Delft University of Technology

Faculty of Civil Engineering and Geosciences
Department of Hydraulic Engineering

Feasibility of a Power Plant

Blue Energy in the Dutch Delta

Master thesis

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This study has been accomplished in cooperation with

Preface

This document concludes my research on the *Feasibility of a power plant, Blue energy in the Dutch Delta*, which is done within the framework of my graduation thesis at the Delft University of Technology. The work described in this report was carried out between July 2008 and March 2009, in cooperation with VolkerWessels, Rijkswaterstaat and Deltares.

My interest for renewable energy started when I attained the course on Waterpower Engineering at the TU Delft in 2007. The ever increasing need for energy, the exhaustion of fossil energy sources in the near future together with innovative technologies for energy generation has inspired me in such a way that I decided to graduate on a renewable energy project. At that moment I was totally unfamiliar with the existence of "Blue energy." The opening of a small pilot at Wetsalt in May 2008 showed me the large possibilities of this new technology.

Working on this thesis has been very challenging. The unfamiliarity of Blue energy, and the prevailing opinion that 'energy out of water' is not interesting in a flat country like The Netherlands, are facts which are not easy to deal with. However, it was satisfying to see that a number of interesting locations do exist, and that indeed a large potential for Blue energy is available in the Netherlands.

Over the last months I have been helped by a lot of people. All who have helped me know they have, and I am very grateful to them. Still I have a few words of thanks. First, I would like to thank Jan Post who introduced me into this promising technology. Thank you for all your input and your answers to my critical questions. I also want to thank Gé Beaufort, Wouter Don, and Frank Kleissen who gave me the opportunity to work at their companies and who have helped me in many different ways during my research. Thanks also go to the TU Delft members of my graduation committee, Professor Vrijling, Hans van Duivendijk, and Robert-Jan Labeur, for sharing their contacts and their comments on my work. I want to thank my parents for giving me the opportunity to find my own way in life and the unconditional confidence they have had in me over the years. Last, many thanks go to my girlfriend Stefanie. Thank you for your support during my graduation period and your everlasting positive spirit.

Enjoy reading.

Rutger Quak
Delft, March 2009

Abstract

Blue energy in general

The search for renewable energy has grown considerably over the last years. Blue energy is a form of renewable energy which is not yet used at commercial scale, but which might have a large potential in the next decades. Blue energy is a technique that converts the difference of molar free energy between fresh river water, and salt sea water into electricity. This can also be stated as the use of the differences in osmotic pressures to generate electricity. Two techniques exist which can be used to do this: Pressure Retarded Osmosis (PRO), which is being developed by Statkraft in Norway, and Reversed ElectroDialysis (RED), under development by Wetsus in The Netherlands. In this study the second technology has been chosen because of easy access to crucial knowledge about the technology.

In the process of RED a large storage battery is created by using different cells of fresh and salt water, which are separated from each other by membranes, see Figure 1. These membranes retain water, but let positive or negative ions pass through (two different types of membranes are used). Due to the osmotic pressure differences the Na+ and Cl- ions will change cells in opposite directions. In this way a storage battery is created. The effluent of the technology is brackish water, the mixture of the incoming fresh and salt water flows.

Theoretically, 1,5MW can be won when mixing flows of 1m^3/s of river water with sea water. In the system losses of 0,3MW occur, and for pumping at most 0,2MW is necessary. 1,0MW remains as the net power available for the public network.

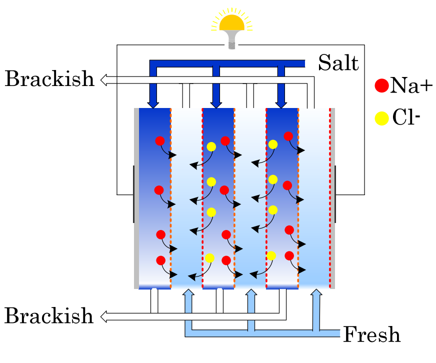
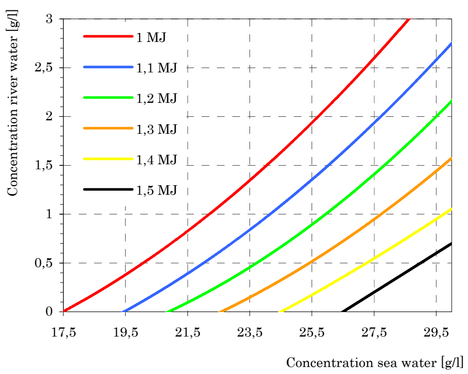


Figure 1: *Reversed electrodialysis (RED)*



Graph 1: *Potential of Blue energy*

In The Netherlands a number of interesting locations exists where Blue energy might be feasible. The most interesting location is the Delta area because of the large amounts of fresh water which are directed to that the Delta. The Afsluitdijk (large-scale) and sewage treatments plants (small-scale) are also interesting locations for Blue energy.

Objectives

This focus of this study is not in particular the technology of Blue energy itself, but on the other aspects that are important to make Blue energy a success. The objectives of this report read:

"The first objective of this study is to gain insight in the conditions that need to be fulfilled by a specific location in order to construct a feasible large-scale power plant at that location."

"The second objective of this study is to find a suitable location in the Dutch Delta and determine whether and on which scale this location is feasible."

In this study, large-scale is defined as a power plant which can deliver a net power of 100-500MW.

Important aspects

In Figure 2 a schematic overview is given of a Blue energy power plant. It shows the most important aspects which need to be considered. On the left hand side of the power plant two incoming water flows are shown; salt (seawater) and fresh (river water). These flows have the same size but a different salt concentration. Both flows have to be pumped up, and filtered before they enter the actual membrane installations in the power plant. The effluent of the plant is brackish water, shown on the right. Because of the fact that the potential of Blue energy depends on the occurring salt concentrations, the three flows have to be separated from each other. The incoming flows may neither be influenced by each other, nor by the brackish flow. Furthermore, for a large-scale power plant large flows are needed, in the order of 100-500m³/s for both incoming flows.

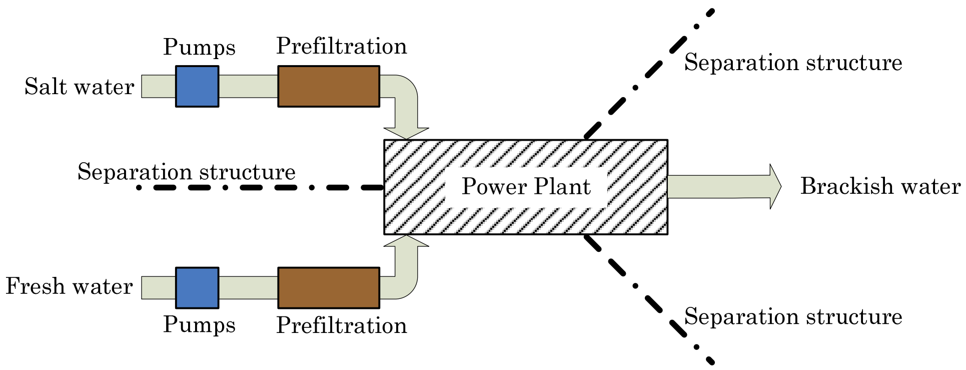


Figure 2: *Schematic overview of a Blue energy power plant*

Chapter 5 gives, in short, some design formulas in order to determine the most important parameters for a power plant when the available flows and salinities are known.

Dutch Delta alternatives

Extensive research to the characteristics of the Dutch Delta showed that, at present, five locations exist in the area which might be feasible for Blue energy on a large-scale. Three locations are considered to be most interesting at present; the Botlek area, the outlet sluices of the Haringvliet, and the Krammersluizen. In a far future, when closing-of the Nieuwe Waterweg is imaginable, it might be possible to build a power plant in the Nieuwe Waterweg with a size of 500-1.500MW. In this study the Botlek alternative has been deepened out.

Botlek alternative

The implications of a power plant in the Botlek area are shown in Figure 3. It can be seen that an almost perfect separation between the three different water flows exist. Near the power plant two structures need to be implemented. The first is a barrier in the Oude Maas (1) with shipping locks. The second is a barrier in the Hartelkanaal (2). Fortunately this second barrier, together with shipping locks, exists already; the Hartelkering, which is part of the Delta works. This barrier, which is open under normal circumstances, has to be closed permanently.

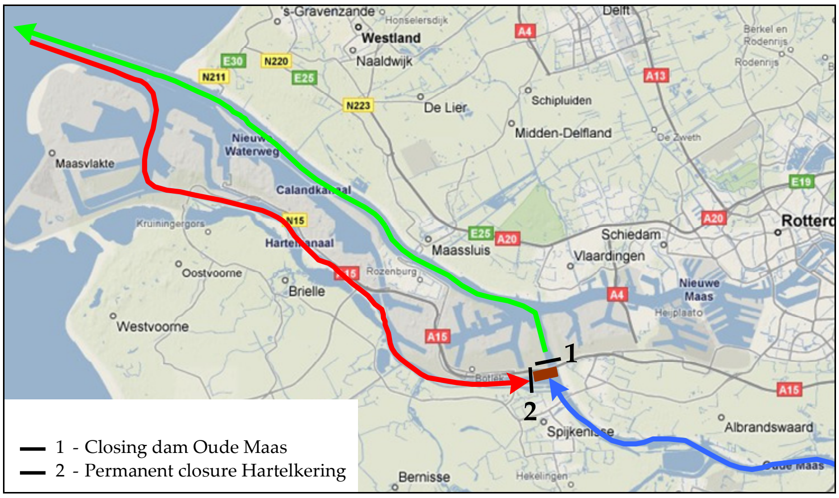
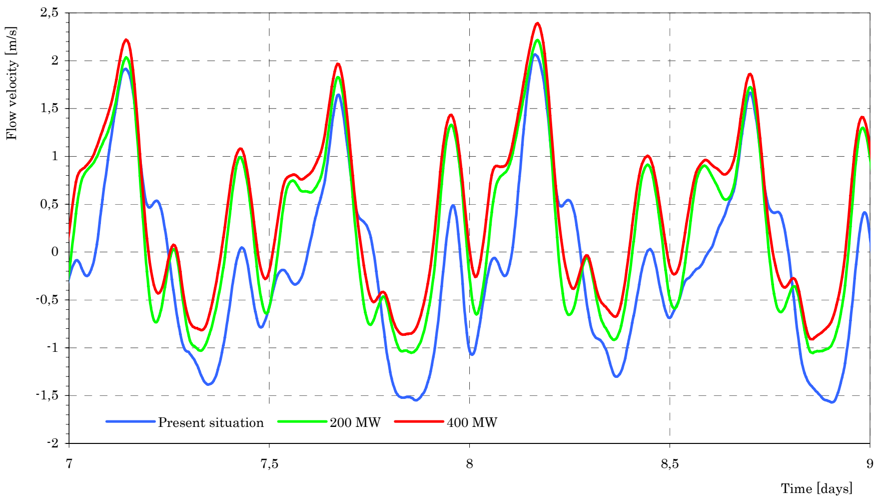


Figure 3: Overview of the different flows for a power plant in the Botlek area. Blue represents fresh, red represents salt, and green corresponds to the brackish flow

In the Botlek fresh water is withdrawn from the Oude Maas. This river discharges at present considerable amounts of fresh water. The remaining flow (which is not used in the power plant) has to be diverted to either the Nieuwe Maas, or the Haringvliet. Salt water is taken in from the Hartelkanaal, and brackish water is discharged onto the Oude Maas and Nieuwe Waterweg. The main aspects when considering this location are:

- What is the maximum salt water flow through the Hartelkanaal
- What salinity occurs at the salt water intake of the power plant
- How much fresh water can be made available for Blue energy

A number of hydraulic simulations, done with the Maasvlakte II model in the Delft3D Flow software, have been used to determine the hydraulic influences of the power plant. The maximum flow through the Hartelkanaal is mainly determined by the occurring velocities in the canal. These cannot increase too much for navigation purposes. The simulations show that the tidal movement is dominant in this area. The discharges (and consequently the velocities) that occur in the normative sections (where the cross-section is small, which causes high velocities) of the Hartelkanaal caused by the tide are much higher than those needed for the power plant. In Graph 2 the flow velocities in the present situation are compared with calculated velocities when implementing a power plant of approximately 200 and 400MW (200 and 400m³/s of salt water needed). It can be seen that the peak velocities hardly increase. The increase of these peak velocities (positive in the figure, which corresponds to the inland direction) is on average 6%, in case of a 400MW plant. These velocities occur in less than 3% of the time. Furthermore, flow velocities up to 2,5m/s are acceptable for modern vessels. It is thinkable that a larger flow (500m³/s) is also possible, but this has not been simulated.



Graph 2: *Flow velocities in normative sections of the Hartelkanaal*

The salinities that occur near the salt water intake of the power plant are very high, up to 27,5g/l. This salinity is hardly influenced by for example fresh water discharges or tidal movements. Furthermore, no vertical salinity gradient occurs in the Hartelkanaal.

The fresh water availability has been determined with a statistical analysis. Many claims on fresh water exist; agriculture, drinking water and limitation of the salt intrusion through the Nieuwe Maas. Next to this, the present river regime will change in the future due to climate changes. By taking all these aspects into consideration it is possible to estimate the flow which can be made available for Blue energy in the Botlek area. The statistical analysis showed that a power plant which needs a fresh water flow of 400m³/s can run at full power for 88-96% of the time. At times with insufficient river discharges, a smaller flow is directed to the power plant. Taking this into account gives an efficiency of 96-99%, depending on the climate scenario. In the analysis it is determined (based on statistical data) that 70% of the flow at Lobith is directed to the Delta (in the critical periods with low river discharges), and that 400m³/s of this flow is needed in order to limit the salt intrusion.

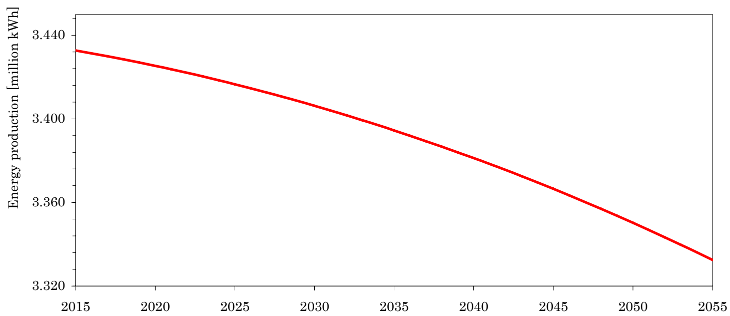
From the above can be concluded that a Blue energy power plant in the Botlek area is feasible, hydraulically speaking. The fresh and salt water flows will be 400m³/s. On the

Figure 4: *Overview of the changing salt concentrations in the Delta area due to the implementation of a power plant (blue=0g/l, red=30g/l)*

salt water side the salinity will be around 27,5g/l. The fresh water has a salinity of 0,3g/l which is just regular river water.

The change in salt concentration in the Rotterdam harbour area is shown in Figure 4. In the right part of the figure, the separation between salt, fresh and brackish water can be clearly seen at the power plant location. The salt intrusion via the Nieuwe Maas is slightly influenced, it moves inland over a distance of 5-8km. This holds under the condition that the surplus of fresh water in the Oude Maas is diverted to the Haringvliet. Diverting this to the Nieuwe Maas would decrease this extra salt intrusion.

The installed power in the power plant will be 472MW, and the net power available for the public network will be 416MW. The yearly production of the power plant is shown in Graph 3. In this production the changing river regime due to climate changes is implemented. In 2015 the present situation is used, in 2055 the G+ scenario. The efficiency of the power plant is very high, varying from almost 94% in the beginning of the life cycle of the plant to 91% in 2055. This is much higher than both other renewable and conventional energy sources.



Graph 3: *Energy production of the power plant during its lifetime, in million kWh*

The power plant needs approximately 315km² of membrane and covers an area of 13 hectares. This space is available in the Botlek area.

A net present value calculation is used to determine the economic feasibility of the power plant. In the analysis the most interesting cost items are:

- Membrane price of € 2,-/m². Depreciation time 5-10 years
- Prefiltration installations: 1.000 million Euros. Depreciation time 20 years
- Electrical facilities, pumps and pipelines: 550 million Euros. These installations have a depreciation time varying from 20 to 40 years

- Costs of additional infrastructure (i.e. barriers): 1.200 million Euros. This infrastructure can be used for the entire life time of the power plant

The power plant is constructed in 5 years and has a lifetime expectancy of 40 years. Taking all these aspects into account together with a few index numbers and a discount ratio of 6%, a cost price of 8,4-9,4 cents/kWh is found, depending on the membrane depreciation time. This is comparable with wind energy.

Content

PART C Blue energy in Dutch Delta

Introduction

Energy is at the moment a widely discussed subject. More and more people realise that the availability of fossil fuels is finite, and that world wide supplies are rapidly decreasing. It has been estimated that with the present energy consumption the coal and gas supplies will be exhausted in a foreseeable future. Next to this, environmental issues have become very important in the last decades. Reduction of CO_2 emission is a key factor within the framework of reducing greenhouse effects. According to the Kyoto protocol (United-Nations 1998), the Parties to the United Nations Framework Convention on climate change have committed themselves to reduce their greenhouse gasses emission considerably. In the Netherlands the government has set the objective of a reduction of 30% by 2020, compared to 1990 (Cramer, van der Hoeven et al. 2008).

Figure 1: *Conventional power plants, running on coal (left and middle) and gas (right)*

However, a world without electricity is nowadays inconceivable. People, cannot live anymore without using electricity. It has become a necessity of life. This need for energy will always exist, the world needs energy.

This all together makes that the search for renewable energy has grown considerable. The advantages of renewable energy, the lack of emission of greenhouse gasses and the infinite availability have made that more and more research is done to all forms of renewable energy. Renewable energy exists in many different forms. Wind turbines, solar energy and hydropower are the best known and applied forms. Fairly unknown is the use of the difference in molar free energy in fresh and salt water, for instance river and seawater, for the generation of electricity. This form of renewable energy is called **Blue energy**. Blue energy is already known for a long time (see section 1.1), but so far, high membrane prices have prevented this technology from market entry. Nowadays, membrane technology has made a lot of improvement, and also prices for membranes have clearly declined. The ever increasing prices for oil and gas make it even more interesting. The feasibility of a Blue energy power plant in the Netherlands is investigated in this report.

The study consists of four parts see Figure 2. Part A gives a short description of Blue energy and the aspects which have to be dealt with when considering this technique. In the same chapter an overview of possible locations in the Netherlands is given followed by a motivation for Blue energy in the Dutch Delta. The second chapter in this part covers the objectives of this study.

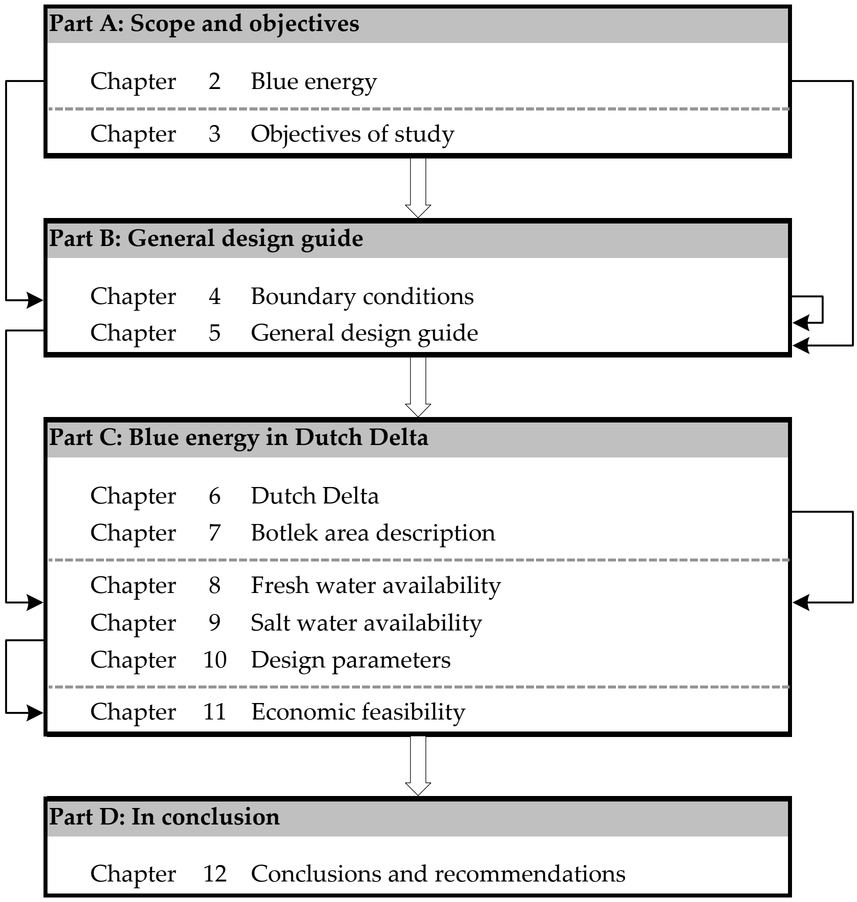


Figure 2: *Structure of report*

Part B deals with the characteristics of Blue energy. Boundary conditions which need to be fulfilled for the feasibility of Blue energy are discussed, and a general design guide for a Blue energy power plant is given.

Part C is subdivided in three sections. The first gives an extensive description of the Dutch Delta and comes up with different possible locations within the Delta. One of these locations is chosen, for which in the second subsection the most important parameters for a design are discussed. From this the power plant parameters can be determined which is done in Chapter 10. The last subsection deals with the economic feasibility of a power plant at this location.

In Part D, the overall conclusions and recommendations for further study are given.

In this report a number of cities, canals, rivers, and lakes are mentioned. In order to have an idea of the exact locations of all these places Appendix A gives an overview of the topography of the Dutch Delta. Next to this, important locations used in the simulations done with the Maasvlakte II model (see Chapter 8) are shown. This appendix might be useful for the reader, when unfamiliar with the Delta area, when reading this report.

PART A

Scope and objectives

Chapter 1

Blue energy

Blue energy is a form of renewable energy, which is not yet used to date on a large scale basis, but might have a large potential in a near future. It is based on the difference of osmotic pressure of fresh water and salt water. This difference, caused by a salinity difference, can be used to generate electricity. The global energy output from estuaries is estimated at 2,6TW (Wick and Schmitt 1977), which is approximately 20% of the worldwide energy demand. This shows the large potential of Blue energy.

The first section of this chapter starts with a short history about the development of Blue energy. Subsequently, in section 1.2 and 1.3 two methods for generating energy with the principle of Blue energy are discussed followed by some advantages and disadvantages in section 1.4. The potential of Blue energy is discussed in section 1.5. The last sections of this chapter deal with the possibilities of Blue energy in The Netherlands, and why the Delta area is most interesting.

1.1 A short history

In 1784 the French priest and physicist Jean-Antoine Nollet put a pig's bladder filled with wine in a barrel of water. To his surprise, the bladder swelled and finally burst. Osmotic energy was converted into an increase in pressure. This was the first known observation of osmotic pressure. In 1901 the Dutch scientist Jacobus H. van't Hoff managed to derive a formula which can be used for calculating the osmotic pressure Π (Hoff 1901). For his work Van 't Hoff received the Nobel Prize for Chemistry in 1902.

A couple of decades later R.E. Pattle identified this phenomenon as a potential energy source. He found that when a river mixes with seawater free energy equal to that of a

680ft. (207 meter) waterfall is lost (Pattle and Mikaye 1954). He found that by using semi-permeable membranes this potential can be used to obtain power.

During the 1970s, Professor Sidney Loeb developed membrane technology for the desalination of seawater (Loeb 1998). Prof. Loeb's recent research has been focused in the area of pressure retarded osmosis (PRO) as a source of energy. This process is especially attractive in Israel due to the high osmotic pressure of Dead Sea brine. His aim was to use PRO to capture the available osmotic energy from Dead Sea brine when brought into contact with brines of lower osmotic pressure, such as the Mediterranean Sea or Jordan River water.

In the last couple of years Wetsus in the Netherlands focuses on the technique of Reversed ElectroDialysis (RED, see section 1.3). In Norway, Statkraft is busy with the development of Pressure Retarded Osmosis (PRO, see section 1.2) (Skilhagen, Dugstad et al. 2008). These techniques can both be used to generate energy from water solutions with different salt concentrations. Both techniques are successfully tested in a laboratory, and are scaled up to a 1 kW (approximately 1.000 m^2 membrane necessary) scale for further research.

1.2 Pressure retarded osmosis

Pressure retarded osmosis (PRO) is the first known technique to convert energy contained in fresh water to electrical energy. In this process the fresh water will, permeate through a semi-permeable membrane. This membrane allows the passage of water, and retains salt as shown in Figure 1.1. Driving force is the difference in free energy available in both types of water. This difference expresses itself in a water level or pressure difference between salt and fresh water, which can be used to generate electrical power in a turbine.

When the water level on the salt water side is not pressurized, which means atmospheric pressure at the surface, the surface level differences can be as high as over 200 meters (Skilhagen, Dugstad et al. 2008). This difference can be used for power generation.

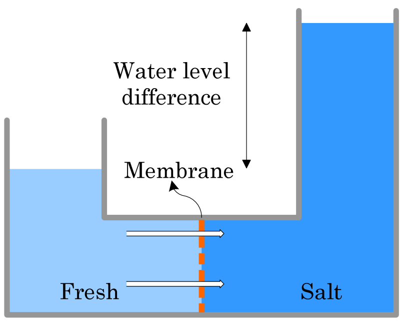


Figure 1.1: *Pressure retarded osmosis*

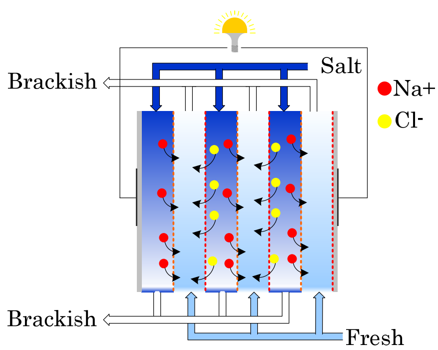


Figure 1.2: *Reversed electrodialysis*

1.3 Reversed electrodialysis

The second process to convert free energy in fresh water to electrical energy is reversed electrodialysis (RED), see Figure 1.2. Again, fresh and salt water are separated from each other by using semi-permeable membranes. In contrast with PRO, in the RED process both the salt and fresh water flow along the membranes instead of through the membranes. On both sides of a fresh water cell two different membranes, both retaining water, are placed. First, on one side a cation exchange membrane is placed. This membrane allows positive ions to pass through the membrane. On the opposite side of the cell an anion exchange membrane lets negative ions pass through. The chemical potential differences causes the transport of ions through the membranes from the concentrated solution (sea water) to the diluted solution (fresh water) (Post, Veerman et al. 2007). In this way the Na+ ions and Cl- ions in the salt solution will change cell in opposite direction. The salinity gradient results in a potential difference over each set of membranes (Post, Veerman et al. 2007). For seawater in combination with river water this will be approximately 80mV. When stacking many cells a so called REDStack (see section 1.3.1) is created with a total voltage of the number of cells multiplied with 80mV. This process can be compared with a large storage battery.

1.3.1 REDStack

For the generation of electricity on a large scale using Blue energy, large amounts of membranes are required. To make the process not extremely space consuming stacks are made, see Figure 1.3. In these stacks small fresh and salt water cells are separated from each other by the membranes. The water cells have a height in the order of 0,2mm. The membranes are much thinner. As mentioned in section 1.3 the technique uses two different membranes. A cation membrane which allows positive ions to pass through and an anion exchange membrane allowing negative ions to pass.

Figure 1.3: *REDStack, (± 1,5kW)*

1.3.2 200 kW unit

Each Blue energy power plant using the RED process for generating electricity will be made of a number of 200 kW units. Each unit has the size of a regular 40ft sea container, and consists a number of REDStacks. In this way a breakdown can be fixed very soon, and only a small part (200 kW) has to be stopped in case of failure. Every unit has three water connectors. These are for the supply of fresh and salt water, and for discharging brackish water. Furthermore, a connection point to connect to the power net has to be fitted on the unit.

Every square meter of membrane has a specific power of approximately 1 to 2 W. This means that, in order to produce 200 kW, a membrane surface of at most 200.000m^2 is needed. The cells with water are approximately 0,2mm high, see Section 1.3.1. When using the total height of a sea container (2.590mm) this 200.000m^2 of membrane can easily fit in the container. Approximately 60 to 70% of the container volume is then used for membranes (in stacks) and water. The remaining 30-40 percent is used for hoses and pipes to transport the water.

To produce 200 kW of electrical power about 200 liters of fresh water and 200 liters of salt water are needed every second. So the pipelines which supply the unit with water have to be able to transport 0,2m^3/s. The discharge pipeline for brackish water needs to transport 0,4m^3/s.

1.4 Advantages and disadvantages

Using Blue energy has many advantages:

- Blue energy is a totally renewable source of energy.
- No fossil fuels are used
- There is no emission of carbon dioxide
- Blue energy is always available
- Blue energy can have a lot of advantages on ecological scale

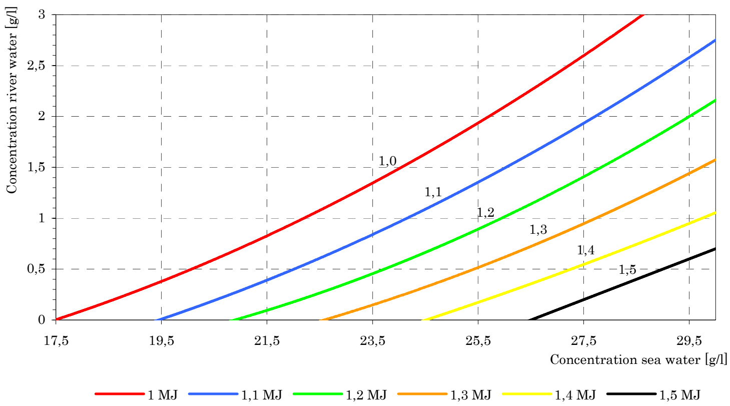
Disadvantages of Blue energy are:

- When applying at a large scale it might be necessary to change the hydraulic system and water management rules, because a lot of fresh and salt water is needed
- Depending on the situation large infrastructural works are needed
- At this moment Blue energy is still said to be very costly compared to conventional energy sources, due to high membrane prices
- Blue energy has never been applied before at commercial scale

1.5 Potential

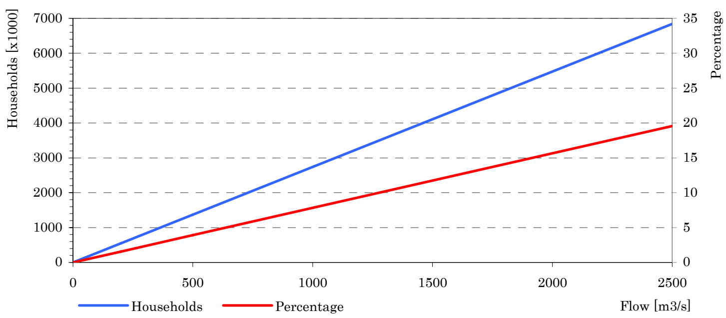
The amount of energy which is available when mixing solutions with different concentrations depends on a couple of things. First, the mixing ratio is an important factor. This ratio shows in which proportions the different solutions are mixed. Second, the occurring concentrations of the dissolved substances have a large influence. A larger gradient results in a larger potential. That is why Sidney Loeb (Loeb 1998) focused on using PRO at the Dead Sea brine, which has a very high salt concentration. The potential is not linear proportional to the available gradient, but to the natural logarithm of the ratio between both salt concentrations.

Mixing one cubic meter of fresh river water with one cubic meter of salt seawater has a theoretical available amount of energy of 1,5MJ (Post, Veerman et al. 2007). This 1,5MJ holds when the salt concentration of the fresh water is approximately 0,5g/l, and 28g/l for seawater. Comparing this with hydropower, this is equivalent to the head of a waterpower dam of over 200m high. When using different concentrations the potential changes as can be seen in Graph 1.1. In this graph the potential is shown as a function of both the salt concentrations on the sea side and the river side. The North Sea has near the coast a salt concentration of approximately 28-31g/l, depending on the location. A river which is not influenced by the sea has a concentration of 0,3 to 0,5g/l. From the graph can be seen that in case of a decrease of the salt concentration on the seaside, the potential declines very fast. With a concentration of 20 g/l on the sea side mixed with river water the potential just below 1,1MJ, which is almost 30 percent lower than with normal sea water. The same holds for higher concentrations on the river side.



Graph 1.1: *Theoretically available free energy when mixing a cubic meter seawater with the same amount of River water (Post, Veerman et al. 2007)*

Of course not the total amount of 1,5MJ can be converted in electricity. Test and research results show that approximately 1,0MJ can be won in an energy plant (Post, Veerman et al. 2007). This includes energy and pumping losses. If every second a volume of one cubic meter of both fresh and salt water is available, controlled mixing of these two can produce enough electricity to supply over 2.700 families (one family uses 3.200kWh electricity every year, www.cbs.nl). In Graph 1.2 the potential (in number of households and percentage of the total use of energy) as a function of the availability of fresh and salt water can be found. Note that to reach this potential not only fresh water needs to be available, but also the same amount of salt water.



***Graph 1.2**: Blue energy potential*

In the Netherlands large amounts of fresh river water and seawater are available, which are both needed for Blue energy. On average the river Rhine discharges 2.200 m^3/s (van der Linden and van Zetten 2002). This means an electricity potential of over 6 million households. Of course not all this energy is practically available but even with a use of 10 or 20% it is an enormous source of renewable energy.

1.6 Possible locations

A suitable location for Blue energy has to fulfill at least three conditions. The first is about the quantities of water needed. For a power plant with a reasonable size, which might be able to concur with a conventional coal or gas fuelled energy plant, large quantities of water are needed. Every cubic meter of both fresh and salt water represents a power of approximately 1 MJ. A Blue energy plant which has to produce for example 500 MW, which is equivalent to a reasonable conventional energy plant, has to be provided with a volume of approximately 500 m^3/s of fresh and salt water. Moreover, the effluent of the power plant is brackish water, in this case a flow as large as 1.000m^3/s, which has to be discharged. From this can be concluded that only a couple of locations may be suitable for applying Blue energy at a large scale. The second condition for a Blue energy plant is that the available salt gradient is large enough. The last requirement for Blue energy is that a power plant has to run at full power for a large part of the time.

In the Netherlands a few locations are available where fresh river water meets the salt sea. On the map in Figure 1.4 can be seen where fresh water meets the salt water from the sea. Next to this, in Figure 1.5 locations where large quantities of fresh water are discharged are shown by arrows. In the following sections these locations will all be discussed briefly.

Figure 1.4: *Fresh water meets salt water*

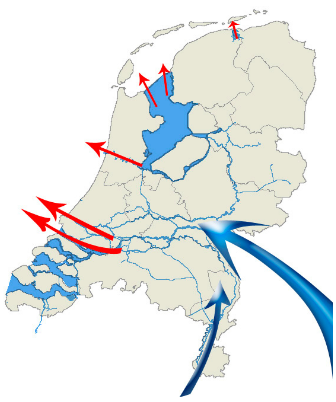


Figure 1.5: *Discharge of fresh water*

1.6.1 Lauwersoog

In the North of the country, on the border between the regions Groningen and Friesland Nature Reserve Lauwersmeer is located. This Nature Reserve covers approximately 9.000 hectares. Off course, flora and fauna is a very important factor in the park. A large variety of animals can be found in this park; birds, fish, but also a lot of Scottish Highlanders and horses The lake in this Nature Reserve was formed by closing of the, at that time called, Lauwerssea from the Waddensea in 1969. Main reason for this was safety against high water levels at sea. The lake covers approximately 2.000 hectares.

The waterdepth in the lake is very small. Most places are less than one meter deep. Only in some channels the water depth can be as large as 10 meters. The water level is kept strictly at 0,93 meters below NAP. This is done because of safety reasons. The surplus of rainwater from the three northern regions is directed to the lake, and discharged onto the Waddensea. In case of a strong wind from the north-west, it is not possible to discharge water to the sea, which implies that the lake has to act as a storage basin.

When building a Blue energy power plant at this location two things will be very important. First, the flow of fresh water, which might be quite small. The second aspect which is important in this area is the separation of the different water flows. Salt water will be taken in from the Waddensea, and fresh water from the lake. But the brackish water will probably be discharged directly onto the Waddensea. It is important to investigate what the influence is of this brackish water is on the salinity of the sea. The inlet of salt water must be chosen such that it is not subjected to salinity influences by the brackish water (recirculation may occur).

Figure 1.6: *Overview Lauwersoog*

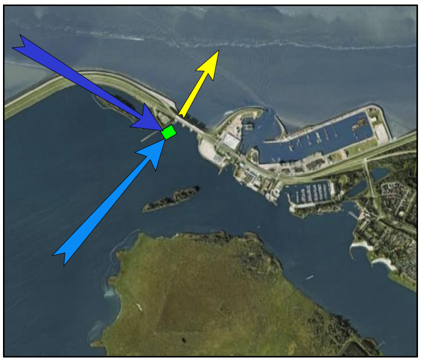


Figure 1.7: *Possible location Blue energy power plant. In blue, incoming waterflows (darkblue: salt water, lightblue: fresh water). Yellow: brackish water*

Flow

The outlet sluices of the Lauwersmeer discharge on average 42m³/s onto the Waddensea. Unfortunately, this discharge is not very constant. It varies from zero for periods which can last up to a month, to over 300m³/s for very short periods.

