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# Osmotic power plants: Potential analysis and site criteria

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## Abstract

**Osmotic power plants belong to the ocean renewable energy sources exploiting the potential of salinity gradients, which occur in the mixing zone of river and sea water at the mouth of rivers.**

**The global potential of salinity gradient energy is huge and theoretically only limited by the world's river water flux into the oceans. In practice, only a small amount of this potential can be exploited. Taking technical constraints of the energy conversion into account, the global technical potential is calculated to approx. 5.200 $\text{TWh}_{el}$/a. Based on the fact that the extractable river water is limited to sustain the ecological stability of the river, the ecological potential for osmotic power plants is introduced. Being a subset of the technical potential it is calculated to 520 $\text{TWh}_{el}$/a.**

**In theory, every river-mouth is a possible location for an osmotic power plant, but there are several practical constraints. Site criteria to identify suitable regions for osmotic power plants are defined and the potentials for selected regions are calculated.**

**Keywords:** osmotic power, potential analysis, salinity gradient energy, site criteria

## 1. Introduction

Osmotic power plants are one way to use the energy of salinity gradients in a technical process. Salinity gradient energy always occurs, when two solutions with different salinity mix with each other. One example is the mixing of ocean and river water taking place at the mouth of rivers. This process is part of the natural global water cycle. Therefore the salinity gradient energy belongs to the renewable energy sources. In osmotic power plants salinity energy can be converted into electricity. Analog to conventional hydro power plants, the process allows stable, non-fluctuating electricity generation. This is a major advantage compared to fluctuating renewable energies like photovoltaik or wind power. Recently osmotic power gained a lot of attention due to the opening of the world's first osmotic power plant at the end of 2009 in Hurum (Oslofjord), Norway.

Here we show an approach, how to calculate the potential of utilising salinity gradient energy in osmotic power plants. The potential is analyzed on a global and regional level. Different potential definitions are also taken into consideration. Additionally to the common potential values, an approach has been developed to calculate the ecological potential for osmotic power plants. The ecological potential allows a more realistic assessment of the exploitable potential for osmotic power plants. The calculation of the ecological potential is based on the amount of usable water which is limited due to ecological constraints (e.g. ecological stability of the river).

Another major task for the further development of osmotic power plants is to answer the question how suitable sites for osmotic power plants can be identified. Here the major site criteria are discussed.

## 2. Method

To examine the potential of electricity generation by osmotic power plants, the different potential terms are defined first (see chapter 2.1). Based on this the different potential values are calculated by using river discharge data (see chapter 2.2). In addition, the boundary conditions given by the characterization of the different water bodies are taken into account for the calculations (see chapter 2.3).

### 2.1 Definition of potential terms

The **theoretical potential** of a renewable energy source is the physical maximum usable energy in a specific region during a specific period of time. For salinity power plants the theoretical potential is given by the Gibbs Free Energy of mixing. It is calculated by assuming complete, ideal mixing of ocean and river water. Parameters for calculating the theoretical potential are the temperature and the salinity of river and ocean water as well as the river water discharge into the ocean. The mixing ratio between ocean and river water is assumed to be unlimited due to the fact that the river water discharge into the ocean is very small compared to the water volume of the world ocean.

In practice, only a small part of the theoretical potential can be exploited. Therefore the **technical potential** takes the technical constraints of the energy conversion process in osmotic power plants into account by using a technical power plant model. The technical potential is a subset of the theoretical potential.

The process configuration of the examined osmotic power plant is shown in Fig. 1. The potential assessment is based on the Pressure-Retarded-Osmosis (PRO) concept.

