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Final Report

The potential of osmotic energy in the EU

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Consortium Leader

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Executive Summary

In the context of renewable energy supply in the Member States of the European Union, energy generation using osmotic power plants represents a future possibility. **The first part of this study therefore examines osmotic energy technologies** in terms of their technical state of development, a technical comparison of osmosis technologies with each other and other energy systems, as well as an economic overview. **In the second part of the study, the potential for osmotic energy generation in the EU Member States is determined**. The aim of the study is thus to provide an overview of the technology systems and the general energy potential. Information regarding the energy potential from osmosis was gathered through a combination of literature searches and interviews with experts in the field.

Osmotic power plants are relatively new technologies and there are still **technical challenges to overcome.** These include the development of more efficient technology components, such as membranes. In order to remain competitive with other established renewable energy technologies, research and development must therefore be constantly driven forward.

The evaluation of osmosis energy systems indicates that **three systems will soon reach marketable scaling**. These are pressure retarded osmosis (PRO), reverse electrodialysis (RED), and ionic nano osmotic diffusion (INOD) technology which is an evolution of RED technology based on nanotechnologies. Both PRO and RED, which are currently at technology readiness level (TRL) 7, and INOD with TRL 6-7, offer good modular scalability and can guarantee continuous operations. The membranes within the stack components in particular offer potential for improving the efficiency of the technologies by using modern materials, such as nanotechnologies. In addition to PRO and RED technologies, there are also capacitive mixing technologies, but these are still in the development stage with a TRL of 4.

The **levelised cost of electricity** (LCoE), the investment costs (CAPEX) and operating costs (OPEX) are presented as part of the economic feasibility study. For PRO a LCoE of 0.15–0.19 €/kWh is anticipated in the short term, which is expected to fall to below 0.09 €/kWh after upscaling and technology development. For RED a reduction from 0.11–0.12 €/kWh to 0.05 €/kWh in 2030 for the 100 MW scale is forecast. INOD is expected to reach a LCoE of 0.08 €/kWh within the next 5 years from 0.15 €/kWh for the first 1 MW commercial plant. However, the initial investment costs are very high and depend on the size of the plant systems. Operating costs are estimated to be rather low with 3–5% compared to the CAPEX.

In the second part of the study, the theoretical and the technical **energy potentials at estuaries of rivers in the Member States of the European Union** are determined. The estuaries of rivers flowing into seas are considered in each case, as the necessary differences in salinity between fresh water (rivers) and sea water (salt water) can be utilised here. For some countries (Luxembourg, Austria, Slovakia, the Czech Republic, Hungary), which have no estuaries due to their continental location, or countries with no permanent or too small river flowrates (Belgium, Denmark, Malta, Cyprus, Slovenia) no potential can be determined. For the other countries, based on historical average flow rates, there is a total theoretical potential of around 70.6 GW, which corresponds to an estimated technical power potential of 6.4 GW at a river water withdrawal rate (proportion of river water that is removed for the osmosis system and returned to it shortly afterwards) of 20% as a conservative assumption and an efficiency of 45%. The market assessment done by Sweetch Energy confirms the overall osmotic power potential in the EU as estimated is around 6.6 GW, with an average withdrawal rate between 15% and 20%.

With an operating time for the osmotic energy systems of 8,000 h/a (equivalent to a 91% load factor), this **can provide approximately 50.8 TWh of energy annually, which represents 1.7% of the electricity generation in the EU in 2021**. The load factor takes into account various factors such as downtime for maintenance, unexpected failures, and exceptionally low river flows. The impact of climate change on the frequency, severity and duration of droughts is beyond the scope of this study and has not been taken into account when assessing the osmotic energy generation potential. France, Germany, Italy, the Netherlands and Romania in particular have considerable potential. Despite high flow rates, Nordic countries only have a comparatively low potential due to low salinity differences between rivers and the adjacent seas.

The detailed assessment of the power and energy potential in the EU Member States can be found in the **datasheets** published together with this report.

In addition to the potential from rivers and oceans, there is further **potential from hypersaline sources** like desalination brines, natural sources (hypersaline lakes, salt domes, hypersaline geothermal water) or industrial brines (brine waste water, oil field brines, evaporation ponds – solar salterns). However, their potential was not assessed in this study.

In summary, osmosis technologies offer a promising alternative for energy generation as they are **renewable, supply stable electricity** on a 24/7/365 basis (except for maintenance and exceptionally low river flow), can be switched on/off within minutes, produce no direct CO_2 emissions and have low operating costs. However, there are currently only pilot plants in the small-scale sector, but this is set to change in the coming years up to 2030. The investment costs for the construction of power plants are also still high. However, the theoretical and technical energy potential is large and can make a good contribution to renewable energy transformation in the future.

Table of Content

Acronyms

Acronyms	Meaning
AEM	Anion Exchange Membranes
AFM	Activated Filter Media
BoP	Balance of Plant
CAPEX	Capital Expenditure
CapMix	Capacitive Mixing
CEM	Cation Exchange Membranes
CF	Cartridge Filter
CMX	Cation Exchange Membrane
EU	European Union
FFH	Fauna-flora-habitat
GAC	Granular Activated Carbon
IEM	Ion Exchange Membrane
INOD	Ionic Nano Osmosis Diffusion
LCoE	Levelised Cost of Electricity / Energy
MEB	Mixing Entropy Batteries
MF	Microfiltration
NF	Nanofiltration
OPEX	Operational Expenditures
PRO	Pressure Retarded Osmosis
PV	Photovoltaics
RED	Reverse Electrodialysis
RO	Reverse Osmosis
SGE	Salt Gradient Energy
TFC	Thin-film Composite
TRL	Technology Readiness Levels
UF	Ultrafiltration
WACC	Weighted Average Cost of Capital

Definitions

Definitions	Explanation
Brackish water	Mixture of fresh water and sea water with salt concentration from 0.5% to 3.5%
Fresh water	River water with salt concentration up to 0.5% by weight
Salt water	Sea water with salt concentration up to 3.5% by weight
Hypersaline sources	Water sources with salt concentration of 3.5% or more by weight

1 Introduction and approach

The use of renewable energies is becoming increasingly important in society for a successful transformation of energy supply. One promising option for generating clean energy is salinity gradient energy (SGE) (synonyms: osmotic energy or blue energy), which is generated especially in estuaries by the potential difference between water bodies with different salt concentrations (e. g. fresh water from the rivers and salt water from the oceans). The technology of osmotic power plants based on this principle has made considerable progress in recent years. These power plants are able to generate renewable energy close to consumption centres in the EU. The SGE can therefore be allocated to energy from hydropower.

Estuaries, where fresh water from terrestrial drainage mixes with sea water, are the most obvious locations for the utilisation of SGE, as this is where the deepest salinity gradients are available and many of them are located in or near a city. The first studies to quantify the global SGE resources in estuaries were carried out in the 1970s and estimated the global theoretical SGE potential at 1.4 to 2.6 TW. For Europe, only isolated studies have been carried out for specific regions. [1]

Several technologies have been developed to utilise the SGE. Three of these technologies are membrane-based and are called pressure retarded osmosis (PRO), reverse electrodialysis (RED) and ionic nano osmosis diffusion (INOD) as a further development of RED which are all in higher stages of development. Recently, other technologies such as capacitive mixing (CapMix) or mixing entropy batteries (MEB) have also gained in importance but are still in the earlier development stages. The difference between PRO and RED lies essentially in the different permeability of the membranes for ions or water molecules. In PRO, the water molecules diffuse from the side with a low salt concentration (fresh water side) to the side with a high salt concentration (salt water side). This increases pressure in a chamber on the salt water side used to drive a turbine generating electricity. In the RED, however, the membranes are permeable to ions. The difference in concentration creates an electrical potential between two electrodes, which can be used to generate energy. MEB use electrochemical cells and capacitors to generate energy. These technologies have the potential to significantly improve the production of renewable energy from salt water in the future.

The aim of this study is to present and compare the osmosis technologies that can be used in the future. Both technical and economic parameters are presented and compared with each other. The technical optimisation potential is also a target parameter. In addition, the theoretical and technical energy potentials through osmosis for the EU Member States are determined in the second part of the study.

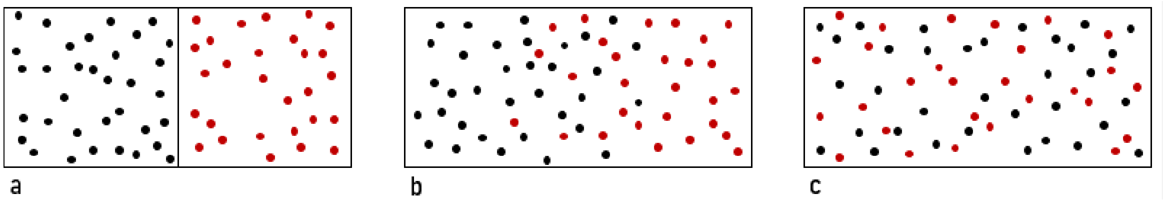
Information regarding the energy potential from osmosis was gathered through a combination of literature searches and interviews with experts in the field. Scopus and other literature databases were utilised for conducting literature searches, employing keywords such as "osmosis technologies, potentials of osmosis energy, efficiency of osmosis technologies". The interviews with industrial companies active in the construction and operation of osmotic power plants were conducted in Nov. 2023 and Dec. 2023 and focused on both technical and economic issues. A sample questionnaire can be found in Appendix A.1. The structure of the study is as follows: First, it explains the technologies and their operating principles. The individual components are discussed in particular. Second, the economic parameters of the systems are discussed. Next, the theoretical potential for suitable estuaries in the EU Member States is estimated. Finally, the main results and conclusions are summarised.

2 Osmotic power plants

2.1 Leading forces and theoretical specific energy

Osmosis is based on the process of diffusion – a term that describes the compensation of a concentration gradient between two substances through a transport of molecules. This process can be illustrated by Figure 1: Two gases or liquids are separated by a wall (a). When this wall is removed (b), the molecules begin to move and the substances begin to mix. This process continues until the concentration gradient is eliminated (c).

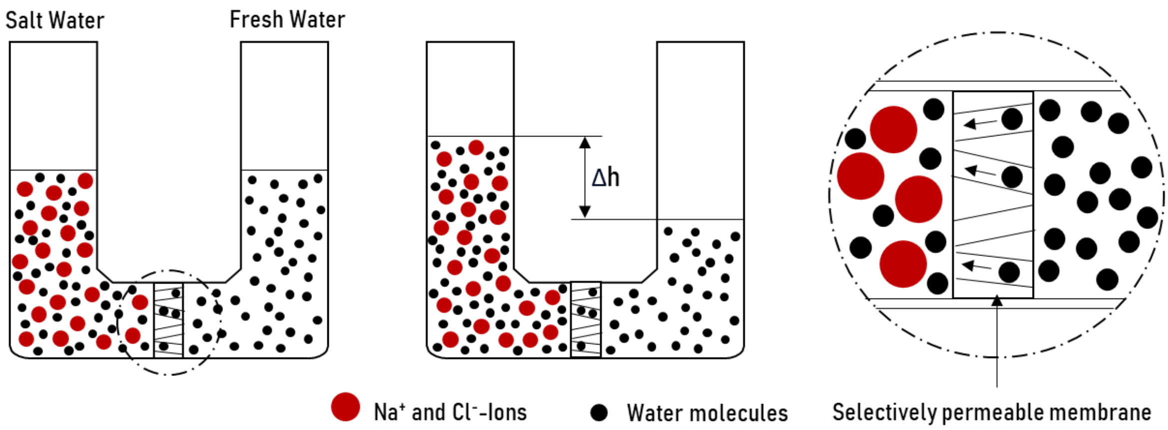
Figure 1: Process of diffusion.



(a) Two gases or liquids are separated by a wall. (b) When this wall is removed, the molecules begin to move and the substances begin to mix. (c) This process continues until the concentration gradient is eliminated. Source: own representation (based on [2]).

In the case of osmosis, the liquids are not separated by a wall, but by a selectively permeable membrane [2]. This process can be illustrated by Figure 2: In a U-shaped tube, two liquids are separated by a selectively permeable membrane. Between these two liquids, there is a concentration gradient that aims to be compensated [3].

Figure 2: Process of osmosis.



Source: own representation (based on [2]).

In the case of most osmotic power plants, these two liquids are salt water and fresh water. The salt water contains positively and negatively charged ions – mainly natrium- and chloride-ions (Na^+ and Cl^-) [4]. These ions (displayed in red) are bigger than the water molecules (displayed in black) and are not able to pass through the membrane (see Figure 2). The selectively permeable membrane allows only the water molecules to pass through [2]. In order to equalise the concentration gradient, the water molecules from the side with the lower solute concentration (fresh water side) diffuse to the side with the higher solute concentration (salt water side) [5]. This causes the level of the salt water solution to rise, until the concentration is equalised or until the hydrostatic pressure within the tube compensates the osmotic pressure that leads the molecules to pass through the membrane [6].

The pressure on the salt water side rises until it reaches a limit, called the osmotic pressure. The maximum osmotic pressure can be defined as the greatest possible pressure difference developed between a solution and its pure solvent. However, this so-called potential osmotic pressure is often not achieved.

The osmotic pressure can be approximated by the van't Hoff law [2]:

$$p_{\mathrm{osm}} = \frac{n}{V} R \cdot T, \tag{1}$$

with p_{osm}: osmotic pressure of a solution (Pa), n: number of particles in the solution (mol), V: volume of the solution (m^3), R: universal gas constant with the value 8.314 J/(mol K), T: absolute temperature of the solution (K). This law can be used as an idealised expression for an approximation of the actual osmotic pressure. In practice, further restrictions come into play, such as the selectivity of the membrane, which is not always perfect: Some of the salt molecules will be able to diffuse through the membrane, reducing the effective osmotic driving force [7].

According to van't Hoff law, the theoretical maximum thermodynamic energy $E_{\mathrm{max,theo}}$ (MJ/m^3) from mixing salt water with fresh water would be:

$$E_{\mathrm{max,theo}} = i \cdot c_{\mathrm{salt}} \cdot k_{\mathrm{B}} \cdot T, \tag{2}$$

where i is the number of osmotically active particles in the solution (for NaCl, $i = 2$), c_{salt} is the salt concentration of the salt water (mol/m^3), k_{B} is the Boltzmann constant $8.314 \cdot 10^{-6}$ (MJ/(mol K)) [8] and T is the absolute temperature (K). For example, for sea water with a NaCl concentration of 3% (approx. 30 g/l or 510 mol/m^3) and a temperature of 25°C, the theoretical maximum energy for the unit volumetric flow would be:

$$E_{max,theo} = 2 \cdot 510\ \frac{\mathrm{mol}}{\mathrm{m}^3} \cdot 8.314 \cdot 10^{-6}\ \frac{\mathrm{MJ}}{\mathrm{mol\ K}} \cdot 298.15\ K \approx 2.5 \frac{\mathrm{MJ}}{\mathrm{m}^3}. \tag{3}$$

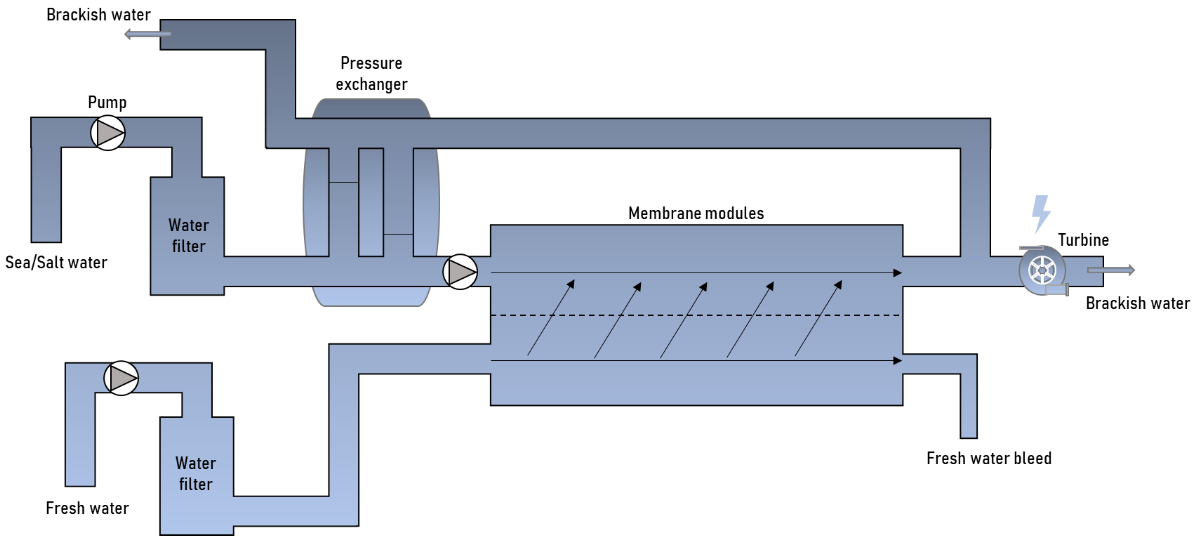
This means that approximately 2.5 MJ is dissipated when 1 m^3 of sea water mixes with fresh water, meaning that in case of SGE a fresh water flow of 1 m^3/s can potentially generate 2.5 MW [9]. If brine (higher salinity than sea water) is used as a salt water flow, the generation capacity per m^3/s should be higher. The exact extent is unclear, as the equations explained above only refer to lower salt concentrations, but not to hypersaline sources. For these different equations might be necessary.

SGE can be captured through different technologies such as PRO, RED including INOD, or CapMix / MEB [10]. An osmotic power plant can be established at sites where two bodies of water with different salinity gradients meet. This can be found in engineered systems as well as in nature. For example, at an estuary where fresh water and sea water meet or where a desalination plant discharges into the ocean [11].

2.1.1 Pressure retarded osmosis (PRO)

PRO was first mentioned in 1973 by Prof. Sidney Loeb [9] at the Ben-Gurion University of Negev in Israel. It is based on the process of osmosis and generates SGE. As seen in Figure 3, fresh water and salt water are pumped into a chamber (membrane modules) and separated by a selectively permeable membrane. This membrane allows only water molecules to pass through. Due to the fact that salt water contains a higher solute concentration, the fresh water diffuses into the salt water. The goal is to eliminate the concentration gradient and dilute the salt water into brackish water. This creates a higher pressure on the salt water side, which is then used to operate a turbine [9]. There are two types of PRO systems based on their structure: single-stage and multi-stage. The single-stage PRO system is characterised by a simpler design, featuring two chambers - one with fresh water and the other with sea water, separated by a semi-permeable membrane. This setup facilitates a direct osmotic process across a single membrane interface. On the other hand, the multi-stage PRO system is more intricate, consisting of several stages connected in series. Each stage in this system has its own set of fresh and salt water chambers and semi-permeable membranes. This sequential configuration allows for a gradual increase in osmotic pressure as water moves through each stage, leading to enhanced efficiency and control over the osmotic process.