Because of the fact that the discharge of the outlet sluices varies greatly a large buffer is needed in order to make the flow continuous. Assume that 25 percent of the available average discharge (which is quite a lot) is used. This is approximately 10m³/s. Furthermore, assume that a water level fluctuation of 50cm is allowed on the lake. With this information it is not difficult to calculate that the buffer on the lake is able to provide the power plant with fresh water for 11,5 days. Considering the fact that especially in summer the average discharges are very low, and can even be zero for quite a long time, this location is probably not suitable for a power plant of 10m³/s. So a large buffer has to be realized, or a much smaller power plant has to be built.

Salt concentration

The salt gradient at the Lauwersoog is quite large. The lake contains fresh water with a very low salinity. The salinity at the Waddensea near Lauwersoog varies slightly around 28 g/l. The variation is probably caused by the fact that the discharge of fresh water onto the Waddensea is not constant. When the outlet sluices are closed the salinity will increase, but when opened, the salinity will decrease because of the mixing that occurs.

Maximum potential

When using the salinities from the previous section in the RED process it should be able to produce 1,0MW per mixed cubic meter of fresh and salt water. When it is possible to use 10m^3/s of both fresh and salt water the total potential will be around 10MW.

Advantages and disadvantages

A disadvantage of this location is the fact that the power plant will be built next to a nature reserve. Furthermore, the plant will largely influence the water balance of the lake. These two facts will make the choice for a Blue energy power plant a politically very sensitive project. Another disadvantage is that not much fresh water is available. For a large-scale power plant this is not enough. This small discharge is at the same time an advantage when building a small power plant; when discharging only 20m^3/s of brackish water onto the Waddensea, it might turn out that this mixes very easily with the Sea. This is an advantage when considering the location of the salt water intake.

Possible design power plant

The design of a power plant at this location might be quite easy. The power plant can be build west of the outlet sluices. Here water from the lake can be easily taken in. For the location of the salt water intake and the brackish water outlet calculations have to be done to determine where these have to be built. This depends mainly on the main currents in the sea, and on the speed with which the brackish water mixes with salt water.

1.6.2 Afsluitdijk

At the Afsluitdijk a large fresh water lake, Lake IJssel, is separated from the Waddensea by a 30 kilometre long dike. In 1932 the lake was formed by closing of the Zuiderzee, by means of the Afsluitdijk. This dike provides a strict separation of salt and fresh water. Lake IJssel covers an area of approximately 1100 km^2. The average depth of Lake IJssel is about 3,5 to 4 meters. This depth varies greatly, from very shallow up to about 7 meters at maximum.

The lake is fed with fresh water from a couple of rivers and canals of which the IJssel is the largest with an average flow of 340m^3/s. Large outlet sluices discharge water from the lake onto the Waddensea. These sluices are located at both ends of the dike.

Flow

The outlet sluice at the east side of the dike, Kornwerderzand, discharges on average 200m³/s onto the Waddensea. The sluices on the west end side of the dike are a little bigger, and discharge almost 250m³/s. Due to water level fluctuations on the Waddensea, discharging the fresh water is not a continuous process. Discharging depends on tide levels on the Waddensea. Furthermore, in summer less fresh water is available than in winter time.

The flow that can be used at this location is quite large. In the present situation the two outlet sluices discharge together approximately 450m³/s onto the Waddensea. Because of the fact that Lake IJssel is quite large, the lake can be used as a buffer in order to absorb differences in the availability of fresh water. Assuming a flow of 450m³/s, and a water level fluctuation on the lake of 50cm provides a buffer of 0,55km³, which is enough to ensure this flow for more than 14 days. This could be enough to guarantee the constant discharge of 450m³/s. Calculations have to show that this flow is really available during the year. A slight change in the discharge distribution of the flow at Lobith can also be applied to guarantee this discharge.

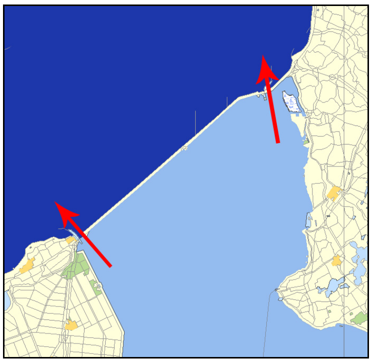


Figure 1.8: *Overview Afsluitdijk*

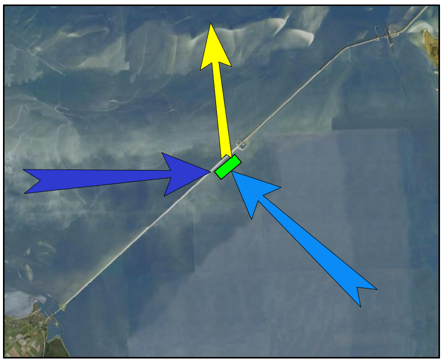


Figure 1.9: *Possible Blue energy plant*

Salt concentration

The salt concentration of Lake IJssel is very low. The lake is only fed with fresh water from rivers and canals. The concentration is around 0,2-0,5g/l. Salt concentrations on the Waddensea are a little difficult to determine. This is caused by the discontinuous discharging process of the outlet sluices. Every time the sluices open their gates, a large fresh water bubble builds up. This bubble influences salt concentrations in the Sea. In a hypothetical case that no water from Lake IJssel is discharged onto the Waddensea, the concentration will be almost as high as the concentration on the North Sea, which is around 28g/l.

Maximum potential

Assuming that the water which is discharged onto the Waddensea (and consequently has a lower salinity) can be refreshed quickly enough (by sea water) it might be possible to generate a gross power of 1MW for every cubic meter of fresh and salt water. With a total flow of 450m³/s this means 450MW, enough for 1,2 million households.

Advantages and disadvantages

A large advantage of this location is the availability of the strict separation between salt and fresh water. Furthermore, fresh water is abundantly available, and with Lake IJssel there is a large buffer which can be used. A disadvantage of this location might be the lack of availability of really salt water. Calculations have to show that the Waddensea is able to refresh the brackish water, which is discharged by the power plant, fast enough.

Possible design power plant

Also at this location the design of the power plant is quite simple. It can be built somewhere along the dike. Most attention has to be paid to the location of the salt water intake, and the discharge location of the brackish water. Maybe it is necessary to build a large embankment in order to separate brackish and salt water. It might even be required to build an extra basin in which the brackish water can be mixed with salt water before it is discharged onto the Waddensea. Another option to separate the salt water intake from the brackish water is to transport the salt water over some distance to the power plant.

1.6.3 IJmuiden

IJmuiden is also a possible location for a large scale Blue energy power plant. In IJmuiden the Noordzeekanaal discharges its water onto the North Sea. This canal is located between Amsterdam, the Capital of the Netherlands, and the city of IJmuiden. It is used by large sea-going vessels which have to enter the port of Amsterdam. The channel is quite large, 15m deep and about 250m wide. In the mouth of this canal a large complex with shipping locks, outlet sluices and a pumping station is situated. This complex separates the canal from the North Sea.

Flow

The outlet sluices discharge the surplus of water onto the North Sea when the tide is low enough. In case of high water levels at sea, and a large discharge in the Noordzeekanaal, the pumping station is used to discharge the water. On average, a flow of $40m^3/s$ can be guaranteed. The total average flow is about $90m^3/s$. In an extreme situation discharges through the outlet sluices or pumping station can be as high as $260m^3/s$.

The water level on the canal is carefully monitored and regulated. The water level is strictly kept at NAP -40cm. At this location fewer possibilities are available for buffering water. With a flow of $40m^3/s$, a canal length of about 26 kilometers, a width of 250 meters, and a water level fluctuation of 20cm a buffer of $1{,}3x10^6$ m^3 can be created. This is enough to provide the power plant for 9 hours. The Markermeer, east of Amsterdam might also be used as a buffer.

Salt concentration

The canal, together with the locks and outlet sluices form a complex system. Because of the fact that the locks are used very frequently a lot of salt water enters the canal. In the canal itself the salt water hardly mixes with fresh water. In fact, fresh water flows on

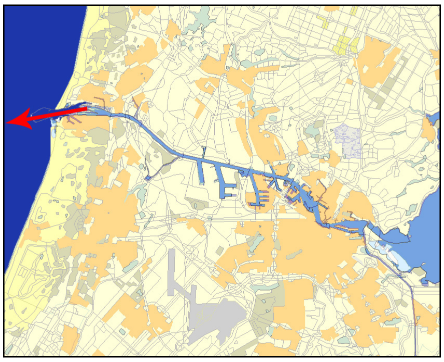


***Figure 1.10**: Overview IJmuiden*

***Figure 1.11**: Possible power plant IJmuiden*

top of the salt water. This implies that near the bottom of the canal the salinity is high, up to about 20g/l. At the surface of the water the concentration of salt is much lower, varying from about 3g/l to 8g/l. By means of the locks, outlet sluices and pumping station the location of the salt tongue can be controlled.

Maximum potential

Salt concentrations in this area are a problem for Blue energy. The fact that water in the canal is layered could be used by taking in salt water from the bottom of the canal, and fresh water from the upper layers. But with the present concentration the potential is quite low. In the most favorite situation the gross power which could be generated from mixing one cubic meter of both fresh and salt water is 0,8MW. Pumping and electrical losses make that the net power is even lower.

In order to make this location suitable for Blue energy the total system has to be changed. One possibility is to make the canal fresh. This could be done by filling the shipping locks with fresh water, instead of salt water. This implies that extra pumps are needed, which means an extra loss. In this situation it might be possible to use about $40m^3/s$ for Blue energy, or a production of approximately 40MW.

Advantages and disadvantages

The biggest disadvantage of this location is that large changes have to be made to the present situation. In addition, extra pumping losses are introduced as a result of which the net power available for the public network is lower.

An advantage of this location is that a strict separation between fresh and salt water is available. Furthermore, building a power plant near the shipping locks is will not be a very big problem in this highly industrialized area.

Possible design power plant

A design for a Blue energy plant in IJmuiden can be made without any problems. Fresh water can be taken in from the canal, under the condition that the system is changed to a total fresh water system, instead of a vertical layered system with fresh water on top of a salt water tongue. Salt water can be taken in from the North Sea side of the shipping locks. The only concern in this case will be the exact location of the salt water intake, and the brackish water discharge point.

Another option might be to design a number of smaller power plants which are located along the channel. These plants can use fresh water from the surrounding areas and salt water from the bottom of the Noordzeekanaal. Calculations have to be done in order to determine what happens with the size and location of the salt tongue in the channel when part of this water is subtracted for Blue energy.

1.6.4 Delta

The Dutch delta is a very complex system of waterways, estuaries, lakes, rivers and channels. The largest part of the flow in the Rhine is discharged trough the Waal and the Lek to the Delta. Also the total discharge of the river Meuse flows to the Delta. Within the delta there are a couple of possibilities for the water to flow to the North Sea.

Flow

The average discharges of the Rhine and Meuse are 2.200m^3/s and 300m^3/s respectively. Most of these discharges flow through the Delta into the North Sea. The Nieuwe Waterweg, west of Rotterdam discharges on average 1.300m^3/s. To the south, outlet sluices in the Haringvliet discharge almost 800m^3/s.

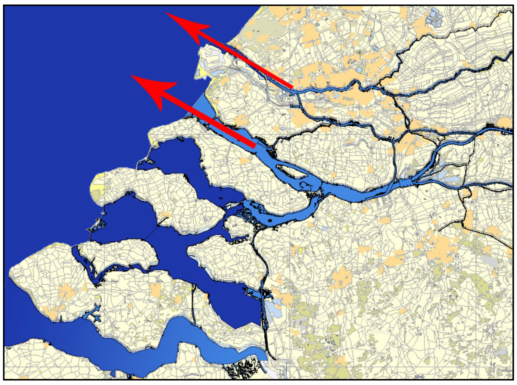


***Figure 1.12**: Overview Delta*

Salt concentration

At a couple of locations in the Dutch delta strict separation structures exist between salt and fresh water. Examples of these are the Philipsdam between the Oosterschelde, Grevelingen and Volkerak, the Oesterdam in the South, and the outlet sluices of the Haringvliet. The Nieuwe Waterweg is an open connection with the North Sea. Tides, water levels, and currents influence the water level, flow, and salt concentration in this canal. The salt tongue in this canal is a dynamic one. It changes position and size depending on the behaviour of the North Sea, and river discharges.

Maximum potential

The Dutch Delta has a very large potential for Blue energy. Because of the fact that on average 2.100m^3/s is discharged onto the North Sea an enormous amount of energy could be generated. The biggest problem in the Delta is the Nieuwe Waterweg. At present most of the water of the Rhine and Meuse flows through this canal in order to control the salt tongue. But because of this salt tongue it is not possible to utilize a Blue energy plant at this location. In order to fix this problem the system has to be changed drastically. When this is done it might be possible to use a large part of the total fresh water discharge for Blue energy. This implies a net power of 2.000MW. When keeping the Delta in its present state it might still be possible to build a Blue energy plant for example at the outlet sluices of the Haringvliet. This would result in a plant with a net power of 500-600MW.

Advantages and disadvantages

A large advantage is the availability of fresh water. The complexity and size of the Delta is also an advantage. Water can be guided through different waterways to the North Sea. At the same time, a disadvantage is the open connection with the North Sea by means of the Nieuwe Waterweg. To use that as a location for Blue energy extensive measures have to be taken.

Possible design power plant

A power plant could be build at a number of locations in the Delta: The Nieuwe Waterweg, Haringvliet, Krammersluizen, Botlek, and the Brielse Meer might all be suitable locations for a power plant. All these locations require different hydraulic structures.

1.6.5 Sewage treatment plant

A last location might be at a sewage treatment plant. The waste product of such an installation is relatively clean and fresh water. When located near the sea this water might be easy to use for a small Blue energy power plant. In The Hague two large installations are located; Harnaschpolder and Houtrust, which together discharge the water onto the North Sea by use of a high-pressure pipeline. The average discharge of these two installations together is approximately 2,5m^3/s. This is a rather small amount compared to the other locations discussed in foregoing sections. Still, this is enough for producing 2,5MW of electricity, enough for almost 7.000 households. Of course, this energy could also be used in the sewage treatment plant itself.

***Figure 1.13**: Sewage treatment plant. Harnaschpolder, Rijswijk*

A big advantage of this small discharge is that the brackish water which is discharged into the sea by the Blue energy plant can mix very fast with the seawater. A cell with brackish or maybe fresh water, which can have negative effects for the supply of salt water, will not have time enough to form in the large amount of salt water.

Because of its small potential this location is not considered in this study.

1.6.6 Summarizing

Locations discussed in sections 1.6.1 to 1.6.4 are suitable for a Blue energy power plant. The characteristics of these locations are summarized in the following table:

	Lauwersmeer	Afsluitdijk	IJmuiden	Delta
Flow to use [m^3/s]	10	450	40	500-2.200
Salinity difference [g/l]	0,3 – 28	0,3 - 28	0,3 – 28	0,3 - 28
Potential [MW]	10	450	40	500-2.000

Table 1.1: *Summury characteristics of possible locations in the Netherlands*

The first row gives characteristics about the flow at the different locations, which might be made available for Blue energy. The second row shows that for every location it should be possible to change the system and environment in such a way that a sufficient separation between the salt and brackish water flow can be created. When this condition is fulfilled the specific power will be approximately 1MW/m^3/s. From these first two rows, the third is determined.

1.7 Dutch delta motivation

The focus of this report is mainly on the large scale application of Blue energy, see also section 2.2. With large scale is meant that the power plant in this design has to be able to deliver at least 100MW to the public network. From Table 1.1 in the foregoing section can be concluded that only two possible locations remain as suitable locations for such a power plant. Lauwersmeer and IJmuiden are interesting locations, but do not have such a large potential as the Afsluitdijk and the Delta.

When considering the fresh water availability it can be seen that the both options score pretty good. Building a power plant at the Afsluitdijk implies that Lake IJssel can be used as a buffer, which is very convenient to overcome fluctuations in the fresh water discharge. The Delta option has on average a much larger flow available than the Afsluitdijk option. When building a 100-500MW power plant it should be possible to make the fresh water flow available. However, for both options this salt water availability has to be confirmed by calculations.

The salt water availability might be a problem in the Afsluitdijk option. Large measures might be needed to assure the separation of salt and brackish water. Because of the complexity of the Delta system, with all the lakes, canals, and estuaries, it is assumed that these measures will be less radical.

Considering these criteria it can be seen that the Delta is slightly preferable compared to the Afsluitdijk. This fact, combined with the fact that the total potential of the Delta is much higher makes that the focus of this report is aimed at the Delta.

Chapter 2

Objectives of study

2.1 Project description

Blue energy has never been applied before on a large scale. It was in june 2008 that the first test on a scale larger than a laboratory scale has started[1]. But most of the research is still done by scientists in laboratories[2]. This makes that no guarantees can be given about the feasibility of Blue energy on a large-scale basis. However, the research results from the last couple of years are very promising. Membrane prices, which at the beginning of this century were incredibly high, have dropped considerably. Performances of the membranes and the technology used, have improved seriously as well. As a result, more and more people believe in the overall feasibility of Blue energy.

Research to the technique of Blue energy is done by Wetsus in Leeuwarden, The Netherlands, and by Statkraft in Norway. But the feasibility of a power plant is highly depended on the actual site of the power plant. The site has to meet various criteria. It is not totally clear yet what conditions need to be fulfilled by a specific site in order to be a suitable location for Blue energy.

Furthermore, as discussed in the previous chapter, the Dutch Delta seems to be a logical location for Blue energy because of the large fresh river water flow that meets the North Sea. No insight exists whether it is possible to build a feasible large scale Blue energy power plant in this area.

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[1] In June 2008 a pilot (1kW) at Wetsalt, Harlingen (The Netherlands) has been opened by the Minister of Trade
[2] Research to the RED process is done by Wetsus, Leeuwarden (The Netherlands)

2.2 Objectives

The main goal of this report is to discuss the feasibility of a Blue energy power plant in the Dutch Delta. However, this feasibility is not determined by the technology of Blue energy, but on the conditions which need to be fulfilled by a certain location to make Blue energy successful at that specific location. So the objectives of this report read:

"The first objective of this study is to gain insight in the conditions that need to be fulfilled by a specific location in order to construct a feasible large-scale power plant at that location."

"The second objective of this study is to find a suitable location in the Dutch Delta and determine whether and on which scale this location is feasible."

2.3 Research strategy and study questions

To reach these objectives a number of steps have been taken during this study. In order to deal with all aspects of Blue energy it is important to understand the techniques that are used to generate electricity in a Blue energy power plant. As discussed in the previous Chapter two techniques can be used in a power plant, PRO and RED. In this study the choice is made for RED because this technique is being developed in The Netherlands, which means easy access to crucial information. However, the conditions that need to be fulfilled by a location to be suitable for a power plant using PRO are approximately the same. Part B of this report is the result of the research done to RED. It covers the most important aspects when considering a RED power plant. In the second Chapter of Part B a tool is described which can be used to determine power plant parameters when a location is considered feasible for Blue energy.

The second step is to find a suitable location in the Dutch Delta. Therefore, extensive research has been done to the Delta system as a whole. From this analysis five locations have been found in the Delta area where a power plant could be constructed. From these locations one is chosen to deepen out its feasibility.

When the power plant at the chosen location turns out to be feasible the parameters of the power plant are determined with the help of the tool which was described in Part B. Last, the economic feasibility of the power plant is determined.

PART B

General design guide

Chapter 3

Boundary conditions

The first objective of this study is to gain insight in the conditions that need to be fulfilled by a specific location in order to construct a feasible power plant. Knowledge about the principles of Blue energy and the operation of such a power plant is of great importance to determine these conditions. Figure 3.1 gives a schematical overview of a Blue energy power plant and its components. In this chapter these components are all shortly discussed. In section 3.1 the salt content of both incoming water flows is discussed followed by the size of these flows in section 3.2. The separation of water flows is dealt with in section 3.3. Because of the fact that some energy is needed to push the fresh and salt water through the Blue energy installations pump sections are needed which is described in section 3.4. Furthermore, the water has to be filtered before it can flow into the membrane installations. This is the subject of section 3.5. Concluding this chapter is sections 3.6, which deals with some RED characteristics.

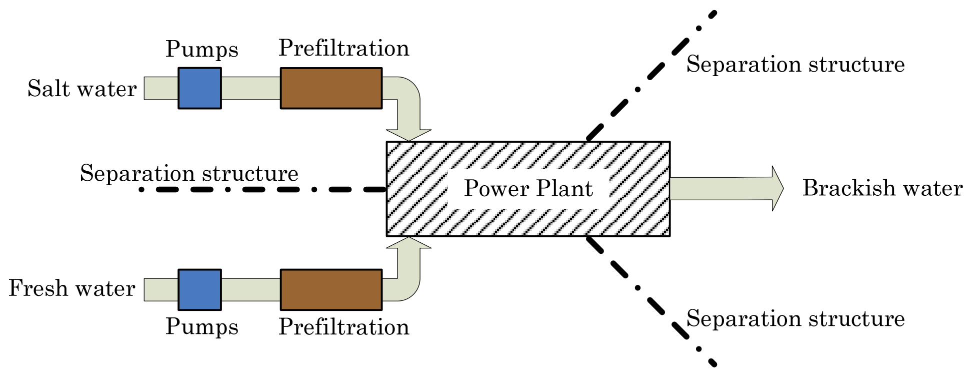


Figure 3.1: *Schematic overview of a Blue energy power plant*

3.1 Salt content

In section 1.5 can be clearly seen that the potential of Blue energy depends largely on the salt concentrations in both flows of water. A river which is not influenced by the sea has a concentration of approximately 0,3-0,5g/l NaCl. On the other side, the concentration of the North Sea near the coast is approximately 28g/l. When using these types of water the gross power which can be generated with reversed electro dialysis is approximately 1,5MJ (Post, Veerman et al. 2007).

From the relation in Graph 1.1 can be seen that a larger difference in salinity results in a larger potential. In analogy with hydropower, this salinity difference can be seen as the water level difference across a dam; more power can be generated with a larger difference. When the difference in the concentration decreases the potential also decreases. For this study it is assumed that whenever the concentration on the fresh water side increases above 1g/l NaCl the location is not economically feasible. The restriction on the salt water side is set to 25g/l. In a worst case scenario, when using these concentrations, the gross power which can be generated is only 1,15MJ for every cubic meter of fresh and salt water.

3.2 Flow

Blue energy uses the difference in free energy between fresh and salt water. When designing a large scale power plant a lot of both fresh and salt water is needed. One of the objectives of this report is to design a large-scale power plant. Large scale is in this study defined as a power plant which can deliver 100-500MW to the public network. The basis for this choice lies in the fact that this is a size which corresponds to a size of an average conventional power plant. This large scale condition implies that large water flows are generated. Both on the salt and fresh water side a flow of approximately 100-500m^3/s of water is needed. These flows have to be directed to the power plant. Furthermore, the effluent of the plant is a large volume of brackish water, in this case at least 200-1.000m^3/s. The system has to be able to deal with these volumes of water.

3.3 Separation of water flows

In the previous section two incoming water flows are discussed, salt and fresh water. Because of the fact that the potential of a Blue energy plant depends on the salinity gradient it is important to separate both flows from each other. To achieve the largest gradient the best way to separate fresh water and salt water is with a fixed structure. This can be a dam, a dike, sluices, or a combination of these. In this way the fresh water is not influenced by salt water and vice versa, resulting in the largest possible gradient and potential.

Discharging the brackish water is a second important issue. When discharging the effluent of the power plant directly onto the sea will result in a bubble with a lower salt concentration. When the intake for salt water is located within this bubble the potential for a Blue energy plant will decrease (recirculation will occur). So, discharging the brackish water has to be separated from the salt and fresh water flows as well.

3.4 Pumping

In order to push the salt and fresh water through the installation (membrane installations, prefiltration, and pipelines) both incoming water flows need to have a certain energy level. Research and tests show that over the total installation a difference in energy level of five meters water column has to be available. This implicates that both the fresh and salt water need to be pumped up to a level of 5m water column above the highest water level of the area where the brackish water is discharged, see Figure 3.2.

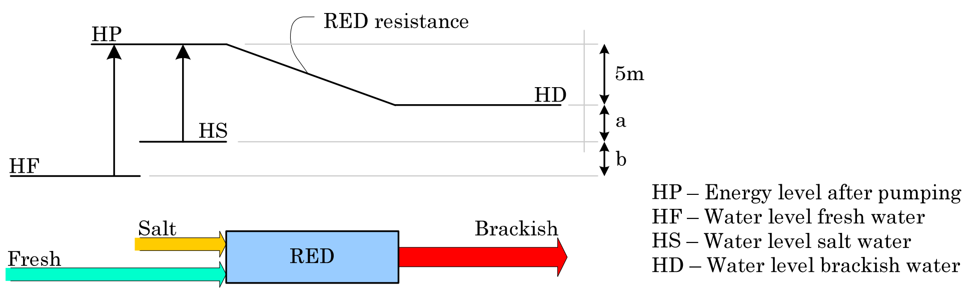


Figure 3.2: *Energy levels within a Blue energy power plant*

3.5 Prefiltration

When using RED for electricity generation large surfaces of membranes have to be used. In order to make the process space efficient these membranes and water cells are piled up into a so called REDStack, see section 1.3.1. The cells for fresh and salt water are approximately 0,2 millimetres thick. Within these cells both fresh and salt water flow along the membranes, it will not pass through the membranes. To prevent these cells to be obstructed by material which is carried along with sea or river water, particles larger than 50 micron have to be filtered out of the water. Prefiltration of both river water and sea water is therefore required for running a Blue energy plant.

No restrictions exist concerning the nature of the substances carried with the water through the RED cells. All substances which are found in river and sea water can pass through a REDStack, with the only limitation that all particles larger than 50 micron have to be filtered out.

A study performed by Wetsus showed that micro-filtration is the best way to filter both the fresh and salt water. The choice for this method of filtration is based on three criteria. Firstly, energy consumption of the filtration method is important. Micro-filtration is not very energy consuming. It uses a pressure head of only 20cm water column to filter the water. Secondly, space needed for filtration should not be too large.

Space usage with micro-filtration is not quite efficient, but still it is not larger than the space needed for membrane installations. Finally, costs are a very important aspect. Micro-filtration turns out to be very cost effective.

The principle of micro-filtration is based on separation of suspended particles from a fluid with the use of a filter. This filter can be a layer of sand, but also a fine wire mesh. Because of the fact that filtration speed in a sand layer is very low the choice is made to use a wire mesh, which has a much larger filtration speed. The mesh is winded around a drum, like a centrifuge. The difference with a centrifuge is that the drum rotates very slowly, and the water flows freely through the mesh. An example of such a drum, with a diameter of approximately 5m, is shown in figure.

Figure 3.3: *Drum for usage in the prefiltration installations*

The drum is placed in a box. The incoming water is pumped into the centre of drum and flows radially through the mesh into the box. The dirt particles are trapped in the mesh. From the box the water is discharged to the next section of the power plant.

On a regular basis, the mesh is cleaned by a couple of nozzles which are placed just above the drum. These nozzles clean the mesh with high pressure jets. This is the most energy consuming part of the prefiltration installation. The water which now contains all dirt particles is collected in a funnel-shaped debris collector which is installed in the upper part of the drum.

3.6 RED characteristics

- Theoretically about 1,5MW is available for electricity generation when mixing one cubic meter of sea and river water (mixing ratio r=1) every second in a Blue energy plant. In the installation a number of losses occur. Test and research results show that 1,2MW/m3/s can be produced with a mixing ration r = 1. It has to be checked that the salt concentrations, occurring at a certain location, are such that the theoretical 1,5MW can be won. See also Graph 1.1

- The ideal mixing ratio, r = Qfresh/Qsalt for RED is not exactly one, but practical considerations make that a ratio of 1 is more convenient
- Specific power of a membrane: At present 1,5W/m2. In the next few years it is possible to achieve a specific power of 2-3W/m2
- Both the fresh and salt water have to be free of particles larger than 50 micron

Chapter 4

General design guide

In the previous chapter a number of components of a Blue energy power plant have been discussed. In this chapter a general design guide is given to determine the important characteristics of these components. Section 4.1 starts with a determination of the power which can be generated by a certain plant. This is followed by the membrane size in section 4.2. Sections 4.3 and 4.4 then deal with the prefiltration area and the pump area respectively. Finally the total size of a power plant can be calculated which is done in section 4.5. The last section gives an overview of all formula's which are presented in this chapter.

4.1 Power generation

As mentioned in section 1.5 the theoretical available power when every second mixing one cubic meter of fresh water with one cubic meter of salt water is 1,5MW. Test and research results show that 1,2MW per cubic meter fresh and salt water can actually be won with the RED process. This is called SP_{gross} and has the dimension of power per cubic meter per second [MW/m^3/s], which corresponds to energy per cubic meter [MJ/m^3].

$$SP_{gross} = 1,2 \quad \frac{\text{MW}}{\text{m}^3/\text{s}} \tag{4.1}$$

Some of the energy generated in the power plant is needed for pumping. From Figure 3.2 in section 3.4 can be seen that both salt and fresh water need to be pumped up. Both flows have to be pumped up to a level of five meters water column above the water level of the basin where the brackish water is discharged. In the most unfavorable position, with a high water level at the brackish side, and low water levels at the intake sides, the power needed follows from

$$SP_{pump} = \rho \cdot g \cdot H \quad \frac{\mathrm{W}}{\mathrm{m^3/s}}$$

$$SP_{pump;salt} = \rho_{salt} \cdot g \cdot (HHD - LHS + 5) \quad \frac{\mathrm{W}}{\mathrm{m^3/s}} \tag{4.2}$$

$$SP_{pump;fresh} = \rho_{fresh} \cdot g \cdot (HHD - LHF + 5) \quad \frac{\mathrm{W}}{\mathrm{m^3/s}} \tag{4.3}$$

where

$SP_{pump;salt}$	specific power needed for salt water pumps
$SP_{pump;fresh}$	specific power needed for fresh water pumps
ρ_{salt}	density of salt water, 1.025 kg/m^3
ρ_{fresh}	density of fresh water, 1.000 kg/m^3
HHD	highest water level brackish water side
LHS	lowest water level salt water intake
LHF	lowest water level fresh water intake

Adding (4.2) and (4.3) gives the total specific power (in $\frac{\mathrm{W}}{\mathrm{m^3/s}}$) needed for pumping:

$$SP_{pump;total} = \rho_{salt} \cdot g \cdot (HHD - LHS + 5) + \rho_{fresh} \cdot g \cdot (HHD - LHF + 5) \quad \frac{\mathrm{W}}{\mathrm{m^3/s}} \tag{4.4}$$

This is the net power which is needed for pumping the water through the prefiltration and membrane installations. Within the pump sections a number of losses occur. First, the pump itself has an efficiency of approximately 85%. Second, the engine has an efficiency of 95%. Finally, a frequency converter, which is needed in order to be able to change the flow, has an efficiency of 95%. This gives an overall pumping efficiency of 77%. With this information one can find the net specific power which can be delivered to the public network:

$$SP_{net} = SP_{gross} - SP_{pump;total} \cdot \frac{1}{\eta_{pump} \cdot \eta_{engine} \cdot \eta_{fr.converter}} \qquad \frac{\mathrm{MW}}{\mathrm{m^3/s}} \tag{4.5}$$

where

SP_{net}	net specific power
η_{pump}	efficiency pump
η_{engine}	efficiency engine
$\eta_{fr.converter}$	efficiency frequency converter

The total power which can be delivered to the network by a Blue energy plant is:

$$P_{gross} = Q \cdot SP_{gross} \quad \mathrm{MW} \tag{4.6}$$

$$P_{net} = Q \cdot SP_{net} \quad \mathrm{MW} \tag{4.7}$$

$$E = 8{,}76 \cdot \mu \cdot Q \cdot SP_{net} \quad GWh \tag{4.8}$$

in which

P_{gross}	gross power generated by the power plant
P_{net}	net power delivered to the public network
Q	flow of fresh and salt water
E	Total energy generated by the power plant in one year
μ	Factor for the availability of water

The factor 8,76 in equation (4.8) arises when converting power (in MW) to an amount of energy (in this case GWh) in a year. The factor μ is a factor for the availability of water and has a value between 0 and 1. In an ideal situation this factor is 1, but it can happen that in certain periods of the year the fresh water availability is not sufficient for running the power plant at full power. In that case the power plant has to run at a lower efficiency, which causes μ to decrease (it is averaged over the year). See also Chapter 7.

4.2 Membrane surface

Now that the total power of the Blue energy plant is calculated it is possible to determine how much membrane is needed for the power generation:

$$A_{membrane} = \frac{P_{gross}}{SP_{membrane}} \quad \text{m}^2 \tag{4.9}$$

As mentioned in section 1.3.1 the membrane is piled up in REDStacks. These stacks are placed together in a box with the size of sea container. Such a box is able to hold enough membrane for generation of 200 kW. With the total gross power known from equation (4.6) the number of units can be calculated as

$$U = \frac{P_{gross}}{200} \frac{MW}{kW} = 5 \cdot P_{gross} \tag{4.10}$$

where

U Number of 200 kW units in the power plant (dimensionless)

4.3 Prefiltration area

The filter for micro-filtration can filter water at speeds of approximately 30 to 50m/h. When filtering a cubic meter of water the mesh surface can be calculated as follows (take care of the dimensions):

$$A_{mesh} = \frac{Q}{v_{filter}} \quad \text{m}^2 \tag{4.11}$$

where

A_{mesh} surface needed for prefiltration
v_{filter} filter speed

As explained in section 3.5 in the upper part of the drum a funnel-shaped debris collector is installed. This collector collects the water which has cleaned the mesh. Because of this, the water level of the water which has to be filtered cannot be as high as the drum itself. This means that not the total circumference of the drum can be used for filtration of the water. It is assumed that approximately 70% of the circumference of the drum can effectively be used for prefiltration.

Furthermore, the mesh of this filtration method is very thin. Consequence of this is that the mesh has to be supported at regular small distances (see also Figure 3.3 in section 3.5), which makes that not the total surface of the mesh can be used to filter the water. For now it is assumed that 25% of the mesh surface is used for support of the mesh. When using a drum with a fixed diameter d the length of this drum can be calculated as

$$L_{drum} = \frac{A_{mesh}}{2 \cdot \pi \cdot \frac{d}{2} \cdot 70\% \cdot (100-25)\%} \quad \text{m} \tag{4.12}$$

The diameter of the drums varies between 0,8 to 4m, and the length can be chosen between 1,2 and 6m. Note that for both fresh and salt water prefiltration installations are needed, so this calculation has to be done for both flows. With a mixing ratio of 1:1, the size of the drums for salt water will be the same as for fresh water.

Assuming that drums with a diameter of 2 meters are used, the drums can be placed in sea containers. Using a filter speed of 30 meters per hour, a length of the containers of 12 meters, it can be found that the number of units (sea containers) for prefiltration is approximately the same as for membrane installations (see equation (4.10)).

4.4 Pump area

For the pump area no exact information is yet available about the area which is needed. For now it is assumed that it takes at most 50 % of the surface needed for membrane installations.

4.5 Total power plant area

In the previous sections a number of equations are given with which it is possible to calculate the main characteristics of the power plant. The total area needed for the power plant can be calculated from these.

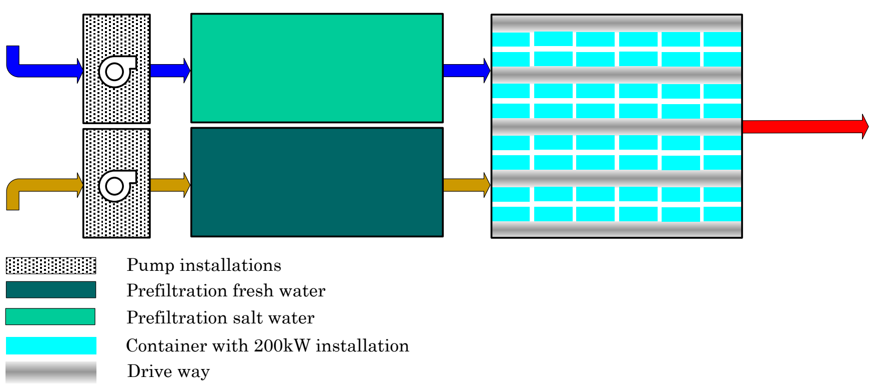


***Figure 4.1**: Possible layout of a small power plant*

The membrane installations are installed in units with the size of 40ft containers. Equation (4.10) gives a relation for the number of units which have to be installed. Each 200kW unit uses a surface of approximately 30m², equivalent with a standard shipping container. For accessing and changing the units, free space is required in the power plant. It is assumed that approximately 2/3 is used for the 200kW units, and 1/3 for driveways and free space. Considering different kinds of lay-outs of the power plant shows that this is a reasonable assumption. In Figure 4.1 a possible layout is shown of a power plant, including prefiltration and pumps. In the right part of the figure the actual power plant with the 200kW units are shown. This layout can be changed in almost every way the user likes.

