renewable energy source

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ABSTRACT

The mixing of freshwater and seawater where rivers flows into the salty ocean releases large amounts of energy. This energy can be harvested and made into electricity using pressure retarded osmosis (PRO). This is the concept of osmotic power, a new and yet unexploited source of renewable energy. The idea of exploiting the energy from mixing fresh water and sea water with PRO was first developed by Prof. Sidney Loeb in the early seventies. After some years in the eighties with limited progress in the field, the Norwegian power company Statkraft engaged in technology development in the mid nineties aiming at cost-effective osmotic power production. Today Statkraft is the world leader in development of osmotic power, and have made state of the art achievements during the last few years. The work has been focused on the design and production of a semi-permeable membrane optimized for osmotic power. During these years the power density of the membrane has increased from less than 0,1 W/m^2 up to today's membranes producing close to 3 W/m^2. The target of 5 W/m^2 necessary to produce osmotic power on commercial basis seems within a few years time. The development has consisted of testing existing membranes, and improving these, as well as designing completely new membranes. An insight to this work will be given, and also give some results from the testing of existing and novel membranes operated in PRO. The world's first osmosis driven power plant will be put into operation during 2009 in the southeast of Norway. The main objectives of the prototype are twofold. Firstly, confirming that the designed system can produce power on a reliable 24-h/d production. Secondly the plant will be used for further testing of technology achieved from parallel research activities to substantially increase the efficiency. These activities will mainly be focused on membrane modules, pretreatment of water, pressure exchanger equipment and power generation (turbine and generator). The presentation will give a brief introduction to the prototype system, the expectations for operation and maintenance, and also some outline of the next steps in the development of osmotic power. The paper gives a general overview of the obstacles that needs to be addressed, and expectations of the results that should be achieved. With these assumptions handled, osmotic power can develop into a new, renewable source of energy well capable of competing on the energy market in the near future. Once again, Prof. Sidney Loeb contributes to solve one of the major challenges to establish a sustainable world for the next generations.

Keywords: Osmotic power; Renewable energy

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Dedicated to Prof. Sidney Loeb (1916–2008). December 14, 2009, Sede-Boker, Israel

1. Introduction

During the past decade, global climate change challenges and the world's steadily growing demand for energy have brought the need for more renewable energy to the top of the international community's agenda. Therefore, the United Nations decided at the first World Summit on Sustainable Development (2002, Johannesburg) to create a specific forum dedicated to further advance the deployment of renewable energy sources: the International Conference for Renewable Energies. At the forum's first meeting, all countries reaffirmed their commitment "to substantially increase with a sense of urgency the global share of renewable energy in the total energy supply." During a follow-up meeting in 2008, it was clearly stated that in order to reach this goal, it is imperative to use both existing and new renewable energy sources.

Based on more than a hundred years of experience in developing and operating hydropower, the Norwegian utility company Statkraft* has set the course for corroborating its leading role in renewable energy generation by investing in the quest of new renewable energy sources in strategic areas. As a result the company is today the world leader in development of osmotic power, and has made state of the art achievements during the last years.

2. Background

The pressure on the environment caused by human activities and especially the climate change challenges related to continuously increasing greenhouse gas emissions, calls for a thorough research of alternatives. Since the Kyoto Protocol in 1997, efforts to reduce carbon emissions have been intensified. Among others, the EU adopted an integrated energy and climate change policy in December 2008, including ambitious targets for 2020. It aims at bringing Europe onto a more sustainable energy track – towards a low-carbon future with an energy-efficient economy, which will cut greenhouse gases emissions by 20%, reduce energy consumption by 20% through increased energy efficiency, and meet 20% of Europe's energy needs from renewable sources.

Despite these globally shared efforts, fossil fuels will continue to remain the most important source of energy in the decades ahead, as they are the world's main source of low-cost and broadly available energy. In addition, the global consumption of energy is growing, so the need for more renewable energy will become even more pressing in addition to the need to reduce our dependency on finite and carbon-intensive fossil fuels as an energy source.

In this context of climate and environmental challenges, R&D has a key role to play in finding new solutions. From a company's perspective, R&D is also about safeguarding business outlook and shaping growth ambitions. This means that we need to improve existing technologies as well as work on building new renewable energy solutions.