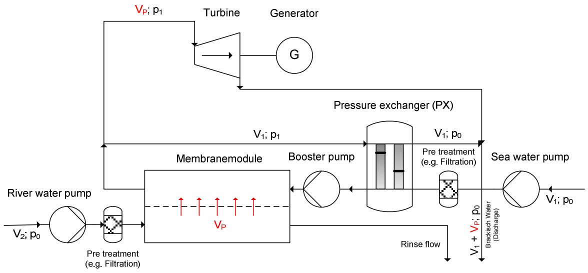

**Figure 1:** Schematic view of the power plant configuration (PRO concept)

The technical basis data to calculate the net electrical power plant output is summarized in Table 1. Beside the technical basis data for the power plant components, the operating point is defined by the pressure ratio $\Delta p/\pi$ (ratio between the pressure difference across the membrane modules $\Delta p$ and the mean osmotic pressure $\pi$ in the membrane modules), the volume flow ratio (ratio between ocean and river water) and the permeation factor (ratio between permeate and river water). These values are also included in Table 1.

| Categorie | Unit | Value |
|---|---|---|
| Turbine outlet pressure | [bar] | 1 |
| Membrane pressure drop | [%] | 1,6 |
| Mixing losses in PX* | [%] | 2,6 |
| Pump efficiency | [-] | 0,85 |
| PX* efficiency | [-] | 0,96 |
| Turbine efficiency | [-] | 0,9 |
| Generator efficiency | [-] | 0,97 |
| PX* inlet pressure | [bar] | 1,7 |
| Pressure ratio $\Delta p/\pi$ | [-] | 0,5 |
| Volume flow ratio | [-] | 1:1 |
| Permeation factor | [-] | 0,9 |
| Capacity factor | [-] | 0,913 |

*: Pressure exchanger

**Table 1:** Basis data of the technical power plant model

The generated electrical energy is calculated with the capacity factor and the net power plant output.

Analog to the theoretical potential, the technical potential is calculated by assuming the utilisation of the complete river water discharge for generating electricity in osmotic power plants. The pumping power to transport the river and sea water from the intake points to the power plant location is neglected. In practice the required pumping power differs depending on the local conditions. Pumping power might be required to compensate frictional losses (in the transport or pre-treatment system) or height differences.

Beside the technical constraints of the energy conversion, another very important factor restricting the technical potential is the amount of usable river water. The amount of water which can be extracted out of a river is site specific and therefore limited by the ecological stability of the river and/or legal regulations. The **ecological potential** of osmotic power plants is therefore introduced as a subset of the technical potential which takes ecological restrictions of water extraction into account.

For the calculation of the ecological potential it is assumed, that 10 % (extraction factor) of the long term annual mean discharge is extractable for a use in osmotic power plants. This estimate is based on the characteristical seasonal water discharge data of german rivers. The main criteria for the definition of the water extraction factor is, that the resulting river water flow after the water extraction does not fall below a specified value. That value is defined by the natural long term mean low river water discharge in the course of a characteristical mean discharge year.

Additionaly, the extracted water flow must be maintained, because an efficient operation of osmotic power plants requires a constant volume flow in the course of one year to reach high capacity factors. During times of high discharge (typically during the winter) the extraction of larger volume flows might be ecological possible, but out of economic reasons, it is not reasonable to design the plant to a maximum discharge value which occurs only during a few days of a year.

The yearly changes in river discharge are not taken into account. According to conventional river water power plants the operating time, respectively the net power output, might be reduced during low discharge years.

The **economical potential** of osmotic power plants is not evaluated in this study.

## 2.2 Discharge data

The discharge data used to calculate the potential values for osmotic power plants on a continental basis is summarized in Table 2. The discharge values are taken from a discharge model (2009 version) of the Global Runoff Data Centre (GRDC) [1].

The model also provides regional discharge values for pre-defined regions or regions, that can be self-defined (see chapter 5).

| Continent | annual discharge [$km^3/a$] | mean discharge [$m^3/s$] | share [%] |
|---|---:|---:|---:|
| Europe | 2.752 | 87.205 | 7,62 |
| Africa | 3.511 | 111.257 | 9,72 |
| Asia | 11.603 | 367.676 | 32,13 |
| North America | 5.475 | 173.492 | 15,16 |
| South America | 11.083 | 351.198 | 30,69 |
| Australia* | 1.685 | 53.394 | 4,67 |
| World | 36.109 | 1.144.222 | 100 |

*: incl. Oceania

**Table 2:** Continental discharge data [1]

### 2.3 Characterization of water bodies

The salinity of the different water bodies is characterized by the global mean salinity values of world ocean water (approx. 35 [2]) and world river water (approx. 0,13 [3]). The mixing temperature is approximated by the long term mean surface temperature of world ocean water (16,1 °C [4]).