With these assumptions the total floor surface for the membrane installations can be calculated as

$$\begin{aligned} A_{membrane\ installations} &= 30 \cdot U + 50\% \cdot 30 \cdot U \\ &= 45 \cdot U \quad \mathrm{m}^2 \end{aligned} \tag{4.13}$$

In section 4.3 is concluded that the area needed for prefiltration is the same as for the membrane installations.

$$A_{prefiltration} = 45 \cdot U \quad \mathrm{m}^2 \tag{4.14}$$

Section 2.4 concluded that for pumps about 50% of the surface for membrane installations is needed.

$$\begin{aligned} A_{pumps} &= 50\% \cdot 30 \cdot U \\ &= 15 \cdot U \quad \mathrm{m}^2 \end{aligned} \tag{4.15}$$

For the total area needed for the power plant it is assumed that another 10% of free space is needed. With this information it is now possible to calculate the total surface for a Blue energy plant as

$$\begin{aligned} A_{total} &= (A_{membrane\ installations} + A_{prefiltration} + A_{pumps}) \cdot 110\% \\ &\approx 115 \cdot U \quad \mathrm{m}^2 \end{aligned} \tag{4.16}$$

This equation shows that for every 200kW unit a total area of 115m² needs to be available.

The height of the total factory is very low. The area with the membrane installations has to be high enough for a shipping container and some supplementary installations above the containers. This would mean a height of 5 meters at maximum. When the containers are placed in such a way that replacing one container means that it has to be lifted over the other containers the height of the factory will increase to 10 meters at maximum.

A way of reducing the total area which is needed for the power plant is building the prefiltration installations on top of the membrane installations area. These areas have approximately the same size which makes this measure easy to implement. Consequently, the building for will become higher, up to approximately 15m. A disadvantage of this measure is that the structure and foundation for the power plant has to made stronger, due to the large water quantities in the upper parts of the building.

4.6 Summary design formulae

For calculation of the size of a random power plant some equations are derived in the previous section. In the following table these are summarized. With this table, a power plant with a random size can be calculated.

Parameter	Formula
Theoretical specific power to be won from mixing 1m³ fresh water with 1m³ salt water	$SP_{gross} = 1{,}2 \ \frac{\text{MW}}{\text{m}^3/\text{s}}$
Spefic power needed for pumping	$SP_{pump;total} = \rho_{salt} \cdot g \cdot (HHD - LHS + 5) + \rho_{fresh} \cdot g \cdot (HHD - LHF + 5)$
Net specific power	$SP_{net} = SP_{gross} - SP_{pump;total} \cdot \frac{1}{\eta_{pump} \cdot \eta_{engine} \cdot \eta_{fr.converter}} \ \frac{\text{MW}}{\text{m}^3/\text{s}}$
Gross power to be generated	$P_{gross} = Q \cdot SP_{gross}$ MW
Net power available of the network	$P_{net} = Q \cdot SP_{net}$ MW
Number of 200kW units	$U = \frac{P_{gross} \ MW}{200 \ kW} = 5 \cdot P_{gross}$
Prefiltration area (take care of the dimensions)	$A_{mesh} = \frac{Q}{v_{filter}}$ m² $L_{drum} = \frac{A_{mesh}}{2 \cdot \pi \cdot \frac{d}{2} \cdot 70\% \cdot 75\%}$ m
Surface membrane installations	$A_{membrane\ installations} = 45 \cdot U$ m²
Surface prefiltration	$A_{prefiltration} = 45 \cdot U$ m²
Surface pump area	$A_{pumps} = 15 \cdot U$ m²
Total area needed for the power plant	$A_{total} \approx 115 \cdot U$ m²

Table 4.1: *Summary design formulae*

PART C

Blue energy in Dutch Delta

Chapter 5

Dutch Delta

The Dutch delta is a complex system of rivers, waterways, open and closed estuaries, and high-water-level protection works (see Figure 1.12). The rivers Rhine and Meuse flow through this Delta to the North Sea. Within this Delta a number of locations might be feasible for a Blue energy power plant. In order to find these suitable locations insight has to be created in the total system and its use. Section 5.1 deals with this system description. Furthermore salt concentrations are an important factor for Blue energy, so an overview of these concentrations in the Delta will be given in section 5.2. Because Blue energy will only be feasible on a large scale basis after 5-10 years a couple of possible future scenarios will be given in sections 5.3 to 5.6. In section 5.7 a number of locations in the Delta area are discussed as potential locations for Blue energy. In the last section, one of these alternatives is chosen to deepen out its potential.

Appendix A gives an overview of the topography of the Delta. When the reader is unfamiliar with certain names in this chapter, please check this appendix.

5.1 System description

The river system of The Netherlands mainly consists of two rivers. The first, and also the largest one, is the river Rhine, which enters the country at Lobith near Arnhem at the German border, with an average flow of 2.200m^3/s. This river is divided in three river branches which are described below. The second river is the Meuse, which enters from Belgium near Maastricht, in the region of Limburg. This river is a small one with an average discharge of 320m^3/s, which is far less than the river Rhine. This volume flows directly to the Biesbosch and flows out in the North Sea through the Haringvliet.

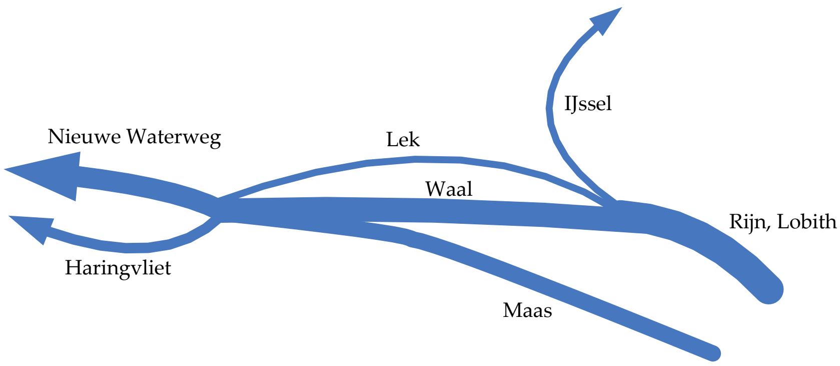


Figure 5.1: *Schematic view of rivers Rhine and Meuse*

5.1.1 Overview River Rhine

In Figure 5.1 a schematic overview of the river Rhine (Rijn) is given. It enters the country near Lobith at the German border. The flow is divided over a couple of river branches. The first branch is the river IJssel, which has a length of approximately 125km and is directed northwards. The mouth of the river is located near Kampen and it flows out in Lake IJssel (IJsselmeer).

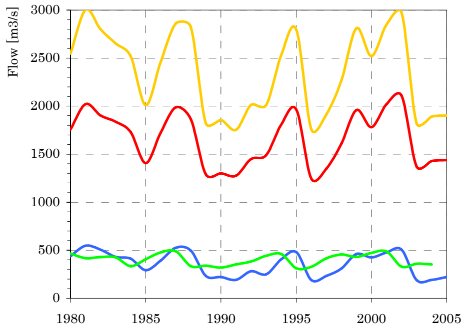
The main part of the Rhine water flows through the Lek and the Waal. These two rivers split in the eastern part of the country, and converge again in the western part of the country. Within the Dutch Delta the water can be discharged to the North Sea in two different ways. The northern branch is called “Nieuwe Waterweg.” This is an open connection with the North Sea. A large part of the total discharge flows through this part of the Delta. Furthermore, the water can be discharged through the Hollans Diep and Haringvliet. At the mouth of the Haringvliet large outlet sluices are located. When the water level at the North Sea is low enough these sluices can be opened to discharge water from the Haringvliet into the Sea. These sluices are the main instrument to control the flow of the Rhine. In closed situation almost the total flow will pass through Rotterdam and the Nieuwe Waterweg. When opened, part of the flow is directed to the Haringvliet.

A negligible small flow is discharged to the Westerschelde through the sluices of Bath (not shown in the figure). This flow is so small that it is not considered in this study.

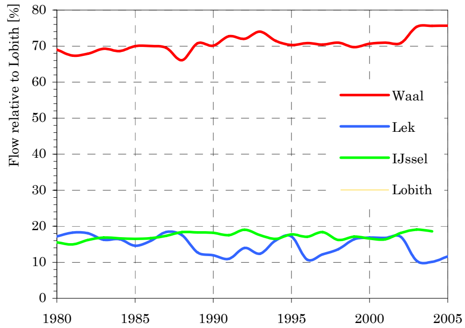
5.1.2 Discharge

In Appendix B the average flow at Lobith is presented in a graph. From this figure can be seen that the average flow is around 2.200m^3/s over the 20th century. In summer the average flow is a little less, about 1985m^3/s, and in winter a little higher. The maximum flow is much higher, in some years more than five times as high as the average flow. In the 20th century the highest recorded flow was 12.600m^3/s. Minimum flow at Lobith is just below 1.000m^3/s. In 1947 the lowest flow (620m^3/s) was recorded.

In the graphs below the discharges of the different Rhine branches can be seen. In Graph 5.1, absolute values of the average flows are plotted. From the graph it is clear that the discharge of the three different river branches follows discharges at Lobith directly. The second graph shows the discharge of each river branch relative to the discharge at Lobith. From this graph can be concluded that the rivers IJssel and Lek both take account of approximately 15% of the discharge of Lobith. The remaining 70% flows through the Waal to the Delta area.



***Graph 5.1**:Absolute flow [m³/s] of the different Rhine branches*



***Graph 5.2**: Flow [%] of Rhine branches relative to the flow at Lobith*

Within the Delta there are a couple of possibilities for discharging the water to sea. As mentioned before, a small part of the total river discharge will flow to the Bathse Spuisluizen at the Westerschelde, which is not considered here. Both the Nieuwe Waterweg and the Haringvliet are used to discharge most of the Rhine water to the North Sea. The exact discharges depend on the situation, and can differ from day to day. This is explained in the following section.

5.1.3 Policy and management

The policy which is pursued in the Netherlands concerning the discharge of the large river branches is quite simple[1]:

- The discharge of the Nieuwe Waterweg should, when possible, be equal to or above 1.500m3/s
- In a situation with a high river flow (at Lobith) the water has to be discharged to the North Sea as soon as possible

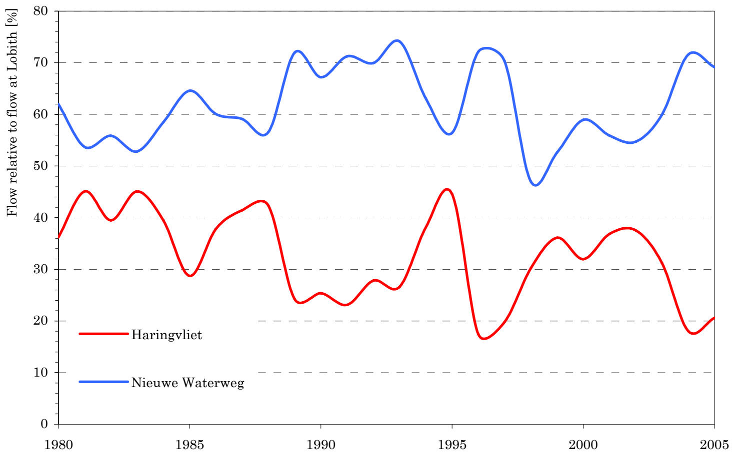
The Nieuwe Waterweg is an open connection with the North Sea. Seawater can flow freely into the country during high tide. In its normal state the transition from salt to fresh water is somewhere in the city of Rotterdam. In case of extreme high water levels at the North Sea, together with low river discharges, salt water can intrude the country as far as Gouda. This is not a desirable situation because water intakes for agriculture, potable water and industry cannot be used when the salinity is too high. In a near future this situation, which is nowadays not a regularly occurring situation, might occur more often. Sea level rise and changing river regimes, due to climate changes, make that salt water can intrude the country further and more regularly (Beijk 2008).

To prevent this, the flow through the different Rhine branches is, in its normal state, guided directly to the Nieuwe Waterweg and into the North Sea. In this way the salt intrusion into the delta can be controlled. The discharge is kept above 1.500m³/s as long as possible. The sluices at the mouth of the Haringvliet are used to control this. From

[1] This is confirmed by verbal communication with experts from Rijkswaterstaat

the control schedule of these sluices can be found that the sluices are opened above a discharge of 1.200m³/s at Lobith. The sluice opening is then 25m², which is very small. Below this discharge, the sluices are closed and the total Rhine flow is guided to the Nieuwe Waterweg. Only at 1.800m³/s or more the sluice opening is increased. This implies that part of the total flow is discharged through the Haringvliet into the North Sea.

In Graph 5.3 this can all be seen clearly. In years with a low average flow at Lobith, for example 1989-1993 (see also Graph 5.1), the largest part of this flow, about 70% is directed to the Nieuwe Waterweg. As mentioned before, this is done in order to control salt intrusion, by keeping the flow around 1.500m³/s in the Nieuwe Waterweg. Result of this is that in the same period Haringliet discharges are low, around 25%.



***Graph 5.3:** Discharge of Haringvliet and Nieuwe Waterweg, relative to the flow at Lobith (which is set to 100%)*

In a situation with high discharges at Lobith, for example 1999-2002, the absolute flow in the Nieuwe Waterweg is only slightly higher than with low average flow at Lobith, but the Haringvliet discharge increases considerably.

From the above can be concluded that the flow through the sluices of the Haringvliet is inversely proportional to the flow through the Nieuwe Waterweg.

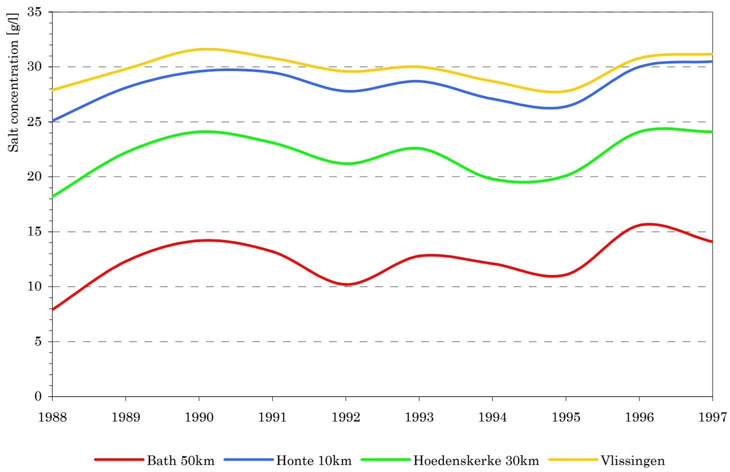
5.2 Salt concentration in the Delta

For Blue energy a gradient in salt concentration, or salinity is needed. A large difference means a large potential. In order to find a suitable location for a Blue energy power plant insight has to be created in the occurring concentrations in the Dutch Delta. The Delta consists of a number of large estuaries. Some are open and are influenced by water from the North Sea. Others are closed, or only open in order to drain fresh water into the sea. Furthermore, there are a couple of lakes, river branches, and channels among which of course the Nieuwe Waterweg, the most important canal for discharging Rhine flow. In the following sections each estuary or lake, river branch and channel will be dealt with, from south to north.

5.2.1 Westerschelde

The Westerschelde is an open estuary. The reason that it is not closed within the framework of the Delta works is that the port of Antwerp has to be easily accessible. Furthermore, the Westerschelde is the mouth of the river Schelde. This river rises in Northern France and flows through Belgium to Antwerp and into the Westerschelde. On average, the Schelde discharges 125m^3/s onto the Westerschelde. Near Bath, an outlet sluice is located. This sluice discharges fresh water from the Bathse Spuikanaal and Markiezaatsmeer onto the Westerschelde. On average only 10 to 20m^3/s is drained by these outlet sluices.

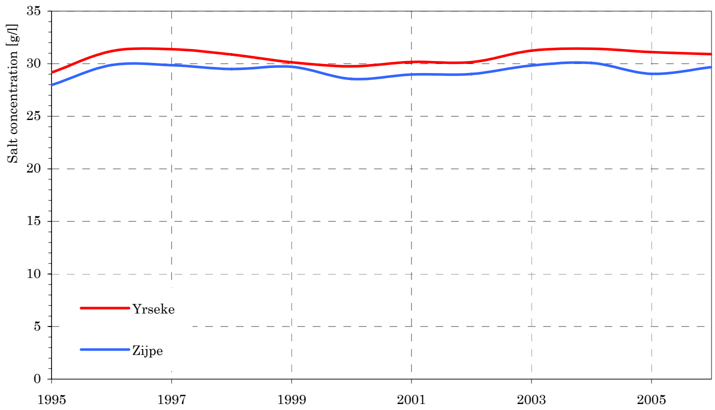
Due to the influence of the fresh water from the Schelde en Bathse spuikanaal the salinity along the Westerschelde has a large gradient. Near Vlissingen at the North Sea the salinity is the same as on the sea. Near Bath, 50km further into the country, the salinity is less than half the salinity at Vlissingen. This can be seen in Graph 5.4



Graph 5.4: *Salt concentration along the Westerschelde. Distances mentioned in the graph are measured from Vlissingen, along the centerline of the Westerschelde*

5.2.2 Oosterschelde

The Oosterschelde is just like the Westerschelde an open estuary. In contrast with the Westerschelde, the Oosterschelde can be closed of from the sea in case of a storm surge. A large storm surge barrier has been built for this purpose at the mouth of the Oosterschelde. Another difference with the Westerschelde is that there are no major fresh water flows which enter the Oosterschelde. This makes that the total estuary is influenced by the sea. The salinity is everywhere almost as high as at the mouth of the estuary, where it has a value of about 28-30g/l. In Graph 5.5 two locations are shown where the salinity is measured over a couple of years. These locations are located at two land inward ends of the Oosterschelde. Zijpe is located near the Krammersluizen, where the Oosterschelde is connected via sluices in the Phililpsdam to the Volkerak. Yrseke is located at the south-east end of the Oosterschelde near the Oesterdam.



Graph 5.5: *Salt concentration Oosterschelde*

5.2.3 Veerse Meer

In between North and South Beveland/Walcheren, just south of the Oosterschelde the Veerse Meer can be found. This is an artificial lake, which was formed after closing of the Veerse Gat with a dam within the scope of the Delta Works. On the east side it used to be separated from the Oosterschelde by the Zandkreekdam. Since 2004 this dam has been opened a little to allow salt water form the Oosterschelde to enter the Veerse Meer. Up to 2004 the water was brackish with a varying salinity. Nowadays the salinity has increased to almost the same level as the Oosterschelde.

5.2.4 Grevelingenmeer and Volkerak

The Grevelingenmeer is a large lake in between Schouwen Duiveland and Goeree Overvlakkee, which was originally planned to be a fresh water lake. It is closed of by the Brouwersdam from the sea. In 1978 a sluice in the dam has been opened to allow sea water from the North Sea into the Grevelingenmeer. The lake has become a salt water lake with a salinity which is the same as the North Sea.

At the east side, the Grevelingenmeer is closed of by the Grevelingendam. East of this dam the Volkerak is located. This is a fresh water lake which is connected via the Volkeraksluizen (ship locks) to the Hollands Diep and Haringvliet.

5.2.5 Haringvliet

As mentioned before, the Haringvliet is used to discharge large quantities of fresh water to the North Sea. At the mouth of the Haringvliet large outlet sluices are build which are only opened in case of a large Rhine discharge at Lobith and low tide. In this way there is no intrusion of salt water into the Haringvliet. However, section 5.5 discusses the changing management of the outlet sluices, which will result in some salt intrusion.

5.2.6 Nieuwe Waterweg

Last interesting part of the Delta is the Nieuwe Waterweg. This channel forms together with the Nieuwe Maas a waterway connection between Rotterdam and the North Sea. It is an open connection, so seawater can intrude freely into the country. As already mentioned before, with high sea levels and low river discharges, salt water can come as far as Gouda. In a normal state the transition between salt and fresh water is located in the centre of Rotterdam city. Because the salinity varies a lot along the Nieuwe Waterweg and Nieuwe Maas, it is not plotted in a graph.

5.2.7 Overview of salt concentrations in Delta

In Figure 5.2 salt concentrations which have been described in the previous section are shown schematically in a map. The areas with totally salt water, sea water, are clearly shown in blue. This corresponds to a salt content of 29g/l and higher. White represents areas with fresh water (0,3g/l).

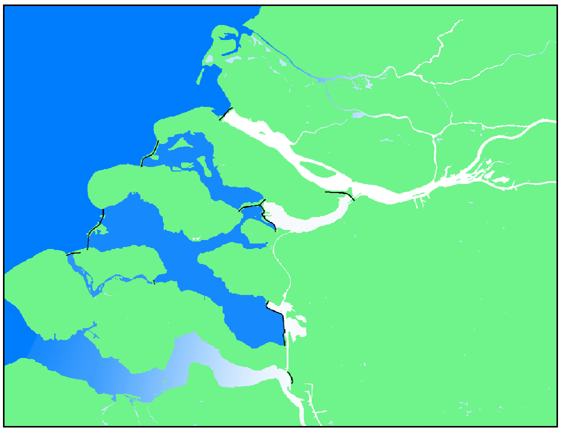
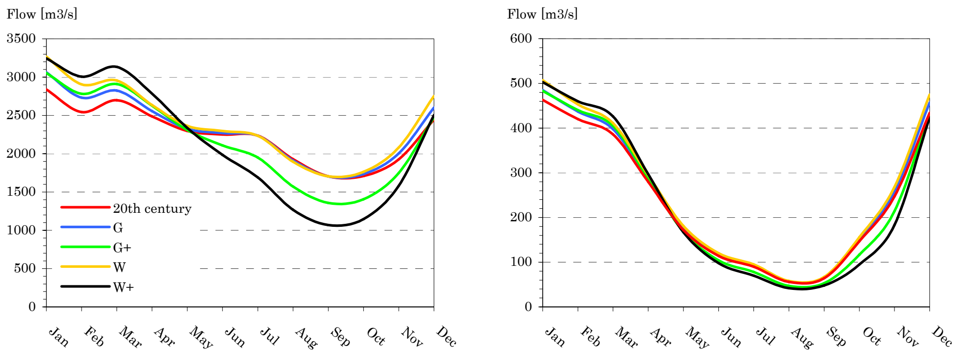


Figure 5.2: *Overview salt concentrations in Delta; white represents fresh, blue represents salt*

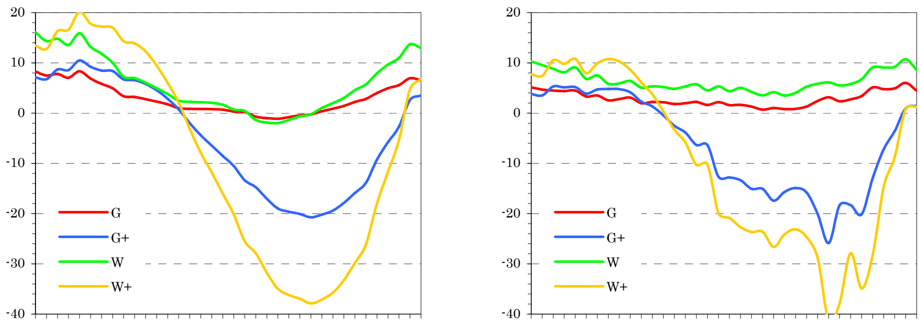
The areas with a strict separation between salt and fresh water can be clearly seen in the figure; from south to north, at the Oesterdam, the Phillipsdam, and at the outlet sluices of the Haringvliet. The gradient along the Westerschelde can also be seen very clearly. The gradient along the Nieuwe Waterweg cannot be seen easily in this figure.

5.3 Changing river regime

One of the effects of climate change in Europe and especially the Netherlands is a changing river regime. Higher temperatures, melting glaciers, and more intensive rainfall makes that the water of the river Rhine will change from predominantly melt water to rainwater. High discharges will become higher, low discharges become lower. In 2006 the Royal Dutch Institute of Meteorology released a report about climate change. In this document the Institute presented four different climate scenarios. In Appendix C these different scenarios are shown. For each scenario calculations are made by RIZA and Carthago in order to predict river discharges in the future (Wit, Buiteveld et al. 2007). In Graph 5.6 the river regime at the end of the 20th century is compared with the predictions for the four different scenarios. Contiguous, Graph 5.7 shows relative discharge changes. From the graph can be seen that high discharges can increase up to 20%. Low discharges can decrease even more, up to 40% in the most unfavorable scenario (W+ scenario).



Graph 5.6: *Future discharges [m3/s] of the Rhine (left) and Meuse (right)*



Graph 5.7: *Relative change [%] of river regime due to climate change, left: Rhine, right: Meuse*

5.4 Salinization Volkerak?

The Volkerak has a large problem with blue-green algae (cyanobacteria). The Volkerak used to be a transition zone between sea and river. After the finishing of the Delta works it became a large fresh water lake with a fixed water level. Since 1994 growth of the algae in the lake has increased to a dangerous level. The algae are a huge threat to both animals and mankind. In 2002 about 5.000 birds were killed by the algae. Swimming is dangerous, and therefore prohibited.

One option for tackling this large problem in the Volkerak is making the lake brackish or salt again (Verspagen, Boers et al. 2005). The algae can not live in brackish or salt water so this can be a remedy for this problem. The decision for this problem has not been taken yet, as there are a number of negative effects caused by this measure.

5.5 Changing management Haringvlietsluizen

As from 2010 management of the outlet sluices at the Haringvliet will change slightly. In order to let the tidal movement get into the Haringvliet, the outlet sluices will be set ajar. With this opening in the sluices salt water can intrude the Haringvliet and the area will be subjected to tides. With this measure the physical separation of salt and fresh water will change into a transition zone where the fresh river water will gradually mix with sea water.

5.6 Halskanaal Goeree Overflakkee

Another possible change which might be implemented in the Delta is an artificial channel or bay-area for pleasure cruising. This channel will be built where the region of Goeree Overvlakkee is most narrow. It will connect the Grevelingen and Haringvliet with each other in order to relieve the Volkeraksluizen.

5.7 Identification possible locations

As discussed in section 1.7 the choice has been made to identify the possibilities for Blue energy in the Dutch Delta. In Chapter 3 the conditions which have to be fulfilled by a certain location to be suitable for Blue energy have been discussed. After analysing the Delta area in the foregoing section a number of locations have been found which could be used. Figure 5.3 shows an overview of the Delta with these locations.

1. Botlek
2. Nieuwe Waterweg
3. Maasvlakte
4. Haringvlietsluizen
5. Krammersluizen

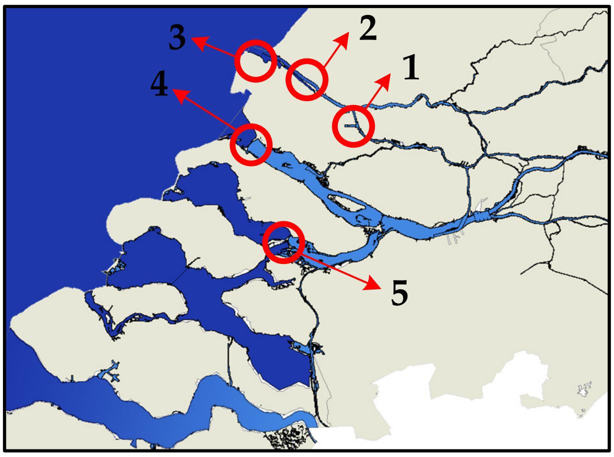


Figure 5.3: *Identification possible locations for Blue energy in the Dutch Delta*

In order to valuate each location for its suitability for Blue energy a number of criteria have been drawn up. For every location an evaluation is made how the particular location performs for each criterion.

The following criteria are used:

- Availability and characteristics of salt water flow (total flow, salt content)
- Availability and characteristics of fresh water flow (total flow, salt content)
- Possibilities for discharging the effluent of the power plant (brackish water)

- Possibilities of separating the three different water flows
- Total potential (defined by the flow and specific power)
- Availability of a site for the power plant
- Number of new large infrastructural structures, and adaptations of existing constructions
- Influence and changes on the existing hydraulic system and flow management
- Influence on navigation activities

In the next sections the locations are one by one discussed on the criteria given above. For every location a map is shown of the location with the three different water flows. Blue represents the fresh water flow, red the salt water flow, and green corresponds to the brackish water flow.

5.7.1 Botlek

The first location where a Blue energy power plant might be possible is in the Botlek area, in the Port of Rotterdam, see Figure 5.4. Fresh water can be distracted from river the Oude Maas. At present, this river discharges a fair amount of fresh water from the Rhine and Meuse to the Nieuwe Waterweg. The present average discharge is 600-700m³/s, the maximum discharges are much higher.

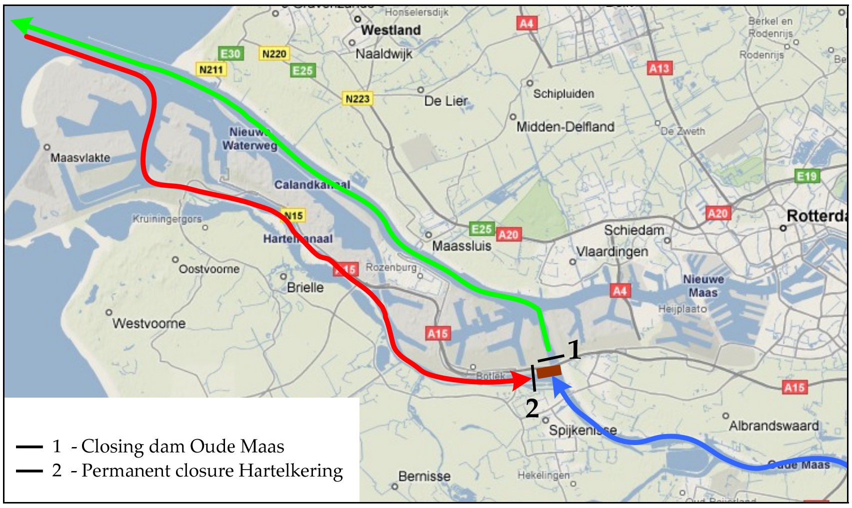


Figure 5.4: *Location 1, Botlek area*

Salt water at this location can be provided by the Hartelkanaal. At present this canal discharges a small amount, in the order of 100m³/s, fresh water to the Maasvlakte harbour basins. With a power plant implemented in the system this discharge will be changed to an inland directed salt water discharge. The canal is at the smallest point approximately 110m wide, and has a depth of 7-8m. These facts combined with a maximum allowable flow velocity of 1m/s makes that a discharge of 500-700m³/s might be possible through this canal. However, the hydraulic regime in the channel is largely influenced by tidal movements. The discharges through the channel as a result of the tides can be considerable. This fact could imply that an extra large salt water discharge might not be too large for navigation purposes.

The effluent of the power plant can be discharged on the Oude Maas, north of the crossing with the Hartelkanaal. From here-on it will flow into the Nieuwe Waterweg which will transport it to the North Sea.

In order to create a sufficient separation between the three water flows a barrier might need to be built in the Oude Maas. Furthermore, the Hartelkering at the east-end of the Hartelkanaal has to be closed permanently (a lock is already available). These two measures will make that locally a perfect separation is created. However, it can be seen from Figure 5.4 that near the mouth of the Nieuwe Waterweg the brackish water flow will come into contact with the salt water flow. This might lead to lower occurring salinities at the salt water intake of the power plant. Furthermore, a large fresh water discharge from the Nieuwe Maas can come into contact with the salt water flow at the same location. This also might lead to lower salinities. This interaction has to be investigated.

All this together makes that the power plant at this location might become quite large. An available flow of 500m^3/s and the assumption that the salinity at the salt water intake will not be influenced too much by the brackish water from the power plant, or the fresh water from the Nieuwe Maas, a power plant of 500MW is possible. In this area the space needed for the power plant is available. Building part of the power plant onto the water is also an option.

The influence on the total hydraulic system is considerable, but not insuperable. Part of the fresh water discharge from the Oude Maas has to be diverted to the Nieuwe Maas or Haringvliet. The salt balance in the Nieuwe Waterweg might be influenced slightly, and because of the fact that the Oude Maas is closed-off no more (or in any case less) tidal influences are found upstream. For navigation, the implementation of a power plant at this location might be considered as a little disaster. Closing of the Oude Maas and Hartelkanaal implies that a lot of ships have to use locks, which causes an enormous economic damage.

5.7.2 Nieuwe Waterweg

This option is located in the Nieuwe Waterweg, very close to the North Sea, see Figure 5.5. Fresh water can be provided by the Nieuwe Waterweg. This channel is able to discharge very large amounts of water, due to a width of 500m and depth of 20m. Salt water will be taken in from the Calandkanaal. The dimensions of this channel are in the same order of magnitude as the dimensions of the Nieuwe Waterweg, so the salt water flow can also become very large. Considering these flows, it might even be possible to build a power plant of 1.000MW at this location. Space for a power plant of this size is available.

A problem that might occur at this location will be the separation between the salt water flow and the brackish water from the power plant. Just a few kilometres from the power plant, these flows will interact with each other. Recirculation of the water might occur. This problem might be (partly) resolved by considerably lengthening the breakwater between the Calandkanaal and Nieuwe Waterweg.

The influence on the total hydraulic system is considerable. In order to create a sufficient separation between fresh and brackish/salt the Nieuwe Waterweg has to be closed of. A large barrier, with a large complex of shipping locks, is needed. The

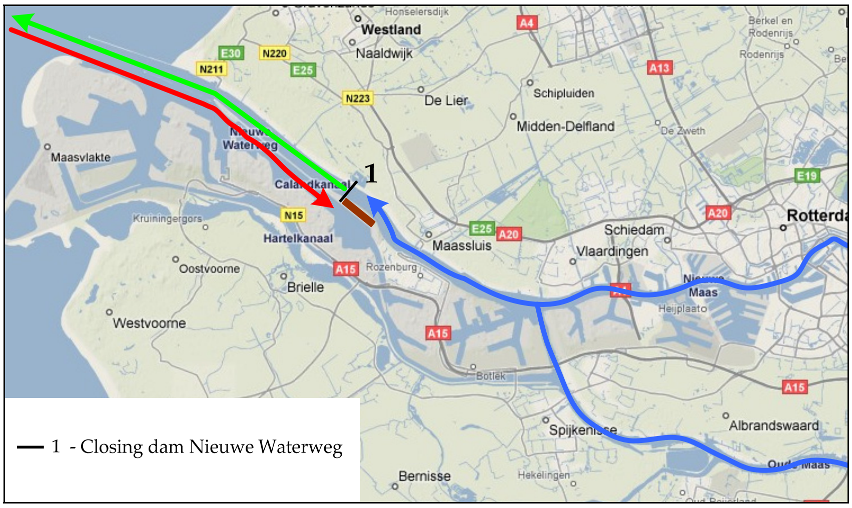


Figure 5.5: *Location 2,Nieuwe Waterweg*

implementation of this barrier means that the present tidal influences (which can be felt far upstream) disappear. Salt concentrations and water levels will change considerably. Some of these changes will have positive consequences, others might be undesirable. Furthermore, at present the Nieuwe Waterweg discharges large amounts of fresh water, especially at high river discharges. Only a part of this flow will be used for Blue energy. The remaining part has to be diverted to the Haringvliet. Another option is to implement outlet sluices or a pumping station (or maybe a combination) in the barrier.

A last aspect, which at present is decisive for the feasibility of this location, is the impact of this option on shipping activities. The Nieuwe Waterweg is extensively used by seagoing vessels and inland navigation. A power plant at this location would result in an enormous economic damage.

5.7.3 Maasvlakte

The location of the power plant in this third option is located at the Maasvlakte, see Figure 5.6. The power plant will be build between the Dintelhaven, Calandkanaal, and Beerkanaal, where a site can be made available. Just as the Botlek location this option uses the Hartelkanaal. However, instead of making this channel totally salt, it will be used for fresh water supply. This fresh water is guided to the Dintelhaven where it is extracted into the power plant. The salt water will be withdrawn from the Beerkanaal or the harbour basins. Discharging the brackish water from the power plant might lead to problems. Discharging it onto the Calandkanaal will definitely cause recirculation. One option to prevent this is moving the salt water intake across the Maasvlakte to the North Sea. After the construction of Maasvlakte II this would imply that pipelines of several kilometres are necessary, with a very large overall cross section. A second option would be to discharge the brackish effluent just north of the Hoek van Holland breakwater. This option also leads to the use of long and large pipelines. However, with these measures it might be possible to construct a power plant up to 500MW.

The influence of this option on the hydraulic system is not very radical. The fresh water discharge through the Hartelkanaal will be raised. Furthermore, the Oude Maas might have to be closed in order to control the occurring salinity in the Hartelkanaal. For the

Figure 5.6: *Location 3, Maasvlakte*

same reason it might be necessary to re-close the Beerdam, which was opened in 1997. The necessity of these last two measures needs to be investigated. It could be that the salt intrusion does not reach the Dintelhaven. When these measures turn out to be necessary the economical consequences for navigation are quite considerable. Next to this, shipping activities are very important in this area. The power plant might introduce currents in the harbour basins which are unacceptable. This needs to be studied.

5.7.4 Haringvlietsluizen

The fourth option is located at the outlet sluices of the Haringvliet, see Figure 5.7. A strict separation between fresh and salt water is found here. The Haringvliet will take care of the supply of fresh water. It can discharge flows up to and over 3.000m^3/s. Salt water can be taken in directly from sea or via a still to construct Scharrezee of channel through Goeree-Overvlakkee. Obviously, the brackish water can directly be discharged onto the North Sea. The challenge in this option is the separation of salt and brackish water. When taking salt water directly from the North Sea, recirculation will definitely occur. Using the channel which still has to be constructed, the brackish water and salt water need more time to come into contact with each other. In this case the salinity at the salt water intake might not be influenced anymore. When it is possible to minimize this interaction it is possible to construct a power plant with a size up to 1.000MW.

