Delft University of Technology, MSc. Thesis Civil Engineering

Pumped hydropower storage in the Netherlands

A study at large-scale energy storage and the transformation of the Slufter from a silt depot to a pumped hydro-electricity storage system

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Preface

This graduation thesis is written as part of the Master specialization Hydraulic Engineering at the Faculty of Civil Engineering and Geosciences of the Delft University of Technology in the Netherlands.

The thesis is divided in parts to keep it structured. The following parts are discerned:

Part A	poses the problems and provides an extensive contextual literature study of the energy market and power generation
Part B	defines the criteria to solve the issue and makes a first leap at solving the problem by looking at possible energy storage methods and designing alternatives
Part C	is focused on the development and proposition of a specific solution: The Slufter
Appendices	forms the back-up of this thesis and comprises of all the appendices

Together, these parts form one chronological analysis towards creating a feasible energy storage solution for the Netherlands.

I wish you pleasant reading…

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Acknowledgements

To acknowledge every person that has contributed to the conception of this thesis is impossible, so I hope that the sentiments expressed to those mentioned on this page can be extended to all contributors.

First, I would like to thank my daily supervisor ir. Ad van der Toorn, for continuously inspiring and helping to a degree that is noticeable only with an attentive ear. I believe that because of this, the learning process has been even greater.

Many thanks to my professors prof.dr.ir. Bas Jonkman and dr.ir. Wout Broere, for being a part of my thesis committee and taking off some time from their busy schedules to read my submissions critically.

A special word of thanks to ing. Gert Jan ter Haar and engineering firm Lievense for being so hospitable and opening up their doors and knowledge. The possibility to go in any time and ask questions has been the support from the right direction and has been very motivational throughout the process.

This thesis is more than the words and applied physics presented in the following pages. It represents the months of work, the stress, the excitement of a proven hypothesis… and all the bits and pieces of small contributions from family and friends in any form, either technical or motivational…the little push in the back when *Murphy's law* is valid. An evaluation of the thesis has been added to *Appendix Z.*

My gratitude is endless

Abstract

While Europe moves towards modern renewable energy sources, the problems of variability and intermittency remain largely unsolved and contribute to the unreliability of these energy sources. At the same time, the problems of balancing the daily peak-demand is still performed with expensive conventional fossil fueled units because there are no cleaner alternatives. Sitting perfectly in between supply and demand is a solution with the potential of solving both problems: energy storage.

The possibilities for large scale energy storage are limited due to under-developed technologies, such as chemical batteries and conceptual ideas of hydrogen fuel cells. This is accompanied by the denial for a need of energy storage by the promoters of international power trade. It remains a mystery where the power will come from when all countries need their maximum output during peak hours and when the entire region produces low wind power due to low wind speeds.

Whereas developing technologies offer potential for future application, hydropower shines by being used for decades for the purposes of energy storage in the form of Pumped Hydropower Storage (PHS). The exclusivity of hydropower for elevated countries is challenged by offering alternatives for PHS in the Netherlands. These alternatives are grouped according to their favor for either surface size with the Storage Islands, or towards the depth with the Underground PHS's. Due to the uncertainty and low suitability of possible locations for Underground PHS, the Storage Islands have the preference, supported by the strong Dutch tradition of living with water and land reclamation. Among the alternatives is a silt depot in the Maasvlakte which is losing its purpose, named the Slufter, which outperforms the others in a cost-benefit analysis due to the low expected primary investment and the highly suitability for this application without changing Dutch topography and in which the currently stored contaminated silt of 78 million m^3 can be maintained.

Transforming the Slufter from a silt depot to an energy storage system is worked out technically. A high reservoir is created at a level of +39m NAP that is enclosed by an upgrade of 17 meters to the current dams at +23m NAP. Major failure mechanisms have been modeled and analyzed using two finite-element method software packages and it was found that the fast lowering of the reservoir level is normative for dam stability. The technical design is finalized so that the planning and costs of the construction could be made in order to speak qualitatively about the design. The system confirms its potential with a competitive unit price of 54 €/MWh and possibilities are offered for expansion of the 3.14 km^2 reservoir as a result of the future demand for storage.

A profitable system is created that generates power during the day and stores power in the night with the interaction between the high reservoir and the lower lying North Sea. The performance is optimized to be similar to a medium power plant with a peak power output of 470 MW and with an energy storing capacity of 2.16 GWh, the generation duration is 6 hours at maximum capacity (while power output drops with the reservoir level). With this performance, the system satisfies the peak-balancing needs of Zuid-Holland, Zeeland and a large part of Noord-Holland, while providing enough wind power balancing to fit the needs of Zuid-Holland in the coming decade. Using the imbalance between the daily and nightly power prices, the system annually benefits €20 million from power trade and saves €10 million fuel costs.

