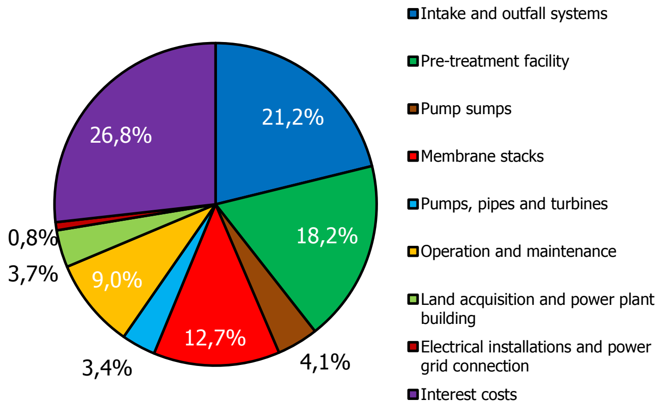
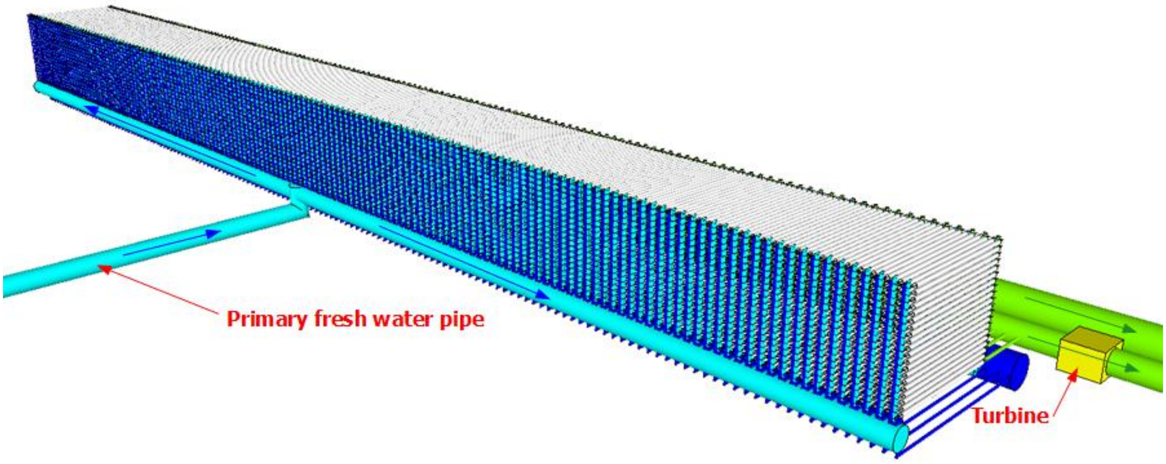
The feasibility of a commercial osmotic power plant





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Challenge the future

Preface

This master thesis concludes my research on the feasibility of a commercial osmotic power plant. It is written in the framework of my graduation at Delft University of Technology and was conducted at the department of Hydraulic Engineering at the faculty of Civil Engineering and Geosciences.

My interest in hydropower began to increase during the first year of the specialisation Hydraulic Structures. The large civil works combined with the social importance in the sense of renewable energy attracted me. This was for me the reason to follow the course on Waterpower Engineering (CT5304) and, after passing the course, to graduate in the direction of Waterpower Engineering. The lecturers of the course, ir. W.F. Molenaar and ir. A. van der Toorn, introduced me to the subject of osmotic power. This form of renewable energy is only tested at laboratory and pilot scales, but interested parties believe that osmotic power could be exploited at a commercial scale in the near future. This statement initiated me to analyse the feasibility of commercial exploitation of an osmotic power plant.

Working on this thesis has been very challenging for me. The renewable, innovative form of energy production and the interface with physics, chemistry and economics made this thesis very diverse. It was therefore not a disappointment that I had to conclude that the commercial exploitation of osmotic power is, with the present technology and knowledge, far from being feasible.

This master thesis is supervised by the graduation committee, prof. drs. ir. J.K. Vrijling (TU Delft – Department of Hydraulic Engineering), ir. W.F. Molenaar (TU Delft – Department of Hydraulic Engineering) and dr. ir. J.H.G. Vreeburg (TU Delft – Department of Water Management). I would like to thank my graduation committee for their support and critical comments on my work. I also would like to thank my family and friends for their support during this intensive period.

Enjoy reading!

Rick Kleiterp

Delft, January 2012

Summary

Osmotic power is a form of renewable energy which is currently not used at a commercial scale, but it might have the potential to be exploited in a sustainable manner in the near future. It uses the principle of osmosis, which is known for over a century and is used since recent years for several membrane applications like desalination and filtration. The salinity gradient between fresh river water and salt sea water, separated by a membrane, causes an osmotic flow which can be converted into electricity by using one of the two types of osmotic power generation:

1. Pressure retarded osmosis (PRO), which uses semi-permeable membranes for the development of an osmotic pressure.
2. Reversed electro dialysis (RED), which uses ion-selective membranes for the development of an electric current.

Osmotic power can be produced by a continuous inflow of fresh and salt water into the osmotic power plant, and by a continuous discharge of the brackish effluent. The larger the fresh water availability and salinity gradient, the larger the amount of produced energy will be. As a rule of thumb, a continuous flow of 1 m^3/s river water mixed with sea water represents a gross capacity of approximately 1 MW.

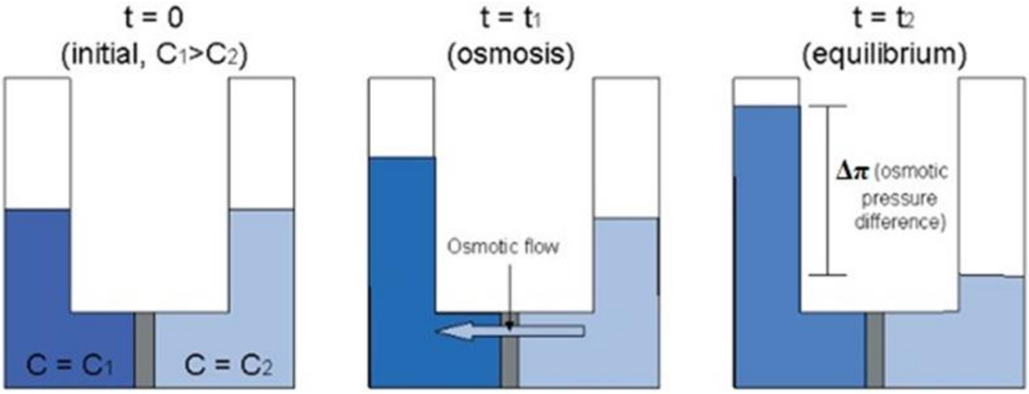

Figure 2.1: Schematic presentation of pressure retarded osmosis.

Osmotic power is a form of renewable energy which is still under development. The technology is known for more than a century, but ineffective membranes and the high membrane price ensured that the production of osmotic power was not feasible for a long time. In recent decades however, the necessity for other membrane-applications has led to further development of membranes. The improved effectiveness and the lower membrane price resulted in new feasibility studies on the production of osmotic power. With an increasing membrane power density and decreasing membrane price, osmotic power could be a feasible source of renewable energy in the future. Studies, held at laboratory scale, concluded that osmotic power is a promising source of renewable energy in the future. The next step in the development was the up scaling from laboratory to a pilot scale. At present, two interested parties, Statkraft (PRO) and REDstack (RED), operate a small-scaled power plant. According to Statkraft and REDstack, the results of these pilot plants are promising. REDstack believes that an energy unit rate of 8 cents/kWh should be possible for a commercial-scaled power plant.

However, what is lacking in these studies is the actual design of the osmotic power plant. Scaling up of an osmotic power plant to a commercial scale has a major impact on the design of the main infrastructure:

- Separation structures between fresh, salt and brackish water
- Intake and outfall systems
- Pre-treatment
- Membrane stacks
- Pumps, pipes and turbines (or converters)

The question is whether a commercial osmotic power plant is feasible if the capital costs of the main infrastructure are included. Is a marketable energy unit rate equal to 8 cents/kWh possible? Answering this question is the objective of this thesis.

In order to answer the research question, the thesis is divided into a number of parts. In Part II of the thesis, a suitable power plant location is selected. A number of locations are considered and judged on a number of requirements. The most important requirements are the salinity gradient, fresh water availability and the possibility to separate the flows in three-ways. The effluent of the osmotic power production is a brackish solution which should be discharged out of the power plant. If this brackish solution is discharged into the salt or fresh water source, the brackish solution could be retaken into the power plant (see figure 2.6) which will affect the osmotic power production because it will decline the salinity gradient. The selected power plant location is the Haringvliet – Grevelingen location. This location is suitable because, apart from a large salinity gradient and fresh water availability, it is suitable for a three-way separation (see figure 4.10).

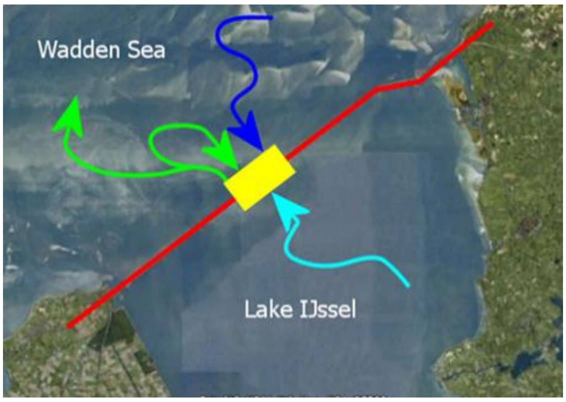

Figure 2.6: Recirculation problem.

Figure 4.10: Power plant location Haringvliet – Grevelingen.

In Part III of the thesis, 6 case studies are conducted:

1. 25 MW PRO power plant
2. 200 MW PRO power plant
3. 1 MW PRO power plant
4. 25 MW RED power plant
5. 200 MW RED power plant
6. 0.55 MW RED power plant

The objective of these case studies is to obtain the net energy production and total capital costs of the power plant. The Haringvliet – Grevelingen location is used for the 25 and 200 MW power plant. The 1 and 0.55 MW power plant are a special case, because these power plants will be integrated in a sewage treatment plant (STP). In order to obtain the net energy production and total costs of the power plants, the power plant should be dimensioned. In the case studies therefore, the dimensions and energy consumption (or losses) of the main infrastructure are determined.

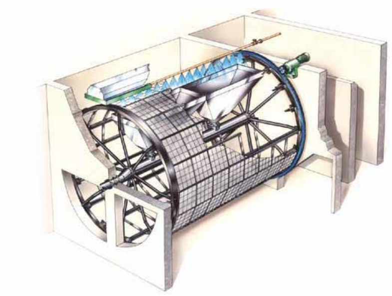

Figure 6.21: Micro-filtration drum [29].

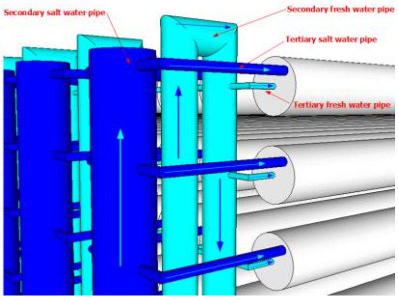

Figure 6.26: Inflowing solutions into the pressure vessels.

Figure 6.32: The position of the pumps, pipes and turbines.

In part IV of the thesis, the net energy production and total capital costs of the power plants are used to obtain the energy unit rate. However, the revenues and investments over the lifespan of the power plants will result in high energy unit rates.

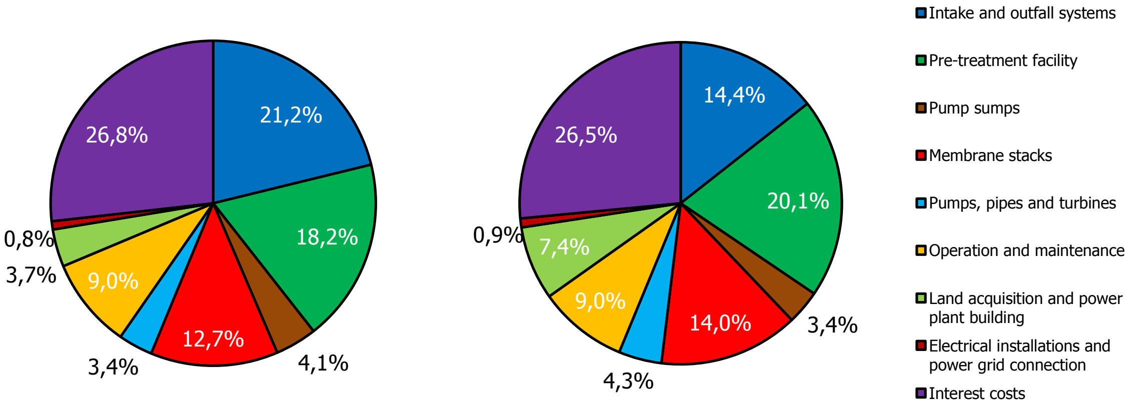

Figure 9.3 and 9.4: Distribution of the energy unit rate in case of the 25 MW (left) and 200 MW (right) PRO power plant.

Power plant		Energy unit rate	
25	MW PRO	1.15	€/kWh
200	MW PRO	3.71	€/kWh
1	MW PRO	0.19	€/kWh
25	MW RED	0.75	€/kWh
200	MW RED	1.21	€/kWh
0.55	MW RED	0.33	€/kWh

Table 9.1: The energy unit rate for the different power plants.

According to table 9.1, the economy of scale does not apply. The energy unit rate will not remain the same or decrease for increasing power plant capacities. The main reason for this is that the fresh water availability decreases for increasing power plant capacities which will result is a smaller net energy production.

The high energy unit rates are mainly due to the intake and outfall systems and the pre-treatment facility. The energy unit rate could be decreased when some expected and recommended developments are considered:

- A development in membrane power density and cost reduction of the membranes.
- Obtaining more knowledge about the phenomenon of recirculation. If an optimum is found in which no recirculation will occur when the flows are separated in only two ways, capital costs on the intake and outfall system or additional infrastructure could be saved.
- Obtaining more knowledge about the pre-treatment of the different flows of an osmotic power plant. If it appears that a pre-treatment facility is not required, the energy unit rates will become significantly lower.
- The development of a membrane bioreactor for the treatment of sewage water.

The developments will have a significantly impact on the energy unit rate (see figure 10.5):

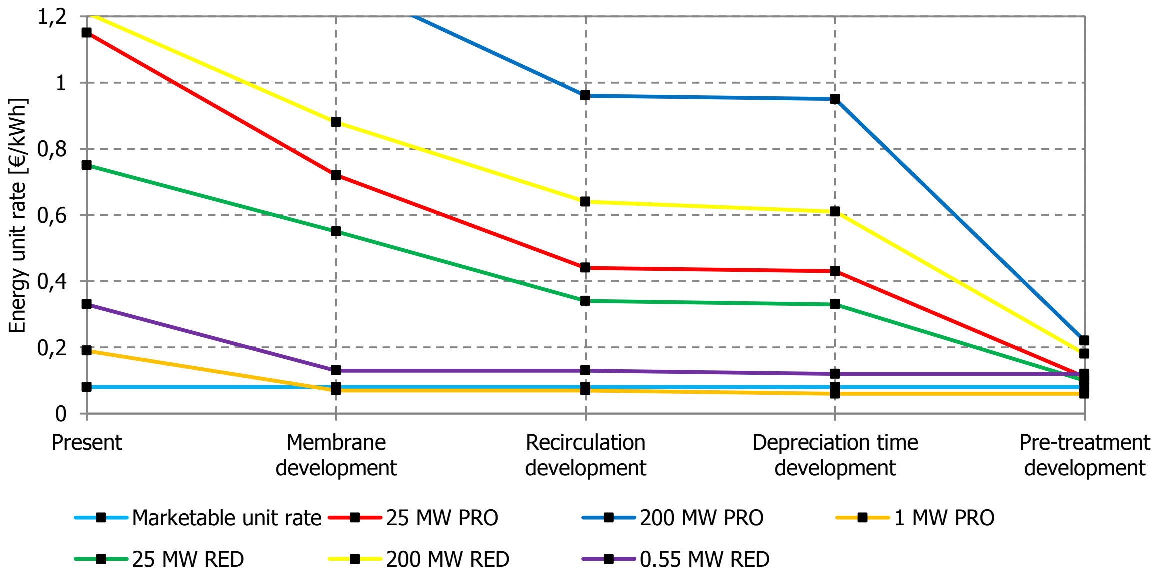

Figure 10.5: Energy unit rate when the developments are considered.

The thesis ends with the conclusion in Part V. With the present technology and knowledge, the energy unit rate deviates too much from a marketable energy unit rate. The commercial exploitation of an osmotic power plant is therefore far from being feasible. However, when a number of developments are considered the energy unit rate will decline towards a marketable energy unit rate. The commercial exploitation of an osmotic power plant could therefore become feasible in the near future. Though, the question is whether these developments are reasonable. Especially the development in recirculation and pre-treatment seems to be an utopia. Therefore, the answer to the research question is that the future commercial exploitation of osmotic power appears to be only feasible when a small-scaled PRO power plant is integrated in a STP under the assumption that a membrane bioreactor is present at the site of the STP.

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Nomenclature

Symbols

a	amount	[-]
A_w	water permeation coefficient	m/s·Pa
b	scale factor	[-]
c	cost factor	€/unit
C	costs	€
D	diameter	m
E	energy	J
F	Faraday constant	96.485 C/mol
f	friction coefficient	[-]
g	acceleration of gravity	9.81 m/s^2
h	head	m
H	height	m
i	ion concentration per dissociated solute molecule	[-]
J	flux	mol/m^2s
k	resistance to salt diffusion through porous substrate	s/m
L	length	m
M	molar mass	kg/mol
$NPSH$	net positive suction head	m
p	pressure	Pa
P	power	W
Q	discharge or flow rate	m^3/s
r	area resistance	$\Omega \cdot m^2$
R	universal gas constant	8.314 J/mol·K
S	salinity	g/l
t	time	s
T	absolute temperature	K
u	velocity	m/s
V	electric potential	V
$\overline{V}_c$	molar or specific volume of solution	m^3/mol
W	power density	W/m^2
x	mole fraction	[-]
z	static head	m
z	valence of ions (in equation 2.1 and 2.4)	[-]

Greek letters

Δ	difference	[-]
η	efficiency	[-]
μ	molar free energy	J/mol
ξ	local loss factor	[-]

π	osmotic pressure	Pa
ρ	density	kg/m^3
$\bar{\upsilon}$	partial molar volume at given temperature and pressure	m^3/mol
φ	electrochemical potential	V

Subscripts

$€/kWh$	unit rate per kWh
atm	atmospheric
avg	average
c	concentrated solution
Cl	chloride
d	diluted solution
eff	effective
eq	equivalent
f	friction
H_2O	water molecule
hrs/yr	hours per year
i	charge (in J_i)
i	component (in all other cases)
L	local
m^3/yr	volume per year
Na	sodium
$NaCl$	sodium chloride molecule
opt	optimal
osm	osmotic
s	suction
w	water
0	initial conditions

Superscripts

0	standard conditions
PRO	pressure retarded osmosis
RED	reversed electro dialysis

Chapter 1
Introduction

At present, the global energy supply is largely based on oil, natural gas and (brown) coal (see figure 1.1). The global reserves on these fossil fuels are finite and the link between global energy consumption and environmental problems such as climate change are widely acknowledged. Because of the environmental problems and the fact that the mining of fossil fuels becomes increasingly expensive, alternative methods have been developed to gain energy. One of the alternatives is nuclear power (see figure 1.2), but this alternative is under a severe public debate. Proponents of nuclear power claim that nuclear power is a clean, safe and cheap form of energy (about 4 cents/kWh instead of an energy unit of about 10 cents/kWh for fossil fuelled power plants). The opponents, on the other hand, argue that nuclear power is a threat to humanity and the environment.

Figure 1.1: Conventional power plants running on coal (left) and gas (right).

Figure 1.2: Nuclear power plant.

Another alternative is to gain energy from renewable energy sources. Though humans have been using most of these sources for thousands of years, so far only a tiny fraction of the technical and economic potential of renewable has been captured and exploited. The most common forms of renewable energy are solar, wind and hydropower (see figure 1.3).

Figure 1.3: Renewable energy sources: solar (left), wind (middle) and hydro power (right).

In the Netherlands, the annual energy consumption is about 900 TWh [1]. A small amount of this consumption, about 3.8% in 2009, originates from renewable energy sources. The Dutch climate and energy policy is that by 2020 14% of the total energy consumption should have been produced by renewable energy sources [2]. This implies a substantial growth, which can be achieved by intensifying the current forms or developing new forms of renewable energy. A potential new form of renewable energy is the use of the difference in molar free energy between two solutions. This form of renewable energy is called osmotic power.

The technology of osmotic power is known for over a century, but the exploitation was not economically feasible for a long time. Nevertheless, positive developments in recent years initiated new studies to the exploitation of osmotic power at a laboratory scale. These studies concluded that osmotic power is a promising source of renewable energy in the future. The positive conclusions resulted in small-scale pilot plants which are being operated at the moment. This thesis will analyse if an osmotic power plant is feasible when the power plant is designed for commercial purposes. In contrast to a laboratory scale, a commercial osmotic power plant requires a suitable location and large civil infrastructure. The question to be answered is whether a commercial osmotic power plant is feasible if the capital costs of the civil infrastructure are included. This is the subject of this thesis.

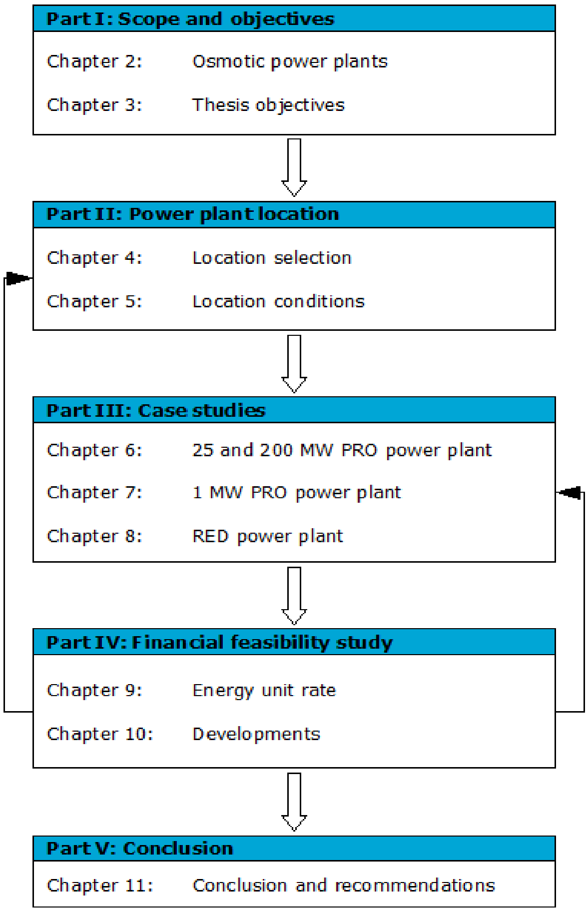

Figure 1.4: Structure of the thesis.

The thesis consists of five parts (see figure 1.4). The first part gives a description of osmotic power plants and the objectives of the thesis. The rest of the thesis structure is explained in section 3.2.

Part I

Scope and objectives

Chapter 2
Osmotic power plants

Osmotic power is a form of renewable energy which is currently not used at a commercial scale, but it might have the potential to be exploited in a sustainable manner in the near future. It uses the principle of osmosis, which is known for over a century and is used since recent years for several membrane applications like desalination and filtration. The difference in molar free energy between two solutions, separated by a membrane, causes an osmotic flow which can be converted into electricity by using one of the two types of osmotic power generation.

This chapter will contain a description of osmotic power plants. After a short history in section 2.1, the theory behind the two types of osmotic power generation is explained in section 2.2. Section 2.3 describes the area of application, and the important parameters which determine the capacity of an osmotic power plant are given in section 2.4. The main infrastructure of an osmotic power plant is described in section 2.5. This chapter ends with a description of the past, present and future development of the exploitation of osmotic power in section 2.6.

2.1 A short history

The phenomenon of osmosis was first observed by the French priest and physicist Jean-Antione Nollet in 1748. He put a pig's bladder filled with wine in a barrel of water. He discovered that the water inside the barrel was able to permeate through the bladder, but the wine was not. The bladder swelled and finally burst. The energy between the water and wine increased the pressure inside the bladder. This was the first known observation of osmotic energy and pressure. For the following 200 years, the phenomenon was only observed and further developed in laboratories. The pig's bladder was soon replaced by membranes, and the Dutch scientist Jacobus H. van't Hoff earned the Nobel Prize for Chemistry in 1902 for his formula which can be used for calculating the osmotic pressure (see equation 2.3). In 1954, R.E. Pattle identified the phenomenon of osmosis as a potential energy source. He discovered that when a river mixes with sea water a large amount of free energy is lost. He found out that by using semi-permeable membranes the free energy can be used to obtain power.

By 1960, the membrane technology was well developed but membranes were only used in a few laboratory and small, specialized industrial applications. The reason was that membranes in general suffered from four problems that prohibited their widespread use as a separation process. They were unreliable, too slow, too unselective and too expensive. This changed during the early

1960s when Professor Sidney Loeb developed a new membrane technology. The new technology changed the use of membranes as a separation process from laboratory to a commercial use. The improved membranes ensured the development of all kinds of membrane applications, like desalination of sea water, different filtration techniques, artificial kidneys, etc.

During the last decades, the membrane technology has increasingly improved. The improving membrane characteristics have ensured a growing membrane market which resulted in a decrease in membrane price. These developments initiated new studies to the use of membranes in osmotic power production. The studies resulted in two kinds of osmotic power generation which are still in development at the moment: Pressure Retarded Osmosis (PRO) and Reversed Electro Dialysis (RED).

2.2 Osmotic power generation

2.2.1 Pressure retarded osmosis

Pressure retarded osmosis (PRO) is a process that uses the osmotic pressure difference for the generation of electricity. Two solutions of different salinity are placed in a compartment and separated by a semi-permeable membrane. This membrane allows the solvent (i.e. water) to permeate and retains the solute (i.e. dissolved salts).

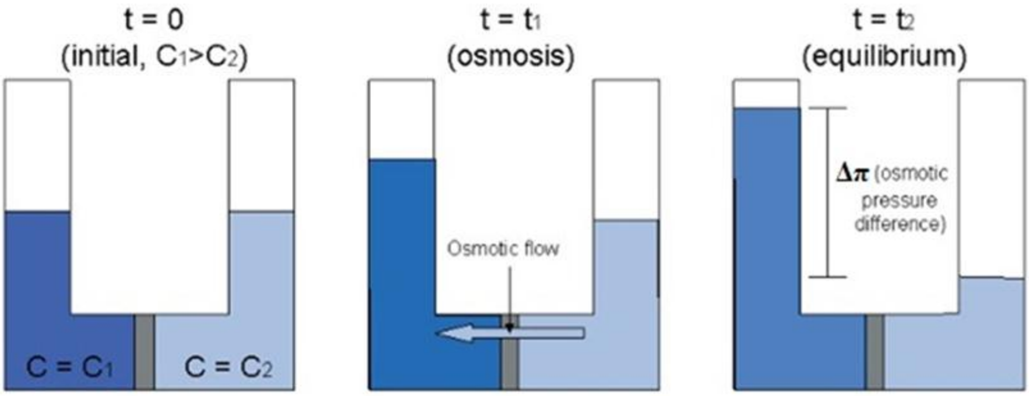

Figure 2.1: Schematic presentation of pressure retarded osmosis.

The molar free energy difference between the two solutions causes a transport of water molecules from the diluted salt solution (right compartment in figure 2.1) to the more concentrated salt solution (left compartment in figure 2.1). This transport is called osmosis. To understand why water molecules are transported to the concentrated solution, the molar free energy is further described.

The molar free energy of a component i is given by [3]:

$$\mu_i = \mu_i^0 + \bar{\upsilon}_i \cdot \Delta p + R \cdot T \cdot \ln\left(x_i\right) + \left|z_i\right| \cdot F \cdot \Delta\varphi \qquad \textbf{(2.1)}$$

During PRO, no transport of ions will occur. The last term of equation 2.1 is therefore equal to zero $\left(|z_i| \cdot F \cdot \Delta\varphi = 0\right)$. The pressure in the diluted salt solution compartment is equal to the atmospheric pressure, so no pressure difference will be applied on the diluted salt solution $\left(\Delta p_d = 0\right)$. The molar free energy gradient between the diluted (subscript d) and the concentrated salt solution (subscript c) reduces to [3]:

$$\begin{aligned} \Delta\mu_{H_2O} &= \mu_{H_2O,c} - \mu_{H_2O,d} \\ \bar{\upsilon}_{H_2O,c} \cdot \Delta p_c + R \cdot T \cdot \ln\left(x_{H_2O,c}\right) &= R \cdot T \cdot \ln\left(x_{H_2O,d}\right) \end{aligned} \quad \textbf{(2.2)}$$

Initially, the system of equation 2.2 is not in equilibrium. The H_2O mole fraction, a measure of the water concentration, of the diluted salt solution is larger than the H_2O mole fraction of the concentrated salt solution and the pressure difference compared to atmospheric conditions in the concentrated salt solution compartment is small. Since the system pursues to reach equilibrium, the H_2O mole fraction of the concentrated salt solution should increase. This is achieved by the transport of water molecules from the diluted salt solution to the concentrated salt solution. This transport is called osmosis.

During the osmotic flow, water molecules permeate through the membrane which causes an increasing hydraulic pressure difference over the membrane. The growth of this hydraulic pressure difference is limited. In other words, the transport of water molecules through the membrane is retarded. The transport of water molecules from the diluted salt solution at atmospheric pressure to the higher-pressure concentrated salt solution results in a pressurization of the volume in the concentrated salt solution compartment. The Δp_c term in equation 2.2 increases. The added water molecules cause an increase in mole fraction and a decrease in salinity of the concentrated salt solution. The concentrated salt solution becomes brackish. The osmotic flow continues until the left hand side of equation 2.2 equals the right hand side and equilibrium is reached. At equilibrium, the molar free energy on either side of the membrane is equal and the system of equation 2.2 becomes:

$$\Delta\pi_{osm} = \frac{i \cdot R \cdot T}{M_i}\left(S_{i,c} - S_{i,d}\right) \quad \textbf{(2.3)}$$

Equation 2.3 is known as the van't Hoff equation [4]. This equation represents the hydraulic pressure difference over the membrane at equilibrium. This hydraulic pressure difference is called the osmotic pressure difference. A derivation from equation 2.2 to the van't Hoff equation is given in Appendix A.2.1. For a 35 g/l NaCl solution, the theoretical osmotic pressure is 29 bars at 20°C. This corresponds to a water column of 290 m. This water column is comparable to that of a large reservoir dam, like the Hoover dam in the United States.

The pressurized volume in the concentrated solution compartment can be converted into electricity by discharging the brackish effluent through turbines. However, once equilibrium is reached the osmotic flow stops and hence the possibility of electricity generation. This problem is solved by a continuous inflow of a concentrated and diluted solution to the power plant, and a continuous discharge of the brackish effluent out of the power plant. In this way, equilibrium will never be reached and electricity can be generated non-stop.

2.2.2 Reversed electro dialysis

Reversed electro dialysis (RED) is a process which uses the electrochemical potential difference for the generation of electricity. In contrast with PRO, RED uses multiple ion-selective membranes instead of one semi-permeable membrane. A number of cation (C in figure 2.2) and anion (A in figure 2.2) exchange membranes are stacked in an alternating pattern between a cathode and an anode. The compartments between the membranes are alternately filled with a dilute salt solution and a concentrated salt solution. Cation exchange membranes are incorporated with negatively charged groups which will allow transport of cations and retain anions. Anion exchange membranes are incorporated with positively charged groups which will allow transport of anions and retain cations.

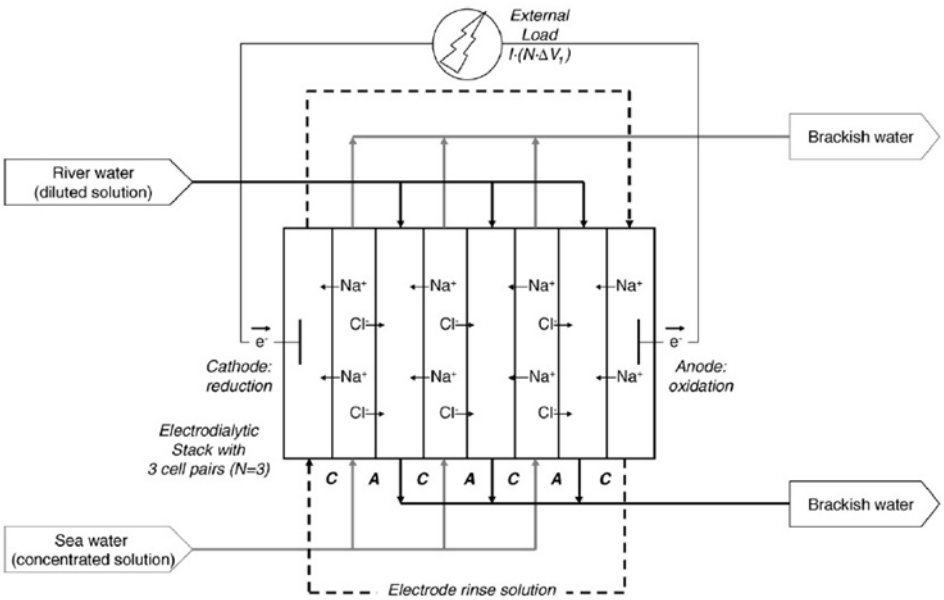

Figure 2.2: Schematic presentation of reversed electro dialysis.

The molar free energy gradient between the two solutions causes a transport of ions through the membranes from the concentrated salt solution to the diluted salt solution. To understand why ions are transported to the diluted salt solution, the molar free energy in the case of RED is described.

Equation 2.1 for the molar free energy also applies for RED. In contrast with PRO, ions are being transported through the membrane instead of water molecules. A hydraulic pressure difference is therefore not possible (Δp=0). The difference in molar free energy between the diluted (subscript d) and the concentrated NaCl solution (subscript c) reduces to [3]:

$$\Delta\mu_{NaCl} = \mu_{NaCl,c} - \mu_{NaCl,d}$$

$$\frac{R\cdot T}{|z_{Na}|F}\ln\left(x_{Na,c}\right)+\frac{R\cdot T}{|z_{Cl}|F}\ln\left(x_{Cl,c}\right)=\frac{R\cdot T}{|z_{Na}|F}\ln\left(x_{Na,d}\right)+\frac{R\cdot T}{|z_{Cl}|F}\ln\left(x_{Cl,d}\right)+\Delta\varphi$$

$$|z_{Na}|=|z_{Cl}|=1 \quad x_{Na}=x_{Cl}=x \tag{2.4}$$

$$\Delta\varphi=\frac{2\cdot R\cdot T}{F}\ln\left(\frac{x_c}{x_d}\right)$$

Equation 2.4 states that the electrochemical potential difference (Δφ) is the only driving force for the transport of ions. Initially, the system of equation 2.4 is not in equilibrium. The mole fraction of the concentrated salt solution is larger than the mole fraction of the diluted salt solution. Since the system pursues to reach equilibrium, the mole fraction of the diluted salt solution should increase. This is achieved by the transport of ions from the concentrated salt solution to the diluted salt solution. This transport is called osmosis.

During the osmotic flow, Na^+ ions permeate through the cation exchange membrane in the direction of the cathode and Cl^- ions permeate through the anion exchange membrane in the direction of the anode. The solution in the compartment of the cathode is positively charged due to the transport of positive Na^+ ions towards the cathode. The solution in the compartment of the anode is negatively charged due to the transport of negative Cl^- ions towards the anode. Electro-neutrality of the solution in the cathode compartment is maintained via reduction at the cathode surface, and in the anode compartment via oxidation at the anode surface. As a result, an electron can be transferred from the anode to the cathode via an external electric circuit. This electrical current and potential difference over the electrodes can be used to generate electricity. The potential difference over the electrodes is equal to the potential difference over a membrane times the number of membranes.

The osmotic flow stops when the electrochemical potential over a membrane is equal to zero. At that point, the concentration of ions on either side of the membrane is equal and equilibrium is reached. Theoretically, a voltage of 80 mV between a diluted and concentrated solution is possible at equilibrium [3]. As in PRO, the electricity generation stops when equilibrium is reached. This problem is also solved by the continuous inflow of a concentrated and diluted solution, and a continuous discharge of the brackish effluent. In this way, equilibrium will never be reached and electricity can be generated non-stop.

2.3 Area of application

According to section 2.2, the area of application should meet two important requirements. The first requirement is a difference in molar free energy, which ensures an osmotic flow that eventually can be transformed into energy. A difference in molar free energy can be obtained by separating two solutions with a different solute concentration by membranes. The larger the difference in solute concentration, the more energy could be produced. The second requirement is the availability of the inflowing solutions because the power plant should continuously be fed with solutions. The larger the availability the more energy could be produced.

So, the area of application should have a large difference in solute concentration and large solution availability. In the Netherlands, these requirements are met at the boundaries of river and sea water. At these locations, the difference in solute concentration (salinity), and the availability of river water (low salinity) and salt water (high salinity) are suitable for the production osmotic power. As a rule of thumb, a continuous flow of 1 m^3/s river water mixed with sea water represents a gross capacity of approximately 1 MW [5].

Another location where osmotic power could be exploited is at a sewage treatment plant (STP). The effluent of a STP is relatively clean and fresh water. When the STP is located near the shore, the effluent can be used to produce a small amount of osmotic power.

2.4 Capacity of an osmotic power plant

The capacity of an osmotic power plant is affected by the theoretical osmotic energy, membrane characteristics and practical osmotic energy.

2.4.1 Theoretical osmotic energy

The osmotic energy which theoretically can be produced is affected by local conditions: salinity gradient, temperature and fresh water availability. The most important parameter is the salinity gradient. The higher the salinity gradient the larger is the difference in molar free energy and thus the larger is the energy production. This parameter determines, together with the temperature, the theoretical osmotic pressure (see equation 2.3) or electrochemical potential difference (see equation 2.4). These differences represent a theoretical osmotic energy. The relation between the salinity difference and theoretical osmotic energy in the case of PRO is given in figure 2.3:

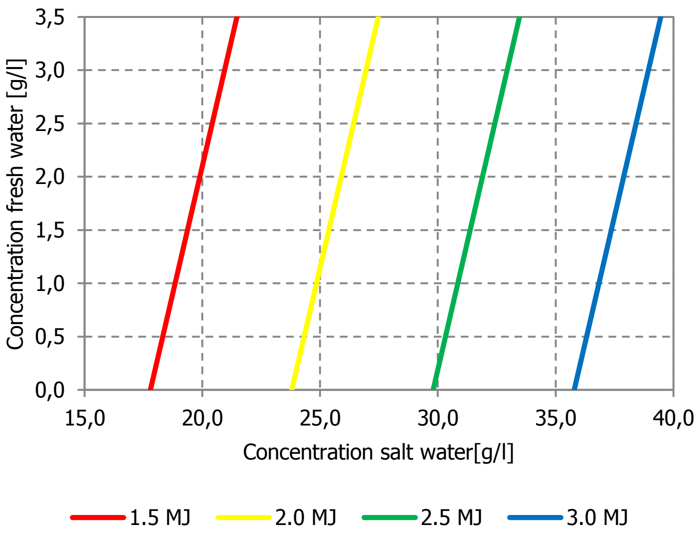

Figure 2.3: Theoretical osmotic energy in the case of PRO between fresh and salt water at 20°C based on equation 2.3.

A similar relation could be obtained for the RED case. The theoretical osmotic energy multiplied with the fresh water flow through the power plant results in the power plant capacity. However, the theoretical osmotic energy cannot be used completely. The reason for this rests with the membrane characteristics, which will decrease the theoretical osmotic energy to an effective osmotic energy and eventually to a practical osmotic energy.