Figure 3: Schematic of a PRO installation.



Source: own representation based on [12].

As the diluting salt water cannot expand [11], pressure builds up on the salt water side of the membrane module [9]. Due to the increased pressure, the brackish water is pushed out of the chamber and split into two pathways. One part of the brackish water flows through a turbine that generates electricity. Another part flows back to the pressure exchanger to increase energy efficiency. The pressure exchanger utilises the pressure of the returned brackish water and feeds it into the salt water that flows into the chamber [9]. The pump between the pressure exchanger and the membrane modules is used to build up the pressure so that the water flows in the direction of the turbine and not backwards in the other direction. The optimal operating pressure should be kept close to $p_{\mathrm{osm}}/2$ to maximise the power output. For a river and sea water pairing this pressure is about 13.0–13.5 bar [13]. The entire process is carried out continuously by feeding in fresh and salt water with the help of pumps to guarantee a constant water flow [9]. These osmotic power plants can also be built underground [14].

One of the issues of interest for research is the recovery of energy by PRO using treated sewage and concentrated brine, stemming from a sea water desalination plant. By diluting the concentrated brine through PRO, it is also hoped that this will reduce its environmental impact. The environmental impacts are similar to those of other hydropower systems, including effects on local ecosystems due to a disturbance of the natural course of the river or the creation of artificial water reservoirs [15].

The first prototype of a PRO installation was introduced by Statkraft on 24 November 2009 in Norway [9]. It was constructed following the original osmotic plant schematic by Loeb [9] and ran on river and sea water. The main purpose of the prototype was to test out new PRO technologies, focusing on novel selectively permeable membranes. It was originally designed to produce 10 kW of power [16], becoming the world's first large-scale osmotic power plant by 2015 [9]. The first prototype provided 2,000 m^2 of membranes and per m^2 of membrane had an output of 1 Watt or 1 W/m^2, which adds up to an overall output of 2 kW [9]. Meanwhile Statkraft and SINTEF [16] stated that the output had to be at least 4–6 W/m^2 for PRO to be profitable in the energy market of Norway. Statkraft [17] discontinued the first pilot plant in 2013, because it was not able to compete economically with power producers that were already well-established.

PRO is also a part of the Mega-ton Water System [15] in Japan, a research and development project funded by the Funding Program for World Leading Innovation R&D on Science & Technology. Its main objective is to conduct research on water treatment systems, more specifically converting sea water into fresh water and recycling/reusing treated sewage.

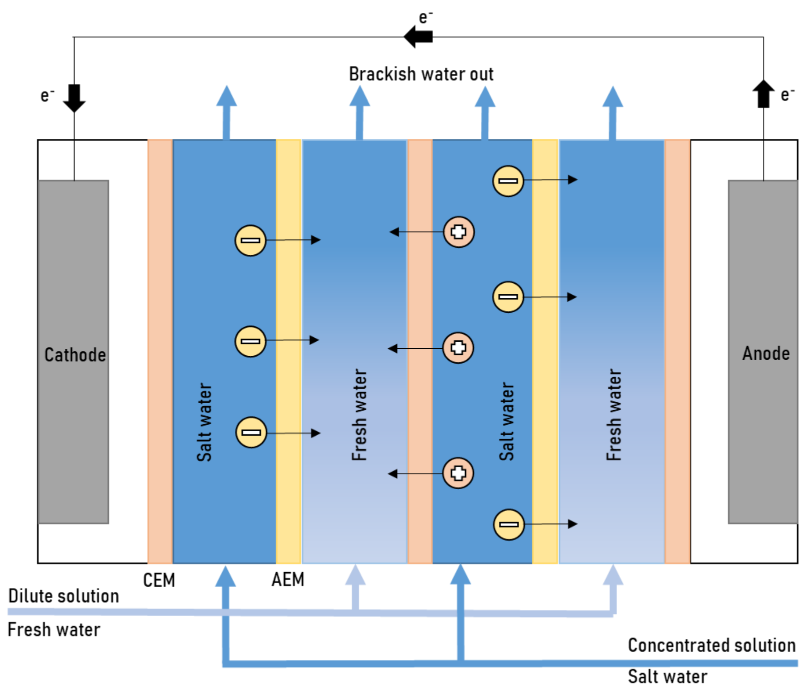
Another PRO power plant from SaltPower [18] was commissioned in 2023. The power plant is located at Hobro, Denmark and uses PRO technology. It has an output of 75–95 kW. The membrane power is 1.5-1.9 W/m^2. SaltPower mainly uses hypersaline sources (brines) to generate osmotic energy. So far, these are the only pilot plants in the PRO area.

2.1.2 Reverse electrodialysis (RED)

Another technology alongside PRO for generating osmotic energy is RED. RED takes advantage of the positively and negatively charged ions contained in salt water and uses two types of membranes to generate power through osmosis:

- Cation exchange membranes (CEM) that only allow positive ions to pass through. Anion exchange membranes (AEM) that only allow negative ions to pass through.

Figure 4: Schematic of a RED membrane (2-cell system).



Source: own representation (based on [10]).

Salt water (concentrated solution, marked as dark blue) is led between the two membranes, with fresh water (dilute solution, marked as light blue) or the cathode on the other side (see Figure 4).

To equalise the salinity gradient, the ions from the salt water pass through the membranes into the fresh water. This is a significant difference to PRO, where the membrane is permeable to the water molecules. The membranes are arranged in so-called stacks, which consist of several membranes stacked on top of each other. The chambers in this stack are arranged in such a way that the CEM and AEM alternate. There are electrodes at the ends of the stack that allow current to flow through the stack. When the saline solution flows through the stack, the difference in concentration creates an electrical potential between the two electrodes, which can be used to generate energy [4] by converting the ionic current into electric current through redox reactions [19].

The first and only pilot plant was developed by REDstack in 2014 and runs on fresh water out of the Ijsselmeer and salt water out of the Waddenzee (Table 1). REDstack develops and manufactures the membrane stacks itself. These stacks consist of hundreds of membrane pairs. In that regard, the voltages of the individual membrane pairs add up to the total voltage of the stack. REDstack develop the housing around the membrane stacks as well. [18]

Table 1: Technical data for RED plants.

Parameter			
Location	Afsluitdijk NL	Alicante ES[1]	Afsluitdijk NL
Technology	REDstack using river water and sea water	REDstack on brine and treated municipal waste water	REDstack using river water and sea water
Commissioning year	2014	2023	2025
Power size	1 kW	1 - 2 kW	16.5 kW
Membrane performance	0.7 to 1 W/m^2, due to low temperatures and low salt gradient	2.0 to 6.0 W/m^2, due to high salinity gradient with brine	0.7 to 1 W/m^2, due to low temperatures and low salt gradient
Special features of the systems	first RED pilot plant worldwide; full process schema installed and operational	-	full process installed and operational, increasing the current stack size to industrial size stacks

[1] No further information on the reference system received

REDstack's aim is to develop, upscale and commercialise SGE. That includes optimising the stacks by increasing membrane area, reducing the cost of production and enhancing the flow through the membranes. They are also working on minimising the environmental impact, maximising energy generation and making the membrane stacks more durable [4]. Until now, REDstack has upscaled their membrane area per stack from 0.25 m^2 to 250 m^2. They state that power density amounts to ≥1 W/m^2 and energy efficiency (theoretical energy from salt gradient versus membrane performance) is at ≥80% for the membrane stack [18]. The overall efficiency is estimated at 35 to 45%.

The amount of power that can be generated through RED depends on technical points – for example, the selectivity of the membranes or the resistance within the electrochemical cell. Similar to PRO, the extent of the salinity gradient between the two bodies of water, as well as the temperature of the water, determines the electrical energy potential [4].

In addition to the classic RED technology, there is also the INOD technology developed by the company Sweetch. It is based on a similar principle but works with nanomembranes. INOD is based on a physical phenomenon (nano osmosis diffusion) that was discovered about ten years ago by Lydéric Bocquet (French Public Research Institute CNRS and ENS). INOD is at the crossroads of fundamental research innovation, rapid scale-up strategy and go-to-market development executed by Sweetch Energy. The core innovation behind INOD relies on the nature and characteristics of the materials of which the osmotic generator is composed rather than the design of the system. What matters is how the core components promote an efficient and large ionic current flowing out of the system [18]. The main difference between RED and INOD is that the INOD technology developed and patented by Sweetch Energy uses a highly selective membrane. This was specifically designed to harness osmotic power potentials, is based on nanotechnologies and achieves a much higher efficiency than any other RED technologies. [18]

In 2024, Sweetch Energy’s first demonstration site will be commissioned in Barcarin (Bouche-du-Rhône), in the south of France. The demonstration installation is set to have a total capacity of up to 50 kW (ap-prox. 400 MWh annually), which will be installed in successive steps to demonstrate the modular aspect of the technology. The first pre-commercial MW plants are set to be commissioned in 2025, at sites in France identified and currently under analysis. [18]

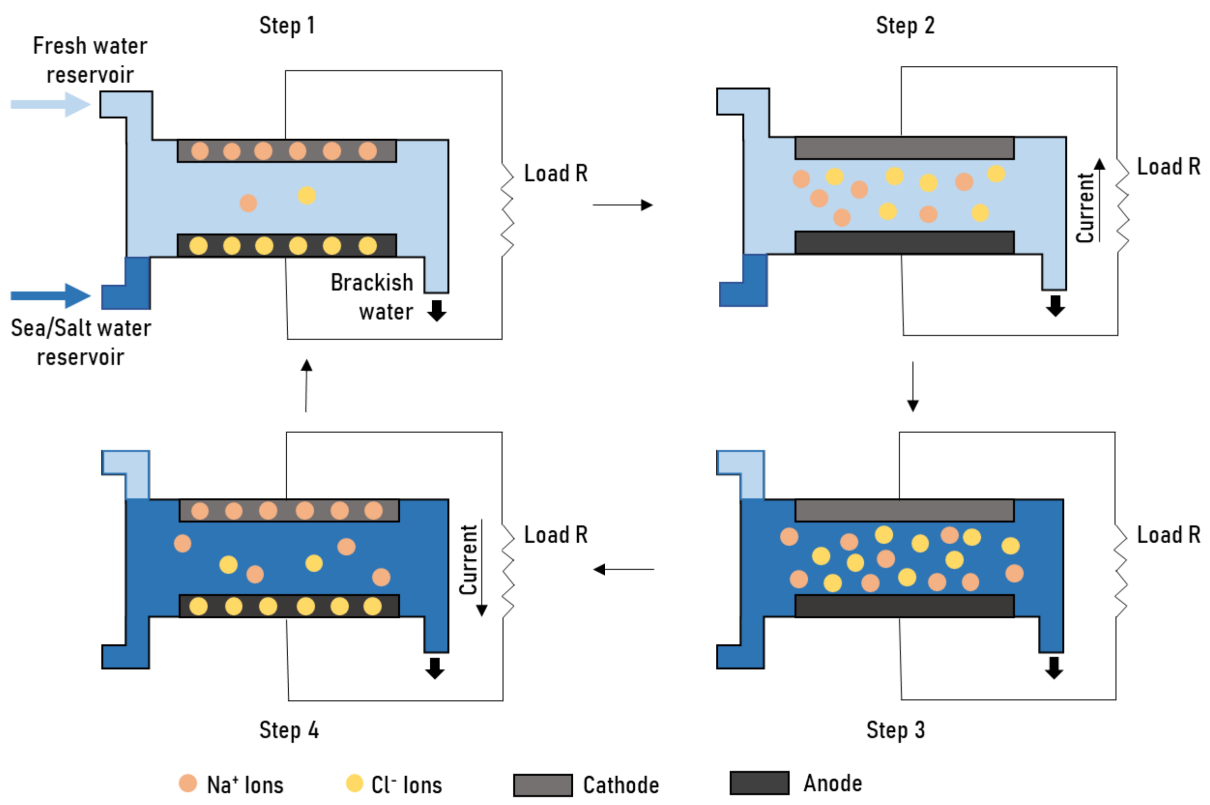
2.1.3 Mixing entropy battery (MEB)

The MEB is a membrane and turbine-free method to harness SGE through a four-step cycle (see Figure 5), and a form of „capacitive mixing“- a technique to harvest energy from the difference in salinity between two bodies of water [20].

It consists of electrodes that are alternately flooded with fresh water and sea water. Electrons are transferred between these electrodes through an external circuit.

During step 1, the sea water is rapidly replaced by fresh water or waste water. Step 2 contains the release of Na^+ and Cl^- from the electrodes into the solvent; energy is used for this purpose. The current flows from the anionic electrode towards the cationic electrode. During step 3 the waste water is rapidly replaced by sea water. Step 4 contains the reincorporation of Na^+ and Cl^- into the electrodes. The current reverses direction. Overall, the energy recovered in step 4 is greater than the energy invested in step 2, resulting in net energy recovery. However, the power output of the MEB is lower than technologies including membranes (such as PRO and RED). A comparative value for the electrode area would be 0.1 W/m² for MEB [21].

Figure 5: Schematic of the four-step energy recovery cycle of the MEB.



Source: own representation (based on [21]).

As the MEB is currently still the subject of research and development with a technology readiness level (TRL) of 4 there are no pilot plants yet. The MEB has been tested by researchers with treated waste water from the Palo Alto Regional Water Quality Control Plant and sea water from the Pacific Ocean (average salt content approx. 35 ‰) [21]. It was possible to recover 1.6 MJ/m^3 by operating a small MEB. When a waste water treatment plant is located at the coast and discharges into the ocean, the energy recovered could be used to power the waste water treatment plant [21]. Due to the development status and because it is assumed that the MEB will not reach marketable potential in the near future, the technology will not be examined in more detail in the following chapters.

2.2 Plant components for PRO

The power output of a PRO plant is determined by its individual components and their interactions. To produce a positive and profitable net power output, the energy input may not exceed the energy output generated by the plant. The water coming into the chamber is pumped through filtration/pre-treatment before it is pumped into the chamber containing the membrane (as seen in Figure 3). The membrane has to be designed for maximum power density and pre-treatment is inevitable in order to ensure that the membrane is less prone to blockage and fouling [9].

Pumping and pre-treatment require an energy input that has to be considered and also kept at a minimum. By installing a pressure exchanger, energy can be recovered to contribute to a positive net power output [13]. To maximise positive net power output, the pressure exchanger and the turbine used to generate power have to be designed to be as efficient as possible.

2.2.1 Membrane

The idea of generating osmotic power using PRO was introduced in the 1970s, but was hampered by the lack of suitable membranes with the optimal structure to enable high performances. Since then, membranes with the desired characteristics (regarding structure, robustness and permeation) have been developed. They also achieve the target power density of 4–6 W/m^2 with brine water [13]. The desired properties of a membrane for PRO are a strong porous support layer in order to tolerate high pressures, low internal concentration polarisation, high water permeability and high salt rejection [22]. The performance of a PRO membrane is usually measured by its power density [13] and influenced by the structure and the permeation rate of the membrane, whereby these depend on the material used [23].

PRO membranes typically consist of polymeric compounds that are well known from drinking and waste water treatment plants [5]. The two most common materials for PRO membranes are cellulose triacetate and polyamide thin-film composite (TFC) [24]. In 2009, Statkraft utilised the flat-sheet membrane [22]. Flat-sheet membranes are characterised by their easy fabrication, low cost, easy cleaning and low maintenance needs [25]. When it comes to membranes that could generate economically viable energy, various researchers refer to thin-film composite (TFC) hollow fibre membranes. They consist of a very thin polyamide selective layer and a porous support layer made out of hollow fibre substrate [13, 15, 26, 27, 28]. Hollow fibre membranes are characterised by their self-supporting structure and large packing density [25]. Polymer materials for TFC-PRO hollow fibre membranes include for example: Matrimid®, polyetherimide, P84 co-polyimide and polyethersulfone [13].

In accordance with desired membrane properties, Han et al. [13] define the power density by membrane water permeability, salt permeability and a substrate structural parameter. They continue to list the transport properties of a number of TFC-PRO hollow fibre membranes as well as TFC-PRO flat-sheet membranes. For a hollow fibre membrane called TFC-1 they state a water permeability of $11.94 \cdot 10^{-9}$ m s^{-1} kPa^{-1}, salt permeability of $1.3 \cdot 10^{-7}$ m s^{-1}, maximum power density of 16.5 W/m^2, a burst pressure >16 bar and a substrate structural parameter of 640 µm [13]. Generally, there is a trade-off between water permeability and selectivity (rejection of salt) of the membrane. The higher the permeability, the lower the selectivity [23].

Additionally, membranes in PRO systems are economically advantageous due to their high packing density and efficient use of space. Their design allows for a higher number of membrane modules per pressure vessel, optimising the required membrane area for a given power plant capacity and membrane power density. This efficiency in spatial utilisation and membrane capacity can lead to reductions in both the capital cost of membranes and energy losses associated with water bleed (unpenetrated fresh water moving through the membrane) [29].

Companies currently looking into the development of effective membranes for PRO include Koch Membrane, Toray Industries, General Electric, Nitto Denko/Hydranautics and Hydration Technology Innovations.

One aspect that is detrimental to the performance, selectivity and permeability of the PRO membrane is deformation and fouling [23], with deformation being a result of high pressure and structural instability [13]. Unwanted material included in the incoming water can accumulate on the membrane, which leads to fouling, therefore reducing the water flux and the overall PRO performance [29]. To limit membrane fouling, there are three different strategies:

a) Pre-treating the incoming water by removing certain substances such as silicates (as described in 3.3.2),
b) Modifying the structural characteristics of the membrane / developing antifouling membranes,
c) Cleaning the PRO membranes while operating (by backwashing or chemical cleaning) [13].

2.2.2 Filter & pre-treatment

To prevent membrane fouling, the pre-treatment of the incoming feed water is crucial for the PRO performance. Rivers for example contain organic material, silt and additional contents that vary with the seasons [9]. In Ju et al. [30], the scientists divide the pre-treatment methods into two groups: conventional pre-treatment and membrane-based pre-treatment methods. Conventional pre-treatment methods include granular activated carbon (GAC) and activated filter media (AFM) [30]. Membrane-based pre-treatment methods include nanofiltration (NF), ultrafiltration (UF), microfiltration (MF) and a cartridge filter (CF) [31].

According to Statkraft [9], the pre-treatment amounts to mechanical filtration. More specifically Statkraft [29] stated, that the best way to pre-treat water for PRO power plants is microfiltration. With regards to PRO, Ju et al. [30] stated that GAC and NF were more effective than UF. While listing the different pre-treatment methods, Ju et al. also mention some manufacturers: Dow (NF), A/G technology (UF), Millipore (CF, MF), Sunghong-Lab in Korea (GAC) and Dryden Aqua (AFM) [30].

2.2.3 Pressure exchanger

To maintain a constant production of power in a PRO system, the sea water flux has to be kept at a set pressure [9]. This can be achieved by pumps that actively reduce the net output. To minimise this energy loss, pressure exchangers are installed as energy recovery devices. They use the pressure of the recirculated brackish water to generate pre-pressure. The brackish water is then discharged into the sea. Pressure exchangers have to be efficient to help ensure that the generated energy by PRO is greater than the energy necessary for pre-treatment, and pressurising [13].