Statkraft has been engaged in developing new renewable energy technologies since the early 90's. Based on the company's history as a major Norwegian power generator, our focus has been on harvesting the energy that is available along the far-reaching Norwegian coastline. For more than a decade we have been working internally and in close collaboration with R&D parties as well as universities in order to find ways to produce renewable energy from the natural forces of the ocean.

3. The power of osmosis

It has been known for centuries that mixing freshwater and seawater releases energy. For example, a river flowing into the salty ocean is releasing large amounts of energy. The challenge is to utilise this energy, since the energy which is released from the mixing of salt and freshwater leads only to a very small increase of the local water temperature. During the last few decades at least two concepts for converting this energy into electricity instead of heat have been identified.

One of these is pressure retarded osmosis (PRO). Thanks to this technology it may be possible to utilise the enormous potential of a new, renewable energy source. This potential represents a worldwide electricity produc-

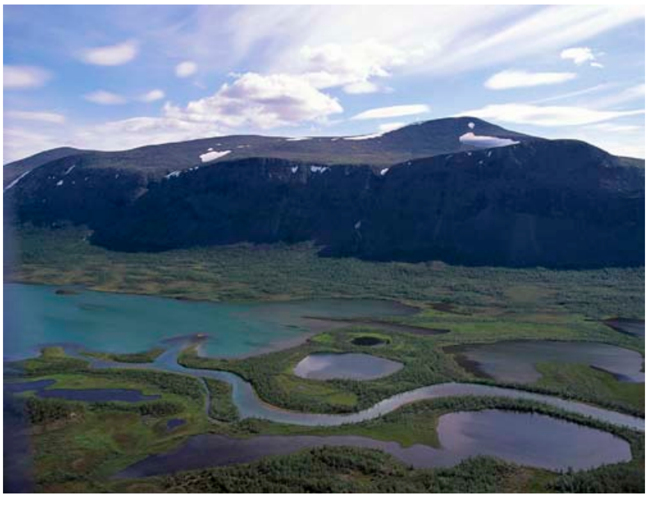

Fig. 1. Example of the river outlet where energy is released when fresh water meets seawater.

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[*] Statkraft develops and generates electricity from water, wind, biomass, sun and natural gas, while also being a major player on the European energy exchanges. In 2008, Statkraft achieved gross operating revenues of € 3.1 billion and employed more than 3000 employees in 23 countries. With an average annual electricity production of about 46,000 GWh only from hydropower, it has become one of the most important renewable energy producer in Europe

tion of more than 1600 TWh per year – equivalent to half the annual power generation in the European Union.

For pressure retarded osmosis, also known as osmotic power, the released chemical energy is transferred into pressure instead of heat. This was first pointed out by Professor Sidney Loeb in the early 1970's, when he designed the world's first semi-permeable membrane for desalination of saline water for production of drinking water based on reverse osmosis.

Statkraft has been engaged in the research and development of osmotic power and related enabling technologies since 1997. Together with its international R&D partners, Statkraft is the main active and most progressive technology developer globally and therefore an osmotic power knowledge hub. The team has made state-of-the-art achievements in terms of developing a new energy efficient membrane technology during the past years.

Osmotic power is based on naturally occurring osmosis, triggered by Nature's drive to establish equilibrium between different concentrations in liquids. Osmosis is a process by which solvent molecules pass through a semi-permeable membrane from a dilute solution into a more concentrated solution as illustrated in Fig. 2.

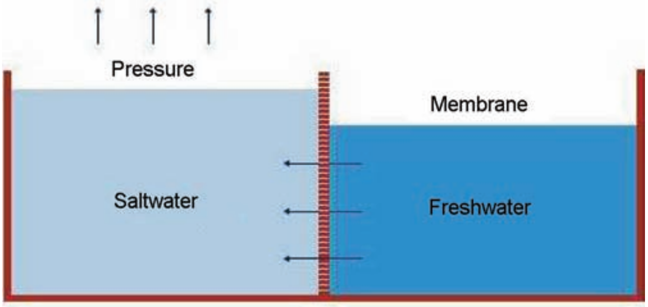

Fig. 2. The principle of pressure retarded osmosis.

The difference in concentration of salt between seawater and freshwater creates a strong force towards mixing. The effects of this strong force to mix can be intensified through a special membrane which separates salt and freshwater in a finite space and which only lets the water pass through the membrane, while the salt ions are rejected. In this way, an osmotic pressure can be achieved by the amount of freshwater moving to the seawater side. This pressure can be in the range of 24–26 bar depending on the salt concentration of seawater.