2.4.2 Membrane characteristics

The most important membrane characteristics which affect the osmotic energy are the molar flux and the resulting power density.

2.4.2.1 Molar flux

The molar free energy gradient causes a permeation of water molecules (PRO) or ions (RED) through a semi-permeable membrane. The rate of permeation is called the molar flux. In order to maximize the electricity generation, the molar flux should be as high as possible. For PRO, the molar flux can be calculated from the volumetric water flux J_w [3]:

$$J_{H_2O} = \frac{J_w}{\overline{\overline{V}}_c} = \frac{A_w}{\overline{\overline{V}}_c} \cdot \left(\Delta\pi_{eff} - \Delta p \right) \quad \textbf{(2.5)}$$

From equation 2.5 it can be deduced that the molar water flux (the osmotic flow) stops when the hydrostatic pressure difference over the membrane equals the effective osmotic pressure difference. The reason that an effective value of the osmotic pressure difference is used, instead of the theoretical value, is the transport resistance of the membrane. The effective osmotic pressure difference, which also represents the effective osmotic energy, is expressed as [3]:

$$\Delta\pi_{eff} = \pi_c - \pi_d \cdot \exp\left(J_w \cdot k\right) \qquad \textbf{(2.6)}$$

For RED, the molar flux can be calculated from the charge flux J_i divided by the Faraday constant [3]:

$$J_{\mathrm{NaCl}} = \frac{J_i}{F} = \frac{1}{F \cdot r}\left(\Delta\varphi_{eff} - \Delta V\right) \qquad \textbf{(2.7)}$$

From equation 2.7 it can be deduced that the molar salt flux (the osmotic flow) stops when the potential difference over the membrane equals the effective electrochemical potential difference. In practice, the driving force for the transport of ions deviates from $\Delta\varphi - \Delta V$ and therefore a corrected driving force $\Delta\varphi_{eff} - \Delta V$ is used.

The molar flux causes a hydrostatic pressure difference (PRO) or an electrochemical potential difference (RED) over the membranes. Both differences can be converted into electricity. The amount of generated electricity per membrane area depends on the power density of the membranes.

2.4.2.2 Power density

The power density indicates the amount of energy per membrane area that can be generated. The higher the power density, the smaller is the total membrane area required to obtain a certain capacity. For PRO, the power density is equal to the product of the volumetric water flux and the hydrostatic pressure difference over the membrane [3]:

$$W^{PRO} = J_w \Delta p = A_w\left(\Delta\pi_{eff} - \Delta p\right)\Delta p \qquad \textbf{(2.8)}$$

However, the volumetric water flux and hydrostatic pressure difference are conflicting parameters. The volumetric water flux is the highest where the hydrostatic pressure difference is the lowest and vice versa (see figure 2.4).

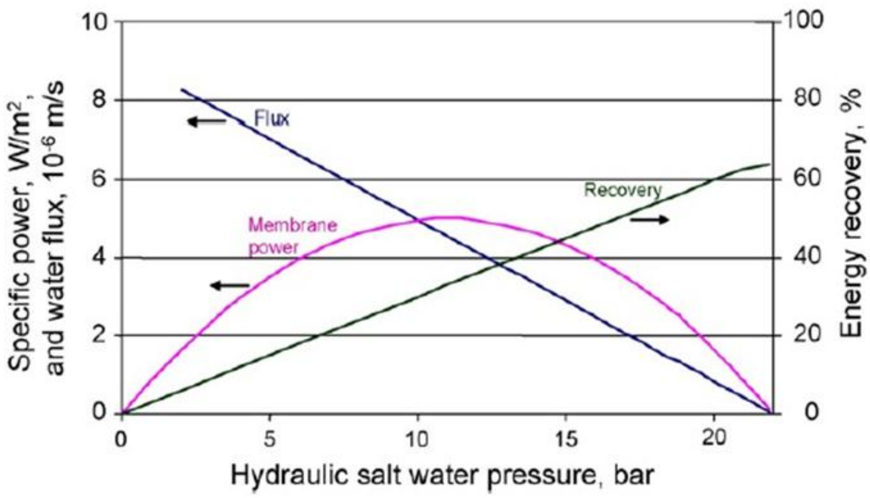

Figure 2.4: The relation between flux and power density for a particular case [6].

According to figure 2.4, the power density has an optimum. The optimal power density can be derived from differentiating equation 2.8 with respect to the hydrostatic pressure difference over the membrane. The optimal power density is [3]:

$$W_{opt}^{PRO} = A_w \frac{\Delta\pi_{eff}^2}{4}$$
$$\Delta p = \frac{1}{2}\Delta\pi_{eff} \qquad \textbf{(2.9)}$$

According to equation 2.9, the optimal power density is achieved when only half of the effective osmotic pressure is used.

For RED, the power density is equal to the product of half the current density and the potential difference over the membrane [3]:

$$W^{RED} = \frac{J_i}{2}\Delta V = \frac{1}{2r}\left(\Delta\varphi_{eff} - \Delta V\right)\Delta V \qquad \textbf{(2.10)}$$

As in PRO, an optimal power density can be derived from differentiating equation 2.10 with respect to the potential difference over the electrodes. The optimal power density is [3]:

$$W_{opt}^{RED} = \frac{1}{2r}\frac{\Delta\varphi_{eff}^2}{4}$$
$$\Delta V = \frac{1}{2}\Delta\varphi_{eff} \qquad \textbf{(2.11)}$$

According to equation 2.11, the optimal power density is achieved when only half of the effective electrochemical potential difference is used.

2.4.2.3 Steady-state power density

The optimal power density is the power density at initial conditions. Due to the osmotic process, the power density decreases in time. The change in optimal power density in a certain time interval gives an average power density [3]:

$$W_{avg} = \frac{\int_{t_0}^{t} W_{opt}\,dt}{t - t_0} \qquad \textbf{(2.12)}$$

From equation 2.12 it can be deduced that the average power density is negligible when the residence time is infinitely small or large. The residence time should therefore be optimized in such a way that the average power density almost equals the optimum power density. This can be achieved by the regulation of the in- and outflow of the solutions. Eventually, the average power density converges to a steady-state power density and electricity generation.

2.4.3 Practical osmotic energy

The membrane characteristics reduce the theoretical osmotic energy into a practical osmotic energy. Both in PRO and RED, the practical osmotic energy is about half the theoretical osmotic energy. The capacity of the power plant can be determined by multiply the practical osmotic energy with the fresh water flow through the power plant:

$$P_{power\ plant} = E_{osm;practical} \cdot Q_{fresh} \qquad \textbf{(2.13)}$$

The capacity calculated with equation 2.13 is a gross capacity. The osmotic power production process causes energy losses which will affect the net capacity of the power plant.

2.5 Main infrastructure

This section will briefly describe the main infrastructure of an osmotic power plant.

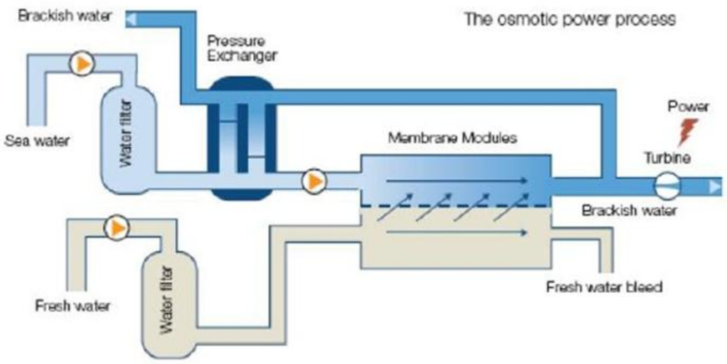

Figure 2.5: Schematic representation of a PRO power plant.

2.5.1 Separation between fresh, salt and brackish water

Section 2.4.1 described the importance of a salinity gradient. A constant gradient is required in order to produce a constant amount of energy. In order to maintain a constant gradient, a separation of the flows is necessary. This can be achieved by using the current geology or fixed structures like dams, dikes, sluices or a combination of these. The separation ensures that the salinity of the one flow is not affected by the salinity of the other flow, and vice versa, resulting in a constant salinity gradient.

The effluent of the osmotic power production is a brackish solution. This solution has a higher salinity than the fresh water flow and a lower salinity than the salt water flow. The discharge of the brackish effluent in one of the two water sources causes a local bubble of a different salinity. When one of the intakes of the osmotic power plant is near the discharge location of the brackish effluent, a recirculation flow might occur. The result of such a flow is that the water taken in is contaminated with brackish water. This will reduce the salinity gradient and thus the energy production. The discharge of the brackish solution is therefore one of the important issues for an osmotic power plant.

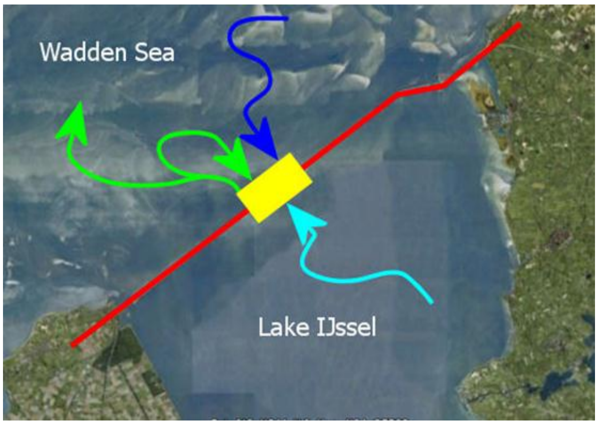

Figure 2.6: Recirculation problem.

The recirculation problem is visualized in figure 2.6. The fresh water (cyan) flow is separated by a hard separation (red) from the salt water (blue) flow and brackish effluent (green) discharge. Because the salt water flow and brackish water discharge are not separated from each other, the brackish effluent can flow back into the power plant.

At present, little is known about how to solve the recirculation problem. The most obvious solution to exclude the possibility on recirculation is to construct the osmotic power plant at a location where the three flows can be separated from each other (i.e. a three-way separation). However, a three-way separation is hardly available with the present geology or infrastructure in the Netherlands (see chapter 4).

2.5.2 Intake and outfall systems

An intake system is required in order to feed the osmotic power plant continuously with fresh and salt water. The intake system consists of an intake, which will take in the water at the intake location, and a tunnel, which will transport the water towards the power plant. For a PRO power plant, the ratio of fresh and salt water is 1:2 [5]. The reason for this ratio is that a part of the salt water is used in a pressure exchanger (see figure 2.5). The pressure exchanger ensures that the salt water flow is able to flow into the pressurized compartment. For a RED power plant, the ratio is 1:1. An outfall system is required in order to discharge the brackish effluent out of the power plant. For a PRO power plant the ratio of fresh, salt and brackish is 1:2:3. For a RED power plant, this ratio is 1:1:2.

2.5.3 Membrane stacks

Membranes are required in order to separate the fresh from the salt water flow, so that the practical osmotic energy can be produced. An osmotic power plant requires a certain membrane area, which is affected by the power plant capacity and the power density of the membranes. Due to space-saving considerations, the membranes are wounded into modules. These modules have a high packing density, i.e. a large membrane area in a small volume. The modules in turn are compactly stacked. In a PRO power plant, the membrane modules are placed in membrane stacks (see figure 2.7). In a RED power plant, the membrane modules are stacked in containers (see figure 2.8).

Figure 2.7: Membrane stack.

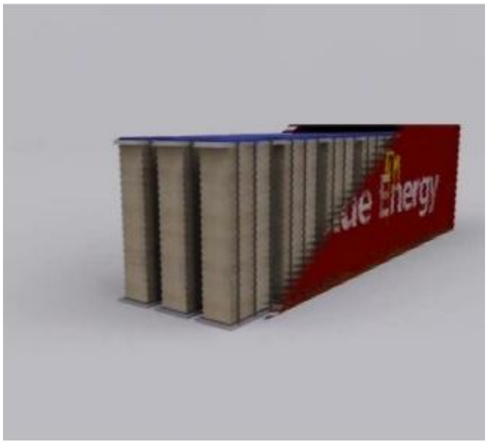

Figure 2.8: REDstack container.

2.5.4 Pre-treatment

The high packing density of the membrane modules ensures that the membranes are sensitive for contamination. Small particles can block the pores of the membranes, salts can precipitate and the membranes could provide a habitat for bacteria and algae. These contaminations will negatively affect the energy production. A pre-treatment of the inflowing solutions could therefore be desirable.

2.5.5 Pumps, pipes, turbines and converters

Pumps and pipes are required to transport the water flows through the osmotic power plant. For a PRO power plant, turbines are required in order to convert the pressurized brackish effluent into electricity. For a RED power plant, converters are required in order the convert the potential difference over the electrodes into electricity.

2.6 Past, current and future state of development

Osmotic power is a form of renewable energy which is still under development. The technology is known for more than a century, but ineffective membranes and the high membrane price ensured that the production of osmotic power was not feasible for a long time. In recent decades however, the necessity for other membrane-applications has led to a growth of the membrane market (see section 2.1). The ever-growing demand for clean drinking water, for example, caused a development in filtration and desalination plants. This development caused not only a decrease in membrane price, but also an increase in membrane effectiveness. Figure 2.9 shows the development in membrane price[1].

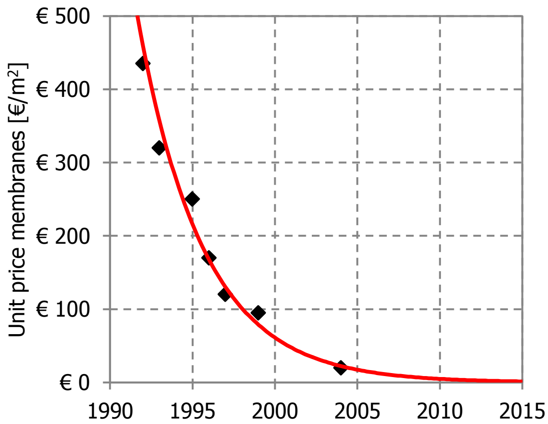

Figure 2.9: Development of membrane price [7].

The current membrane price is about 5 €/m^2 [8], but experts[2] have indicated that within a few years it will be possible to produce membranes at a unit rate of 2 €/m^2 [7; 8].

The improved effectiveness and the lower membrane price resulted in new feasibility studies on the production of osmotic power. With an increasing membrane power density and decreasing

[1] The data in figure 2.9 originate from interested parties and should therefore be read with a certain level of objectivity.

[2] The mentioned experts are related to interested parties, so the expected membrane price should be read with a certain level of objectivity.

membrane price, osmotic power could become more feasible. These studies, held at laboratory scale, concluded that osmotic power is a promising source of renewable energy in the future. The next step was the up scaling from a laboratory to a pilot scale.

At present, the development of producing osmotic power is in the pilot phase. For both PRO and RED a pilot plant is being operated. The Norwegian company Statkraft operates a PRO pilot plant with a capacity of 2 – 4 kW and a membrane power density of 3.0 W/m^2 [9]. The estimated fresh water flow is, according to the rule of thumb in section 2.3, 4 L/s. In the Netherlands, the Dutch company REDstack operates a pilot RED plant with a capacity of 50 W and a membrane power density of 1.0 W/m^2 [10]. The estimated fresh water flow for this power plant is 0.5 L/s.

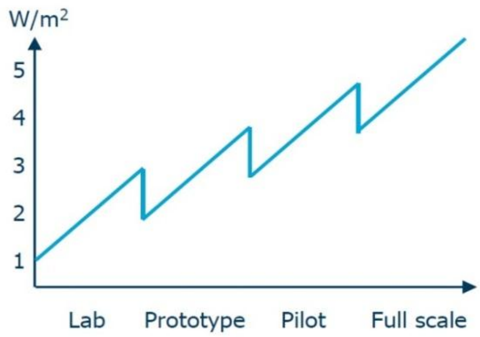

Figure 2.10: The expected power density for a PRO plant according to Statkraft [11].

The desired future development is, besides a further improvement of the membrane power density (see figure 2.10), an up scaling of the pilot plants to a full-scale capacity. Studies on a full-scale power plant have already been held. In 2009, a study has determined that the Botlek area in the Netherlands is a suitable location for a 472 MW power plant [8]. This power plant would produce energy at a unit rate of about 8 cents/kWh. Another project, "Natuurlijk Afsluitdijk", intends to construct a 200 MW power plant at the Afsluitdijk by 2015 [12]. The desired future development of Statkraft and REDstack is given in table 2.1:

	Statkraft (PRO)			**REDstack (RED)**		
	2014	2017	?	2012	2013	2015
Capacity	2 MW	25 MW	?	50 kW	1 MW	200 MW
Stage	Pilot	Demo	Full-scale	Pilot	Demo	Full-scale
Estimated flow rate	2 m^3/s	25 m^3/s	?	50 L/s	1 m^3/s	200 m^3/s
Power density	3.5 W/m^2	5.0 W/m^2	?	1 W/m^2	2 W/m^2	2 W/m^2
System efficiency	60%	80%	?	70%	70%	70%

Table 2.1: Desired future development of Statkraft and REDstack.

REDstack believes that it will be possible to produce osmotic power at an energy unit rate of about 8 cents/kWh in the near future [13].

Chapter 3
Thesis objectives

3.1 Research question

In the previous chapter is described that the growing membrane market and increasing power density initiated new feasibility studies on the commercial exploitation of osmotic power. Most of these studies concluded that osmotic power is a promising source of renewable energy. An energy unit rate of 8 cents/kWh should be possible in the near future.

However, one issue is lacking in these studies. The issue is the actual design of the power plant. Scaling up the power plant has a major impact on the design of the main civil infrastructure. Apart from a larger membrane and pre-treatment area, it requires large flow rates through the power plant. The main civil infrastructure should ensure that the flow rates can be transported through the power plant. Also important is how the brackish effluent will be discharged. The power plant location should be able to discharge the effluent without occurring recirculation.

The lacking design of the main infrastructure initiated this thesis. The purpose of this thesis is to discuss the financial feasibility of the commercial exploitation of osmotic power. Is an energy unit rate equal to 8 cents/kWh really possible in the near future? The financial feasibility will not be determined by the technology of osmotic power, which already has been proven, but on the design of the main civil infrastructure. The research question is therefore:

"Is a commercial osmotic power plant feasible if the capital costs of the main civil infrastructure are included?"

The capital costs of the main civil infrastructure are defined as the costs which should be invested once for a period equal to the depreciation time of the considered infrastructure. A financial feasibility study will be held in order to answer the research question. The input parameters in this financial feasibility study are the revenues from the energy production and the investments during the lifespan of the power plant. A number of case studies will be held in order to obtain these parameters for a number of cases. The relations between the different components which determine the financial feasibility of an osmotic power plant are given in a relation diagram in figure 3.1:

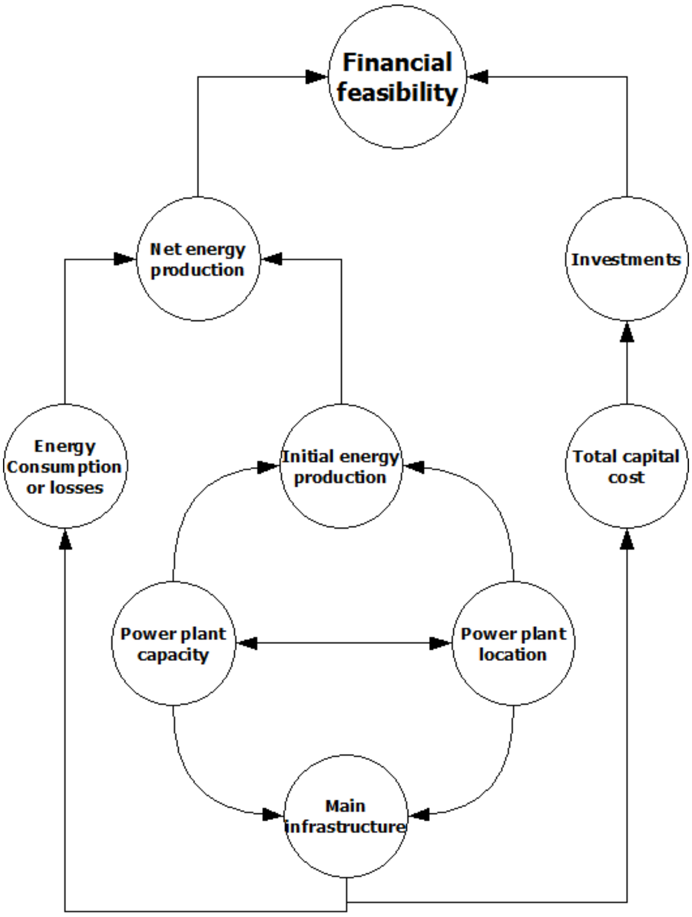

Figure 3.1: Relation diagram of the different components in the financial feasibility study.

In order to answer the research question, the thesis is subdivided into a number of parts. The parts are described in the next section.

3.2 Thesis structure and sub-questions

3.2.1 Part I: Introduction and objectives

The first part of the thesis contains an introduction to the subject and the thesis objectives.

3.2.2 Part II: Location selection

According to figure 3.1, there is a complex relation between power plant location and capacity. The power plant capacity is affected by the power plant location and vice versa, and both the power plant capacity and location affect the initial energy production and the dimensions of the main infrastructure. In order to simplify the complex relation, a fixed power plant location should be chosen. Therefore, in Part II of the thesis the most suitable location for an osmotic power plant will be chosen. The sub-question to be answered in Part II of the thesis is:

1. *What is the most suitable location for an osmotic power plant?*

The selected location will be considered in the case studies in Part III of the thesis.

3.2.3 Part III: Case studies

Part III of the thesis will contain multiple case studies. In these case studies, the total capital costs and net energy production of a number of power plants will be determined. In order to obtain these parameters, the dimensions of the main infrastructure and the power plant area should be obtained. The dimensions of the main infrastructure and power plant area will determine the total capital costs and energy consumption/losses of the power plant (see figure 3.1). The energy consumption/loss will determine, together with the initial energy production, the net energy production of the power plant. The sub-questions to be answered in each case study are therefore:

2. *What are the dimensions of the main civil infrastructure?*
3. *What is the required area of the osmotic power plant?*
4. *What is the net energy production of the osmotic power plant?*
5. *What are the total capital costs of the osmotic power plant?*

The power plant in the case studies will differ in capacity and type of osmotic power generation. A small-scaled, medium-scaled and a large-scaled osmotic power plant will be considered. The main case study of the thesis will be the 25 MW PRO power plant, a capacity which Statkraft wants to achieve in 2017 (see table 2.1). The results of the 25 MW PRO power plant will be used for a large-scaled 200 MW PRO power plant, a capacity which REDstack wants to achieve in the future, and a small-scaled 1 MW PRO power plant. The case study of the 1 MW PRO power plant will be a special type, because this power plant will be integrated in a STP. After completing the case studies of the PRO power plants, the cases will be considered if RED is applied instead of PRO. So, 6 case studies in total will be conducted.

The results of the case studies will be considered in the financial feasibility study in Part IV of the thesis.

3.2.4 Part IV: Financial feasibility study

Part IV of the thesis contains a financial feasibility study. In the financial feasibility study, the net energy production and total capital costs of the different power plants will be used in order to obtain the revenues and investments over the lifespan of the power plant. The revenues and investments over the lifespan of the power plant will result in a required energy unit rate. The resulting energy unit rate will be compared to the marketable energy unit rate of 8 cents/kWh. When the energy unit rates of the different power plants are known, it will be analysed what the energy unit rates will be if some expected and recommended developments are considered. The sub-questions to be answered in this part of the thesis are therefore:

6. *What are the energy unit rates of the different power plants?*
7. *What will be the energy unit rates of the different power plants if some expected and recommended developments are considered?*

3.2.5 Part V: Conclusion and recommendations

In the conclusions and recommendations, the results of the case studies and financial feasibility study will be used to make a judgement on whether a commercial osmotic power plant is financial feasible or not. A distinction will be made on the feasibility of a commercial osmotic power plant with the present technology and knowledge, and the future feasibility if the expected and recommended developments are considered.

The thesis structure is given in figure 3.2:

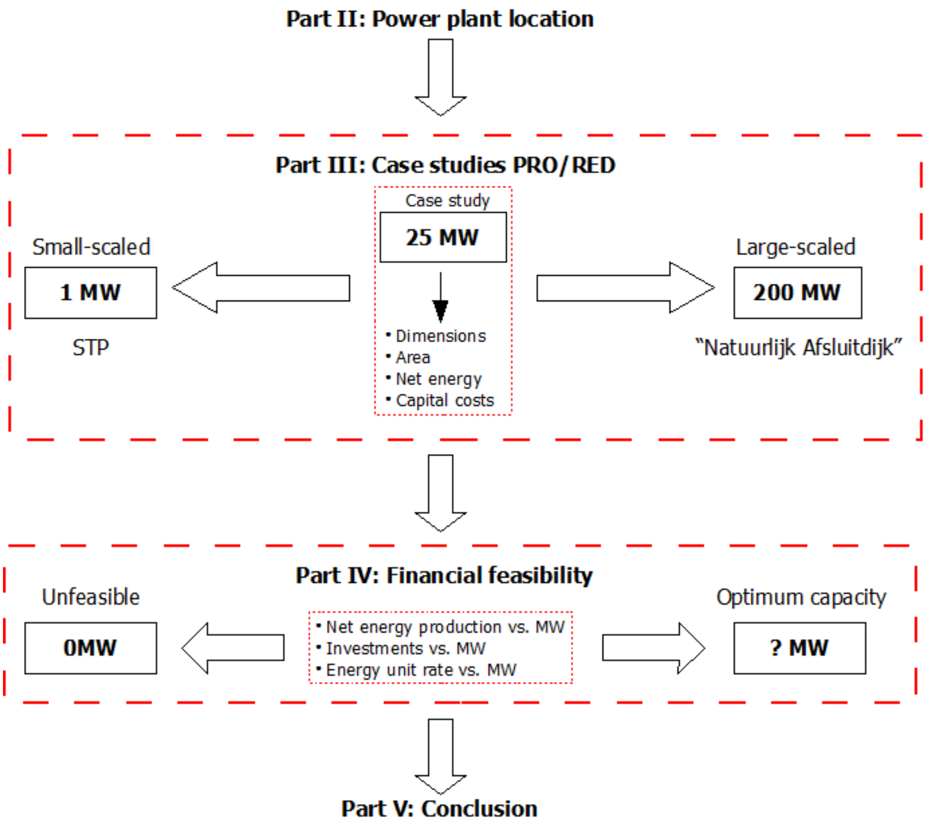

Figure 3.2: Thesis structure.

Part II
Power plant location

Part II of the thesis contains the selection of the most suitable power plant location for the 1, 25 and 200 MW osmotic power plant. This location will be determined in chapter 4. The conditions at the selected location determine, together with the power plant capacity, the practical osmotic energy. The practical osmotic energy for the location will be determined in chapter 5. The scope of part II of the thesis is illustrated in red in the relation diagram of section 3.1:

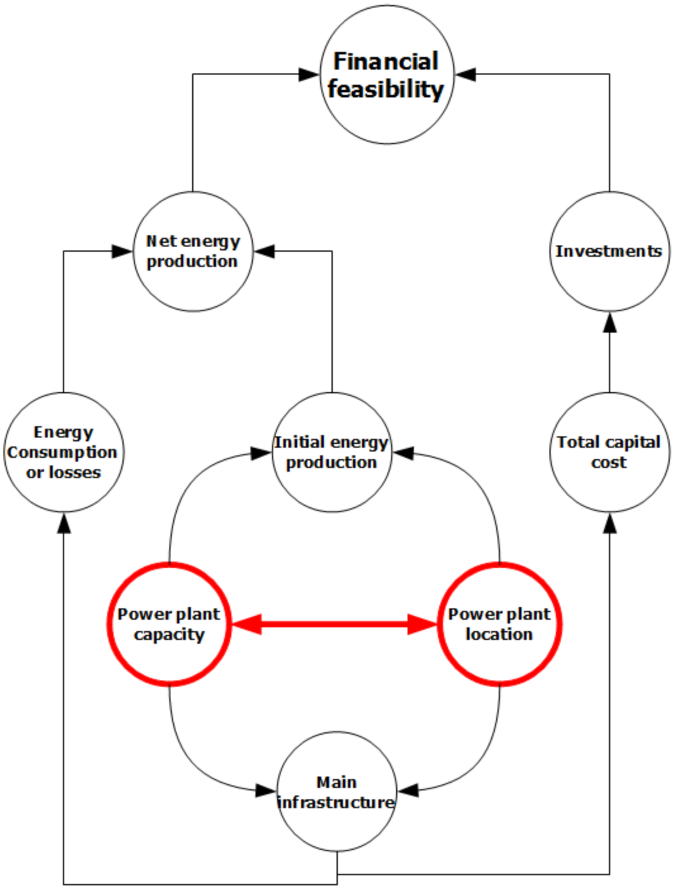

Figure 3.1: Relation diagram of the different components in the financial feasibility study.

Chapter 4

Location selection

In the Netherlands, the annual average of incoming fresh water is 110 billion m^3 [14]. Twenty-seven per cent of this quantity comes from precipitation; the rest is supplied by rivers entering the country from abroad. The majority of the fresh water, 77.8 per cent, flows through the Dutch water system to shore where it is discharged to sea through one of the fresh water outlets. The remaining part of the fresh water evaporates (17.6 per cent) or is used by households, agencies, industry and agriculture (4.6 per cent).

All locations where excess fresh water is discharged to sea are potential sites for an osmotic power plant. However, all locations have different conditions and suitability. This chapter will determine the most suitable location for the 25 MW power plant which is also able to accommodate the 200 MW power plant. For the 1 MW power plant, integrated in a STP, a suitable STP will be found.

4.1 Potential locations for an osmotic power plant

In 2009, a study has determined the potential locations for an osmotic power plant in the Netherlands [8]. These locations are given in figure 4.1.

Figure 4.1: Potential power plant locations in the Netherlands.

In figure 4.2 – 4.9, all these locations are illustrated separately with the fresh water flow (cyan), salt water flow (blue), brackish water flow (green), present infrastructure (red) and additional infrastructure (purple).

1. Lauwersoog

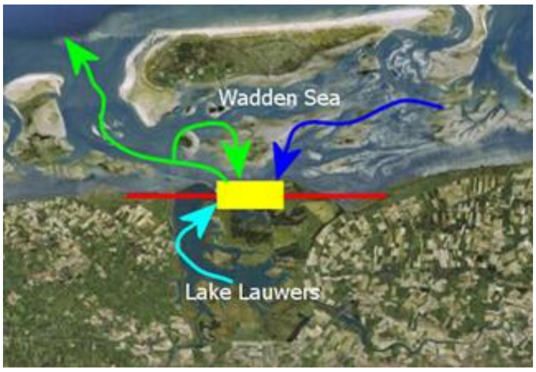

Figure 4.2: Power plant location Lauwersoog.

2. Afsluitdijk

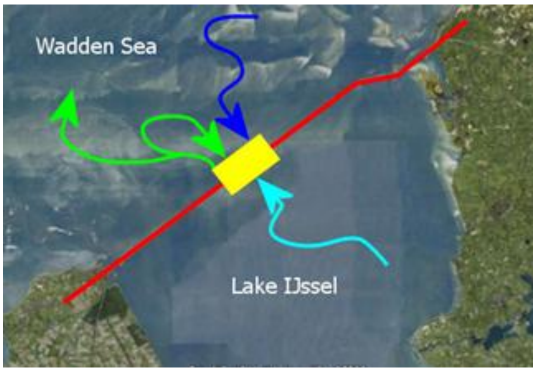

Figure 4.3: Power plant location Afsluitdijk.

3. IJmuiden

Figure 4.4: Power plant location IJmuiden.

4. Botlek area

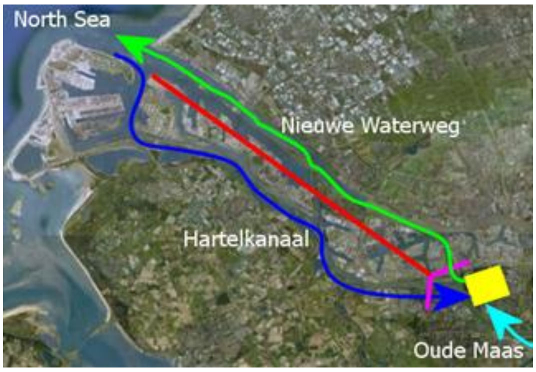

Figure 4.5: Power plant location Botlek.

5. Nieuwe Waterweg

Figure 4.6: Power plant location Nieuwe Waterweg.

6. Maasvlakte

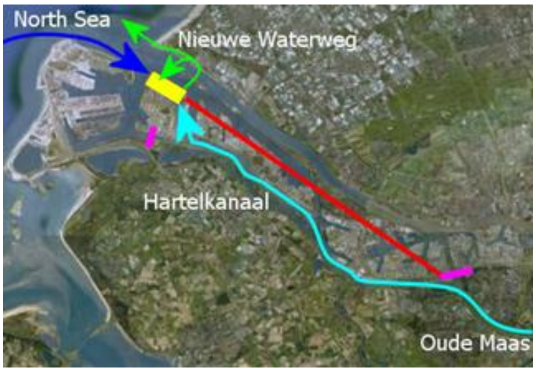

Figure 4.7: Power plant location Maasvlakte.

7. Haringvliet

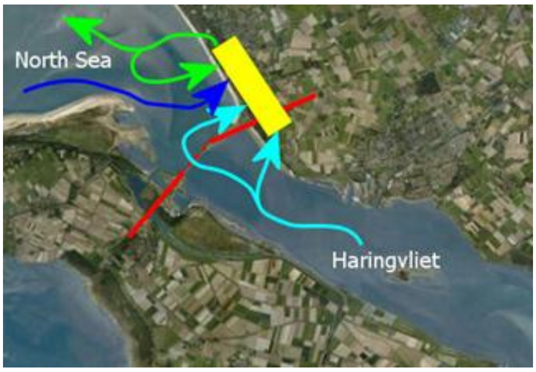

Figure 4.8: Power plant location Haringvliet.

8. Krammersluizen

Figure 4.9: Power plant location Krammersluizen.

Two potential locations can be added to the locations given above. One of these locations is situated between the cities of Stellendam and Goedereede on the island Goeree Overflakkee. The difference with the location given in figure 4.8 is that salt water can now be taken from Lake Grevelingen. Lake Grevelingen is, like the Haringvliet, a former estuary of the North Sea which was closed off from the North Sea by the Brouwersdam, as a part of the Delta Plan, in 1971. In 1978, a sluice was constructed inside the Brouwersdam in order to restore the water quality of Lake Grevelingen. This sluice, which has an average intake flow rate of 140 m^3/s [15], transports sea water from the North Sea to Lake Grevelingen. The salinity of Lake Grevelingen is therefore as saline as the North Sea. The major advantage of this location is that a three-way separation is possible:

- The salt and fresh water flow are separated by the island Goerree-Overflakkee
- The salt and brackish water flow are separated by the Brouwersdam
- The fresh and brackish water flow are separated by the Haringvlietdam

The three-way separation ensures that the possibility on recirculation is reduced to a minimum. This big advantage, together with other characteristics, ensures that the Haringvliet – Grevelingen location is an interesting option for an osmotic power plant. The only disadvantages are the long water transportation and that, for a very large salt water intake flow rates, the intake sluice in the Brouwersdam might be adjusted. The Haringvliet – Grevelingen location is given in figure 4.10.

9. Haringvliet – Grevelingen

Figure 4.10: Power plant location Haringvliet – Grevelingen.

10. STP Houtrust

Figure 4.11: Power plant location STP Houtrust.

The other potential location for an osmotic power plant is a sewage treatment plant (STP). About 4.5 per cent of the annual average incoming fresh water in the Netherlands is used by households, agencies, industry and agriculture. A part of this percentage ends in a STP where polluted water is treated. The effluent of the plant, relatively clean and fresh water, is discharged to surface water. When a STP is located near the shore, the effluent can be used for a small osmotic power plant. The flow rate of the effluent is very small compared to the river discharges, but the effluent might be able to supply energy to a number of households. Integrating an osmotic power plant in a STP has two advantages. The first advantage is that the small amount of brackish water, which is discharged to the sea, can mix very fast with the sea water. The possibility on recirculation therefore seems to be minimal. The second advantage is that a large part of the main infrastructure of the power plant, the fresh water supply and pre-treatment facility, is already partly present. This will reduce the total capital costs of the power plant. An example of a STP, STP Houtrust near the city Scheveningen, is given in figure 4.11.

The two advantages make the integration of an osmotic power plant in a STP an interesting option to consider in the case studies. The fresh water flow rate of one single STP cannot compete with the flow rate of rivers, but with a lot of STP's near salt water osmotic power could be applicable at small scale at many different locations (see figure 4.12).

Figure 4.12: Overview STP's in the Netherlands [14].

4.2 Location selection

Before the most suitable location for the osmotic power plant is selected, the locations given in the previous section will be briefly evaluated on a number of criteria for an osmotic power plant:

1. Availability fresh water; salt water is assumed to be infinitely available
2. Salinity gradient
3. Possibility to separate the flows in three-ways with existing infrastructure or geology
4. Possibility on recirculation
5. Surface area availability
6. Impact and changes on the existing hydraulic system and flow management
7. Number of additional infrastructure (not directly related to the power plant) and adaptations of existing constructions
8. Impact on the shipping industry

The evaluation of location 1 – 5 is given in table 4.1:

	Lauwersoog	Afsluitdijk	IJmuiden	Botlek	Nieuwe Waterweg
Fresh water availability	Small 10 m^3/s	Large 450 m^3/s	Small 40 m^3/s	Large 500 m^3/s	Large 1.000 m^3/s
Salinity gradient	Medium 0.3 – 24 g/l	Medium 0.3 – 24 g/l	Medium 3 – 31 g/l	Large 0.3 – 31 g/l	Large 0.3 – 31 g/l
Three-way separation	None	None	None	Yes	Yes
Possibility recirculation	Large	Large	Large	Small	Small
Surface area availability	Large	Large	Small	Small	Small
Impact hydraulic system	None	None	None	1 additional 1 adaptation	1 additional
Additional infrastructure	None	None	None	Medium	Medium
Impact shipping industry	None	None	None	Large	Large

Table 4.1: Evaluation of location 1 – 5.

The evaluation of location 6 – 10 is given in table 4.2:

	Maasvlakte	Haringvliet	Krammersluizen	Haringvliet Grevelingen	STP Houtrust
Fresh water availability	Large 500 m^3/s	Large 650 m^3/s	Large 500 m^3/s	Large 650 m^3/s	Small 1 m^3/s
Salinity gradient	Large 0.3 – 31 g/l	Large 0.3 – 31 g/l	Large 0.3 – 31 g/l	Large 0.3 – 31 g/l	Large 2 – 31 g/l
Three-way separation	None	None	Yes	Yes	No
Possibility recirculation	Large	Large	Small	Small	Small
Surface area availability	Large	Large	Small	Large	Large
Impact hydraulic system	2 additional	None	1 adaptation	None	Small
Additional infrastructure	Medium	None	Large	None	None
Impact shipping industry	Large	None	None	None	None

Table 4.2: Evaluation of location 6 – 10.

4.2.2 25 and 200 MW power plant

All potential locations described in the previous section comply with the two important requirements; there is a fresh water flow and a salinity gradient available. However, not all the locations are suitable for the 25 and 200 MW power plant. The selected location should comply with a number of requirements. The most suitable location for the 25 and 200 MW will be determined by imposing a number of requirements.

4.2.2.1 Availability fresh water

The selected location should be able to accommodate a 25 MW and a 200 MW power plant. This implies a minimum flow rate of about 200 m^3/s (according to the rule of thumb in section 2.3). Sea water is assumed to be infinitely available. This requirement excludes the locations Lauwersoog and IJmuiden.

4.2.2.2 Three-way separation and the possibility on recirculation

The second requirement deals with the problem of occurring recirculation (see section 2.5.1). At present, little is known about what happens when the effluent of the power plant is discharged in the source where also the salt or fresh water intake is located. This lack of knowledge requires further study on the recirculation problem. In the case studies, it is assumed that the possibility on recirculation is minimized by imposing the requirement that a three-way separation is a requisite. This requirement excludes the locations Afsluitdijk, Maasvlakte and Haringvliet.