Another problem when using the outlet sluices as a strict separation between fresh and salt water is the reduced possibility to discharge large amounts of water in periods with extremely high river discharges. Part of it might be diverted to the Nieuwe Waterweg, but because of the safety against flooding has to be guaranteed, part of the outlet sluices have to keep their function.

When constructing a large power plant at this location at some points in time large quantities of fresh water, which at present are directed to the Nieuwe Waterweg, are diverted to the Haringvliet. An important consequence of this is a larger salt intrusion in the Rotterdam area (Nieuwe Maas, Oude Maas, Hollandse IJssel). This is an unwanted situation, so in order to prevent this it might be necessary to construct one

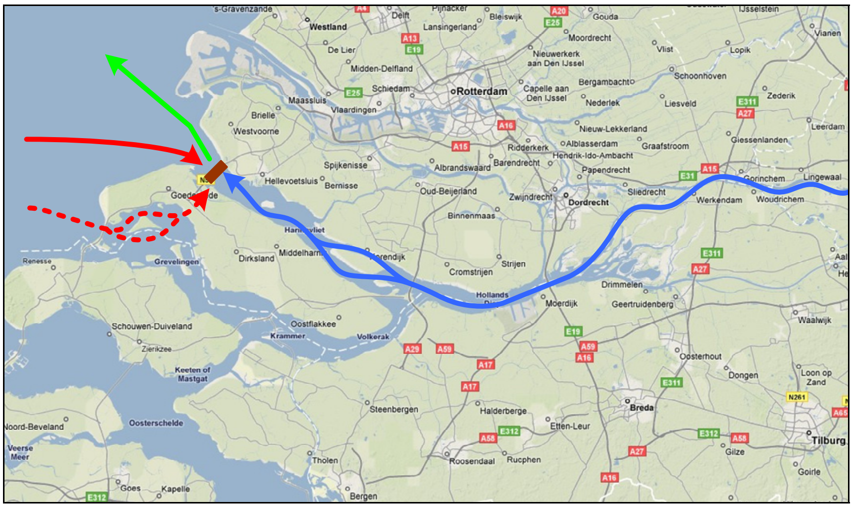


Figure 5.7: *Location 4, Haringvlietsluizen*

(large) or more barriers in this area. These barrier(s) might be open at times with enough fresh water. In this way a half open delta is created, which is also suggested by the second Delta committee.

Apart from mainly decreasing flows through the northern part of the Delta (Nieuwe Maas, Oude Maas, Nieuwe Waterweg), the increasing average flow through the Haringvliet, and the salt intrusion which might increase, no other drastic hydraulic changes are introduced. For navigation, only the barrier(s) which might be necessary in the northern part of the Delta are a negative effect.

5.7.5 Krammersluizen

The last option is also a very interesting location. At the Krammersluizen, three different basins come together but are separated from each other by artificial dams, see Figure 5.8. On the eastside the Volkerak is found (which, at this moment, is a fresh water lake, see also section 5.4). West of the dams the Greveling is found, a large salt water lake. On the south side the outer ends of the Oosterschelde are located, which is an open connection to the North Sea.

This separation is an ideal situation for Blue energy. A few adaptations to the Volkeraksluizen (which are located between the Volkerak and Hollands Diep) to make these able to discharge large amounts of fresh water onto the Volkerak would make that enough fresh water can be made available for Blue energy. Salt water can be supplied by either the Grevelingen or the Oosterschelde. The brackish water can consequently be discharged onto the other basin. It is estimated that a power plant of 400-500MW might be feasible at this location.

Apart from the Volkeraksluizen which have to be adapted, the Brouwersdam which is located at the mouth of the Grevelingen has to be changed. This dam should, in case of a 500MW power plant, be able to discharge 500m³/s, next to tidal flows. Fortunately, plans already exist for creating a tidal power plant in the dam. This would imply that changing the dam can be combined with the adaptations for Blue energy.

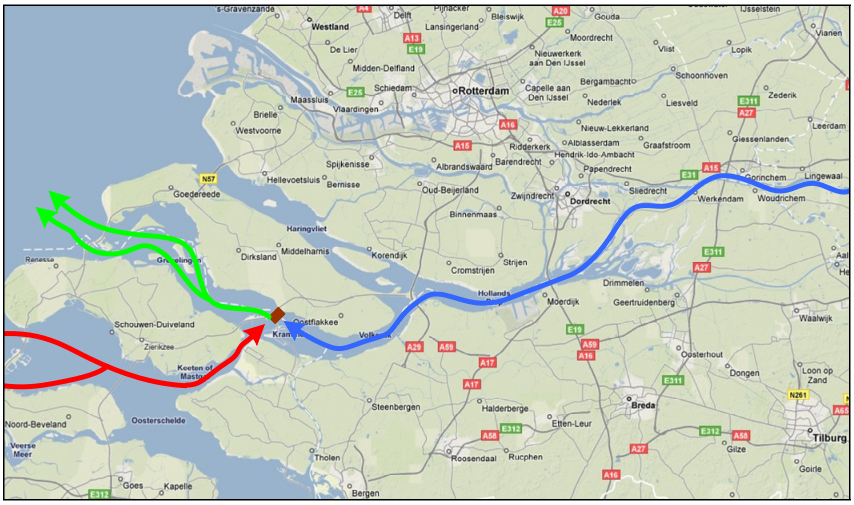


Figure 5.8: *Location 5, Krammersluizen*

Hydraulically, implementation of a power plant at this location mainly influences the climate of the Volkerak. This lake, which at present hardly discharges water, will have to discharge large amounts of fresh water. The problem of algae in the lake might also be resolved as a result of this large discharge. Otherwise, when it has been decided to make the lake salt again, the same opportunities for Blue energy might be found at the Volkeraksluizen.

When constructing a very large power plant, the salt intrusion problem described in the Haringvliet option, will also occur when choosing this location. So it might be necessary to build one or more barriers in the northern Delta area.

5.8 Choice of location

In the remaining part of this study one of the locations described before will be deepened. A choice has to be made which option is the best or most interesting to elaborate. All locations can, taking into account the estimations and assumptions made in previous sections, be made suitable for a large scale power plant, 100-500MW.

Technically, it looks like a very large Blue energy power plant is feasible in the Nieuwe Waterweg. But because of the large implications and the economic damage that will be caused by closing of the Nieuwe Waterweg this option is not considered any longer. On a long term basis it might be necessary to close the Nieuwe Waterweg due to rising sea levels. In that case, Blue energy definitely has to be considered

The Botlek and Maasvlakte options show a number of similarities. Both options use the Hartelkanaal as a water supply channel. Therefore, the estimated potential of both locations is the same, approximately 500MW. Furthermore, for both options the Oude Maas has to be closed of and also a barrier has to be created in the Hartelkanaal. On the other hand, a few differences exist which are unfavourable for the Maasvlakte option. The latter has few possibilities to separate the salt and brackish flow. Large pipelines are needed to overcome this problem. Next to this, the Hartelkering becomes worthless because an extra barrier is created at the Beerdam. Last, summing up the number of additional infrastructural works shows that for the Maasvlakte option more constructions are needed. Therefore it is decided that the Maasvlakte is not a suitable location for Blue energy.

Now, only three options remain; Botlek, Haringvliet, and Krammersluizen. In order to make the right choice between these three the impacts of these options when implementing a 500MW power plant are compared. Nine criteria have been mentioned in section 5.7. The remaining options all fulfil the first three, fifth and sixth criteria, so the choice will be made on basis of the other aspects. In the following table a short overview is given of the performance of all alternatives on the criteria.

	Botlek	Haringvliet	Krammersluizen
Number of constructions			
New	1	1	0
Adaption of existing	1	1	2-3
Salt intrusion	0	0-1	0-1
Separation water flows	Easy	Very difficult, large implications	Already available
Hydraulic influence	Medium	Large	Large
Impact for navigation	Large	Small	Small

Table 5.1: *Overview impact of implementing a 500MW power plant at locations Botlek, Haringvliet, and Krammersluizen*

These three locations seem at this moment all very suitable for Blue energy. However, the implications for implementing a power plant near the Haringvliet sluices are very substantial. A power plant at this location will not be feasible on the short-term. Therefore it is decided not to elaborate this alternative any further in this study.

Choosing between the other options is rather difficult. Both have pro's and con's. However, in the remaining part of this study the Botlek option is dealt with. The choice for this alternative is mainly based on the fact that for the Krammersluizen the hydraulic feasibility of a power plant is almost certain, in contrast to the Botlek option which might turn out not to be feasible because of salt concentrations which are too low, or a not sufficient water flow through the Hartelkanaal. Therefore, the Botlek option is hydraulically more interesting.

Chapter 6

Botlek area description

In this chapter a description of the Botlek area is given. Section 6.1, 6.2, and 6.4 discuss the characteristics of the supply and discharge channels for the power plant. Each section gives a description of the most important characteristics of the channel followed by the consequences due to the implementation of the power plant. In section 6.3 a storage-area calculation of the Hartelkanaal is made in order to determine the tidal movements. For the exact location of different cities, rivers and canals, see again Appendix A.

6.1 Supply channel fresh water

Fresh water for the Blue energy power plant will be supplied by the river Oude Maas. This channel used to be the mouth of the river Maas. However, since the closure of the Afgedamde Maas, and the construction of the Bergsche Maas the river has become part of the lower reaches of the Rhine. After the Second World War the channel has been improved for increasing shipping activity in the Rotterdam area. Nowadays it is part of the route for seagoing vessels to the port of Moerdijk and Dordrecht, and for inland navigation to the Maasvlakte.

The Oude Maas starts at the city of Dordrecht where the Beneden Merwede splits in the Noord, which flows to the Nieuwe Maas, and the Oude Maas. To the west of Dordrecht the Dordtse Kil flows out into the Oude Maas. The channel is situated along the cities of Dordrecht, Zwijndrecht, Puttershoek, and Spijkenisse. In the Botlek area it meets the Nieuwe Maas, and these two together form the Nieuwe Waterweg.

6.1.1 Dimensions

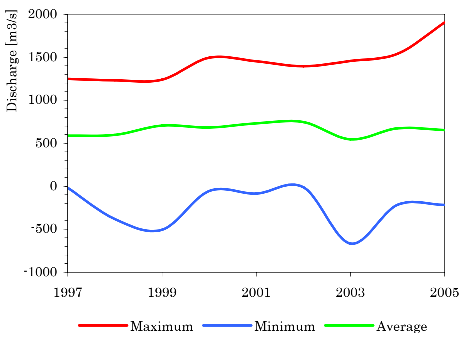
The river has a length of approximately 30 kilometers. The depth of the channel is on average about 10m, but it can be as high as 20m. The width of the river varies between 200 and 400m.

The largest vessels which sail on the river is a push boat with six barges, see Figure 6.1. Furthermore, seagoing vessels with a length of 201m, a width of 32m, and a maximum draught of 9,5m sail on the Oude Maas.

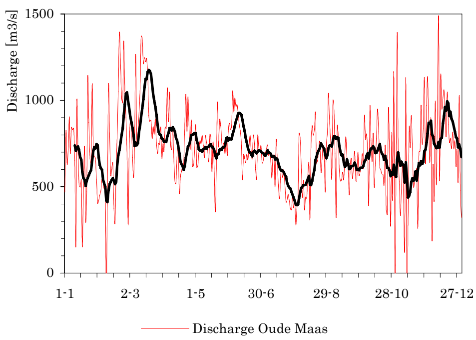
Figure 6.1: *Push boat with 6 barges*

6.1.2 Discharge data

The Oude Maas is one of the three main channels which discharge a large part of the Rhine discharge at Lobith. Graph 6.1 shows the average discharge of the river over the years 1997 to 2005 at Puttershoek, a city halfway down the river. In this graph also the minimum and maximum discharges are shown. In Graph 6.1 a time-series of the discharge over the year 2006 is shown. It can be seen that the discharge varies greatly.



Graph 6.1: *Minimum, average, and maximum discharges of the Oude Maas*

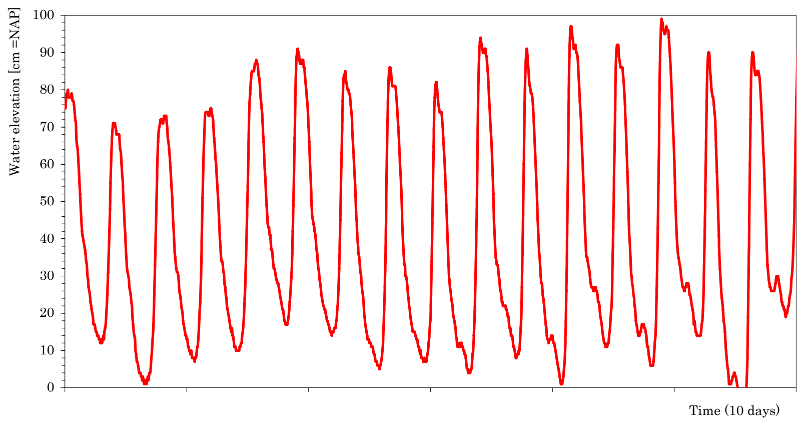


Graph 6.2: *Instanteneous discharge of the Oude Maas in 2006*

When calculating the rate of flow, using the maximum discharge and the smallest cross section, it can be found that this is 0,75 m/s at maximum. However, due to the fact that a large part of the Oude Maas is subjected to tidal influences the rate of flow can be over 5km/h, which is equivalent to 1,4 m/s.

6.1.3 Waterlevel data

The Oude Maas and Nieuwe Waterweg form an open connection with the North Sea. Along the river there exists a significant influence of the tide. In Graph 6.3 water levels in Dordrecht, which is situated at the end of the Oude Maas, are shown. The influence can clearly been. The amplitude of the tidal movement in Dordrecht is approximately 1,0m.



Graph 6.3: *Water level in the city of Dordrecht over a period of 10 days in August 2006*

6.1.4 Consequences implementation Blue energy

In Figure 5.4 can be seen that two structures are needed in order to implement a Blue energy power plant in the Botlek. One of these structures is a closure dam in the Oude Maas together with a number of locks for navigation. This dam is situated just north of the crossing with the Hartelkanaal. Furthermore the Hartelkering will be closed. These measures make that the influence of the tide on the Oude Maas might disappear. However, the tide can still influence the Oude Maas via the Nieuwe Maas.

A second consequence of the closure of the Oude Maas and Hartelkering is that the discharge which used to flow through the river to the Nieuwe Waterweg and North Sea cannot pass these points anymore. Part of this flow has to go somewhere else. It has to be diverted to the Nieuwe Maas, or to the Haringvliet. The new discharge through the Oude Maas, however, will not be zero. For the power plant large quantities of fresh water are needed which are supplied by the Oude Maas. The discharge through the river will be as big as the flow needed for the power plant. For a 100 to 500 MW power plant this means a flow of 100 to 500m^3/s.

6.2 Supply channel salt water

The supply of salt water for a Blue energy plant in the Botlek is done by use of the Hartelkanaal. The channel has been built in the sixties of the 20th century. It connects the Oude Maas with Europoort and the Maasvlakte. At first, the channel was a fresh water channel, separated from the salt water in the port of Rotterdam by the Beerdam on the west side. On the east side it was closed of from the Oude Maas by the Hartelsluizen (shipping locks). In 1997 the Beerdam, which separated the Hartelkanaal from the Maasvlakte was opened. The fresh water channel changed into a brackish – salt water channel with a lot of tidal influences. At the same moment, at the east side, the channel was opened as well and a large storm surge barrier together was constructed to keep out sea water in case of large storm surges. For navigation purposes, on the north side of the Hartelkering locks are located.

The channel is used for inland navigation. Ships can easily access the Maasvlakte and the Calandkanaal without having to take a dangerous detour.

6.2.1 Dimensions

The total length of the Hartelkanaal from Maasvlakte (Beerdam) to Hartelkering is approximately 18,5km. The channel is much smaller compared to the Oude Maas. The average depth is 7m, and the width varies between 110 and 360m. The channel is used by the same type of ships as the Oude Maas, except for the seagoing vessels.

In order to be able to calculate the total surface of the Hartelkanaal, including two harbour basins the channel is divided in six different sections. For each section a characteristic length and width are determined from which the total surface can be calculated. This is done in Appendix D. The total surface of the Hartelkanaal area is almost 5,2 million square meters (520ha).

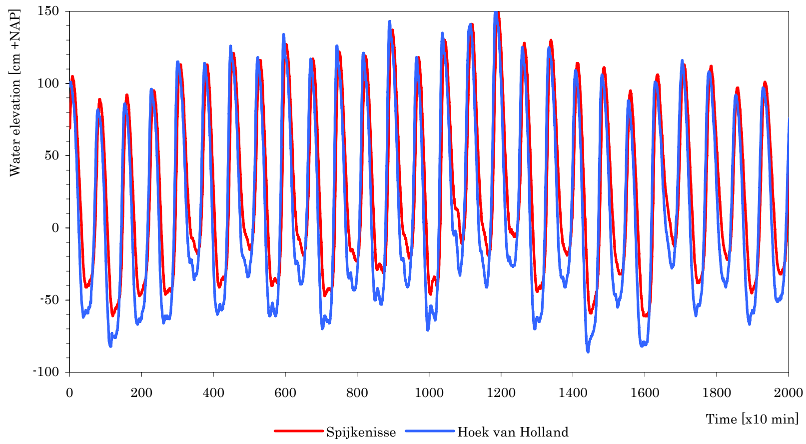
6.2.2 Discharge data

Not much data is available about the flow through the Hartelkanaal. In (Ballot 2008) an estimation is made for this discharge by subtraction of the Maasmond discharge by the discharge at Maassluis. With this analysis it turns out that the average discharge through the Hartelkanaal is approximately 140m^3/s. Related to the discharge at Lobith this is between 7 and 10%. This estimation is confirmed with flow velocities measured at the Suurhoffbrug (bridge) which, multiplied with the cross section at the bridge, gives a same estimation of the average discharge.

6.2.3 Water level data

No data about the water level in the Hartelkanaal is available. Because of the fact that the total length of the Hartelkanaal is short compared to the wavelength of a tidal wave, the assumption can be made that water levels are the same over the total length of the channel. When comparing water level data of Spijkenisse and Hoek van Holland this assumption is confirmed. The water level at Spijkenisse only differs from the water level at Hoek van Holland with low tide. This difference is at maximum at the moment of low tide and is approximately 20cm. This difference can be explained by the influence of the river discharge. This influence is larger at Spijkenisse than at Hoek van Holland.

In Graph 6.4 one month of water level data at Hoek van Holland is shown. From these data the tide amplitude can be calculated. This is done by calculating the difference between the water levels at respectively high tide and low tide. On average this is approximately 1,75m. Springtide gives an amplitude of 2,2m and neap tide 1,5m.



Graph 6.4: *Water levels in Hoek van Holland and Spijkenisse compared*

6.2.4 Consequences implementation Blue energy

At present, both ends of the Hartelkanaal are open connections. The west side is not changed, but the east end of the channel is closed of. This is done at first by simply closing the Hartelkering. Later-on, this storm surge barrier can be replaced by a regular dike or closure dam. Shipping vessels need to use the shipping locks next to the Hartelkering.

The characteristics of the Hartelkanaal will totally change. At present the channel discharges part of the fresh water from the Rhine to the Maasvlakte and onto the North Sea. In the new situation, with the Blue energy power plant implemented, the channel will consist of totally salt water, and the flow will, apart from the tidal movements, be directed inland.

6.3 Storage area calculation

A global analysis of the effect of the tidal movements on the Hartelkanaal can be done with a storage-area calculation. With this calculation an estimation can be made of the total flow of water into the Hartelkanaal as a result of the tide.

When applying this calculation two conditions need to be fulfilled. The first condition has to do with the fact that the area for which the calculation is done is a closed area except for the mouth at the sea side. In the new situation, with the power plant implemented, the Hartelkering will be closed. With this measure, the Hartelkanaal together with the Dintelhaven, form a closed area with a water level variation at the mouth (Beerdam). The second condition can be checked with the following equation:

$$\frac{L_{wave}}{L_{area}} \geq 20 \qquad (6.1)$$

where

L_{wave} Tidal wave length

L_{area}	Characteristic length (maximum length) of the area for which the calculation is done

When this condition is fulfilled the water levels at both end of the area will be approximately the same. With this fact, the average flow in and out of the area due to the tidal movement can easily be calculated.

The tidal wave length can be calculated as

$$\begin{aligned} L &= c \cdot T_s \\ c &= \sqrt{g \cdot d} \end{aligned} \tag{6.2}$$

in which

L_{wave}	tidal wave length
T_s	tidal wave period
c	wave speed of a long wave
g	gravitational constant
d	average depth

An average depth of 7m, and a tidal wave period of 44.700s gives a tidal wave length of 370km. Now the ratio from equation (6.1) can be calculated as

$$\frac{370}{18{,}5} = 20$$

With this, the second condition is also fulfilled. With both conditions fulfilled a couple of terms in the equation of motion can be cancelled, and the equation reduces to

$$Q = A_{area} \cdot \frac{dh(t)}{dt} \tag{6.3}$$

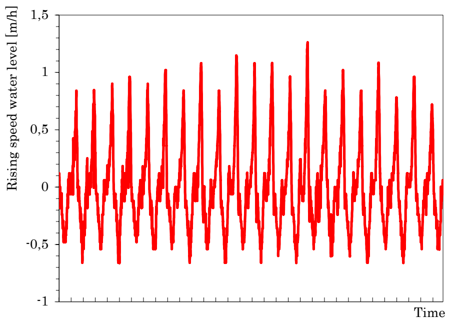
in which

Q	Discharge
A_{area}	Storage area
$\frac{dh}{dt}$	Change of water level

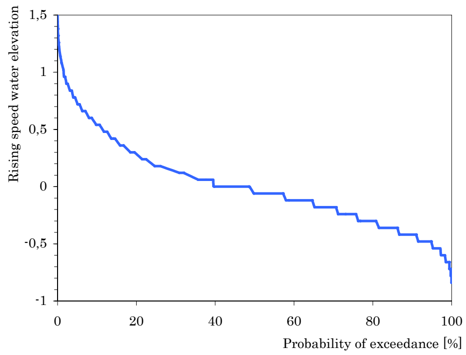
With the storage area of 5.169.450m², see section 6.2.1, and an average tide amplitude of 1,70m, see section 6.2.3, the average discharge can be calculated as

$$\begin{aligned} Q_{average} &= A_{area} \cdot \frac{\Delta h}{\Delta t} \\ &= 5.169.450 \cdot \frac{1{,}70}{\frac{1}{2} \cdot 44.700} \\ &= 393 \quad \tfrac{m^3}{s} \end{aligned} \tag{6.4}$$

This discharge is an average discharge over a period in which the water level is constantly rising. Just before the water level reaches its highest point, the actual discharger will be much lower, reaching zero at the moment of turning. Halfway during rising tide the discharge will be larger than this average. The maximum discharge depends on the speed with which the water levels at the mouth of the basin are rising, the so-called rising-speed. Graph 6.5 shows the rising-speed at Hoek van Holland for a period of one month. In Graph 6.6 these data is transformed to an exceedance curve.



Graph 6.5: *Rising speed of the water level at Hoek van Holland for a period of one month*

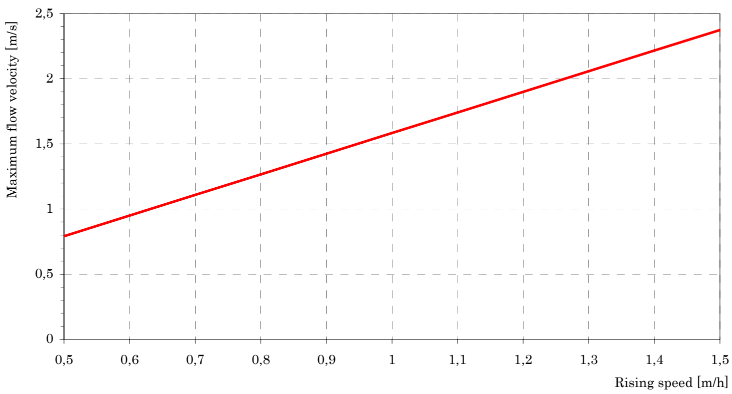


Graph 6.6: *Exceedance curve of the water level rising speed at Hoek van Holland*

This curve shows with what probability a certain rising-speed is exceeded. It can be seen that there is only a very small chance that the rising speeds exceeds 1 m/h (only 1,5% of the time). The rising speed which corresponds with a probability of exceedance of 5% is 0,75m/h. Calculation of the discharge with this rising speed follows from

$$\begin{aligned} Q_{5\%} &= A_{area} \cdot \frac{\Delta h}{\Delta t} \\ &= 5.169.450 \cdot \frac{0,75}{3600} \\ &= 1077 \quad \tfrac{\mathrm{m}^3}{\mathrm{s}} \end{aligned} \tag{6.5}$$

When comparing the outcome of (6.5) to (6.4), it can be seen that the flow in the Hartelkanaal varies a lot. Consequently, the occurring velocities in the channel also show a large variation. In Graph 6.7 this can be seen. The graph shows the flow velocities as a function of the rising speed of the water level. Only positive values of the rising speed (rising tide) are shown, not the total range of possible velocities is shown.



Graph 6.7: *Flow velocities in the Hartelkanaal as a function of the water level rising speed at Hoek van Holland.*

6.4 Discharge channel brackish water

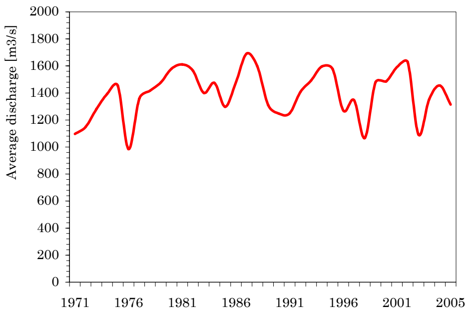
The effluent of the Blue energy power plant, brackish water, will be discharged onto the Oude Maas, just north of the Botlek bridge. From here-on it will flow through the last 2km of the Oude Maas and then into the Nieuwe Waterweg. This is a canal which connects the city of Rotterdam with the North Sea. Construction of this channel was finished in 1872.

6.4.1 Dimensions

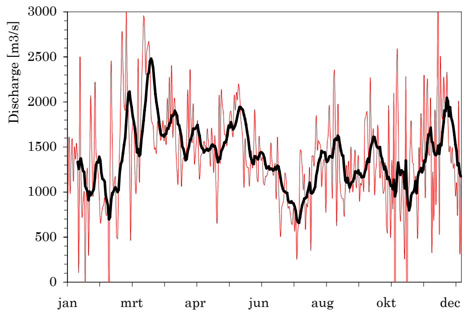
From the crossing of the Oude Maas, Nieuwe Maas, and Nieuwe Waterweg in the Botlek area, this last canal has a total length of approximately 20 km. The Nieuwe Waterweg is used by large sea going vessels, but also for inland navigation. Because of the fact that over the years the dimensions of sea going vessels increased over and over again, the Nieuwe Waterweg has also been deepened a number of times. The present depth of the canal varies around 15 to 17m. The width of the channel is 480 to 675m.

6.4.2 Discharge data

The Nieuwe Waterweg is one of the two main connections with the North Sea which discharge a large part of the Rhine flow. From Graph 5.3 in section 5.1 can be concluded that the Nieuwe Waterweg discharges approximately 50 to 75% of the total Rhine discharge at Lobith. As been mentioned in section 5.1.3 the present policy is to keep the discharge in the Nieuwe Waterweg above 1.500m^3/s as long possible in order to control the salt tongue in the area. In Graph 6.8 an overview of average discharges is shown. Next to this, in Graph 6.9, it can be seen that the actual discharge varies largely around this average.



Graph 6.8: *Average discharges of the Nieuwe Waterweg over a period of 35 years*



Graph 6.9: *Instanteneous discharge of the Nieuwe Waterweg over 2006*

6.4.3 Waterlevel data

The Nieuwe Waterweg is subjected to tide influences. The west end of the channel is located at the North Sea with corresponding water levels. The east end is only 20 km away, which implies almost the same water levels. Sea Graph 6.4 for occurring water levels.

6.4.4 Consequences implementation Blue energy

At present, the Nieuwe Waterweg is fed by the Oude Maas and Nieuwe Maas. Both rivers supply fresh river water, in quite large quantities. With the Blue energy power plant in use, the Oude Maas will discharge brackish water into the Nieuwe Waterweg. This will be done with a constant discharge of 200 to 1.000m^3/s, depending on the size of the power plant (100-500MW). The exact location of the salt tongue in the Nieuwe Waterweg, and consequently the Nieuwe Maas might change position.

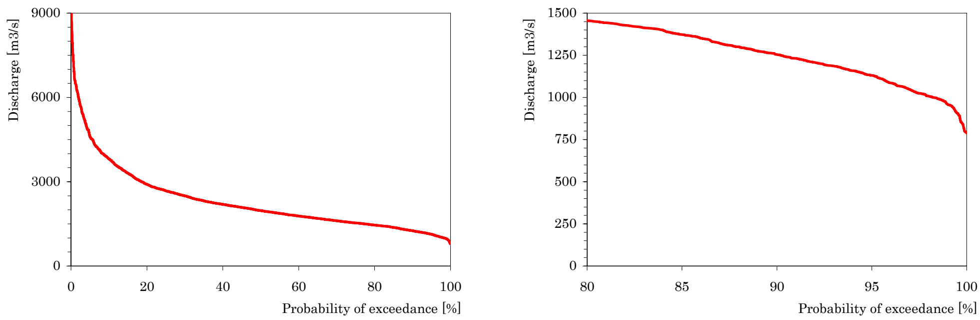
Chapter 7

Fresh water availability

This chapter discusses the availability of fresh water for a power plant in the Botlek area. The fresh water that flows through the Dutch Delta mainly comes from the River Rhine, which enters the country at Lobith. Therefore in section 7.1 first the discharge of the Rhine at Lobith is discussed and analyzed. In the subsequent section is determined which part of the Rhine flow is directed to the Dutch Delta. Section 7.3 then deals with the question which part of the flow through the Delta is used for other purposes. In section 7.4 is then determined how much water can be made available for Blue energy followed by section 7.5 which describes how to determine the final efficiency of the power plant when considering the fresh water availability.

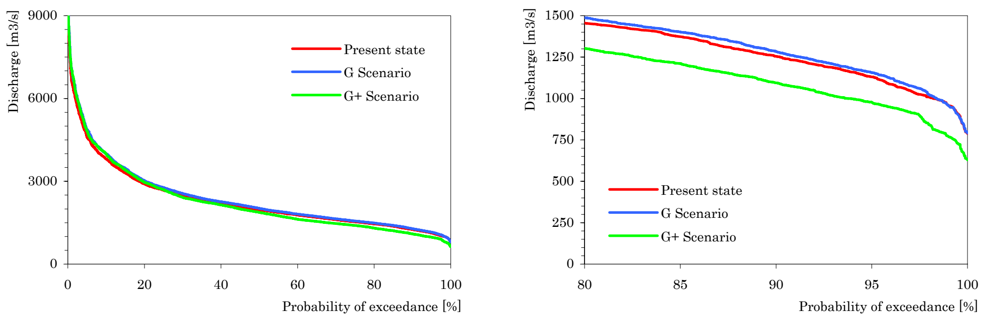
7.1 Analysis discharge Lobith

The largest source of fresh water for the Dutch Delta is the river Rhine. The Rhine enters the country at Lobith with an average flow of 2.200m^3/s, see also section 5.1. Although there are a lot of claims on fresh water, a large part of this flow could be made available for use in a Blue energy power plant. Because of the fact that for economic reasons a Blue energy power plant has to run at full power for a large part of the time it is important to know how much water is available with a certain probability. During a large period of time the discharge was measured at Lobith. This data is used in a statistical analysis to determine a flow duration curve for the flow at Lobith. This curve shows the probability in time that a certain discharge is exceeded, see Graph 7.1. For example, when it is required that the power plant has to run at full power for 80% of the time, a flow of almost 1.500m^3/s at Lobith is available.



Graph 7.1: *Flow duration curve of the discharge at Lobith. Right, an enlargement of the graph with the highest exceedance probabilities is shown*

Unfortunately, due to changing climate conditions, the regime of the river Rhine will change in the future. Because of the fact that historical data is used for this calculation the data has to be corrected for these climate changes. Use is made of the graphs in section 5.3. The following graphs show the same flow duration curve for Lobith, together with the corrected curves. It can be seen that the influence of climate change can be very large. The G scenario, which is chosen as scenario to calculate with up till 2015, is a favorable scenario. The G+ scenario however changes the flow at Lobith in such a way that the flow duration curve moves downward considerably. These three scenarios are dealt with in this study.

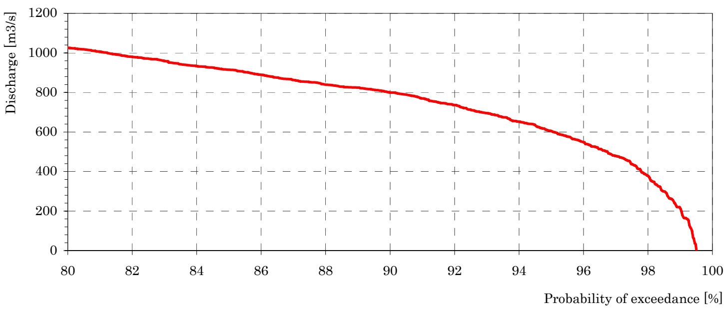


Graph 7.2: *Flow duration curve of the discharge at Lobith, in the present situation and corrected for the G and G+ climate scenario. Right, an enlargement of the graph with the highest exceedance probabilities is shown*

7.2 Fresh water in Dutch Delta

Not the total river flow at Lobith is directed to the Dutch Delta. There are a couple of other channels which discharge part of the flow at Lobith, and extra flow is available from the river Meuse, and due to rainfall. Furthermore, a few other claims are done on the fresh water flow. Therefore, it is important to determine what discharge can be made available in the Dutch Delta.

In the Delta two main channels discharge fresh water to the North Sea, being the Nieuwe Waterweg and the Haringvliet. The Nieuwe Waterweg is fed by the Oude Maas and the Nieuwe Maas. It is assumed that the total discharge through these river branches can be made available for Blue energy. In Appendix B time series of the flow at the Nieuwe Maas, Oude Maas, and Haringvliet can be found, together with a time series of the summation of these three different river discharges. From these graphs it is not easy to determine an estimation for the flow through the Delta. Again a statistical analysis has been made from which a flow duration curve can be determined, see Graph 7.3. With this graph it is possible to determine what discharges could be made available in the Delta for Blue energy. Note that this curve is not corrected for the different climate scenarios.



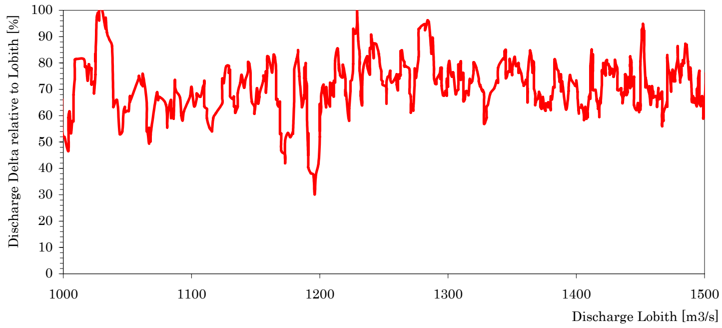
Graph 7.3: *Flow duration curve of the fresh water discharge to the Dutch Delta. Note that this curve is not corrected for the different climate scenarios*

In order to be able to deal with the different climate scenarios the summation discharges are related to the flow at Lobith at the same moment. At first this relation seems not to be very useful. The flow through the Delta related to Lobith varies from day to day within a range of 40% to 140%. The average flow through the Delta is approximately 84%, but this number is not really interesting for Blue energy. Because of the fact that a Blue energy power plant has to run at full power for a large percentage of the time, the lowest available discharges are most interesting. When analysing the data it can be seen that the flow through the Delta is most of the time well enough above 60% compared to Lobith (12% of the measurements). Only in 24% of the cases the flow through the Delta is less than 70% compared to Lobith. With this information it can be concluded that 60 to 70% of the flow at Lobith is directed to the Delta.

Unfortunately, a low ratio does not necessarily mean a low absolute flow. So to check the value of 60 to 70% from the previous paragraph an analysis is made of the ratios as a function of the absolute flow at Lobith. In Graph 7.4 this is shown for a range with low discharges at Lobith, 1.000-1.500m^3/s. From this graph it is clear that with low absolute values of the flow at Lobith a fraction of 60 to 80% is directed to the Dutch Delta. Therefore, the assumption is made that 70% of the flow at Lobith is directed to the Delta.