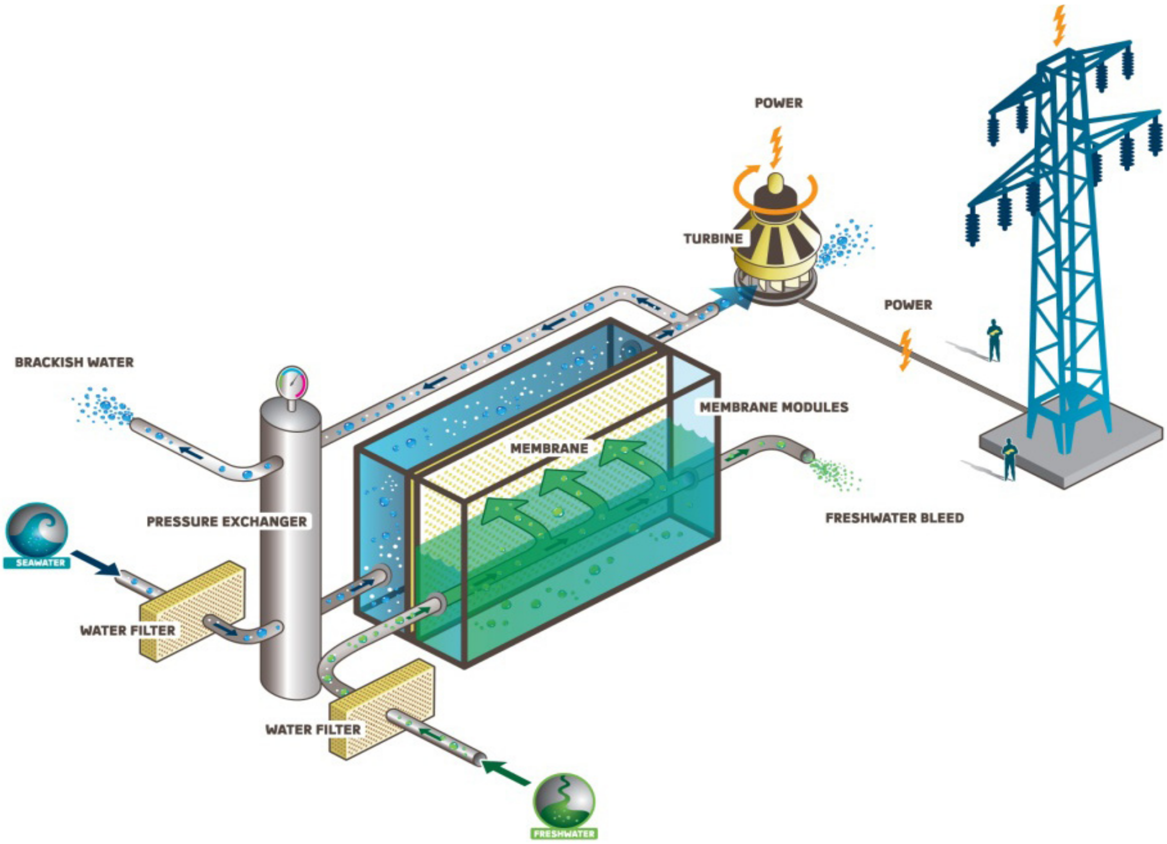

Fig. 3. The principle of osmotic power utilises the energy outcome of mixing water with different salt gradients. In the process the water with low salt content moves through the membrane to the side with the higher salt concentration and creates increased pressure due to osmotic forces. Given the sufficient control of the pressure on the saltwater side, approximately half the theoretical energy can be transformed to electrical power, meaning that the operating pressure is in the range of 11–14 bar enabling the generation of 1 MW per m^3/s of freshwater.

More precisely, in a PRO system filtered freshwater and seawater are led into a closed system as illustrated in Fig. 3. Before entering the membrane modules, the seawater is pressurised to about half the osmotic pressure, approximately 12–14 bar. In the module freshwater migrates through the membrane into the pressurised seawater. This results in an excess of diluted and pressurised seawater which is then split into two streams. One third of this pressurised seawater is used for power generation in a hydropower turbine, and the remaining part passes through a pressure exchanger in order to pressurise the incoming seawater. The outlet from such a plant will mainly be diluted seawater (brackish water) that will be led either back to the river mouth or into the sea.