4.2.2.3 Additional infrastructure

Two of the remaining locations (Botlek and Nieuwe Waterweg) require additional infrastructure which will increase the total capital costs of the power plant. For the financial feasibility study however, it is more interesting to verify if an osmotic power plant is feasible without constructing additional infrastructure in the first place. The third requirement for the power plant location is therefore that the construction of additional infrastructure should be avoided. This requirement excludes the locations Botlek and Nieuwe Waterweg.

4.2.2.4 Impact on hydraulic conditions, flow management and shipping industry

The two remaining locations are Krammersluizen and Haringvliet – Grevelingen. The last requirement for the power plant location is that the impact on hydraulic conditions, flow management and shipping industry should be minimized. However, the location Krammersluizen implies a brackish effluent discharge to Lake Grevelingen. This will have a major impact on the hydraulic conditions and flow management of Lake Grevelingen. Therefore, this location will be excluded.

4.2.2.5 Selected location

The selected location for the 25 and 200 MW power plant will be the Haringvliet – Grevelingen option (see figure 4.10). This location is with a large fresh water availability, a large salinity gradient and with the current knowledge of recirculation the most suitable location.

4.2.3 1 MW power plant integrated in a STP

For the 1 MW power plant integrated in a STP, there are a lot of options (see figure 4.12). However, not all the options are suitable. The location for the 1 MW power plant should comply with the following requirements:

- The location should be near a salt water source
- The STP should have a minimum dry weather capacity of 1 m^3/s

One STP which complies with the imposed requirements is STP Houtrust in the city of Scheveningen (see figure 4.11). This STP discharges its effluent to the North Sea, which is located about 1.300 m from the STP. The capacity of this STP varies between 1 m^3/s (dry weather discharge) till 3.8 m^3/s (wet weather discharge). The advantage of this STP is, apart from the advantages given in section 4.1, that a drainage channel is located next to the STP that can be used for the osmotic power plant. The STP Houtrust will therefore be selected for the 1 MW power plant.

4.3 Changing Haringvliet management

Since many years the European Commission intends to improve the fish migration in Europe. Migratory fish like salmon, sea trout and eel migrate upstream the rivers to mate in higher-lying areas. However, the barriers in the Dutch delta block the large-scale passage of these fish. In order to improve the migration, the Haringvliet outlet sluices should be put ajar. The intention to put the Haringvliet outlet sluices ajar is called the Ajar-resolution. This resolution implies that salt water can intrude into the Haringvliet, which will affect the production of osmotic power adversely.

The resolution was first adopted in 2000, but the implementation has been postponed several times ever since. The reasons for the postponements include fresh water warranty, lack of regional support and budget overrunning of compensation measures. In June 2011 however, the Dutch government decided to re-adopt the Ajar-resolution even though it was rejected in the coalition agreement of 2010 [16]. The threat of financial and legal consequences, imposed by the European Commission, ensured that the Dutch government changed their opinion.

The new course of the Dutch government has led to much criticism. At present, the political debate is running again and new solutions are discussed. The question is how the Ajar-resolution will develop in the coming years. The resolution has been re-adopted, but history has shown that resolutions can be repealed. In the case study is therefore assumed that the Haringvliet will remain completely fresh. If the re-adopted Ajar-resolution will eventually be implemented, further studies should determine the exact consequences for an osmotic power plant.

Chapter 5
Location conditions

In chapter 4 the locations for the different power plants are determined. The 25 and 200 MW power plant will be designed for the Haringvliet – Grevelingen location, and the 1 MW power plant for STP Houtrust. This chapter contains a description of the fresh water availability (section 5.1), salinity gradient (section 5.2) and temperature (section 5.3). The salinity gradient and temperature determine the practical osmotic energy, which will be determined in section 5.4. The chapter ends with the elevation levels in section 5.5.

5.1 Fresh water availability

5.1.1 Haringvliet – Grevelingen

The majority of the incoming fresh water in the Netherlands is discharged through the Dutch delta to the North Sea. Within the Dutch delta, there are two discharge options. The first option is through an open connection to the North Sea: the Nieuwe Waterweg. The Nieuwe Waterweg is a 600 m wide channel which connects the port of Rotterdam to the North Sea. The North Sea tide affects the water level, currents and salinity in the channel and further inland. In order to control the salt water intrusion, the majority of the water in the Dutch delta is discharged through the Nieuwe Waterweg to the North Sea. The policy is that the discharge of the Nieuwe Waterweg should, when possible, be equal or above 1.500 m^3/s.

To achieve this minimum discharge of 1.500 m^3/s, the second option for the fresh water discharge is used: the Haringvliet outlet sluices. The orifices of the outlet sluices can be adjusted in order to achieve the desired discharge in the Nieuwe Waterweg. At high tide and low river discharges the outlet sluices will close so that the fresh water flow in the Dutch delta is guided through the Nieuwe Waterweg. The orifices of the sluices increase as more water must be discharged through the Haringvliet. The annual average discharged fresh water at the Haringvliet outlet sluices for the period 1995 – 2009 is given in figure 5.1 [17]:

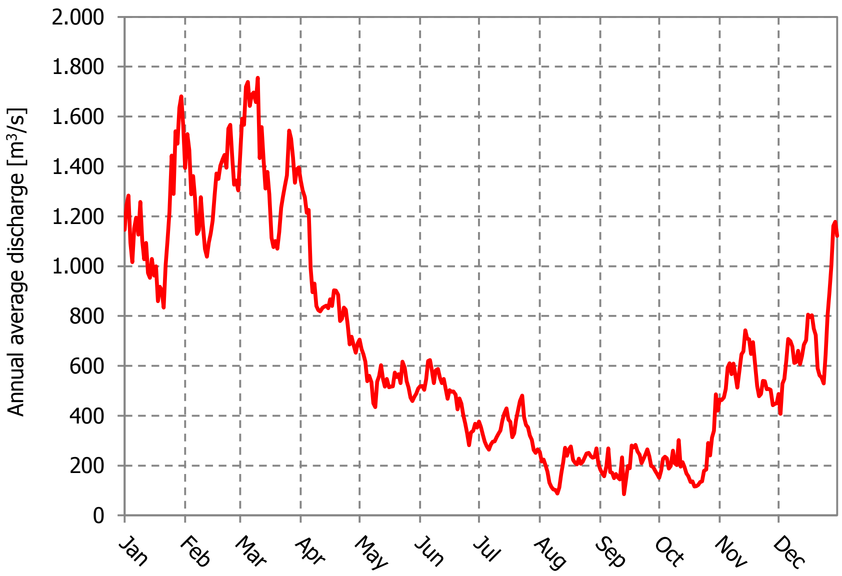

Figure 5.1: The annual average fresh water discharge at the Haringvliet outlet sluices.

The water that is discharged through the Haringvliet outlet sluices, the excess fresh water, is used for the osmotic power plant. According to figure 5.1, the minimum available excess fresh water has a constant flow rate of about 100 m^3/s. This would imply that it is possible to design an osmotic power plant with a constant fresh water flow rate of 100 m^3/s. However, this is not correct. During periods of low river discharges, the outlet sluices of the Haringvliet could be (partly) closed. This will affect the energy production, depending on the design flow rate through the power plant.

In order to consider the time of low river discharges in the case studies, the percentage is determined that the design flow rate can flow into the power plant. During the determination, the following scenarios are considered:

- When the excess fresh water discharge is higher than the design fresh water flow rate through the power plant, the design fresh water flow rate is taken in.
- When the excess fresh water discharge is lower than the design fresh water flow rate, the excess fresh water discharge is taken in.
- When the Haringvliet outlet sluices are closed, no fresh water is taken in and the production process is stopped.

The result of the determination is given in figure 5.2:

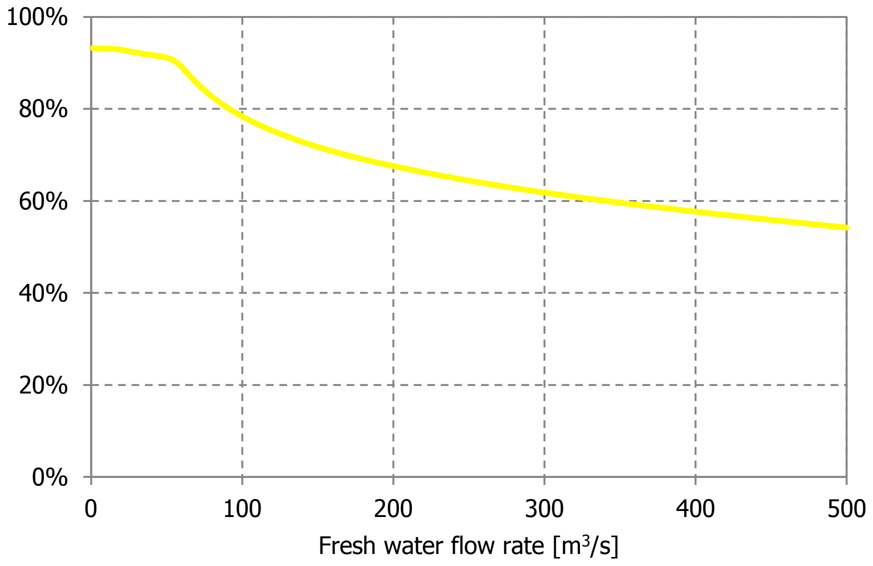

Figure 5.2: Fresh water intake flow rate availability.

5.1.2 STP Houtrust

The capacity of STP Houtrust is during dry weather conditions 1 m^3/s. Therefore, a constant fresh water availability equal to 1 m^3/s is assumed.

5.2 Salinity gradient

5.2.1 Haringvliet – Grevelingen

The salinities of the surface water at the Haringvliet – Grevelingen location are given in figure 5.3 and 5.4 [17]. The data is used of monitoring locations Scharendijke diepe put (salt water) and Haringvliet outlet sluices (fresh water). An overview of the monitoring locations is given in Appendix A.1.

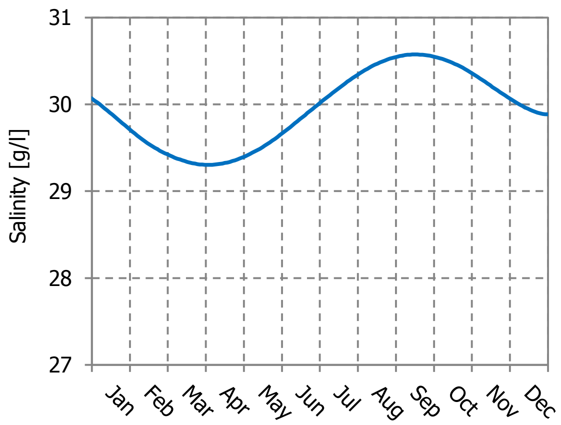

Figure 5.3: The average sea water salinity at Scharendijke diepe put.

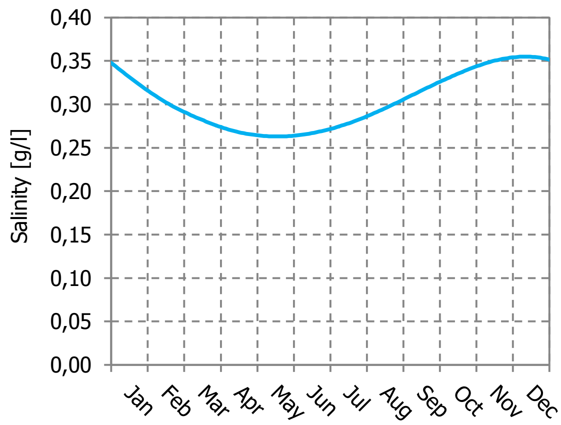

Figure 5.4: The average fresh water salinity at the Haringvliet outlet sluices.

5.2.2 STP Houtrust

STP Houtrust receives fresh water from the present infrastructure. The incoming fresh water flow in a STP has a salinity of about 0.5 – 2 g/l [18]. The used value in the case study is 2 g/l because the fresh water salinity of a STP near the shore is affected by salt water intrusion. The salt water will be taken in from the North Sea. The salinity of the North Sea near the STP is given in figure 5.5 [17]. The used monitoring location is Ter Heide 2 km offshore.

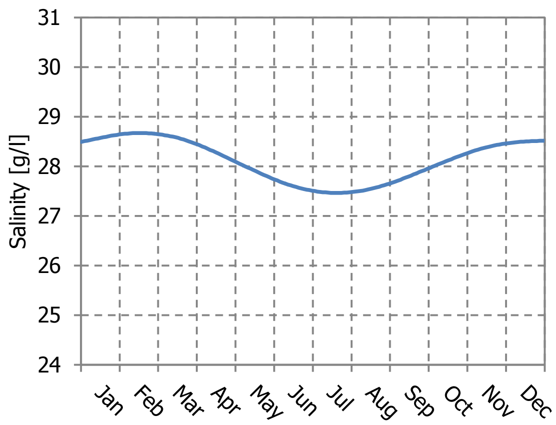

Figure 5.5: The average sea water salinity at Ter Heide 2 km offshore.

5.3 Temperature

5.3.1 Haringvliet – Grevelingen

The annual average water temperature for the Haringvliet – Grevelingen location is given in figure 5.6 [17]. For the temperature data, the same monitoring locations are used as in section 5.2.1.

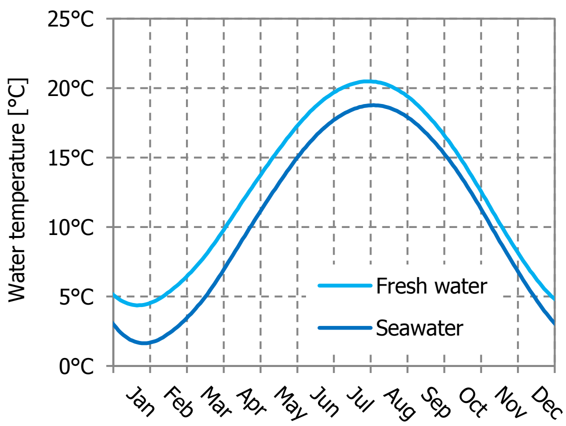

Figure 5.6: The annual average water temperature.

5.3.2 STP Houtrust

The annual average fresh water temperature for STP Houtrust is assumed to be equal to the annual average fresh water temperature given in figure 5.6. The annual average sea water temperature is given in figure 5.7 [17]. The used monitoring location is Noordwijk meetpost.

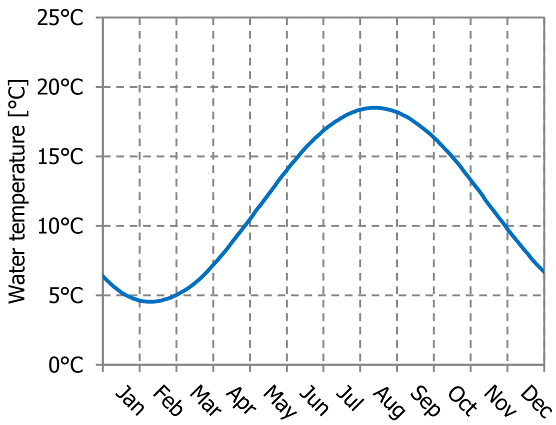

Figure 5.7: The annual average sea water temperature at Noordwijk Meetpost.

5.4 Practical osmotic energy

The practical osmotic energy is defined as the gross osmotic energy which actually can be produced in practice.

5.4.1 Haringvliet – Grevelingen

5.4.1.1 PRO

In the case of a PRO power plant at the Haringvliet – Grevelingen location, the data of section 5.2 and 5.3 can be substituted into the van't Hoff equation (equation 2.3) in order to calculate the theoretical osmotic pressure (see Appendix A.3). Half of this pressure is used for the production of osmotic power in order to achieve the optimal power density (see section 2.4.2.2). The result is a variation in potential practical osmotic energy which is given in figure 5.8.

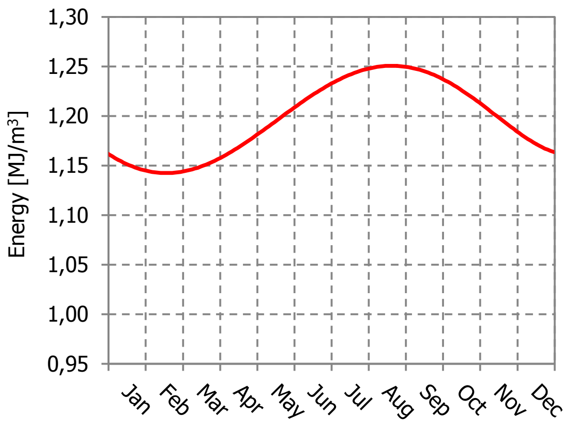

Figure 5.8: The practical osmotic energy in case of a PRO power plant at the Haringvliet – Grevelingen location.

The determination of the practical osmotic energy is given in Appendix A.2. The average practical osmotic energy is about 1.20 MJ/m^3. A continuous flow of 1 m^3/s river water mixed with sea water represents a gross capacity of approximately 1.2 MW. This is larger than the 1 MW which would be achieved when the rule of thumb (see section 2.3) is used.

5.4.1.2 RED

The practical osmotic energy in case of a RED power plant at the Haringvliet – Grevelingen location is determined in Appendix A.3. The result is given in figure 5.9:

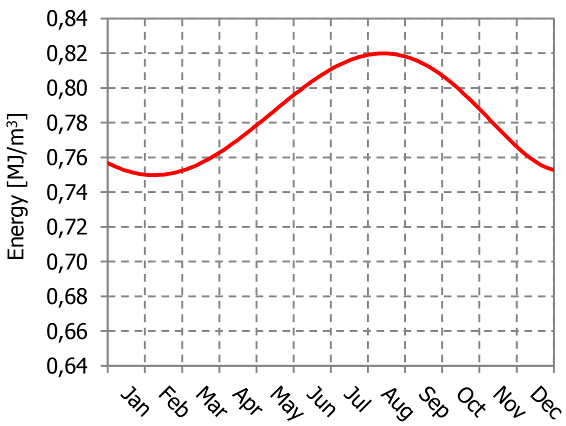

Figure 5.9: The practical osmotic energy in case of a RED power plant at the Haringvliet – Grevelingen location.

The average practical osmotic energy is about 0.78 MJ/m^3.

5.4.2 STP Houtrust

5.4.2.1 PRO

In analogy to section 5.4.1.1, the practical osmotic energy of STP Houtrust is given in figure 5.10:

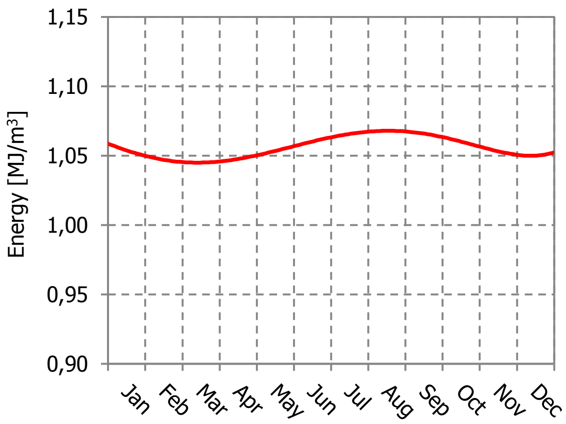

Figure 5.10: The practical osmotic energy in case of a PRO power plant at STP Houtrust.

The average practical osmotic energy is about 1.06 MJ/m^3.

5.4.2.2 RED

In analogy to section 5.4.1.2, the practical osmotic energy of STP Houtrust is given in figure 5.11:

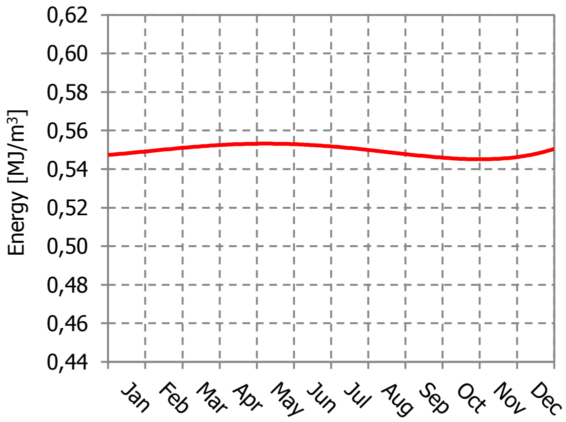

Figure 5.11: The practical osmotic energy in case of a RED power plant at STP Houtrust.

The average practical osmotic energy is about 0.55 MJ/m^3.

5.5 Elevations

5.5.1 Haringvliet – Grevelingen location

The surface level of the power plant is NAP + 0.50 m [19]. The water- and bottom levels are given in table 5.1:

	Haringvliet	Lake Grevelingen	North Sea
Bottom level	NAP – 6.00 m	NAP – 6.30 m	NAP – 5.60 m
ALW	NAP + 0.50 m	NAP	NAP – 0.80 m
AHW	NAP + 0.70 m	NAP	NAP + 1.80 m
Used water depth	6.50 m	6.30 m	7.40 m

Table 5.1: The elevation levels for the Haringvliet – Grevelingen location.

Because the discharge of the brackish solution is influenced by the North Sea tide, the elevation level of the power plant at the end of the production process becomes important. This issue is described in Appendix B.3.

5.5.2 STP Houtrust

The surface level of the STP is NAP + 3.3 m [19]. The fresh water flow arrives at the STP submerged, so it will be assumed that the elevation of the fresh water flow at the end of the treatment process is about NAP + 2.3 m. The salt water flow is under the influence of the North Sea tide (see table 5.1).

Part III

Case studies

In part III of the thesis, a number of case studies will be conducted.

Chapter 6: 25 and 200 MW PRO power plant (Haringvliet – Grevelingen location)

Chapter 7: 1 MW PRO power plant (STP Houtrust)

Chapter 8: 1, 25 and 200 MW RED power plant

The main case study will be the 25 MW PRO power plant. This case study will be conducted in chapter 6. This chapter contains the dimensioning of the main infrastructure (see section 2.5), which will eventually result in a net energy production and the total capital costs of the power plant. The results of the 25 MW PRO power plant will be used to obtain the net energy production and total capital costs of the other power plants. The scope of part III of the thesis is illustrated in red in the relation diagram of section 3.1:

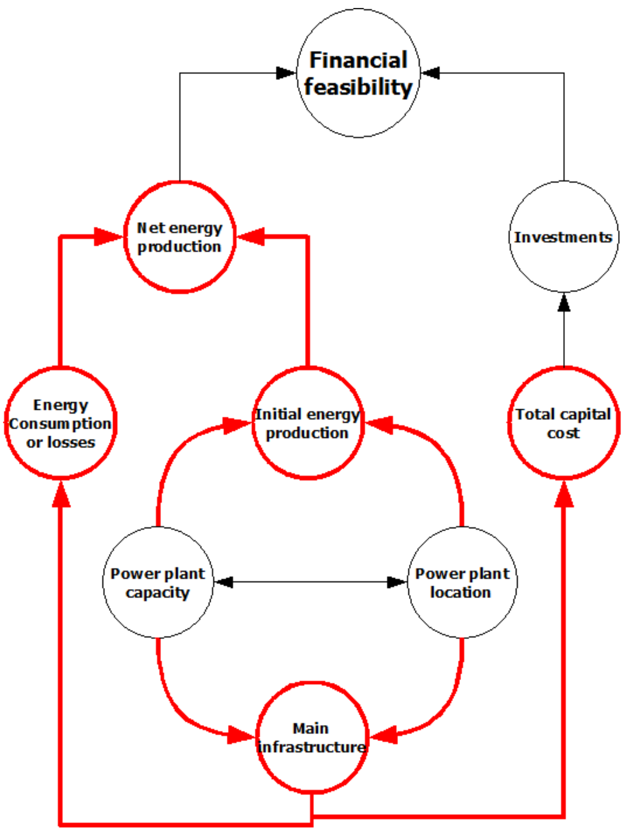

Figure 3.1: Relation diagram of the different components in the financial feasibility study.

Chapter 6

25 and 200 MW PRO power plant

This chapter contains the case studies of the 25 and 200 MW PRO power plant. In the case studies, the initial energy production (section 6.2) and the dimensions of the main infrastructure will be determined (section 6.3 – 6.6). Because of the similarity between the power plants, the majority of the sections are based on the 25 MW PRO power plant. At the end of section 6.2 – 6.6, a brief description is given for the case of the 200 MW PRO power plant. The case studies result in a net energy production (section 6.8) and total capital costs (section 6.8) which will be used in the financial feasibility study.

6.1 Location

The 25 and 200 MW PRO power plant will be constructed on the island Goeree-Overflakkee (see figure 6.1). In chapter 4, it was determined that this location was the most suitable location for a 25 and 200 MW osmotic power plant. The island can be described as an agricultural region with mudflats and nature reserves along the coastline. The presence of agricultural fields implies that there is enough space for an osmotic power plant, so it is decided to sacrifice agricultural fields for the osmotic power plant. This area, which is approximately 1.800 x 2.000 m, is shown in figure 6.2. The actual construction of the power plant will be disregarded in this thesis.

Figure 6.1: Power plant location Haringvliet – Grevelingen.

Figure 6.2: Power plant area.

6.2 Initial energy production

6.2.1 Flow rates through the 25 MW PRO power plant

The practical osmotic energy in case of a PRO power plant (see figure 5.8) at the Haringvliet – Grevelingen location can be converted into a required fresh water flow rate through the 25 MW PRO power plant. This flow rate varies throughout the year (see figure 6.3) and is determined in Appendix A.4. For the 25 MW PRO power plant, the average value of 20.9 m^3/s is used. About 90 per cent of the fresh water permeates through the membranes [20]. The rest of the fresh water, the so-called fresh water bleed, is not used and will be transported back to the start of the process. The required flow rate through the fresh water intake system reduces therefore with 10%. The required flow rate through the fresh water intake system is equal to 18.8 m^3/s.

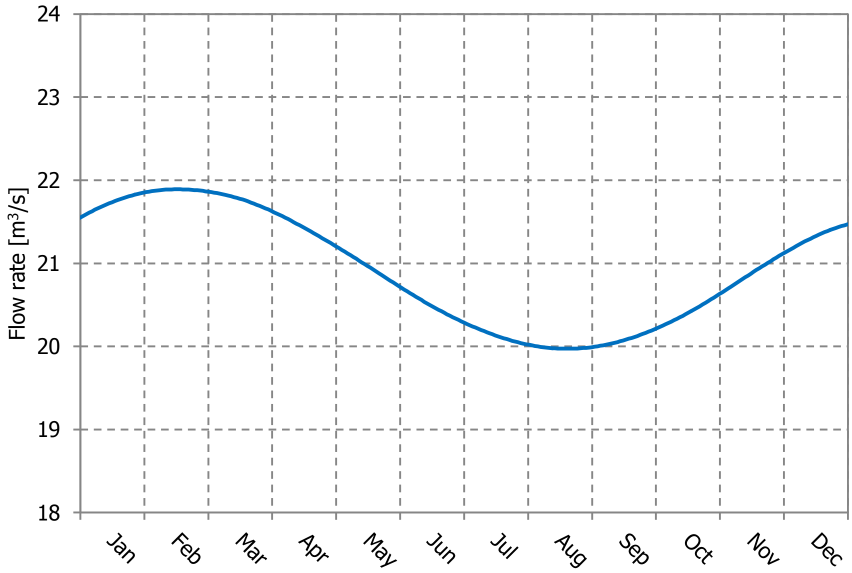

Figure 6.3: Required fresh water flow rate through the 25 MW PRO power plant.

The salt water intake system requires a flow rate of two times the fresh water flow rate through the power plant [20]. The reason for this is that a part of the salt water is required for the pressure exchanger. The average required flow rate through the salt water intake system is therefore 41.8 m^3/s. No bleed will occur in the case of the salt water flow, because the salt water inside the salt water compartment will become brackish due to the permeated fresh water.

The required discharge for the brackish water outfall system is the summation of the permeated fresh water flow rate through the membranes and the salt water flow rate through the power plant. The average required flow rate through the outfall system is therefore equal to 60.6 m^3/s.

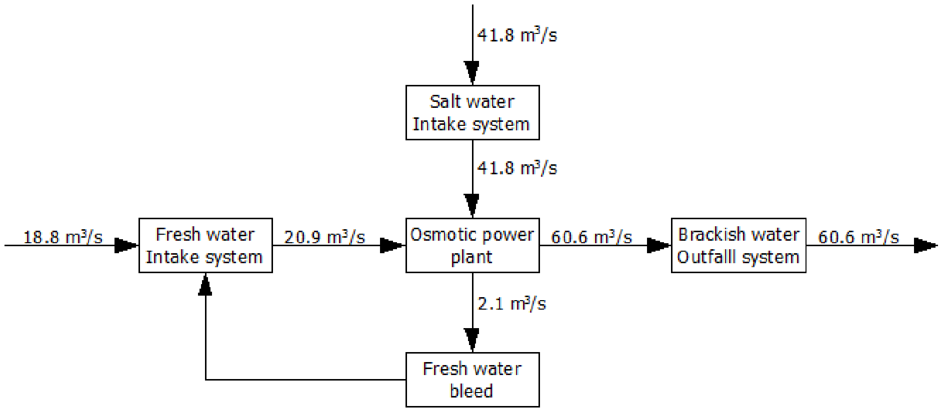

Figure 6.4: The average required flow rates through the 25 MW PRO power plant.

Figure 6.4 displays all the average required flow rates. However, these flow rates will not result in the desired capacity of 25 MW. Energy losses due to the production process results in a smaller net capacity of the power plant. In order to specify the influence of the energy losses due to the production process, the flow rates given in figure 6.4 will be used despite the smaller net capacity.

6.2.2 Initial energy production of the 25 MW PRO power plant

The initial energy production of the 25 MW PRO power plant can be calculated by using equation 6.1:

$$E_{produced} = E_{osm} \cdot Q_{fresh} \cdot t_{hrs/yr} \quad \textbf{(6.1)}$$

The average practical osmotic energy of 1.2 MJ/m^3 and the constant fresh water flow rate of 20.9 m^3/s result in an initial energy production of 220 GWh/yr. However, section 5.1.1 already described that a fresh water flow rate is not available for 100% of the time. This implies that the power plant cannot run at its full capacity. According to figure 5.2, the 25 MW PRO power plant can run on average for 92.8% of the time at full capacity. This will reduce the initial energy production to 204 GWh/yr.

6.2.3 200 MW PRO power plant

In analogy to the previous two sections, the required flow rates and initial energy production can be obtained in the case of a 200 MW PRO power plant. The required flow rates through the power plant are:

- Fresh water flow rate through power plant: 167.3 m^3/s
- Fresh water through intake system: 150.6 m^3/s
- Salt water flow rate: 334.6 m^3/s
- Brackish water discharge rate: 485.1 m^3/s

The capacity of the 200 MW PRO power plant is 8 times larger than the 25 MW PRO power plant. However, an eight times larger capacity will not imply that the initial energy production is eight times higher. The reason for this is that the fresh water availability decreases for increasing capacity. A fresh water flow rate of 167.3 m^3/s is available for only 70.2% of the time. The fresh water availability and practical osmotic energy (given in section 5.4.1.1) will result in an initial energy production for the 200 MW PRO power plant of 1.229 GWh/yr. This is a 6 times higher energy production compared to the 25 MW PRO power plant.

6.3 Intake and outfall system

The first stage of the osmotic power production is the continuous feed of fresh and salt water to the power plant. However, the fresh and salt water source of the selected location (see figure 6.1) is at a considerable distance from the power plant location given in figure 6.2. Both the fresh and salt water flow rate should therefore be transported over a long distance to the power plant. This transport will be achieved by constructing an intake system. The intake system consists of an intake, which will take in the water at the intake location (see 6.3.3), and a tunnel, which will transport the water towards the power plant.

The last stage of the production process is the discharge of the effluent to the North Sea. This transport will be achieved by construction of an outfall system. In analogy to the intake system, the outfall system will consist of an outfall and a tunnel. Because the intake and outfall system show many similarities, both systems are considered in this section.

6.3.1 General

The intake and outfall system can be open (e.g. canals) or closed (e.g. pipes or tunnels). In the case study, a closed tunnel system will be considered (see section 6.3.4). A closed system implies that the transport of water from the source to the power plant is a pressurized transport. The driving force behind this kind of transport is a difference in energy level, represented by a water level difference, on each side of the system. This difference will cause a flow from the side with the high energy level to the side with the low energy level. The energy level of a water column is a summation of three hydraulic heads:

- Static head $z_{1,2}$
- Pressure head $\frac{p_{1,2}}{\rho g}$
- Velocity head $\frac{u_{1,2}^2}{2g}$

During the transport energy is lost due to friction and local losses. Local losses are caused by sudden changes in cross section or direction. The water transport stops when the energy level (the summation of the hydraulics heads and losses) on the low energy level side equals the energy level at the high energy level side.

The abovementioned transport can be described by the Bernoulli formula:

$$z_1 + \frac{p_1}{\rho_1 g} + \frac{u_1^2}{2g} = z_2 + \frac{p_2}{\rho_2 g} + \frac{u_2^2}{2g} + h_f + h_L \qquad \textbf{(6.2)}$$

When the water source at the high energy level side is assumed to be infinite and the axis of the tunnel is taken as reference level, the Bernoulli equation reduces to:

$$z_1 = \frac{p_2}{\rho_2 g} + \frac{u_2^2}{2g} + h_f + h_L \qquad \textbf{(6.3)}$$

The reduced Bernoulli equation is visualized in figure 6.5:

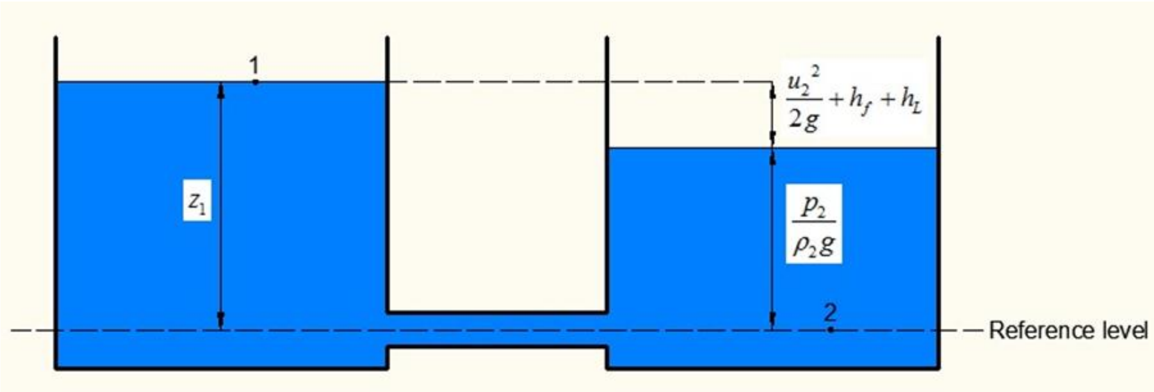

Figure 6.5: Schematization of the pressurized water transport.

The water level difference on the right side of figure 6.5 is equal to the summation of the velocity head, friction loss and local losses. This summation is the total head loss due to the water transport. The expression of the total head loss due to the water transport, which is derived in Appendix B.4, is:

$$\Delta h = \frac{8Q^2}{g\pi^2 D_{eq}^4}\left(1 + f\frac{L}{D_{eq}} + \sum \xi\right) \qquad \textbf{(6.4)}$$

The total head loss expressed by equation 6.4 is the water level difference which needs to be overcome by extra pumping. This extra pumping reduces the net energy production of the power plant, so the total head loss should be minimized. This can be achieved by considering in the design:

- The position of the intakes and outfall
- The basic design of the intakes and outfall system
- The dimensions of the intakes and outfall system

6.3.2 Types of intakes and outfalls

There are several types of intakes and outfalls:

- Bank-side intakes and outfalls
- Bed intakes and outfalls
- Submerged intakes and outfalls

The decision on what type of intake to use depends on the local conditions. The power plant will be constructed in an area which is characterised by shallow mudflats, harbours or nature reserves along the coast. The presence of shallow and nature areas along the coast ensures that a bank-side and bed intake or outfall is not suitable, because:

- A bank-side or bed intake in shallow areas results the entrainment of silt into the power plant.
- A bank-side or bed outfall in shallow areas will result in erosion. The shallow areas can be considered as nature reserves, so erosion is undesirable.
- The water in shallow areas is often polluted due to human and animal contact.
- A bank-side or bed intake in shallow areas, for large intake volumes, requires a very wide intake in order to prevent high intake velocities.

From the abovementioned points can be concluded that an adequate depth is required in order to prevent silt entrainment, erosion, high intake velocities and the intake of polluted water. A submerged intake and outfall at a certain distance from the shore is therefore the most suitable option.

6.3.3 Position

The position of the submerged intakes and outfall has a major influence on the total head loss, because these positions result in a trajectory from the intake to the power plant position (or from the power plant to outfall position). The trajectory in turn provides a total length and local changes in direction, which affects the total head loss given in equation 6.4.

However, the positions of the intakes, outfall and power plant are still variable at this moment. In order to simplify the determination of the optimum power plant position, the intake and outfall positions are assumed to be fixed points. These points and the resulting fixed trajectory to the boundary of the power plant area (see figure 6.2) are described below. The rest of the trajectory will be determined during the water transport optimization.

Figure 6.6: Location fresh water intake (cyan) and brackish water outfall (green).

Figure 6.7: Depth at fresh water intake (cyan) and brackish water outfall (green) [21].

The fresh water intake is located in the Haringvliet about 500 m offshore of Stellendam (see figure 6.6). The minimum local water depth is 6.2 m (see figure 6.7). The design of the intake (see section 6.3.4) and the maximum allowed intake velocity (see section 6.3.5.1) will determine whether this depth is adequate (see section 6.3.6). From this location, an intake tunnel runs in a straight line towards the inner harbour of Stellendam. Inside the harbour, the tunnel makes a 140° bend and continues inland. After 250 m inland, the tunnel makes a 90° bend and continues in a straight line until it reaches the eastern corner of the power plant area. The fixed length of the fresh water intake tunnel (from intake location until the eastern corner of the power plant area) is approximately 2.250 m. The fixed trajectory consists of one 90° bend and one 140° bend.

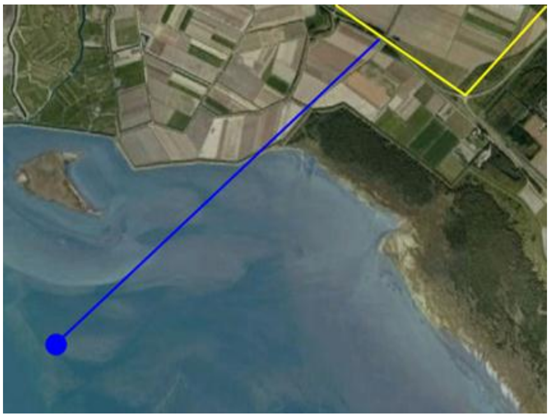

Figure 6.8: Location salt water intake.

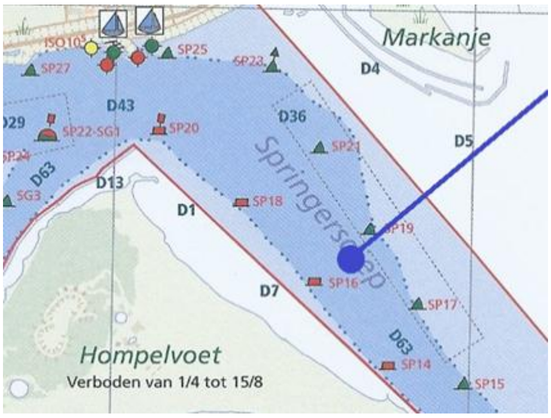

Figure 6.9: Depth at salt water intake [21].