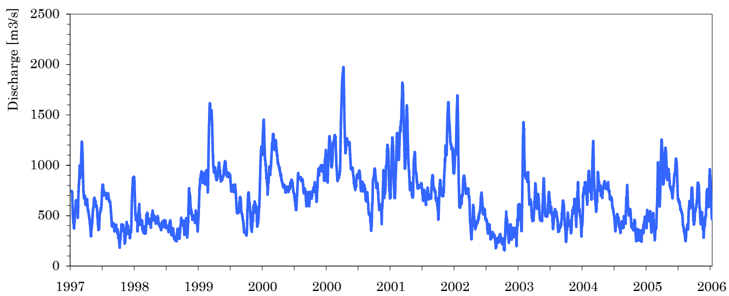
7.3 Condition flow Nieuwe Maas

From section 5.1.3 it is clear that the present policy is to keep the discharge through the Nieuwe Waterweg above 1.500m^3/s as long as possible. Only in cases of very low discharges at Lobith, the flow through the Nieuwe Waterweg will be lower. This is done in order to control the salt tongue in this canal. A situation in which the salt



Graph 7.4: *Discharge through the Dutch Delta related to the discharge at Lobith, in periods with low overall river discharges*

tongue penetrates the country further is an undesirable situation. Therefore it is important to take measures to guarantee that the salt tongue does not move too much land inward. When the Blue energy power plant is implemented in the hydraulic system, the Nieuwe Waterweg is fed by the effluent of the power plant, a certain discharge of brackish water, together with the discharge of the Nieuwe Maas. Because of the fact that the Oude Maas is closed of with a dam and locks the salt tongue cannot influence that area anymore. The only way for the salt to intrude the country is via the Nieuwe Maas. Graph 7.5 shows ten years of discharge data of the Nieuwe Maas at the Brienenoord bridge. Together with the knowledge that at present a situation in which the salt tongue intrudes the country too far happens only occasionally (Beijk 2008), it is assumed that a flow 400 to 600m^3/s at the Nieuwe Maas should be enough to guarantee that the salt tongue will not intrude too far.



Graph 7.5: *Fresh water discharge of the Nieuwe Maas over a period of 10 years*

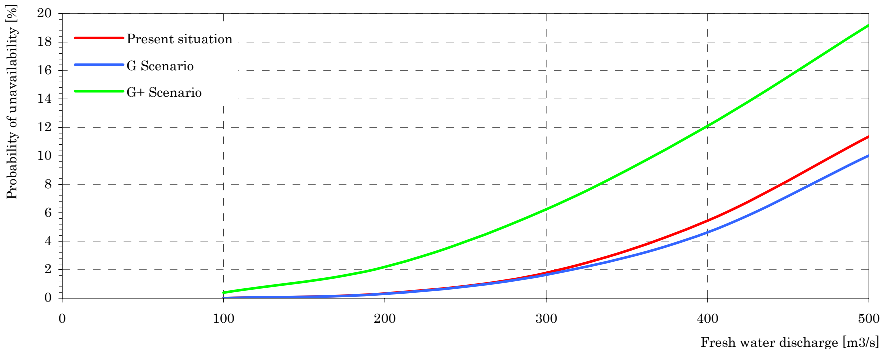
This is a very large claim on fresh water in the Delta. This part of the total available flow is not available for Blue energy. It changes the flow duration curve, which moves down with the value of 400 to 600m^3/s.

7.4 Availability fresh water for Blue energy

With the assumptions and information from the previous sections in this chapter, it is now possible to calculate how much fresh water is available for Blue energy in the Botlek. To be clear, the assumptions which are made are

- Deal with two climate scenarios; the G scenario, and the G+ scenario. These are compared to the present situation
- 70% of the flow at Lobith is directed to the Dutch Delta, and could be made available for Blue energy (Delta flow condition)
- Within the Dutch Delta, 400m³/s is needed to flow through the Nieuwe Maas in order to control the salt intrusion. This flow is therefore not available for Blue energy. (Nieuwe Maas condition)

Statistical data of ten years flow at Lobith is used as starting point. This data is corrected for the climate scenarios which results in three data sets (present situation, G scenario and G+ scenario) for the flow at Lobith. These data sets are multiplied with 70% to find the flow which is directed to the Dutch Delta. Last, each entry in all datasets is lowered with 400m³/s for the flow needed for the Nieuwe Maas. These calculations results in three datasets with discharges in the Botlek available for Blue energy. A statistical analysis is done to produce Graph 7.6.

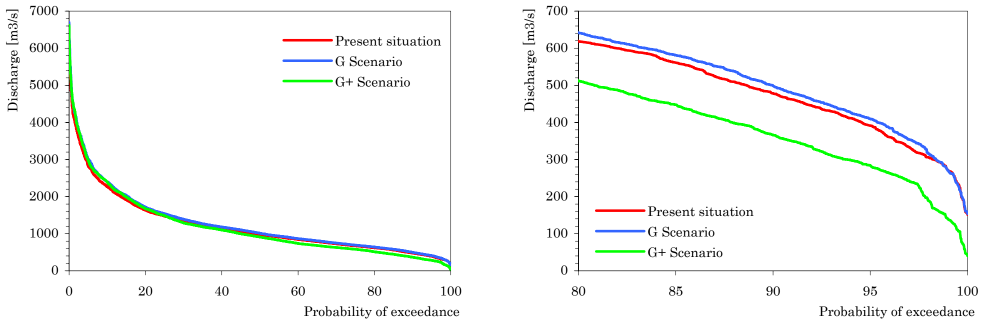


Graph 7.6: *Probability of unavailability of fresh water in the Botlek area for a Delta flow condition of 70%, and a Nieuwe Maas condition of 400m³/s*

The graph shows for different power plant sizes the unavailability of the fresh water flow. This unavailability means that in that certain percentage of the time the plant can not run at full power. For example, a power plant that needs to be provided with 500m³/s of fresh water in the G scenario can for 10% of the time not run at full power. This implies that for 90% of the time enough fresh water is available to run at full power.

The unavailability does not mean that the power plant has to be stopped. It means that the total flow needed for full power is not available. However, there is still some flow available which can be used to run the power plant at a lower rate than full power. This is dealt with in section 7.5.

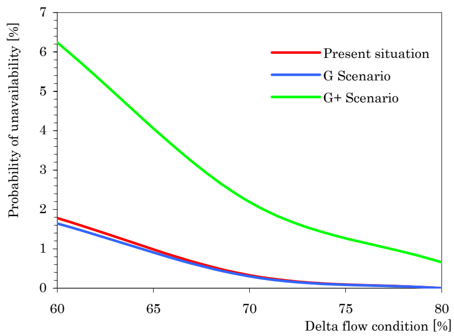
Off course these datasets can also be shown in a flow duration curve, see Graph 7.7. These graphs again show with what percentage of the time a certain discharge is exceeded.



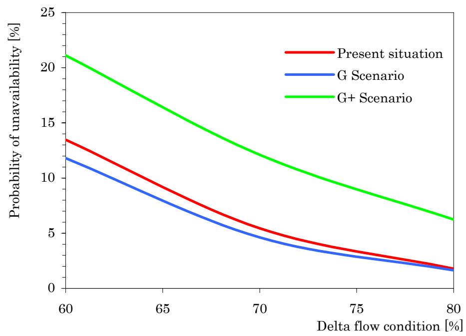
Graph 7.7: *Flow duration curve for the availability of fresh water for Blue energy in the Botlek area. Right, an enlargement of the graph with the highest exceedance probabilities is shown*

7.4.1 Sensitivity of the Delta flow condition

In section 7.2 an assumption is made which fraction of the discharge at Lobith is directed to the Delta (Delta flow condition). In order to determine the influence of this condition a sensitivity analysis is done for this parameter. In Graph 7.8 an overview is given for the probability of unavailability of fresh water as a function of the Delta flow condition. The graph shows the unavailability for a power plant that needs to be provided with 200m³/s fresh water, with a Nieuwe Maas condition of 400m³/s. Graph 7.9 shows the same, but now for a larger power plant.



Graph 7.8: *Sensitivity of the fresh water availability for a changing Delta flow condition for a power plant of 200MW*



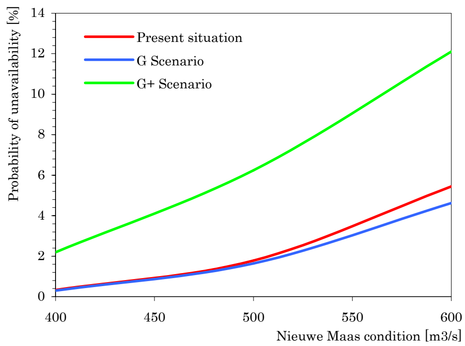
Graph 7.9: *Sensitivity of the fresh water availability for a changing Delta flow condition for a power plant of 400MW*

From the graphs can be seen that the Delta flow condition is more important with a large power plant compared to a small one. This seems quite logical; a small power plant needs less fresh water than a large power plant. This can also be seen when looking at Graph 7.6, the unavailability grows exponentially with the size of the power plant. Furthermore, the curves for the G+ scenario seem to descend faster than the ones for the other scenarios. This implies that the G+ scenario is more sensitive for the Delta flow condition. This difference reduces when choosing a larger power plant.

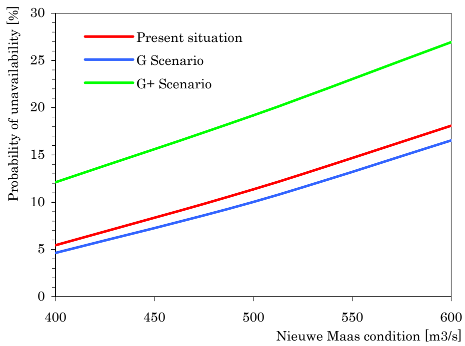
Considering the fact that the average flow at Lobith is 2.200m³/s, and does not often decrease below a value of 1.000m³/s an increase of 10% which flows to the Delta means that an extra 100 to 220m³/s is available for Blue energy. This consideration makes that the Delta flow condition has a large influence on the availability of fresh water.

7.4.2 Sensitivity Nieuwe Maas condition

The influence of the Nieuwe Maas condition is also evaluated with a sensitivity analysis. The following two graphs show again the probability of unavailability of fresh water, but now as a function of the Nieuwe Maas condition. The left graph shows again the unavailability for a plant with a fresh water flow of 200m³/s, with a Delta flow condition of 70%. The right graph shows the same for a 400m³/s plant.



Graph 7.10: *Sensitivity of the fresh water availability for a changing Nieuwe Maas condition for a power plant of 200MW*



Graph 7.11: *Sensitivity of the fresh water availability for a changing Nieuwe Maas condition for a power plant of 400MW*

It can be seen that the influence is quite considerably. This can be explained by the fact that every cubic meter which is needed to flow through the Nieuwe Maas cannot be used in the power plant. So when the Nieuwe Maas condition is increased, the available flow for Blue energy decreases with the same amount. Therefore this condition has a large influence on the availability of fresh water for Blue energy.

7.5 Efficiency Blue energy power plant

In section 7.4 the probability of non-availability of fresh water is determined and shown in a number of graphs. It is mentioned that the non-availability does not mean that the power plant has to be stopped. It means that the flow for running the power plant at full power is not totally available. However, there will be some flow available, which is smaller than the full power flow. It is possible to determine what flow is on average available at the moment that there is not enough water to run full power. Table 7.1 shows a few numbers for the availability of fresh water, with a Delta flow condition of 70% and a Nieuwe Maas condition of 400m³/s.

With this data a calculation can be made for the overall efficiency of the power plant. First the availability of fresh water to run at full power is determined as

$$P_{av} = 100 - P_{unav} \tag{7.1}$$

with

P_{av} = Probability of availability fresh water for full power
P_{unav} = Probability of unavailability fresh water for full power

Full power flow	Climate scenario	Probability unavailability	Flow when not full power
100 m3/s	Present	0 %	-
	G	0 %	-
	G+	0,38 %	62 m3/s
300 m3/s	Present	1,78 %	252 m3/s
	G	1,64 %	247 m3/s
	G+	6,24 %	219 m3/s
500 m3/s	Present	11,36 %	387 m3/s
	G	10,02 %	389 m3/s
	G+	19,19 %	345 m3/s

Table 7.1: *Overview of unavailabilities of fresh water for Blue energy in the Botlek considering different power plant sizes. The right column shows the average flow that is available in case the plant cannot run at full power*

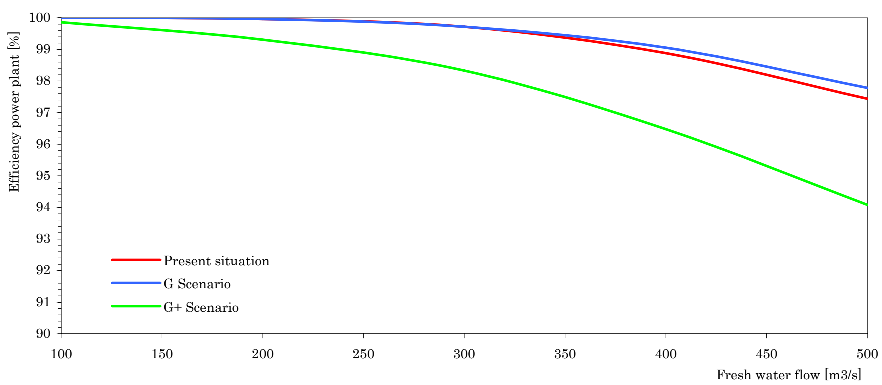
Now the overall efficiency can be calculated as a weighed average of the available discharges in time:

$$E = \frac{P_{av}}{100} \cdot Q_{full} + \frac{P_{unav}}{100} \cdot Q_{not\ full} \tag{7.2}$$

in which

E = Overall efficiency power plant
Q_{full} = Discharge at full power
$Q_{not\ full}$ = Average discharge when flow for full power is not available

For the situation with a Delta flow condition of 70%, and a Nieuwe Maas condition of 400m^3/s the efficiency of the power plant is shown in the graph below. It can be seen that the efficiencies are quite high. Even in a situation with a large power plant with the G+ scenario the efficiency is approximately 94%. This can be explained by the fact that the fresh water through the Delta is quite high, see also Graph 7.1.



Graph 7.12: *Overall efficiencies of a power plant, due to the availability of fresh water, in the Botlek area as a function of its size*

Chapter 8

Salt water availability

In this chapter the availability of salt water for a power plant in the Botlek area is determined. A numerical model is used to execute these calculations. The main focus of the simulations lies on the flow through the Hartelkanaal and the occurring salinity in the canal. Those parameters determine the size of the power plant. Appendix E gives an overview of the simulations that have been done. In the first section of this chapter a short description of the model which is used is given. Section 8.2 deals with the initial and boundary conditions of the model followed by a validation of the model in section 8.3. Section 8.4 discusses how the actual power plant is implemented in the existing model. In section 8.5 a choice is made for the final power plant size. Sections 8.6, 8.7, and 8.8 deal with the sensitivity of the salinities that will occur at the power plant intakes. In the last section, 8.9, a short conclusion is given.

8.1 Origin of the model

The model used in this study is called "Maasvlakte II". It is used in the past to determine the influence of the construction of the second Maasvlakte on the occurring velocities at the mouth of the Nieuwe Waterweg and Calandkanaal, and at sea, next to the second Maasvlakte. The aim of the model was to determine if the construction of the second Maasvlakte would not cause velocities to increase in such a way that entering the port of Rotterdam would become more difficult or maybe even impossible. Figure 8.1 shows the exact location of the model area in a Google Earth view. Next to this the computational grid together with the bathymetry used in the model is shown. It can be seen in the computational grid that the cel-density in the area of the second Maasvlakte is very high, i.e. the cellsize is very small. This is done in order to be able to calculate velocities with a high accuracy.

The model is a sub-domain of a larger model owned by Rijkswaterstaat. This larger model is used to determine the boundary conditions for this Maasvlakte II model. The model used in this study has been used in the past for a number of studies already. A lot of verification tests haven been done. Furthermore, the model is calibrated on many different aspects.

The model has a number of important characteristics. The area covered by the model is not only discretized in horizontal directions, but also over the vertical. The water column is divided in nine layers. Each layer covers a certain part of the total vertical. The upper and lower layers have smaller dimensions (7-10%) than the middle layers (10-15%). This is done in order to be able to calculate the salt concentrations in the upper layers more accurate, and to cope with shear stresses near the bottom. A second aspect of the model is the time-step used in the calculations. It is set to 0,125 minutes based on the Courant condition[1]. A slightly larger time step should be possible when determining the Courant condition, but during spin-up of the model it turns out that in that period the model is not stable anymore.

The model is solved by using the "Delft3D-FLOW" software. Delft3D-FLOW is a multi-dimensional (2D or 3D) hydrodynamic (and transport) simulation program which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing, see (WL-Delft-Hydraulics October 2007).

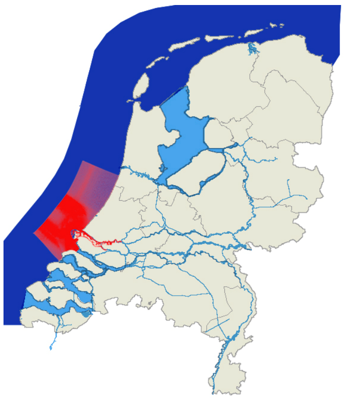


***Figure 8.1:** Location of the model*

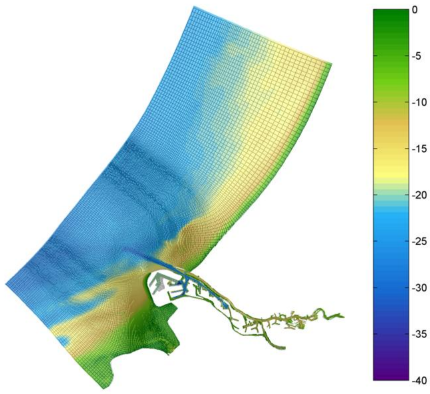


***Figure 8.2:** Computational grid and bathymetry used in the model*

8.2 Initial and boundary conditions

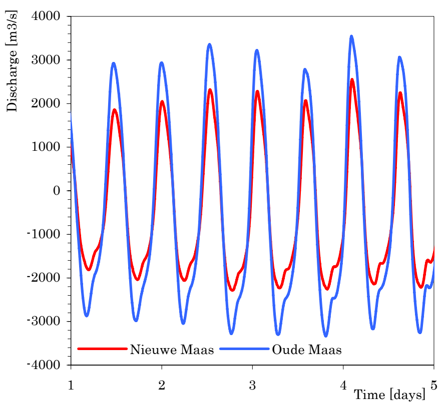
As mentioned in the previous section the model used is a sub-domain of a larger model. The boundary and initial conditions for the model are therefore created with the larger model. The model used in this study has an open boundary at sea. At this boundary water levels are prescribed, together with the salinity. Because of the fact that the phase of the tide is not at every location the same the conditions change along the boundary. At the west-end side of this boundary the salinity is considered to be constant with a

[1] The Courant condition is a condition for convergence while solving certain partial differential equations numerically. Given the properties of the computational grid (characteristic size of grid cells), the gravitational acceleration, and a total water depth, an assumption for the maximum time-step can be calculated.

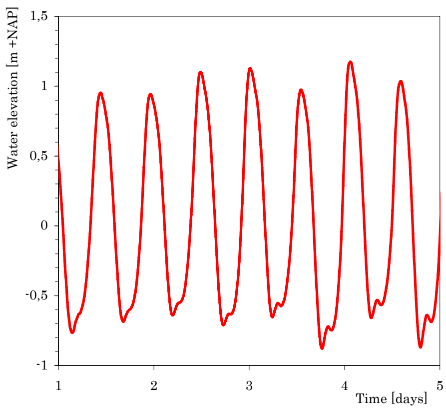
value of 35 g/l. Along the North and South boundary at the North Sea the salinity which is prescribed along these sections decreases towards the coast. Near the coastline the salinity is approximately 28 g/l, depending on the location along the coast.

At the east end of the model two open river ends are found; the Nieuwe Maas, and the Oude Maas. At both boundaries a discharge is prescribed, also together with a value for the occurring salinity. At the locations of the boundaries the tide has a large influence on the occurring water levels and discharges. Therefore the discharge which is prescribed is not a constant value, it varies from a large positive to a large negative discharge, which can be seen in Graph 8.1. Under regular circumstances the tide has no influence on the salinities which occur at these boundaries. Therefore the salinities prescribed at the river boundaries of the model are constant with a value of 0,3g/l. Only a small river discharge combined with an extreme sea-water level can result in a considerable salt intrusion.

Not many different boundary conditions are available for the model. In fact, the model with the larger domain has only been used to simulate a period of nine days in the summer of 2001. So, for the model used in this study, only boundary conditions for this period are available. The period which has been simulated is from the 14th of August, 10:10 Am to the 23rd of August, 9:30 Am. During this period the average discharge of the Rhine at Lobith is approximately 1.600m³/s, which can be considered as a low discharge, only 35% of the time the discharge at Lobith is equal to, or smaller than 1.600m³/s. Furthermore, the meteorological conditions at sea were friendly which results in a water level at the sea boundary of the model which is only caused by tides, not by wind set-up. In the simulation no meteorological effects are taken into account.



Graph 8.1: *Boundary conditions prescribed at the river boundaries of the model*



Graph 8.2: *Boundary condition prescribed at the sea boundary of the model*

8.3 Model validation, summary

A number of aspects play an important role by the use of this model for the present study. First, the model has to perform well hydrodynamically. Water levels, discharges and flow velocities calculated by the model have to reflect reality. Second aspect, which is important in this study, is the simulation of the salt movement in the Delta area. Salt concentrations calculated in the model need to be in the same order of magnitude compared to the real situation.

A simulation has been done in present state to be able to determine the performance of the model. In Appendix F an overview is given of the validation of the model. The model has been validated for water levels, discharges, flow velocities and salinity. From the appendix can be concluded that the model shows a good representation of the real situation. However, a number notes have to be made.

Flow velocities

Not much data is available about occurring flow velocities. In (Ballot 2008) some data of the flow velocities in the Hartelkanaal near the Suurfhoffbrug are given. Comparing these with the velocities in the simulation shows that the velocities calculated are a good representation of the occurring velocities.

Because of the lack of flow velocity data, a qualitative analysis is made of the velocities occurring in the mouth of the Nieuwe Waterweg. These figures show flow velocity profiles which can be explained when related to the phase of the tide. This implies that the calculated velocities are a good representation of the occurring velocities.

Horizontal eddy diffusivity

An important parameter for the salt movement in the model is the Horizontal eddy diffusivity. This parameter is implemented in the software in order to be able to deal with the process of diffusion in a simulation. The value of the parameter is expected to be found between 0,2 and 1m^2/s. Two simulations have been done to determine what the influence of this parameter is. This influence turns out to be location-dependent. When considering the salt concentration in the harbour basins of the Maasvlakte a higher value of the parameter shows a smaller vertical salt gradient, see Graph F.9. However, in the figure can be seen that the differences are not very large. When compared with measurements it can be seen that a lower value shows a more realistic representation of reality. When considering the vertical salt gradient in the Hartelkanaal the influence appears to be a little different. At this location the vertical gradient is with both values approximately the same. The difference between both simulations lies in the fact that a higher value results in a lower value of the salinity over the total vertical. The difference can be up to 40%.

From the point described above it is not possible to find a conclusion about the influence of the Horizontal eddy diffusivity. Therefore, two simulations will be done in the new situation, with a power plant implemented in the model, to determine what the influence of the parameter is in the new situation.

8.4 Implementation of a power plant

For the implementation of the power plant a number of changes have to be made to the system, and therefore to the model used. The first large change made is the closure of the Oude Maas and the Hartelkering. This is done with the help of a thin dam, which in the model respresents a line with the property that flow velocities perpendicular to that line are always zero. Across the Oude Maas and the Hartelkanaal such a thin dam is implemented in the model.

The second change is the implementation of the power plant. For the hydraulic situation this means a subtraction of water from the Hartelkanaal (west of the thin dam) and from the Oude Maas (south of the closure dam). These discharges are mixed in the power plant and than discharged back into the model, north of the closure dam in the Oude Maas.

A last change which has to be made to the model has to do with the boundary condition at the Oude Maas. Because of the closure of the Oude Maas the discharge which flows through this river in the present situation has to be lowered to the value needed to supply the power plant. This could be done by setting the boundary condition at the Oude Maas exactly equal to the discharge which is subtracted by the power plant. But because of the fact that the model calculates numerical approximations of all parameters, problems could occur with continuity in this part of the model. When for example the discharge for the power plant is approximated at some moment by the model at 99m^3/s instead of 100m^3/s, and the inflow at the boundary is approximated with 101m^3/s, more water flows into this sub-domain of the model than out of it. This could lead to overflow or other strange outcomes. To prevent this, the boundary is changed to a water level boundary.

The remaining part of the discharge of the Oude Maas, which is not used to supply the power plant, can be diverted to the Nieuwe Maas, or to the Haringvliet. In this study it is assumed that the water is diverted to the Haringvliet. This is done because up-scaling of the boundary condition at the Nieuwe Maas is not an easy job due to the fact that the tide has a large influence on the instantaneous discharge at that specific location. This choice has a lot of influence on the consequences for the Nieuwe Maas and Nieuwe Waterweg. With the implementation less fresh water is directed to the Nieuwe Waterweg which implies a larger salt intrusion in the Delta area.

8.5 Size of the power plant

8.5.1 Expectations

As discussed before two factors are decisive for the choice of a power plant size. First, the capacity of the Hartelkanaal to supply the power plant with salt water is a very important factor. The canal is not only used as a supply channel for Blue energy, but also for shipping. Therefore, velocities in the channel may not become too large. So the first determining factor for the choice of a power plant size is the maximum flow velocity in the Hartelkanaal.

In section 6.3 a storage area calculation has been made. This calculation showed that due to tidal movements on average 400m^3/s will flow into the Hartelkanaal with rising tide in a situation with a closed Hartelkering. Together with the fact that the Hartelkanaal is not a very large channel and that velocities which occur in the present situation are already quite high for shipping, it is expected that the maximum discharge for Blue energy through the channel will not be much larger than 200m^3/s. In that situation the channel has changed from a fresh water discharge channel to a salt water discharge channel with a little higher average discharge.

The second factor has to do with the power to be delivered by the power plant. The power of a Blue energy power plant largely depends on the salinity of the salt water which is taken in. When this salinity decreases the power delivered by the plant reduces considerably. For this study it is assumed that the minimum salinity at the salt water side of the power plant has to be 25g/l, see section 3.1.

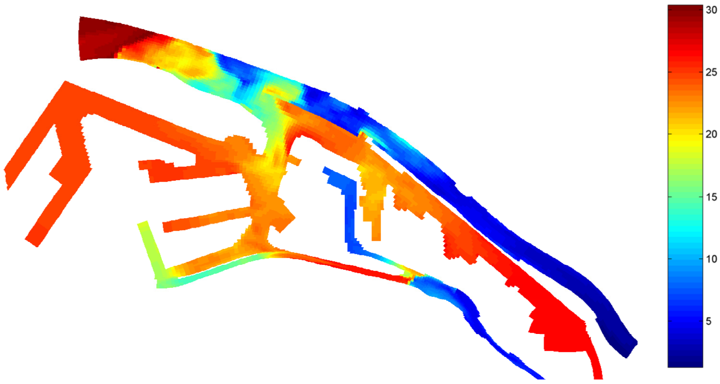


Figure 8.3: *Interaction between salt and fresh water in the upper layer of the vertical. Blue represents totally fresh water, red corresponds to sea water.*

At the mouth of the Nieuwe Waterweg a lot of interaction exists between the fresh water discharged by the Waterweg and the salt water from the North Sea. In Figure 8.3 this interaction can clearly be seen. In the present situation fresh water from the Nieuwe Waterweg can only be pushed into the harbour basins of the Maasvlakte by the upcoming tidal wave from the North Sea. With a power plant implemented in the system it is conceivable that the chance of sucking fresh or brackish water from the Nieuwe Waterweg into Maasvlakte harbour basins becomes larger. This might lead to an unacceptable situation because the Hartelkanaal is fed by the upper parts of these harbour basins. Therefore it is expected that the size of the power plant is limited by the salinity which will occur in the Hartelkanaal.

Another system characteristic which might play a role in the occurring salinity has to do with differences in water depth. The mouth of the Hartelkanaal is only approximately 7m deep. The harbour basins which have to provide salt water to the Hartelkanaal are over 25m deep. This implies that water which flows into the channel comes out of the upper layers of the harbour basins. At present a large salinity gradient exist over the vertical in the Europahaven. Fresh water from the Hartelkanaal and Nieuwe Waterweg flows on top of the Salt water. For that reason the salinity at the power plant intake might be negatively influenced.

8.5.2 Discharges and flow velocities

Three simulations have been done to determine the maximal size of the power plant. The first factor which is important for the size of the power plant is the velocities that

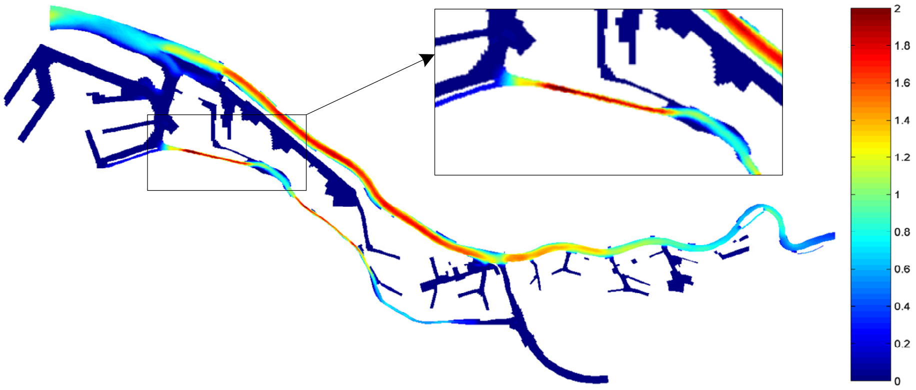


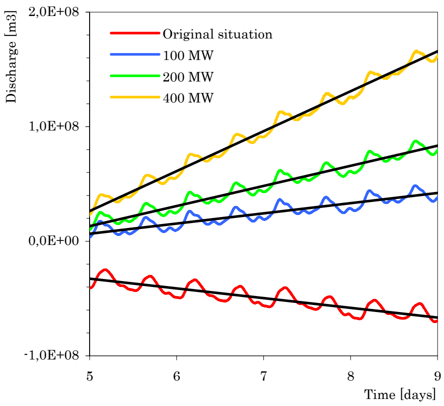
Figure 8.4: Overview of the occuring depth averaged flow velocities at rising tide, when peak velocities occur. A situation with a 100MW power plant is shown, implementing a 200 or 400MW plant, or the present situation gives a similar figure.

occur in the Hartelkanaal. In the figure above, the depth averaged flow velocities are shown at a moment with maximum velocities. The figure shows a situation with a power plant of 100MW implemented. When plotting the same figure for a power plant of 200MW, 400MW, or the present situation gives approximately the same picture.

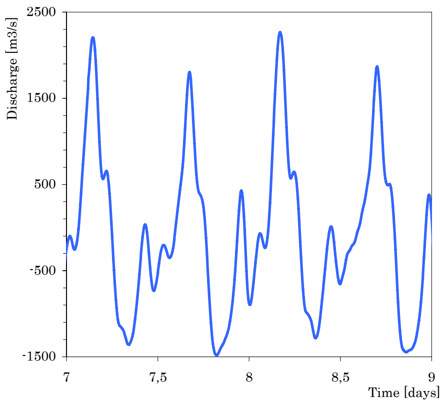
It can be clearly seen that the highest velocities in the Hartelkanaal occur near the mouth of the channel. This can be explained by the fact that the tidal movement will be largest in that area, the largest discharges along the channel will occur here. Furthermore, at this location the channel is quite narrow. At the Suurhoffbridge the cross section of the channel is not larger than approximately 900m^2.

Discharges

The flow velocities are a direct result of the occurring discharges. In Graph 8.3 the cumulative discharge in the mouth of the Hartelkanaal are shown for the present situation, and three scenarios with power plants implemented of respectively 100MW, 200MW, and 400MW.



***Graph 8.3:** Cumulative discharge at the mouth of the Hartelkanaal in different scenarios*



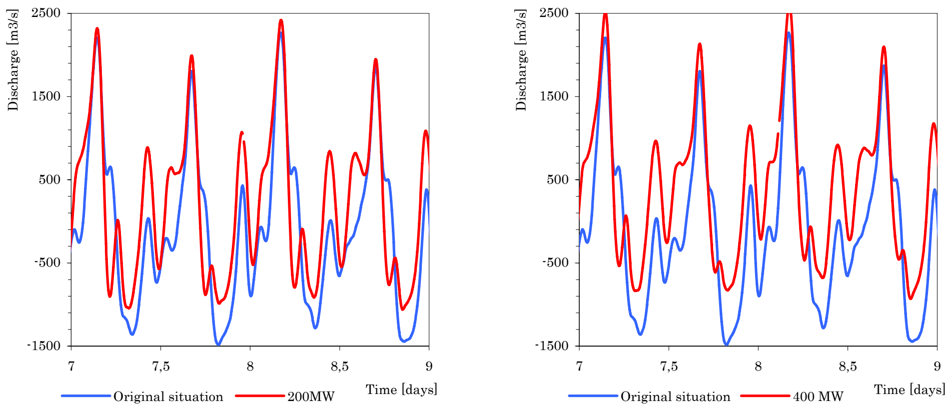
***Graph 8.4:** Instanteneous discharge in the mouth of the Hartelkanaal in the present situation*

From the figure it can be easily calculated what the resulting average discharge is. The original situation is clearly different from the scenarios with a power plant. The average cumulative discharge slopes downward, with a slope of 98m³/s. This is in the same order of magnitude as discussed in section 6.2. Note that a negative discharge is in the direction of the North Sea, a positive discharge is directed inland.

The other three scenarios all have a positive slope, which implies an inland directed discharge. Calculating these discharges gives an average of 103, 204, and 403m³/s respectively. This is totally in accordance to the power plant size of respectively 100, 200, and 400MW.

Graph 8.4 shows the instantaneous discharge in the mouth of the Hartelkanaal in the present situation. It can be seen that the maximum discharges that occur are much larger than the average of 400m³/s calculated in the storage area calculation, section 6.3. Furthermore, the peak discharges are also much larger than the fresh water discharge in the present situation. It can be concluded that the tidal movement is the dominant process in the mouth of the Hartelkanaal.

The following graphs show again the instantaneous discharge in the mouth of the Hartelkanaal, but now together with discharges that occur when a 200MW or a 400MW power plant is implemented.



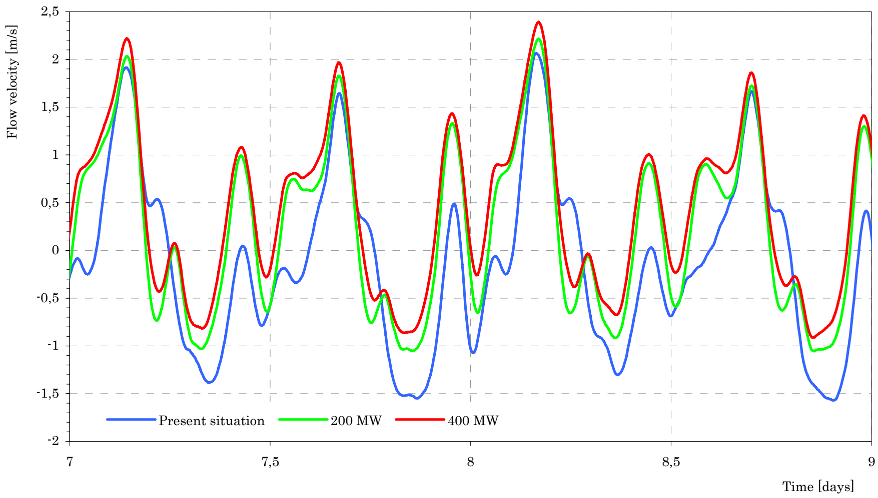
Graph 8.5: *Discharge at the mouth of the Hartelkanaal, the present situation compared with a 200MW plant (left) and a 400MW plant (right)*

It might not be totally clear from the picture, but the peak discharges with an inland direction (positive in the figure) hardly increase compared to the present situation. With a power plant of 100 or 200MW these peak discharges are the same as in the present situation. Only when implementing a 400MW power plant the peak discharges increase slightly. The marginal increase of the peak discharges can be explained by the fact that the tidal movement is dominant at times of rising tide. Discharges caused by the tide are much larger than the discharge needed for the power plant. Therefore, no extra discharge is initiated by the power plant.

The magnitude of the negative peak discharges (in the direction of the North Sea) do decrease considerable. This can be explained by the fact that with a power plant implemented the fresh water discharge from the present situation is transformed to a salt water discharge in inland direction. At falling tide, when the tidal discharge is directed to the North Sea, the power plant still needs to be provided with salt water. Therefore the peak discharges in the direction of the sea are much lower.

Flow velocities

When the discharges from the previous section are transformed to flow velocities in the Hartelkanaal near the Suurhoffbrug the same pattern is observed. The following graph shows flow velocities for a period of two days with a power plant of 200MW and 400MW compared to the present situation. Again, peak flow velocities in inland direction hardly increase, but the magnitude of the negative peak velocities do decrease. It can also be seen that velocities in inland direction have a larger magnitude than seaward flow velocities. The inland flow velocities are therefore normative for the choice of the power plant size.