These pressure exchangers or other energy recovery equipment are already in use in desalination plants and save up to 60% of the overall energy input [9].

2.3 Plant components for RED

In a RED stack, chemical energy is directly converted into electrical energy without the need of moving parts as is the case with PRO [32]. The parameters with the biggest influence on RED performance are the structure of the membrane, spacer geometry, concentration of feed water, flow rates of the feed water and temperature [33]. All of these parameters are closely linked to one another and it is necessary to look at the RED stack and its operating parameters as a whole in order to make statements about the ideal configurations of individual parameters.

2.3.1 Membrane and spacers

The membranes required for RED are ion exchange membranes (IEMs) that transport counter-ions (ions of the opposite charge). Ideally, they should be 100% selective by allowing only counter-ions to pass through and by rejecting water and co-ions. In practice, commercial IEMs have a high permselectivity (≥ 90%), but are not 100% selective (permselectivity = 1).

IEMs are polymeric films containing anionic or cationic exchange groups, classified as anion exchange membranes (AEMs) and cation exchange membranes (CEMs) respectively. The materials are generally based on hydrocarbon and perfluorocarbon, with perfluorocarbon membranes typically used in chlor-alkali processes or fuel cells, because of their high thermal and chemical stabilities. The material poly (2,6-dimethyl-1,4-phenylene oxide) is often used in RED applications containing excellent properties for membrane-forming, a high temperature for glass transition, low costs and high chemical, hydrolytic and thermal stabilities.

A large factor in the development of IEMs are inexpensive materials, because most processes for IEM preparation are generally complicated and involve toxicity risk management as well as a number of manufacturing steps. Typically, these processes are not energy efficient. The commercial IEMs that are currently available do not fulfil the requirements for RED given the fact that they have not been designed for this process. Nazif et al. [32] list Nafion, Dow, Astom, Asahi Glass (Selemion) and Fumatech as manufacturers of commercially available IEMs, pointing out the cation exchange membrane (CMX) as a suitable candidate for RED. The CMX is a CEM that was examined under RED conditions.

The membrane properties that are most desired for RED include high permselectivity, low electrical resistance, high mechanical and chemical stability as well as low costs. In addition, fixed charge density, ion exchange capacity and swelling degree are also important properties regarding the RED process in itself. To improve and acquire specific IEM properties the modification of the membranes via surface modification, varying functional groups, using different polymers/additives, polymer blending or by treating the base membrane after the fabrication have all been tested.

Consequently, the structure change of an IEM affects their permselectivity and area resistance. Thin membranes for example contain lower area resistance but could also have lower permselectivity. A higher permselectivity entails a higher voltage output. Nonetheless relatively thin membranes are favourable for RED, because in this case the ion transfer occurs faster.

Different designs for IEMs have been developed: nanoporous membranes, nanofluidic RED systems, pore-filling membranes and profiled membranes. The use of profiled membranes is frequently mentioned in research literature [19, 32–34] and their underlying idea is based on removing the spacers and therefore removing the spacer shadow effect. The spacers are a part of the RED stack with the purpose of keeping the membranes apart in order to allow the feed solutions to flow through the compartments. For commercial electrodialysis the spacers are typically 0.3–1 mm thick, while for RED the thickness lies between 0.1–0.3 mm. They cover a large portion of the membrane and have a negative effect on RED performance by increasing the area resistance and reducing the movement of ions. This is called the spacer shadow effect. Pressure drops within the RED stacks that are often related to the geometric design of the spacers also occur. Profiled IEMs reduce pumping costs and eliminate the cost of expensive spacer material. They increase the area of active membrane and reduce electrical resistance as well as the stacks' sensitivity to fouling [32]. New developments indicate that a significant reduction in cost price is within reach.

2.3.2 Filter and pre-treatment

Similar to PRO, the power density has been observed to drop significantly when RED stacks are fed with natural water instead of an artificial solution. While inorganic fouling decreases the power density up to 8%, the accumulation of organic matter can decrease the power density up to 40% [19]. Simões et al. [19] observed microorganisms and biofilm covering the spacer open area, while Nam et al. [34] noticed clogged spacers at the inlet, inorganic fouling of all components in the chamber of the cathode and scale fouling of the cathode shielding membrane (CEM). It is concluded by Vital et. al. [35] that biofouling can be kept at a stable minimum, not affecting the performance.

IEMs are prone to numerous types of fouling including biofouling, scaling, adhesion of organic matter and colloidal fouling. Fouling leads to a reduction of ion flux and an increase of the membrane and stack resistance. With preferential channelling – a blockade of feed water compartments by colloidal fouling or scaling – it can also lead to a significant pressure drop. AEMs are more susceptible to fouling based on organic matter due to their negative nature. Through a polydopamine coating of the membrane surface biofouling can be prevented. However, the negative impact of spacer fouling outweighs the impact of AEM fouling. CEMs are prone to inorganic fouling and scaling by the precipitation of salts [32].

Fouling in RED can be monitored by 2D fluorescence spectroscopy and component analysis. Anti-fouling strategies include membrane modification, pre-treatment of the feed solutions, periodic feed water switching, cleaning agents and air sparging [32]. REDstack discloses on their website [36], that their pre-treatment includes wedge wire screens coated with anti-fouling material, sand filtration, air sparging and the use of suitable membranes to prevent the stacks from fouling. With regard to RED, Ju et al. [30] came to the conclusion that MF and UF were more effective than CF at improving the quality of the feed water measured by parameters like concentration of organic matter.

Another fact that has to be considered concerning pre-treatment is the existence of multivalent and divalent ions in natural water, such as calcium (Ca^{2+}), magnesium (Mg^{2+}) and sulphate (SO_4^{2-}). In RED systems they lead to a decrease in power density, maximum voltage and permselectivity as well as an increase in stack resistance by moving against the concentration gradient. The removal of divalent and multivalent ions during pre-treatment or alternatively the use of monovalent-selective ion exchange membranes has been proposed [19, 32–34].

2.3.3 Feed water

Before entering the RED stack, the feed water has to be pumped into a filtering unit for pre-treatment. Afterwards it is stored in buffering tanks [33] or pumped into the RED system. Power losses by pumping have to be accounted for, when calculating the net power density [32].

The optimal range for feed concentration depends on the membrane configuration, the geometry of the stack and the flow velocity [32]. In all cases studied [19, 32–34] it was stated that the use of hypersaline solutions – instead of natural water – decreases the stacks resistance and lowers the potential of organic fouling in the AEM. In order to achieve the maximum power density Tedesco et al. [33] find the concentration of the dilute solution to be between 0.01-M and 0.1-M NaCl, sodium chloride. Higher concentrations of the dilute solution can, in turn, lead to a reduction of membrane permselectivity. However, Tedesco et al. [33] state that the best value for dilute solution concentration has to be decided case by case.

Regarding the feed conductivity, Nam et al. [34] supplied their RED pilot plant with waste water effluent with 1.3–5.7 mS/cm and sea water with 52.9–53.8 mS/cm. With 1,000 cell pairs and 250 m^2 of total membrane area they achieved a power production of 95.8 W with 0.38 W/m^2 per total membrane and 0.76 W/m^2 per cell pair [34]. Tedesco et al. [33] operated their plant with brackish water with a conductivity of 3.4 mS/cm and real brine with a conductivity between 190 and 215 mS/cm [33]. Their pilot plant with 125 cell pairs and around 50 m^2 IEMs installed produced about 40 W of power with 1.6 W/m^2 per cell pair, with peaks up to 60 W with 2.6 W/m^2 per cell pair. The higher power density they achieved, in comparison to Nam et al., can be contributed to the higher salinity of the feed waters [34].

Regarding flow rate, Nam et al. [34] supplied their pilot plant with feed water at a flow rate of 2.34 t/h and a linear velocity of 1.5 cm/s. Tedesco et al. [33] observed that the flow rate is only appreciable at the lowest flowrate (16 l/min), where the amount of power produced was reduced by 20–30%. Regarding flow velocity they stated that values above 2–3 cm/s led – for the conditions investigated – to high hydraulic losses, resulting in negative net power [33].

3 Working parameters for osmotic power plants

This chapter describes the operating parameters of osmotic power plants in more detail. Due to the fact that PRO technology has been known for longer and has been better investigated, more information on this technology can be presented below. References are provided for RED technology where the relevant data is available.

3.1 Optimal working pressure

One of the key challenges in designing and operating PRO plants is determining the optimal operating pressure. The optimal pressure is the pressure at which the power output of the plant is maximised.

A study by Salamanca et al. [7] focuses on the Magdalena River mouth in Colombia as a potential site for PRO-based SGE production. The study addresses challenges in PRO technology, emphasising membrane performance and power density above 5 W/m² in order to be profitable. The estimation of potential net power production considers various factors, including pumping and pre-treatment energetic costs, as well as turbine efficiency. Salamanca et al. propose a counter current flow design, maintaining the optimal pressure throughout the process. The optimal pressure refers to the force applied from outside the system to facilitate the osmotic process. In PRO, this pressure is strategically introduced to the draw solution (typically sea water) to counteract the osmotic pressure created by the salinity gradient between the draw solution and the feed solution (usually river water).

To track the optimal pressure, Salamanca et al. [7] employ a sensitivity analysis by varying external pressures (approximately from 10.5 to14.5 bar) applied to the draw solution and observing the impact this has on power production. The maximum simulated pressure is set to half the osmotic difference between the river and sea water at their inlets, aligning with the conventional theoretical optimal pressure assumption of an ideal single-stage PRO process. By decreasing the pressure, the maximum power production is determined. The findings reveal that for the specific counter current flow design considered, the optimal operating pressure is 11.5 bar. The study also shows that operating slightly above this optimal pressure (up to 12 or 12.5 bar) can be beneficial: By applying a bit more pressure than the theoretically optimal pressure, a significant reduction in purge salinity with only a minimal reduction in power output occurs. This could also avoid the negative effects of membrane scaling [7], which refers to the undesirable accumulation of salts and other materials on the membrane surface, leading to reduced efficiency and increased maintenance requirements.

The idea that the theoretical optimal pressure in a PRO process should be approximately half of the osmotic pressure difference between low and high salinity waters is supported by various studies. This includes the work of Naghiloo et al. [29], who examined a 25 MW PRO plant located at the Bahmanshir River in Iran, as well as Ortega et al. [37], who investigated the suitability of the PRO process in the Caribbean using the León River in Colombia, and the findings of Helfer et al. [9]. Meanwhile, due to practical process effects such as draw dilution and reverse salt flux, the practically optimal pressure is usually less than half the osmotic gradient. An example of this principle can be seen in a PRO setup involving river water and sea water, where, if the osmotic pressure difference is 26 bar, the ideal operational pressure is suggested to lie within the range of 10–13 bar [9, 37]. Helfer et al. [9] emphasise that the maximum theoretical power is not influenced by the volume of the draw solution, but rather depends solely on the operating pressure and the water flux through the permeator, which in turn is determined by the membrane type (permeability) and osmotic pressure differential. However, in a practical PRO system, the volume flow rate of the incoming draw solution, to which the operating pressure is applied, impacts system inefficiencies. This implies that higher net powers can be achieved by applying greater pressures to the draw solution. Too low a draw solution flow increases membrane costs, while too high a flow rate can damage membranes. Loeb [38, 39] has indicated that for an energy-efficient system, the volume of the draw solution should match at most twice the volume of the permeate.

In conclusion, the determination of the optimal operating pressure is a significant factor in ensuring the efficiency and effectiveness of PRO plants. The collective research consistently underscores the importance of this parameter. A common thread in these studies [7, 9, 29, 37] is the strategy of utilising half of the osmotic pressure difference between the solutions to optimise power density. This approach is not only a theoretical preference but also an operational guideline that has been affirmed through various research efforts in different geographical contexts.

3.2 Semipermeable membrane

Salamanca et al. [7] claim that, in the context of PRO and RED, a significant obstacle lies in optimising membrane performance. It is widely acknowledged, particularly following the Statkraft power plant's experiences [40], that a crucial factor affecting the economic viability of a PRO facility is the membrane's power density surpassing 5 W/m².

Intensive research is focused on addressing this concern: Wan et al. [41] have developed membranes with remarkably high-power densities (a thin-film composite hollow fibre membrane with a power density of 38 W/m² at 30 bar by using 1.2-M NaCl solution and deionised water as draw and feed solutions, respectively.), Nagy et al. [42] have modelled fouling mechanisms and their impact on PRO (a 0.5 mm thick accumulated foulant on the membrane reduces the maximum power density by 40%), and Long et al. [43] have offered insights into energetically efficient operational strategies. Various control strategies (including a feedback controller to manage the coordination of feed and draw pump speeds as well as loading, and a straightforward perturb and observe algorithm to track the maximum power point and maximum specific energy) [44] have been proposed. Further control strategies such alternative process configurations [45], including integration with desalination processes [46, 47], have also been put forward. Given these advancements and the anticipated resolutions to current challenges, PRO emerges as a viable choice [48] for harnessing SGE at the specific research site. The membrane's physical attributes play a significant part in PRO processes, particularly its salt and water permeabilities.

Naghiloo et al. [29] suggest that with advancements in membrane technologies, achieving power densities of 12 W/m² and 14 W/m² could lead to a reduction in the electricity sale price for their 25 MW PRO plant by 5% (to 0.391 €/kWh) and 8% (to 0.378 €/kWh), respectively. However, it is important to consider that higher power densities might result in greater operational and maintenance costs, especially if they necessitate more frequent membrane replacements or put additional strain on system components. Moreover, the current state of membrane technology might limit how far power density can be increased without incurring substantially higher costs, as advanced membranes capable of higher power densities are often more expensive to produce. These factors collectively contribute to the relatively modest reductions in the electricity sale price observed with improvements in membrane power density. The research also suggests that choosing spiral membrane modules over other alternatives is a cost-effective strategy [29].

According to Helfer et al. [9], concentration polarisation is a significant challenge in membrane development, as it reduces the concentration gradient across the membrane and thus limits water flux. Concentration polarisation involves the accumulation of solute on the feed side or depletion on the draw side near the physical interfaces. Concentration polarisation can be external when it affects the active layer of the membrane interface and internal when it occurs on the membrane support layer. Both types of concentration polarisation result in a decrease in the actual effective transmembrane salinity gradient, impacting the efficiency of osmotic power generation. Despite this, achieving higher membrane power density is crucial to ensuring the economic viability of osmotic power plants.

Also, Salamanca et al. [7] performed additional simulations. These simulations tried to assess the potential increase in power production that could be achieved by employing membranes with greater permeability and implementing more energy-efficient pre-treatment processes. If a hypothetical membrane were to exhibit double water permeability, the resulting power production could be nearly doubled, increasing by 100%. Similarly, a 25% increase in both water and salt permeabilities would yield comparable outcomes, albeit requiring a reduction in the membrane area. Combining a doubling of permeability with a 75% decrease in pre-treatment costs would result in a substantial power production increase, exceeding triple the original value, reaching 19 MW.

3.3 Temperature

Abdelkader et al. [49] claim that the performance of PRO is significantly affected by the temperatures of both the feed and draw solutions. Variations in water temperatures, influenced by seasonal changes (sea water temperatures range from -2 to 35 °C throughout the year) and geographical locations, impact the properties of solutions, including density, diffusion coefficient, viscosity, and osmotic pressure. Additionally, solution temperature affects membrane characteristics such as thickness, porosity, pore size, and permeabilities. While some studies suggest an increase in water and salt permeabilities with rising temperatures [50, 51], others report conflicting results [52]. The membrane structural parameter – which refers to a membrane's internal characteristics, such as pore size, layer thickness, tortuosity, porosity, and support layer structure, which collectively determine its efficiency in water and solute transport - may decrease [50] or remain unchanged [51] with increasing temperatures, leading to a lack of consensus in the literature. The reverse osmosis (RO)-PRO hybrid system's specific energy consumption, as quantified by Wang et al. [50], significantly decreases when the operating temperature in the PRO sub-system is raised from 25 °C to 50 °C. This decrease amounts to 14.41% with 35.1 g/l NaCl draw solution and 17.93% with a 70.1 g/l NaCl solution, achieved under optimal conditions. This hybrid system, integrating PRO with sea water reverse osmosis, is designed to reduce the energy consumption of desalination processes. By extracting osmotic energy from the RO brine, the PRO not only supplements the RO process but also helps in reducing brine discharge, contributing to lower ocean pollution. This finding is consistent with observations for salt water concentrations in the range of 16–46 g/l NaCl, where an increase in temperature from 6 °C to 36 °C has been associated with enhanced performance [51]. Salamanca et al. [7] observed that the variation in temperature, examined in their study had a minimal impact on the outcomes. Given the significant impact of temperature on PRO performance, it is crucial to keep in mind changes in solution temperatures when designing or evaluating the efficiency of PRO systems.

For the RED system, an increase in temperature results in an increase of power density and feed conductivity. The resistance of the stack and the viscosity are reduced, allowing the ions to move more easily. On the other hand, the spacer shadow effect is increased [32]. Lower temperatures have a negative effect on the RED performance [19].

3.4 Salt concentration

The research conducted by Salamanca et al. [7] used average values from the collected experimental data over the observation period (every 30 minutes in both river and sea from 4 to 25 February 2017). To consider the data's variability, simulations were performed using both the highest and lowest salinity values. The river's salinity ranged from a minimum of 0.11 g/l to a maximum of

0.46 g/l, while the sea's salinity varied between 30.1 g/l and 34.9 g/l. When both sea and river salinities are at their lowest power outcome levels, the power capacity (nominal 5.8 MW) is expected to decrease by about 20% (4.7 MW). Conversely, when salinities reach their highest levels, there is a potential increase in power capacity of approximately 7% (6.2 MW). In scenarios combining these extremes - the lowest in both the river and the sea, and the highest in both - the total variability in power capacity could range from a decrease of up to 24% to an increase of up to 17%. It is noteworthy that higher river salinity has a more significant negative impact compared to the positive effect of higher sea salinity, despite the river measurements being more precise. This could be explained by an issue called salt flux, which inherently occurs opposite to the direction of water permeation. This salt flux negatively impacts the effective salinity gradient across the membrane.

3.5 Hydrodynamics

Another deviation from ideal behaviour is caused by hydrodynamics near the membrane surface, leading to concentration polarisation [7]. Hydrodynamics in a PRO system refer to the fluid flow characteristics, especially near the membrane surfaces. Hydrodynamics in PRO originate from the flow of saline and fresh water solutions as they interact with the semi-permeable membrane. They are influenced by factors such as system design (the configuration of the PRO system, including the arrangement of the membranes and the spacing between them), fluid properties, and operational conditions. For instance, the velocity profile, turbulence, and boundary layer characteristics at the membrane surface are all part of the system's hydrodynamics. Salamanca's non-linear model of a SGE plant [7] also confirms that higher salinity in fresh water results in a more pronounced reduction in water flux and, consequently, power density. This model incorporates complex equations with exponential terms to account for concentration polarisation, affecting the osmotic pressures on both sides of the membrane. A key feature of this model is its heightened sensitivity to changes in the feed concentration compared to the draw solution, due to the internal polarisation effect occurring where water transport happens, i. e., on the feed side.