The salt water intake is located in Lake Grevelingen about 2.700 m offshore (see figure 6.8). The local water depth is 6.3 m (see figure 6.9). Also in the case of the salt water intake, the design of the intake (see section 6.3.4) and the maximum allowed intake velocity (see section 6.3.5.1) will determine whether this depth is adequate (see section 6.3.6). From this location, an intake tunnel runs in a straight line towards the south-western part of the power plant area. The fixed length of the salt water intake tunnel is approximately 4.000 m.

The brackish water outfall is located in the North Sea, just west of the Haringvliet outlet sluices (see figure 6.6). The minimum local water depth is 4.3 m (see figure 6.7), but the depth is influenced by the North Sea tide. From this location, an outfall tunnel runs in a straight line through the outer harbour of Stellendam until it reaches the shore. From there it makes a 140° bend and continues in the same trajectory as the fresh water intake tunnel until it reaches the eastern corner of the power plant area. The fixed length of the brackish water outfall tunnel is approximately 2.000 m.

6.3.4 Basic design

The offshore intake and outfall locations imply that the basic design of the intake and outfall system should consist of an intake (or outfall) tower and a rectangular intake (or outfall) tunnel. Other options would be an open canal or closed pipeline. An open canal will be disregarded in the case study because:

- A canal is hard to construct due to the presence of harbours (fresh intake and brackish outfall, see figure 6.6) or nature reserves (salt intake, see figure 6.8).
- Canals require a lot of maintenance (maintenance dredging).
- Canals ensure land loss and require additional infrastructures, like viaducts.

A closed pipeline will be disregarded, because a pipe is less flexible when large design flow rates are considered (pipes have limited dimensions). A rectangular tunnel could be easily enlarged in the horizontal direction.

The basic design of the intake and outfall system does not have a large influence on the total head loss. The only factor within the basic design which has a minor influence on the total head loss is the applied construction material. Each material has a certain roughness which influences the friction factor given in equation 6.4. Because the influence of the applied construction material on the total head loss is only minor, the decision on what type of material to apply will depend on the specific weight and unit price of the applied material. Because the tunnel is submerged, a sufficient tunnel weight is required in order to prevent buoyancy. The most suitable construction material is the material with the lowest price ratio (see table 6.1).

	Specific weight	**Unit price**	**Ratio**	**Price ratio**
Steel	7.800 kg/m^3	0.65 €/kg [22]	1	0.65 €/kg
Concrete	2.400 kg/m^3	0.10 €/kg [23]	3.25	0.33 €/kg
HDPE	950 kg/m^3	1 €/kg [24]	8.20	8.20 €/kg

Table 6.1: Price ratio of the commonly applied construction materials.

In table 6.1, the price ratios are determined for the most common construction materials of an intake tunnel. For example, when a steel tunnel is applied the price ratio per kilogram is about € 0.65. When a concrete tunnel is applied instead of a steel tunnel, 3.25 times more concrete is required in order to achieve the same weight of the steel tunnel. This results in a price ratio of 0.33 €/kg. This is much cheaper than in the case of a steel tunnel. Concrete will therefore be the applied material. The basic design of the intake and outfall system is given in figure 6.10:

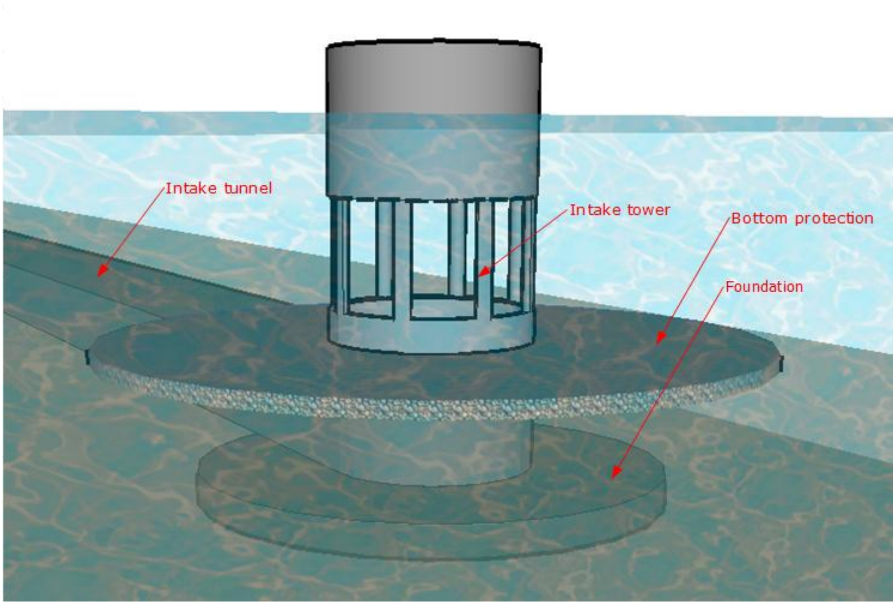

Figure 6.10: Basic intake and outfall system design.

The intake tower has a circular shape and ensures that the intake velocity will not exceed the maximum allowed intake velocity of 0.30 m/s (see section 6.3.5.1). The intake tower rises above the water surface in order to prevent collisions and to create sufficient space for the hoist equipment of the shut-off valves. The shut-off valves ensure that the intake of water can be stopped for maintenance. From the intake tower, a rectangular tunnel transports the water towards a pump sump. The cross section of the fresh water intake system is illustrated in figure 6.11:

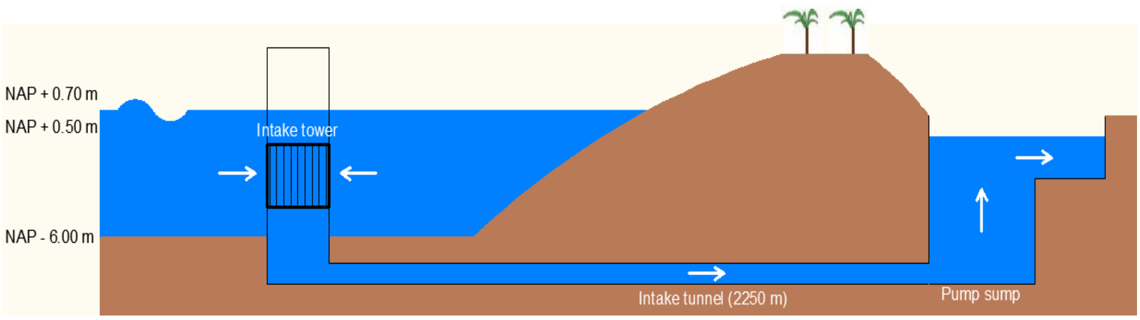

Figure 6.11: Schematic cross section fresh water intake system.

The effluent of the power plant, brackish water, will be collected in a discharge sump. From the discharge sump the brackish water will be discharged to the North Sea through the outfall tunnel and outfall tower. Because the water level of the North Sea is affected by the tide, the water level of the discharge sump should be sufficient in order to be able to discharge to brackish water by gravity. The energy level at the end of the production process is determined in Appendix B.3 and is equal to NAP + 2.9 m. The cross section of the outfall system is given in figure 6.12:

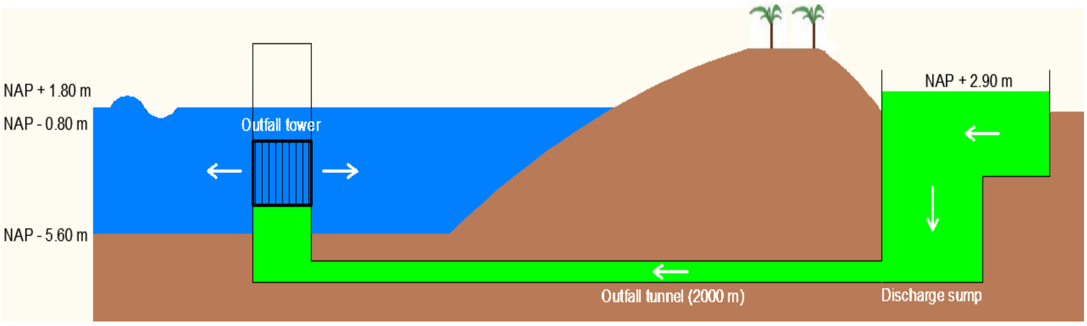

Figure 6.12: Schematic cross section outfall system.

In Appendix B.2 more is described about the basic design. The presence of an agricultural area not only provides a sufficient space for an osmotic power plant, it also allows a relatively simple construction method. The intake and outfall system can be built in-situ or by prefabrication in a construction pit.

6.3.5 Characteristics

6.3.5.1 Intake velocity

The intake velocity of the power plant has a major impact on the design of the water intakes. The higher the intake velocity, the smaller the dimensions of the intakes could be. However, a large intake velocity has a negative effect on the ecology and shipping industry. Especially fish are most vulnerable to the effects of a large intake velocity. Fish can be sucked into the water intakes. The total amount of sucked fish can be reduced by using a lower intake velocity and additional infrastructure.

A compromise should be found for the intake velocity. The used intake velocity in the design case is of the same order as the intake velocity commonly used at cooling water intakes for conventional power plants in the Netherlands [25]. The rate of the intake velocity used is 0.30 m/s.

6.3.5.2 Unit rate

The unit price of the intake and outfall tunnels is estimated at 500 €/m^3 [26]. This value is based on the capital costs of tunnels and culverts. In section 9.6.1, the influence of the tunnel unit rate on the energy unit rate will be determined in a sensitivity analysis. The capital costs of the intake and outfall towers are higher, but will be neglected because the large tunnel lengths ensure that the capital costs of the tunnels are much larger than the capital costs of the towers.

6.3.6 Dimensions

The dimensions of the intake and outfall tunnel have a major influence on the total head loss. According to equation 6.4, a twice as large equivalent diameter implies a 16 times smaller total head loss when the flow rate is taken as a constant. However, the larger equivalent diameter the higher the capital costs will be. Also the length of the tunnel and the local energy losses due to the tunnel trajectory will affect the total head loss. The total head loss must be overcome by pumps in a later stage of the osmotic power production. Pumping up the total head loss reduces the net energy production of the power plant, so the head loss should be minimized.

An optimization of the equivalent diameter will result in a large total head loss, because the capital costs of the long intake tunnel have the biggest impact. By using the optimum equivalent diameter, the net energy production of the power plant will decrease which is contrary to the purpose of the power plant. Dimensioning the tunnel as such that no head loss will occur implies a very large equivalent diameter which will increase the capital costs. In order to proceed with the dimensioning of the tunnel, a compromise will be made in which the net energy production of the power plant is considered as the most important. In the case studies therefore, the requirement is imposed that the total head loss should not exceed 1 m.

The required cross sections which result in a maximum total head loss of 1 m are determined in a cross section analysis which is described in Appendix B.5. The results in case of the 25 MW PRO power plant are given in table 6.2:

	Fresh water intake	**Salt water intake**	**Brackish water outfall**
Flow rate	18.8 m^3/s	41.8 m^3/s	60.6 m^3/s
Length	2.250 m	5.975 m	2.000 m
Equivalent diameter	4.1 m	6.5 m	6.4 m
Inner cross section	4.4 x 3 m	11.1 x 3 m	10.7 x 3 m
Internal wall	0	1	1
Wall thickness	0.45 m	0.55 m	0.55 m
Outer cross section	5.3 x 3.9 m	12.7 x 4.1	12.4 x 4.1 m
Intake flow area	67.4 m^2	154.4 m^2	N.A.
Intake velocity	0.28 m/s	0.27 m/s	N.A.

Table 6.2: Cross section analysis results in case of the 25 MW PRO power plant.

According to table 6.2, the resulting intake velocities will not exceed the maximum required intake velocity. The depths at the intake location are therefore sufficient.

6.3.7 Area

The intake and outfall tunnels are partly submerged or underground. These parts will therefore not be considered in the total area of the power plant. The different sumps of the power plant are above the ground, so these sumps will contribute to the total power plant area. However, the area of the sumps depends on the pre-treatment facility of the power plant which will be discussed in section 6.4.

6.3.8 Energy loss

6.3.8.1 Intake system

The dimensions of the intake systems, given in section 6.3.6, result in a total head loss by using equation 6.4. The total head loss for both intake systems is about 1.0 m because that was an imposed requirement in the cross section analysis. The total head loss should be overcome by pumps in a later stage of the osmotic power production. The energy line of the fresh water intake system is given in figure 6.13. A comparable energy line could be given for the salt water intake system but will not be given because of its resemblance to the fresh water energy line.

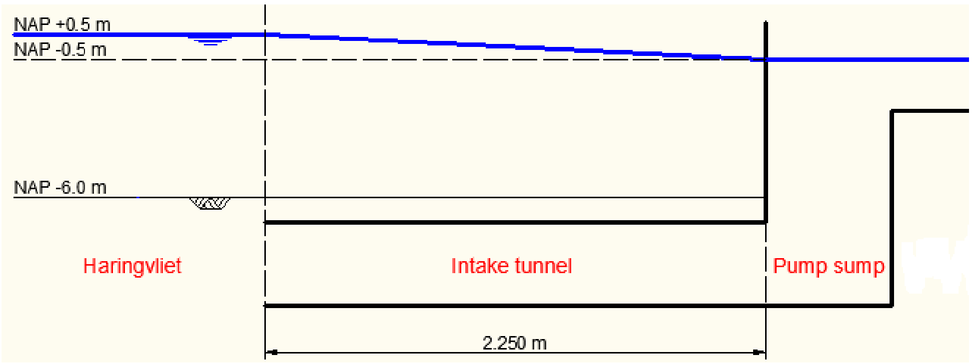

Figure 6.13: Energy line fresh water intake system.

6.3.8.2 Outfall system

The discharge of the brackish water flow is a special case because the discharge is influenced by the North Sea tide. The average high water is NAP + 1.8 m, but during a storm surge the outside water level can reach levels up to NAP + 3.6 m [17]. These levels ensure that the power plant, with a surface level of NAP + 1.0 m, is not able to discharge the brackish water. This problem is described in Appendix B.3. The solution is to run the power plant at an end level of NAP +2.9 m. The power plant downtime due to this end level is 0.60% which is equal to an energy loss of 1.2 GWh/yr.

6.3.9 Capital costs

The capital costs of the intake and outfall systems in case of the 25 MW PRO power plant are, with the assumed unit rate given in section 6.3.5.2, about € 230.000.000,-.

6.3.10 200 MW PRO power plant

An eight times larger power plant capacity will imply:

- An eight times larger flow rate through the different tunnels(see section 6.2.3)
- A decreasing length of the salt water intake tunnel because of the increased power plant area

According to equation 6.4, an eight times larger flow rate results in a 64 times larger total head loss. In order to counterbalance the larger total head loss, a larger equivalent diameter is required. Because the equivalent diameter in equation 6.4 is to the fourth power, an eight times larger flow rate requires only a 2.8 times larger equivalent diameter in order to obtain the same total head loss. A larger equivalent diameter (and in case of the salt water intake system a decreasing tunnel length) will also affect the head loss due to friction, so the required equivalent diameter could be even smaller. The required equivalent diameters for the different tunnels which result in a maximum total head loss of 1 m are determined in Appendix B.5. The resulting relations between the flow rate through the tunnel and equivalent diameter are given in figure 6.14 – 6.16:

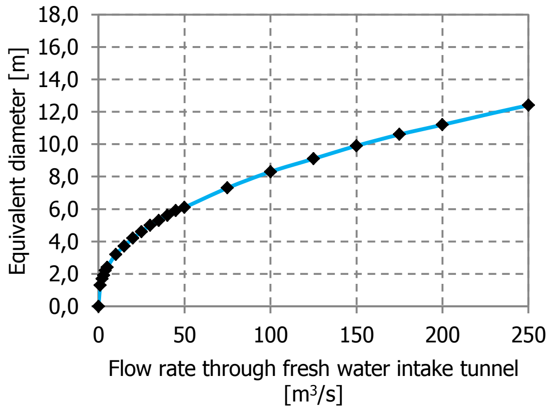

Figure 6.14: Required equivalent diameter fresh water intake tunnel.

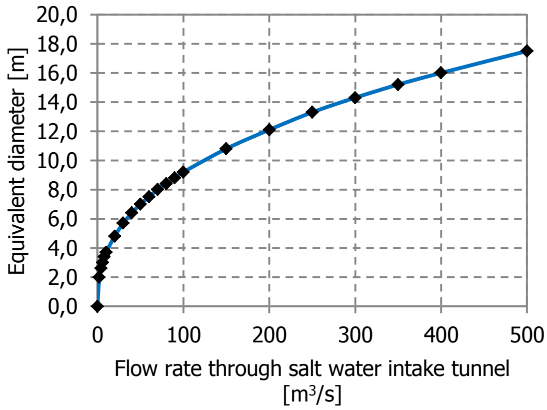

Figure 6.15: Required equivalent diameter salt water intake tunnel.

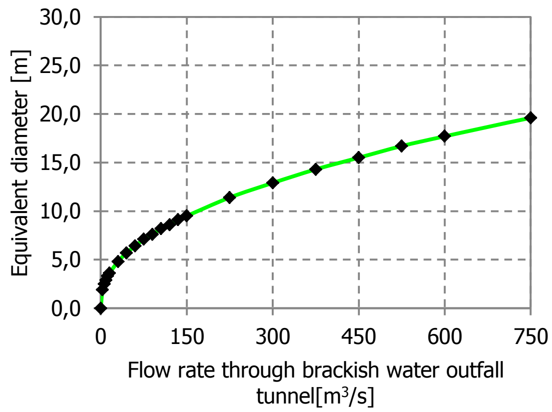

Figure 6.16: Required equivalent diameter brackish water outfall tunnel.

The required equivalent diameters will eventually result in a relation between the power plant capacity and the capital cost of the intake and outfall systems. The calculations which are required in order to obtain this relation are described in Appendix B.5. The result is given in figure 6.17:

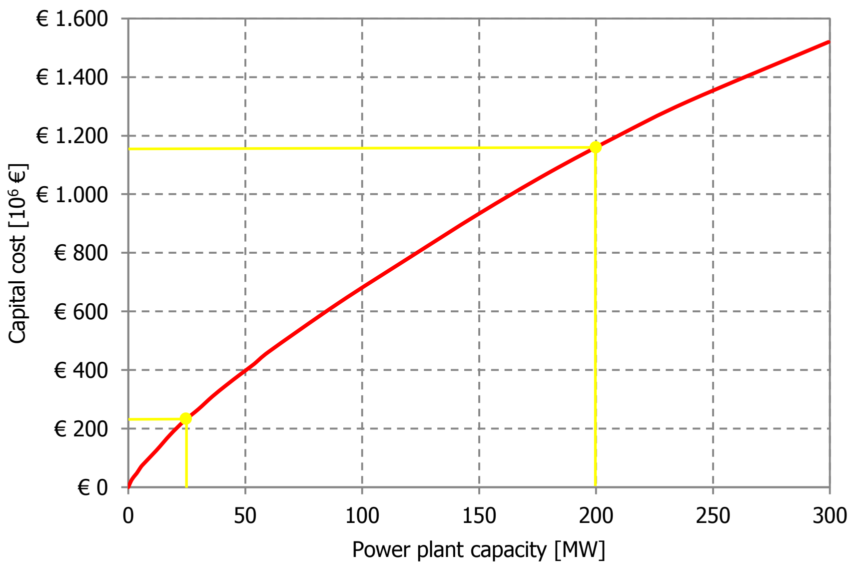

Figure 6.17: The relation between power plant capacity and capital costs of the intake and outfall systems.

The capital costs of the intake and outfall systems in case of the 200 MW PRO power plant are € 1.135.000.000,-. An eight times higher capacity of the power plant results in a 5 times larger capital costs of the intake and outfall systems.

The energy line given in figure 6.13 also applies in case of a 200 MW PRO plant. The total head loss must be overcome by pumps in a later stage of the osmotic power production. The optimum end energy level of a 200 MW PRO plant appears to be the same as the optimum end energy level of the 25 MW PRO power plant. The power plant downtime due to this end level is therefore also 0.60% which is equal to an energy loss of 7.4 GWh/yr.

The area of the pump sumps of the 200 MW PRO power plant depends, like the 25 MW PRO power plant, on the pre-treatment facility. This will be discussed in section 6.4.

6.4 Pre-treatment

The second stage of the osmotic power production is the pre-treatment of the inflowing solutions. These solutions contain suspended solids, colloidal particles, dissolved solids and micro-organisms which could contaminate the semi-permeable membranes. The contamination of the semi-permeable membranes will result in a decrease of energy production which could be prevented by pre-treatment of the inflowing solutions. This chapter contains a description of the types of pre-treatment and will determine the capital costs, energy consumption and required area of the pre-treatment facility.

6.4.1 General

An osmotic power plant requires a large area of membranes (see section 6.5) which, due to space-saving considerations, is wounded into a number of modules. These modules have a certain packing density, i.e. a certain membrane area per module volume. The higher the packing density, the lower is the amount of modules required which could have a positive impact on the capital costs and net energy production of the power plant. However, a large packing density has a major disadvantage.

A semi-permeable membrane applied in PRO allows the permeation of water molecules. In order to make this permeation possible the pore size of the membranes should be large enough (order of magnitude 0.1 – 1 nm). The used water flows in PRO not only contain water molecules, it will also contain:

- Suspended solids (order of magnitude >5 μm) are self-settling non-dissolved substances in a fluid.
- Colloidal particles (order of magnitude 0.4 – 5 μm) are dispersed not self-settling substances in a fluid.
- Dissolved solids (order of magnitude <0.4 μm) are not self-settling dissolved substances in a fluid.
- Micro-organisms (order of magnitude 0.01 - 10 μm) like viruses, bacteria and algae.

A semi-permeable membrane module is sensitive for fouling when water flows through the modules. Fouling is the accumulation of undesired material. Suspended solids or colloidal particles could block the membrane modules (particulate fouling), dissolved solids could precipitate on the membrane surface (precipitate fouling) or micro-organisms could settle on the membrane surface (bio fouling). Fouling will reduce the water flux through the semi-permeable membranes and thus the energy production. The fouling sensitivity level of a membrane module depends on the packing density of the module. The larger the packing density the smaller is the width of the small flow channels between the membranes, i.e. the spacers. The smaller the width of the spacers the larger is the possibility that a particle gets stuck inside the spacer and thus will occur fouling.

The possibility on fouling could be reduced by removing the suspended solids, colloidal particles, dissolved solids and micro-organisms of the water before it flows into the membrane modules. This could be achieved by applying certain pre-treatment types.

6.4.2 Types of pre-treatment

Pre-treatment of water is used for several water types, such as:

- Drinking water
- Surface water
- Process water
- Waste water

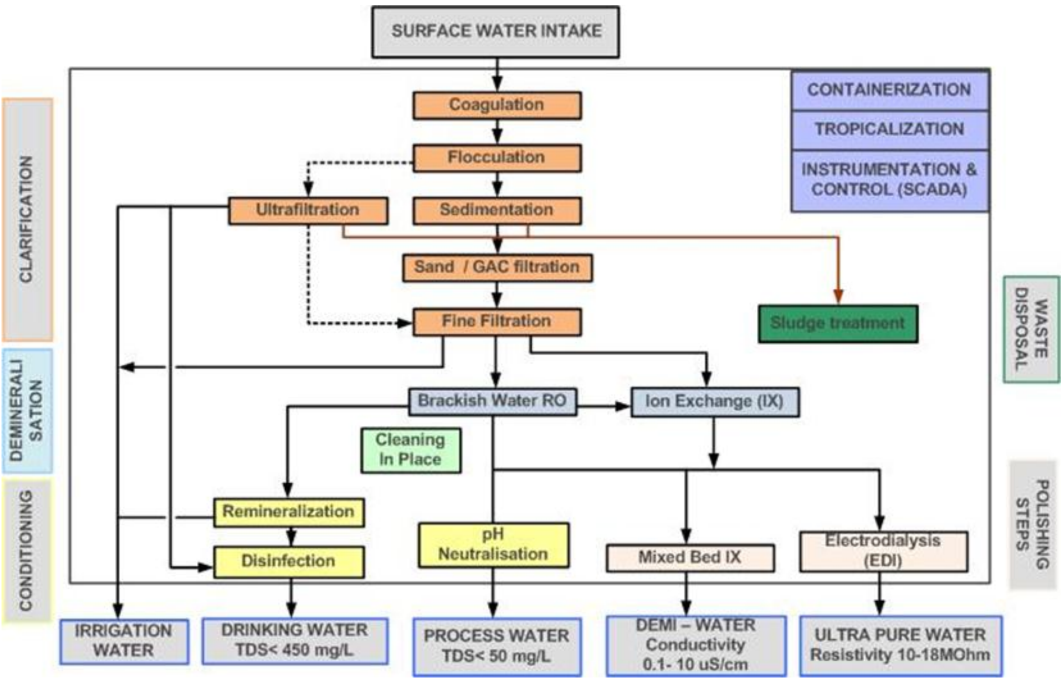

Figure 6.18: Treatment types for several water types.

The fresh and salt water flow rate of an osmotic power plant can be considered as process water. According to figure 6.18, the most commonly used treatment types for process water are:

- Coagulation
- Flocculation
- Sedimentation

- Sand filtration
- Granular Activated Carbon (GAC) filtration
- Fine filtration
- pH neutralisation

A brief description of each treatment is given in Appendix C.1. Whether to use all the common treatment types, just a few or none at all depends on a number of issues.

6.4.2.1 Optimum between water quality, pre-treatment and membrane configuration

The first issue is the optimisation between water quality, pre-treatment and membrane configuration. When the inflowing water is 100% clear the possibility on fouling is minimal. The width of the spacers could be minimized in order to maximize the packing density. Modules with a high packing density will have a positive effect on the net energy production because the water is diverted over fewer modules. The diversion over less modules will also have a positive effect on the total capital costs of the power plant because less modules implies less pumps, pipes and turbines.

When the water quality is deteriorating the possibility on fouling will increase. In order to prevent fouling the membrane configuration could be modified. By enlarging the width of the spacers the possibility that a particle will block a spacer decreases. Though, a larger spacer width implies a lower packing density and thus more modules are required. This will have a negative effect on the net energy production and total capital costs.

Another option is to apply certain pre-treatment types before the water will flow into the modules. By applying pre-treatment, the particles which could result in fouling will be removed. Pre-treatment will have a positive effect on the packing density and net energy production. However, the different pre-treatment types have a certain capital costs and energy consumption so it will affect the total capital costs and net energy production of the power plant.

Treatment	€/m^3 annual production capacity
Coagulation	0.10 – 0.25
Flocculation/sedimentation	0.15 – 0.25
Sand filtration	0.70 – 1.50
GAC filtration	0.50 – 0.90
Micro-filtration	0.05 – 0.15
Ultra filtration	1.00 – 2.00
pH neutralisation	0.35 – 0.60

Table 6.3: The cost factor per treatment type.

The optimum solution is a balance between water quality, membrane configuration and pre-treatment which results in a cost-effective maximized net energy production.

6.4.2.2 Development osmotic power production

The second issue is the current state in the development of osmotic power production. The previous section described that an optimum solution between water quality, membrane configuration and pre-treatment should be found in order to maximize the net energy production in a cost-effective manner. However, the exploitation of osmotic power is not yet as developed that this optimum solution is known. This issue should be solved by additional studies and from the findings of the pilot power plants. The aim of these studies and pilot plants should be that in the future the optimum membrane configuration and required treatment types are known for given water qualities. An example of a fully developed membrane application is the desalination of sea water. For a desalination plant, which also uses the principle of osmosis, the required membrane configuration is known when the water quality of the inflowing salt water and the desired quality of the effluent (drinking water) is given. However, the purpose of an osmotic power plant (energy) is different than that from a desalination plant (drinking water) so another optimum solution should be found.

6.4.2.3 Capital costs and energy consumption

The third issue is the capital costs and energy consumption associated with the different treatment types. The capital costs of a pre-treatment type can be estimated with the following general formula [27]:

$$C_{pre\text{-}treatment} = c \cdot Q^{b}_{m^3/yr} \tag{6.5}$$

The symbol c in equation 6.5 represents the cost factor of a pre-treatment type. The cost factors per pre-treatment type are given in table 6.3 [27]. The symbol b in equation 6.5 represents a scale factor. In the case of an osmotic power plant, the relation between the power plant capacity and flow rate though the pre-treatment facility is linear. The scale factor is therefore equal to 1. The capital costs of a number of common treatment types for process water are given in table 6.4:

Treatment	€/m^3	Treatment fresh Q=20.9 m^3/s	Treatment salt Q=41.8 m^3/s
Coagulation	0.175	€ 115.500.000,-	€ 230.000.000,-
Flocculation/sedimentation	0.20	€ 130.000.000,-	€ 264.000.000,-
Sand filtration	1.10	€ 726.000.000,-	€ 1.452.000.000,-
GAC filtration	0.70	€ 462.000.000,-	€ 924.000.000,-
Ultra filtration	1.50	€ 990.000.000,-	€ 1.980.000.000,-

Table 6.4: The capital costs of common treatment types for process water applied on the 25 MW PRO power plant.

When, for example, ultra-filtration is applied, the capital costs of the pre-treatment facility (with an annual production capacity of $6.6 \cdot 10^8$ m^3 fresh and $13.2 \cdot 10^8$ m^3 salt water) will be about 3 billion euro. This is 180 times larger than the annual revenues from the energy production when the initial energy production (see section 6.2.2) is considered and an energy unit rate is assumed equal to 8 cents/kWh. The same problem will occur when other treatment types are applied. It seems to be costs prohibitive to use a pre-treatment facility.

However, Statkraft believes that there actually is a possibility to design a cost-effective pre-treatment facility. Based on their field tests with river and sea water, a relative coarse form of filtering in combination with periodic flushing- and cleaning operations appears to be sufficient [28]. The coarse form of filtering can be achieved by using micro-filtration. Also REDstack has confidence in micro-filtration [13]. The pre-treatment facility of their 10 kW RED pilot plant at the Afsluitdijk, which will be constructed in 2012, will consist of micro-filtration.

Besides the high capital costs, some of the treatment types consume a large amount of energy. These treatment types will reduce the net energy production of the power plant. For example, ultra-filtration requires a constant pressure of 1 bar (see figure 6.19). This is 8.3% of the initial energy production of the power plant in the case study.

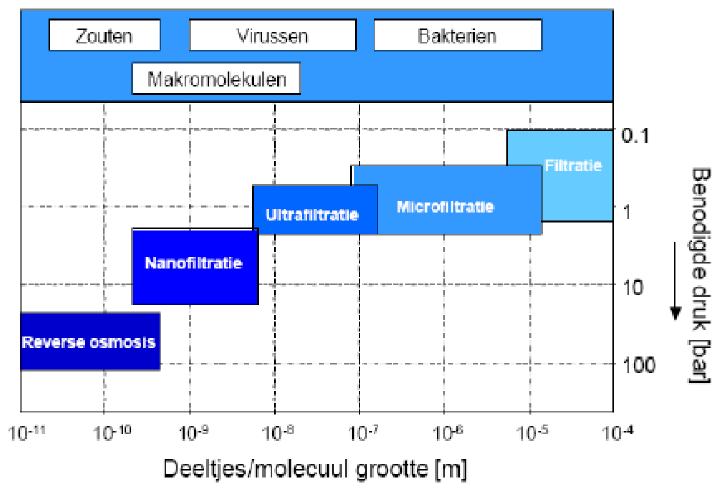

Figure 6.19: The required energy for different filtration types.

6.4.2.4 <u>Selected pre-treatment in the case studies</u>

The decision on what type of pre-treatment to apply is affected by two contradicting requirements. On one hand, a pre-treatment facility is required which will reduce the possibility on fouling. On the other hand, a pre-treatment facility with low capital costs and energy consumption is required. The best option to reduce the possibility on fouling is to apply a very fine filtration. The finer the filtration, the smaller the possibility on fouling will be. However, the finer the filtration the higher are the capital costs and energy consumption (see figure 6.19). Cheaper and less consumable filtering types are available, but these types have a relative coarse type of filtering and will increase the possibility on fouling. The two contradicting issues indicate that a cost-effective pre-treatment facility with a maximized energy production is difficult to achieve.

The two interested parties, Statkraft and REDstack, believe that micro-filtration is a good option. Micro-filtration is a relative coarse type of filtering and the cheapest treatment type available. It seems that Statkraft and REDstack want to analyse what the result will be when the cheapest treatment type is applied. The findings of their pilot plants will conclude whether the decision to apply micro-filtration was a good one.

The abovementioned difficulties also apply for the 25 MW PRO power plant. At this stage in the osmotic power development it is interesting to analyse the financial feasibility when the cheapest treatment type is applied. Therefore, micro-filtration will be used in the case study under the assumption that the coarse type of filtering will not affect the energy production of the power plant. The effect of applying micro-filtration on the net energy production of the osmotic power plant still has to be determined by the pilot plants.

6.4.3 Position

The pre-treatment facility will be placed in the pump sumps. The position of the pre-treatment facility and pump sumps is illustrated in figure 6.20:

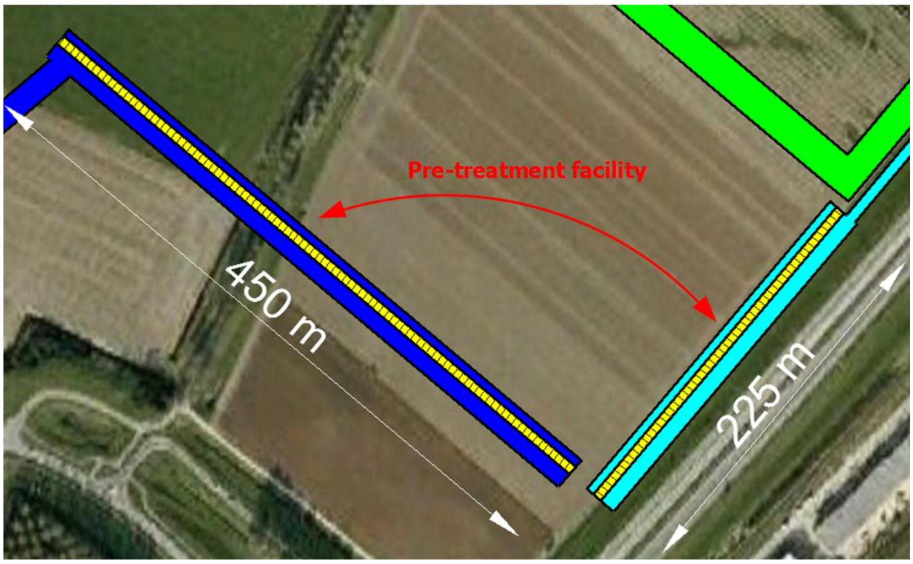

Figure 6.20: The position of the pre-treatment facility.

6.4.4 Basic design

The used treatment type in the case study is micro-filtration (see figure 6.21). Micro-filtration consists of a drum where a filter is strained around its exterior. The drum rotates slowly and is continuously hosed from nozzles which are placed above the drum. Micro-filtration is suitable for blocking micro-organisms and suspended solids.

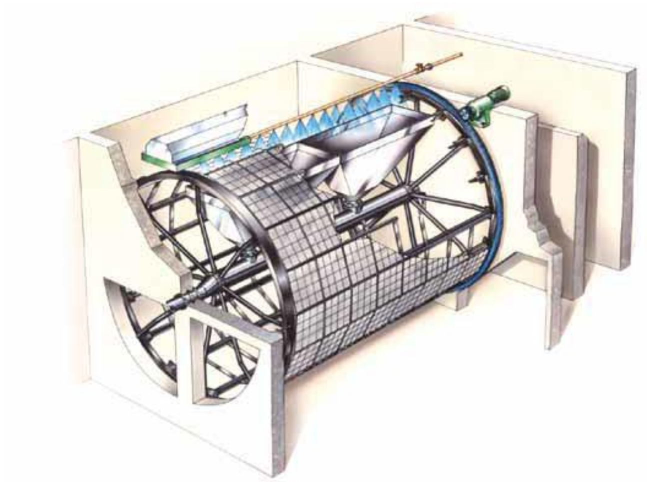

Figure 6.21: Micro-filtration drum [29].

The micro-filtration drums are aligned next to each other in the middle of the pump sump. The water is transported from the sources through the intake tunnels towards this pump sump. At the boundary of the pump sump, pumps are placed in order to transport the water to the next stage of the osmotic power production. During the transport of the water from the end of the intake tunnel to the pumps, the water flows through the micro-filtration drums. A basic design of the pre-treatment facility is illustrated in figure 6.22:

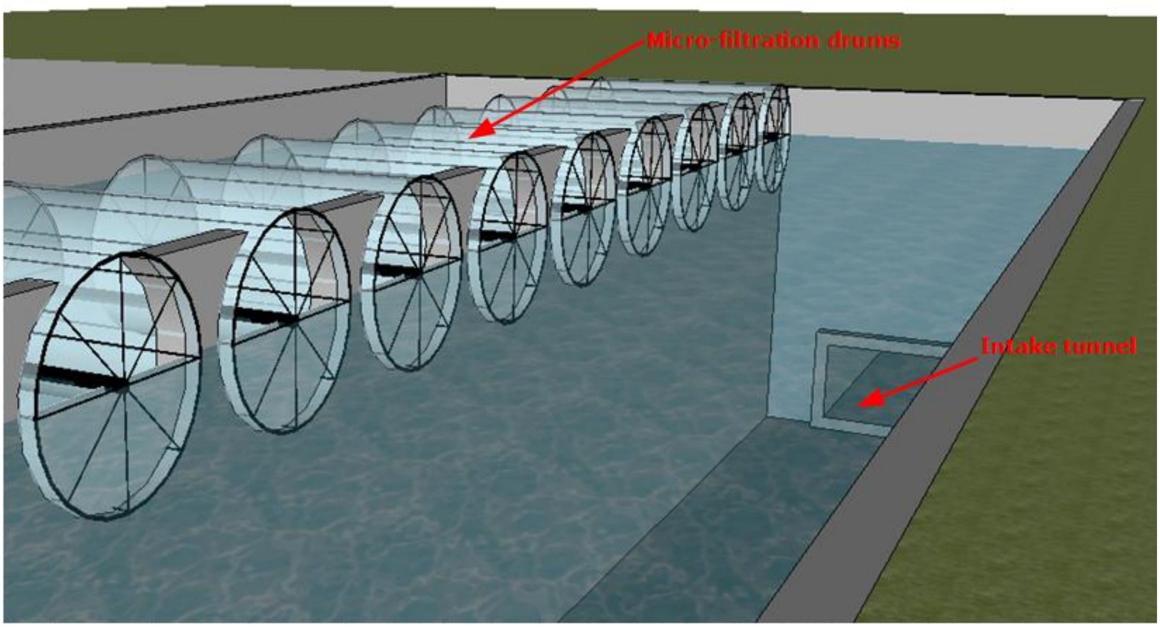

Figure 6.22: Basic design pre-treatment facility.

6.4.5 Characteristics

6.4.5.1 Micro-filtration

In Appendix C.2, some characteristics of a single micro-filtration drum are given [29]. The used and calculated (see Appendix C.3) characteristics in the case study are given below:

- Capacity: 1.500 m^3/hr
- Diameter: 3.5 m
- Length: 6.0 m
- Volume: 57.73 m^3
- Filter area: 65.97 m^2
- Water flux: 0.0063 m^3/m^2s

6.4.5.2 Cost factor micro-filtration

The cost factor of micro-filtration is assumed to be equal to 0.1 €/m^3 (see table 6.3). In section 9.6.2, the influence of the micro-filtration cost factor on the energy unit rate will be determined in a sensitivity analysis.

6.4.5.3 Unit rate pump sumps

The unit rate of the pump sumps is assumed to be equal to 300 €/m^3 [26]. This value is based on the capital costs of access ramps of tunnels.