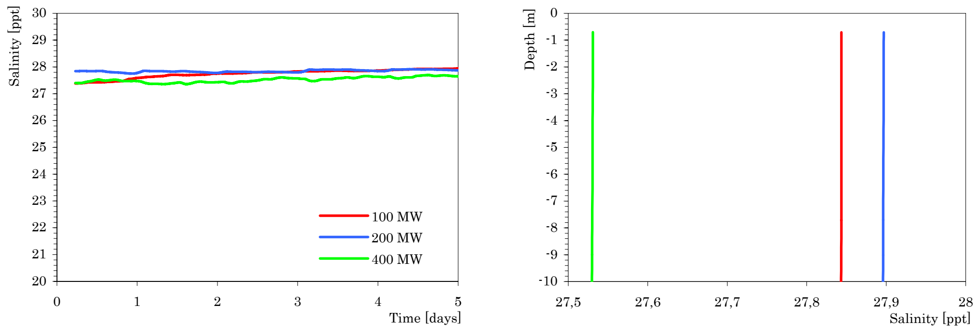
Graph 8.6: *Flow velocities occuring at the Suurhoffbrug in the Hartelkanaal, comparison of the present situation with power plants of 200 and 400MW implemented*

When analyzing the flow velocities it is found that the peak velocities, which occur only in less than 3% of the time, increase with an average of 6%. The maximum increase is 15%, which occurs only 0,3% of the time. These results show that a power plant of 400MW can be implemented without unacceptable consequences for navigation. Furthermore, flow velocities up to 2,5m/s are nowadays not a problem for shipping.

8.5.3 Salinity at salt water intake

The second factor which determines the size of the power plant is the occuring salinity at the salt water intake of the plant. Graph 8.7 shows the salinity in time in the upper layer of the Hartelkanaal near the salt water intake for three different sizes of the power plant. It can be seen that the power plant size has hardly any influence on the salinity at the intake. For these three plant sizes the salinity will lie between 27,5ppt and 28ppt. From this graph also becomes clear that the intake salinity is independent of time, and therefore independent of the tidal phase.

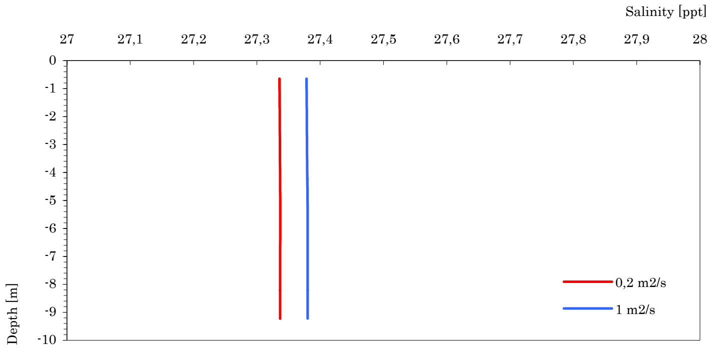
The right part of Graph 8.7 shows at a certain moment in time the salinity for the three scenarios over the depth near the salt water intake. It shows that the water is totally mixed over the depth. No vertical salinity gradients exist at the end of the Hartelkanaal. The explanation lies in the fact that the harbour basins which feed the Hartelkanaal are also well mixed, see Figure 8.5.



Graph 8.7: *Occuring salinities at the salt water intake of the power plant. Left, as a function of time. Right, at a fixed moment in time, over the depth*

Influence horizontal eddy diffusivity

In section 8.3 the influence of the horizontal eddy diffusivity is discussed. It was not possible to determine the exact value of the parameter. Therefore, it was decided to check the influence of the parameter in the new situation, with the power plant implemented. In the following graph the salinity over depth is shown at a certain moment in time for two simulations; one with a horizontal eddy diffusivity of 0,2 m^2/s and one with 1m^2/s.

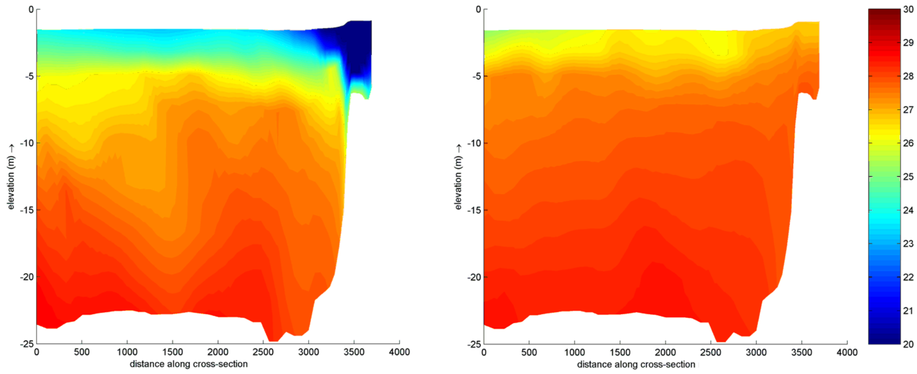


Graph 8.8: *Influence of the horizontal eddy diffusivity at the salinity near the salt water intake of the power plant*

It turns out that the parameter has negligible influence on the salinity at the salt intake of the power plant. The salt movement in the Hartelkanaal is in both simulations practically the same.

Influence depth differences

In section 8.5.1 the influence of depth differences between the Hartelkanaal and the harbour basins of the Maasvlakte are discussed. From the previous sections became clear that the occurring salinity at the power plant intake is almost as high as at sea, just offshore. From the following picture becomes clear that the depth differences hardly influence the salinity in the Hartelkanaal. The figures show a cross section of the Europahaven, reaching from the Beerkanaal on the left to the mouth of the Hartelkanaan on the right. The left picture shows the present situation, the right one with a power plant implemented. The presence of a relatively brackish layer at present can be clearly seen. In the new situation, however, no eminent gradient exists anymore over the vertical. So it can be concluded that the depth differences hardly influence the occurring salinity.



(a) (b)

Figure 8.5: *Overview of the salinity in the cross section of the Europahaven. The left end of the figures corresponds to the Beerkanaal, the left end with the mouth of the Hartelkanaal*

8.5.4 Choice

Despite all expectations discussed in section 8.5.1, it can be concluded from previous sections that it is possible to implement a 400MW power plant in the Botlek area. It turns out that the normative peak flow velocities in the Hartelkanaal are hardly influenced, and still have a magnitude which is acceptable for navigation. Furthermore, the salinity at the salt intake of the power plant does hardly depend on the power plant size. Therefore it is decided to continue with a power plant size of approximately 400MW, which needs to be provided with 400m^3/s of both fresh and salt water.

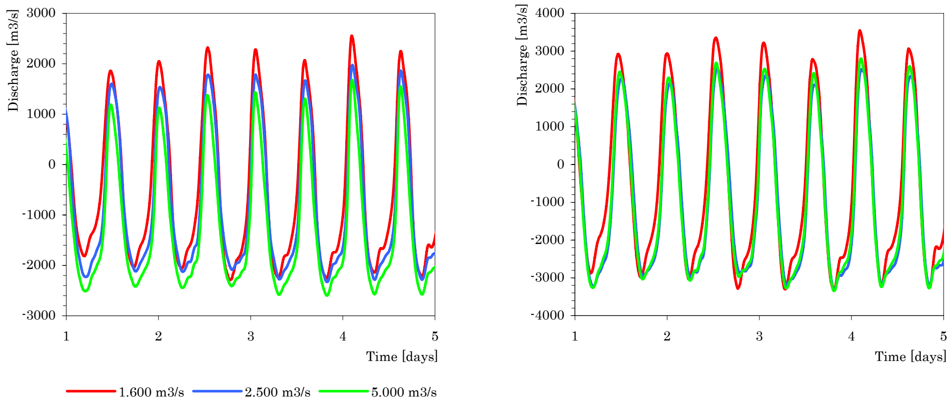
8.6 Influence river discharge

Upscaling river discharge

Figure 8.3 in section 8.5.1 shows the interaction between salt and fresh water in the mouth of the Nieuwe Waterweg. The salt water intake of the power plant is located in the Hartelkanaal, which is fed by the harbour basins of the Maasvlakte. These basins, on their turn are fed by the North Sea. Water flowing into the harbour basins flows through the area where salt and fresh water meet. It is conceivable that fresh or brackish water from the mouth of the Nieuwe Waterweg flows into the harbour basins and subsequently influence the salinity in the Hartelkanaal. In case of a high river discharge this influence might be larger because the fresh water from the Nieuwe Waterweg reaches further into the North Sea.

In the original model a river discharge at the Oude and Nieuwe Maas is prescribed which corresponds to a discharge at Lobith of approximately 1.600m^3/s. In order to determine the influence of the river discharge on the salinity at the salt intake side of the power plant this discharge at Lobith needs to be scaled up. Unfortunately, due to the fact that the riverside boundary conditions of this model are largely influenced by the tidal movement it is not possible to scale-up the discharge independently. This problem is solved by using a one-dimensional model, which has a larger domain, reaching a lot further upstream the river-system to a point without tidal influences. This 1D model has been used to simulate the same period in time with a higher discharge at Lobith, being 2.500m³/s and 5.000m³/s, from which new discharge conditions are subtracted to use in the power plant model.

The new boundaries, corresponding to respectively 2.500m³/s and 5.000m³/s at Lobith are shown in Graph 8.9, together with the original boundary conditions. It can be seen that the seaward (negative) discharges are larger in case of the 2.500m³/s and 5.000m³/s at Lobith, and the inland discharges (positive) are lower. This implicates a higher river discharge at both the Nieuwe Maas and Oude Maas.



Graph 8.9: *Boundary conditions for the riverside of the model after upscaling, compared to the original conditions. Left, Nieuwe Maas. Right, Oude Maas*

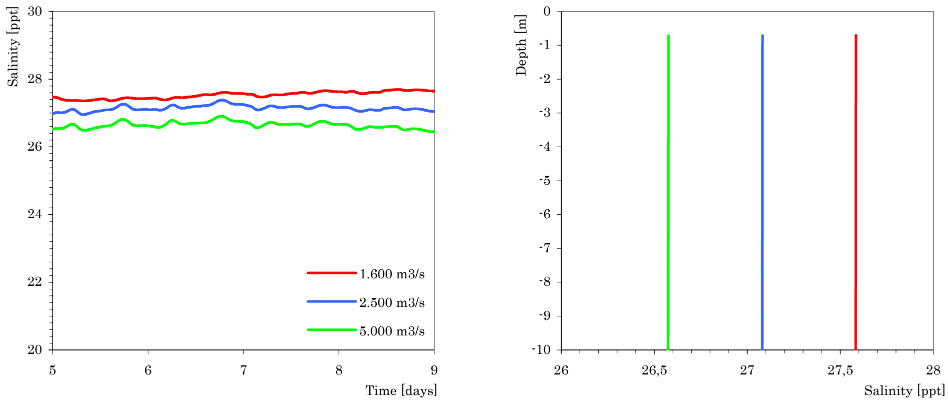
The upscaling is validated with measurements from periods with a similar river discharge at Lobith, and approximately similar circumstances at the North Sea. It turns out that the discharges and water levels in the model give a good reflection of the real situation.

Results

The graphs below show the salinity at the power plant intake for the three different scenarios. From these graphs can be concluded that the influence of the fresh water river discharge is only marginal. At 5.000m³/s the salinity at the intake is approximately 1g/l lower compared to the case of 1.600 m³/s at Lobith. Analysis of the flow at Lobith learns that a discharge of 5.000m³/s is exceeded only 4% of the time.

8.7 Measures for increasing salinity

In case of a high river discharge the salinity at the salt water intake of the power plant decreases slightly, see also previous section. When, for some reason, this is considered not to be an acceptable situation it might be possible, with some minor adjustments of



Graph 8.10: *Influence of the river discharge on the occurring salinities at the salt water intake of the power plant Left, as a function of time. Right, at a fixed moment in time, over the depth*

the system, to increase the salinity. The most obvious solution in this respect is to reduce the interaction between fresh (or brackish) water from the Nieuwe Waterweg and the water in the harbour basins of the Maasvlakte which feed the Hartelkanaal. This can be done by lengthening the breakwater in between the Nieuwe Waterweg and the Calandkanaal near Hoek van Holland, see Figure 8.6.

Figure 8.6: *Schematic representation of a lengthening of the breakwater between the Calandkanaal and Nieuwe Waterweg, at Hoek van Holland*

The influence of this measure at the location of the breakwater can be seen clearly in the maps shown below. It shows the salinity in the upper layer of the vertical. The figure on the left shows a situation with a discharge at Lobith of 5.000m^3/s in the present configuration (with a 400MW power plant implemented). The second map shows the same situation with a lengthening of the breakwater with 3km.

However, the objective of this measure is to increase the salinity at the power plant intake. The following two graphs show the salinity at the intake, the first one as a function of time, the second one over the depth. The salinity at the intake in the situation of an implemented lengthening of the breakwater is slightly higher than without breakwater. This increase is, however, very small; approximately 0,6ppt. This conclusion, next to the fact that the salinity is already very high at the intake, make that the option of lengthening the breakwater is not further investigated in this study.

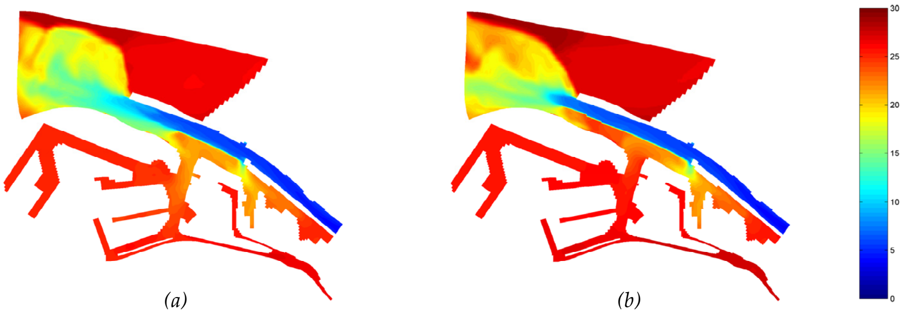
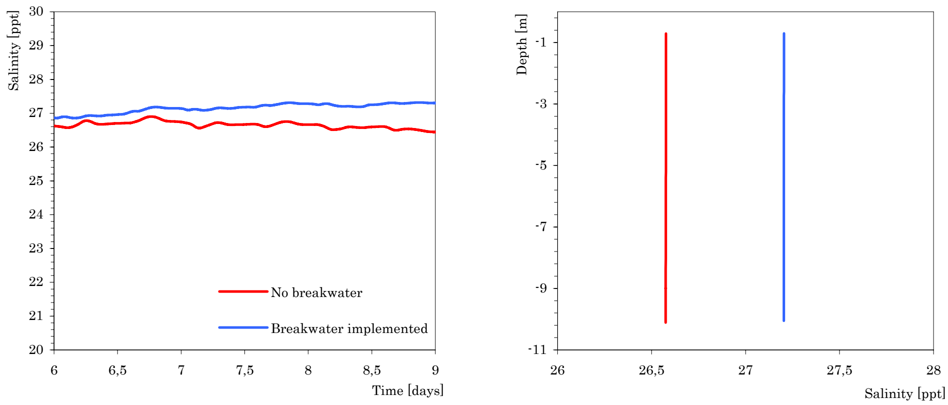


__Figure 8.7:__ Overview of the influence of breakwater length on the interaction between fresh and salt water. The figure shows the interaction in the upper layer of the vertical. (a) shows the situation with the present configuration, (b) a situation with a 3km longer breakwater

8.8 Open Oude Maas

An important disadvantage of a Blue energy plant at this location is that the Oude Maas, which is a main route for navigation, has to be closed off. This implies a large economic damage. It is thinkable that in a situation with an open Oude Maas, and a considerable fresh water discharge it might be possible that the intake of fresh water is not influenced by the brackish water discharge of the power plant. In this case the brackish water has to be mixed with the fresh water from the river and discharged directly to the North Sea. Two simulations show however that at times of rising and high tide the salinity at the intake increase to levels which might be unacceptable for Blue energy. The following two maps show the salinity at two different moments in time. The first one is at falling tide, just before low tide. At that moment the east-end part of the Oude Maas is dark-blue, which corresponds to a salinity close to zero. In this figure the brackisch water discharge of the power plant can be seen as a yellow to light-blue cloud in the Oude Maas, near the crossing with the Nieuwe Maas. The second picture shows the situation at rising tide, just before high tide. At that moment the east-end part of the Oude Maas has changed to a light-blue color, which means a salinity of 5 to 10ppt.



__Graph 8.11:__ Influence of the breakwater length on the occuring salinity at the salt water intake of the power plant Left, as a function of time. Right, at a fixed moment in time, over the depth

The explanation of this rise in salinity at the fresh water intake can be found in the tidal movement. At rising tide, the brackish water which is discharged by the power plant at falling tide is pushed back into the Oude Maas. Because the occurring discharges due to the tidal movement are really large compared to the discharge of the power plant, 2.000 to 3.000m^3/s and 800m^3/s respectively, the total amount of brackish water is pushed back. After some mixing, the salinity at the power plant intake reaches values of 5 to 6ppt at maximum. The average salinity at the intake is approximately 2,5ppt. Together with a salinity of 27ppt at the salt water intake this would imply a gross power of approximately 0,99$MW/m^3/s$. The net power which can be delivered to the public network will be as low as 0,5 to 0,6$MW/m^3/s$, which is this study is considered to low to be economically feasible.

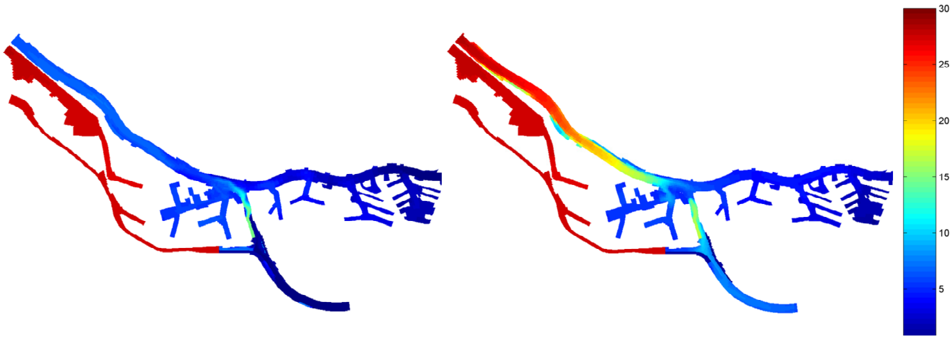


Figure 8.8: *Overview of occuring salinities near the bottom in a situation without a barrier in the Oude Maas. The left map shows the salinity at falling tide. The Right map is at rising tide*

One note has to be made together with this conclusion. The power plant is located very close to the boundary of the model. Because of the fact that in this simulation the Oude Maas is not closed off, the boundary is influenced by the implementation of the power plant. Especially the occurring salinities at the boundary might not represent a real life situation. At rising tide the brackish water from the power plant reaches the boundary, which can be seen in the right figure above. The salinities which are prescribed at this boundary (which only hold at times when the discharge is directed into the model) might not be totally right. At rising tide the brackish water flows through the boundary, out of the model, but in principle it does not come back into the model at the moment of turning discharges. At that moment the model calculates again with salinities which are prescribed. This problem can partly be solved by using a Thatcher-Harleman time lag. This time lag represents the return time for concentrations from their value at outflow to their value specified by the boundary condition at inflow. This time lag is set to 60 minutes for this simulation. This choice has to be confirmed by use of a larger model, which is not done in this study.

Half-open barrier

When taking a closer look at the left map of Figure 8.8 it can be seen that the brackish water effluent from the power plant is immediately transported away in the direction of the North Sea. An even closer look at the occurring salinities shows that only at rising tide the salinity at the fresh water intake increases. It is thinkable that when closing-off the Oude Maas it might be possible that the barrier is open for navigation at falling tide, and that locks are used in times of rising tide. This reduces the economic damage for navigation at the Oude Maas.

Unfortunately, from this study it does not become clear if this solution is feasible. The opening of the barrier at falling tide (just after high tide) depends largely on occurring water levels at both sides of the barrier. When, at rising tide, large water level differences occur between the north and south side of the barrier it might take a long time before the water levels have been levelled out.

Furthermore, the discharge regime of the Oude Maas, and consequently of the total system are influenced considerable when choosing this option. More research needs to be done in order to determine if this is possible.

8.9 Conclusion

From this chapter can be concluded that a power plant which needs to be provided with 400m^3/s of salt water is feasible when considering the availability of salt water. This discharge can be reached without unacceptable rises in the peak velocities in the Hartelkanaal. The maximum increase is 15%, to a value of 2,4m/s which occurs in less than 0,3% of the time.

The salinity that occurs at the salt water intake will be in the range of 26,5 to 28g/l. These values can be reached without extra measures to be taken. The occurring salinity at the power plant intake is mainly influenced by the fresh water river discharge. At very high discharges the salinity decreases to values of 26,5g/l. At relatively low discharges the salinity occurring at the intake can be as high as 28g/l.

A situation with an open Oude Maas is considered not feasible. In that situation there is no strict separation between fresh water and the brackish water discharged by the power plant. A half-open Oude Maas, with a barrier that is opened at falling tide, and closed at rising tide might be a solution to limit the economical damage for navigation.

Chapter 9

Design parameters

In the previous chapters the three different water flows (salt, fresh, and brackish) are discussed, together with the aspect of separation of these flows. From Chapter 8 is found that a power plant which needs to be provided with a salt water flow of 400m³/s is feasible. The consequences on the fresh water side for a power plant of this size can be found in Chapter 7. In this chapter the consequences of implementing a power plant with this size are discussed together with the most important power plant design parameters. The first section starts with the water management consequences induced by the power plant. Section 9.2 subsequently discusses the flows that will be used by the power plant and the overall efficiency of the plant. Sections 9.3, 9.4, and 9.5 deal with the actual power plant parameters. Sections 9.6 and 9.7 discuss both the closure dams that have to be created in order to make the power plant work. The last section, 9.8, compares in short the power plant with Wind energy.

9.1 Water management consequences

The water management of the Dutch Delta has to adapt when implementing a Blue energy power plant. In the foregoing chapters the changes which have to be made to the system have been described:

- Closure of the Oude Maas
- Permanent closure of the Hartelkering
- Intake of river water from the Oude Maas near Spijkenisse, 400m^3/s

- Intake of sea water from the Hartelkanaal west of the Hartelkering, 400m³/s
- Discharge of a mixture formed by both intake flows into the Oude Maas and Nieuwe Waterweg, 800m³/s

9.1.1 Fresh water discharges

At present a large part of the fresh water discharges to the North Sea through the Oude Maas. With the power plant implemented only 400m³/s of water will flow through the Oude Maas. This implies that the remaining part of the discharge, on average 300-400m³/s has to be diverted. It can be directed to the Haringvliet, or to the Nieuwe Maas. The latter has the advantage that in this way it is possible to control the salt intrusion via the Nieuwe Maas. However, this is only of importance in case of dry weather with consequently very low river discharges.

The instruments to control where the fresh water will be directed to are the outlet sluices at the Haringvliet. Opening up the sluices makes that the fresh water will be diverted to the Haringvliet. Keeping it closed will cause the water to flow through the Nieuwe Maas. This makes that the schedule for controlling the sluices has to be updated.

In the present situation the Hartelkanaal discharges a small fresh water flow. By closing of the Hartelkering and taking in water for the power plant on the west side of the dam implies that the average discharge through the Hartelkanaal will be directed inland.

9.1.2 Tidal influences

In the present situation the tidal movements reach quite far into the Dutch Delta. In the city of Dordrecht the difference between low and high tide are still 60 to 100cm. In the new situation the Oude Maas is closed-off which implies that the tidal movement cannot intrude the country anymore via this channel. However, the Nieuwe Maas is still open. It is therefore thinkable that the tidal movement can still be felt on the Oude Maas in spite of the fact that it is closed-off. The tide might reach the Oude Maas via the 'back door.'

9.1.3 Salinities

Due to the construction of a power plant in the Botlek the salt content at a number of

Figure 9.1: *Overview of the changing salt concentrations in the Delta area due to the implementation of a power plant (blue=0g/l, red=30g/l)*

locations in the area change drastically. In Figure 9.1 an overview is given of the salinity in the Rotterdam area at a fixed moment in time. The left map shows the salinity at present time, the right figure with the power plant implemented. The largest changes occur in the Hartelkanaal in which at present a large salt gradient exists. Furthermore, at the crossing of the Nieuwe Maas, Oude Maas, and Nieuwe Waterweg the salinity changes considerably. This is mainly caused by the discharge of brackish water from the power plant. Also the salt tongue in the Nieuwe Waterweg changes position a little.

9.1.4 Salt intrusion Nieuwe Maas

As already mentioned in the previous section the implementation of the power plant influences the location of the salt tongue in the Nieuwe Waterweg and Nieuwe Maas. This is a very important result. The intrusion of the tongue may not reach too far because fresh water intakes for drinking water and agriculture might be affected. The maps below show the salinity in the Nieuwe Waterweg and Nieuwe Maas. The left two maps show the present situation and are compared with the situation with a power plant implemented. The west-end of each map is located at the mouth of the Nieuwe Waterweg, the east-end boundary near the Brienenoord bridge.

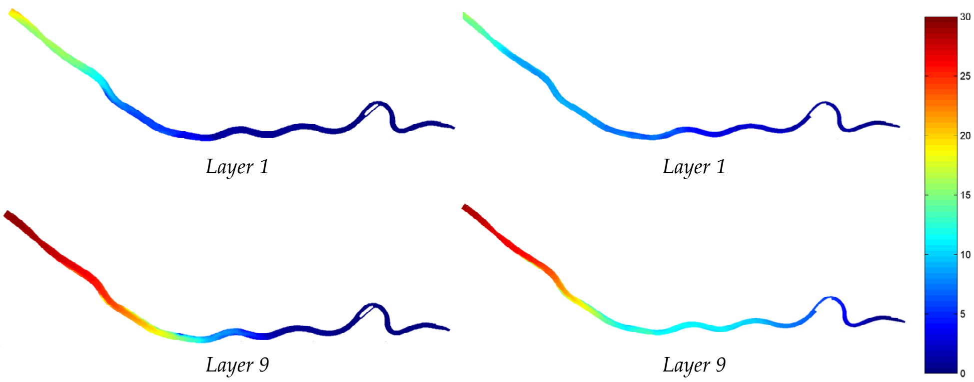


Figure 9.2: *Overview of the changing salt intrusion along the Nieuwe Waterweg and Nieuwe Maas as a result of the power plant construction. The two maps on the left-hand site show the present situation. The new situation is shown on the right*

It might not be totally clear from the maps, but when taking a closer look at the salinity data it can be found that the in the Nieuwe Waterweg the change of position of the salt tongue depends on time and location. The dominant movement of the salt tongue at the mouth of the Nieuwe Waterweg is directed seaward. Near the crossing with the Oude Maas in the Botlek area it moves inland, which can be explained by the brackish water discharge from the power plant. In the Nieuwe Maas the influence is more obvious. The salt tongue moves inland over a distance of 5 to 8 kilometres, depending on time and location. This is not a problematic consequence, especially considering the fact that the fresh water discharge at the Nieuwe Maas could be raised a little with the fresh water which is diverted from the Oude Maas. In that case the additional intrusion will be even less. From this can also be concluded that the salinity at the Oude Maas will not be influenced via the ‘back door,’ which means that the salinity at the power plant intake will be very low, around 0,3g/l.

9.1.5 Salinity Maasvlakte

At present a large salinity gradient exist over the vertical in the Europahaven. Fresh water from the Hartelkanaal and Nieuwe Waterweg flows on top of the Salt water. This can be seen in the Figure 8.4 in section 8.5.3. In the new situation, with a power plant implemented in the system, the salinities that occur in the harbour basins of the Maasvlakte change. The relatively brackish layer, which at present flows on top of salt water, disappears almost entirely. This might have consequences for navigation which need to be investigated.

9.2 Water availability

In the previous chapters the availability of both fresh and salt water are determined. A statistical analysis has been done in order to calculate the fresh water availability, and hydraulic calculations have been done to determine the salt water usage.

9.2.1 Salt water

Hydraulic calculations have been done in order to determine how much salt water could be made available for Blue energy in the Botlek area. From Chapter 8 it became clear that the exploitation of a power plant which needs to be provided with a salt water flow of 400m^3/s would not lead to any considerable problems. Furthermore, the salt content of the water turned out to be quite high, on average 27,3g/l. This salt water salinity is averaged over time as a function of different river regimes. Estimations, based on statistical data, have been made to determine the flow duration curve of the Nieuwe Maas. This curve is subsequently used to determine a probability of exceedance curve for the salinity at the power plant intake.

9.2.2 Fresh water

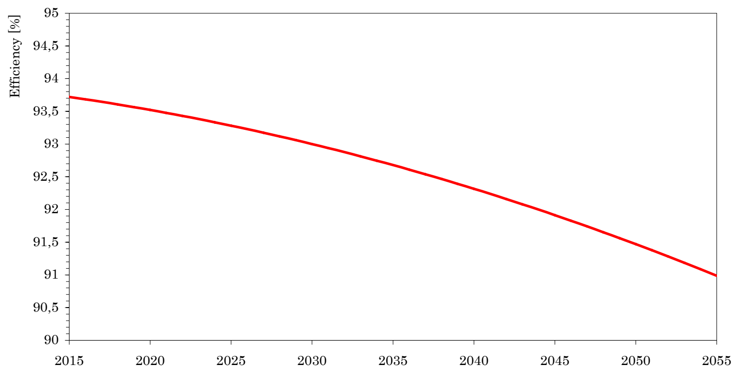
A statistical analysis of the availability of fresh water in the Delta has been discussed in Chapter 7. The salt water availability has been found to be 400m^3/s. When using a mixing ratio of 1, which is considered to be the most convenient ratio, the same amount of fresh water needs to be taken in by the power plant. The analysis showed that a flow of 400m^3/s will not be available 100% of the time, when taking the Delta Flow condition and Nieuwe Maas condition in account. Graph 7.6 shows that a flow of 400m^3/s for Blue energy is available in approximately 95% of the time (unavailability of 5%), when considering the present scenario or G scenario. In case of the G+ scenario, the availability is a little less, approximately 88% of the time. When the full power flow is not available, the average flow that can be used for Blue energy is 320m^3/s for the present and G scenarios, and 280m^3/s for the G+ scenario. This makes a total efficiency of 99% and 96,5% respectively, which can also directly been seen in Graph 7.12.

It is assumed that the salinity at the fresh water intake will not change when implementing the power plant. The occurring salinity at the fresh water intake will therefore somewhere around 0,3g/l.

Efficiency in time

The different climate scenarios were discussed in section 5.3. But what scenario to chose for the design of a Blue energy power plant. At political level, it has been decided that issues concerning water quantity up to 2015 the G scenario will be used. For 2050 the G+ scenario will be used. This decision has also been followed in this study.

For the fresh water availability this means that the scenario which needs to be dealt with changes in time. At the start of exploitation the present situation (which is almost the same as the G scenario) has been used to determine the efficiency. At the end of the life time of the power plant this has changed to the G+ scenario. Intermediate years are determined by interpolation. An analysis is made of the overall efficiency concerning fresh water availability for the life time of a Blue energy power plant, in which an extra downtime of 5% is included. This down time could be caused by for example contamination of one of the intake flows, or a breakdown in the power plant or network facilities. Graph 9.1 shows the overall efficiency of the power plant.



Graph 9.1: *Overall efficiency of the power plant during its lifetime*

9.3 Power parameters

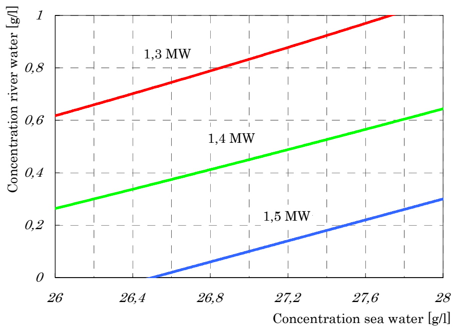
In Chapter 4 a design guide has been made for calculating the most important design parameters of a Blue energy power plant. The following sections all shortly deal with an aspect in the power plant design at the Botlek area.

9.3.1 Specific power

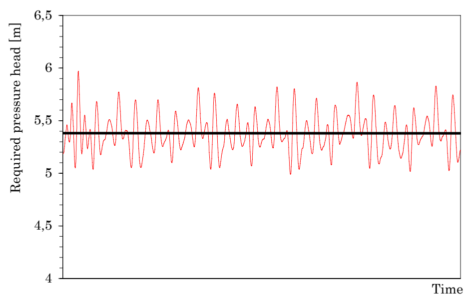
A fresh water intake with a salinity just above zero, and a salt water intake with a salinity of on average 27,3g/l makes that the gross specific power available is 1,48MW/m^3/s, see Graph 9.2. System losses decrease this power to 1,18MW/m^3/s, which is the gross specific power (SP_{gross}).

9.3.2 Pumps

Pumps are needed to push up the water which has been taken in to a level 5 meters above the water level of the brackish water basin. The total head which have to be



Graph 9.2: *Determination specific power of the power plant*



Graph 9.3: *Pressure head required for the salt water flow*

delivered by the pumps depends on the water level differences between intake and outlet side. For simplicity it is assumed that the time the water spends in the total installation is zero, which means that no time-lag needs to be dealt with when determining water level differences. Analysing the water level differences between the salt water intake and outlet shows that the salt water has to be pumped up over 5,4m, see Graph 9.3. The water level difference between fresh water intake and outlet is not known because of the fact that the water level at the fresh water size is unknown. It is assumed that no difference exists between these two levels.

Using a pump efficiency of 85%, an engine efficiency of 95%, and an efficiency of the frequency converter of 95% it can be found that the total specific power needed for the pump installation is almost 0,14MW/m^3/s.

9.3.3 Installed power

With the information from the previous sections and the design guide from Chapter 4 the installed power can now be calculated as

$$\begin{aligned} P_{gross} &= Q \cdot SP_{gross} \\ &= 400 \cdot 1{,}18 = 472 \ MW \end{aligned} \tag{9.1}$$

The power which will be available for the public network is

$$\begin{aligned} P_{net} &= Q \cdot SP_{nett} = Q \cdot (SP_{gross} - SP_{pump;total} \cdot \tfrac{1}{\eta_{pump} \cdot \eta_{engine} \cdot \eta_{converter}}) \\ &= 400 \cdot (1{,}18 - 0{,}14) = 416 \ MW \end{aligned} \tag{9.2}$$

The theoretical amount of energy which can be generated by the power plant, and is available for the public network, over a period of one year can now be determined as

$$\begin{aligned} E &= 8{,}76 \cdot Q \cdot SP_{net} \\ &= 8{,}76 \cdot 400 \cdot 1{,}04 = 3644 \ GWh \end{aligned} \tag{9.3}$$

This amount has still to be corrected for the overall efficiency (μ).

9.3.4 Membranes

The membrane surface which is needed depends on the specific power which can be delivered by the membranes. This specific power is assumed to be 1,5W/m^2, which corresponds to the present state of technology. In a near future, within 5 years from now this power might be doubled to 3W/ m^2. This increase in power is important for the membrane surface, but even more for the economic analysis, see Chapter 10. A doubling of specific power means halving the costs. A higher specific power is by scientists considered to be unfeasible.

The total surface of membrane can now be calculated with equation (4.9) as

$$\begin{aligned} A_{membrane} &= \frac{P_{gross}}{SP_{membrane}} \\ &= \frac{472\ MW}{1,5\ \frac{W}{m^2}} = 315 \cdot 10^6\ m^2 \end{aligned} \tag{9.4}$$

When stacking the membranes in units with the size of a sea container (for purposes of transport and easy handling), approximately 2.360 units are needed. This is calculated with equation (4.10).

9.4 Pump area

The pumps which are used in the power plant are typical pumps having a large flow rate (400m^3/s) and a low pressure head (approximately 5m). The intake side has a rectangular shape, which is totally submerged in the open intake channels. An analysis based on these assumptions of the life cycle costs shows that for each flow (salt and fresh water) 16 pumps are needed with a diameter of 3m. Each pump has consequently a flow of 25m^3/s. The submergence of the pump is approximately 2,5m below the lowest water level. The required synchronous speed of the pumps is 135rpm.

With this information it is possible to estimate the total area which is needed for the pumping station. 16 pumps with a diameter of 3m implies a length (perpendicular to the incoming flow direction) of each station of approximately 100m (16x6m, which includes some space for the difference in length between the water-intake and pump). The width of the pump station is assumed to be approximately 50 meters. For two pumping stations (fresh and salt) the area which is needed for pumps comes down to 1 hectare. This is considerably less than at first assumed in section 4.4.

9.5 Total area

With the previous information now the total area which is needed for the Blue energy power plant can be determined. In section 4.3 was substantiated that the area for prefiltration is approximately the same as the area for the membranes. Furthermore, for hydraulic reasons and to limit the total area, the prefiltration installation is placed on top of the membrane installations. With 1/3 of free space in the factory (see section4.5), and an extra free space for the total power plant of 10% the total area is determined as

$$\begin{aligned} A_{total} &= (A_{membrane\,installations} + A_{pumps}) \cdot 110\% \\ &= (2.360 \cdot 45m^2 + 10.000m^2) \cdot 110\% \approx 127.820\ m^2 \end{aligned} \tag{9.5}$$

By placing the prefiltration on top of the membrane installations only four buildings are needed on the power plant site. First, a large industrial building for membrane installations and prefiltration. This building will cover an area of 106.000m,[2] will have a height of approximately 12m, and therefore has a volume of $1{,}4 \cdot 10^6$ m^3. Second, two buildings for the pumping stations for fresh and salt water are needed, which will both have a volume of approximately 20.000m^3. Last, a small building for operation will be needed. This will be a very small building compared to the other three.