The osmotic pressure of these solutions is calculated by using the detailed composition of the two water bodies (Seawater composition according to [2]; River water composition see [3]). The temperature of the two solutions is assumed to be equal to the mixing temperature of 16,1 °C. By using the electrolyte chemistry simulation tool *OLI Stream Analyzer,* the osmotic pressure is calculated to 26,23 bar for world ocean water respectively 0,06 bar for world river water.

## 3. Results

Based on the assumptions in Chapter 2 the resulting potential values are presented. The theoretical potential of salinity gradient energy for each continent is shown in Table 3.

| Continent | theoretical potential [$GW_G$] | [$TWh_G/a$] |
|---|---:|---:|
| Europe | 241 | 2.109 |
| Africa | 307 | 2.690 |
| Asia | 1.015 | 8.890 |
| North America | 479 | 4.195 |
| South America | 969 | 8.492 |
| Australia* | 147 | 1.291 |
| World | 3.158 | 27.667 |

*: incl. Oceania

**Table 3:** Theoretical potential of salinity gradient Energy (Index G: Gibbs Energy)

The theoretical potential of salinity gradient energy is independent from a concrete conversion technology.

The results for the calculation of the technical potential are summarized in Table 4.

Similar to the procentual share of the continental discharge (see Table 2), the continents with the highest technical potential are Asia and South America (with approx. 1/3 of the global potential each). The total global potential sums up to 647 $GW_{el}$ or 5.177 $TWh_{el}/a$. For other possible salinity power conversion technologies like reverse electrodialysis (RED) plants, the technical potential might differ from the here shown values which are explicitly related to PRO-plants under the defined conditions in Table 1.

| Continent | technical potential [$GW_{el}$] | [$TWh_{el}/a$] |
|---|---:|---:|
| Europe | 49 | 395 |
| Africa | 63 | 503 |
| Asia | 208 | 1.664 |
| North America | 98 | 785 |
| South America | 199 | 1.589 |
| Australia* | 30 | 242 |
| World | 647 | 5.177 |

*: incl. Oceania

**Table 4:** Technical potential for PRO-plants

The practical relevance of the technical potential is limited, because the restricted river water availability is not considered here. Therefore the ecological potential is calculated with the results shown in Table 5.

| Continent | ecological potential [$GW_{el}$] | [$TWh_{el}/a$] |
|---|---:|---:|
| Europe | 5 | 39 |
| Africa | 6 | 50 |
| Asia | 21 | 166 |
| North America | 10 | 79 |
| South America | 20 | 159 |
| Australia* | 3 | 24 |
| World | 65 | 518 |

*: incl. Oceania

**Table 5:** Ecological potential for PRO-plants

The worldwide ecological potential sums up to 65 $GW_{el}$ or 518 $TWh_{el}/a$. According to the worldwide use of electrical energy (2005: approx. 15.000 $TWh_{el}$ [5]) the maximum contribution of osmotic power plants would be approx. 3,5 % of the worldwide electrical energy consumption.

## 4. Discussion

The here shown values for the technical and ecological potential are explicitly related to the technical power plant model defined by the values in Table 1. The use of different values leads to a different technical model which results also in the change of the potential values. Regarding the basis data, it has to be differentiated between the technical values and the values defining the operating point of the osmotic power plant. The technical values are related to state of the art performance data of the components. The room for further improvements in this area is considered to be small. As a result, the impact of small changes of the technical values (see Table 1) on the calculated potential values would as well be small.

In the contrary the operating point variables have a significant influence on the potential values. The potential values in Table 4 and 5 have been calculated with an pressure ratio of 0,5. This value has been used, because the membrane power is peaking at that point. The corresponding operating pressure of the power plant is approx. 10 bar. On the one hand, increasing the pressure ratio would mean increasing the operating pressure and therefore also the power plant electrical output. On the other hand, the membrane power decreases which would result in an increase of the required membrane area (constant volume flow) and therefore in higher investment costs. In the end the choice of the operating pressure ratio is a question of economical optimisation.