6.4.6 Dimensions

The dimensions of the pre-treatment facility are calculated in Appendix C.3. The results are given below:

- Number fresh water drums: 50
- Number salt water drums: 100
- Diameter drum: 3.5 m
- Length drum: 6.0 m
- Length fresh water pump sump: 225 m
- Length salt water pump sump: 450 m
- Cross section fresh and salt water pump sump: 140 m^2

6.4.7 Area

The area required for the pre-treatment facility depends on the number of drums required. The micro-filtration drums should be aligned next to each other in horizontal direction. This will result in a very long line of micro-filtration drums (see figure 6.20). When it is assumed that the distance between two consecutive drums is 1 m, the length of the fresh and salt water pre-treatment facility becomes 225 m and 450 m respectively. With an estimated width of the sump, in which the drums are placed in, of 20 m the required area becomes:

- Area fresh water drums: 4.500 m^2
- Area salt water drums: 9.000 m^2

It appears that the pre-treatment facility has a major impact on the total power plant area. The two pump sumps determine the total length and width of the power plant. In addition to the issues of a pre-treatment facility (capital costs and energy consumption), the required area should be added. Micro-filtration is a cheap treatment type, but the filtering is coarse and it appears to be space consumable. This will result in a higher land acquisition and, in a later stage, higher energy loss due to water transportation (see section 6.6). Other treatment types, for example ultra-filtration, have higher capital cost but are less space consumable than micro-filtration drums. This will work positively on the land acquisition and energy consumption due to the water transportation. The required area for a certain treatment type should therefore be taken into account in the optimization of the power plant.

6.4.8 Energy loss

6.4.8.1 Head loss over the micro-filtration drums

The micro-filtration drums will result in some head loss. However, this head loss is so small that it will not be considered in the case study [18]. The energy line after the pre-treatment stage will not be given because of its resemblance with the energy line given in figure 6.13.

6.4.8.2 Energy consumption micro-filtration drums

The micro-filtration drums require energy in order to rotate. According to figure 6.19, micro-filtration requires a minimal pressure of about 0.3 bar. This pressure is transformed into an annual energy consumption in Appendix C.3 and is equal to 16.5 GWh/yr.

6.4.9 Capital costs

6.4.9.1 Micro-filtration drums

The capital costs for the pre-treatment facility depend on the annual capacity. With a unit rate of 0.10 €/m^3 for micro filtration (see table 6.3), the total capital costs for the pre-treatment facility become about € 198.000.000,-.

6.4.9.2 Pump sumps

The capital costs of the pump and discharge sumps depend on the length of the pre-treatment facility and the cross section of the sumps. The capital costs of the different sumps are determined in Appendix C.3 and are equal to € 45.000.000,-.

6.4.10 200 MW PRO power plant

A 200 MW PRO power plant implies larger flow rates through the power plant and thus a larger pre-treatment facility. The 8 times higher power plant capacity requires an 8 times larger flow rate (see section 6.2.3). Because the amount of micro-filtration drums is linear related to the flow rate, also 8 times more micro-filtration drums are required. This will provide a problem. The length of the fresh and salt water pre-treatment facility in the case of a 200 MW PRO power plant will be 1.800 m and 3.600 m respectively. The extremely large length of the pre-treatment facilities ensures that the 200 MW PRO power plant will not fit in the area given in figure 6.2. Solutions to this problem could be using another position of the pre-treatment facility or applying another treatment type which requires less space. Because another treatment type will increase the capital costs and energy consumption, another position of the pre-treatment facility is chosen. The position of the pre-treatment facility in the case of a 200 MW PRO power plant is given in figure 6.23. The yellow lines in the fresh and salt water sump represent the lines with micro-filtration drums. The fresh water sump contains two lines of micro-filtration drums (one on each side). The combined length of the micro-filtration drums in the fresh water sump is equal to 1.800 m which was determined earlier in this section. The length of the salt water sump is 3.600 m.

Figure 6.23: The position of the pre-treatment facility in the case of a 200 MW PRO power plant.

The capital costs of micro-filtration are linear related to the annual capacity of the pre-treatment facility. An 8 times higher power plant capacity results therefore in an 8 times higher capital costs. The capital costs for the pre-treatment facility in case of a 200 MW PRO power plant are therefore € 1.584.000.000,-. The capital costs of the different sumps are € 270.000.000,-.

The same principle applies for the energy loss of a 200 MW PRO power plant. An eight times larger pre-treatment facility consumes 8 times more energy. This results in an energy consumption of 130 GWh/yr.

6.5 Membrane stacks

In the third stage of the osmotic power production the fresh and salt water flow is transferred into osmotic energy. The osmotic energy is produced at membrane stacks in which the semi-permeable membranes are placed. This section will determine the required stack dimensions, capital costs and energy losses.

6.5.1 General

The theory behind the osmotic flow through semi-permeable membranes is already described in section 2.2.1.

6.5.2 Types of membrane modules

There are several types of membrane modules available:

- Spiral-wounded (see figure 6.24)
- Hollow fine fibres
- Capillary fibres
- Plate- and frame
- Tubular

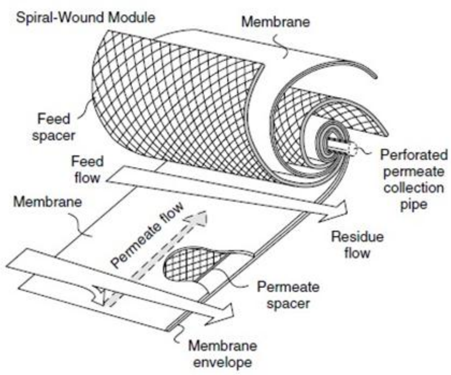

Figure 6.24: The spiral-wounded membrane module.

Each of the membrane module types has its own qualities and suitability for a certain membrane application. Important points of consideration are the pressure resistance, fouling sensitivity, costs and required space. The type of membrane which is the most suitable for producing osmotic power is the spiral-wounded type [30; 7]. Spiral-wounded modules are resistant to high pressures, and are less sensitive to fouling compared to the other modules.

6.5.3 Position

It is assumed that the membrane stacks are distributed evenly over the length of the salt water pump sump. The distance between two consecutive membrane stacks is 40 m which is sufficient for the transport pipes and for maintenance. The position of the membrane stacks is illustrated in figure 6.25:

Figure 6.25: The position of the membrane stacks.

6.5.4 Basic design

Due to space-saving considerations the membranes are wounded into modules. These modules have the characteristic of a large membrane area in a small volume. The standard spiral-wounded membrane module has a diameter of 20 cm and a length of 100 cm [30]. Larger modules, up to 30 cm in diameter and 150 cm in length, are available but those are produced by only a few manufacturers. In the case study the standard type will be used. The packing density of spiral-wounded membrane modules is 300 – 1.000 m^2/m^3 [7]. According to section 6.4.2.1, the potential packing density is affected by the water quality and pre-treatment. Because the relation between water quality, membrane configuration and pre-treatment is not yet determined, an assumed value for the packing density is used in the case study. The used value in the case study is 775 m^2/m^3 [31].

Five to seven modules could be housed in a pressure vessel which ensures that the osmotic pressure can built up [30]. In the case study, it is assumed that 7 modules are housed in one pressure vessel. The fresh water flow will be supplied to the central axis of the pressure vessel under atmospheric pressure (see figure 6.26). It flows through the membrane modules inside the pressure vessel in which a large part of the flow permeates radially to the salt water compartment. Because water is incompressible, the added water molecules will increase the pressure inside the salt water compartment.

The salt water flow is supplied to the pressure vessel outside the central axis (see figure 6.26). Because the salt water compartment is pressurized, pressure exchangers are necessary in order to enable salt water to flow into the pressure vessels. The added water molecules to the pressurized salt water compartment results in a pressurized brackish solution.

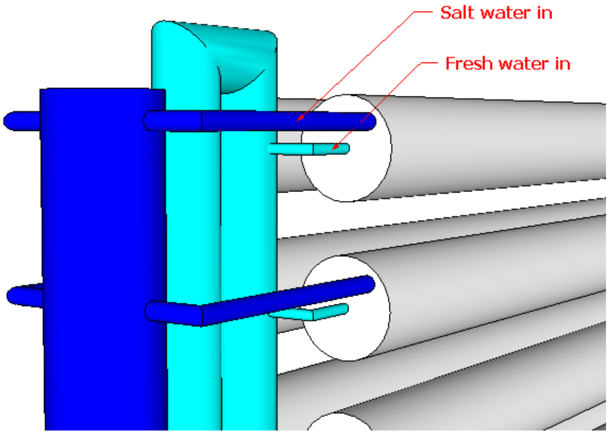

Figure 6.26: Inflowing solutions into the pressure vessels.

The pressure inside the pressure vessels can be relieved by discharging the brackish solution at the other end of the pressure vessels (see figure 6.27). Turbines are driven during the pressure release. Another discharged solution is the fresh water bleed. The fresh water bleed is the part of the fresh water flow that does not permeate through the membranes. The bleed is discharged out of the pressure vessels and transported back to the pump sump where it can be reused.

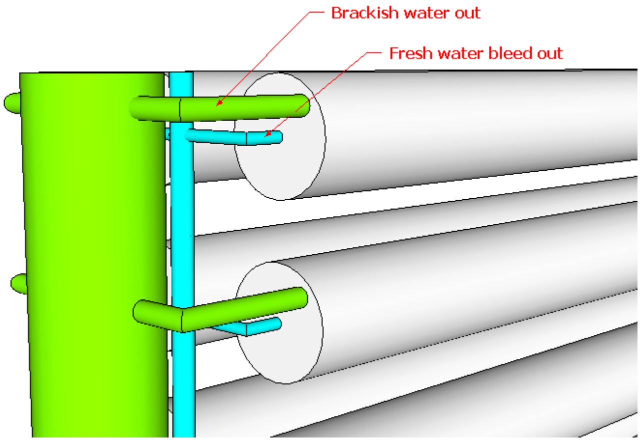

Figure 6.27: Discharged solutions from the pressure vessels.

The pressure vessels are grouped together in membrane stacks. A part of a membrane stack is illustrated in figure 6.28:

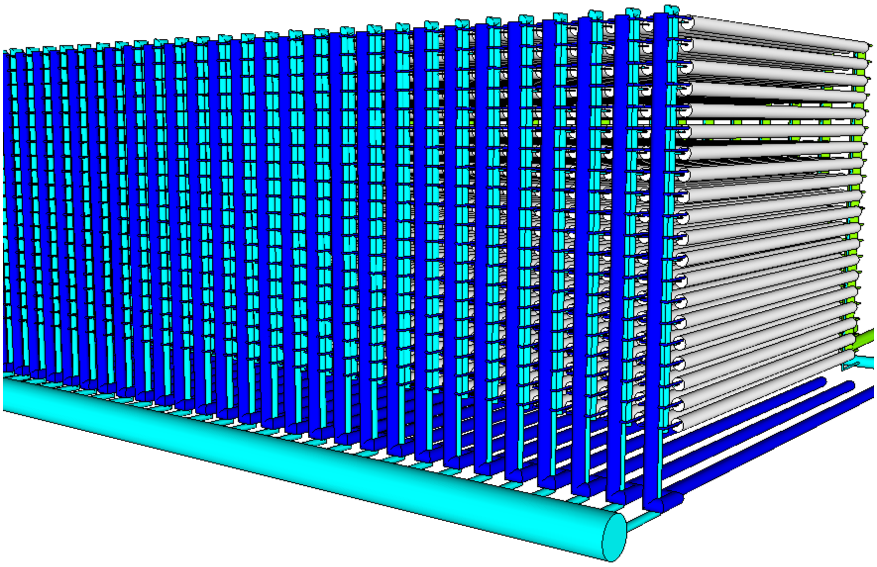

Figure 6.28: Membrane stack configuration.

6.5.5 Characteristics

6.5.5.1 Water flux

The water flux used in the case study originates from an experiment that was conducted in 2009 [32]. The results for a 35 g/l concentrated solution and a 2.5 g/l diluted solution are given in figure 6.29:

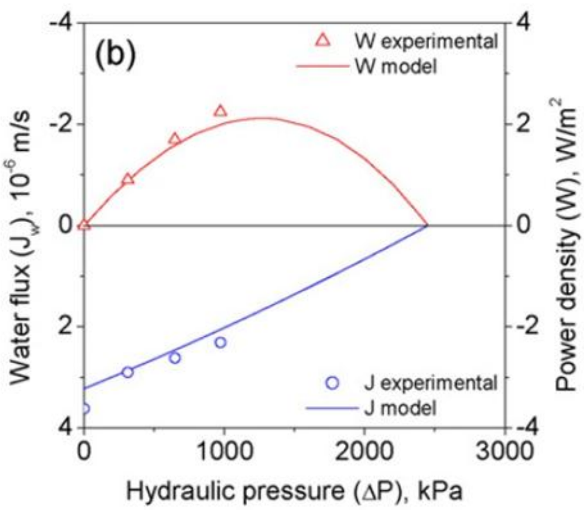

Figure 6.29: Water flux and power density as a function of the applied hydraulic pressure [32].

The salinity used in the experiment is almost similar to the salinity used in the case study. The results of the experiment can therefore also be used in the case study. The hydrostatic pressure difference over the membranes in the case study is equal to 1.200 kPa. According to figure 6.29, the corresponding water flux is $2.0 \cdot 10^{-6}$ m/s.

6.5.5.2 Power density

The water flux and the hydrostatic pressure difference over the membranes results in a power density. The used power density in the case study is determined by using equation 6.6:

$$W^{PRO} = J_w \Delta p = 2.0 \cdot 10^{-6} \cdot 1200 \cdot 10^3 = 2.4 \, \text{W/m}^2 \qquad \textbf{(6.6)}$$

The used value for the power density is 2.4 W/m^2. This is smaller than the expected future power density of 5.0 W/m^2. For the case study, the value of 2.4 W/m^2 is used. In chapter 10, a conclusion will be made on the feasibility of an osmotic power plant when the power density increases to 5.0 W/m^2.

6.5.5.3 Fresh water bleed

The percentage of the fresh water bleed, a part of the fresh water flow that does not permeate through the membranes, is assumed to be equal to 10% [20].

6.5.5.4 Unit rate membranes

The current membrane price is about 5 €/m^2 [7]. This price includes the price of the pressure vessel and connections. Experts have indicated that within a few years it will be possible to produce membranes at a cost price of 2 €/m^2 [7; 8].

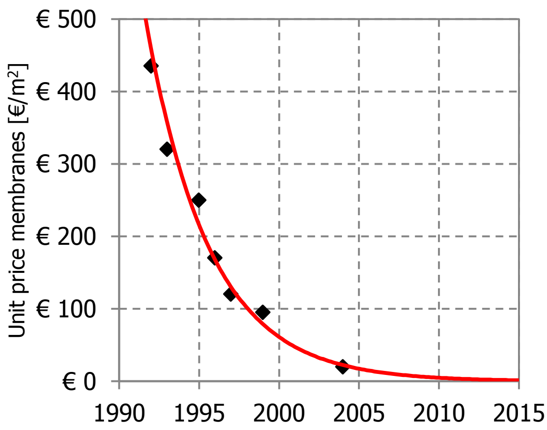

Figure 6.30: Development in membrane price [7].

However, this value is based on ion-selective membranes in the case of a RED power plant. The semi-permeable membranes have a larger pore size, so it could be assumed that semi-permeable membranes are cheaper than ion-selective membranes. Though, due to the lack of pricing information the unit rate of 5 €/m^2 is used in the case of a PRO power plant. In chapter 10, a conclusion will be made on the feasibility of an osmotic power plant when the membrane unit rate decreases to 2 €/m^2.

6.5.6 Dimensions

The dimensions of the membrane stacks can adopt a lot of different values. The most important dimensions are the stack height and stack length. However, both dimensions affect other parameters in the design of the power plant. The stack height, for example, affects the required area and energy consumption. The higher the stack the smaller is the required area per stack which positively affects the total area of the power plant. Though, the higher the stack the larger is the energy consumption of the power plant because of the higher water elevation. The optimum stack height can be found by considering the land price, power plant area, area per pressure vessel and energy consumption. The assumed stack height in the case study is 6 m. The used stack length in the case study is 92 m. This length is chosen as such that exact 10 membrane stacks are required.

Now the assumed stack height and length are known, the rest of the dimensions can be determined. The determination of the dimensions is elaborated in Appendix D. The results are:

- Membrane area: 10.416.667 m^2
- Module amount: 427.781
- Pressure vessel amount: 61.112
- Membrane stack amount: 10

6.5.7 Area

The required area per stack is 644 m^2. This value results in a stack area and volume per MW equal to 258 m^2/MW and 1.546 m^3/MW respectively. For the 10 membrane stacks, the required stack area is 6.440 m^2.

6.5.8 Energy loss

The pressure inside the pressure vessels will increase to a constant pressure of 1.200 kPa. Energy is produced by releasing discharging the pressurized brackish solution. In section 2.5.2 was described that 1/3 of the brackish water flow is used for the energy production. The rest of the brackish solution is required to pressurize the salt water flow in a pressure exchanger. The initial energy production, which is already determined in section 6.2, can be determined by multiplying the pressure inside the pressure vessels by 1/3 of the brackish water flow rate (which is equal to the fresh water flow rate). However, because of the fresh water bleed the resulting brackish water flow rate is lower than expected. The fresh water bleed should therefore be considered as an energy loss during the production process. The energy loss due to the fresh water bleed is determined in Appendix D and is equal to 6.8 GWh/yr.

6.5.9 Capital costs

The capital costs of the membrane stacks depend on the required membrane area. With a unit rate of 5.0 €/m^2, the capital costs for the membranes stacks in case of the 25 MW PRO power plant become € 52.100.000,-.

6.5.10 200 MW PRO power plant

A 200 MW PRO power plant implies a larger membrane area than the 25 MW PRO power plant. The amount of membranes, capital costs, energy loss and area of the membrane stacks are linear related to the power plant capacity. The 200 MW PRO power plant requires therefore 80 membrane stacks with a total membrane area of 83.600.000 m^2. The capital costs are € 418.000.000,-. The position of the membrane stacks in case of the 200 MW PRO power plant is given in figure 6.31:

Figure 6.31: The position of the membrane stacks in the case of the 200 MW PRO power plant.

The energy loss due to the fresh water bleed is in the case of a 200 MW PRO power plant equal to 41 GWh/yr.

The required area of the membrane stacks is in the case of a 200 MW PRO power plant equal to 50.400 m^2.

6.6 Pumps, pipes and turbines

The water should be transported from the pump sumps to the membrane stacks. This is achieved by pumps which will transport the water flows through pipes. The pipes end at the membrane stack where the osmotic pressure will be built up. The osmotic pressure is released by letting the pressurized water flow along turbines. The turbines transfer the osmotic pressure into electricity. This chapter will determine the dimensions, capital costs and energy consumption of the pumps, pipes and turbines.

6.6.1 General

The pressurized transport of water through pipes is already described in section 6.3.1.

6.6.2 Types

6.6.2.1 Pumps

There are many different types of pumps available. Each type of pump has its own suitability for transported medium, volume flow and elevation. All the pumps can be mechanically classified into two categories: centrifugal pumps and vertical pumps. Centrifugal pumps impart velocity and pressure to the medium as it moves past or through the pump impeller and convert some of that velocity into additional pressure. Vertical pumps displace the medium by a moving element (piston, plunger, rotor, lobe or gear) and raise the pressure of the medium. The complete classification is given in Appendix E.1.

The pumps of the osmotic power plant should transport a large volume flow over a long distance (in horizontal and vertical direction). A pump which complies with these demands is a centrifugal pump with the impeller between bearings. This type will be considered in the case study.

6.6.2.2 Turbines

There are several types of turbines available for the large-scale energy generation. These types can be classified in two manners in which the energy is converted. The first manner is by a water jet (which is supplied by a penstock) that is aimed at the blades of the turbines. The type of turbines which uses water jets is called impulse or equal pressure turbines. The second manner is by a fan that rotates in a space completely filled with water, through which the water flow is led. A pressure drop takes place in the fan. This type of turbine is called the reaction or overpressure turbines.

The turbines of the osmotic power plant should convert the pressurized brackish water (which is transported out of the membrane stacks) into electricity. During the electricity generation the pressurized brackish water is depressurized. The type of turbine which is the most suitable for the depressurization is of the reaction or overpressure type.

6.6.3 Position

The position of the pumps, pipes and turbines is illustrated in figure 6.32. In the case study it is decided to apply for each membrane stack 1 fresh water pump, 1 salt water pump, 1 pressure exchanger and 1 turbine.

Figure 6.32: The position of the pumps, pipes and turbines.

A zoomed-in overview is given in figure 6.33:

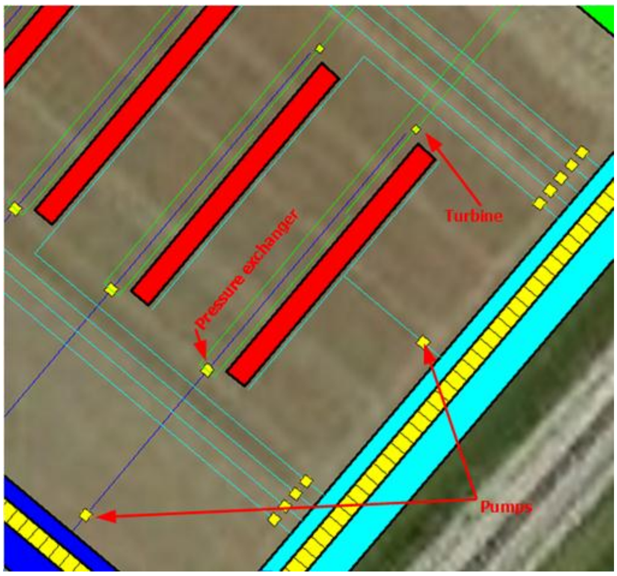

Figure 6.33: A zoomed-in view of the pumps, pipes and turbine position.

6.6.4 Basic design

The fresh water flow will be transported from the fresh water pump sump towards the fresh water side of the membrane stacks. During the transport, the water flow is divided over a number of pipes. The flow rate through the different pipes is given in figure E.2 in Appendix E.2. The transport pipe which runs from the pump sump until the membrane stack is called the primary fresh water pipe. When the fresh water flow reaches the membrane stack it will flow vertically through one of the 150 secondary fresh water pipes. At the required elevation level, the pressure will be released in order to let the fresh water flow into the pressure vessels through 40 tertiary fresh water pipes at atmospheric pressure. The basic design of the fresh water side of the membrane stacks is given in figure 6.34:

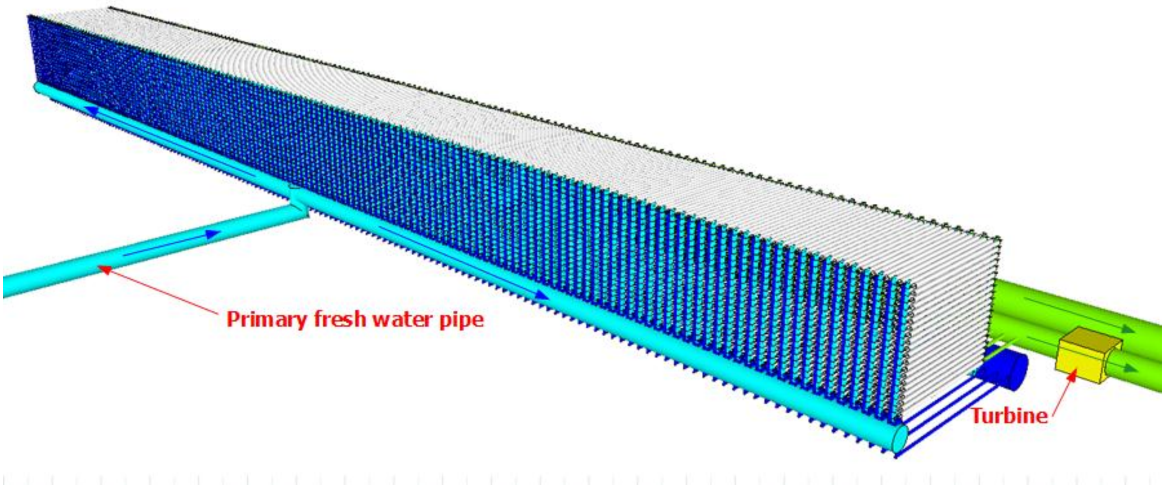

Figure 6.34: The design of the fresh water side of the membrane stack.

The salt water flow will be transported from the salt water pump sump through the primary salt water pipe towards the membrane stack. It reaches the stack at the brackish water side. At that side the salt water will flow through a pressure exchanger in which the salt water is pressurized. The primary salt water pipe continues running along the membrane stack. The pressurized salt water is divided over 150 secondary salt water pipes which will transport the salt water under the membrane stack to the fresh water side. There, the salt water will be transported upwards and eventually it will flow into the pressure vessels through the 40 tertiary salt water pipes. A designation of the pipes at the fresh water side of the membrane stack is given in figure 6.35:

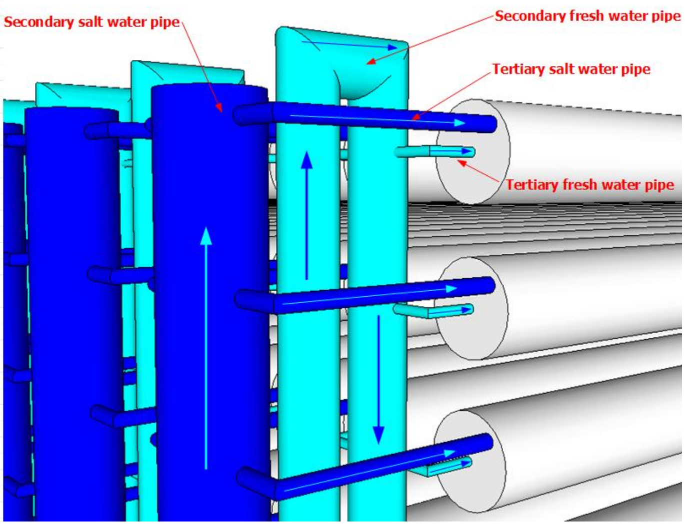

Figure 6.35: Designation of the pipes at the fresh water side of the membrane stack.

The effluent of the power plant is a flow of brackish water. The effluent is discharged out of the pressure vessels through the tertiary brackish water pipe into the secondary brackish water pipe. In this pipe the brackish water flow is transported downwards to a primary brackish water pipe. There are two primary brackish water pipes. Two third of the brackish water flow is required to pressurize the inflowing salt water. This implies that 2/3 of the membrane stack is required for the pressure exchanger. Therefore, two third of the secondary brackish water pipe discharges the brackish water to a pressure exchanger pipe. This part of the effluent flows through the pressure exchanger and eventually flows into the brackish water pit. One third of the secondary brackish water pipes discharge the brackish water to a turbine pipe. This part of the effluent drives a turbine and eventually flows into the brackish water pit. The basic design of the brackish water side of the membrane stacks is given in figure 6.36:

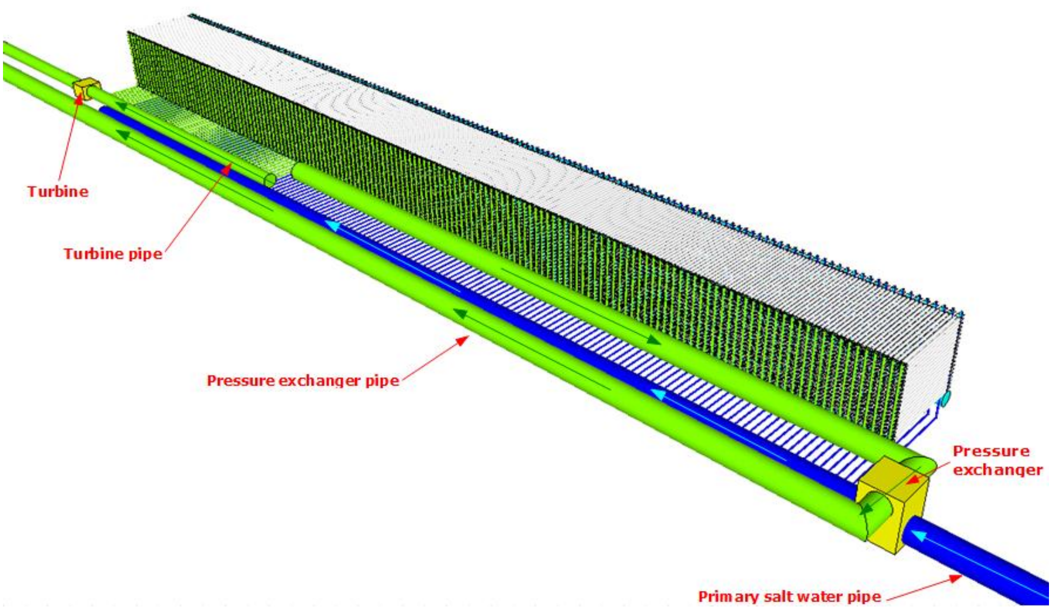

Figure 6.36: The design of the brackish water side of the membrane stack.

The designation of the pipes at the brackish water side is given in figure 6.37:

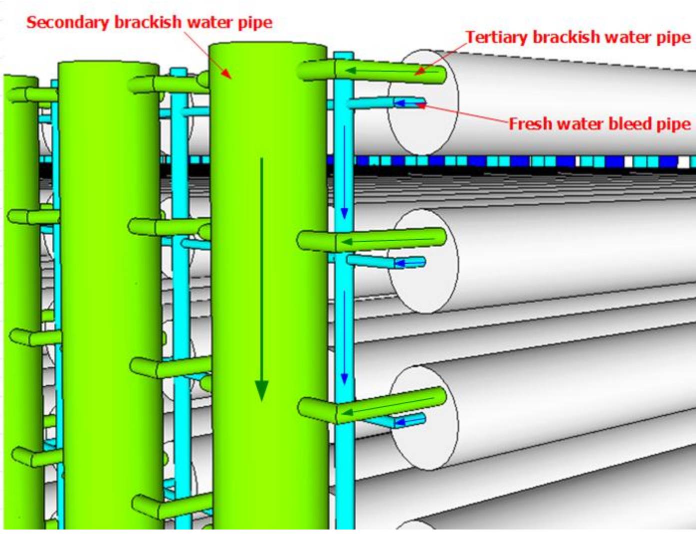

Figure 6.37: Designation of the pipes at the brackish water side of the membrane stack.

6.6.5 Characteristics

6.6.5.1 Q-H curve pump

The Q-H curve is the relation between the volume flow and the potential delivered pressure at a constant speed of the pump. The Q-H curve differs for each pump and is supplied by the manufacturer of the pump. The choice on what pump to use depends on the network characteristic. The network characteristic is the relation between the volume flow through the pipe system (with a certain diameter and trajectory) and the required pressure to elevate the water to the desired level and to overcome the total head loss. Because the volume flow in the case study is constant, the selected pump should have a Q-H curve that intersects with the required flow rate and pressure of the network characteristic. The intersection between the two relations is called the working point of the pump. In the case study it is assumed that the selected pump has a Q-H curve which is illustrated in figure 6.38:

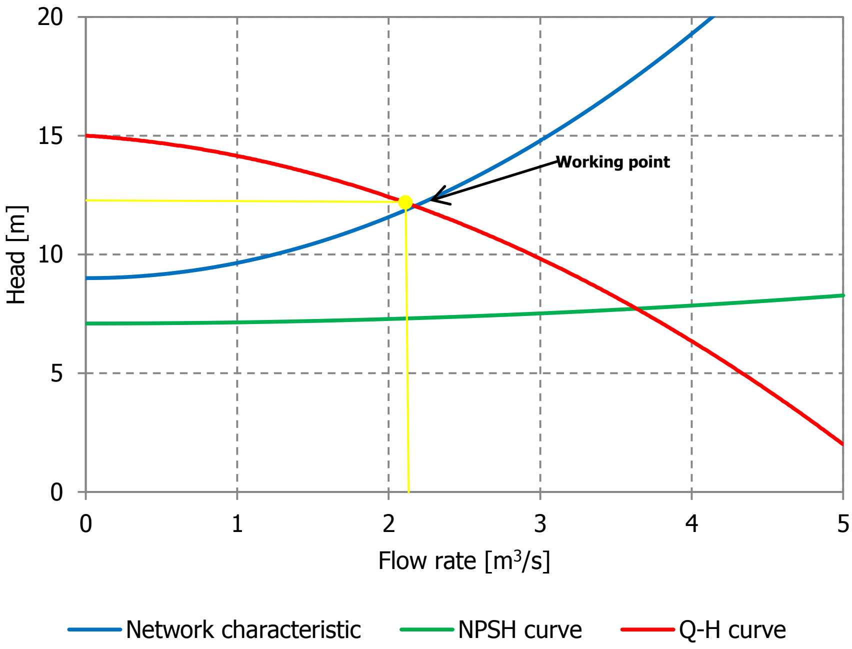

Figure 6.38: Assumed Q-H curve of the fresh water pump.

6.6.5.2 Net positive suction head (NPSH) curve

The net positive suction head curve is the relation between the volume flow and the required margin between the energy level at the suction side of the pump and the vapour pressure of the water to prevent too much cavitation. Cavitation is the formation of vapour bubbles at the suction side of the pump which will be pressurized at the outlet side. The formation of vapour bubbles will occur when the local pressure at the pump impeller is lower than the actual vapour pressure of the fluid at the current temperature. The effect of cavitation is extra wearing of the pump which is unacceptable. To avoid cavitation, the available NPSH should be larger or equal to the required NPSH. The available NSPH is a function of suction head at the pump impeller, the atmospheric pressure and the vapour pressure:

$$NPSH_{available} = h_s + \frac{u^2}{2g} + h_{atm} - h_{vapour} \tag{6.7}$$

In figure 6.38, the assumed available NPSH is given for a negative head at the pump of -2 m (the pump impeller is above the water level of the source), an atmospheric pressure of 10 m water column and the vapour pressure at T=20°C. The selected pump in the case study should have a required NPSH which is smaller than the available NPSH given in figure 6.38. The required NPSH is supplied by the manufacturer.

6.6.5.3 Pump efficiency

The pump efficiency is defined as the ratio of the imposed power to the fluid by the pump to the supplied power to drive the pump. The pump efficiency is a function of the discharge and the head and can be visualized by a curve. This curve has a maximum efficiency for a certain volume flow. The pump in the case study should be selected as such that the maximum efficiency coincides with the working point given in figure 6.38. In the case study, it will be assumed that the pump efficiency is equal to 0.68.

6.6.5.4 Turbine and generator efficiency

The combined turbine and generator efficiency is the ratio of the actual produced osmotic energy by the expected osmotic energy production. In the case study, it will be assumed that the combined turbine and generator efficiency is equal to 0.85.

6.6.6 Dimensions

6.6.6.1 Pipes

The diameter of the different pipes is determined by an optimization. The summation of the capital costs and the energy costs should be minimized. The capital costs of a pipe will be determined by using a cost estimation formula of pipes [27]:

$$C_{pipes} = 500 \cdot D \cdot L \qquad \textbf{(6.8)}$$

The length of the pipes is known because of the assumed position of the pumps, pipes and turbines (see section 6.6.3). The required diameter will be determined by using equation 6.4.

The flow rate through the pipes and the local losses are determined in Appendix E.2. The total head loss can be expressed in energy costs by using equation 6.9:

$$C_{energy} = \frac{\Delta H \cdot Q \cdot \rho \cdot g}{\eta_{pump}} \cdot t_{hrs/yr} \cdot C_{€/kWh} \qquad \textbf{(6.9)}$$

The optimal pipe diameter is found by minimizing the summation of the capital and energy costs. The determination of the optimal pipe diameter in case of the primary fresh water pipe is given in figure 6.39:

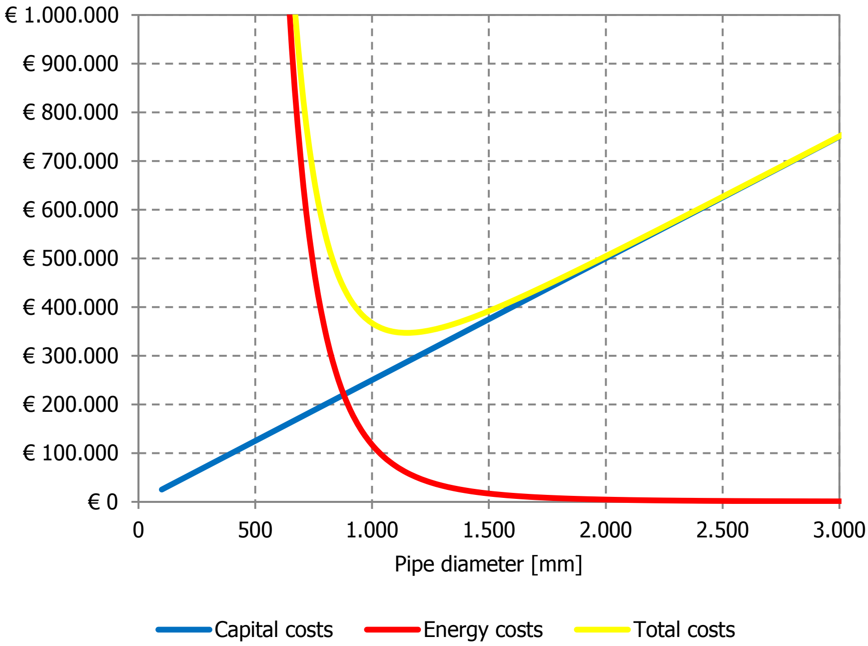

Figure 6.39: The determination of the optimum primary fresh water pipe diameter.

According to figure 6.39, the optimum diameter for the primary fresh water pipe is equal to 1.150 mm. The rest of the pipe diameters are given in table 6.5. The secondary and tertiary pipes are determined by using the ratios between the flow rates through the pipes (see Appendix E.3).

	Primary	**Secondary**	**Tertiary**
Fresh	1.150 mm	100 mm	16 mm
Salt	2.050 mm	170 mm	27 mm
Brackish	1.700 mm (pressure exchanger) 1.300 mm (turbine)	170 mm	27 mm

Table 6.5: The required pipe diameters.

6.6.6.2 Pumps

The required pump diameter is assumed to be equal to the diameter of the adjacent pipe.

6.6.6.3 Pressure exchangers

The required diameter for the pressure exchanger is assumed to be equal to the diameter of the primary salt water pipe.

6.6.6.4 Turbines

The required turbine diameter is assumed to be equal to the diameter of the brackish turbine pipe.

6.6.7 Area

In section 6.4.7, it is determined that the power plant area is affected by the pre-treatment area. The area required for the pumps, pipes and turbines is therefore not considered.

6.6.8 Energy loss

6.6.8.1 Water transportation

The fresh and salt water pumps transport the water from the pump sump to the membrane stacks. This transport requires energy. The amount of the energy consumption depends on the required elevation height and is determined by using equation 6.10:

$$E_{pump} = \frac{\Delta H \cdot Q \cdot \rho \cdot g}{\eta_{pump}} \cdot t_{hrs/yr} \quad \textbf{(6.10)}$$

An energy line of the fresh water transport is given in figure 6.40. This energy line is associated with the furthest membrane stack from the fresh water pump sump (see figure 6.32).

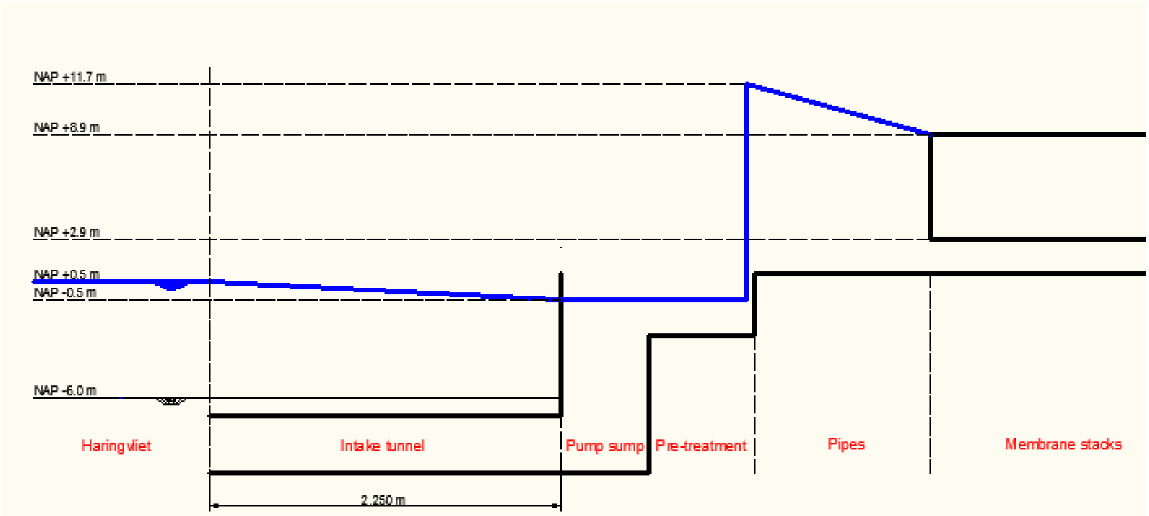

Figure 6.40: Energy line of the fresh water flow during the water transportation stage.