One point of consideration for the construction of the industrial building is the foundation. With large volumes of water in the membrane installations, and especially in the prefiltration, the content of the building is very heavy. Therefore, the foundation has to be very strong. The building itself, however, can be constructed as a standard industrial buiding.

9.6 Closing dam Oude Maas

In order to separate the fresh water intake from water which is influenced by salt it is inevitable to close-off the Oude Maas. For navigation purposes it is necessary to create locks in this barrier. As described in section 6.1.1, both sea going vessels and inland navigation use the Oude Maas as shipping route. Therefore it is assumed to construct two locks with different sizes. The first lock is located in the middle of the Oude Maas and is able to handle the largest vessels. The second lock, on the eastside of the first lock is a smaller one to handle inland navigation and other ships. To determine the size of the locks it is necessary to investigate the shipping intensity on the Oude Maas. With that analysis it can also be determined if two locks are sufficient. The following picture gives an overview of the area with the barrier and locks implemented. In contrast to what the picture shows, the west part of the barrier will be used for the power plant as well. If not, the west part of the barrier will become smaller.

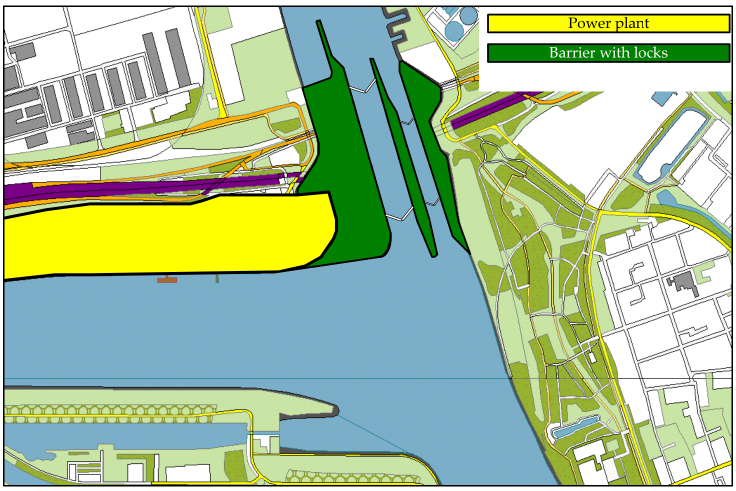


Figure 9.3: *Layout of the Oude Maas barrier*

When the solution of the half-open Oude Maas is applied, it is thinkable that another opening in the barrier is created with only one door (a simple sliding door for example),

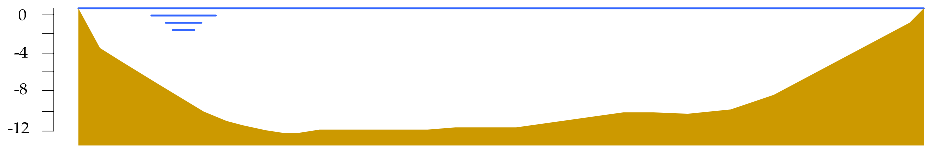


Figure 9.4: *Depth profile of the Oude Maas at the location of the new barrier*

which is closed at rising tide, and open with falling tide. In this way not all shipping traffic has to pass through the shipping locks is case of falling tide, which might prevent accidents to occur.

The depth profile of the Oude Maas at the location of the barrier is shown in Figure 9.4. When analysing the depth data it is found that the average depth is approximately 9 meters. With a width of approximately 350m, the total cross section covers 3.150m^2. The total volume which is needed to fill the barrier is approximately 1,2 million m^3.

9.7 Closure Hartelkering

In the Hartelkanaal the storm surge barrier which has been built within the framework of the Deltaplan has to be closed permanently. The barrier has been built to withstand high water levels from the sea side at times of a storm surge. At closed condition the barrier is able to withstand water levels as high as 3m above NAP. Its design is such that some water will flow over the top of the barrier. Next to this, it is thinkable that the barrier is not totally water tight in closed position.

Figure 9.5: *Overview of the Hartelkering*

For the use of the barrier in the power plant design it might be necessary to change the barrier in such a way that it becomes completely water tight. In that situation the salt water on the west side cannot influence fresh water on the east side.

North of the present barrier a lock is located which can be used for navigation. An analysis of the shipping intensities has to show that one lock is sufficient when the Hartelkering is closed permanently.

9.8 Comparison with wind energy

In order to valuate the impact of this large Blue energy power plant, a comparison is made with wind energy. The power plant in this study delivers approximately 400MW to the public network, which is enough for almost 1,1 million households. At January the 1st of 2008, all 1.800 existing wind turbines in The Netherlands produced on annual basis 3,7 million kWh, which is slightly more than the 400MW power plant. This implies that a Blue energy power plant of this size is able to produce the same amount of electricity as all running wind turbines in the country!

However, also in wind energy a lot of technical progress is being made. In the near future, new wind turbines will be able to produce 3-5MW at full power, which corresponds to approximately 6-10 million kWh a year (load factor of 25%). When calculating the number of new wind turbines that are necessary to produce the same amount as this Blue energy power plant, one can find that 350-550 turbines are needed! With a mutual distance of approximately 200m this would imply a line of 70 to 110 kilometres. These modern wind turbines have diameter of approximately 100 meters, and the height of the axis is found 80 meters above ground level.

Figure 9.6: *Wind turbines at sea*

Chapter 10

Economic feasibility

This chapter discusses the economic feasibility of the power plant in the Botlek area. It deals with all cost aspects of the power plant in the first three sections of the chapter. The costs of the power plant are divided in three categories; costs directly related to the power plant (section 10.1), costs of additional infrastructure which is not directly related to the power plant (section 10.2), and operation and management (section 10.3). Section 10.4 deals with the benefits of the power plant, followed by a cost price determination in section 10.5. A sensitivity of three different cost items is done in section 10.6. Finally, in the last section a number of aspects which are very important to keep in mind when valuating this economic analysis.

10.1 Construction costs of the power plant

The construction costs of the power plant contain the expenses which have to be made for the installations in the power plant. These costs are divided into four main items.

Membranes

A lot of discussion is going on about prices of membranes. A couple of years ago Blue energy was thought to be unfeasible because of very high membrane prices. Technological progress in the membrane industry has caused that prices have dropped considerably over the last couple of years. Experts indicate that within a few years it will be possible to produce membranes for Blue energy at a cost price of 2 €/m^2. Experiments on laboratory scale have shown that this is a realistic estimation. The problem for Blue energy, however, lies mainly in the fact that it is not possible yet to produce membranes at such a large scale as needed for Blue energy (315 million m^2 are needed for the power plant in the Botlek area). At this moment it is being investigated if productions lines can be expanded in order to produce large quantities, at a reasonable price. Some people even think that producing membranes at a cost price of 1 US$/$m^2$ will be possible in a near future.

In this economic analysis it is assumed that the membranes can be produced at 2 €/m^2. This price includes assembly into stacks and all other material which is needed to construct a stack (for example spacers).

Prefiltration

As discussed in section 3.5, prefiltration is an important part of a Blue energy power plant. Studies have pointed out that micro-filtration is the best option to use for Blue energy. However, this technology has never been used before on such a large scale, combined with the mesh which for Blue energy needs to be very fine. At this moment tests are being done in order to determine the performance of this solution.

Experts[1] have said that the costs of a prefiltration installation suitable for the power plant in the Botlek area will lie around 1.000 Million Euros.

Pumps

Two large pumping stations are needed to run the Blue energy power plant. These pumps have to run at full power for almost 100% of the time. Only at times of a low river discharges, a breakdown in the plant, or when replacing the membrane installations, the pumps will be turned down a little. The total flow and pressure head together make that the pumps have a large energy consumption. Analysing the life cycle costs of the pump installations shows that the operation costs (which consists of electrical power) are much higher than the capital investment costs. Fortunately, the electrical power needed for the pumps will be delivered by the power plant itself, only at start-up external power is needed. The investment costs of the pump installations are estimated to be 150 Million Euros.

Electrical facilities and pipelines

The membrane price of 2 €/m^2 stated above, does not include pipelines. In order to get the water from the channels to the pumps, prefiltration, membrane installations, and back to the Oude Maas, a lot of pipelines are needed. Furthermore, connecting the power plant to the public network also needs a couple of electrical installations. These costs are estimated to be 200 Million and 100 Million Euros respectively.

10.2 Cost of additional infrastructure

Apart from the investments which need to be done for the power plant itself, a number of other investments are necessary to make the Blue energy power plant work. Closing of the Oude Maas and Hartelkanaal are inevitable measures. In the Oude Maas a new

[1] Experts at Wetsus and Hubert in The Netherlands have confirmed this

barrier, together with a complex of shipping locks will be built. In the Hartelkanaal the Hartelkering will be permanently closed. A number of measures need to be taken to assure water tightness of the barrier. Furthermore, some adjustments need to be made to the layout of the Hartelkanaal, near the salt water intake. It might also be necessary to adapt (enlarge) the navigation lock.

These costs for these hydraulic measures are estimated to be 500 Million Euros for the barrier in the Oude Maas, and 50-100 Million Euros for the adaptations to be made to the Hartelkering and Hartelkanaal lay-out.

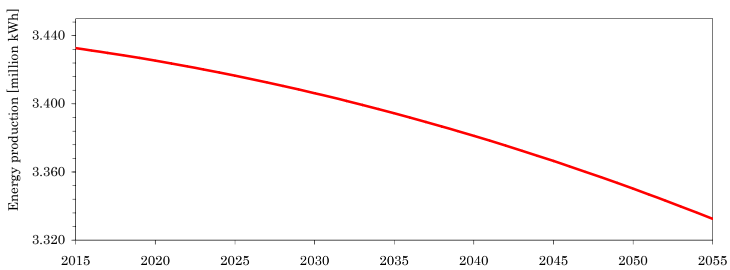
Next to this, a site where the power plant will be built has to be purchased, a heavy industrial building needs to be built on it, and some infrastructural works are needed. These costs are estimated to be approximately 600 Million Euros.

10.3 Operation and management

During exploitation expenses will be made for operation and management. These costs are assumed to be 3% per year of the investments for power plant parts. For the additional infrastructure this percentage is assumed to be 0,5% per year. When calculating this it can be found that for Operation and Management approximately 50 to 60 Million Euros per year is needed.

10.4 Benefits

The financial benefits of a Blue energy power plant rise from the sales of electricity. Section 9.2 discussed the overall efficiency of the power plant in the Botlek. Together with the total energy which can be produced by the plant, see equation (9.3), the electricity production can be calculated as a function of time. This is shown in the following graph.



Graph 10.1: *Energy production of the power plant during its lifetime, in million kWh*

The gradient in the figure is a direct result of the gradient in the efficiency, which is caused by the changing river regime due to climate changes. Using the average energy consumption for a family in 2006 these amounts of energy are enough to provide almost 1,1 million households. With a prospect of a declining energy consumption in the coming years this number could even increase.

10.5 Cost price determination

In order to determine the cost price for a kWh produced by a Blue energy power plant a net present value calculation has been done. From this analysis a cost price of Blue energy will be found which gives a net present value of zero. This implies that the overall result of the construction and exploitation of the power plant is zero.

Depreciation time and lifespan

It is assumed that the power plant will be built for an exploitation period of 40 years. An important factor in the analysis is the depreciation time of the different components of the power plant and additional infrastructure. The economic lifespan of the latter is assumed to be 40 years. The life span of the power plant components is much shorter. Prefiltration, pipelines and electrical installations will be able to function properly for a period of approximately 20 years. The lifespan of the membrane installations is even shorter. At present the membranes are assumed to be replaced every 5 to 10 years.

Reinvestments for membranes will be done every 5 or 10 years (two different analyses have been made). The reinvestment for especially the prefiltration is so large that it is decided to do this over a period of 4 years.

Other parameters

A number other parameters are important for the analysis:

Discount ratio	6 %
Index ratio energy prices	2 %
Index ratio operational activities	2 %
Index ratio building costs	2 %
Construction time	5 year

The discount ratio is the value used in the net present value analysis. The Index ratios are corrections per year for the parameters given. It is assumed that the power plant together with the additional infrastructure will be built in 5 years. The expenses for this construction are distributed evenly over this period, except for the membrane investments. These are spent in the last two years of construction.

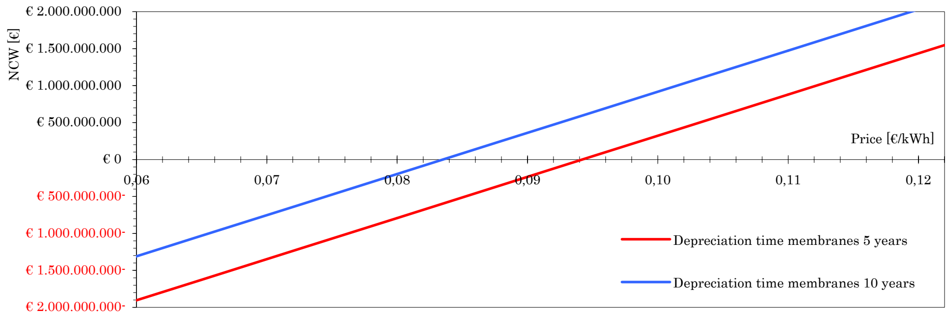
Net present value

The investments and benefits over time are shown in Graph 10.2. It shows clearly the large investments in the construction period of the power plant, and the reinvestments for membranes and power plant parts that need to be done during exploitation. The size of the benefits bars depend off course on the still to find cost price. This is done by calculating for each benefit and expense the net present value (2010 is used as base year), adding these up, and subsequently choose the cost price of Blue energy in such a way that the overall net present value becomes zero.

Graph 10.3 shows that the cost price of electricity generation by the Blue energy power plant will have a cost price within a range 8,4 cents/kWh to 9,4 cents/kWh, depending

***Graph 10.2:** Overview of all benefits and costs over the lifetime of the power plant*

on the depreciation time of the membrane installations. From this it can be directly concluded that this depreciation time has only a marginal influence (1 cent/kWh) on the total cost price. The real depreciation time, and therefore also the cost price will be found somewhere in the middle.



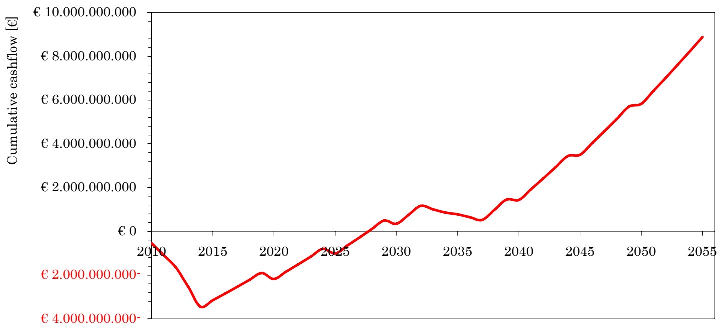
***Graph 10.3:** Net present value as a function of the price for Blue energy in cent/kWh*

The best way to value these prices for Blue energy is to compare them to cost prices for other electricity sources. The cost price of electricity generated in a power plant running on coal lies around 5 cents/kWh. Nuclear energy has approximately the same price. When comparing Blue energy to these conventional types of electricity generation, it turns out that Blue energy is more expensive than conventional methods. However, when comparing to other forms of renewable energy the picture changes considerably. Wind energy, which is already used on a large scale has a cost price varying between 8,8 cents/kWh and 10,3 cents/kWh depending on the location of the turbines (onshore, or offshore). These prices are of the same order of magnitude compared to Blue energy, which would mean that Blue energy is a very interesting form of renewable energy.

10.5.1 Cashflow

Graph 10.4 shows the cumulative cashflow during the life cycle of the power plant (with a depreciation time of 5 years for the membrane installations, 10 years shows approximately the same figure). It can be seen that the moment when the sum turns from negative to positive is reached after 18 years, in 2028. This is called the Break Even Point. At this point the cumulative discounted benefits equal the cumulative discounted expenditures.

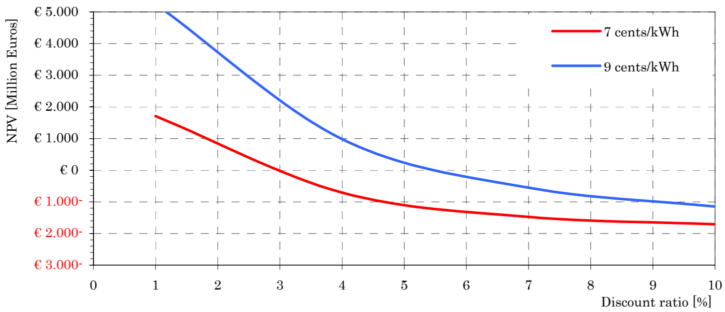
Another interesting point which can be seen in this graph is the maximum negative cumulative cashflow of approximately -3.500 million Euros. This is found at the end of 2014 where construction of the power plant has just finished. This shows that starting up a Blue energy power plant is highly capital intensive.



Graph 10.4: *Cumulative cashflow over the lifetime of the plant*

10.5.2 Internal rate of return

The internal rate of return is a capital budgeting method used to decide whether long-term investments should be made. It can be calculated as the discount ratio that results in a net present value of zero. In Graph 10.5 the net present value is shown as a function of the discount rate for both a cost price of 7 cents/kWh and 9 cents/kWh (for the case in which the membranes have to be replaced every 5 years). The corresponding IRR values are respectively 3,0% and 5,5%. Both percentages are quite low for commercial business. When aiming for an IRR of 10% a cost price is found of just over 13 cents/kWh.



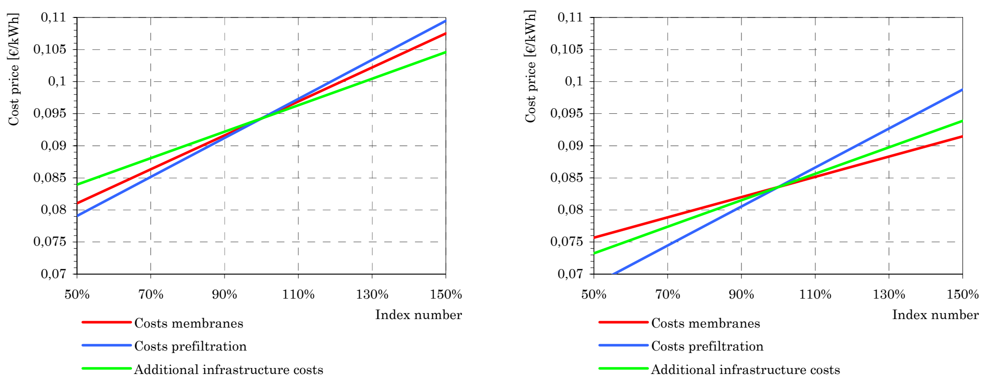
Graph 10.5: *Net present value as a function of the discount ratio*

10.6 Sensitivity analysis

The analysis made in the previous section is sensitive to changing economic parameters. When considering the costs size of the balance it can be seen that a few items have a very high cost, sometimes even compared with a low lifetime expectance. Therefore three groups of cost changes are defined for which the influence on the cost price is determined:

- Costs of the membranes and correspondingly the reinvestment for membranes. A large investment has to be made for the membrane installations. Together with a very low depreciation time (5-10) years this could lead to a significant influence on the overall cost price
- Costs of the prefiltration. For prefiltration an even higher investment has to be made at the start-up of the power plant. Because the depreciation time is only 20 years this item can also have a large influence on the overall cost price
- Cost of additional infrastructure. This item is almost 1.200 million Euros. From practical experience has become clear that these kinds of investments are often underestimated. Therefore it is important what the influence is on the overall cost price.

The following graphs show the influence of these parameters on the overall cost price. A depreciation time for membranes of 5 years is used in the left graph, 10 years has been used in the right graph.

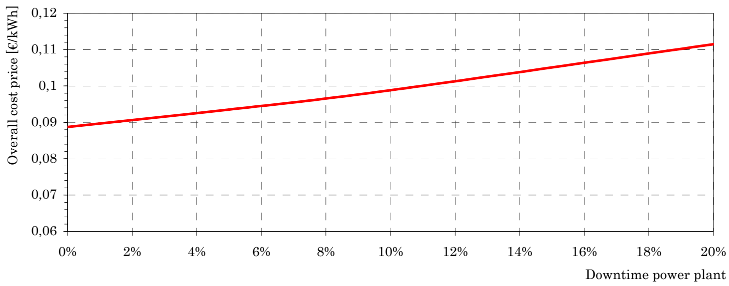


Graph 10.6: *Influence of different cost items on the cost price for Blue energy for a membrane depreciation time of 5 years (left) and 10 years (right)*

From the graphs it becomes clear that none of the three different cost items has a dominant influence on the overall cost price. However, it turns out that the prefiltration cost item has relatively the largest influence, which implies that further developments of Blue energy also needs a strong focus on prefiltration. Furthermore, the influence of the additional infrastructure, which is a large cost item, has not an extremely large influence on the overall cost price. This can be explained by the long lifetime expectance of 40 years.

In order to determine the sensitivity in the uncertainty of the benefits a number of calculations have been made with different efficiencies in the power plant. This is done by changing the extra downtime in the analysis. The overall cost price as a function of this extra downtime is shown in Graph 10.7.

In the original analysis a downtime of 5% (apart from the reduced efficiency due to a lack of fresh water) was assumed. This corresponds to 18 days. A downtime of 20% means 10,5 weeks.



Graph 10.7: *Influence of the overall downtime on the cost price for Blue energy*

The downtime in the graph can also be seen as a reduction in efficiency due to an arbitrary cause, for example a lack of demand on the energy market, or a lower specific power due to salinity fluctuations.

10.7 Discussion

A lot of assumptions have been made in this economic analysis, all of which need to be proven true in practice.

Membrane costs

The costs for membranes have been set to 2 €/m² which is a very important assumption. As discussed in section 10.1 a number of indications exist that this price can be reached in a near future. However, it has not been proven yet that this price will be reached. Furthermore, no production line does exist at the moment which can produce large amounts of membrane.

On the other hand, the analysis is based on a specific membrane power of 1,5W/m², which is a value that has been proven to be realistic. Scientists even predict that within 2 to 5 years this value can increase to 3W/m². In that case the membrane costs will directly reduce to 50% which has a large impact on the overall cost price.

Prefiltration costs

Prefiltration is a very high cost item. Although a lot of research is already being done to this part of the process, it still needs a lot of attention. The depreciation time of 20 years is also very important. Research has to show that this is a realistic value. A lower lifetime expectance results in a significant rise in overall cost price. On the other hand, it is possible that only a part of the prefiltration installations have to be replaced after 20 years. Increasing the lifetime expectance of (parts of) the prefiltration can have a large positive influence on the cost price.

Additional infrastructure costs

A number of investments need to be done which do not directly relate to the power plant. In case of the Botlek power plant a barrier in the Oude Maas has to be built, together with the permanent closure of the Hartelkering. This introduces a large cost item. Fortunately, these implementations might also be positive for other affairs. Think about protection against high water levels from sea. When neglecting these costs in the analysis the overall cost price will decreases at least 1 cent/kWh.

Not considered cost items

In the economic analysis done in this chapter two cost items are not dealt with:

- First, the economic damage due to the closure of the Oude Maas and Hartelkering. This causes a lot of economic damage for navigation, which is not taken into account
- Second, the costs for demolition of the power plant at the end of its lifetime, and the costs for removing and processing the membranes when these cannot be used anymore in the plant. The same holds for the filters of the prefiltration installations.

PART D

In conclusion

Chapter 11

Conclusion and discussion

11.1 Conclusions

This section contains the conclusions of this study. The conclusions are directly related to the objectives which were stated in Chapter 2 and the results of this study that are discussed in Parts B and C of this report. The objectives are repeated below:

"The first objective of this study is to gain insight in the conditions that need to be fulfilled by a specific location in order to construct a feasible large-scale power plant at that location."

"The second objective of this study is to find a suitable location in the Dutch Delta and determine whether and on which scale this location is feasible."

Blue energy in general

In the second chapter of this report a short description of the technology "Blue energy" is given. From this chapter it becomes clear that large amounts of electricity can be generated using this technology. When mixing a flow of 1m^3/s of both fresh river water and salt sea water a net power of 1MW can be generated in a RED power plant.

The first objective states that the conditions for a "large-scale" power plant have to be investigated. Large-scale is in this study defined as a power plant which can deliver at least 100-500MW to the public network. The most important conditions involve the water flows that are generated by a power plant. Three different water flows have to be dealt with. First, two incoming flows, salt water and fresh water, both with a rate of 100-500m^3/s. Second, one flow with brackish water, which has a flow rate equal to the summation of both incoming flows (200-1.000m^3/s). The hydraulic system has to be able to cope with these flows, or it has to be adapted in such a way that these flows can be handled.

The second aspect that turns out to be very important when applying Blue energy is the salt content of both incoming flows. On the fresh water side the salt concentration has to be very low, in the order of 0,3g/l. The salt water flow needs to have a very high concentration, 27-28-g/l, which is approximately equal to the salt concentration at sea, just offshore. When these salt contents are influenced, for whatever reason, the amount of power which can be generated by a power plant rapidly decreases.

The third aspect that plays a major role in the search for a suitable location for Blue energy is the possibility of separation of the three water flows. Especially the separation of the brackish water flow with the salt one is often underestimated. The system has to be able to deal with three different water flows which cannot interact. Otherwise, radical measures have to be taken to create this separation.

Blue energy locations in the Netherlands

Five locations have been identified around the country for Blue energy. Only two of these locations are interesting for Blue energy at a large scale, being the Afsluitdijk and the Delta. The Delta is more interesting because of the fact that far more fresh water is available in the Delta area.

Within the Delta five locations are interesting:

- Botlek area, see below
- Nieuwe Waterweg, at the moment not a realistic option because of the enormous economical damage which is caused by the closure of the Nieuwe Waterweg. However, if this is done this location is very interesting for Blue energy. It might be possible to construct a 1.000MW power plant
- Maasvlakte, not a very interesting location
- Haringvliet, an interesting location because of the availability of the strict separation between fresh and salt water. However, separation between brackish and salt will be difficult. When this problem could be solved by for example the construction of the Scharrezee at this location a power plant of at least 500MW might be feasible
- Krammersluizen, most interesting location because of the availability of three different waterways (Oosterschelde, Grevelingen, and Volkerak) for the supply and discharge of the water flows. A 200-500MW plant is feasible at this location

Feasibility of a power plant in the Botlek area

A very interesting location for Blue energy is in the Botlek area, near the Hartelkering. Closing of the Oude Maas with a barrier and shipping locks and a permanent closure of the Hartelkering makes that a perfect separation between the three water flows is created.

Salt water is supplied by the Hartelkanaal. Simulations have shown that a flow of 400m^3/s can be generated without negative consequences for navigation. Furthermore, the occurring salinity near the power plant intake turns out to be approximately 27,3g/l, which is hardly influenced by river discharges of tidal movements. Fresh water is supplied by the Oude Maas. A statistical analysis showed that, due to the availability of fresh water, a power plant which needs a flow of $400m^3/s$ is can run with an efficiency between 94% an 99%, depending on the climate scenario.

This together makes that a power plant with an installed power of 472MW is feasible. The power which can be delivered to the public network is approximately 416MW. On average 3.400 million kWh can be generated every year, enough to supply over 1 million families with electricity. This is done in a power plant which needs $315km^2$ of membrane, stacked in 2.360 200kW units. The plant covers an area of 12,8ha.

The efficiency of the power plant is very high, varying from almost 94% in the beginning of the life cycle of the plant to 91% in 2055. This is much higher than both other renewable and conventional energy sources.

A few consequences of the power plant are:

- Closure of the Oude Maas with a barrier and shipping locks, which is a negative consequence for shipping activities
- Permanent closure of the Hartelkering, which is also a negative consequence for shipping activities
- A slightly extra salt intrusion in the Nieuwe Maas (5-8km), which can be prevented by diverting a little more fresh water to the Nieuwe Maas (this water is available)
- The Hartelkanaal and Maasvlakte harbour basins become totally salt

An economic analysis of a power plant in the Botlek shows that the cost price of electricity generated will lie around 8,4 to 9,4 cents/kWh. This is comparable to prices for wind energy. In this analysis a number of estimates have been made about the exact costs of the power plant components. Some uncertainties about these costs still exist. Most important are the costs for membranes and prefiltration. Next to this, the depreciation time of the membrane installations and prefiltration are also very important for the cost price of Blue energy.

11.2 Recommendations

The conclusion of this report is that a power plant of over 400MW is feasible in the Botlek area. However, this study has focussed on a lot of aspects concerning Blue energy in general, and this specific location. Therefore, not all aspects have been dealt with in detail. This section deals with some recommendations for further study.

Blue energy

From the economical analysis it becomes clear that prefiltration has approximately the same influence on the cost price as the membrane installations. More research needs to be done to the prefiltration installations. Furthermore, the exact costs of these installations have to be investigated together with the depreciation time.

Interesting locations

In this study a number of locations are shortly discussed but not deepened out. One of these locations is at the Afsluitdijk. For this location a perfect fresh-salt separation exists, but a brackish-salt separation might be quite difficult to create. The location along the Afsluitdijk, and the dominant flows in the Waddensea are important factors when trying to create this separation. More research needs to be done to this.

A second location, which is not deepened out, but which might be a very interesting location for Blue energy on the short-term are the Krammersluizen. Extensive research needs to be done to the measures which need to be taken for the implementation of a power plant at this location, and to determine the consequences.

Botlek alternative

More research needs to be done in order to verify the feasibility of a power plant in the Botlek area, and determine the exact consequences:

- An estimation of the economical damage for navigation, caused by closing of the Oude Maas and Hartelkanaal, has to be determined
- The influence of the implementation of the power plant at the total river system has to be determined. What happens with occurring water levels, discharges, and salt concentrations upstream is not determined in this study.
- Morphological consequences caused by the implementation of the power plant have to be investigated. By closing of two waterways the morphological condition of the system might be totally changed.
- Locally, near the power plant intakes, large flow velocities might occur. This needs to be investigated together with the consequences of these flow velocities
- In this study the choice for a power plant size is mainly determined by the occurring velocities in the longitudinal direction of the Hartelkanaal. It is known that at the mouth of the Hartelkanaal, near the Beerdam, large eddies can occur, which can be a problem for navigation. The influence of the power plant on these local occurring velocities needs to be investigated
- Next to this, the vertical salinity gradient in the Maasvlakte harbour basins (a fresh water layer flows on top of salt water) will almost totally disappear, the basins will become salt. The implications for navigation due to this change need to be investigated
- Ecological consequences of the implementation of the power plant have to be investigated. The closure of two large canals in the Botlek area, and the coherently changing water management might lead to positive or negative ecological changes. These need to be investigated

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Appendices

A. Topography Delta area

In this appendix the topography of the Delta area is shown. The first two maps show the most important waterways in the regions of Zeeland and Zuid-Holland. Also some interesting locations are shown on the map, such as storm surge barriers, shipping locks, and outlet sluices are shown. The third map is an overview of the model grid which is used for hydraulic simulations. A number of interesting locations are shown in the grid.