3.6 Pressure exchanger

The efficiency of a current PRO power plant can be significantly enhanced by incorporating energy recovery devices, specifically pressure exchangers, to pressurise the incoming draw solution. Loeb et al. [53] were the first to demonstrate the crucial role of pressure exchangers in achieving cost-effective PRO systems, as they substantially reduce parasitic power consumption. The absence of energy recovery devices would result in the generated energy barely offsetting the costs associated with pressurising the incoming solutions, especially the draw solution.

3.7 Energy balance

In the energy balance of PRO systems, the net power output is notably affected by the efficiency of its components and operational procedures. According to Salamanca et al. [7], about 55% of energy losses are due to pre-treatment, highlighting its significant influence on overall efficiency. Pumping and turbine inefficiencies contribute to 6.25% and 15% of energy losses, respectively. Reducing pre-treatment costs by 25% could potentially double the net power output, and a 75% reduction could lead to an almost threefold increase [7]. However, the energy distribution in Naghiloo's 25 MW PRO plant, operating with 32 °C, 40 g/l saline water from the Persian Gulf, and 21 °C, 1.2 g/l fresh water from the Bahmanshir River [29], presents a different scenario: intake and outfall losses account for 2.25%, pre-treatment consumes 10.68% of energy, membrane loss is at 3.33%, and transmission and generation losses constitute 20.37% of the initial energy. Ortega et al. [37] emphasise the importance of salinity differences between river and ocean waters in evaluating osmotic power plants' potential. In the León River delta, for instance, the salinity is consistently around 35 g/l at a depth of 17 metres. Ortega et al. also point out that mechanical inefficiencies in components such as pumps and pressure exchangers are a source of energy loss, estimating overall mechanical efficiency of osmotic power plants to be about 70% [37]. These findings underline the importance of optimising system components and processes to enhance the efficiency and feasibility of PRO systems. Consequently, the actual power output of a PRO plant is influenced by various factors, including frictional pressure drops across the permeator, equipment configuration, inefficiencies in pumping and rotating components, all power inputs (such as pressurising fresh water and sea water, pre-treatment), and the imperfect semipermeable nature of currently available membranes.

4 Technical comparison of the systems

4.1 Technological readiness level

The TRL is important for evaluating technologies as it provides a standardised method for assessing the maturity of a technology. The TRL system comprises nine levels that assess the progress of a technology from the concept phase to market launch.[1]

The PRO systems currently have a TRL of 7 and are expected to reach a TRL of 9 before 2030.

RED by REDstack reached a TRL of 7 in 2023. Budget and planning for upscaling to TRL 8 have been approved and are available. TRL 8 will be realised in 2025. TRL 9 is in preparation, with site selection currently taking place. [54]

The INOD® technology developed by Sweetch Energy is in its pre-industrial phase (TRL 6/7); a demonstration plant in real-life conditions will be commissioned in the second quarter of 2024 in the south of France, in cooperation with Compagnie Nationale du Rhône, (CNR- an affiliate of the Engie Group). Sweetch Energy plans to reach TRL 9 by 2026, as it will then commission its first commercial MW-scale osmotic plants, amongst other partners (several sites already identified). [18]

4.2 Design sizes (nominal capacity)

The design size is determined by the location of the plant and follows from the amount of feed water available in m^3/s.

The PRO system is modular and can easily be scaled up. There is no upper limit of size. Desalination plants which also use the principle of osmosis for desalination now have over 50,000 membranes. For a PRO system with a similar membrane area of around 450 m^2, the equal capacity would be around 50–70 MW. Currently the PRO modules produced by SaltPower consist of 125–150 membranes per module.

For RED technology, any size between 1 kW (2023) and expected 1,000 MW in 2030 can also be realised, as the technology and equipment are fully scalable and modular. The location of the plant should be as close to both feed waters as possible to reduce the length of piping and minimise required pumping capacity. Pre-treatment of the feed waters has an impact on the space requirements. These however are site specific. It is expected that demonstration size installations, which first prove the TRL 9 level up to 5 MW power plants, will be the first to be installed.

For the INOD® systems there are no limitations to nominal capacities, as installations can span from tens of kW-sized units to MW and even GW-sized osmotic power units. Given their design, INOD® generators are already inherently modular. Maximal site capacities and the number of individual modules depend on available river flows. Individual modules are stacked and linked accordingly to form an osmotic power unit. Several osmotic power units may be located on various locations along the river shore. [18]

[1] TRL Level: 1. Basic principles observed and reported 2. Technology concept and/or application formulated 3. Analytical and experimental critical function and/or characteristic proof-of-concept 4. Component and/or breadboard validation in laboratory environment 5. Component and/or breadboard validation in relevant environment 6. System/subsystem model or prototype demonstration in a relevant environment 7. System prototype demonstration in an operational environment 8. Actual system completed and "qualified" through test and demonstration 9. Actual system proven through successful mission operations

4.3 Efficiency of the systems

PRO technology currently generates around 2.9–4.5 MJ from 1 m^3 of fresh water, applicable to hypersaline brine. This depends on the implementation and the water quality. It is expected that the efficiency will increase with higher capacities.

With RED technology, on the other hand, 1 MJ (gross) can be generated from 1 m^3 of sea water with 1 to 2 m^3 of river water (fresh water). The scaling has no influence on the gross generation potential. The own power consumption for RED amounts to approx. 25% of the gross generation, i. e. this is a 75% net efficiency. This does not include the conversion efficiency of the stack. The overall efficiency with all components is around 45%. In this case a fully continuous generation around the clock (365/24/7) is assumed, e. g. the plant is designed to work with seasonal fluctuations.

The efficiency of the technologies is also determined by the extent to which the parameters (working pressure, temperature, salt concentration) influence the working behaviour. For the PRO system, the overall power output is not only determined by the power density of the membranes. The design and efficiency of the turbine and the devices used to recover energy also play an important part in the performance of PRO [3]. Technically, the temperature has a positive effect on the efficiency as electric resistance is lower in warmer waters. The efficiency reduces when the fresh water feed contains salt and when the salt water feed contains a low level of salt. Daily and seasonal fluctuations are to be expected when the water flow rate and properties such as temperatures and salinity change. Seasonal/daily fluctuations due to river flow fluctuations can be avoided by dimensioning the plant capacity to the lowest available feed water flow. Thus, daily and seasonable fluctuations can often be limited to variations on temperature and salinity gradients, depending on location.

4.4 Power capacity depending on water flow

The water demand depends on the specific PRO technology application case. When SaltPower PRO technology is used for solution mining for salt production, the technology primarily only uses the water already committed to this operation. There is no countable additional water consumption. If the technology is used for solution mining of gas storage caverns (for storage of hydrogen, carbon dioxide, or natural gas), the brine produced can optionally be diluted before being discharged to generate electricity. In this case, the water consumption can optionally be 2–3 times higher than when only used for flushing the cavern.

With RED technology, the water requirement is determined by the availability of feed water, with the fresh water feed probably being the limiting factor, simply because more salt water is available. It is wise to first dimension an installation to the minimum available fresh water feed. In later stages increasing capacity of the plant can be an option with the potential to operate the plant with a dynamic range. This will be an economic consideration based on the costs of building either a plant suitable for base-load purposes or one with over capacity under minimum flow conditions, in order to be able to accommodate the increased flows of the fresh water feed.

4.5 Comparison of the osmotic energy technologies

In 2023, SaltPower and REDstack had a TRL of 7, indicating that their technologies are advanced and being tested in prototypes at scale. Sweetch is slightly behind with a TRL between 6 and 7, indicating an earlier development phase, but expected to catch up very soon (by 2026) with a MW scale. By 2030, all three companies expect to reach a TRL of 9, indicating fully commercially usable technologies.

All three companies emphasise that their systems operate continuously and are fully modular and scalable, indicating flexibility to adapt to different site conditions and energy requirements. In terms of water consumption, SaltPower mainly uses hypersaline solutions up to fully saturated brine, while REDstack mainly uses fresh water and sea water and can also use brine. Sweetch uses fresh and sea water. The INOD technology of Sweetch can also be operated with high salinity brines.

The membrane output per square metre differs significantly. SaltPower achieves 1.5 to 1.9 W/m² and can achieve up to 5 W/m² under optimal conditions. REDstack is at 0.7 to 1 W/m² with the same potential due to low salinity of sea water at the pilot plant. Sweetch achieves significantly higher values of around 20 W/m² in laboratory tests; information from real tests is currently still subject to confidentiality. The membrane types used are also different: SaltPower uses hollow fibre membranes, REDstack relies on flat anion and cation exchange membranes (AEM/CEM) and Sweetch on nano-based membranes made of biological materials. In terms of seasonal fluctuations, all three companies are dependent on temperature and salinity gradients as well as the availability of feed water, with SaltPower stating that it has no fluctuations because it uses hypersaline brines. In terms of land consumption, SaltPower and REDstack require around 1 m²/kW, while Sweetch requires slightly more space at 0.9 for a 10 MW osmotic power plant to 1.5 m²/kW for a 1 MW osmotic power plant. The data is summarised once again in Table 2.

Table 2: Technical comparison of the osmotic energy systems [18].

	SaltPower	**REDstack**	**Sweetch**
Functional principle	PRO	RED	INOD
TRL 2023	7	7	6–7
TRL 2030	9	9	9
Mode of operation	continuous	continuous	continuous
Modularity and scalability	fully modular and scalable	fully modular and scalable	fully modular and scalable
Water used	mainly hypersaline solutions up to fully saturated brine	mainly fresh- and sea water, also brine	fresh and sea water, also brine
Typical membrane performance in W/m²; maximum values in brackets	1.5–1.9 (5)	0.7–1 (5)	~20 (laboratory test)
Type of membranes	hollow fibre membranes	flat AEM / CEM	nano membranes (bio-sourced)
Stack conversion efficiency in MJ/m³ (Percentage of theoretical energy in %)(1)	~2.9–4.5	~1 (40%)	currently being tested in real operation
Seasonal fluctuations	no fluctuations; availability of feed water	temperature and salinity gradients; availability of feed water	temperature and salinity gradients; availability of feed water

	SaltPower	REDstack	Sweetch
Land use in m^2/kW;	~1	~1	0.9–1.5
Land use in m^2 / MWh/a (8000h)	~0.12	~0.12	0.11-0.19

(1) The theoretical energy is calculated in Chapter 2.1 with a value of 2.5 MJ/m^3 (equation only applies to low salt concentrations, not for hypersaline sources).

4.6 Comparison to other energy systems

To classify the SGE technologies in relation to other power generation technologies, Table 3 presents a comparison for various aspects that describe the field of application. Osmotic power plants are generally classified as renewable energies and are therefore, like other renewable energies, seen as carbon neutral. Unlike conventional energy sources, which- with the exception of nuclear energy - are not considered to be carbon neutral osmotic power plants do not directly contribute to the emission of climate-damaging gases.

Due to their modularity and scalability, osmotic power plants can also be used at smaller sites, similar to photovoltaic (PV) and wind power plants. In this regard they differ from technologies such as geothermal plants or coal and gas systems, which cannot be installed decentrally due to their design for larger output classes. However, SGE plants are limited to suitable locations where water feed flows with different salinities are available. This is similar to geothermal plants requiring an appropriate heat source. All technologies, including osmotic power plants, can also be used as central power plants. Here, osmotic power plants can also be scaled into the higher megawatt range, comparable to wind power or PV. In terms of system modularity, osmotic power plants are modularly expandable thanks to their stacked components, which is difficult or impossible to do with conventional energy systems. Although osmotic power plants, like most other technologies, are not designed for peak loads, they can be classified as base-load capable at constant water flows. This is in line with the system design usually used for minimum available fresh water flows. Here they offer an advantage over PV and wind energy. In terms of land use, osmotic power plants require very little direct space compared to other technologies. Although conventional energy systems also have a low land use due to the high output of central power plants, the surrounding open space must be taken into account for wind power plants, which leads to a significantly higher land use. Total land use of wind farms could be in a range of 120–178 m^2/MWh/y [68–70], while the values mentioned in Table 3 (1.3–2.4 m^2/MWh/y) refer to the land directly covered by the infrastructure. It is also important to note that the land use figures for osmotic power plants presented here (0.1–0.2 m^2/MWh/y) solely account for the space required by the energy plant itself. Unlike conventional energy technologies, these figures do not include land needed for fuel disposal. However, similar considerations can also be made here for SGE plants that rely on the water feed stocks and are not considered here. Generally osmotic power plants, as renewable energy systems with their necessary buildings and systems being compact in design, - similar to PV and solar thermal energy - are highly accepted. The acceptance of conventional energy systems on the other hand, is now considered to be rather poor. In summary, osmotic power plants offer many positive aspects and have a high potential to be an additional element supporting the energy transition.

Table 3: Comparison of osmotic energy systems with other energy systems [54, 55, 68].

		Carbon neutral	Distri-buted	Centra-lised	System modularity	Peaking	Baseload	Land use in m^2 / MWh / yr	Acceptance
Renewable energy	Osmotic	yes	yes	yes	yes	no	yes	0.1–0.2	good
	Solar PV	yes	yes	yes	yes	no	no	0.28–0.47	good
	Solar thermal and storage	yes	no	yes	yes	no	no	0.23–0.37	middle
	Geothermal	yes	no	yes	no	no	yes	0.41	good
	Onshore wind	yes	yes	yes	yes	no	no	1.3–2.24	middle
	Offshore wind	yes	yes	yes	yes	no	no		middle
	Hydropower	yes	yes	yes	no	no	yes	7.76	good
Conventional energy	Nuclear	yes	no	yes	no	no	yes	0.071–0.08	rather bad
	Coal	no	no	yes	no	no	yes	10	rather bad
	Gas combined cycle	no	no	yes	no	no	yes	-	rather bad
	Gas peaking	no	no	yes	no	yes	no	-	rather bad

5 Economic overview of the technologies

5.1 Economic key figures for PRO

The initial levelised cost of electricity (LCoE) can be assumed to be between 0.15 €/kWh and 0.19 €/kWh. It is expected that the LCoE will arrive at a cost of less than 0.09 €/kWh after development and upscaling of the technology within the next 10 years. The further development of membranes in particular can lead to a reduction in costs via increased efficiency. The LCoE [18] includes all components of the plant: membranes, pressure vessels, racks, turbines, pumps, feed water pre-treatment, frequency converters, control systems, piping, labour etc. Service costs and regular membrane replacements are also included. Expected foundation and housing costs are also included. Not included is the purchase/rental of land as this is usually already available to the expected users of the technology. It should be noted that the footprint of a PRO system is relatively small at up to 1 m2/kW, but corresponding areas must be planned for larger upscaling. An approximate breakdown of CAPEX between various elements of a plant is given in percentages in Table 4.

Table 4: CAPEX parameters for PRO. [18]

Cost point	Percentage
Turbines, pumps and energy recovery devices	6%
Pre-treatment section	13%
PRO system (Ex. membranes and vessels)	30%
Pressure vessels	10%
Membranes	20%
Auxiliary	7%
Engineering	15%

The annual OPEX is expected to be 3–5% of the initial CAPEX. The OPEX primarily consists of costs for membrane replacements. This replacement will not occur annually but only every 5–10 years, but is included in the OPEX consideration as an annual average. [18]

5.2 Economic key figures for RED

For RED from REDstack the LCoE (at 100 MW scale) [18] is expected to decrease from EUR 0.11–0.12 /kWh for the first plant, to EUR 0.05 /kWh with more experience, scaled up production sites and components development. All costs are included in this calculation, from piping, pumping, pre-treatment, building, RED stacks to grid connection.

The first 100 MW is expected to have a CAPEX (all-inclusive) of approx. EUR 900 million. Table 5 shows the distribution of this investment. The system components that are considered part of the energy generation and the energy conversion components correspond to roughly half of the total investment cost. Approximately 35% is needed for the pre-treatment, pumps and piping system and the remaining 15% include the other open investments, like engineering and auxiliary. [18]

Table 5: CAPEX parameters for RED. [18]

Cost point	Percentage
Energy generation and energy conversion components	50%
Pre-treatment section, pumps and piping system	35%
Other costs (Engineering, Auxiliary)	15%

For the INOD® systems, the expected LCoE in the first year of commercialisation should be in the region of 0.20 €/kWh for a first of its kind 1 MW power plant. This number encompasses the costs for the INOD® system (34%), balance of plant (BoP) and surrounding hydraulic infrastructures (31%), and OPEX costs (35%, accounting for life cycle & replacement of components). These electricity generation costs will fall significantly with larger power plants. Again, these numbers are based on a generic estimate, and site specifications could impact this estimation. For example, larger sites will entail a larger percentage of the LCoE in the BoP. Alternatively, industrial sites with existing hydraulic infrastructures will have drastically lower costs. [18]

Within 10 years of commercialisation, costs should diminish due to technological improvements, scaling effects, and the structuration of the osmotic industry, and allow the LCoE to approach 0.05 €/kWh. Here, the INOD® system would account for 20%, BoP for 50%, and OPEX for 30% of total costs. CAPEX-wise, projections are set to decrease over time as seen in Table 6.

Table 6: Cost parameters for INOD. [18]

		1 MW	Commercial MW year 1	Commercial MW year 5	Commercial MW year 10
Capex in Mio. €/MW	INOD stacks	10	5	2.1	1
	BoP	5	5	3.7	3.3
	Total(1)	15	10	5.8	4.3
OPEX in Mio. €/a		0.7	0.4	0.2	0.1
LCOE in €/MWh(2)		241	147	85	59
Membrane lifetime in a(3)		5	5	7	10

(1) Within 10 years of commercialisation, costs should diminish due to technological improvements, scaling effects, and the structuration of the osmotic industry.

(2) A 7% weighted average cost of capital (WACC) is used as it is the benchmark for other technologies.

(3) The expected lifetime of the equipment (membranes and others) is currently set at 5 years in the models of Sweetch [50] (which is conservative compared to other benchmarks. In desalination systems for instance, where membranes are subject to high pressures, lifetimes of 8 to 10 years are expected and reflected in the OPEX. As the technology evolves, this lifetime progressively reaches industry benchmarks.

5.3 Comparison of the osmotic energy technologies

For a better comparison, Table 7 summarises the different SGE technologies regarding their economic indicators. Table 4 shows that SaltPower does not provide a specific value for the investment costs (CAPEX). REDstack has the highest investment costs at EUR 900 million for the first 100 MW, while Sweetch has significantly lower investment costs at EUR 500 million.

It should be noted that the structure of the site is also a key factor for the capital costs and can lead to cost differences of up to 20%. This was also noted in the earlier study "Renewable Power Generation Costs" [56] in 2014.