A comparable energy line could be given for the salt water transportation but will not be given because of its resemblance to the fresh water energy line. The required elevation height and the resulting energy losses are determined in Appendix E.3. The total energy loss due to the water transportation is 89 GWh/yr.

6.6.8.2 Turbine and generator efficiency

The energy loss due to the turbine and generator efficiency is equal to 30.6 GWh/yr (see Appendix E.3).

6.6.9 Capital costs

6.6.9.1 Pipes

The capital costs of the pipes are determined in Appendix E.3 and are equal to € 13.000.000,-.

6.6.9.2 Pumps

The capital costs of the pumps are determined by using an empirical formula of the costs determination of turbines. In the case study, it is assumed that the same empirical formula can also be applied for the pumps and pressure exchangers:

$$C_{pumps} = 1.7 \cdot 10^{5} \cdot a_{pumps} \cdot H^{0.18} \cdot D^{2} \quad \textbf{(6.11)}$$

The amount of pumps, the elevation height and the pump diameters are already determined in the previous sections. The total capital costs of the pumps and pressure exchangers are about € 22.000.000,-.

6.6.9.3 Turbines

The capital costs of the turbines are about € 7.000.000,-.

6.6.9.4 Total capital costs

The total capital costs of the pipes, pumps and turbines are about € 42.000.000,-.

6.6.10 200 MW PRO power plant

A 200 MW PRO power plant implies 8 times more membrane stacks than the 25 MW PRO power plant. This results in 8 times more pumps, pressure exchangers and turbines. The length and diameter of the pipes given in section 6.6.6 depends on the power plant configuration. The power plant configuration of the 200 MW PRO power plant is given in figure 6.31. This configuration differs from the configuration of the 25 MW PRO power plant. The energy loss due to the water transportation and the capital costs of the pumps, pipes and turbines are determined in Appendix E.4. The results are given in figure 6.41 – 6.42.

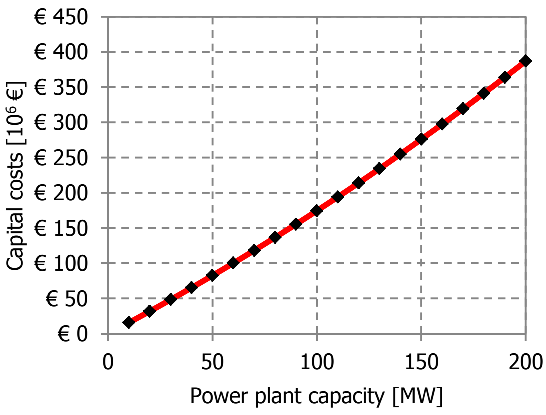

Figure 6.41: Relation between power plant capacity and capital costs of the pumps, pipes and turbines.

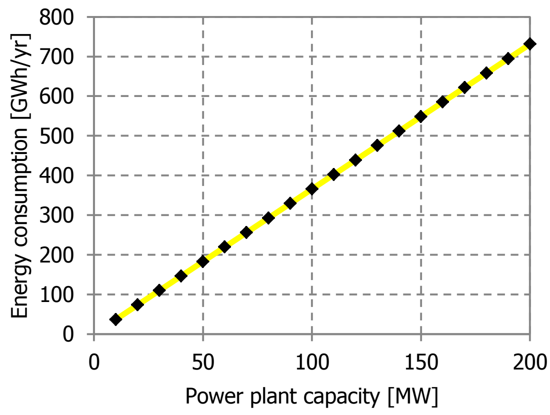

Figure 6.42: Relation between power plant capacity and energy loss due to water transportation.

The capital costs of the pumps, pipes and turbines in case of the 200 MW PRO power plant are about € 385.000.000,-. An eight times higher power plant capacity results in a 9 times higher capital costs of the pumps, pipes and turbines. The energy loss due to the water transportation is about 730 GWh/yr. This is 8 times higher than the energy loss due to the water transportation in the case of the 25 MW PRO power plant. The energy loss due to the turbine and generator efficiency is 184.4 GWh/yr.

6.7 Power plant area

From the case studies conducted in this chapter, it can be concluded that the required area of a PRO power plant is mainly affected by the used pre-treatment. The decision to apply micro-filtration (see section 6.4.2) resulted in large sumps. The configuration of these sumps determined the total required power plant area. The configuration of the sumps in the case of the 25 MW PRO power plant (see figure 6.20) resulted in a required area of about 10 hectares. The area within the sumps appeared to be sufficient for the membrane stacks and piping (see figure 6.32). The sump configuration of the 25 MW PRO power plant was not sufficient for the 200 MW PRO power plant, because the sumps would become too large. The solution was a new sump configuration for the 200 MW PRO power plant (see figure 6.23). With the new sump configuration, the 200 MW PRO power plant fitted in the area given in figure 6.2. The area with the sumps appeared also to be feasible for the membrane stacks and piping.

The fact that the 200 MW PRO power plant required another sump configuration implies that there is no linear relation between power plant capacity and required area. The 25 MW PRO power plant requires about 10 hectares, so the ratio between power plant capacity and area is 2.5 MW/ha. The 200 MW PRO power plant with the other sump configuration requires about 144 hectares, so the ratio decreases to 1.4 MW/ha. An eight times higher capacity results in a 14.4

times larger power plant area and a 1.8 times smaller ratio between the power plant capacity and area. These figures become more dramatically when the net energy production (see section 6.8) of the two power plants is considered. These figures are given in table 6.6:

	Gross capacity	**Efficiency**	**Net capacity**	**Required area**	**Ratio**
25 MW PRO	25 MW	29.4%	7.4 MW	10 ha	0.74 MW/ha
200 MW PRO	200 MW	10.9%	21.8 MW	144 ha	0.15 MW/ha

Table 6.6: The ratio between capacity and area when the net capacity of the power plant is considered.

According to table 6.6, an eight times higher capacity results in an eight times smaller ratio between the capacity and area. These ratios could be enlarged by applying a less space consumable pre-treatment type, e.g. ultra-filtration. The required space for ultra-filtration is of the same order of magnitude as the required area of the membrane stacks. A smaller power plant area reduces the energy consumption of the pumps (shorter distances) and capital costs (shorter pipe lengths). However, the application of ultra-filtration will severely increase the capital costs and energy consumption of the power plant.

The power plant area appears to be an important issue in the design of an osmotic power plant. The total required area, which is affected by the applied pre-treatment, affects the net energy production (energy consumption pumps) and capital costs of the main infrastructure. Costs which are not considered in the case study are the land acquisition and building costs. Land acquisition does not have a large influence on the total capital cost, but for the sake of completeness it will considered in this section. By assuming a land price of 6 €/m^2 [33], the capital costs due to land acquisition become about € 600.000,- for the 25 MW PRO power plant and € 9.000.000,- for the 200 MW power plant. A building for the power plant does have a large influence on the total capital costs. When it is assumed that the complete power plant area should be covered by a building with a unit rate equal to 400 €/m^2 [26], the capital costs due to the building of the 25 and 200 MW PRO power plant will become about € 40.000.000,- and € 575.000.000,- respectively.

6.8 Net energy production

6.8.1 25 MW PRO power plant

The net energy production of the 25 MW PRO power plant is given in table 6.7:

Initial energy production (section 6.2.2)	+ 204 GWh/yr	+100%
Power plant downtime outfall (section 6.3.8.2)	– 1.2 GWh/yr	–0.6%
Energy consumption pre-treatment (section 6.4.8.2)	– 16.5 GWh/yr	–8.1%
Fresh water bleed (section 6.5.8)	– 6.8 GWh/yr	–3.3%
Fresh and salt water transportation (section 6.6.8.1)	– 89 GWh/yr	–43.6%
Turbine efficiency loss (section 6.6.8.2)	– 30.6 GWh/yr	–15%
Net energy production	+ 59.9 GWh/yr	+29.4%

Table 6.7: The net energy production of the 25 MW PRO power plant.

The net energy production of the 25 MW PRO power plant is 59.9 GWh/yr. This is about 29.4% of the initial energy production. The produced energy is sufficient to supply energy to over 17.100 households.

6.8.2 200 MW PRO power plant

The net energy production of the 200 MW PRO power plant is given in table 6.8:

Initial energy production (section 6.2.3)	+ 1.229 GWh/yr	+100%
Power plant downtime outfall (section 6.3.10)	– 7.4 GWh/yr	–0.6%
Energy consumption pre-treatment (section 6.4.10)	– 132 GWh/yr	–10.7%
Fresh water bleed (section 6.5.10)	– 41 GWh/yr	–3.3%
Fresh and salt water transportation (section 6.6.10)	– 730 GWh/yr	–59.4%
Turbine efficiency loss (section 6.6.10)	– 184.4 GWh/yr	–15%
Net energy production	+ 134.2 GWh/yr	+10.9%

Table 6.8: The net energy production of the 200 MW PRO power plant.

The net energy production of the 200 MW PRO power plant is 134.2 GWh/yr. This is about 10.9% of the initial energy production. The produced energy is sufficient to supply energy to over 38.300 households.

6.9 Total capital costs

6.9.1 25 MW PRO power plant

The total capital costs of the 25 MW PRO power plant are given in table 6.9. Costs which are not considered in the previous sections are the capital costs due to electrical installations and the connection to the power grid. These capital costs are assumed to be equal to € 10.000.000,-.

Intake and outfall systems (section 6.3.9)	€ 230.000.000,-
Pre-treatment facility (section 6.4.9)	€ 198.000.000,-
Pump sumps (section 6.4.9)	€ 45.000.000,-
Membrane stacks (section 6.5.9)	€ 52.100.000,-
Pumps, pipes and turbines (section 6.6.9)	€ 42.000.000,-
Land acquisition and power plant building (section 6.7)	€ 40.600.000,-
Electrical installations and power grid connection	€ 10.000.000,-
Total capital costs	€ 617.700.000,-

Table 6.9: The total capital costs of the 25 MW PRO power plant.

The total capital costs given in table 6.9 result in an energy unit rate of 1.15 €/kWh (see chapter 9) when a return-on-investment time of 15 years is assumed.

6.9.2 200 MW PRO power plant

The total capital costs of the 200 MW PRO power plant are given in table 6.10. Costs which are not considered in the previous sections are the capital costs due to electrical installations and the connection to the power grid. These capital costs are assumed to be equal to € 80.000.000,-.

Intake and outfall systems (section 6.3.10)	€ 1.135.000.000,-
Pre-treatment facility (section 6.4.10)	€ 1.584.000.000,-
Pump sumps (section 6.4.10)	€ 270.000.000,-
Membrane stacks (section 6.5.10)	€ 418.000.000,-
Pumps, pipes and turbines (section 6.6.10)	€ 385.000.000,-
Land acquisition and power plant building (section 6.7)	€ 584.000.000,-
Electrical installations and power grid connection	€ 80.000.000,-
Total capital costs	€ 4.456.000.000,-

Table 6.10: The total capital costs of the 200 MW PRO power plant.

The total capital costs given in table 6.10 result in an energy unit rate of 3.71 €/kWh (see chapter 9) when a return-on-investment of 15 years is assumed. The higher energy unit rate for a larger capacity contradicts with the economy of scale (see section 6.10).

6.10 Conclusion

The 25 MW PRO power plant will produce an amount of osmotic energy equal to 59.9 GWh/yr, which is 29.4% of the initial energy production. Together with the capital costs of the power plant, the power plant efficiency will result in an energy unit rate of 1.15 €/kWh. When a 200 MW PRO power plant is considered, the energy unit rate will become 3.71 €/kWh. An eight times higher power plant capacity will result in a 3.2 times higher energy unit rate. This contradicts with the economics of scale, which states that a larger power plant capacity should result in an equal or lower energy unit rate.

The increase of the energy unit rate in case of the 200 MW PRO power plant is due to the fresh water availability (see section 5.1). A conventional 200 MW power plant will have an annual production of 1.753 GWh/yr. In case of the 200 MW PRO power plant, the fresh water availability of 70.2% resulted in an initial energy production equal to 1.229 GWh/yr (see section 6.2.3). This is an energy loss of 524 GWh/yr due to the fresh water availability.

The energy unit rates of both power plants could be redefined when it is assumed that fresh water is unlimitedly available. The results are given in table 6.11:

	25 MW PRO	**200 MW PRO**
Extra energy production	+ 15.2 GWh/yr	+ 524.2 GWh/yr
Net energy production	+ 75.1 GWh/yr	+ 658.4 GWh/yr
Efficiency	34.3%	37.6%
Energy unit rate	0.92 €/kWh	0.76 €/kWh

Table 6.11: Energy unit rates when fresh water is assumed to be unlimitedly available.

Table 6.11 shows that the economics of scale applies when the osmotic power plant capacity increases from 25 to 200 MW and fresh water is assumed to be unlimitedly available. In reality however, the fresh water availability decreases for an increasing power plant capacity which will cause an increase of the energy unit rate. This section has shown that the fresh water availability of the power plant location is of major importance for the feasibility of an osmotic power plant. In chapter 4, the Haringvliet – Grevelingen location was chosen because, among others, the average excess water discharge was large. However, the fresh water availability decreases rapidly for increasing power plant capacities (see figure 5.2) which will have a major impact on the energy unit rates. The Haringvliet – Grevelingen location is therefore probably not the most suitable location for a large osmotic power plant. Further studies to the most suitable location, with a large fresh water availability and some storage capacity as a buffer in times of low fresh water discharges, are required. In the remainder of this thesis, the Haringvliet – Grevelingen location will be maintained.

Chapter 7
1 MW PRO power plant

One of the issues of an osmotic power plant is the pre-treatment of the water flows. A pre-treatment facility involves high capital costs and some types of treatment consume a lot of energy. A potential solution to these problems is to integrate an osmotic power plant into a sewage treatment plant (STP). A STP has the advantage that there already is a pre-treatment facility present, so this will save on capital costs. The potential capacity of such a plant is small, but it might be feasible to supply osmotic energy to a number of households or the STP self. This chapter will determine if a STP is suitable for the integration of an osmotic power plant.

7.1 Location

The 1 MW PRO power plant will be integrated in STP Houtrust near the city of Scheveningen. This location seems to be a suitable location for an osmotic power plant integrated in a STP. The STP is located near a salt water source, the North Sea, and the fresh water is provided though the sewage system. A hard separation is present but a three-way separation is not available. Though, the discharge of brackish water is assumed to be small enough to prevent recirculation. The STP is designed to process a flow rate of 1 m^3/s during dry conditions, and 3.6 m^3/s during wet conditions [34]. The case study will be based on dry conditions. The location of the STP as well as the different flows is given in figure 7.1.

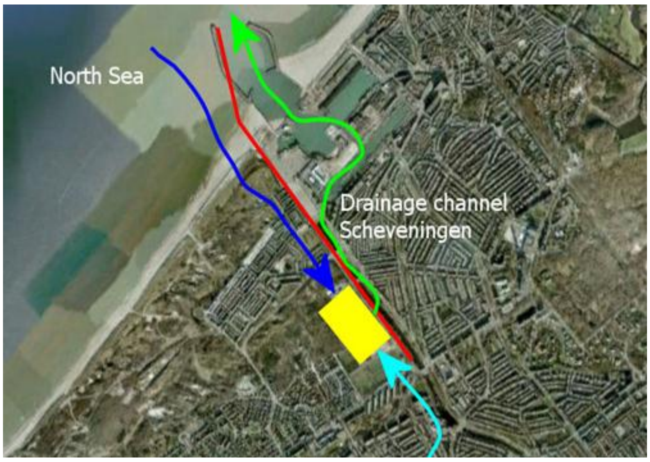

Figure 7.1: Location of the 1 MW PRO power plant integrated in STP Houtrust.

7.2 Initial energy production

7.2.1 Flow rates

In analogy to the previous chapter, the required flow rates through the power plant can be determined. The practical osmotic energy given in section 5.4.2 is used to obtain the required flow rates through the power plant (see figure 7.2):

- Fresh water flow rate: 0.95 m^3/s
- Salt water flow rate: 1.90 m^3/s
- Brackish water discharge: 2.76 m^3/s

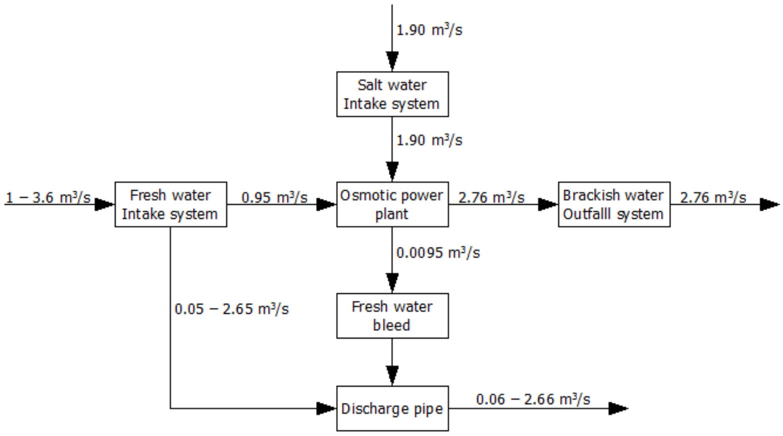

Figure 7.2: The average required flow rates through the 1 MW PRO power plant.

7.2.2 Initial energy production

The initial energy production can be determined by using equation 6.1. The initial energy production of the 1 MW PRO power plant is 8.9 GWh/yr.

7.3 Intake and outfall systems

The major advantage of integrating an osmotic power plant in a STP is that the infrastructure is already present. The STP Houtrust is dimensioned to receive a fresh water flow rate of 1 m^3/s during dry conditions and 3.6 m^3/s during wet conditions. The infrastructure for the supply of the fresh water flow rate is therefore already present. The water is treated and discharged through a pipeline to a location on the North Sea, 2.5 km offshore. This diameter of this pipeline is estimated at 2.000 mm (see figure 7.3):

Figure 7.3: The discharge pipe of STP Houtrust [34].

The idea behind the integration of an osmotic power plant in a STP is that the discharge pipe will be used for the salt water supply. The infrastructure for the salt water supply is therefore already present.

Infrastructures which are not present are the outfall system of the brackish effluent (see section 7.6) and a discharge pipe in case of wet conditions. The discharge pipe should be constructed to discharge the difference in STP capacity during dry conditions (=3.6 m^3/s) and power plant capacity (=0.95 m^3/s). This pipe will run from the power plant to the Scheveningen discharge channel and will measure 120 m. The diameter is assumed to be equal to 2.000 mm.

The capital costs of the discharge pipe are determined by using equation 6.8 and are equal to € 120.000,-. However, when some modification costs are included the capital costs of the intake and outfall systems are estimated at € 500.000,-.

7.4 Pre-treatment

The pre-treatment facility of STP Houtrust consists of certain types which are given in figure 7.4 [34]:

Figure 7.4: The treatment types of STP Houtrust.

1. The polluted sewage water enters the STP at the influent building.
2. Coarse debris is removed by raked bar screens.
3. In the primary settling tanks, settled sludge and floating oil/grease are removed.
4. In the biological tanks a biological decomposition of organic material occurs by activated sludge.
5. The activated sludge is removed in clarifiers.
6. The treated water, the effluent, is discharged to the North Sea at the effluent building.

The question now is whether these treatment types are sufficient for an osmotic power plant. The semi-permeable membranes are sensitive to fouling (see section 6.4.1). In order to prevent fouling, suspended and dissolved particles should be removed from the inflowing solutions. However, with the current treatment types of STP Houtrust only the coarse particles will be removed. The water quality of the effluent is insufficient to produce osmotic power. Therefore, more treatment types are required which will make the osmotic power plant cost-ineffective because of the high capital costs (see table 6.3). A solution will be to modify the treatment facility and add micro-filtration drums to the process. However, adding micro-filtration drums to the STP will turn this case study into an almost exact copy of the two case studies conducted in the previous chapter.

However, there is a solution to make the effluent of a STP suitable for producing osmotic power without adding treatment types. In the past years, the increasingly strict discharge requirements resulted in a development of STP's. One of the developments is the application of a membrane bioreactor for the treatment of sewage water. A membrane bioreactor consist of micro-filtration drums, ultra-filtration and conventional treatment types. Ultra-filtration is suitable for the filtration of very small particles (order of magnification 0.01 – 0.1 µm), so the effluent of a membrane bioreactor is very suitable to use in osmotic power production.

Because a conventional STP does not have the presumed advantage of the presence of a pre-treatment facility, in the remainder of the case study it will be assumed that STP Houtrust is equipped with a membrane bioreactor. The capital costs and energy consumption of the membrane bioreactor will be attributed to the sewage treatment process. The addition of an osmotic power plant to the STP will therefore result in zero capital costs and energy consumption for the pre-treatment facility.

7.5 Membrane stacks

The membranes of the 1 MW PRO power plant have the same characteristics as the membranes used in section 6.5. The 1 MW PRO power plant integrated in a STP requires 1 membrane stack. The required dimensions of the membrane stack are:

- Membrane area: 417.500 m^2
- Module amount: 17.150
- Pressure vessel amount: 2.450
- Stack height: 6 m
- Stack length: 37 m

The total capital costs of the membrane stack are € 2.100.000,- and the energy loss due to the fresh water bleed is 0.30 GWh/yr.

7.6 Pumps, pipes and turbines

The position of the pumps, pipes, turbine and membrane stack is given in figure 7.5:

Figure 7.5: The position of the pumps, pipes, turbines and membrane stack of the 1 MW PRO power plant.

The effluent of the STP ends in an effluent building (see figure 7.4) where it is pumped to a location on the North Sea, 2.5 km offshore. The fact that the effluent is pumped out of the STP implies that there is already a pump present. This pump will elevate the salt water flow to the required level.

The required diameters for the different pipes are given in table 7.1:

	Primary	Secondary	Tertiary
Fresh	850 mm	110 mm	17 mm
Salt	1.400 mm	180 mm	29 mm
Brackish	1.200 mm (pressure exchanger) 850 mm (turbine)	180 mm	29 mm

Table 7.1: The required pipe diameters.

The diameters of the fresh water pump, turbine and pressure exchanger are 850 mm, 850 mm and 1.400 mm respectively. The length of the pipes can be determined from figure 7.5. The capital costs are determined with the same equations as used in section 6.6.9. These equations result in a level of the capital costs equal to € 1.230.000,-. When some modification costs are included, the level of the capital costs increases to € 1.500.000,-.

The energy consumption of the pumps depends on the elevation heights. The required elevation of the fresh water side is equal to the summation of:

- The head loss due to the water transport from pump to membrane stack (≈1.5 m)
- The height of the membrane stack (=6 m)

The total elevation height of the fresh water flow rate is equal to 7.5 m. This results in an energy consumption of 0.9 GWh/yr. The required elevation of the salt water is a summation of:

- The difference in water level of the North Sea and surface level at the power plant (≈3.5 m)
- The head loss due to the water transport from intake location to pump (≈1.5 m)
- The head loss due to the water transport from pump to membrane stack (≈1 m)
- The height of the membrane stack (=6 m)

The total elevation height is equal to 12 m. This results in an energy consumption of 2.8 GWh/yr. The total energy consumption of the pumps of 3.7 GWh/yr.

The energy loss due to the turbine and generator efficiency is equal to 1.3 GWh/yr.

7.7 Power plant area

The osmotic power plant will be constructed at the site of the STP (see figure 7.5). Therefore, no additional area is required. This will result in no capital costs due to land acquisition and power plant building.

7.8 Net energy production

The net energy production of the 1 MW PRO power plant integrated in STP Houtrust is given in table 7.2:

Initial energy production (section 7.2.2)	+ 8.9 GWh/yr	+ 100%
Fresh water bleed (section 7.5)	− 0.3 GWh/yr	− 3.3%
Fresh and salt water transportation (section 7.6)	− 3.7 GWh/yr	− 41.7%
Turbine efficiency loss (section 7.6)	− 1.3 GWh/yr	− 15%
Net energy production	+ 3.6 GWh/yr	+ 40%

Table 7.2: The net energy production of the 1 MW PRO power plant.

The net energy production of the 1 MW PRO power plant is equal to 3.6 GWh/yr. This is 40% of the initial energy production. The produced energy is sufficient to supply energy to over 1.000 households, or it can be used for the sewage treatment process itself.

7.9 Total capital costs

The total capital and modification costs of the 1 MW PRO power plant are given in table 7.3. Costs which are not considered in the previous sections are the capital costs due to electrical installations and the connection to the power grid. These capital costs are assumed to be equal to € 400.000,-.

Intake and outfall systems (section 7.3)	€ 500.000,-
Membrane stacks (section 7.5)	€ 2.100.000,-
Pumps, pipes and turbines (section 7.6)	€ 1.500.000,-
Electrical installations and power grid connection	€ 400.000,-
Total capital costs	€ 4.500.000,-

Table 7.3: The total capital costs of the 1 MW PRO power plant.

The total capital costs given in table 7.3 result in an energy unit rate of 0.19 €/kWh (see chapter 9) when a return-on-investment time of 15 years is assumed. This energy unit rate will only be achievable when STP Houtrust is equipped with a membrane bioreactor.

7.10 Conclusion

The 1 MW PRO power plant is a special type, so no comparison with other power plants could be made. A conclusion on an osmotic power plant integrated in a STP will be made in section 8.10.

Chapter 8
RED power plant

The previous two chapters determined the capital costs and net energy production of a 1, 25 and 200 MW PRO power plant. This chapter will briefly determine the capital costs and net energy production of the power plant when RED is applied instead of PRO.

8.1 Location

The location considered in case of the 25 MW and 200 MW RED power plant is the Haringvliet – Lake Grevelingen location as used in chapter 6. The considered location for the 1 MW RED power plant integrated in a STP is STP Houtrust as used in chapter 7.

8.2 Initial energy production

The average practical osmotic energy in the case of a RED power plant is lower than in the case of a PRO power plant. The reason for this is that the energy production of a RED power plant differs from a PRO power plant (see section 2.2 and Appendix A.3).

The application of RED instead of PRO reduces the average practical osmotic energy to 0.78 MJ/m^3 (see section 5.4.1.2) in the case of the Haringvliet – Lake Grevelingen location. This is a reduction of 35%. For STP Houtrust, the average practical osmotic energy is 0.55 MJ/m^3 (see section 5.4.2.2) which is a reduction of 47%.

The reduction of the average practical osmotic energy implies that the required fresh water through the power plant should increase in order to achieve the desired capacity. The required salt water flow through the power plant decreases because the ratio between fresh and salt water is 1:1 (see section 2.5.2). The required flow rates for the different RED power plants are given in table 8.1:

	25 MW RED	200 MW RED	1 MW RED (STP)
Fresh water flow rate	32 m^3/s	257 m^3/s	1.67 m^3/s
Salt water flow rate	32 m^3/s	257 m^3/s	1.67 m^3/s
Brackish water discharge	64 m^3/s	514 m^3/s	3.33 m^3/s

Table 8.1: The required flow rates through the different RED power plants.

According to table 8.1, the required fresh water flow rate of the 1 MW RED power plant is 1.67 m^3/s. However, in chapter 7 it has been described that STP Houtrust is designed for a dry condition capacity of 1 m^3/s. Therefore, in the remainder of this chapter it is assumed that the fresh water flow rate through the 1 MW RED power plant is 1 m^3/s. This will reduce the capacity of the power plant to 0.55 MW. The fresh water availability is also an important issue in the case of the 25 and 200 MW RED power plant (see figure 5.2). The initial energy production for the different RED power plants is given in table 8.2.

	25 MW RED	200 MW RED	0.55 MW RED (STP)
Fresh water availability	92.8 %	70.2%	100%
Initial energy production	204 GWh/yr	1.229 GWh/yr	4.8 GWh/yr

Table 8.2: The initial energy production of the different RED power plants.

8.3 Intake and outfall systems

The advantage of applying RED instead of PRO is that the ratio fresh and salt water is 1:1. This will result in smaller dimensions of the salt water intake tunnel and brackish water outfall tunnel. This will reduce the capital costs of the intake and outfall systems. However, the larger fresh water flow rate through the intake tunnel implies that the cross section also should increase. The length and trajectory of the intake and outfall systems are the same as was used in section 6.3. The relation between power plant capacity and capital costs of the intake and outfall systems is given in figure 8.1:

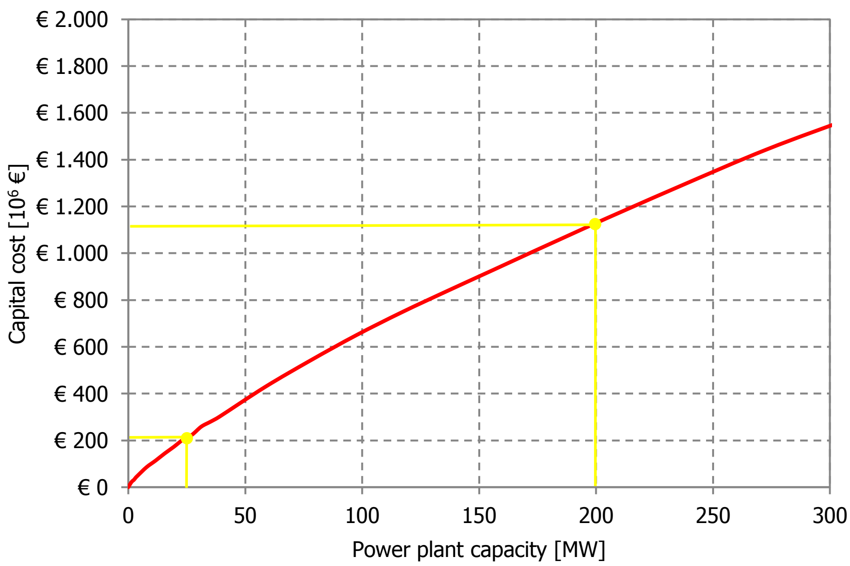

Figure 8.1: Relation between power plant capacity and capital costs of the intake and outfall systems in case of a RED power plant.

The capital costs in the case of a 25 MW RED power plant are about € 210.000.000,-. This is a reduction of about 8.7% compared to the 25 MW PRO power plant. In the case of a 200 MW RED power plant, the capital costs are about € 1.130.000.000,-. These costs are about the same compared to the 200 MW PRO power plant.

The capital costs of the 0.55 MW RED power plant integrated in STP Houtrust are not considered because most of the infrastructure is already present. Only a discharge pipe is required to discharge the difference in STP capacity during dry conditions (=3.6 m^3/s) and power plant capacity (=1.0 m^3/s). The capital costs of this discharge pipe are, together with some modification costs, estimated at € 500.000,-.

The energy loss due to the power plant downtime for the 25 and 200 MW RED power plant is equal to the energy loss due to the power plant downtime for the 25 and 200 MW PRO power plant, respectively 1.2 and 7.4 GWh/yr.

8.4 Pre-treatment

The ion-selective membranes are, as semi-permeable membranes, sensitive for fouling. During RED, an electric current will be obtained by the permeation of ions which are much smaller than water molecules in the case of PRO. This implies that the pore size of the ion-selective membranes is much smaller than semi-permeable membranes and thus a more extensive pre-treatment is required. On the other hand, the permeation of only ions implies that the contaminated water flows along the membranes. This indicates that the pre-treatment could be less extensive. In analogy to PRO, an optimum solution for the pre-treatment should be found.

However, a pre-treatment facility involves high capital costs which will make the osmotic power plant less cost-effective. Therefore, in this case study use will be made of micro-filtration as was also applied in chapter 6. The capital costs and energy consumption of the 25 MW and 200 MW RED power plants are given in table 8.3:

	25 MW RED	**200 MW RED**
Capital costs pre-treatment facility	€ 200.000.000,-	€ 1.625.000.000,-
Pump sumps	€ 36.000.000,-	€ 300.000.000,-
Energy consumption micro-filtration	16.7 GWh/yr	134.3 GWh/yr

Table 8.3: Capital costs and energy consumption of the pre-treatment in case of a 25 and 200 MW RED power plant.

For the 0.55 MW RED plant integrated in a STP, it is assumed that a membrane bioreactor is present (see section 7.4). This will result in zero capital costs and energy consumption.

Just as with PRO, the pre-treatment facility will affect the total power plant area. However, the pre-treatment facility for a RED power plant will be smaller compared to the pre-treatment facility for a PRO power plant. Because the salt water flow rate is half the size in the case of the RED power plant, the salt water pump sump will become smaller. This has a positive effect on the required power plant area and the energy loss due to water transportation. The power plant configuration in the case of a 25 MW RED power plant is given in figure 8.2:

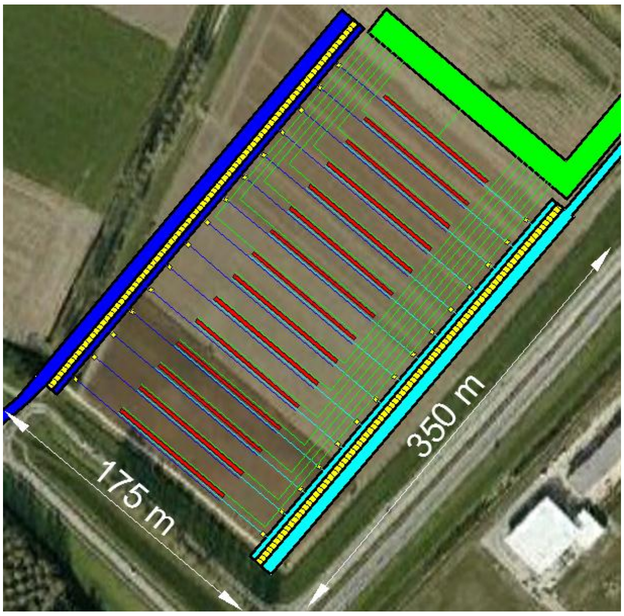

Figure 8.2: The 25 MW RED power plant configuration.

The power plant configuration of the 25 MW RED power plant requires an area of about 6 hectares. This is a reduction of 40% compared to the 25 MW PRO power plant. The 200 MW RED power plant does not fit within the area given in figure 6.2 when the configuration given in figure 8.2 is used. Therefore, a new configuration will be made for the 200 MW RED power plant. This configuration is given in figure 8.3:

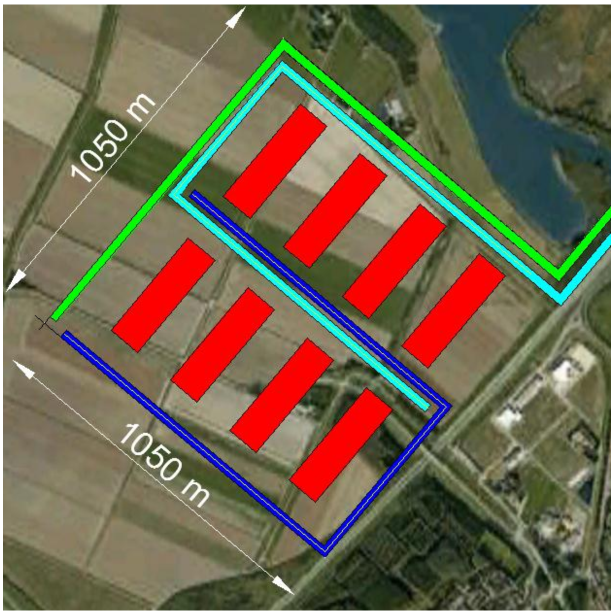

Figure 8.3: The 200 MW RED power plant configuration.

The red areas in figure 8.3 represent each 15 membrane stacks as given in figure 8.2. The configuration of the 200 MW RED power plant requires an area of about 110 hectares. This is a reduction of about 24% compared to the 200 MW PRO power plant.

8.5 Membrane stacks

Due to space-saving considerations, in the case of RED the membranes are also placed into stacks. In this case study, use will be made of the membrane stacks of REDstack (see figure 8.4). Each REDstack represents a capacity of about 1.5 kW.

Figure 8.4: REDstack.

Multiple membrane stacks are placed in a 200 kW unit which has the size of a 40 ft. container (see figure 8.5).

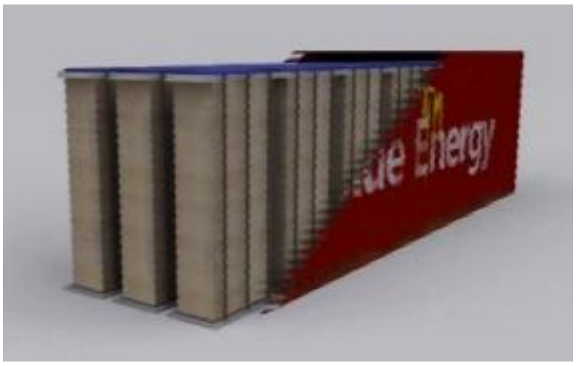

Figure 8.5: Multiple REDstacks in a 40 ft. container.

The capital costs of the membrane stacks depend on the total required membrane area. The required membrane area depends on the membrane characteristics, in which the power density is the most important characteristic. The power density of the ion-selective membranes is smaller than in the case of the semi-permeable membranes in PRO. The current power density is about 1 W/m^2, but REDstack expects that in the future a power density of 2 W/m^2 is possible. The unit rate for the ion-selective membranes is already described in section 6.5.5.4. The current membrane price is about 5 €/m^2, but experts have indicated that within a few years it will be possible to produce membranes at a cost price of 2 €/m^2. In this case study, use will be made of a power density equal to 1 W/m^2 and an unit rate equal to 5 €/m^2. In chapter 10, a conclusion will be made on the feasibility of an osmotic power plant when the power density and unit rate changes. The capital costs of the different RED power plant are given in table 8.4:

	25 MW RED	**200 MW RED**	**0.55 MW RED**
200 kW units	125	1.000	3
Membrane area	25.000.000 m^2	200.000.000 m^2	550.000 m^2
Capital costs membrane stacks	€ 125.000.000,-	€ 1.000.000.000,-	€ 2.750.000,-

Table 8.4: The capital costs of the membrane stacks for the different RED power plants.

Due to the lower power density, the capital costs for the membrane stacks in the case of RED are much higher than in the case of PRO. An advantage of RED in comparison to PRO is that no energy loss will occur due to fresh water bleed. Another advantage is the required stack area per MW. The required stack area per MW is in the case of RED equal to 150 m^2/MW (5 times the area of a 40 ft. container). This is a reduction of 40% compared to PRO, which requires a stack area of 258 m^2/MW (see section 6.5.7). When the required stack volume per MW is determined the reduction becomes even more. The required stack volume per MW in the case of PRO is equal to 1.546 m^3. For RED, the required stack volume per MW is equal to 380 m^3 which is a reduction of 75%. The reductions in required stack area and volume could have a significant influence on the feasibility of the power plant because less area implies, apart from land acquisition, a smaller energy loss due to water transportation.

8.6 Pumps, pipes and converters

There are a number of differences between PRO and RED in the water transportation. The most important is that, because of the smaller required space and volume, the power plant configuration could be more compact. This will reduce the energy consumed for water transportation (in vertical and horizontal direction) and capital costs (length of the pipes and land acquisition). The power plant configuration in the case of a RED power plant was already shown in figure 8.2 and 8.3.

Another difference is the way how the osmotic energy is transferred into electricity. In the case of a PRO power plant, turbines transfer the osmotic pressure into electricity. In the case of RED, converters convert the electrochemical potential difference over the membranes into electricity. This implies that a RED power plant requires converters instead of turbines. Pressure exchangers are not required in the case of RED because the membrane stacks are not pressurized.