To show the influence of the pressure ratio on the potential values a parameter variation is considered here. In Table 6 the values for the ecological potential are shown for a pressure ratio of 0,7 which would mean an operating pressure of approx 14 bar.

| Continent | ecological potential | |
|---|---|---|
| | [GW$_{el}$] | [TWh$_{el}$/a] |
| Europe | 7 | 58 |
| Africa | 9 | 74 |
| Asia | 30 | 243 |
| North America | 14 | 115 |
| South America | 29 | 232 |
| Australia* | 4 | 35 |
| World | 95 | 757 |

*: incl. Oceania

**Table 6:** Ecological potential for PRO-plants with a pressure ratio of 0,7

The increased pressure ratio results in an increased ecological potential of approx. 46 % (compare Table 5 and 6).

With the used extraction factor (see Chapter 2.1), the ecological potential amounts to 10 % of the technical potential (compare Table 4 and 5). If higher extraction factors are to be considered, the ecological potential can be calculated by multiplying the extraction factor with the corresponding value for the technical potential.

The other two parameters defining the operation point (Volume flow ratio and permeation factor) are closely related to each other, when looking at the net power plant output. Assuming a constant permeation factor, a variation of the volume flow ratio to higher ratios (e.g. 2:1) would not increase the net power output of the power plant. On the one hand, the mean osmotic pressure and as a result of that the turbine output is increased for higher volume flow ratios. On the other hand the additional required pumping power of the booster pump (see Fig. 1) is bigger than the additional turbine power. This situation might change if the permeation factor is dependend on the volume flow ratio, e.g. increasing permeation factor with increasing volume flow. A further investigation will be necessary to clarify the relationship between these two parameters. Depending on the relationship an operation with higher volume flow ratios might be reasonable. Finally the choice of the volume flow ratio is also a result of an economical optimisation.

For a regional potential assessment (for example for a single river) local values for the salinity and the temperature of the river and ocean water should be used. Depending on the local conditions huge variations of salinity and temperature are possible (compared to the here used global mean values), resulting in different potential values.

The same applies to the amount of extractable water which should also be specified for the single rivers. Higher, but also lower extraction factors are possible due to differences in the seasonal water discharge behavior of the rivers.

## 5. Site criteria for osmotic power plants

The so far presented potential values are based on the consideration of all river systems worldwide. In practice only a part of the rivers offer suitable conditions for the operation of osmotic power plants, taking practical and economic considerations into account. For the operation of osmotic power plants fresh and salt water are required. Zones of intensive mixing (brackish water zones) should be avoided for the intake facilities.

The structure of the salinity distribution is characterized by the type of river mouth. According to [6] rivers can be classified in well-mixed, partially-mixed, salt wedge and fjord type estuaries. Well- and partially-mixed estuaries can usually be found in regions with a huge tidal range. There is an intensive mixing of river and sea water and the salinity distribution is highly variable. The salinity gradient of the estuary is horizontal. To reach suitable intake areas beyond the brackish water zone, a large, cost intensive pipeline system for water transport (high volume flows) is required. In these cases, the costs for the transport system might dominate the overal costs of the osmotic power plant, making the process economically not feasible. Furthermore, frictional losses in the transport system have to be considered, reducing the net power output of the plant.

Examples for well-mixed estuaries are the North Sea rivers Rhine and Elbe or rivers at the atlantic coast e.g. the Seine. Due to the necessity of an extensive water transport system, well- and partially-mixed estuaries are usually not well suited for the operation of osmotic power plants. The Amazonas is another example with a wide brackish water zone of more than 150 km. Excluding this sinlge river from the worldwide potential considerations the potential values are reduced by 15 % due to the high share according to the total worldwide discharge.

Salt-wedge estuaries are typical for regions with a low tidal impact. They are characterized by a distinctive vertical salinity gradient and a reduced mixing of river and sea water. Examples for salt-wedge estuaries are the Mississippi or the Rhône (France). Fjord Type rivers are also characterized by a vertical salinity gradient. Mixing between river and sea water occurs here only in the surface layers. Fjords are usually very deep and the deeper layers are not influenced by the mixing processes. Both river types offer suitable conditions for osmotic power plants because of their stable salinity conditions and the feasibility of a shorter transport system due to their vertical salinity gradients.