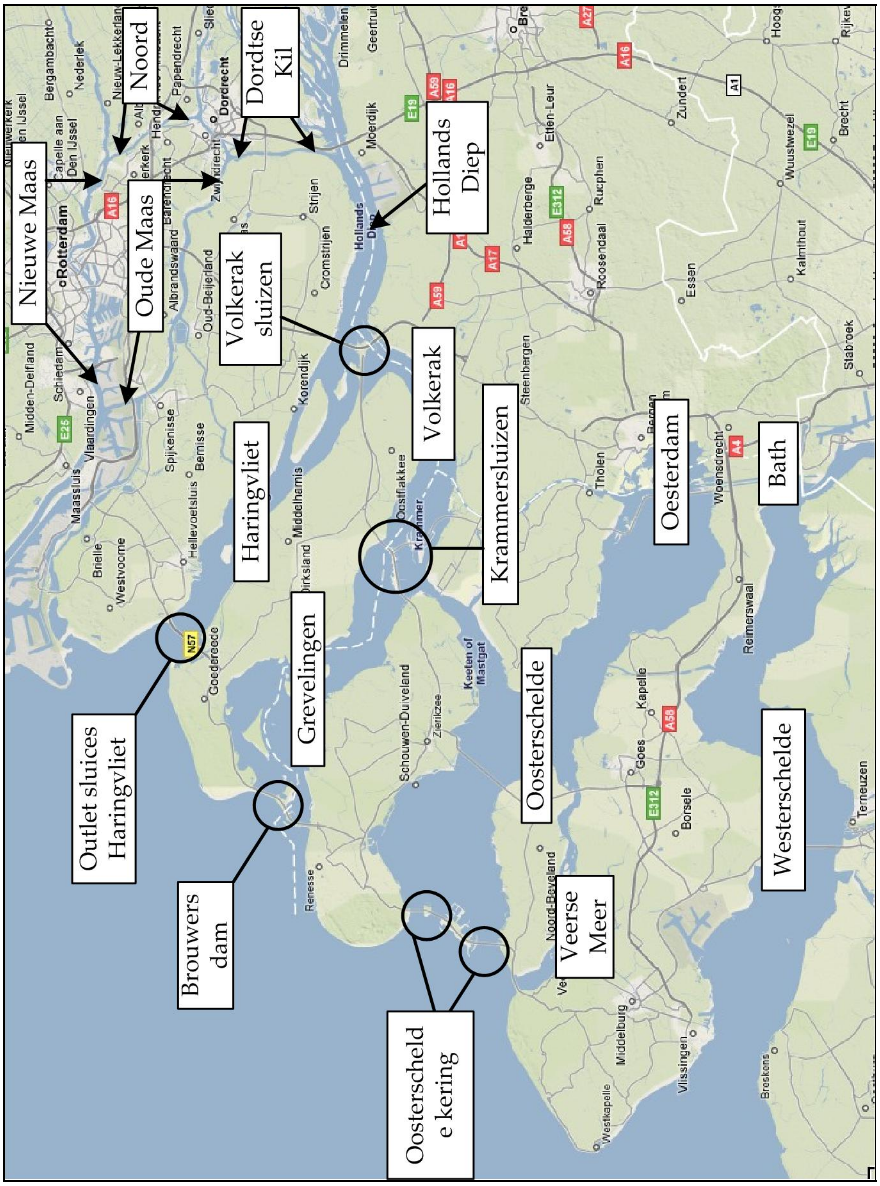


Figure A.1: *Map of Delta area with locations of interest*

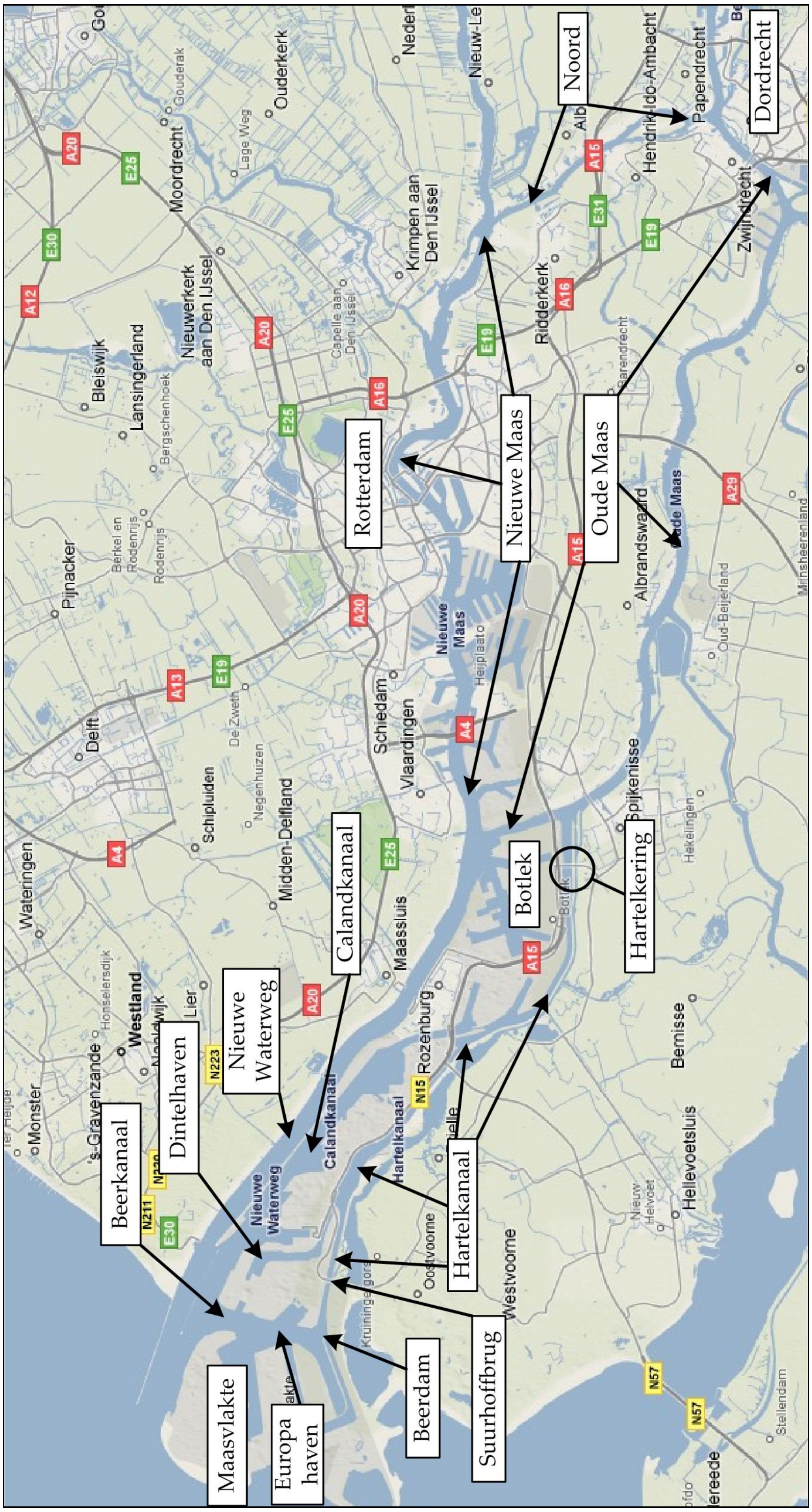


***Figure A.2**: Map of the northern part of the Delta with interesting locations*

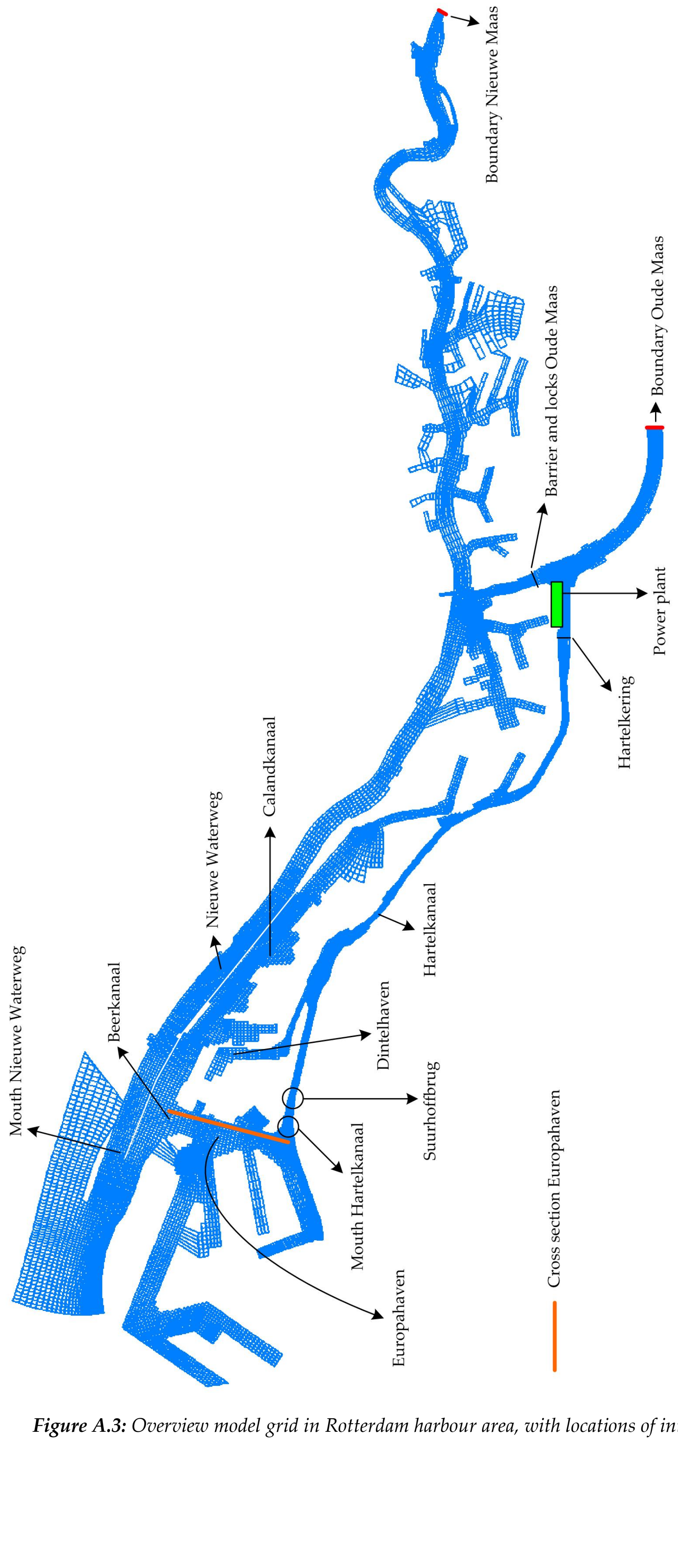
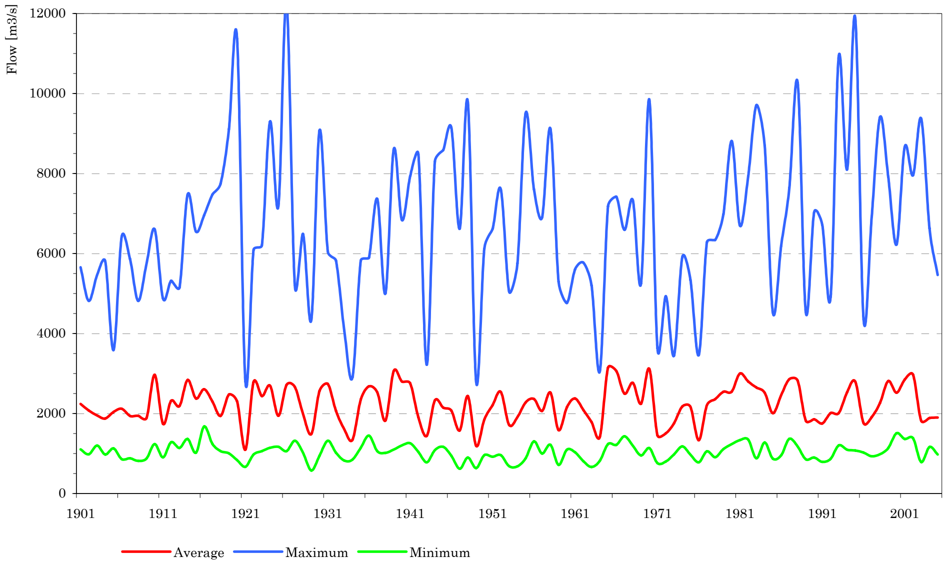


Figure A.3: *Overview model grid in Rotterdam harbour area, with locations of interest*

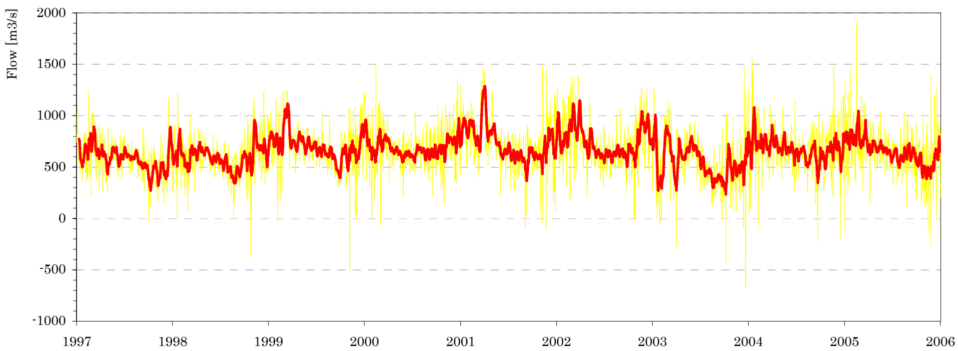
B. Discharges

In this appendix a number of interesting discharge measurements are shown. At different locations around The Netherlands discharges have been measured for a long time. The first graph shows the discharge of the river Rhine at Lobith, where the river enters the country. This is the largest source of fresh water in The Netherlands. It can be seen from the graph that the average discharge over the last century is just over 2.000m³/s.

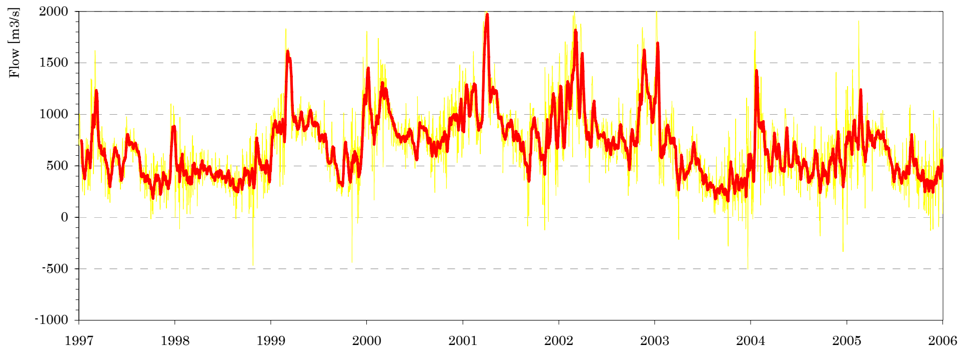


***Graph B.1:** Discharge at Lobith*

In the following three graphs the discharges of three different river branches in the Delta area of the Netherlands are shown for a period of 10 years. These three river branches discharge most of the fresh water which is directed to the Delta to the North Sea.



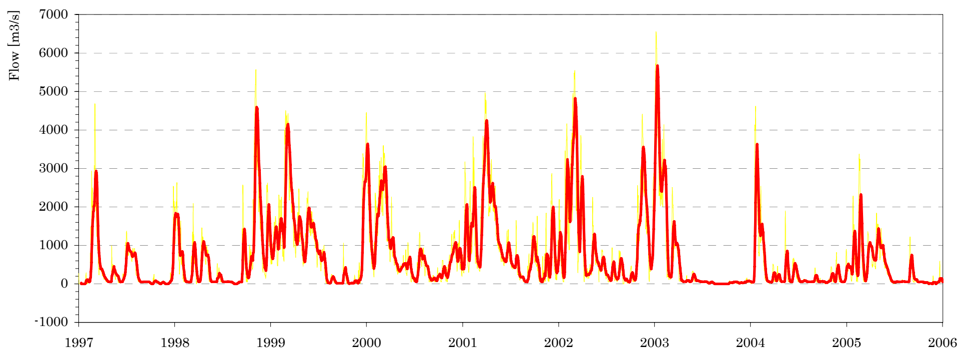
***Graph B.2:** Discharge Oude Maas at Puttershoek*



Graph B.3: *Discharge Nieuwe Maas at Brienenoord bridge*

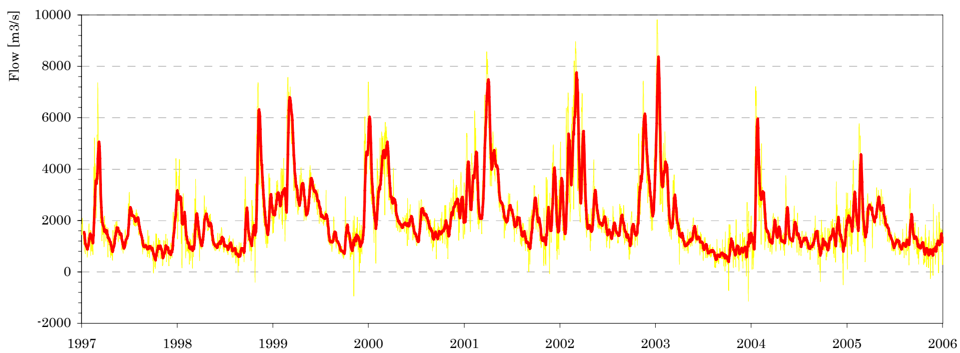
Graph B.2 and Graph B.3 show the discharge of the Oude Maas and Nieuwe Maas respectively. These two together feed the Nieuwe Waterweg, which then discharges these flows to the North Sea.

Graph B.4 shows the discharge of the outlet sluices at the Haringvliet. These are opened in case of high river flows, and when the water level at sea is lower (low tide) than at the Haringvliet. Therefore, this discharge can be zero, but not negative.



Graph B.4: *Discharge outlet sluices Haringvliet*

The last graph shows the summation of the previous three graphs. This is approximately the total fresh water flow which is directed to the Delta.



Graph B.5: *Summation of discharges Oude Maas, Nieuwe Maas and Haringvliet*

C. Climate scenarios

The Royal Dutch Intstitute of Meteorology uses four different scenarios in order to be able to predict climate changes in the next century. These scenarios can be summarized in Figure C.1 below.

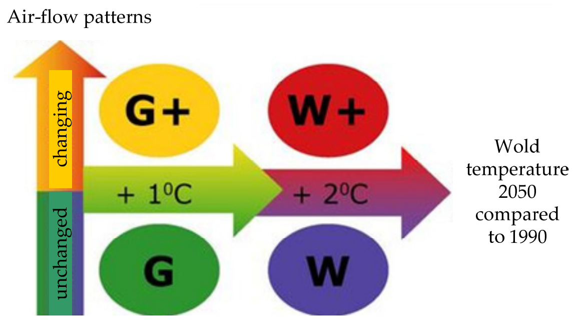


***Figure C.1:** Schematic overview climate scenarios*

The figure shows the changes for the four different scenarios; G, G+, W, and W+. The G stands for 'moderate,' the W for 'warm.' This means for 2050 that in case of a G scenario the World temperature raises 1° Celsius compared to 1990. In case of a W scenario the temperature increases with 2° Celsius. The + sign shows if the air flow patterns above Europe and the oceans will change considerably. If so, this means for the Netherlands milder winter periods with more rainfall, and warmer summer periods with less rainfall. The following table shows all important changing parameters.

2050		G	G+	W	W+
Worldwide temperatrure rise		+1°C	+1°C	+2°C	+2°C
Changing air flow patterns		No	Yes	No	Yes
Winter	Average temperature	+0,9°C	+1,1°C	+1,8°C	+2,3°C
	Coldest winter day	+1°C	+1,5°C	+2,1°C	+2,9°C
	Average rainfall	+4%	+7%	+7%	+14%
	Number of wet days	0%	+1%	0%	+2%
	Once in 10 years 10 day rainfall sum	+4%	+6%	+8%	+12%
	Highest day-averaged windspeed	0%	+2%	-1%	+4%
Summer	Average temperature	+0,9°C	+1,4°C	+1,7°C	+2,8°C
	Warmest summer day	+1°C	+1,9°C	+2,1°C	+3,8°C
	Average rainfall	+3%	-10%	+6%	-19%
	Number of wet days	-2%	-10%	-3%	-19%
	Once in 10 years 1 day rainfall	+13%	+5%	+27%	+10%
	Evaporation	+3%	+8%	+7%	+15%
Sealevel	Absolute rise	15-25cm	15-25cm	20-35cm	20-35cm

***Table C.1:** Impact of the four different climate scenarios*

D. Storage-area Hartelkanaal

The following figure shows the Hartelkanaal area which is subdivided in a number of (coloured) sections. For each of these sections the water surface is estimated.

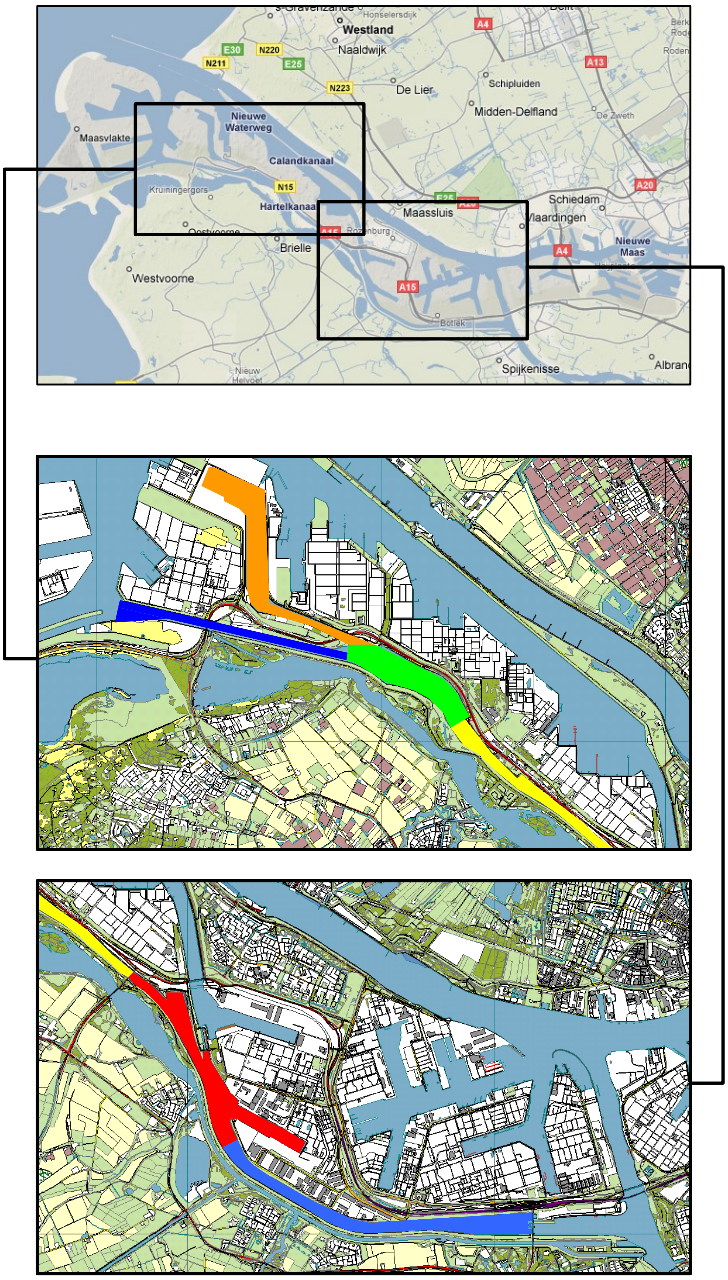


Figure D.1: *Storage area Hartelkanaal and Dintelhaven*

On the next page for each section a characteristic length and width are given, which are used to calculate the water level surface.

	Characteristic length [m]	Characteristic width [m]	Surface [m²]
	3.800	140	532.000
	4.280	260	1.112.800
	2.375	400	950.000
	3.590	175	628.250
	4.730	230	1.087.900
	5.050	170	858.500

Total surface area: 5.169.450

E. Overview simulations Maasvlakte II Model

In the table below all simulations which have been done with the Maasvlakte II model are summurized.

Run nr.	*Change of parameter*	*Value*	*Dimension*	*Relate run to*
Influence Horizontal eddy diffusivity				
1	Hor eddy diffusivity	0,2	m2/s	Run 0, Run 2
2	Hor eddy diffusivity	1	m2/s	Run 0, Run 1
Implementation power plant				
3 A	Implementation power plant Hor eddy diffusivity	100 0,2	MW m2/s	Run 1, Run3B
3 B	Implementation power plant	100	MW	Run 2, Run 3A
4	Implementation power plant	200	MW	Run 2, Run 3B
5	Implementation power plant	400	MW	Run 2, Run 3B, Run 4
Scenario with high fresh water river discharge				
6 A	High river discharge Original model	2500	m3/s	Run 2
6 B	High river discharge Implementation power plant	2500 400	m3/s MW	Run 5
7 A	High river discharge Original model	5000	m3/s	Run 2, Run 6A
7 B	High river discharge Implementation power plant	5000 400	m3/s MW	Run 5
Measures to guarantee the intake of salt water				
8	Lengthening breakwater Hoek v	3000	m	Run 7B
9	Transferring water from west side of Maasvlakte 2 to harbour basin	100	m3/s	Run 7B
Open Oude Maas				
10 A	Open Oude Maas Original boundary conditions Power plant	 400	 MW	Run 5, Run 10B
10 B	Same as Run 10A Thatcher boundary at Oude Maas			Run 5, Run 10A
10 C	Same as Run 10A, but the discharge of brackish water in harbour basin			Run 5, Run 10A

Hor eddy diffusivity of 1m2/s

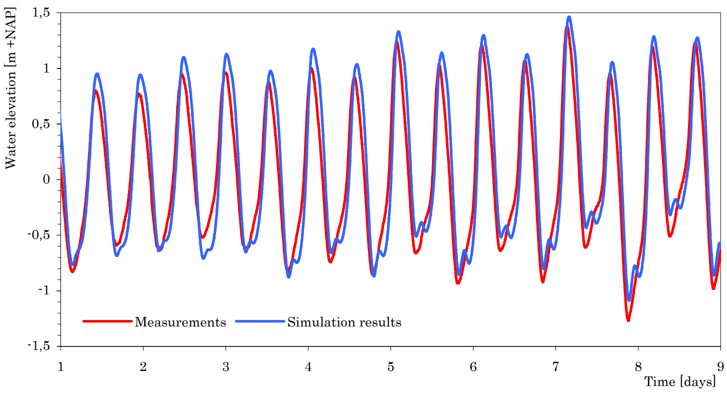
Table E.1: *Overview simulations Maasvlakte II model*

F. Model validation

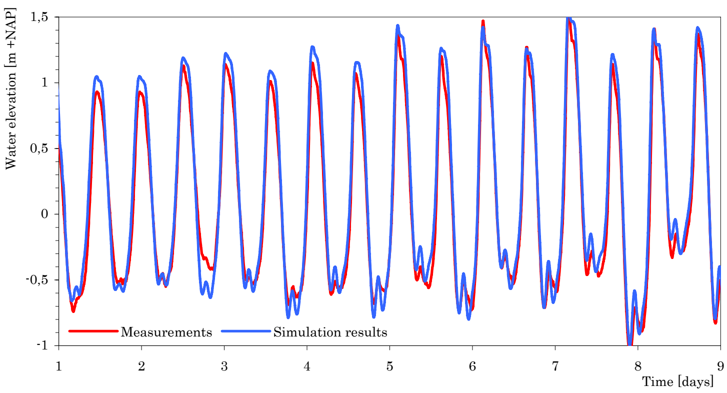
In this appendix the validation of the model which is used to determine the availability of fresh water for the power plant is discussed. The model is validated on successively water levels, discharges and velocities, and salinities. The model has to show a good representation of these parameters in order to be able to determine the feasibility of the power plant when considering the availability of salt water.

F.1 Water levels

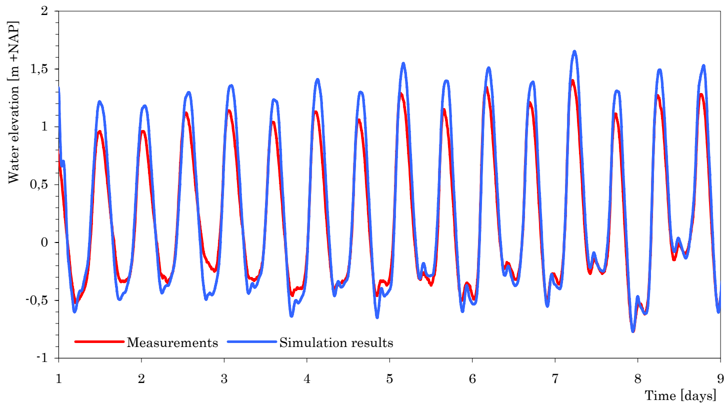
The following graphs show calculated waterlevels at a number of locations in the model area together with measurements at the same time at those locations. The first two graphs show a location at Sea, and one at Hoek van Holland. The 3rd and 4th graphs show two locations which are located inland. The four graphs show that the model is able to simulate water levels quite accurate. At the locations Spijkenisse and Willemsbrug in Rotterdam the extreme waterlevels, low and high tide, are a little over-estimated.



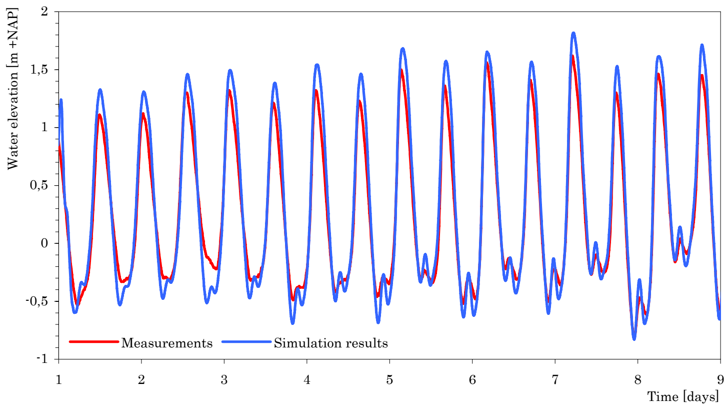
***Graph F.1:** Water level Europlatform at the North Sea*



***Graph F.2:**Water level at Hoek van Holland*

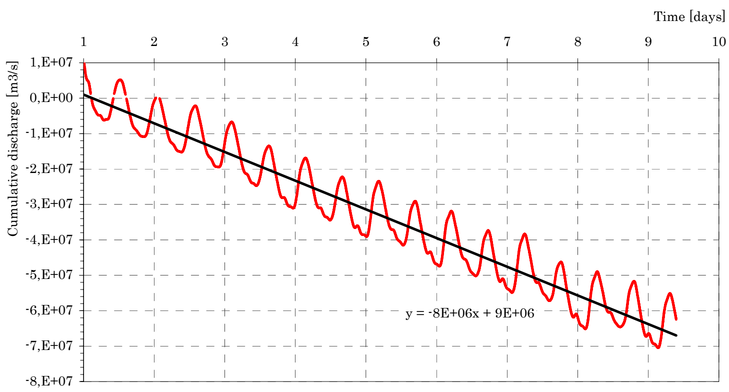


Graph F.3: *Water level at Spijkenisse*



Graph F.4: *Water level at Spijkenisse*

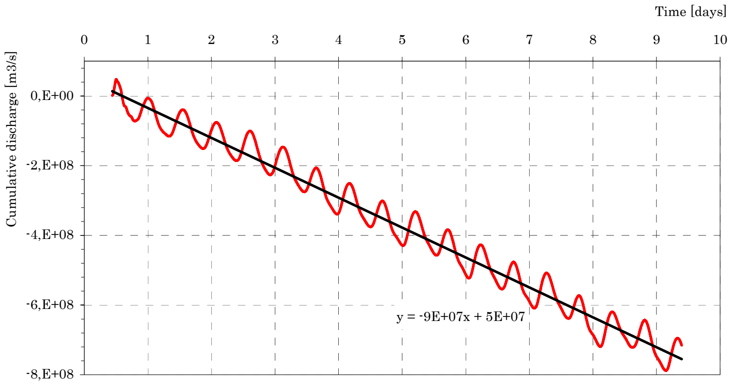
F.2 Discharges



Graph F.5: *Cumulative discharge Hartelkanaal*

In the graph above the cumulative discharge through the mouth of the Hartelkanaal is shown. Using the slope of the trendline, the average discharge can be calculated. When this is done it is found that it has a value of approximately 98m^3/s. This is in accordance with the estimation made in section 6.2.2.

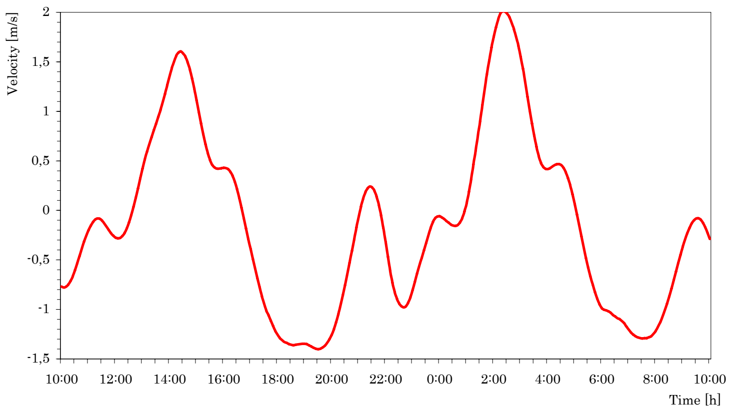
Below, the same graph is shown for the Nieuwe Waterweg. Calculation of the average discharge gives 1050m³/s. This is a little less than the measured average discharge over this period of approximately 1200m³/s.



Graph F.6: *Cumulative discharge Nieuwe Waterweg*

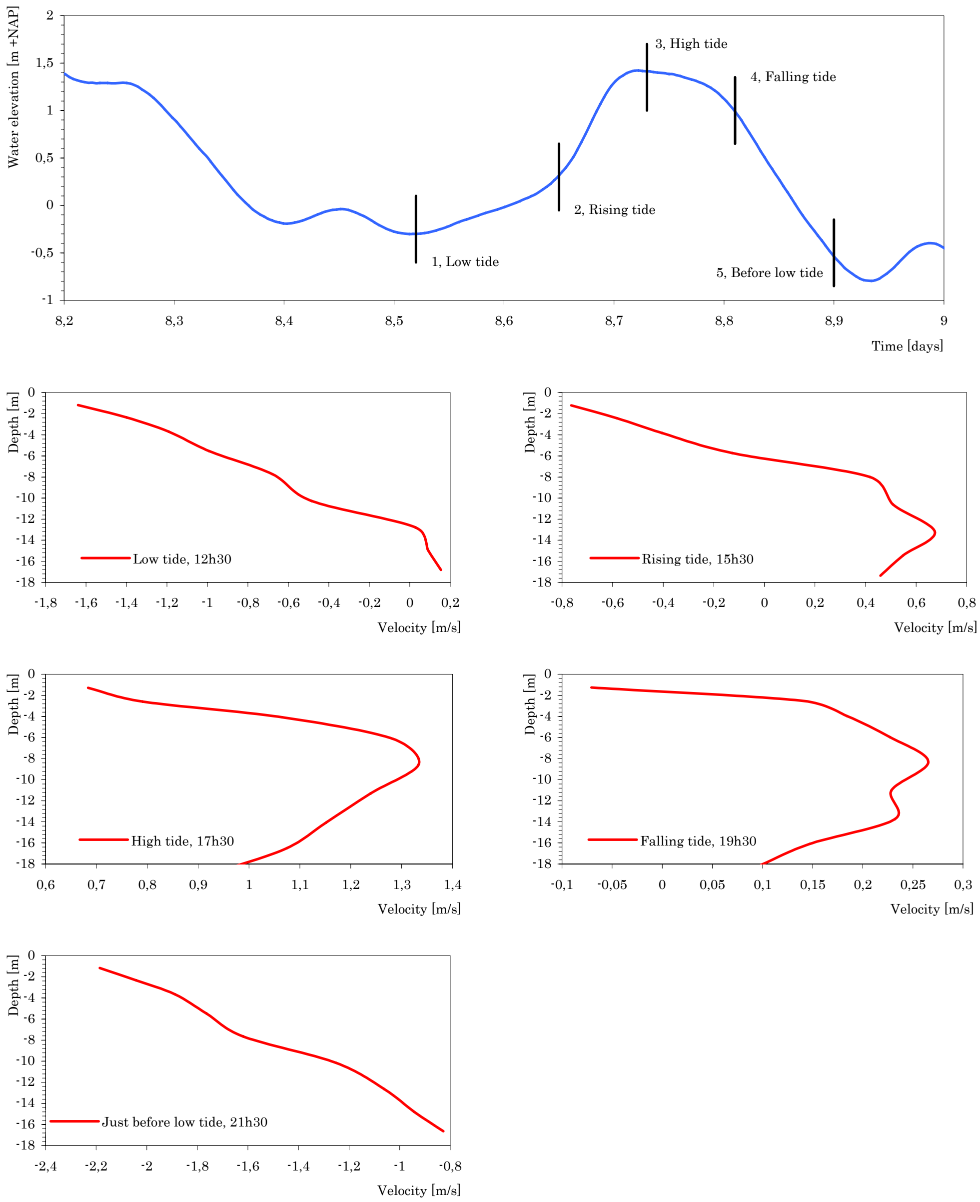
F.3 Velocities

The graph below shows the velocity at the Suurhoffbrug at the 19th of August 2001. The velocity profile agrees with measurements done that day. These measurements can be found in (Ballot).



Graph F.7: *Velocity Suurhoffbrug, 19 Augustus 2001*

Unfortunately no further information on velocities is available. Therefore a qualitative description of the velocities occurring in the mouth of the Nieuwe Waterweg has been made. The following graphs show velocity profiles over the depth at different moments in time, and with different tidal phases.



Graph F.8: *Velocity profiles at different phases of the tidal movement in the Nieuwe Waterweg. The first graph shows the water level, together with the exact moments of the velocity profiles*

The first velocity profile is given at low tide. From the figure becomes clear that the largest part of the cross-section has a negative velocity, which means a velocity that is directed seaward. Only a layer of a few meters near the bottom has a velocity that is positive, or equal to zero. This profile can be explained by the fact that at low tide the fresh water river discharge flows over the salt water tongue.

The second profile shows velocities at rising tide. After low tide, velocities first increase in the lower parts of the vertical. The salt water tongue starts to intrude the channel. Only in the upper part of the vertical the velocity is still directed seaward, which is caused by the fresh water river discharge.

The third profile shows only positive velocities, which means that the water flows in inland direction over the total vertical. Speeds are highest in the middle over the vertical. This can be explained by the fact that the upper layer is slowed down by the fresh water, and the bottom layer is slowed down due to bottom friction.

At falling tide, the fourth profile, velocities are just above or below zero. It can be seen that the upper layer already has turned from a positive to a negative velocity (directed seaward). This is the time of turning tide.

The last profile shows only large negative velocities, which means a large discharge in the direction of the sea. This can be explained by the fact that both the tidal movement is now seaward, as well ass the fresh water river discharge.

F.4 Salinity

No data at all is available about salinities. The only way to verify if the model behaves well, when considering salinity, is common sense, and a little knowledge of the area. Figure F.1 gives an overview of the salinity in the Port of Rotterdam area in three different layers. The first one is the upper layer, the first 50cm of the vertical, the second one (layer 5) is somewhere halfway down the vertical, and layer 9 is just above the bottom. It can clearly be seen that with increasing depth the salt tongue intrudes further into the country. It is known that especially in the Nieuwe Waterweg there always exists a salt gradient over the vertical. Furthermore, it is known that the salt tongue in normal state reaches not further into the country than the city of Rotterdam. This is confirmed by the third map. It is also known that the salt tongue in the Hartelkanaal almost never reaches the Hartelkering, at the east-end of the channel. This is also confirmed by the figures.

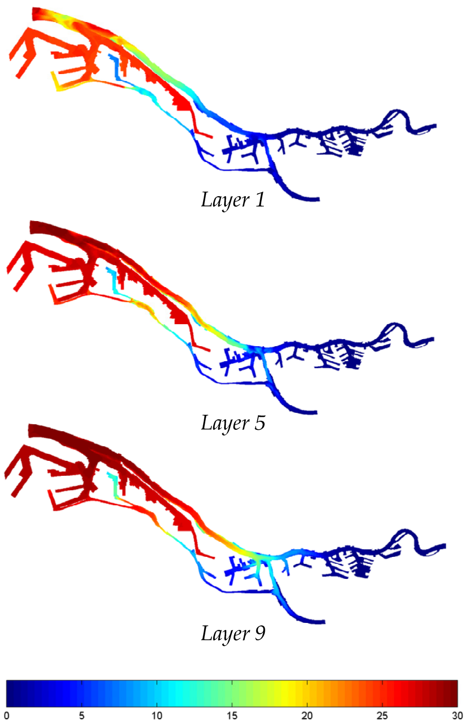


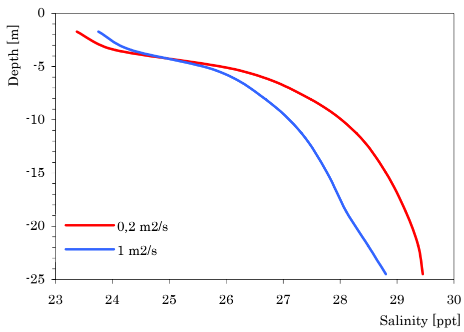
Figure F.1: *Overview of the occurring salinity in the Rotterdam area*

F.4.1 Horizontal eddy diffusivity

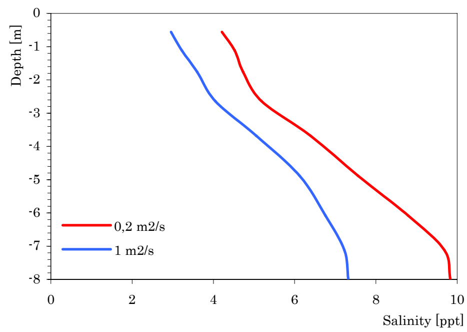
An important parameter which can be used to calibrate the model for salinities is the horizontal eddy diffusivity. This parameter has to be specified by the user and is implemented in the software because of the fact the grid of the model together with the stepsize of the simulation are to coarse to resolve the turbulent scales of motion. In

(Ballot) is already found that for a subdomain of this model a value for the horizontal eddy diffusivity of 1 is more appropriate than the default value of 10. In order to determine the influence of the parameter two simulations have been done. The first one is with a value of 0,2m²/s, and the second one with a value of 1m²/s.

The graph below shows the salinity in the Europahaven at the Maasvlakte at a certain moment in time. It can be seen from the figure that a higher value of the eddy diffusivity induces a smaller vertical salinity gradient, compared to a lower value. When plotting the salinity halfway down the Hartelkanaal something different is found; a higher value gives a slightly higher salinity over the total vertical, see Graph F.10.



Graph F.9: *Salinity over depth in the Europahaven for different values of the horizontal eddy diffusivity*



Graph F.10: *Salinity over depth in the Hartelkanaal for different values of the horizontal eddy diffusivity*

It is not possible to draw a conclusion about the influence of the horizontal eddy diffusivity on the basis of these graphs. However, it is clear that the influence in only marginal, the differences are only 1 or 2ppt. Therefore, the first simulation with a power plant implemented will be done twice, with two different values for the horizontal eddy diffusivity. From these simulations a conclusion will be drawn about the value for the parameter.