Consequently, the higher the salinity gradient between fresh- and saltwater, the more pressure will build up in the system. Similarly, the more water that enters the system, the more power can be produced. At the same time, it is important that the freshwater and seawater is as clean as possible. Substances in the water may get captured within the membrane's support structure or on the membrane surfaces, reducing the flow through the membrane and causing a reduction in power output and overall system efficiency. This phenomenon, commonly known as fouling, is linked to the design of the system, to the characteristics of the membrane, to the membrane module, and to the pre-treatment of the fresh water and the sea water.

An osmotic power plant will to a large degree be designed of existing "off-the-shelf" technology. The key components are the membranes, the membrane modules, and the pressure exchangers and the lion's share of efforts to commercialize osmotic power is dedicated to improving and scaling up these components.

3.1. Environmental issues

The mixing of seawater and freshwater is a process that occurs naturally all over the world. Osmotic power plants will extract the energy from this process without polluting discharges to the atmosphere or water. Moreover, this process produces no other emissions that could have an impact on the global climate. Osmotic power's excellent environmental performance and CO_2-free power production will most likely qualify for green certificates and other supportive policy measures to increase the share of renewable energy.

One area where there has been some discussion is whether there will be a negative effect on the marine environment due to the discharge of brackish water by the osmotic power plant. This may alter the local marine environment and result in changes for animals and plants living in the discharge area. However, the osmotic plant will only displace the formation of brackish water in space without modifying the water quality so this will not be a significant environmental impact.

Since most rivers run into the ocean at a place where people have already built cities or industrial areas such as harbours, most of the potential sites for osmotic power generation can be utilized without affecting pristine areas. Moreover, the plants can be constructed partly or completely underground (e.g. in the basement of an industrial building or under a park) which will make them very discreet. In these areas the environmental impacts on shore are estimated to be of minor importance. These impacts will mainly be related to the building of access roads, channels and connections to the electricity grid. A power plant the size of a football stadium could supply around 30,000 European households with electricity.

Careful building of a plant in already-developed areas will cause no negative effects, since its visual impact can easily be minimised through underground locations or mitigated through appropriate landscaping such as tree and bush planting. It might even be possible to improve the present condition of biotopes along the river or in the estuary and the sea.

3.2. The market potential

To establish an understanding of the potential addition of power generation capacity osmotic power might represent, surveys of the sites where freshwater meets seawater has been made. To evaluate the potential power production from a river detailed information about water quality, seasonal variations, sea water salinity and quality, and also of course the amount of freshwater available is required. Based on this information it is obvious that there are several regions in both the northern and southern hemisphere that has a significant potential. North-America, South-America, Europe, North Asia and Africa all has a substantial resources that can contribute to their renewable energy mix.

The worldwide potential is more than 1600 TWh per year, whereas 170 TWh per year could be generated in Europe. It is likely that osmotic power can make a sizeable contribution to the growth of renewable energy in the future. This would also represent a new attractive business potential for both the commercial power companies and the technology suppliers.

4. Osmotic power development status

The efforts by Statkraft in the field of osmotic power was initiated already in 1997 when the Norwegian research organization SINTEF was engaged to perform feasibility studies of the concept on behalf of the company. The result of the study was that osmotic power could have a significant, global potential and also involved similar activity to hydropower regarding the use of water to produce renewable energy. But the studies also revealed that in particular one component would require significant improvement, and this was the semi-permeable membrane.

Based on the early findings, the work since then has mainly been focused on the design and production of a semi-permeable membrane optimized for osmotic power. From economical calculations and estimations of the development in the energy market, a target for the efficiency of the membranes have been set at 5 W/m^2 for producing osmotic power on commercial basis. During these years the power density of the membrane developed by Statkraft has increased from less than 0.1 W/m^2 up to today's membranes producing close to 3 W/m^2. The development has been aimed at testing commercial membranes, as well as developing new membranes designed for osmotic power.

The main challenges one has experienced when testing existing membranes and also trough the development of new membranes, are related to the internal concentration polarization within the membrane. To exploit the driving force that the osmotic pressure differences represent, the membrane needs to be as thin as possible, but at the same time withstand the pressure difference. The water flux should be in the similar range as the common RO membranes and also the retention of salt is important. Although the best RO membranes today has the potential of producing more than 6 W/m^2 based on their water flux and salt retention, the internal concentration polarization due to the thickness limits the efficiency to less than 1 W/m^2.