Opportunities could exist here in the prospective integration of plants in measures to mitigate climate change (renewal of sea defence facilities, sluices, water and volume management structures).

With regard to operating costs (OPEX), SaltPower states a need of 3–5%/a of CAPEX, while REDstack and Sweetch state operating costs of 2–5%/a of CAPEX. REDstack and Sweetch are similar here, while SaltPower has slightly higher operating costs.

When comparing the LCoE in 2023, SaltPower has an estimated LCoE of 0.15–0.19 €/kWh, while REDstack has a slightly lower LCoE of 0.11–0.12 €/kWh. Sweetch, on the other hand, has the highest LCoE at 0.24 €/kWh. For the LCoE calculated in 2030, REDstack and Sweetch have similar values (0.05–0.06 €/kWh), while SaltPower's LCoE has a higher upper limit (< 0.09 €/kWh).

Table 7: Comparison of the LCoE of osmotic energy systems [18].

	PRO (SaltPower)	RED (REDstack)	RED/INOD (Sweetch)
CAPEX in Mio. €	-	900 (first 100 MW)	500 (assumption:100 MW / first of a kind)
OPEX in %/a	3–5	2–5	4–5
LCoE in 2023 in €/kWh	0.15–0.19	0.11–0.12	0.24
LCoE by 2030 in €/kWh	<0.09	0.05	0.05–0.06

5.4 Comparison to other energy systems

As in the comparison of SGE technologies with other energy systems in Chapter 4.6, the economic indicators will also briefly be compared. The LCoE forecasts for the year 2030 in Table 8 show a clearer picture of the competitiveness of renewable energies compared to fossil fuels. At 0.05–0.09 €/kWh, osmotic energy shows a medium cost spectrum. Solar PV is the most cost-effective technology at 0.02–0.04 €/kWh. These low costs reflect the constant improvements in manufacturing technology, economies of scale and falling material costs Onshore and offshore wind energy is also economically advantageous, with values between 0.04–0.08 €/kWh and between 0.05–0.09 €/kWh, reflecting the efficiency improvements and cost reductions in the wind energy sector.

Unlike variable renewables, osmotic power generation operates as a base load generation plant. Osmotic energy’s average market value is likely to be higher than that of e.g. solar energy, because when variable renewables produce a lot, the market price resulting from the marginal cost rule is generally lower. Another way to take into account the variability of renewables is to add the cost of storage to their LCOE.

In comparison, the cost of coal-fired electricity is higher at 0.08–0.12 €/kWh, possibly reflecting increasing environmental regulations and the cost of rectifying environmental impacts. Gas combined cycle power plants, a more efficient form of gas-fired power generation, shows lower costs than coal at 0.06–0.08 €/kWh, but higher costs than most renewable technologies.

In short, the projections for 2030 suggest that renewable energy technologies such as osmotic power, solar PV and onshore wind will be more cost-effective compared to traditional fossil fuels such as coal and gas.

Table 8: Comparison of the LCoE of energy systems [57-60] (1).

	Renewable energy							Conventional energy		
	Osmotic	Solar PV	Solar thermal	Geo-thermal	Onshore wind	Offshore wind	Hydro-power	Nuclear	Coal	Gas combined cycle
LCoE 2030 in €/kWh	0.05 - 0.09	0.02 - 0.04	0.10 - 0.14	-	0.04 - 0.08	0.05 - 0.09	0.05 - 0.12	-	0.08 - 0.12	0.06 -0.08

(1) The cost of storage to compensate the variability of renewables, such as wind and PV, is not included in the LCoE presented in this table.

5.5 Marketability of power generation with PRO and RED

To make investment decisions, the revenues must cover both the CAPEX and the OPEX over the life cycle of the investment. The LCoE is a commonly used metric to evaluate the average cost per unit of output. The output is the electricity generated through technological options like RED or PRO. To effectively compete with other electricity generation technologies, it is important to achieve grid parity. This means that the LCoE of osmotic energy sources should either be equal to or lower than the market price of electricity. Once the osmotic energy plant is installed, it also operates at electricity market prices that are higher or lower than its LCoE, as long as the market price covers the marginal costs per unit of generated electricity. The high upfront investment and low operational expenditures in combination with uncertain revenues (remuneration or prices for electricity) are challenging for investors because the return on this “already made” investment depends to a very large degree on future market prices.

The future trajectory of electricity prices is intricately tied to the combination of energy sources, advancements in technology for electricity generation, storage and flexibility options, and the ultimate demand for energy. In scenarios where there is a substantial demand for electricity, a notable proportion of renewable energy sources, and a diminishing reliance on biomass, the average annual shadow prices are projected to be approximately 70 $€_{2018}$/MWh in 2035 and around 68 $€_{2018}$/MWh in 2045 with an average deviation from the mean of about ± 40 $€_{2018}$/MWh respectively (as per the 'T45-Strom scenario' of the Long-term scenarios 3 (LFS3) for Germany[2] [61]), according to the Enertile® optimisation[3] [12], an energy system optimisation model.

These annual averages are based on hourly shadow prices that mirror future electricity prices, including peak-load prices, as they are based on the modelled future "real-time" interplay between electricity demand and supply under the conditions specified within the Enertile® model. However, these shadow prices might significantly deviate from real future market prices, since they are a result of economic optimisation and not of a simulated market trade model. This means that technologies are implemented based on location-specific total technology costs, demand and supply and the "marginal cost rule". The results show the respective marginal LCoE of the technology that just came into play (operation to satisfy demand), i.e. shadow price. The shadow prices for 2035 are depicted in Figure 6 and for 2045 in Figure 12 in Annex A.2.
The revenue from market sales (yield multiplied by market prices) should be sufficient to cover the investment, operating, and maintenance costs. To assess this, detailed information on these

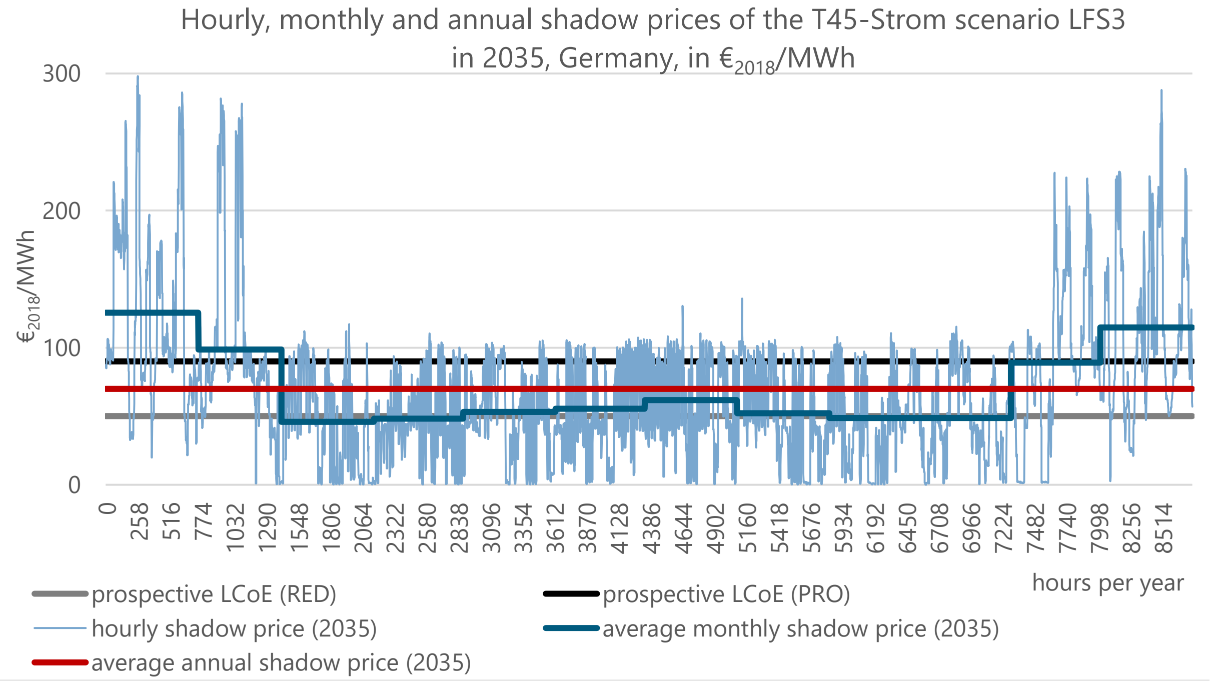
[2] https://langfristszenarien.de/enertile-explorer-wAssets/docs/LFS3_T45_Szenarien_15_11_2022_final.pdf

[3] Fraunhofer 2024: https://www.isi.fraunhofer.de/en/competence-center/energiepolitik-energiemaerkte/modelle/supply-modelling.html

expenses, the generation profile, and ideally hourly market prices is required. The LCoE is a proxy for such assessments. If the LCoE is lower than the average annual market prices, it indicates a favourable condition for investments, and grid parity[4] is achieved. When it comes to grid parity of osmotic technologies, the PRO technology is currently far from reaching it, even with high prices. On the other hand, the RED technology shows promise. Its projected LCoE is lower than the projected average shadow prices of electricity in 2035 and 2045. Even with annual production disruptions (maintenance work) reducing the load factor to around 90%, the expected annual revenues in 2035 and 2045 exceed the expected average costs. Once the investment decision is made and the osmotic electricity generation plant is installed, its capacity factor (load factor) is high due to low marginal costs per unit.

This is similar to solar and wind power, which also require high upfront costs and sufficiently high market prices for the recovery of the investment, while marginal costs are negligible. But once the investment is made the solar power plant would run even when market prices are very low, which is typically the case when solar and wind productions are high. However, unlike solar power, osmotic power generation operates as a base load generation plant. Its average market value price achieved is likely to be higher than the average annual market price (based on shadow prices for 2045 of about 20€$_{2018}$/MWh) and higher than that of e.g. solar energy. This is because maintenance works can be scheduled during seasons of low market prices.

Figure 6: LCoE and shadow prices in 2035 (price base 2018), Germany [21].



Source: own representation
Note: Annual and monthly averages are calculated based on hourly data.
Due to the modularity (stack modules in parallel) of this technology the plants might continue operation on few stack modules (potentially also excess modules) even during maintenance works. One technology provider expects about 8,000 operating hours per year (out of 8,760 h). It should be noted that these shadow prices reflect the marginal costs of generation assets in a specific hour. Some of these assets only operate during hours of high bottlenecks.

[4] Grid parity occurs in case an energy source generates power at a LCoE that is less than or equal to the market price of electricity.

6 Strengths, weaknesses, opportunities and threats

6.1 Strengths

From the considerations presented above, it is clear that osmosis technology has a number of strengths that can make it a promising alternative for energy production. It is a renewable energy source and inexhaustible, as it is based on natural processes, taking into account the available water resources. Unlike fossil fuels or nuclear energy, generating electricity from osmotic gradients produces no direct CO_2 emissions and no pollution, according to the technology companies. Another advantage is that a wide range of water resources can be used. In addition to fresh water and sea water, hypersaline resources can also be used (industrial waste water, etc.) A particular strength of osmotic energy systems compared to other renewable energy systems is their base load capability. They also have a very low land use factor compared to other renewable power generation technologies. The systems are also very scalable and modular and can therefore be individually adapted to the location.

6.2 Weaknesses

Osmosis technology also has some weaknesses that make it difficult to apply this technology on a broad scale. The overall efficiency of the power generation systems is currently still low. The PRO and RED technologies are still in the research and development phase and there is still a need for optimisation, especially in the performance of the membranes. The investment costs for the construction of osmotic power plants are currently still high and may represent an obstacle to the widespread use of the technology. The use of energy from osmotic gradients depends on tides and water currents; the inflows must be designed in such a way that these influences are minimised, which is why the systems are usually designed for a low inflow to ensure a sufficient input flow at all times.

6.3 Opportunities

In terms of opportunities, the companies' research and development activities in particular show that the further development of components such as membranes can lead to a future increase in efficiency and also to a reduction in costs (investments, maintenance costs, etc.). To facilitate the future market entry of osmosis technologies, funding programmes and regulatory support could promote the development and implementation of the technologies. There is also potential for new markets and business models in the field of renewable energies. In particular, according to Sweetch, this new industry could create thousands of new jobs (manufacturing, operations, R&D and suppliers) if only the natural European osmotic potential is considered. On a global scale, the size of the industry could multiply significantly if other geographical areas and applications for the technology are taken into account. According to calculations by Alvarez-Silva, a global osmotic energy potential of 27,000 TWh is assumed. [18]

6.4 Threats

Osmosis technologies also pose a number of risks and challenges. In particular, the ecological consequences of the construction and operation of osmotic power plants must be taken into account. To date, there have been no detailed studies on the extent to which osmotic power plants have an impact on the environment, particularly on the ecosystem in the vicinity of the site. This may be caused by the change in salinity in the water and the impact on fish and other aquatic life. Environmental protection areas (e.g. NATURA 2000 marine protected areas) must also be taken into account when constructing the facilities It is a legally binding requirement for all users that the conservation status of the fauna-flora-habitat (FFH) habitats occurring in the area, the species protected under Annex II of the FFH Directive, the European bird species and other components important for the conservation objectives must not deteriorate as a result of management. The management plans provide information on cases where this is applicable and the respective conservation objectives as well as suitable conservation measures. The nature conservation authorities can provide further information on this[5]. However, these regulations also apply to all other energy technologies. Current projects for osmotic energy production also indicate that the effects would be compatible with Natura 2000 sites. The current REDstack plant in Afsluitdijk, for example, extracts sea water and discharges brackish water into a Natura 2000 site. A significant part of REDstack's current 13-million-euro project is dedicated to the environmental impact assessment and ecological effects.

In addition to the ecological aspects, the technological aspects also harbour some risks. Osmotic power plants are still relatively new technologies and there are still many technical challenges to overcome. These include the development of more efficient technology components, such as membranes. In order to remain competitive with other established renewable energy technologies, research and development must therefore be constantly driven forward. When building the plants, care must also be taken to ensure that the locations are chosen in such a way that the supply lines to the osmotic power plant from sea and fresh water or other water resources are as close to each other as possible in order to minimise increased investment costs or possible interference with nature. However, according to the companies, this must always be examined on a case-by-case basis. [18]

At international level, there seems to be no immediate threat on the EU industry, according to F. Neumann, M. Hamza, Institute for Infrastructure, Environment and Innovation (IMIEU), as reported in annex A.3. Overall, EU initiatives seem to be slightly ahead in the process towards commercial upscaling.

5 http://www.natura2000.rlp.de

7 Potential analysis for osmotic energy in the EU

In addition to the technical and economic evaluation of the osmosis technologies that could be used in the future, the theoretical and technical power potential for the EU Member States is also determined. The theoretical potential initially refers to the total energy potential of the rivers in question. However, the complete utilisation of river water is not possible, in particular due to environmental aspects, and the efficiency of the conversion to electricity is not 100%. Therefore, the technical power potential is determined from the theoretical energy potential with the help of an extraction factor. The energy potentials provide information on prospective target markets for osmosis technologies, as well as an overview of possible energy production volumes for the individual EU countries, which they can then integrate into their regenerative energy supply in the future. The detailed results can be found in the datasheet published together with this report.

7.1 Basics for determining the power and energy potentials

To determine the theoretical osmotic potential, the energy of the brackish water resulting from the mixture of fresh and salt water is relevant and is calculated according to Equation 2 using averaged data for water flows, temperatures and salinities for suitable SGE plants at estuaries. To recapitulate the formula is as follows:

$$E_{\mathrm{max,theo}} = i \cdot c_{\mathrm{salt}} \cdot k_{\mathrm{B}} \cdot T, \tag{4}$$

where i is the number of osmotically active particles in the solution (for NaCl, $i = 2$), c_{salt} is the salt concentration of the salt water (mol/m^3), k_{B} is the Boltzmann constant $8.314 \cdot 10^{-6}$ (MJ/(mol K)) [8] and T is the absolute temperature (K). For example, for sea water with a NaCl concentration of 3% (approx. 30 g/l or 510 mol/m^3) and a temperature of 25°C, the theoretical maximum energy for the unit volumetric flow would be:

$$E_{max,theo} = 2 \cdot 510\ \frac{\mathrm{mol}}{\mathrm{m}^3} \cdot 8.314 \cdot 10^{-6}\ \frac{\mathrm{MJ}}{\mathrm{mol\ K}} \cdot 298.15\ K \approx 2.5\ \frac{\mathrm{MJ}}{\mathrm{m}^3}. \tag{5}$$

This means that approximately 2.5 MJ is dissipated when 1 m^3 of sea water mixes with fresh water, meaning that in the case of SGE a fresh water flow of 1 m^3/s can potentially generate 2.5 MW [9]. Further calculations with specific assumptions are presented in the next section.

7.2 Assumptions for the calculations

Specific assumptions are made below for the calculations of technical power potentials. The assumptions for researching the data on rivers, seas and their influencing parameters are also presented.

To determine the theoretical osmotic potential, the energy of the brackish water resulting from the mixture of fresh and salt water is relevant and is calculated according to Equation 2 using averaged data for water flows, temperatures and salinities for suitable SGE plants at estuaries. It is assumed that 1 m^3 of salt water requires 1 m^3 of fresh water in the SGE plant. In case of higher fresh water requirements, the energy potential is lower. The river flow rates were compiled from several data sources. For the water flow rate of a river $\dot{V}_{\mathrm{riv}}$ (m^3/s), the theoretical power potential $P_{\mathrm{max,theo,river}}$ is given by:

$$P_{\mathrm{max,theo,river}}\ (MW) = E_{\mathrm{max,theo}} \left(\frac{MJ}{m^3}\right) \cdot\ \dot{V}_{\mathrm{riv}} \left(\frac{m^3}{s}\right). \tag{6}$$

Next, the feasible potential is calculated using a withdrawal factor d_w. This restriction is necessary because not all of the river system's discharge can be used for energy production due to environmental aspects. For example, extraction must not lead to a strong imbalance in the ecological, hydrodynamic and sedimentological processes at river mouths. The ecological stability of the systems must be guaranteed despite the extraction [1]. Based on the publication "Practical global salinity gradient energy potential" by Alvarez-Silva et al. a withdrawal factor d_w of 20% was selected. [1] The withdrawal potential $P_\mathrm{withdrawal}$ is therefore calculated by:

$$P_\mathrm{withdrawal}(MW) = P_\mathrm{max,theo,river}\,(MW) \cdot d_\mathrm{w}. \tag{7}$$

With its technical efficiency η, the SGE plant can generate electricity from the available withdrawn water flow. The plant efficiency is assumed to be 45% simplified for all locations. This extracted power P_{tech} describes the technical power potential of a flow:

$$P_{tech}(MW) = P_\mathrm{withdrawal}(MW) \cdot \eta. \tag{8}$$

To determine the energy potential, the technical output P_{tech} is multiplied by the operating time per year for the systems $\mathrm{t_{operate}}$. The annual operating time $\mathrm{t_{operate}}$ is assumed to be 8,000 h. This figure takes into account various factors such as downtime for maintenance, unexpected failures, or exceptionally low river flows. The impact of climate change on the frequency, severity and duration of droughts is outside the scope of this study and has not been considered. However, it is worth noting that the modularity of osmotic stacks in these systems offers a unique advantage. By slightly oversizing the system with a few extra stacks, maintenance can be performed on one stack at a time. This approach allows the rest of the system to continue operating, potentially reducing the impact of maintenance and failure-related downtimes. As a result, the system can maintain nominal power output throughout the year, for 365 days. The resulting energy E_tech is calculated by

$$E_\mathrm{tech.}(MWh) = P_\mathrm{tech,}\,(MW) \cdot \mathrm{t_{operate}}\,(h). \tag{9}$$

Based on these equations, the theoretical and technical power potential ($P_\mathrm{max,theo,river}$ and E_tech) can be calculated for each river to arrive at the total potentials for Europe. To determine the average salt concentrations and temperatures of the seas in the estuaries of the rivers, the data is retrieved via the Copernicus Marine Data Store[6] (cf. data sheets). The data points for temperature and salt concentrations were chosen in the areas near the river mouths, where the river flows into the sea. This choice ensures that the selected data accurately represents the conditions at the estuaries, where fresh water from the rivers mixes with the saline sea water. To determine the theoretical potential, averaged values for the salt gradients and temperatures over the last three years were used.