The power plant configuration in figure 8.2 and 8.3 results in the capital costs and energy consumption. For the 1 MW RED power plant, the same configuration as given in figure 7.5 will be used. The results are given in table 8.5:

	25 MW RED	200 MW RED	0.6 MW RED
Pipe diameter	1.300 mm	1.300 mm	850 mm
Capital costs	€ 20.000.000,-	€ 155.000.000,-	€ 1.500.000,-
Energy consumption	52 GWh/yr	416 GWh/yr	1.6 GWh/yr
Energy loss converter efficiency	30.6 GWh/yr	184.4 GWh/yr	0.8 GWh/yr

Table 8.5: The capital costs of the pumps, pipes and converters for the different RED power plants.

The capital costs given in table 8.5 include the costs of the pipes, pumps and converters. The compacter power plant configuration in the case of a RED power plant results in a reduction of almost 50% compared to a 25 MW PRO power plant and a reduction of almost 40% compared to a 200 MW PRO power plant. The same applies for the energy consumption of the pumps. The pumps of a 25 MW RED power plant consume 55% less energy than the pumps of a 25 MW PRO power plant. In the case of a 200 MW RED power plant, the reduction in energy consumption of the pumps is 56%.

8.7 Power plant area

In analogy to section 6.7, the required area and the ratio between power plant capacity and required area are determined. The results are given in table 8.6. The efficiencies of the power plant are determined in section 8.8.

	Efficiency	Net capacity	Required area	Ratio
25 MW RED	50.7%	12.7 MW	6 ha	2.1 MW/ha
200 MW RED	39.6%	79.2 MW	110 ha	0.72 MW/ha
0.55 MW RED	50%	0.3 MW	N.A.	N.A.

Table 8.6: The ratio between net capacity and power plant area of the different RED power plants.

Applying RED instead of PRO has a positive effect on the ratio between net capacity and power plant area. In case of the 25 MW PRO power plant (0.74 MW/ha, see table 6.6), 2.8 times more area is required in order to obtain the net capacity of a 25 MW RED power plant. For a 200 MW PRO power plant (0.15 MW/ha, see table 6.6), even 4.8 times more area is required. The capital costs due to land acquisition and a power plant building are given in table 8.7:

	Land acquisition	Power plant building
25 MW RED	€ 360.000,-	€ 24.000.000,-
200 MW RED	€ 6.600.000,-	€ 440.000.000,-
0.55 MW RED	N.A.	N.A.

Table 8.7: The capital costs of land acquisition and power plant building for the different RED power plants.

8.8 Net energy production

8.8.1 25 MW RED power plant

The net energy production of the 25 MW RED power plant is given in table 8.8:

Initial energy production (section 8.2)	+ 204 GWh/yr	+ 100%
Power plant downtime outfall (section 8.3)	− 1.2 GWh/yr	− 0.6%
Energy consumption pre-treatment (section 8.4)	− 16.7 GWh/yr	− 8.2%
Fresh and salt water transportation (section 8.6)	− 52.0 GWh/yr	− 25.5%
Converter efficiency loss (section 8.6)	− 30.6 GWh/yr	− 15%
Net energy production	+ 103.5 GWh/yr	+ 50.7%

Table 8.8: The net energy production of the 25 MW RED power plant.

The net energy production of the 25 MW RED power plant is 103.5 GWh/yr. This is about 50.7% of the initial energy production. The produced energy is sufficient to supply energy to over 29.500 households. This is about 1.7 times more than in the case of the 25 MW PRO power plant.

8.8.2 200 MW RED power plant

The net energy production of the 200 MW RED power plant is given in table 8.9:

Initial energy production (section 8.2)	+ 1.229 GWh/yr	+ 100%
Power plant downtime outfall (section 8.3)	− 7.4 GWh/yr	− 0.6%
Energy consumption pre-treatment (section 8.4)	− 134.3 GWh/yr	− 10.9%
Fresh and salt water transportation (section 8.6)	− 416 GWh/yr	− 33.9%
Converter efficiency loss (section 8.6)	− 184.4 GWh/yr	− 15%
Net energy production	+ 486.9 GWh/yr	+ 39.7%

Table 8.9: The net energy production of the 200 MW RED power plant.

The net energy production of the 200 MW RED power plant is 486.9 GWh/yr. This is about 39.6% of the initial energy production. The produced energy is sufficient to supply energy to over 139.000 households. This is about 3.6 times more than in the case of the 200 MW PRO power plant.

8.8.3 0.55 MW RED power plant

The net energy production of the 0.55 MW RED power plant is given in table 8.10:

Initial energy production (section 8.2)	+ 4.8 GWh/yr	+ 100%
Fresh and salt water transportation (section 8.6)	− 1.6 GWh/yr	− 33.3%
Converter efficiency loss (section 8.6)	− 0.7 GWh/yr	− 15%
Net energy production	+ 2.5 GWh/yr	+ 51.7%

Table 8.10: The net energy production of the 0.55 MW RED power plant.

The net energy production of the 0.55 MW RED power plant is 2.5 GWh/yr. This is 51.7% of the initial energy production. The produced energy is sufficient to supply energy to over 700 households. This is about 1.5 times less than in the case of the 1 MW PRO power plant.

8.9 Total capital costs

8.9.1 25 MW RED power plant

The total capital costs of the 25 MW RED power plant are given in table 8.11. Costs which are not considered in the previous sections are the capital costs due to electrical installations and the connection to the power grid. These capital costs are assumed to be equal to € 10.000.000,-.

Intake and outfall systems (section 8.3)	€ 210.000.000,-
Pre-treatment facility (section 8.4)	€ 200.000.000,-
Pump sumps (section 8.4)	€ 36.000.000,-
Membrane stacks (section 8.5)	€ 125.000.000,-
Pumps, pipes and converters (section 8.6)	€ 20.000.000,-
Land acquisition and power plant building (section 8.7)	€ 24.360.000,-
Electrical installations and power grid connection	€ 10.000.000,-
Total capital costs	€ 625.360.000,-

Table 8.11: Total capital costs of the 25 MW RED power plant.

The total capital costs of the 25 MW RED power plant are € 625.360.000,-. These costs are slightly higher than the total capital costs in the case of a 25 MW PRO power plant. The total capital costs given in table 8.11 result in an energy unit rate of 0.75 €/kWh (see chapter 9).

8.9.2 200 MW RED power plant

The total capital costs of the 200 MW RED power plant are given in table 8.12. Costs which are not considered in the previous sections are the capital costs due to electrical installations and the connection to the power grid. These capital costs are assumed to be equal to € 80.000.000,-.

Intake and outfall systems (section 8.3)	€ 1.130.000.000,-
Pre-treatment facility (section 8.4)	€ 1.625.000.000,-
Pump sumps (section 8.4)	€ 300.000.000,-
Membrane stacks (section 8.5)	€ 1.000.000.000,-
Pumps, pipes and converters (section 8.6)	€ 155.000.000,-
Land acquisition and power plant building (section 8.7)	€ 446.600.000,-
Electrical installations and power grid connection	€ 80.000.000,-
Total capital costs	€ 4.736.600.000,-

Table 8.12: Total capital costs of the 200 MW RED power plant.

The total capital costs of the 200 MW RED power plant are € 4.736.600.000,-. These costs are slightly higher than the total capital costs in the case of a 200 MW PRO power plant. The total capital costs given in table 8.12 result in an energy unit rate of 1.21 €/kWh (see chapter 9).

8.9.3 0.55 MW RED power plant

The total capital costs of the 0.55 MW RED power plant are given in table 8.13. Costs which are not considered in the previous sections are the capital costs due to electrical installations and the connection to the power grid. These capital costs are assumed to be equal to € 200.000,-.

Intake and outfall systems (section 8.3)	€ 500.000,-
Membrane stacks (section 8.5)	€ 2.750.000,-
Pumps, pipes and converters (section 8.6)	€ 1.500.000,-
Electrical installations and power grid connection	€ 200.000,-
Total capital costs	€ 5.200.000,-

Table 8.13: Total capital costs of the 0.55 MW RED power plant.

The total capital costs of the 0.55 MW RED power plant are € 4.950.000,-. These costs are slightly higher than the total capital costs in the case of a 1 MW PRO power plant. The total capital costs given in table 8.13 result in an energy unit rate of 0.31 €/kWh (see chapter 9).

8.10 Conclusion

8.10.1 Economics of scale

In analogy to section 6.10, the energy unit rates of both power plants could be redefined when it is assumed that fresh water is unlimitedly available. The results are given in table 8.14:

	25 MW RED	**200 MW RED**
Extra energy production	+ 15.2 GWh/yr	+ 524.2 GWh/yr
Net energy production	+ 118.7 GWh/yr	+ 1011.7 GWh/yr
Efficiency	58.2%	82.3%
Energy unit rate	0.65 €/kWh	0.59 €/kWh

Table 8.14: Energy unit rates when fresh water is assumed to be unlimitedly available.

Table 8.14 shows that the economics of scale applies when the osmotic power plant capacity increases from 25 to 200 MW and fresh water is assumed to be unlimitedly available. In reality however, the fresh water availability decreases for an increasing power plant capacity which will cause an increase of the energy unit rate.

8.10.2 PRO or RED

After completion of this chapter can be concluded that a RED power plant is more feasible than a PRO power plant, because a RED power plant will result in lower energy unit rates. The total capital costs of a RED power plant is comparable to that of a PRO power plant, so the difference in energy unit rate is only due to the large power plant efficiency in the case of a RED power plant. A RED power plant requires less energy for water transportation than a PRO power plant. The reason for the lower energy consumption is that the stack method of a RED power plant is more compact than a PRO power plant. A PRO power plant requires a stack volume of 1.546 m^3 for each MW (see section 6.5.7), a RED power plant only 380 m^3 (see section 8.5). Another advantage of RED compared to PRO is that the pre-treatment area, which has the largest impact on the total power plant area (see section 6.4.7), could become smaller. The smaller power plant area and compacter stack method will result in a lower energy loss due to the water transportation and thus in a higher net energy production of the power plant. The larger power plant efficiency, in turn, will have a positive effect on the energy unit rate.

8.10.3 Osmotic power plant integrated in a STP

The conclusion given in section 8.10.2 does not apply in the special case when an osmotic power plant is integrated in a STP. A PRO power plant integrated in a STP appears to be more feasible than a RED power plant. The capital costs of the intake and outfall systems and pre-treatment facility have, in the case of an ordinary osmotic power plant, the largest impact on the energy unit rate (see chapter 9). When the osmotic power plant is integrated in a STP, this impact is almost negligible. In that case, the membrane stacks have the largest impact on the energy unit rate. When the impact of the intake and outfall systems and pre-treatment almost could be neglected, a PRO power plant integrated in a STP is more feasible than a RED power plant because:

- PRO membranes have a larger power density than RED membranes.
- The practical osmotic energy in case of a RED power plant is lower than in the case of a PRO power plant (see section 5.4).

Part IV

Financial feasibility study

In part IV of the thesis, the financial feasibility of the commercial exploitation of osmotic power will be analysed. The net energy production and capital costs of the different power plants are the input parameters of the financial feasibility study. The net energy production results in revenues, the capital costs results in the required investments over the lifespan of the power plant. The revenues and investments together result in a required energy unit rate. This energy unit rate should be marketable. In the financial feasibility study, it is assumed that a marketable energy unit rate is the order of 8 cents/kWh. This energy unit rate is expected by REDstack in the (near) future (see section 2.6).

In chapter 9, the energy unit rate of the different power plants will be determined. In chapter 10, the energy unit rate will be determined when the expected developments are determined. The scope of part IV of the thesis is illustrated in red in the relation diagram of section 3.1:

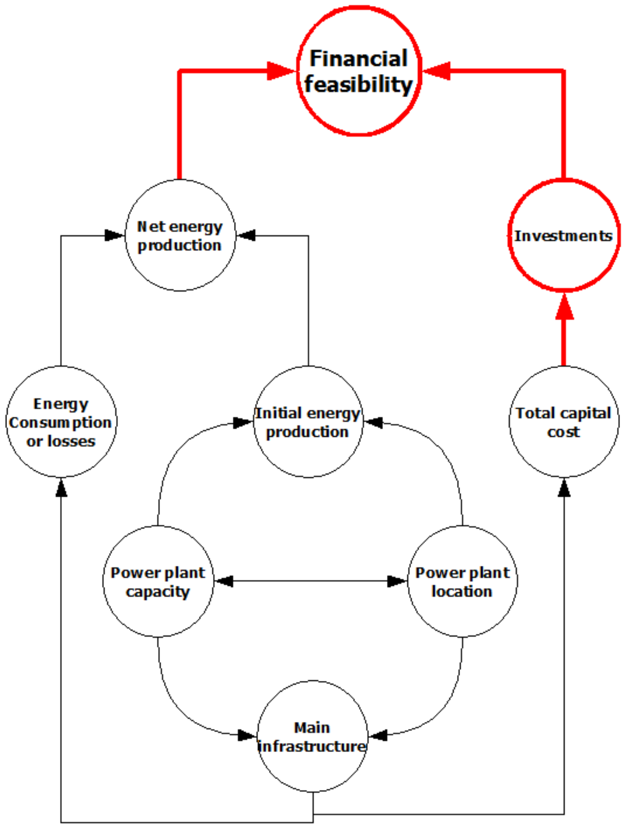

Figure 3.1: Relation diagram of the different components in the financial feasibility study.

Chapter 9
Energy unit rate

The criterion of the feasibility of the commercial exploitation of osmotic power is the energy unit rate. REDstack believes that it will be possible to produce osmotic power at an energy unit rate of about 8 cents/kWh in the near future (see section 2.6). This chapter will determine the energy unit rate of the different power plants, so it can be analysed whether the energy unit rate of 8 cents/kWh is reasonable.

9.1 Investment costs

The capital costs of the different power plants, which are determined in the case studies, result in the investment costs. The investment costs are affected by:

- Capital costs of the power plant (determined in Part III).
- Operational and maintenance costs (see section 9.3).
- Lifespan of the power plant, return-on-investment period and depreciation time of the main infrastructure (see section 9.4.1).
- Interest rate and index ratios (see section 9.4.1).

9.2 Revenues

The revenues from the power plant originate from the osmotic power production only. The osmotic power plants are not subsidised. It is assumed that the net energy production of the different power plants, which is determined in the case studies, is constant throughout the lifespan of the power plant.

9.3 Operation and maintenance costs

During the exploitation of the power plant expenditures will be made for operation and maintenance. These annual costs are assumed to be equal to 1% of the total capital costs of the power plant.

9.4 Energy unit rate determination

In order to determine the energy unit rate for each power plant a net present value calculation will be made. The required energy unit rate of the power plant is the unit rate which gives a net present value of zero at the end of the return-on-investment period. This implies that the cash flow of the construction and exploitation of the power plant is zero.

9.4.1 Lifespan, return-on-investment period and depreciation time

It is assumed that the different power plants will be built for an exploitation period of 50 years. This period does not include the construction period which is assumed to be equal to 5 years. The capital costs of the power plant building, intake and outfall systems, pre-treatment facility and the different sumps are distributed evenly over the construction period; the costs of the membrane stacks, pumps, pipes, turbines (or converters), electrical installations and power grid connection are distributed evenly over the last 2 years of the construction period. Within the construction period, large investments are made which all have to be repaid as soon as the exploitation period begins. The return-on-investment period of the power plants is assumed to be equal to 15 years. In section 9.6, the energy unit rate will be determined for a varying return-on-investment period. Within this period the investments during the construction period (including interest), interest costs during the return-on-investment period and power plant reinvestments should be repaid by the revenues of the energy production. The reinvestments of the power plant depend on the depreciation time of the main civil infrastructure. The pre-treatment facility, pumps, pipes, turbines (or converters), electrical installations and power grid connection are assumed to function properly for a period of approximately 20 years. The depreciation time of the membranes is assumed to be equal to 5 years. Other parameters which are important in the determination of the energy unit rate are the interest rate and the different index ratios:

- Interest rate 6%
- Index ratio energy prices 2%
- Index ratio operational activities 2%
- Index ratio building costs 2%

9.4.2 Cash flow over the lifespan of the power plant

The required energy unit rate of the power plant is the unit rate which results in positive cash flow from the end of the return-on-investment period of 15 years. In order to obtain the cash flow of the power plant, the net present value of the investments and revenues over the lifespan of the power plant should be considered. The investments and revenues over the lifespan of the 25 MW PRO power plant are given in figure 9.1:

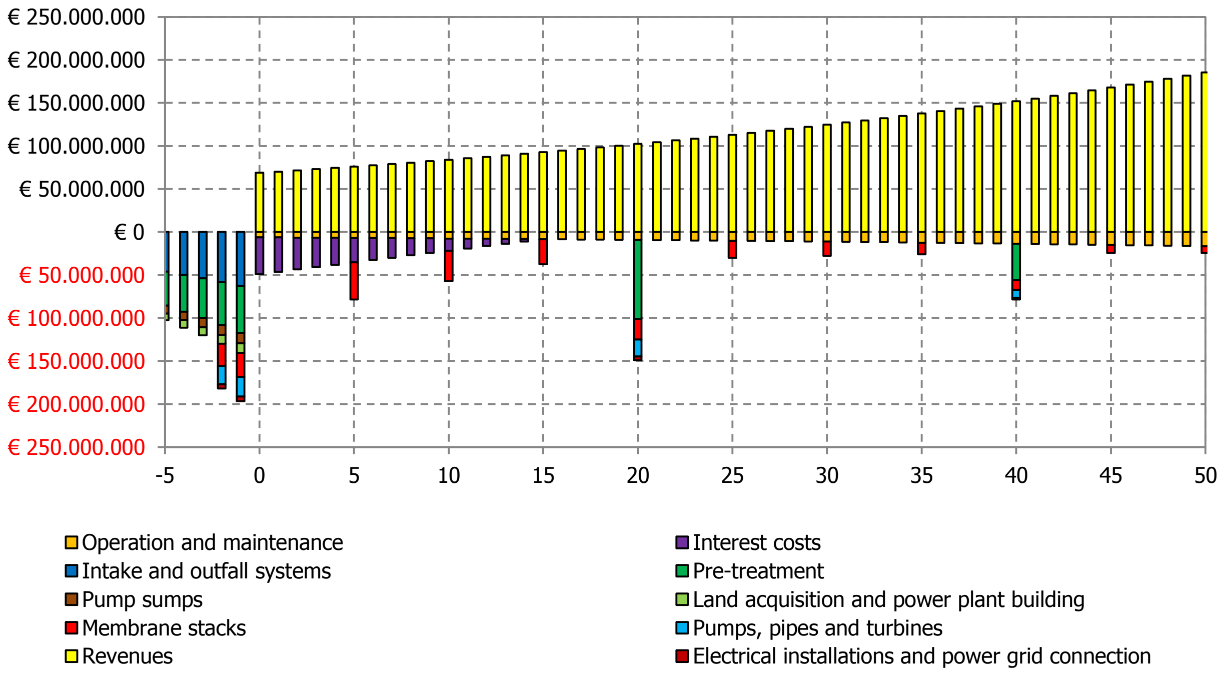

Figure 9.1: The investments and revenues over the lifespan of the 25 MW PRO power plant.

The revenues given in figure 9.1 depend on the energy unit rate of the power plant, which will be obtained by trial and error. The energy unit rate is varied until the net present value is equal to zero after 15 years of exploitation. The cumulative summation of the net present value over the lifespan of the 25 MW PRO power plant is given in figure 9.2:

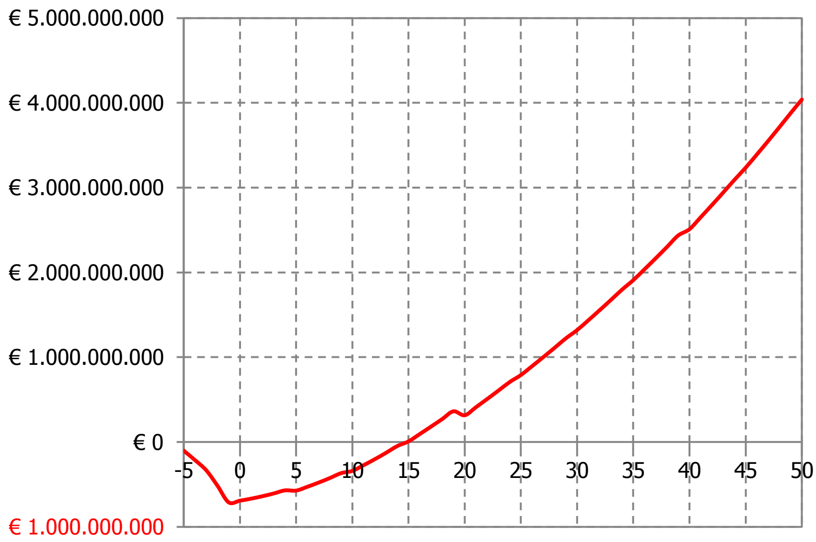

Figure 9.2: The cash flow diagram over the lifespan of the 25 MW PRO power plant.

The diagram of figure 9.2 is known as the cash flow diagram. It shows that the net present value equals zero at the end of the return-on-investment period. From that point, the net present value of the power plant is positive and thus the power plant will be profitable. The corresponding energy unit rate appears to be equal to 1.15 €/kWh. This is considerably more than the 8 cents/kWh which is expected by REDstack (see section 2.6).

Similar graphs can be obtained for the other power plants. The energy unit rate for each power plant is given in table 9.1:

Power plant	Energy unit rate
25 MW PRO	1.15 €/kWh
200 MW PRO	3.71 €/kWh
1 MW PRO	0.19 €/kWh
25 MW RED	0.75 €/kWh
200 MW RED	1.21 €/kWh
0.55 MW RED	0.31 €/kWh

Table 9.1: The energy unit rate for the different power plants.

The energy unit rates of the different power plant are all considerably more than the 8 cents/kWh which is expected by REDstack.

9.5 Distribution of the energy unit rate

Now the energy unit rates are known, it is interesting to analyse distribution of the energy unit rate over the main infrastructure of the power plant. The distribution of the energy unit rate of the 25 MW PRO power plant is given in figure 9.3:

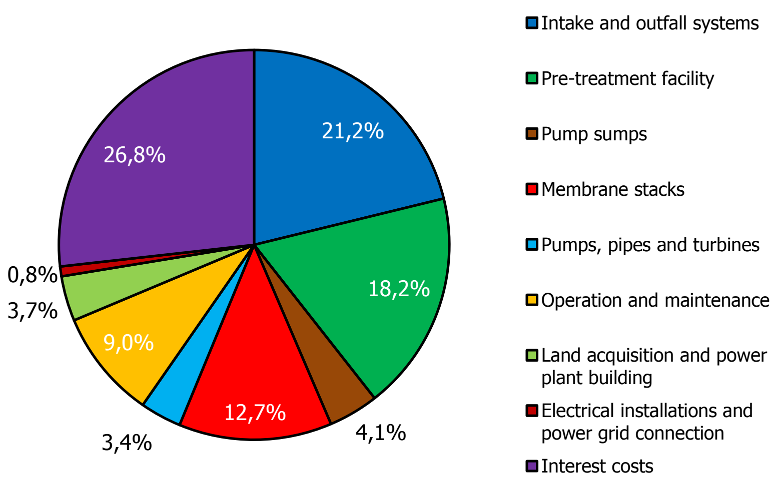

Figure 9.3: Distribution of the energy unit rate in case of the 25 MW PRO power plant.

The energy unit rate of the 25 MW PRO power plant is 1.15 €/kWh. According to the distribution in figure 9.3, the intake and outfall system and pre-treatment facility (including pump sumps) are the most influential infrastructures of the power plant (43.5%). This is in contrast to the past, current and expected development of the exploitation of osmotic power (see section 2.6). The development was slowed down because of the cost-ineffective membranes. However, membrane stacks have only a share of 12.7% in the distribution of the energy unit rate. When the capacity of the PRO power plant increases to 200 MW, the distribution of the energy unit rate is as follows:

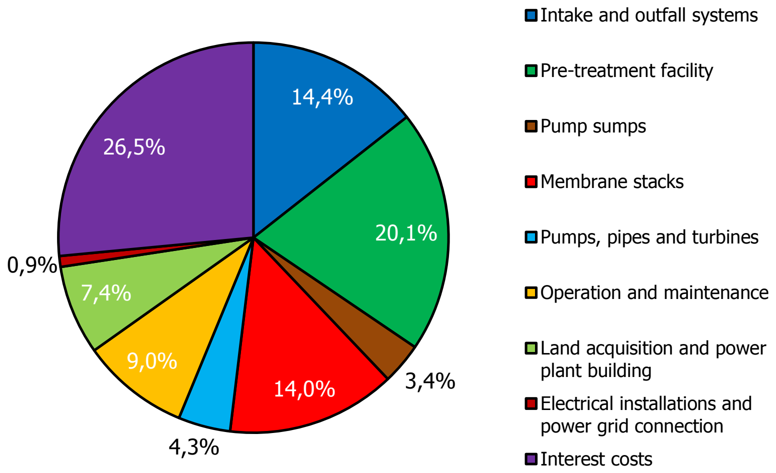

Figure 9.4: Distribution of the energy unit rate in case of the 200 MW PRO power plant.

When the power plant capacity of the PRO power plant increases to 200 MW, the intake and outfall system and pre-treatment facility (including pump sumps) still have the largest impact on the energy unit rate (37.9%). The difference compared to the 25 MW PRO power plant is that the impact of the pre-treatment facility has increased, and the impact of the intake and outfall systems decreased. It can therefore be concluded that the impact of the pre-treatment facility increases for increasing power plant capacities. The impact of the intake and outfall systems is in the case of the 200 MW PRO power plant almost equal to the impact of the membrane stacks.

When a 25 MW RED power plant is considered instead of a 25 MW PRO power plant, the distribution of the energy unit rate is as follows:

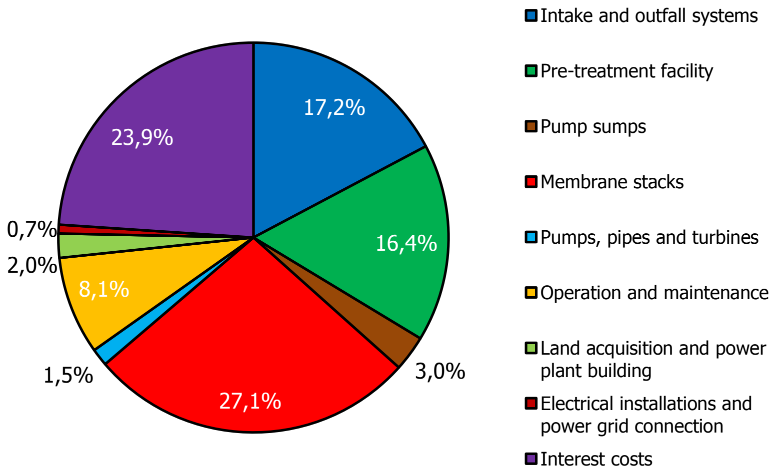

Figure 9.5: Distribution of the energy unit rate in case of the 25 MW RED power plant.

From figure 9.5, it can be noticed that the impact of the membranes has increased sufficiently. The reason for the larger impact is the smaller power density in the case of RED. The ion-selective membranes in the case of RED have a smaller power density (used value 1 W/m^2) than the semi-permeable membranes in the case of PRO (used value 2.4 W/m^2). This resulted in higher capital costs of the membranes and thus a larger impact on the energy unit rate distribution. The power density therefore has an impact on the energy unit rate, but still the impact of the intake and outfall systems and pre-treatment (including pump sumps) is larger (36.6%). However, an improvement in power density is recommended.

Similar figures of the energy distribution could also be obtained for the other power plants. The energy unit rate distribution of all the power plants is given in table 9.2:

	Unit rate	Intake and outfall system		Pre-treatment (including pump sumps)		Membrane stacks		Pumps, pipes, etc.	
	€/kWh	%	€/kWh	%	€/kWh	%	€/kWh	%	€/kWh
25 MW PRO	1.15	21.2%	0.24	22.3%	0.26	12.7%	0.15	3.4%	0.04
200 MW PRO	3.71	14.4%	0.53	23.5%	0.87	14.0%	0.52	4.3%	0.16
1 MW PRO	0.19	4.8%	0.01	0.0%	0.00	53.4%	0.10	12.8%	0.02
25 MW RED	0.75	17.2%	0.13	19.4%	0.15	27.1%	0.20	1.5%	0.01
200 MW RED	1.21	12.1%	0.15	20.7%	0.25	28.4%	0.34	1.5%	0.02
0.55 MW RED	0.31	4.1%	0.01	0.0%	0.00	59.6%	0.20	10.9%	0.03

Table 9.2: Distribution of the energy unit rate.

9.6 Sensitivity analysis

From table 9.2 can be concluded that the energy unit rate is mainly affected by the intake and outfall systems and pre-treatment facility. However, the capital costs of these infrastructures were determined by imposing an unit rate (section 6.3.5.2) or cost factor (section 6.4.5.2). Also the interest rate and return-on-investment period (section 9.4) have an impact on the energy unit rate. This section will analyse what the energy unit rates will be when a certain range of the mentioned parameters is considered.

9.6.1 Unit rate intake tunnel

In section 6.3.5.2, an unit rate of the intake tunnels equal to 500 €/m^3 was assumed. In figure 9.6, the relation between the energy unit rate and a varying unit rate (range 0 – 1.000 €/m^3) of the intake tunnel is shown. The relation in figure 9.6 is obtained by varying the unit rate of the intake tunnel only. All the other parameters (cost factor micro-filtration, interest rate and return-on-investment period) have the same value as used in Part III and section 9.4.

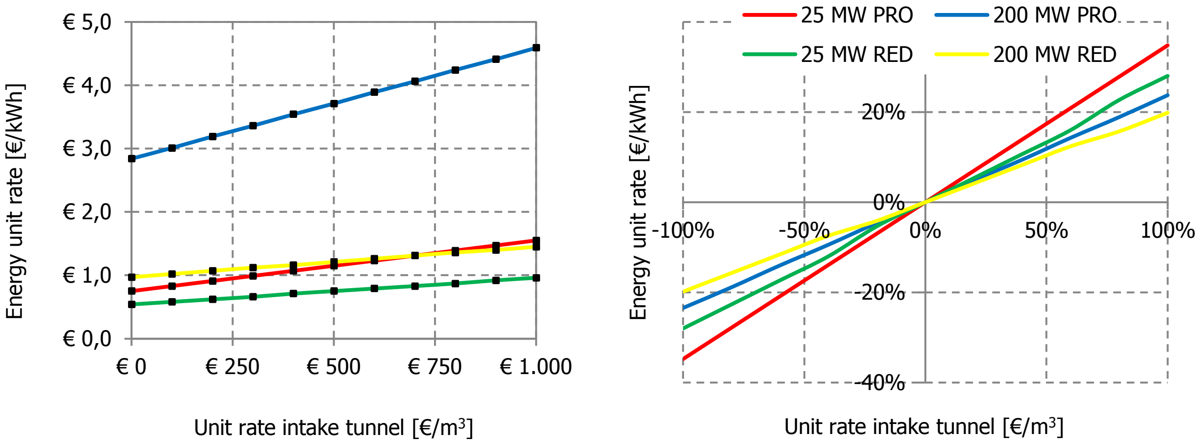

Figure 9.6: Sensitivity analysis intake tunnel (micro-filtration: 0.10 €/m³ ; interest rate: 6% ; return-on-investment period: 15 years).

From figure 9.6 can be concluded that the unit rate of the intake tunnel does have an influence on the energy unit rate, but the energy unit rate will still be significantly high.

9.6.2 Cost factor micro-filtration

In section 6.4.5.2, a cost factor of micro-filtration equal to 0.1 €/m³ (annual capacity) was assumed. In figure 9.7, the relation between the energy unit rate and a varying cost factor (range 0 – 0.2 €/m³) of micro-filtration is shown. The relation in figure 9.7 is obtained by varying the cost factor of micro-filtration only.

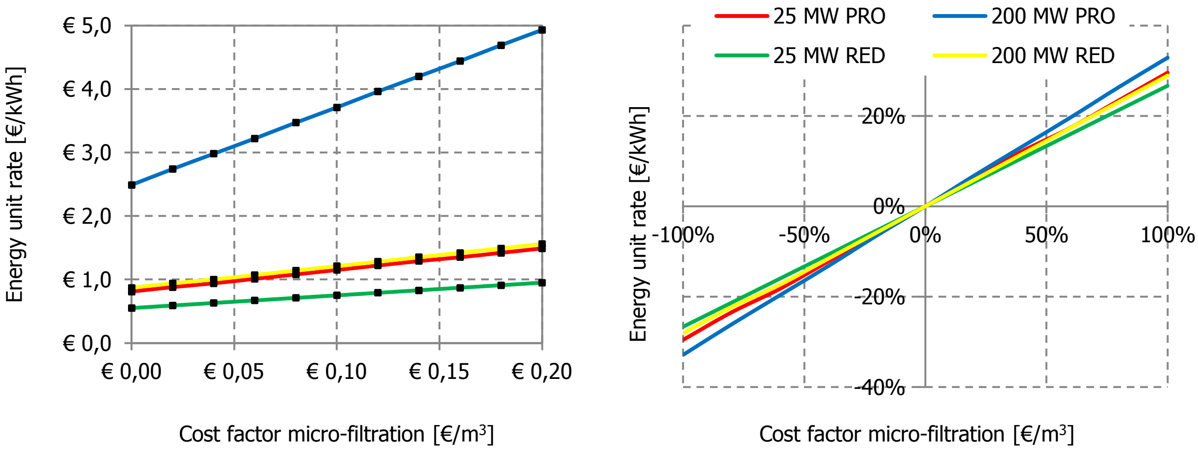

Figure 9.7: Sensitivity analysis micro-filtration (intake tunnel: 500 €/m³ ; interest rate: 6% ; return-on-investment period: 15 years).

From figure 9.7 can be concluded that the cost factor of micro-filtration does have an influence on the energy unit rate, but the energy unit rate will still be significantly high.

9.6.3 Interest rate

The energy unit rates given in table 9.1 are determined with an interest rate of 6%. However, the interest rate will vary throughout the lifespan of the power plant. The relation between the interest rate (range 0 – 10%) and energy unit rate in case of the 25 MW PRO power plant is given in figure 9.8. The relation in figure 9.8 is obtained by varying the interest rate only.

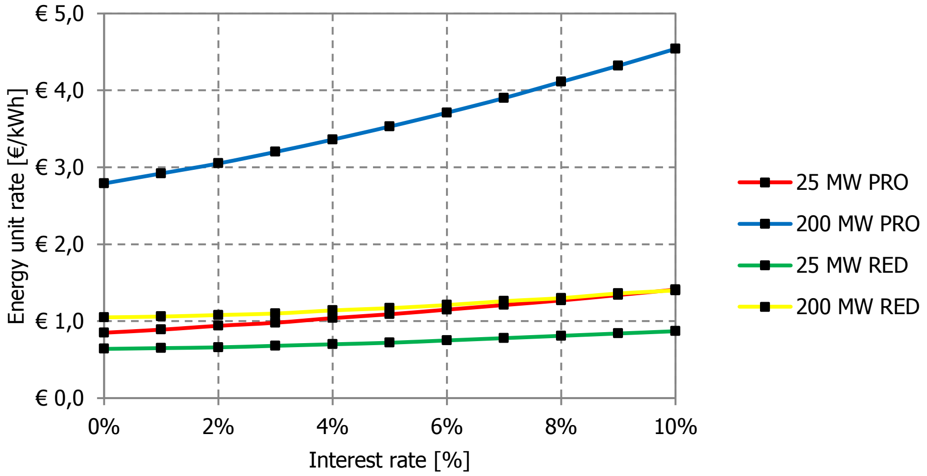

Figure 9.8: Sensitivity analysis interest rate (intake tunnel: 500 €/m³ ; micro-filtration: 0.10 €/m³ ; return-on-investment period: 15 years).

From figure 9.8 can be concluded that the interest rate does have an influence on the energy unit rate, but the energy unit rate will still be significantly high.

9.6.4 Return-on-investment period

In section 9.4.1, a return-on-investment period of 15 years is assumed. The relation between energy unit rate and return-on-investment period (range 5 – 50 years) is shown in figure 9.9. The relation in figure 9.9 is obtained by varying the return-on-investment period only.

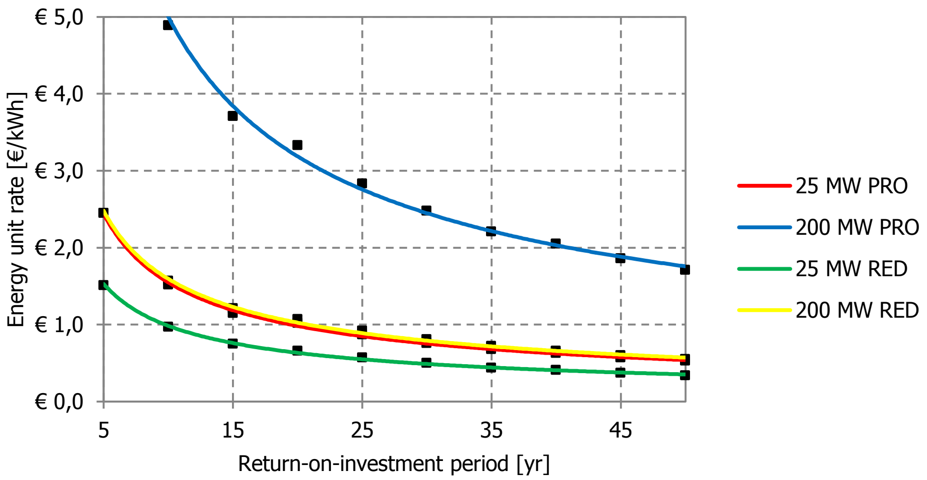

Figure 9.9: Sensitivity analysis return-on-investment period (intake tunnel: 500 €/m³ ; micro-filtration: 0.10 €/m³ ; interest rate: 6%).

From figure 9.9 can be concluded that, even with a return-on-investment period equal to the lifespan of the power plant, the energy unit rates will still be significantly high.

9.6.5 Combined scenarios

From the previous sections, it can be concluded that the energy unit rates will still be too high when the sensitivity of the assumed values in section 9.6.1 – 9.6.4 are analysed. However, the previous sections analysed the sensitivity of the assumed values separately. In this section, the energy unit rates will be determined when a number of scenarios are considered. In total, 10 scenarios will be considered (see table 9.3) in which the first scenario is the most favourable and the last scenario the most unfavourable.

Scenario #	Unit rate tunnel	Cost factor micro-filtration	Interest rate	Return-on-investment period
1	0 €/m^3	0.00 €/m^3	0%	50 yr
2	100 €/m^3	0.02 €/m^3	1%	45 yr
3	200 €/m^3	0.04 €/m^3	2%	40 yr
4	300 €/m^3	0.06 €/m^3	3%	35 yr
5	400 €/m^3	0.08 €/m^3	4%	30 yr
6	500 €/m^3	0.10 €/m^3	5%	25 yr
7	600 €/m^3	0.12 €/m^3	6%	20 yr
8	700 €/m^3	0.14 €/m^3	7%	15 yr
9	800 €/m^3	0.16 €/m^3	8%	10 yr
10	900 €/m^3	0.18 €/m^3	9%	5 yr

Table 9.3: Determination of the considered scenarios.