In addition to the development of the membrane, there are also significant activities on the design and development of the membrane modules. The standard spiral wound module design has limitations both in the internal flow pattern and pressure losses, and there are also limitations in regards to the common design for scaling up to larger units. Since an osmotic power plant will require several million square meters of membrane, the modules should contain several hundreds or even thousands of square meters. In this respect, the following design criteria have been suggested:

- the elements must be able to have flow on both the freshwater and the seawater side of the membrane
- the elements must contain a large membrane area
- fouling must be minimised
- the design must be cost-effective

This development of osmotic power is managed by Statkraft, and is executed mainly by research groups in Germany, Norway and the Netherlands, as well as in the USA. There are, however, several other groups working on elaborative topics both in North America and in Asia.

Based on the last year's results of development of membranes in particular, but also an improved understanding of the system technology and potential, Statkraft decided in fall 2007 to build a complete system for testing the osmotic power concept. Based on this decision Statkraft has designed a prototype plant where pressure retarded osmosis is used to drive a turbine, based on feed of seawater and fresh water from natural sources.

5. The osmotic power prototype

The world's first osmosis driven prototype for power generation has now been put into operation. In the southern part of Norway, approximately 1 h drive from Oslo, a complete prototype of an osmotic power plant has been built. The prototype represents a major milestone towards the commercialization of osmotic power and creates a unique test site for future technology development of osmotic power. The plant did generate the first small kWh of electricity from osmosis in November 2009, and the first proof of the concept of producing power by osmosis has been recorded.

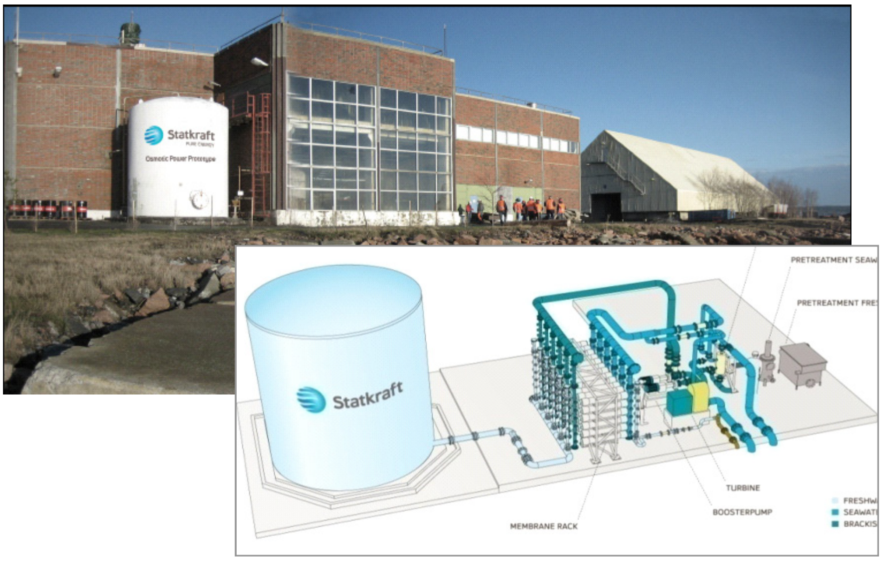

Fig. 4. The osmotic power prototype located at the east coast of Norway.

The prototype is designed to be used as a laboratory for the ongoing development of the technology. In this respect, it will contribute to technology enhancements in order to reach the objective of producing power at a competitive cost, and creating the basis for up-scaling the various components to commercial scale.

In addition to the on-going research, with the main focus being on the membranes and the membrane modules, the prototype will serve as a catalyst for developing partnerships and building relationships with interested parties. The prototype facilitates the creation of partnership for development of osmotic power outside Statkraft's core geographic area, and it increases the awareness of osmotic power among governments and manufacturers that are invited to test the technology. Furthermore, the prototype will be a starting point to test and measure environmental challenges such as measuring potential algae bloom related to the discharge of brackish water.

When building a prototype for a complete new technology, several considerations had to be made related to the choice of location. First of all, fresh water and sea water with satisfactory quality must be available. Secondly, the location shall be available for the researchers, suppliers and also governmental representatives, hence not too far from a large city. Based on these requirements, the small community of Tofte, 1 h drive from Oslo, was chosen.