Given the limitations of available data sources that could provide all the data needed to calculate SGE potentials at once, some further assumptions had to be made. First and foremost, it is necessary to have adequate water flows to operate the SGE facilities. Therefore, the river should have an average discharge (volume, flow) of at least 150 m^3/s. In the absence of water flow data, it is assumed that rivers with a length of at least 250 km from the most distant source and a drainage basin (catchment area, watershed) of at least 10,000 km^2 are suitable for consideration. Another prerequisite is that the river flows into an adjacent sea. The potential is attributed to the country in which the river flows into the sea. In addition, the river must carry water all year round. The potential for the countries in Table 9 was determined on the basis of the above assumptions.

[6] https://data.marine.copernicus.eu/viewer

Table 9: Overview of countries for determining potential.

	List of EU Members	Potential determined	Reason
1	Belgium	No	exclusion by assumptions[1]
2	Bulgaria	Yes	
3	Denmark	No	exclusion by assumptions[1]
4	Germany	Yes	
5	Estonia	Yes	
6	Finland	Yes	
7	France	Yes	
8	Greece	Yes	
9	Ireland	Yes	
10	Italy	Yes	
11	Croatia	Yes	
12	Latvia	Yes	
13	Lithuania	Yes	
14	Luxembourg	No	continental area, no sea connection
15	Malta	No	no permanent flowrates
16	Netherlands	Yes	
17	Austria	No	continental area, no sea connection
18	Poland	Yes	
19	Portugal	Yes	
20	Romania	Yes	
21	Sweden	Yes	
22	Slovakia	No	continental area, no sea connection
23	Slovenia	No	exclusion by assumptions[1]
24	Spain	Yes	
25	Czech Republic	No	continental area, no sea connection
26	Hungary	No	continental area, no sea connection
27	Cyprus	No	no permanent flowrates

[1] Admission criterion: rivers > 250 km long from the most distant source, drainage basin > 10,000 km^2, or mean discharge > 150 m^3/s over the year permanently)

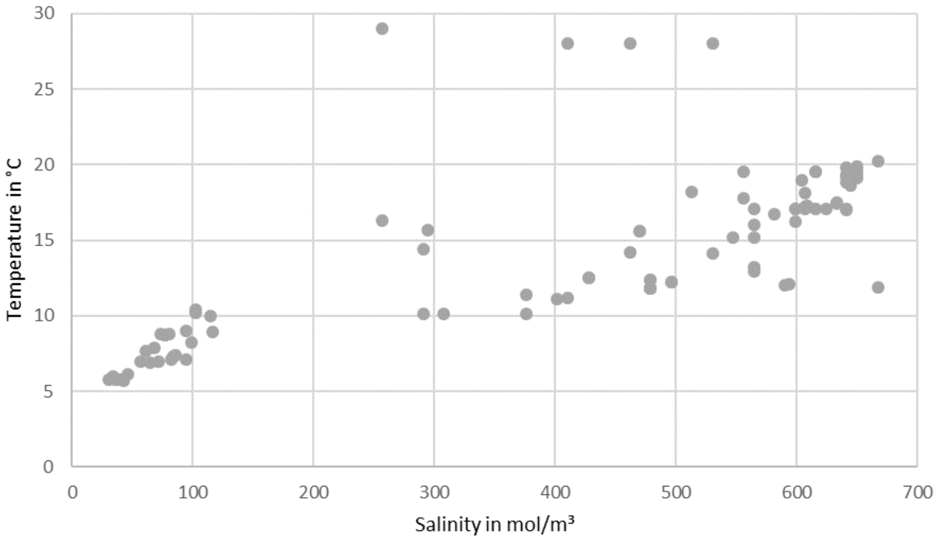
The overview shows that it was not possible to determine a potential for all EU Member States. This applies firstly to those countries that do not have direct access to the sea. These are Luxembourg, Austria, Slovakia, the Czech Republic and Hungary. No potential was determined for Cyprus and

Malta either, as there are no permanent flowing rivers there. No potential was determined for Belgium, Denmark and Slovakia in accordance with the assumptions made above. The potentials for the remaining countries are presented in Chapter 7.3.

7.3 Potential of EU Member States

The theoretical and technical power potentials for the relevant EU countries were calculated in accordance with the previous assumptions. The average of all rivers (01/2021-12/2023) lies between 5.7 and 29 °C for temperature and between 30.8 and 667.4 mol/m³ for salinity (Figure 7).

Figure 7: Temperature and salinity of European rivers



Source: own illustration

In the following description of the country specific potentials, the focus lies on the technical power potentials except when mentioned otherwise. However theoretical potentials are included in the following tables (Table 10 to Table 26) as well.

For Bulgaria, the two rivers Kamchiya and Veleka provide a total capacity of 4.5 MW, assuming 20% extraction, with the Kamchiya accounting for approx. 3/4 of this technical power potential (Table 10).

Table 10: Potential of osmotic energy for Bulgaria.

River	Flow in m³/s	Salinity in mol/m³	Temperature in °C	Theo. potential in MW	Techn. potential in MW	Energy potential in GWh
Kamchiya	26	294.3	15.7	36.8	3.3	26.5
Veleka	9.4	290.9	14.4	13.1	1.2	9.4
Total potential				**49.8**	**4.5**	**35.9**

According to the previous assumptions, Croatia only contains one larger river. However, the Neretva offers a very high potential of approx. 107.6 MW (Table 11) due to its large discharge volume and the high salt content (667 mol/m³) in the outflowing sea (Adriatic Sea near Ploče).

Table 11: Potential of osmotic energy for Croatia.

River	Flow in m^3/s	Salinity in mol/m^3	Temperature in °C	Theo. potential in MW	Techn. potential in MW	Energy potential in GWh
Neretva	378	667.4	11.9	1,195.7	107.6	860.9
Total potential				**1,195.7**	**107.6**	**860.9**

The technical power potential for Estonia amounts to 13.7 MW. Even though the Narva has a high discharge, the salinity differences compared to the Baltic Sea are very low, resulting in only a small usable concentration gradient for osmotic power plants (Table 12).

Table 12: Potential of osmotic energy for Estonia.

River	Flow in m^3/s	Salinity in mol/m^3	Temperature in °C	Theo. potential in MW	Techn. potential in MW	Energy potential in GWh
Pärnu	64	80.4	8.8	24.1	2.2	17.4
Narva	400	68.4	7.9	127.9	11.5	92.1
Total potential				**152.1**	**13.7**	**109.5**

The potential for Finland is approx. 31.1 MW (Table 13), whereby the potential is divided between several rivers and the partial outputs amount to a maximum of 10 MW with a withdrawal rate of 20%. The river volumes in Finland are also very large, but the differences in the concentration of fresh and salt water (Baltic Sea) are small, similar to Estonia's situation (31 to 94 mol/m^3).

Table 13: Potential of osmotic energy for Finland.

River	Flow in m^3/s	Salinity in mol/m^3	Temperature in °C	Theo. potential in MW	Techn. potential in MW	Energy potential in GWh
Kemijoki	553	30.8	5.8	79.0	7.1	56.9
Lijoki	174	35.9	5.8	29.0	2.6	20.9
Oulujoki	262	42.8	5.7	52.0	4.7	37.4
Kokemäenjoki	238	94.1	7.1	104.4	9.4	75.2
Kymi	282	61.6	7.7	81.1	7.3	58.4
Total potential				**345.5**	**31.1**	**248.7**

Of all the countries, France has the greatest potential for the production of osmotic energy (Table 14). This is partly due to the high number of large rivers with correspondingly large outflows, as well as the high concentration differences resulting from the salinity of the Atlantic Ocean (462 to 642 mol/m^3).

Table 14: Potential of osmotic energy for France.

River	Flow in m³/s	Salinity in mol/m³	Temperature in °C	Theo. potential in MW	Techn. potential in MW	Energy potential in GWh
Somme	37	564.7	12.9	99.4	8.9	71.6
Seine	560	564.7	13.2	1,505.7	135.5	1,084.1
Vilaine	72	462.0	14.2	158.9	14.3	114.4
Loire	889	530.5	14.1	2,252.4	202.7	1,621.8
Charente	49	547.6	15.2	128.6	11.6	92.6
Dordogne	380	470.6	15.6	858.6	77.3	618.2
Adour	360	581.8	16.7	1,009.4	90.9	726.8
Aude	44	641.7	17.1	136.3	12.3	98.1
Garonne	650	470.6	15.6	1,468.6	132.2	1,057.4
Rhône	1,900	624.6	17.1	5,727.3	515.5	4,123.6
Oyapock*	1,457	256.7	29.0	1,878.9	169.1	1,352.8
Kourou*	3,000	410.7	28.0	6,169.4	555.2	4,442.0
Sinnamary*	267	462.0	28.0	617.7	55.6	444.8
Maroni*	1,780	530.5	28.0	4,728.2	425.5	3,404.3
Total potential				**26,739.4**	**2,406.5**	**19,252.4**

* French Guyana (Overseas territory); deviation from selection assumptions due to overseas territory

The technical power potential for Germany is estimated at 252 MW (Table 15). The salinity of the North Sea in the estuary area of the rivers is rather middling (377 to 402 mol/m^3) compared to the other seas. This is due in particular to the elongated brackish water zones. Despite the high outflows, the potential can therefore be regarded as being medium in size.

Table 15: Potential of osmotic energy for Germany.

River	Flow in m³/s	Salinity in mol/m³	Temperature in °C	Theo. potential in MW	Techn. potential in MW	Energy potential in GWh
Weser	365	402.1	11.1	693.7	62.4	499.5
Elbe	860	410.7	11.2	1,669.9	150.3	1,202.3
Ems	89	376.5	11.4	158.5	14.3	114.1
Oder	574	102.7	10.2	277.7	25.0	199.9
Total potential				2,799.8	252.0	2,015.9

The potential for Greece is similar to that of Germany, despite lower outflow volumes (Table 16). This is due to the very high salt concentrations (513 to 667 mol/m³) in the Mediterranean Sea (especially the Ionian Sea near Astakos and the Aegean Sea near Thessaloniki).

Table 16: Potential of osmotic energy for Greece.

River	Flow in m³/s	Salinity in mol/m³	Temperature in °C	Theo. potential in MW	Techn. potential in MW	Energy potential in GWh
Achelous	137	667.4	20.2	446.0	40.1	321.1
Pineios (Thessaly)	81	616.0	19.5	242.8	21.9	174.8
Haliacmon	80	616.0	19.5	239.8	21.6	172.7
Struma/Strymon	76	556.1	19.5	205.7	18.5	148.1
Nestos/Mesta	45	556.1	17.8	121.1	10.9	87.2
Vardar/Axios	170	641.7	19.3	530.5	47.7	381.9
Maritsa/ Meriç/Evros	383	513.3	18.2	952.5	85.7	685.8
Total potential				2,738.3	246.4	1,971.6

Italy has the second largest potential after France with 824.5 MW (Table 17). This is partly due to the large number of rivers and the high salt concentrations (565 to 650 mol/m³) in the Tyrrhenian Sea and Adriatic Sea.

Table 17: Potential of osmotic energy for Italy.

River	Flow in m³/s	Salinity in mol/m³	Temperature in °C	Theo. potential in MW	Techn. potential in MW	Energy potential in GWh
Arno	110	650.2	19.1	347.6	31.3	250.3
Tiber	239	641.7	19.8	747.1	67.2	537.9
Garigliano	120	650.2	19.3	379.4	34.1	273.2
Volturno	82	650.2	19.9	259.8	23.4	187.1
Reno	95	564.7	17.1	258.9	23.3	186.4
Po	1460	616.0	17.1	4,340.7	390.7	3,125.3
Tartaro-C.-Po di Levante	218	607.5	17.1	639.1	57.5	460.2
Adige	235	598.9	17.1	679.3	61.1	489.1
Brenta	93	607.5	17.2	272.7	24.5	196.4
Piave	137	633.1	17.5	419.2	37.7	301.8
Tagliamento	92	633.1	17.4	281.4	25.3	202.6

River	Flow in m³/s	Salinity in mol/m³	Temperature in °C	Theo. potential in MW	Techn. potential in MW	Energy potential in GWh
Isonzo/Soča	173	641.7	17.0	535.6	48.2	385.6
Total potential		9,160.8			824.5	6,595.8

The osmotic potential for Latvia with approx. 31 MW is rather low, similar to Finland, and also results from the low salt concentrations (74 to 116 mol/m³) of the Baltic Sea (Table 18).

Table 18: Potential of osmotic energy for Latvia.

River	Flow in m³/s	Salinity in mol/m³	Temperature in °C	Theo. potential in MW	Techn. potential in MW	Energy potential in GWh
Daugava/Western Dvina	640	77.0	8.7	231.0	20.8	166.3
Gauja	71	73.6	8.8	24.5	2.2	17.6
Lielupe	106	77.0	8.7	38.3	3.4	27.5
Venta	98	116.4	8.9	53.5	4.8	38.5
Total potential				**347.2**	**31.2**	**250.0**

The potential for Lithuania with approx. 28 MW is also similar to that of Latvia. However, the entire potential here results from the Neman River with a very high discharge of 634 m³/s (Table 19).

Table 19: Potential of osmotic energy for Lithuania.

River	Flow in m³/s	Salinity in mol/m³	Temperature in °C	Theo. potential in MW	Techn. potential in MW	Energy potential in GWh
Neman	634	102.7	10.4	306.9	27.6	221.0
Total potential				306.9	27.6	221.0

For the Netherlands, this results in a high potential of approx. 675 MW. Two thirds of this results from the high discharge of the Waal (Rhine) (Table 20).

Table 20: Potential of osmotic energy for the Netherlands.

River	Flow in m³/s	Salinity in mol/m³	Temperature in °C	Theo. potential in MW	Techn. potential in MW	Energy potential in GWh
Meuse/Maas	357	479.1	12.4	812.2	73.1	584.8
Scheldt	129	427.8	12.5	262.1	23.6	188.7

River	Flow in m³/s	Salinity in mol/m³	Temperature in °C	Theo. potential in MW	Techn. potential in MW	Energy potential in GWh
Zwarte Water	50	479.1	11.8	113.5	10.2	81.7
Ijssel	380	479.1	11.8	862.7	77.6	621.1
Waal (Rhine)	2,315	496.2	12.2	5,450.8	490.6	3,924.5
Total potential				**7,501.2**	**675.1**	**5,400.9**

According to the previous assumptions, Poland also only has a larger water flow with the Vistula. The potential can be calculated at approx. 53 MW with a high discharge of 1,080 m³/s (Table 21). The salt concentrations of the Baltic Sea near Gdańsk are also somewhat higher than in the places in other countries where the rivers discharge into the Baltic Sea.

Table 21: Potential of osmotic energy for Poland.

River	Flow in m³/s	Salinity in mol/m³	Temperature in °C	Theo. potential in MW	Techn. potential in MW	Energy potential in GWh
Vistula	1,080	114.6	10.0	583.0	52.5	419.7
Total potential				**583.0**	**52.5**	**419.7**

Portugal's potential for the use of osmotic energy is estimated at approx. 431 MW (Table 22).

Table 22: Potential of osmotic energy for Portugal.

River	Flow in m³/s	Salinity in mol/m³	Temperature in °C	Theo. potential in MW	Techn. potential in MW	Energy potential in GWh
Mondego	108	598.9	16.2	311.2	28.0	224.1
Sado	40	609.2	17.3	117.7	10.6	84.7
Minho	340	564.7	15.2	920.5	82.8	662.8
Douro	650	564.7	16.0	1,764.7	158.8	1,270.6
Tagus	500	598.9	17.1	1,445.2	130.1	1,040.6
Guadiana	79	607.5	18.1	232.4	20.9	167.3
Total potential				**4,791.8**	**431.3**	**3,450.1**

Ireland's potential for the use of osmotic energy is estimated at approx. 92.3 MW and is divided between the two-river systems Shannon and The Three Sisters (Table 23).

Table 23: Potential of osmotic energy for the Republic of Ireland.

River	Flow in m^3/s	Salinity in mol/m^3	Temperature in °C	Theo. potential in MW	Techn. potential in MW	Energy potential in GWh
Shannon	208	593.8	12.1	585.8	52.7	421.8
The Three Sisters	157	590.3	12.0	439.5	39.6	316.4
Total potential				**1,025.3**	**92.3**	**738.2**

Compared to the other countries, Romania has a very high theoretical osmotic potential of approx. 717 MW. This is the result of the Danube's very high discharge of 6,450 m^3/s. However, it must be critically questioned whether such high withdrawal volumes from a single river are possible without potentially impacting the ecology of the natural systems (Table 24).

Table 24: Potential of osmotic energy for Romania.

River	Flow in m^3/s	Salinity in mol/m^3	Temperature in °C	Theo. potential in MW	Techn. potential in MW	Energy potential in GWh
Danube	6,450	256.7	16.3	7,968.1	717.1	5,737.0
Total potential				7,968.1	717.1	5,737.0

Spain has a potential of approx. 236 MW, with 2/3 resulting from the theoretical capacity of the Ebro River with approx. 162 MW (Table 25)

Table 25: Potential of osmotic energy for Spain.