The results of the different scenarios are shown in figure 9.10:

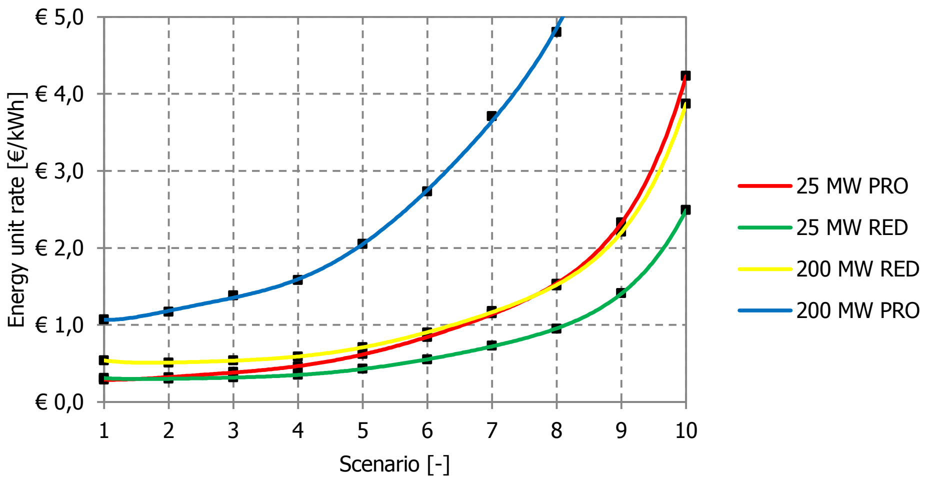

Figure 9.10: Sensitivity analysis combined scenarios.

From figure 9.10 can be concluded that even with the most favourable scenario the energy unit rates will still be significantly high. A lower unit rate of intake tunnels, a lower cost factor of micro-filtration, a lower interest rate or a longer return-on-investment period will not result in a marketable energy unit rate. Only a development in the technology of osmotic power production could result in a marketable energy unit rate. This will be discussed in chapter 10.

9.7 Conclusion

A number of conclusions can be drawn from the energy unit rate distribution:

- An ordinary RED power plant appears to be more feasible than an ordinary PRO power plant (see section 8.10.2)
- A PRO power plant integrated in a STP appears to be more feasible than a RED power plant integrated in a STP (see section 8.10.3)
- The energy unit rate increases for increasing power plant capacities. The decreasing fresh water availability ensures that the economics of scale does not apply (see section 6.10 and 8.10.1)
- The impact of the intake and outfall system and pre-treatment (including pump sumps) is always larger than the impact of the membrane stacks
- The impact of the pre-treatment facility increases for increasing power plant capacities
- The impact of the intake and outfall systems decreases for increasing power plant capacities
- The impact of the membrane stacks increases a little for increasing power plant capacities
- The impact of the pumps, pipes and turbines (or converters) is minor

Chapter 10
Developments

The criterion of the feasibility of the commercial exploitation of osmotic power is the energy unit rate. REDstack believes that it will be possible to produce osmotic power at an energy unit rate of about 8 cents/kWh in the near future (see section 2.6). In the previous chapter, it has been determined that energy unit rates including all the required civil infrastructure are substantially higher. Even with a most favourable scenario (see section 9.6.5) the energy unit rate will still be significantly high. However, the exploitation of osmotic power is still in development. This chapter will determine the energy unit rate when the expected and a number of recommended developments are considered.

10.1 Expected future developments

The expected future developments are an increase in power density and a decrease in membrane price. Statkraft (PRO) expects a future power density of the semi-permeable membranes equal to 5 W/m^2 as can be seen in figure 2.10. REDstack expects a future power density of 2 W/m^2 for the ion-selective membranes. The price of both types of membranes is expected to decrease. The current membrane price is about 5 €/m^2 [7], but experts have indicated that within a few years it will be possible to produce membranes at a unit rate of 2 €/m^2 [7; 8]. The question is whether these developments will have a significant impact on the energy unit rate.

10.1.1 PRO

- Development power density from 2.4 W/m^2 to 5 W/m^2
- Decrease membrane unit rate from 5 €/m^2 to 2 €/m^2

The increase in power density has a positive effect on the required membrane area. A power density of 5 W/m^2 results in less membrane stacks. However, the flow rate through the power does not change. This means that the same flow rate should be divided over less membrane stacks. This will result in higher capital costs of the pumps, pipes and turbines, or in a smaller net energy production because of the energy loss due to the water transport. However, this problem can be solved by maintaining the same amount of membrane stacks and by decreasing the stack height. When the stack height is decreased, the flow rate per membrane stack is maintained and thus the capital costs of the pumps, pipes and turbines will be same. The smaller stack height will affect the net energy production positively because of the lower water elevation.

When the 25 MW PRO power plant is considered, the capital costs of the membranes will decrease by more than a half. A power density of 5 W/m^2 and a membrane price of 2 €/m^2 result in capital costs equal to € 10.000.000,-. The stack height is decreased to 3 m, which will result in an increase of the net energy production by 24.2 GWh/yr.

When the developments are considered in a similar calculation as in section 9.4, the energy unit rate will decrease to 0.72 €/kWh.

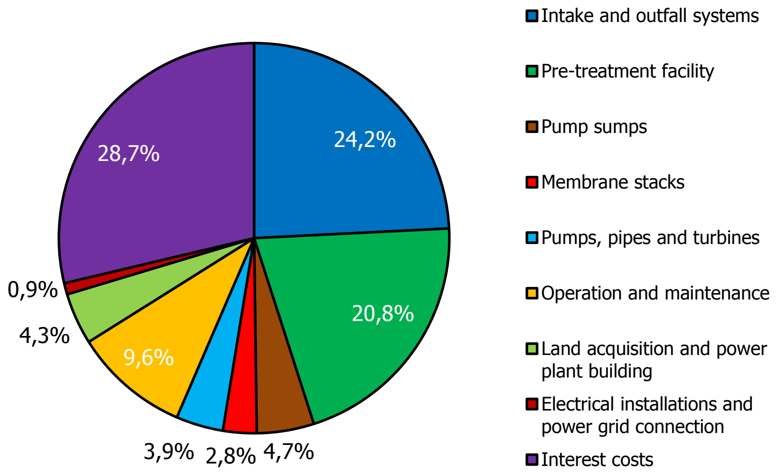

Figure 10.1: Distribution energy unit rate 25 MW PRO power plant when the expected developments are considered.

The development in power density in the case of the 25 MW PRO power plant results in a decrease of the energy unit rate by 37.4%. When a 200 MW PRO power plant is considered, the reduction is even more. The developments result in the case of the 200 MW PRO power plant in an energy unit rate equal to 1.31 €/kWh which is a decrease by 64.7%. When a 1 MW PRO power plant is considered, the energy unit rate decreases to 0.07 €/kWh. This is a marketable value of the energy unit rate. The effect of the developments on the PRO power plants is given in table 10.1:

	Old energy unit rate	**New energy unit rate**	**Reduction**
25 MW PRO	1.15 €/kWh	0.72 €/kWh	37.4%
200 MW PRO	3.71 €/kWh	1.31 €/kWh	64.7%
1 MW PRO	0.19 €/kWh	0.07 €/kWh	63.2%

Table 10.1: Effect energy unit rate on the expected developments in the case of a PRO power plant.

The expected development in the case of PRO will result in a significant decrease in the energy unit rate. A further development of the semi-permeable membranes is therefore recommended. However, the energy unit rate in the case of the 25 and 200 MW PRO power plant is still too high. This is due to the large investments of the intake and outfall systems and pre-treatment facility.

10.1.2 RED

- Development power density from 1 W/m^2 to 2 W/m^2
- Decrease membrane unit rate from 5 €/m^2 to 2 €/m^2

The expected development in the case of a RED power plant is an increase in power density from 1 to 2 W/m^2. This is double the current power density, so it can be assumed that in the future a 400 kW REDstack container could be applied. This will decrease the amount of REDstack containers by 50%. With the expected decline of the membrane price, also the capital costs of the membrane stacks will decrease.

When the 25 MW RED power plant is considered, the capital costs of the membrane stacks will decrease to € 25.000.000,-. The capital costs of the pumps, pipes and converters are maintained because the flow rate through the power plant will remain the same. When the developments are considered in a similar calculation as in section 9.4, the energy unit rate decreases to 0.55 €/kWh.

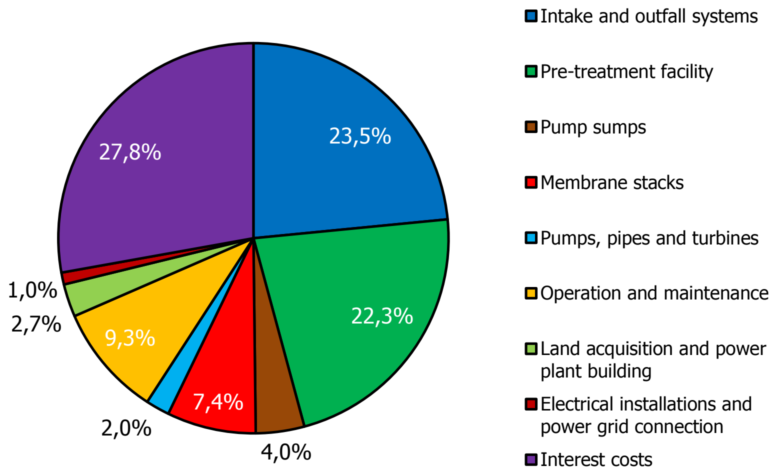

Figure 10.2: Distribution energy unit rate 25 MW RED power plant when the expected developments are considered.

The development in power density in the case of the 25 MW RED power plant results in a decrease of the energy unit rate by 26.7%. The effect of the developments on the rest of the RED power plants is given in table 10.2:

	Old energy unit rate	**New energy unit rate**	**Reduction**
25 MW RED	0.75 €/kWh	0.55 €/kWh	26.7%
200 MW RED	1.21 €/kWh	0.88 €/kWh	27.3%
0.55 MW RED	0.33 €/kWh	0.13 €/kWh	60.6%

Table 10.2: Effect energy unit rate on the expected developments in the case of a RED power plant.

Also in the case of a RED power plant, the development in power density and membrane price has a significant effect on the energy unit rate. However, the energy unit rates are still too high.

10.2 Recommended developments

From the previous section can be concluded that the expected developments are insufficient in order to make the commercial exploitation of osmotic power feasible. The improved power density and membrane price will not result in a marketable energy unit rate, but a further development is recommended. Except in case of the 1 MW PRO power plant a marketable energy unit rate equal to 7 cents/kWh could be achieved. The general conclusion is that the impact of the intake and outfall systems and pre-treatment facility on the energy unit rate is too large. This section will determine whether there are some potential developments which could result in a lower energy unit rate.

10.2.1 Recirculation

- Reduction of the capital costs of the intake and outfall tunnels by learning more about the phenomenon of recirculation

The intake and outfall systems have a significantly large impact on the energy unit rate. The reason for the large impact is the high capital costs of the intake and outfall tunnels. In section 4.2, the Haringvliet – Grevelingen location was selected because this location was able to separate the fresh, salt and brackish water flow. This three-way separation would reduce the possibility on recirculation. However, the disadvantage of this location was that long intake and outfall tunnels were required. The total tunnel length of about 10 km resulted in high capital costs.

One of the recommended developments is to learn more about the phenomenon of recirculation. The goal of the study should be that for different flow rates, the local conditions and the distance between the intake and outfall are optimized in such a way that a recirculation flow will not occur. If an optimum can be found, savings can be made on capital costs of the intake and outfall tunnels. If the mentioned optimum could be found, another power plant location should be considered. The fact that the intake and outfall systems have a significantly large impact ensures that the distance between the fresh and salt water source should be as short as possible. When the possibility on recirculation could be neglected, the most suitable power plant location is the Afsluitdijk (see figure 4.3). This location has a large salinity gradient and fresh water availability, and the small distance between the fresh and salt water source ensures that savings can be made on capital costs of the intake and outfall structures.

When, for example, the Afsluitdijk location appears to be suitable for a 25 MW PRO power plant if the distance between the salt water intake and brackish water outfall is equal to 100 m. In this case, the intake and outfall tunnels could be considerably shorter. A shorter tunnel will have an impact on the required cross section, because the friction term (see equation 6.4) will become smaller. The smaller cross section and tunnel length will have a major impact on the capital costs. In analogy to the cross section analysis conducted in Appendix B.5, the capital costs will become about € 3.500.000,- (when a fixed length of 100 m is assumed for all the tunnels).

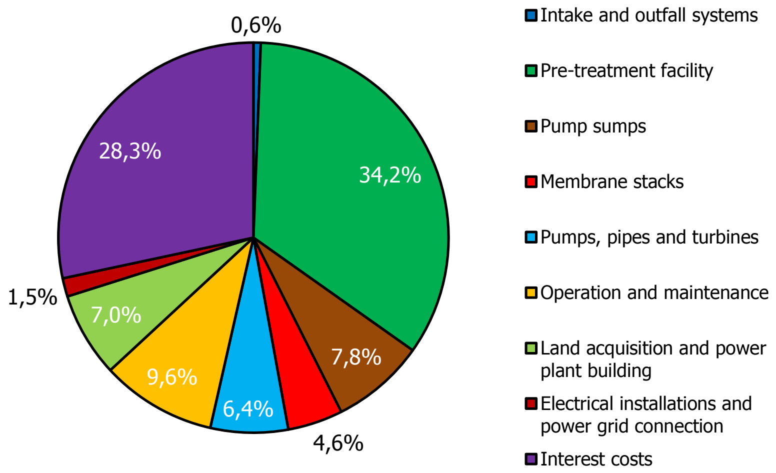

Figure 10.3: Distribution energy unit rate 25 MW PRO power plant when the recirculation problem is solved.

The reduction of the tunnel length has a large impact on the distribution of the energy unit rate (see figure 10.3). The energy unit rate will become about 0.44 €/kWh under the assumption that the conditions at the location Afsluitdijk are equal to the conditions at the Haringvliet – Grevelingen location. For power plants of larger capacities, the brackish discharge will become larger and thus the possibility on recirculation. However, if it is assumed that the possibility on recirculation for large effluent discharges will also be negligible the capital costs of the intake and outfall systems could also be reduced. The effect of this reduction on the energy unit rate of the different power plants is given in table 10.3:

	Old energy rate	**New energy unit rate**	**Reduction**
25 MW PRO	0.72 €/kWh	0.44 €/kWh	38.9%
200 MW PRO	1.31 €/kWh	0.96 €/kWh	26.7%
1 MW PRO	0.07 €/kWh	0.07 €/kWh	0%
25 MW RED	0.55 €/kWh	0.34 €/kWh	38.2%
200 MW RED	0.88 €/kWh	0.64 €/kWh	27.3%
0.55 MW RED	0.13 €/kWh	0.13 €/kWh	0%

Table 10.3: Effect on energy unit rate when the possibility on recirculation is assumed to be negligible.

According to table 10.3, the energy unit rates will still be too high when the capital costs of the intake and outfall systems are almost excluded. Only the 1 MW PRO power plant will have a marketable energy unit rate. According to figure 10.3, the pre-treatment facility (including pump sumps) will have by far the largest impact on the energy unit rate of the 25 MW PRO power plant when the capital costs of the intake and outfall systems could be reduced. The same applies for the other power plants, except for the power plants integrated in a STP. A next recommended development is therefore a development in pre-treatment.

10.2.2 Pre-treatment

- Increasing depreciation time of the membranes
- Exclusion of a pre-treatment facility

The pre-treatment of the different flows is a major issue in the design of an osmotic power plant. The treatment types are expensive and some of the treatment types consume a large amount of energy (see section 6.4). In the case studies, the choice was made to apply micro-filtration because micro-filtration is the cheapest treatment type available (see table 6.3) and it consumes only a small amount of energy. Pilot plants will determine if this coarse form of filtering will be sufficient.

The uncertainties associated with micro-filtration result in a number of potential developments. An adverse development will be that micro-filtration appears to be insufficient for an osmotic power plant. When this is the case, a more extensive pre-treatment facility is required. This development will increase the energy unit rates in table 10.3 and will therefore be disregarded.

An advantageous development could be that the pilot plants will find the optimum between water quality, pre-treatment and membrane configuration when micro-filtration is applied (see section 6.4.2.1). This optimum, together with regular cleaning and flushing operation, could increase the depreciation time of the membranes. When a depreciation time of 10 years is assumed instead of 5 years, the energy unit rates will decease to:

		Old energy rate	New energy unit rate	Reduction
25	MW PRO	0.44 €/kWh	0.43 €/kWh	2.3%
200	MW PRO	0.96 €/kWh	0.95 €/kWh	1.0%
1	MW PRO	0.07 €/kWh	0.06 €/kWh	14.3%
25	MW RED	0.34 €/kWh	0.33 €/kWh	2.9%
200	MW RED	0.64 €/kWh	0.61 €/kWh	4.7%
0.55	MW RED	0.13 €/kWh	0.12 €/kWh	7.7%

Table 10.4: Effect on energy unit rate when the depreciation time of the membranes is equal to 10 years.

According to table 10.4, an increased depreciation time will not have a large impact on the energy unit rates.

Another advantageous development could be that the optimum between water quality, pre-treatment and membrane configuration ensures that no pre-treatment facility is required. The local water quality and the spacer width of the membrane modules will prevent, in that case, the development of fouling. The exclusion of a pre-treatment facility will have a major impact on the design of the power plant, because:

- A pre-treatment facility is not required which will save on capital costs

- No energy is loss due to the pre-treatment of the different flows which will increase the net energy production
- The power plant area could become smaller which will save on capital costs of land acquisition and pump sumps

From figure 6.31 – 6.32 and figure 8.2 – 8.3 can be estimated that, when the pre-treatment facility is excluded, the area of the different power plants could be reduced with 50%. This reduction in power plant area will result in a smaller transportation distance of the water flows. The length of the primary pipes could become smaller, which will have a positive effect on the energy loss due to the water transportation in horizontal direction (see figure 6.40). However, table E.5 in Appendix E.3 shows that the influence of a decreasing pipe length on the energy loss is minor. The decrease in energy due to the water transportation will therefore be disregarded. The decreasing pipe lengths also have a minor influence on the capital costs of pumps, pipes and turbines (or converters). Because of the minor influence, a decrease in capital costs of pumps, pipes and turbines (or converters) will also be disregarded.

When it is assumed that the capital costs on land acquisition and pump sumps decrease by 50%, the energy unit rates of the different power plant will decrease to:

		Old energy rate	New energy unit rate	Reduction
25	MW PRO	0.43 €/kWh	0.11 €/kWh	74.4%
200	MW PRO	0.95 €/kWh	0.22 €/kWh	76.8%
1	MW PRO	0.06 €/kWh	0.06 €/kWh	0%
25	MW RED	0.33 €/kWh	0.10 €/kWh	69.7%
200	MW RED	0.61 €/kWh	0.18 €/kWh	70.5%
0.55	MW RED	0.12 €/kWh	0.12 €/kWh	0%

Table 10.5: Effect on energy unit rate when a pre-treatment facility is not necessary.

According to table 10.5, the exclusion of a pre-treatment facility will have a major impact on the energy unit rates. The resulting energy rates are approaching marketable unit rates.

10.2.3 Membrane bioreactor

In the previous sections, the development of the energy unit rate of the power plants integrated in a STP is considered. However, an osmotic power plant integrated in a STP seems to be only feasible (in case of the 1 MW PRO power plant) when a membrane bioreactor is already present at the site of the STP. At present, there are only 3 STP's with a MBR of which only one is near the shore (see figure 10.4). A development of MBR's in STP's is therefore required.

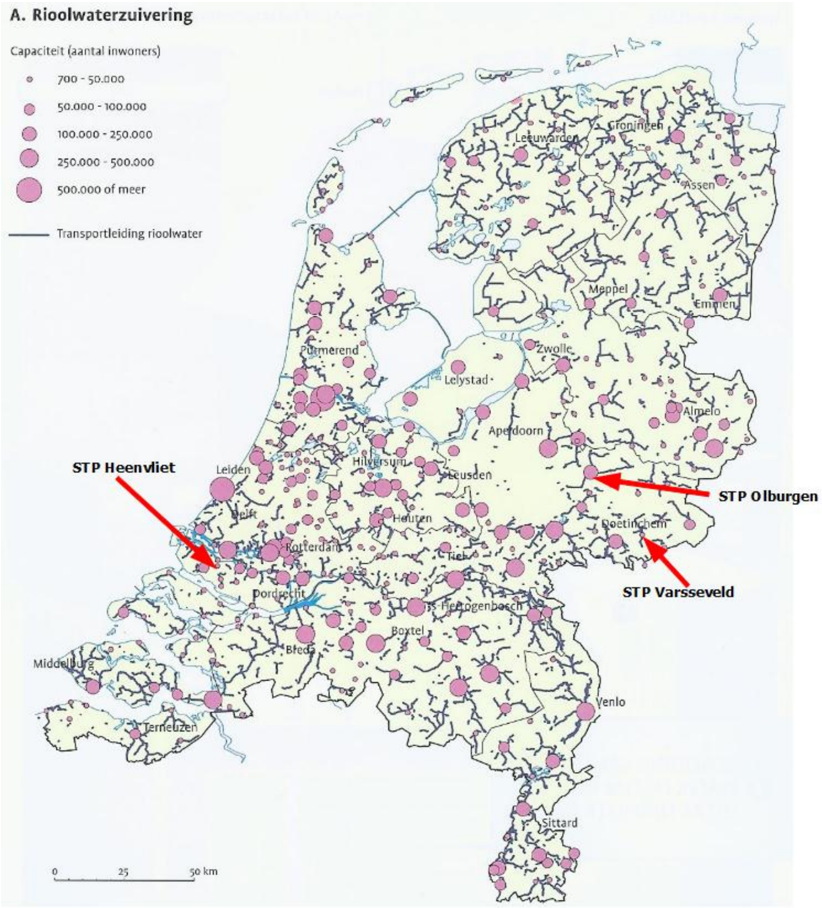

Figure 10.4: The location of the 3 STP's which are equipped with a membrane bioreactor.

10.3 Conclusion

The expected and recommended developments are illustrated in figure 10.5:

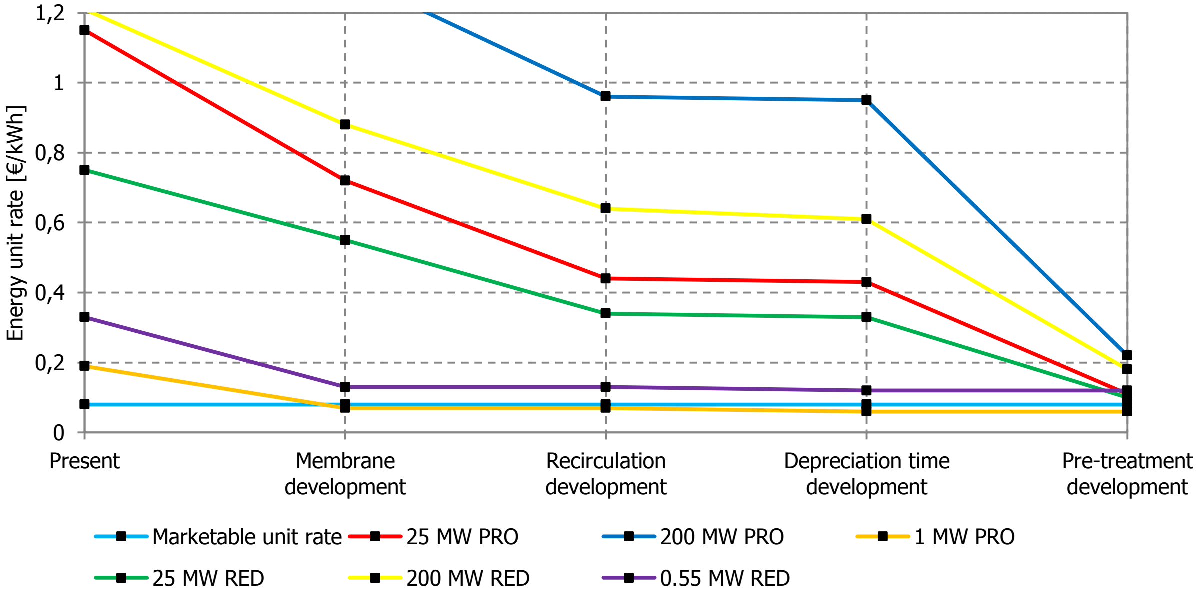

Figure 10.5: Energy unit rate when the developments are considered.

According to figure 10.5, the energy unit rates approach the marketable energy unit rate when a number of expected and recommended developments are considered. Especially when a more favourable interest rate, a longer return-on-investment period or subsidies are considered, the exploitation of osmotic power could become feasible in the future. It is also interesting to analyse the power plant efficiency when the developments are considered. The power plant efficiency is illustrated in figure 10.6:

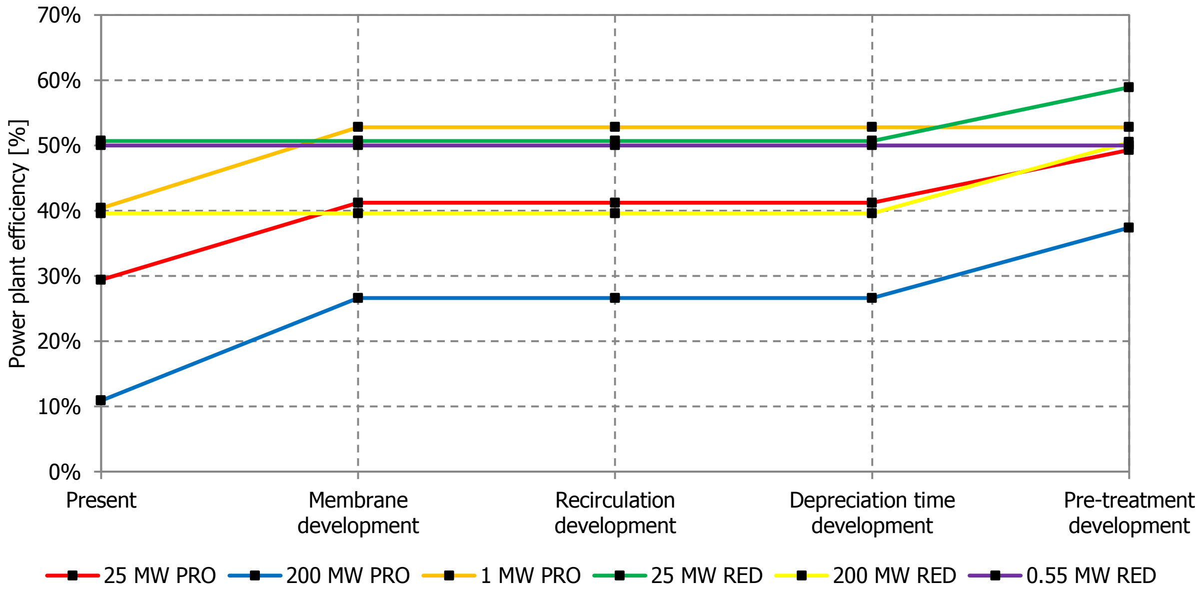

Figure 10.6: Power plant efficiency when the developments are considered.

According to figure 10.6, the maximum power plant efficiency is 59%. This efficiency corresponds with the 25 MW RED power plant. The power plant efficiencies calculated, considering all the required civil infrastructure, are quite different compared to desired future efficiencies given in table 2.1.

Part V

Conclusion

Chapter 11
Conclusion and recommendations

This thesis ends with the conclusion on the commercial feasibility of an osmotic power plant. Because the exploitation of osmotic power is still in development, also a judgement will be made on the recommended developments and the future feasibility of an osmotic power plant.

11.1 Conclusion

The research question of the thesis was:

"Is a commercial osmotic power plant feasible if the capital costs of the main civil infrastructure are included?"

After completion of the financial feasibility study it can be concluded that, with the present technology and knowledge, the commercial exploitation of osmotic power is far from being feasible. An osmotic power plant is technically feasible, but the energy unit rates (see table 9.1) will be too high compared to the marketable energy unit rate of 8 cents/kWh. The high energy unit rate is the result of the high capital costs of the power plant and the low power plant efficiency.

The high capital costs of the power plant are mainly due to the capital costs of the intake and outfall systems and the pre-treatment facility. In the case studies, about 35 – 40% of the energy unit rate is attributed to these two infrastructures. The capital costs of the intake and outfall systems were high because the lack of knowledge on how to solve the recirculation problem ensured that a three-way separation was a requisite. Studies aiming at reduction of recirculation offer opportunities to a decrease in the capital costs of the intake and outfall systems.

The pre-treatment facility also has a large impact on the energy unit rate. Even with the cheapest pre-treatment type, micro-filtration, the capital costs of the pre-treatment facility are high. The disadvantage of micro-filtration is that, at present, it entails many uncertainties. The effect of the coarse type of treatment on the energy production is not yet known. Another disadvantage of micro-filtration is that it requires a large area. By applying micro-filtration, the required power plant area increases by 50%. This will have a negative effect on the net energy production due to the water transportation and, to a lesser extent, the capital costs of the pumps, pipes (or converters).

The low power plant efficiencies are mainly due to the water transportation. In the case of pressure retarded osmosis (PRO), about 40 – 60% of the total energy loss can be attributed to the water transportation. In the case of reversed electro dialysis (RED), this percentage is 25 – 35%. The difference is due to the compactness of the membrane stacks. The PRO power plant requires a stack volume of 1.546 m^3/MW; the RED power plant only 380 m^3/MW.

After the conclusion on the research question, also a number of other conclusions can be made.

11.1.1 Power plant location

Prior to the thesis, it was expected that the fresh water availability and salinity gradient were the most important requirements of a power plant location. After completion of this thesis it can be concluded that this is true. The fresh water availability and salinity affect indeed the net energy production. Especially the fresh water availability has a large impact on the economics of scale. An increasing power plant capacity result in larger required flow rates through the plant and thus a decreasing fresh water availability. The decreasing fresh water availability ensures that the economics of scale does not apply (see section 6.10 and 8.10). The selected power plant location in chapter 4 is therefore probably not the most suitable location. The selected power plant location requires a fresh water flow which is available for a large percentage of the time and some storage capacity in times of low fresh water discharges. Further studies to a suitable osmotic power plant location is therefore recommended.

However, an osmotic power plant demands more of a location. The most important requirement, besides the fresh water availability, is the possibility on a three-way separation. When a three-way separation is not possible, a recirculation flow could decrease the net energy production. It states here could, because the knowledge on how to solve the recirculation problem is still limited. Almost all the locations considered in chapter 4 are not able to separate the three flows without constructing long intake and outfall systems or additional infrastructure. The only location which could separate the three flows is the location Krammersluizen (see figure 4.9). However, the disadvantage of this location is the lack of space and the major impact on the hydraulic conditions of Lake Grevelingen. When studies on how to solve the recirculation problem would come with a solution, the location Afsluitdijk (see figure 4.3) seems to be the best location because of the short distance between the water sources.

Another important requirement is the available space. The ratio between the net power plant capacity and the required power plant area appears to be very small (see table 6.6 and 8.6), which is mainly due to the large required area of the pre-treatment facility. The power plant location should therefore have a large available space.

In case of a small-scaled osmotic power plant integrated in a sewage treatment plant (STP) another importation requirement applies. An osmotic power plant integrated in a STP appears to be only feasible if a membrane bioreactor is present. However, at present there is only one STP near a salt water source with a membrane bioreactor (STP Heenvliet near the city of Rotterdam).

11.1.2 Optimum power plant capacity

In a number of case studies, the net energy production and total capital costs of the power plant were determined. The objective of these case studies was that, together with the financial feasibility, an optimum power plant capacity would be obtained. However, it can be concluded that an optimum power plant capacity is, with the present technology and knowledge, not possible. The 25 MW power plant, which was the main case study of the thesis, appeared to be not feasible. The resulting energy unit rate is significantly high. When the capacity of this power plant increases, the energy unit rate becomes even higher. The reason for the deteriorating energy unit rate is the decreasing net energy production due to the decreasing fresh water availability and increasing energy consumption due to the water transportation. When the capacity of the power plant decreases, the energy unit rate becomes smaller but only when the capital costs of the intake and outfall systems and pre-treatment facility are excluded by integrating the osmotic power plant in a STP. But even then, the energy unit rates will still be too high.

With the present technology and knowledge, there is no optimum power plant capacity because the resulting energy unit rates are all significantly high. However, if a choice should be made than it would be a small scaled power plant integrated in a STP. A small scaled power plant integrated in a STP is at present the least unfeasible option.

11.1.3 PRO or RED

The type of osmotic power generation which is the most suitable is RED, because a RED power plant will result in smaller energy unit rates. The total capital costs of a RED power plant is comparable to that of a PRO power plant, so the difference in energy unit rate is only due to the larger power plant efficiency in the case of a RED power plant. A RED power plant is more compact than a PRO power plant (see section 8.5). This has a positive effect on the net energy production of the power plant, because the water flows should be transported over smaller distances in horizontal and vertical direction.

When an osmotic power plant will be integrated in a STP, a PRO power plant is more feasible than a RED power plant. This is due to the less-effective RED membranes and the lower practical osmotic energy in the case of RED.

11.2 Recommendations

The expected and recommended developments, which are already described in chapter 10, are:

- Conduct a study to the fresh water availability and storage capacity of the locations proposed in this thesis and conclude which location is the most suitable.
- Develop the power density of the membranes. A larger power density will have a large impact on the energy unit rate (see section 10.1).
- Study the phenomenon of recirculation with the diffusion theory from fluid mechanics and conduct a numerical analysis for the locations proposed in this thesis. If an optimum is found in which no recirculation will occur when the flows are separated in only two ways, capital costs on the intake and outfall systems or additional infrastructure could be saved. This will have a large impact on the energy unit rate (see section 10.2.1).
- Obtain more knowledge about the pre-treatment of the different flows of an osmotic power plant. If it appears that a pre-treatment facility is not required, the energy unit rates will become significantly lower (see section 10.2.2).
- Use a membrane bioreactor for the treatment of sewage water (see section 10.2.3).

11.3 The future feasibility of an osmotic power plant

The exploitation of osmotic power is at present far from being feasible. The energy unit rate will deviate too much from the marketable energy unit rate of 8 cents/kWh. Only when some developments are considered, the energy unit rate will decline to a more reasonable energy unit rate. When all the expected and recommended developments are considered, the energy unit rates of the different power plants will be:

		Energy unit rate
25	MW PRO	0.11 €/kWh
200	MW PRO	0.22 €/kWh
1	MW PRO	0.06 €/kWh
25	MW RED	0.10 €/kWh
200	MW RED	0.18 €/kWh
0.55	MW RED	0.12 €/kWh

Table 11.1: Energy unit rates when all the developments are considered.

All the energy unit rates given in table 11.1 are reasonably close a marketable energy unit rate. Especially when a more favourable interest rate, a longer return-on-investment period or subsidies are considered, the exploitation of osmotic power could become feasible in the future. However, the question is whether all of the developments are reasonable.

The development in membrane power density and price is reasonable. The technology of the membranes is still in development, so it could be expected that the power density and price will improve. The same applies for the use of membrane bioreactors in STP's. Increasingly strict discharge requirements of STP's could result in the application of membrane bioreactors in STP's near the shore. A small-scaled osmotic power plant integrated in a STP could therefore be feasible in the future.

A development which is less obvious is the development in the knowledge about the phenomenon of recirculation. It could be imagined that a two-way separation for small flow rates is possible, but for large flow rates the prevention of recirculation becomes increasingly difficult.

Another development, which is the least obvious, is that there is no pre-treatment facility necessary in the future. However, the fact that, at present, the cheapest and most coarse type of treatment results in an unfeasible power plant indicates that an osmotic power plant will be feasible only and only if a pre-treatment facility could be excluded. However, the fact that the membranes are very sensitive indicates that it could be imagined that an osmotic power could not be exploited without a pre-treatment facility. The exclusion of a pre-treatment facility seems therefore to be a utopia.

The uncertainties about the phenomenon of recirculation and the appearance that a pre-treatment facility could not be excluded will also make the exploitation of an osmotic power plant in the future unfeasible. Only the exploitation of a small-scaled PRO osmotic power plant integrated in a STP seems, with an energy unit rate equal to 6 cents/kWh, to be a feasible option. The future will show whether this statement was correct.

References

1. http://www.cbs.nl (central statistical office of the Netherlands)
2. MINISTERIE VAN ECONOMISCHE ZAKEN, LANDBOUW EN INNOVATIE (2011) Energie rapport. *Den Haag*
3. POST, J.W., et al. (2006) Salinity-gradient power: Evaluation of pressure-retarded osmosis and reverse electro dialysis. *Journal of Membrane Science*, 288, pp. 218-230
4. GERSTANDT, K., et al. (2008) Membrane processes in energy supply for an osmotic power plant. *Desalination*, 224, pp. 64-70
5. SWINKELS, C.M., BIJLSMA, A.C.,HOMMES, S. (2009) Blue energy Noordzeekanaal. *Deltares*
6. THORSEN, T., HOLT, T. (2009) The potential for power production from salinity gradients by pressure retarded osmosis. *Journal of Membrane Science*, 335, pp. 103-110
7. MOLENBROEK, E.C.,SCHAAP, A.B. (2004) Haalbaarheid osmotische energiewinning in Zeeland. *Ecofys Netherlands B.V.*
8. QUAK, R.W. (2009) Feasibility of a power plant: Blue energy in the Dutch Delta. *Master thesis. Delft University of Technology*
9. SKRÅMESTØ, Ø.S., SKILHAGEN, S.E., NIELSEN, W.K. (2009) Power production based on osmotic pressure. *Waterpower*, XVI
10. BUISMAN, C.J.N., POST, J.W. (2010) Blue Energy: from smart concept to promising technology. *KWR Watercycle Research Institute Delft*, pp. 19-30
11. GREKKE, B. (2010) The Statkraft prototype plant: Reasons for and experiences from. *Proceedings Osmotic Summit 2010*, *San Diego*, pp. 1-24
12. http://www.natuurlijkafsluitdijk.nl
13. HACK, P. (personal communication, July 22, 2011)
14. NOORDHOFF ATLASPRODUCTIES (2010) De Bosatlas van Nederland Waterland. *Noordhoff Uitgevers*, *Groningen*
15. VRIJLING, J.K., VAN DUIVENDIJK, J., MOOYAART, L.F. (2008) Getijdecentrale in de Brouwersdam. *Delft University of Technology*, p. 7
16. ATSMA, J. (2011) Kabinetsstandpunt t.a.v. Besluit beheer Haringvlietsluizen. *Letter to the chairman of the Dutch House of Representatives*
17. http://www.waterbase.nl (water database of the Dutch Ministry of Infrastructure and Environment)
18. VAN LIER, J.B. (personal communication, November 15, 2011)
19. http://www.ahn.nl (actual elevation level of the surface in the Netherlands)
20. SKILHAGEN, S.E., DUGSTAD, J.E., AABERG, R.J. (2008) Osmotic power – power production based on the osmotic pressure difference between waters with varying salt gradients. *Desalination*, 220, pp. 476-482
21. HYDROGRAFISCHE DIENST (2011) Wateratlas: Zeeland. *ANWB*, *Den Haag*

22. http://www.worldsteelprices.com
23. BALBAID, H. (2011) Application of higher strength concrete in tubular structures. *Master thesis*. *Delft University of Technology*
24. http://www.plasticsinfomart.com
25. VAN GIELS, J. (2008) De effecten van onttrekking van koelwater op vis. *Waterdienst*
26. http://www.bouwkostenkompas.nl (elemental costs database of civil infrastructure)
27. DE MOEL, P.J., VERBERK, J.Q.J.C., VAN DIJK, J.C. (2005) Drinkwater – principes en praktijk. *Sdu Uitgevers*, *Den Haag*
28. MOLENBROEK, E.C. (2007) Energie uit zout en zoet water met osmose. *Ecofys Netherlands B.V.*
29. http://www.hubert.nl (producer of micro-filtration drums)
30. BAKER, R.W. (2004) Membrane technology and applications. *J. Wiley & Sons*, *Chichester*
31. SUNDARAMOORTHY, S., SRINIVASAN, G., MURTHY, D.V.R. (2011) An analytical model for spiral wound reverse osmosis membrane modules. *Desalination*
32. ACHILLI, A., CATH, T.Y., CHILDRESS, A.E. (2009) Power generation with Pressure Retarded Osmosis: An experimental and theoretical investigation. *Journal of Membrane Science*, 343, pp. 42-52
33. http://www.boerderij.nl (current land price of farmland in the Netherlands)
34. http://www.delfluent.nl (operator of STP Houtrust)