5.1. Design of the prototype

The prototype is designed with all necessary systems and components for continues PRO operation. Based on the assumption that a membrane with an efficiency of 5 W/m^2 will be developed during the lifetime of the plant, 10 kW installed power capacity was set as the overall design criteria. This gave the lead for water supply for both water qualities, as well as sizing of the individual components.

The sea water feed to the plant is supplied trough water pipes from approximately 30 m below sea level, just outside the harbour. The water is filtered through a mesh before it enters the plant.

The fresh water at the Tofte location flows from a small lake up in the hillside. The water quality is typical for this kind of water sources in the southern part of Norway. The content of NOM (natural organic matter) is significant, and also the content of other particles. There are also large seasonal variations in the water quality. The water is filtered through a mesh, but for safeguarding of the PRO membranes, the secondary treatment of water is done by ultrafiltration. A major focus activity will be to identify the minimal pre-treatment necessary to operate the plant, and to design the appropriate system optimised to fulfil the requirements for operating the membrane system in a continuous mode through the entire lifetime of the membranes.

Fig. 5. The PRO membranes with pressure vessels and PE piping.

Fig. 6. 2 energy recovery devices recycling the PRO pressure.

For this plant 2000 m^2 of membrane has been installed based on a modified spiral wound 8″ module. This is a convenient and standardised design where membranes easily can be replaced and also a standard that other suppliers can relate to. After some time in operation we also expect to test alternative module design optimised for PRO operation. The first membranes installed are based on conventional cellulose acetate membranes, redesigned for PRO operation. The membranes will be replaced when new and improved membranes are designed and produced in sufficient amounts.

Besides the membrane system, the plant is equipped with 2 specially design energy recovery devices. Although this technology is well proven in desalination system, the installation in this plant is unique due to the low operating pressure. It will be very important to learn the opera-

Fig. 7. The turbine generating electricity in the osmotic power prototype.

tions of these units in PRO, and also to test the efficiency and leakages experienced in a low pressure system.

A turbine with a generator is installed to generate electricity from the pressurised water. With continues flow of water at approximately 12 bar, a Pelton turbine was chosen. To be able to generate as much electricity as possible from the membranes installed, the turbine must be optimised for the correct flow of water at the given pressure. In a full scale installation, the combined efficiency of the turbine and generator is expected to exceed 85%.

The overall objectives of the prototype are twofold. Firstly, confirming that the designed system can produce power on a reliable 24-h/d production. Secondly, the plant will be used for further testing of technology achieved from parallel research activities to substantially increase the efficiency. The performance and efficiency of the individual component, as well as the system efficiency as a whole, will be directed towards the targets for commercial production of osmotic power. These activities will mainly be focused on membranes, membrane modules, pre-treatment of water, pressure exchanger equipment, and power generation (turbine and generator).

5.2. The prototype as an attractive test site

The prototype will be the first complete test site for osmotic power where one can test single components as well as the entire osmotic power system. Statkraft will use the prototype for enabling testing also for groups or companies other than their partners to spur the interest and knowledge for osmotic power. Representatives for technologies such as promising forward osmosis membranes, alternative energy recovery units or alternative solutions for energy efficient pre-treatment of water will be welcome to both gain knowledge as well as possible testing at the site. Statkraft believes that the bridging of knowledge and common efforts among all the different groups working on osmotic power or similar technologies is crucial to achieve commercial operation in the foreseeable future.

6. The road towards commercial osmotic power generation

Based on the information provided in this paper one can clearly understand that there are several technical and system-related tasks to be addressed. And there are today several groups of companies and research institutes working to solve the challenges discussed earlier. So, what is then necessary for establishing osmotic power as one of the contributor to the generation of renewable energy in the future? We believe that to succeed in the development of osmotic power, one need to understand the most important value drivers.

Statkraft has spent significant time and effort on the development of osmotic power, and will continue to do so. The solution is very attractive due to the environmentally friendly solution it represent, but to really make this a new and attractive solution in the renewable energy market one will depend on the three major factors.

6.1. Supplier industry

It is well known that osmotic power was founded in the field for desalination. And there are still significant resemblance looking into the individual components. It is crucial that the future suppliers for osmotic power such as membrane manufacturers are willing to spent time and resources on bringing the technology from where it is today and improve and scale it up into an industrial size.