River	Flow in m^3/s	Salinity in mol/m^3	Temperature in °C	Theo. potential in MW	Techn. potential in MW	Energy potential in GWh
Guadalquivir	164	604.0	19.0	481.2	43.3	346.5
Segura	26	641.7	19.2	81.1	7.3	58.4
Júcar	49	650.2	19.7	155.2	14.0	111.7
Turia	14	650.2	19.3	44.3	4.0	31.9
Ebro	577	641.7	18.8	1,797.4	161.8	1,294.1
Llobregat	21	645.1	18.6	65.7	5.9	47.3
Total potential				2,624.9	236.2	1,889.9

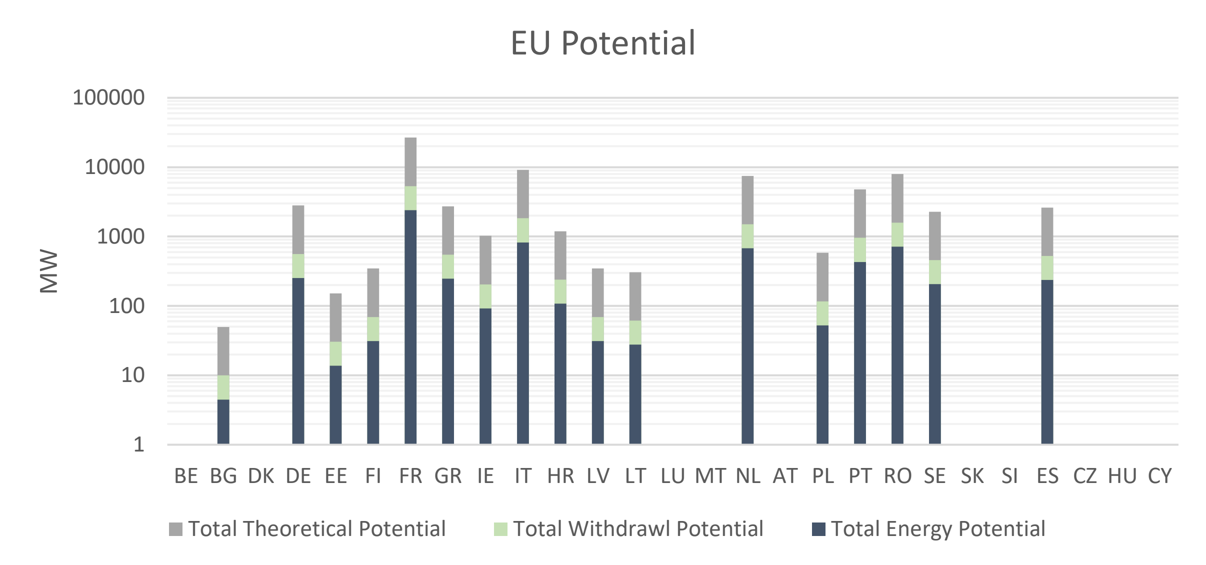
The potential for Sweden is approx. 206 MW. Despite the high number of rivers and the high outflows, the total potential is relatively low. This in turn results from the low salt concentrations in the Baltic Sea (Table 26).

Table 26: Potential of osmotic energy for Sweden.

River	Flow in m^3/s	Salinity in mol/m^3	Temperature in °C	Theo. potential in MW	Techn. potential in MW	Energy potential in GWh
Ätran	53	308.0	10.1	76.9	6.9	55.4
Lagan	82	290.9	10.1	112.3	10.1	80.9
Motala ström	100	94.1	9.0	44.2	4.0	31.8
Norrström	166	99.2	8.2	77.1	6.9	55.5
Ljusnan	226	83.8	7.3	88.4	8.0	63.6
Ljungan	135	71.9	7.0	45.2	4.1	32.5
Indalsälven	448	56.5	7.0	117.8	10.6	84.8
Ångerman	481	82.1	7.1	184.1	16.6	132.6
Umeälven	435	65.0	6.9	131.7	11.9	94.8
Skellefteälven	157	46.2	6.1	33.7	3.0	24.3
Piteälven	156	39.4	5.8	28.5	2.6	20.5
Luleälven	500	41.1	5.8	95.2	8.6	68.6
Kalixälven	289	42.8	5.8	57.3	5.2	41.3
Torne	430	34.2	6.0	68.3	6.1	49.2
Göta älv	554	376.5	10.1	982.3	88.4	707.2
Dalälven	353	85.6	7.4	140.9	12.7	101.4
Total potential				**2.283.9**	**205.6**	**1.644.4**

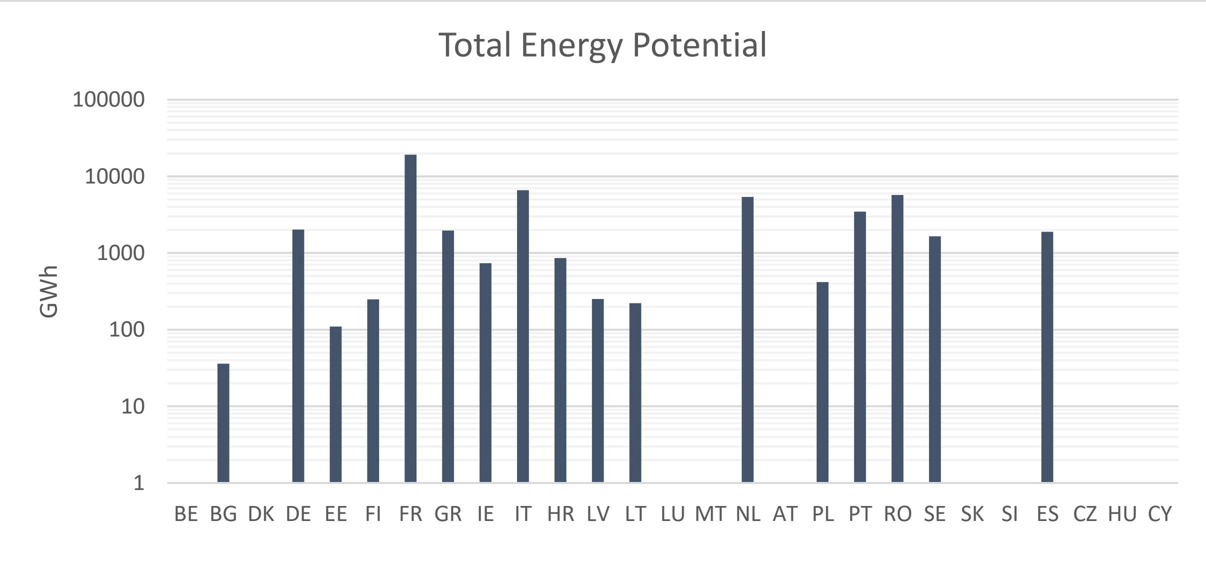
The total theoretical potential can be estimated at approx. 70.6 GW for the European countries. With a withdrawal rate of 20%, and an SGE plant efficiency of 45% this results in a technical power potential of approx. 6.4 GW. The market assessment done by Sweetch Energy confirms the overall osmotic power potential in the EU as estimated is around 6.6 GW, with an average withdrawal rate between 15% and 20% [18]. An additional overview comparing the potentials for the countries can be found in Figure 8 for the power potential, and in Figure 9 for the energy potential.

Figure 8: Osmotic power potential for the EU Member States.



Source: own illustration

Figure 9: Osmotic energy potential for the EU Member States.



Source: own illustration

This technical power potential of 6.6 GW results in a total of 50.8 TWh for the European countries assuming an operating time of 8,000 h/a for the SGE plant, which represents a substantial potential for energy production through osmotic power in the European Union. The technical energy potentials vary considerably between the individual countries, as can be seen from the data provided. France shows the largest technical energy potential for osmotic power plants with 19.2 TWh, followed by Italy with 6.6 TWh, Romania and the Netherlands with 5.7 TWh and 5.4 TWh, respectively. Countries such as Estonia, Finland, Latvia and Lithuania have relatively low potentials due to small differences in salt concentration between river and sea water. Bulgaria has the lowest potential due to low outflows and simultaneously low concentration differences (35.9 GWh).

In order to enable a comparison of the SGE's gross electricity production potential with the current energy production in the EU in 2021, energy volumes by different fuels are shown in Table 27. At

50.8 TWh per year, osmotic energy would account for an added value of around 1.7% of the total energy volumes from 2021. Measured in terms of renewables and biofuels, this is 4.6%. This potential could play an important role in diversifying the energy mix and reducing greenhouse gas emissions in the future, provided that the technology can be developed economically and sustainably. If the electricity generated by petroleum and petroleum products were offset by osmotic energy, this would compensate 13.5 million t of CO_2 annually, assuming a value of 266 g/kWh for petroleum-based products.

All in all, it is clear that the potential in the EU is quite suitable for the utilisation of osmotic energy. Technological progress in comparison with international developments and research into osmotic energy (see Appendix A.3 Osmotic energy in an international context) also appears to be more advanced in the EU and offers great opportunities for the construction and integration of osmotic power plants into renewable energy generation in the EU.

Table 27: Gross electricity production by fuel, EU, 2021. [62]

Type of Energy	Energy in TWh	Share in %
Solid fossil fuels	419.0	14.4
Oil and petroleum products	46.7	1.6
Natural gas and manufactured gases	579.8	19.9
Nuclear	731.7	25.2
Renewables and biofuel	1,101.9	37.9
Hydro (1)	(374.8)	(12.9)
Geothermal (1)	(6.5)	(0.2)
Wind (1)	(386.9)	(13.3)
Solar thermal (1)	(5.2)	(0.2)
Solar photovoltaic (1)	(158.6)	(5.5)
Primary solid biofuel (1)	(92.8)	(3.2)
Other	27.3	0.9
Total potential	**2,906.5**	100.0
Projected osmotic potential	**50.8**	**+1.7**

(1) Already included in the total value of 1,101.9 TWh.

7.4 Influences of parameter fluctuations on energy potential

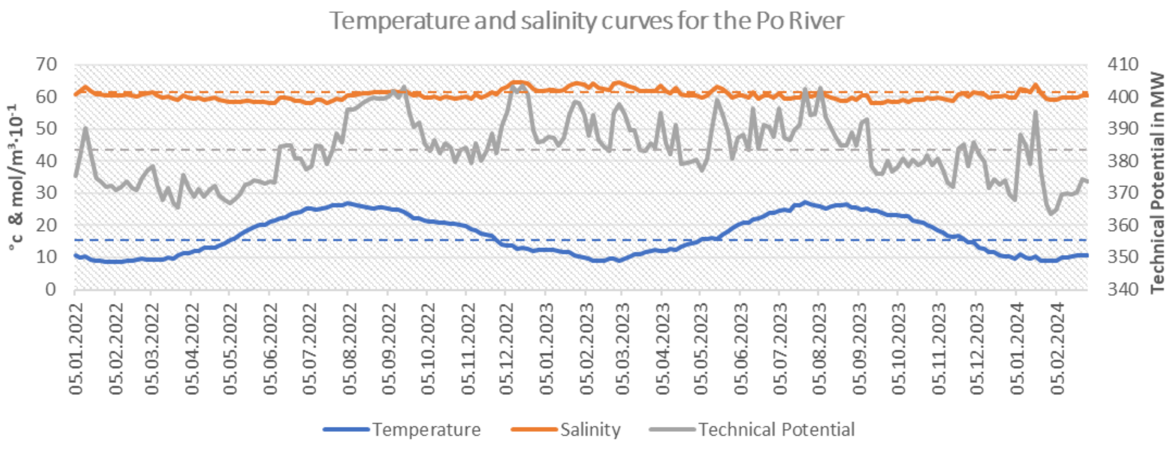
In this study, average annual values were used to determine the potential. For case-specific considerations, however, the data must be considered at a higher resolution. The following Figure 10 and Figure 11 are intended to show, on the basis of river temperature and sea salinity, that each river has different fluctuation widths, which consequently also affect the osmotic energy potential (values are directly included in the potential equation). The Po River in Italy and the Indalsälven River in Sweden were selected for this purpose.

It can generally be seen that the range of fluctuation in salinity is relatively small. For the Po River, the minimum value for salinity in the period under consideration lies between 578.4 and

645.1 mol/m³ (fluctuation range of 66.7 mol/m³). Compared to the mean value of 604 mol/m³, this is a relatively small fluctuation. The situation is similar for the Indalsälven River, where the salinity values fluctuate between 20.5 and 82.1 mol/m³ (fluctuation range: 61.6 mol/m³). The mean value is 59.9 mol/m³. What can be seen, however, is that the salt content in the regions of Europe varies greatly. In the northern regions, in particular, salinity levels tend to be lower, which leads to a lower osmotic energy potential despite often high outflows. Concentrations increase with increasing proximity to the equator.

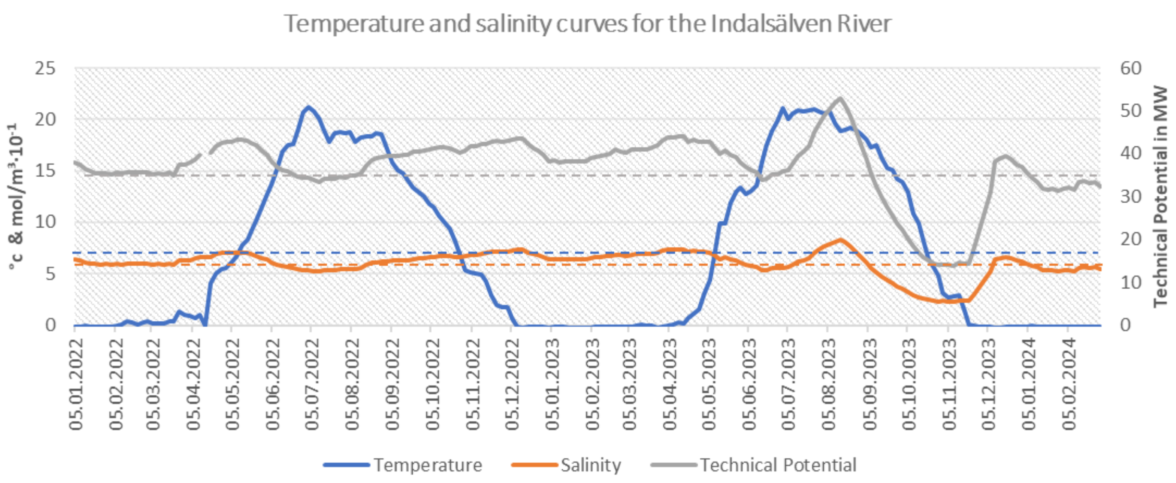
In terms of temperature, there are major annual seasonal variations in the rivers. For example, the temperature fluctuation for the Po River is: minimum value: 8.5 °C, maximum value: 27.1 °C, mean value: 16.9 °C, and the fluctuation range: 18.6 °C. The following values result for the Indalsälven River: minimum value: -0.2 °C, maximum value: 21.2 °C, mean value: 7.2 °C, fluctuation range: 21.4 °C. In principle, it can be seen from the figures that the temperature curves are seasonally dependent. However, according to the potential calculation equations, the temperature has a smaller effect than the salinity.

Figure 10: Temperature and salinity curves for the Po River



Source: Own illustration

Figure 11: Temperature and salinity curves for the Indalsälven River



Source: Own illustration

Table 28 therefore shows the extent to which changes in salinity and temperature can affect the energy potential. This shows that an increase in the salinity of 17.1 mol/m^3 results in an increase in the power potential of 2.8% to 393.7 MW. However, an increase in temperature only results in an increase of 0.3% to 384.1. For the Po River, this results in 377.0 and 403.3 MW for the minimum and maximum salinity (578.4 and 645.1 mol/m^3) in the period under consideration. For the minimum and maximum temperature values (8.6 °C and 27.1 °C), this results in 371.9 and 403.0 MW.

Table 28: Influence of temperature and salinity on the energy potential.

River	Variant	Salinity in mol/m^3	Temperature in °C	Techn. power potential in MW	Percentage change of potential vs average in %
Po	Temperature average Salinity average	604.0	16.9	382.8	-
	Salinity increased by 17.1 mol/m^3	**621.1**	16.9	393.7	+ 2.8
	Temperature increased by 1 °C	604.0	**17.9**	384.1	+ 0.3
	Salinity minimum	**578.4**	25.2	377.0	- 1.5
	Salinity maximum	**645.1**	13.0	403.3	+ 5.4
	Temperature minimum	604.0	**8.6**	371.9	- 2.9
	Temperature maximum	614.3	**27.1**	403.0	+ 5.3

In addition to these values, the discharges of the rivers also play a corresponding role in determining the potential. These must be selected for a design case in such a way that the systems can be operated continuously in order to run economically in the long term. Therefore, sufficiently large and continuous volume flows of the rivers are necessary throughout the year. Furthermore, the design should initially be planned with a low extraction rate.

8 Hypersaline sources

In addition to salt gradients from rivers and oceans, other sources can also be used for osmotic energy generation, particularly for PRO technology. These are hypersaline sources, i.e. deposits with a very high salt content. Sources can be desalination brines, natural resources or industrial brines.

Desalination brines are the concentrated salt water by-product of the desalination process. Desalination is a technology used to remove salt and other impurities from sea water or brackish water to make it suitable for human consumption or other uses. During the desalination process, fresh water is produced as the desired product, while the remaining salt and impurities are concentrated in the form of brine. This brine, known as desalination brine, typically has a higher salt content than the original source water.

Desalination plants are often located near municipal waste water treatment plants. According to the study "Pressure retarded osmosis from hypersaline sources — a review. Desalination" [63] based on the global production of desalination brine, there is a total theoretical energy potential of 8 GWh/a. Assuming a process efficiency of 40% in the research studies, this results in 3.2 GWh/a and 365 MW. The study shows that this energy can be harnessed with a power density of over 5 W per m^2 of membrane. [63]

In addition to desalination plants, natural resources can also be used. These include hypersaline lakes, salt domes and hypersaline geothermal water.

Hypersaline lakes are bodies of water that have a much higher salt concentration compared to typical fresh water lakes. These lakes contain increased levels of dissolved salts, minerals and other substances, resulting in a high salt content. Some examples of hypersaline lakes are the Dead Sea and the Great Salt Lake. These lakes are usually endorheic, i.e. they have no natural drainage, which leads to an accumulation of salt and minerals over time. However, there are no hypersaline lakes in the EU, so there is no exploitable potential here.

Salt domes, also known as salt diapirs, are geological formations consisting of underground salt deposits. These formations are created when thick layers of salt, often created by the evaporation of ancient seas, are buried under layers of sedimentary rock. Over time, the salt flows upwards due to the immense pressure and forms dome-like structures.

Salt domes can vary in size and shape and can be anywhere from a few kilometres to several hundred kilometres in diameter. They are usually located deep underground, and their tops can be exposed to the surface due to erosion or tectonic activity. Salt domes are mainly composed of halite, a mineral form of sodium chloride. According to the study, it is assumed that a single salt dome of 1 km^3 contains an energy potential of 77 TWh. In Germany and Denmark, in particular, there are large salt deposits that can be utilised. [63]

Hypersaline geothermal water refers to underground water sources that have a high salt concentration and are heated by geothermal energy. Geothermal energy is the heat generated by the earth's core, which can be used for various applications, including electricity generation and heating. In certain regions, the water-bearing layers deep underground contain a high content of dissolved salts. These hypersaline water sources are located at a depth of around 1 to 2 km, where they are heated by geothermal heat from the earth's interior. The combination of high salt content and high temperatures distinguishes hypersaline geothermal water from typical fresh water springs. However, the potential for using natural springs has not yet been determined. [63]

In addition to natural sources, industrial brines can also be used. These include brine waste water, oilfield brines (fracking waste water) and evaporation ponds - solar brines.