Suitable regions regarding river mouth type are shown in Fig. 2. Included are regions with low tidal impact where salt-wedge estuaries are assumed to be predominant (e.g. Mediterranean Sea, Gulf of Mexiko) or regions with mostly fjord-type estuaries (e.g. Norwegian Sea, New Zealand).

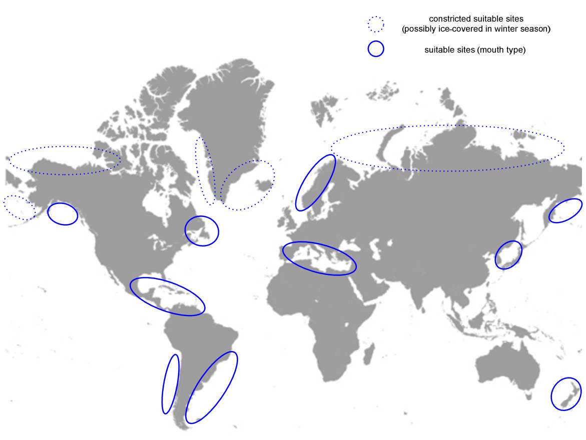

**Figure 2:** Regions with suitable conditions for osmotic power plants regarding river mouth type

For the selected regions in Fig. 2 the ecological potential is calculated based on regional flux data. The regional classification is based on the GIWA-Regions (for details about the GIWA-Regions see [7]). The potential values are calculated based on the technical basis data in Table 1. The results are summarized in Table 7.

The total ecological potential for the selected regions sums up to 15 $GW_{el}$ or 122 $TWh_{el}/a$. Taking only suitable sites for osmotic power plants into account regarding the river mouth type, the potential is reduced compared to the total worldwide potential (see Table 5 and 7).
It has to be mentioned, that not all rivers in the selected regions will offer suitable conditions for osmotic power plants (e.g. Mississippi: high particel load, very flat and wide delta) and there will also be rivers in other regions not considered here offering suitable conditions.

Assuming an increased pressure ratio ($\Delta p/\pi = 0{,}7$) the ecological potential increases (22 $GW_{el}$ respectively 180 $TWh_{el}/a$).

Beside the river mouth type, other side criteria determining the suitability for osmotic power plants are the salinity of the water bodies (applications in regions with low salinity sea water e.g. the Baltic or the Caspian Sea are restricted), the water composition (rivers with a high particle load or a high bio-fouling potential would require intensive pre-treatment) and the general water availability.

| Nr. | GIWA-Region | ecological potential | |
|---|---|---|---|
| | | [$GW_{el}$] | [$TWh_{el}/a$] |
| 1 | Arctic | 4,5 | 36 |
| 2 | Gulf of Mexico | 2,0 | 16 |
| 38 | Patagonian Shelf | 1,7 | 13 |
| 25 | Gulf of Alaska | 1,3 | 10 |
| 21 | Mediterranean Sea | 0,8 | 7 |
| 39 | Brazil Current | 0,7 | 6 |
| 11 | Barents Sea | 0,7 | 6 |
| 64 | Humboldt Current | 0,6 | 5 |
| 9 | Newfoundland Shelf | 0,6 | 5 |
| 63 | Tasman Sea | 0,5 | 4 |
| 28 | East Bering Sea | 0,5 | 4 |
| 33 | Sea of Japan | 0,4 | 3 |
| 29 | West Bering Sea | 0,2 | 2 |
| 12 | Norwegian Sea | 0,2 | 2 |
| 14 | Iceland Shelf | 0,1 | 1 |
| 15 | East Greenland Shelf | 0,1 | 1 |
| 16 | West Greenland Shelf | 0,1 | 1 |
| 4 | Caribbean Islands | 0,1 | 1 |
| | Total | 15,2 | 122 |

**Table 7:** Ecological Potential for the selected regions (GIWA-Regions) according to Fig. 2

## Acknowledgements

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