6.2. Energy utilities

Statkraft strategic long term interest in osmotic power is to include it in the renewable energy portfolio. With the increasing focus on the environment and similar prising of renewable energy, this will also be the case for several other utilities around the world. To be able to verify for the future supplier industry that with the right solutions and pricing level, the demand will be unlimited, more utilities such as Statkraft must show their believes in osmotic power. Statkraft alone will not as a single player be able to establish a global osmotic power market necessary to realise the waste potential.

6.3. Framework conditions

During the last few decades one has seen the growth of new solutions for harvesting renewable energy in Europe. These solutions, such as wind power, solar power and soon also marine energies has been considered much to expensive compared to the alternative fossil solutions. But with the increasing understanding of the consequences and the accompanying expenses using polluting solutions for producing power, a change in the whole market pricing has been establish. These days, several European countries give substantial economical support to the establishment and growth of new, renewable solutions. For example, countries such as Spain, Germany and also Italy have established support schemes for solar power that has spurred a whole new industry. A similar situation is also in the UK where marine energy will be supported for the establishment and growth of a business that is crucial for the country to reach their ambitions for renewable solutions.

These framework conditions will also be critical for osmotic power. With a predictable support scheme and incentives for competitiveness also in the early maturing phase, both the supplier industry and the utilities will be ready to participate. Statkraft has already encouraged the European Union to include osmotic power as a recognised part of the marine energy sector, and will continue to do so also for the individual countries.

7. The competitiveness of osmotic power

The estimated energy cost of osmotic power is comparable and competitive with the other new renewable energy sources, such as wave, tidal and offshore wind being in the range of 50–100 €/MWh. This cost analysis is based to the major extent of the existing market pricing for the individual components in large scale project. For the membranes and also other units that still requires more extensive development one has used the assumption that the future pricing will not be very different from similar technology today due to the enormous potential in the economy of scale for this global market. In the illustration below a comparison with other energy technology is given, and it is obvious that with a success in the areas described in this paper, osmotic power has a bright future.

8. Conclusion

Statkraft are convinced that osmotic power will develop into a new, renewable source of energy, well capable of competing on the energy market of the future.

Once again, in memory of Professor Sidney Loeb, we would like to express our gratitude to and admiration of his vision at a very early stage, his persistence, his ingenuity, and his valuable contribution to solve one of the major challenges humanity is faced with: Establishing a sustainable world for coming generations.

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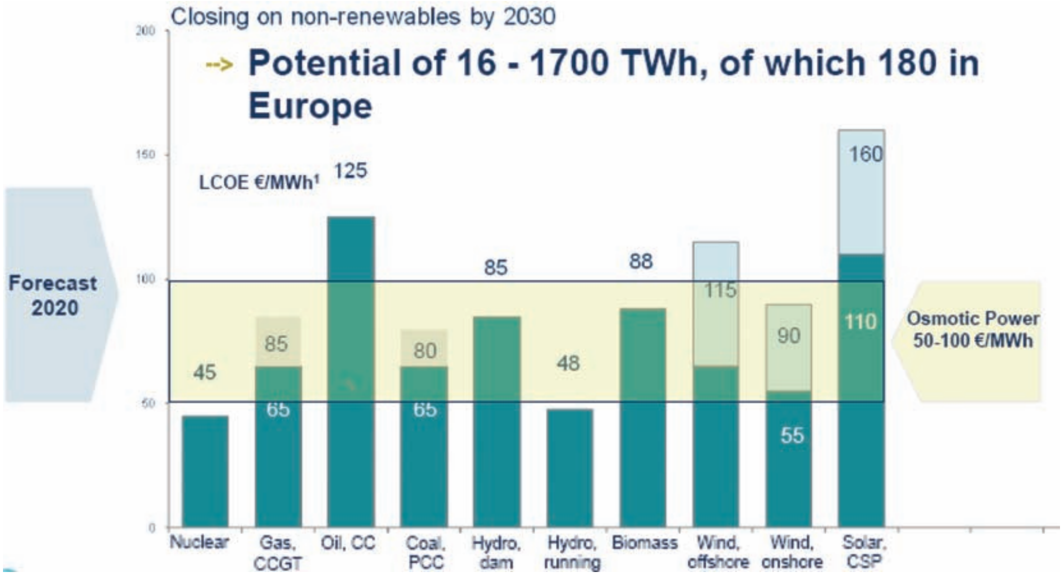

Fig. 8. Competitiveness of osmotic power compared to other renewable and non-renewable sources by 2030.