Industrial brines are salty solutions that are produced as by-products or waste streams in various industrial processes. These brines have a high salt content (salt concentration of 3.5% or more by weight) and may contain other dissolved minerals or chemicals depending on the industry. Industrial brines can be generated in sectors such as food processing, chemical production, tanneries and oil and gas extraction. In comparison, oceans have an average salt content of 3.5% with very low levels of fluctuation.

Brine waste water is a common type of industrial brine. It is produced when water is used for processes such as cleaning, washing or cooling in industrial operations. The water becomes contaminated with salts and other substances, resulting in a brine solution that needs to be treated or managed.

The salt content of industrial brines can vary depending on the industry and specific process. Hypersaline brines, which have a salt concentration of 3.5% or more by weight, are of particular interest due to their potential for energy and resource recovery. It is estimated that hypersaline industrial brines are likely to account for 5% of total global waste water treatment demand and therefore offer a high potential. [63]

Oilfield brine, also known as fracking waste water, is a salty water solution produced during hydraulic fracturing, or fracking. Fracking is a technique for extracting crude oil and natural gas from shale rock formations deep underground. Fracking involves injecting a mixture of water, chemicals and sand into the shale rock to create cracks through which the oil or gas can flow unhindered. The result is that a considerable amount of water flows to the surface with the extracted oil or gas. This water is referred to as oilfield brine or fracking waste water.

Oilfield brines can have a high salt content due to the presence of dissolved minerals and chemicals produced during the extraction process. The exact composition of fracking waste water can vary depending on factors such as the geological formation, the chemicals injected and the water sources used. In the USA alone, the amount of water produced from unconventional gas extraction is estimated at 566 million m^3/yr. [63]

Evaporation ponds, also known as solar salt ponds, are man-made or natural shallow ponds designed for salt production through the evaporation of sea water or brine. These ponds use solar energy to evaporate the water, leaving behind salt crystals that can be harvested.

Solar salt pans usually consist of a series of interconnected ponds or basins. Sea water or brine is first pumped into the first pond, and as the water evaporates due to solar radiation, the salt concentration increases. The concentrated brine is then fed into the subsequent pools, where further evaporation takes place. The process continues until the last pond, where the salt concentration is at its highest and salt crystals begin to form on the surface of the pond.

Solar salt pans can be found on all continents, including in Europe and especially in Portugal, Spain and France, as far as EU countries are concerned. [63]

Overall, hypersaline sources also offer an option for osmotic energy generation. At the same time, osmosis technologies offer the opportunity to improve the efficiency of desalination in the EU salt industry. However, there are still no precise studies on the specific potential, especially for the European region. Harnessing hypersaline sources for osmotic energy production requires fresh water and a nearby site (e.g. a sea) to dispose of the resulting brackish water, which may limit the use of inland hypersaline sources.

9 Conclusion

This study examines osmotic energy technologies and their potential for increasing the utilisation of renewable energy supply in the European Member States. As a result, the technical evaluation of osmotic energy systems shows that three systems will be marketable in the future. These are the PRO, the RED and the INOD technologies. In order to further improve the efficiency of these technologies in the future, the system components in particular, such as the membranes, are constantly being further optimised. The first larger pilot plants have already been realized and are being tested. The output sizes are currently still in the kW range. Plants on a MW scale are planned for the coming years. It should be borne in mind that the investment costs for the construction of such plants are currently still very high compared to other renewable energy technologies.

Measured against this, the fact that the operating costs are seen as rather low is a positive aspect. In terms of LCoE, PRO shows an initial LCoE of 0.15–0.19 €/kWh, which is expected to fall to below 0.09 €/kWh in 2030. For RED (incl. INOD), a decline from 0.11–0.12 €/kWh to 0.05 €/kWh for the 100 MW scale is forecast. For INOD, a reduction from 0.15 €/kWh for the first commercial plant to 0.08 €/kWh within the next five years until the year 2028 is forecast.

In addition to the technical and economic aspects, the study determines the theoretical energy potential for osmotic power plants for the European Member States. With a river water withdrawal rate (proportion of river water that is removed for the osmosis system and returned to it shortly afterwards) of 20% and an efficiency of 45% of an SGE plant, the estimated technical power potential is 6.4 GW in the EU. With an operating time for the osmotic energy systems of 8,000 h/yr (equivalent to a 91% load factor), this can provide approx. 50.8 TWh of energy annually in the EU. The load factor takes into account various factors such as downtime for maintenance, unexpected failures, or exceptionally low river flows. The impact of climate change on the frequency, severity and duration of droughts is beyond the scope of this study and has not been taken into account when assessing the osmotic energy generation potential.

When building the plants, care must also be taken to ensure that the locations are chosen in such a way that the supply lines to the osmotic power plant from sea and fresh water or other water resources are as close to each other as possible in order to minimise increased investment costs or possible interference with nature. This case-by-case analysis is beyond the scope of this study and has not been taken into account when determining the osmotic potential in the EU.

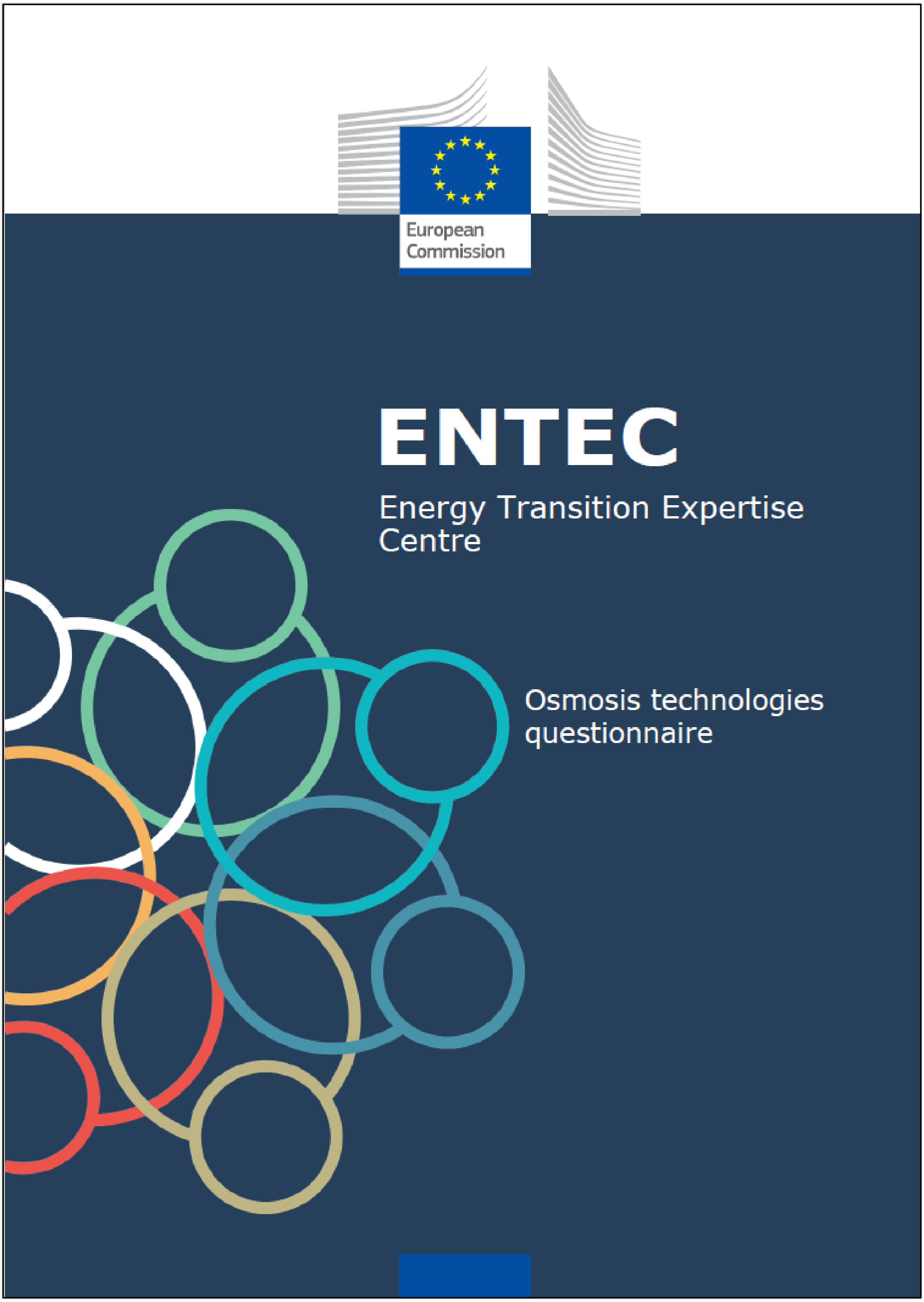
However, the potential must be viewed in a differentiated manner, as there are geographical restrictions for some countries. These include, for example, that in some landlocked countries (Luxembourg, Austria, Slovakia, the Czech Republic and Hungary), there is no potential for osmotic energy from rivers and seas. For these countries, the use of waste water for osmotic energy production via PRO systems may be an option. However, the difficult data situation does not allow a simple estimation of the potential from waste water in this study and should be addressed in further studies. Furthermore, it can be seen that the Nordic countries in the Baltic Sea region, in particular, only have a comparatively low potential due to the small differences in salinity between rivers and seas, despite high outflows. Countries such as France, Germany, Italy, the Netherlands and Romania have rivers with a high technical power potential for generating energy from osmotic power.

The detailed assessment of the power and energy potential in the EU Member States can be found in the datasheets published together with this report.

In addition to the potential from rivers and oceans, there is further potential from hypersaline sources. However, these still need to be investigated in more detail. Harnessing hypersaline sources for osmotic energy production requires fresh water and a nearby site (e.g. a sea) to dispose of the resulting brackish water, which may limit the use of inland hypersaline sources

In summary, osmotic energy technologies offer a promising alternative to conventional energy generation, as they are renewable, produce no direct CO_2 emissions and - unlike solar PV and wind - have a very stable operation 24/365, except for failure, maintenance or exceptionally low river flow. Osmotic energy technologies may become cost competitive with established renewable energy systems in the coming years. However, the investment costs for the construction of power plants are still high but will fall in the coming years. Nevertheless, the technical energy potential is large and can make a good contribution to increasing the share of renewable energies in our future energy mix, while ensuring supply stability.

A.1 Questionnaire for the survey of companies



EnTEC – Osmosis technologies questionnaire

Terms of Reference - The potential of osmotic energy in the EU - Team

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Disclaimer

2

1 Introduction to Osmosis technologies questionnaire

Below you will find technical and economic questions about osmosis technologies. The aim of the survey is to obtain a better understanding of the osmosis technologies themselves and their potential uses for energy generation.

When answering the questions, please note that the data obtained will be included in the report "The potential of osmotic energy in the EU". This report will be published after completion.

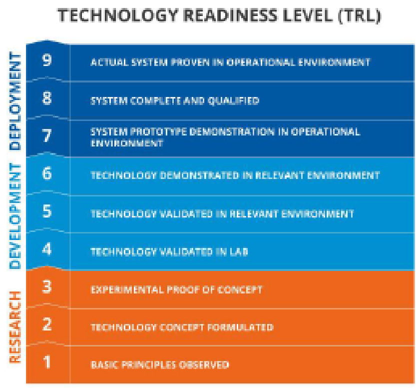
Please use the fields after the questions to answer. If you have any additional material, please return it with the completed questionnaire. If you have relevant sources for the answers to the questions, please include them.

2 Osmosis technologies questionnaire

2.1 Technical questions about osmosis technologies

Question 1: What Technic Readiness Level (TRL) do you assume for osmosis technology (PRO, RED etc.) for the years 2030, 2040, 2050?

Technology	Pressure Retarded Osmosis (PRO)	Reverse Electrodialysis (RED)	Mixing Entropy Battery (MEB)
Technology Readiness Level (TRL) in 2023	TRL 6 / 7 [6]	TRL 7 [1]	TRL 4 [7]



Question 2: What reference plants are there for your technology and what plants are planned for the future?

Please enter the following parameters, if possible:

- Location
- Technology
- Commissioning year
- Power size (MW; MWh)
- Membrane performance (W/m²)
- Special features of the systems

Question 3: What design sizes (nominal capacity) can the systems have (minimum / maximum design size)? Are the systems modular and scalable? Please consider the status quo as well as systems to be developed in the future.

Question 4: How high is the efficiency of the systems (data in KWh/m^3 of fresh water if possible). How does scaling affect the efficiency of the system?

Question 5: Are there technological differences between the membranes (PRO, RED, mixed technologies) in material? What is the power output of the membranes (data in W/m^2 if possible)? Are characteristic curves for salt concentration or stress build-up / voltage for the membranes available?

Question 6: How much do the parameters (working pressure, temperature, salt concentration) influence technology efficiency? Can daily and seasonal fluctuations be expected in the technology systems?

Question 7: Can daily and seasonal fluctuations be expected in the technology systems?

Question 8: What is the water demand of the current technology?

EnTEC – Osmosis technologies questionnaire

2.2 Economical questions about osmosis technologies

Question 1: What is the expected LCOE (Levelized Cost of Energy) target for osmotic energy technologies (data in €/MWh if possible)? Which cost items are included from your point of view?

Question 2: What are the CAPEX and OPEX to identify the economic viability of the technology (data for CAPEX in €/MW, lifetime and OPEX in €/y, €/m³ if possible)?

If possible, please provide the CAPEX data for the following items:

- Piping/pumping (length)
- Filtering
- Stack (membrane €/m², assembly, connections)
- Electronics (DC to AC inverter)
- Building
- Land
- Personnel

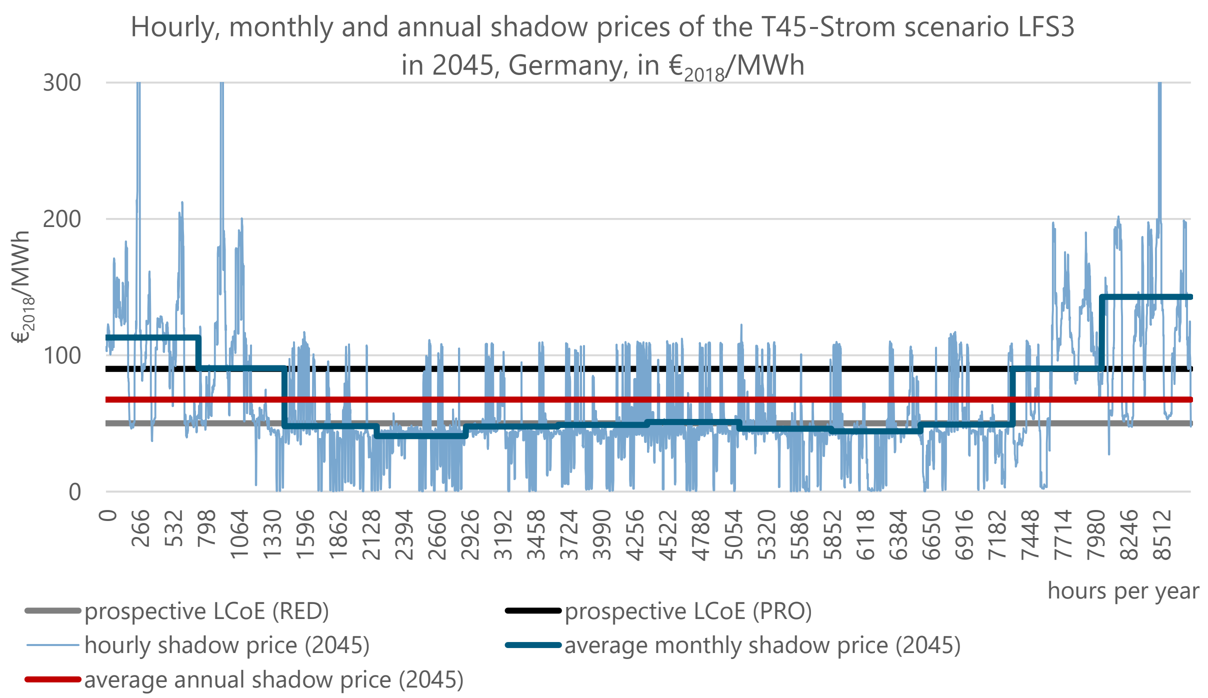
If possible, please provide the CAPEX data for the following items:

- Raw materials and supplies
- Personnel
- Energy costs
- Costs for sales and administration
- Maintenance
- Water usage costs (if necessary)

6

A.2 Shadow prices

Figure 12: LCoE and shadow prices in 2045 (price base 2018) based on the T45-Strom scenario of the LFS3 [51].



A.3 Osmotic energy in an international context

Contribution from: F. Neumann, M. Hamza, IMIEU – Institute for Infrastructure, Environment and Innovation

Outside of the European Union, notably in the UK, Asia (India, Japan, Singapore, Korea and China), the Americas (USA, Canada, Colombia, Brazil), the Middle East (Saudi Arabia, Israel, Jordan), and in Australia there is quite a large and growing body of research carried out on the various dimensions of Osmotic Energy. This research focuses particularly on power production/performance of membranes, their fouling and ways to reduce fouling. Also, a number of pilot installations were built, or are in development.

In **South-Korea**, there was the GMVP project, running from 2013 to 2018 [71] where power was produced with a PRO system from SWRO brine and water from a wastewater treatment plant. The key result of this project was that the installation particularly contributed to enhance the environmental performance of the desalination process by dilution of the desalination brine [72]. The result and part of the installations of this plant will be used to further develop the pilot project in Singapore in the last quarter of 2024 [73], in co-operation with South Korean academic and industrial partners.

In **Japan**, there were a number of pilot installations, notably a PRO system in perspective of the Megaton water project and, more recently an RED system by Yamaguchi University. A follow-up version of this installation is in the development [74].

In **Singapore**, more recently an initiative has been taken by the Public Utility Board (PUB) with co-operation of the National University of Singapore (NUS). This regards power production of desalination brine and fresh water from a wastewater treatment plant with a PRO system. This pilot is now in development and is expected to be in operation end of 2024 [75]. The pilot uses the previous experience and part of the installations of the South Korean GMPV project

In **Colombia,** there is an initiative looking a RED/ or PRO pilot plan near the Magdalena river, making use of an existing port structure, supported by the local energy agency and the University of Barranquilla [76]. A specific site is in process of being selected.

Over-all it seems that currently, EU initiatives seem to be slightly ahead in the process towards commercial upscaling. It is of interest to these initiatives to maintain/further develop their European funding basis to sustain this position.

A.4 Database on osmotic energy potential in the EU

The relevant Excel file is available here.

List of tables

List of figures

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