The Slufter as a storage system offers a promising clean alternative to the current gas-fueled peak-generation-units and potential for the future power market in which variable renewable energy sources play a large role.

Abstract (*Dutch*)[1]

Terwijl Europa zich steeds meer richting de hernieuwbare energiebronnen beweegt, blijven de problemen omtrent de variabiliteit onopgelost en dragen zij bij aan de onbetrouwbaarheid van deze energiebronnen. Tegelijkertijd worden de pieklasten opgevangen met dure, fossiel gestookte centrales door het gebrek aan schone en/of goedkopere alternatieven. Tussen deze vraag- en aanbodsproblemen zit een oplossing met het potentieel om beide op te lossen: energie-opslag.

De mogelijkheden voor grootschalig energie-opslag worden sterk beperkt door onvolwassen technologiën zoals de chemische batterijen en waterstof-brandstofcel. Dit wordt versterkt door een ontkenning van een behoefte aan opslag door aanhangers van internationale handel in energie, ondanks dat de meeste West-Europese landen een soorgelijk levenstijl, dezelfde pieklasten en soortgelijke klimatologische verschijnselen hebben. Het is daardoor een mysterie waar de stroom vandaan moet komen wanneer allen een grote piek-last ervaren en er zwakke windsnelheden in het gebied worden gemeten.

Terwijl de technologiën in ontwikkeling mogelijkheden voor de toekomst bieden, schittert waterkracht door al decennia gebruikt te worden voor energie-opslag in de vorm van *Pumped Hydropower Storage* (PHS). De exclusiviteit van waterkracht voor hooggelegen landen wordt uitgedaagd door het presenteren van mogelijkheden voor PHS in Nederland. Deze alternatieven zijn gegroepeerd volgens de voorkeur voor ofwel een groot oppervlak met de Storage Islands, ofwel de diepte met Underground PHS.

Door de onzekerheid en ongeschiktheid van mogelijke locaties voor Underground PHS, hebben de Storaeg Islands de voorkeur, gesteund door een eeuwenoude Nederlandse traditie om samen met water te leven en land uit zee te creëren. Een van deze alternatieven is een slib-depot dat zijn functie grotendeels heeft verloren genaamd “De Slufter”. Dit alternatief overtreft anderen in een kosten-baten-analyse vanwege de lage investeringskosten en de geschiktheid voor PHS zonder veranderingen in de topografie van Nederland. De plannen incorpereren het opgeslagen slib wat er nu al ligt, wat dus kan blijven liggen.

Het voorstel om van de Slufter een energie-opslag-systeem te maken wordt ondersteund met een technische uitwerking. Een hoog reservoir op +39m NAP wordt omringd door dammen op +40m NAP, een verhoging van 17 m bovenop de huidige +23m NAP. Het systeem bewaart en genereert energie door het pompen van- en het loslaten in de Noordzee. Hiermee presteert de Slufter vergelijkbaar met een gemiddelde energiecentrale in Nederland en met een piek-vermogen van 470 MW. Met een opslag van 2.16 GWh kan gedurende 6 uur stroom gegenereerd worden (terwijl het vermogen daalt met het waterniveau). Gebruikmakend van het verschil in de dagelijkse en nachtelijkse stroomprijs, wordt verwacht dat het systeem €20 miljoen per jaar genereerd en €10 milioen aan brandstofkosten bespaard.

De snelle verlaging van de waterstand is maatgevend voor de stabiliteit. Hiervoor zijn de dammen gemodelleerd met twee eindige-elementen-paketten. De planning en kosten zijn berekend zodat de resultaten kwantitatief kunnen worden besproken. Het systeem bevestigt zijn potentieel met een concurerende eenheidsprijs van 54 €/MWh en er worden mogelijkheden geboden voor verder uitbreiding van het 3.14 km^2 grote reservoir om aan de toekomstige vraag voor opslag te voldoen.

De Slufter als energie-opslag-systeem is een veelbelovende, schone alternatief voor de gas-gestookte pieklast-eenheden en biedt daarnaast mogelijkheden in een toekomstige energie-markt waarin variabele hernieuwbare energiebronnen een grote rol zullen spelen.

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[1] This abstract is offered for the Dutch public as it deals with problems which are specific for the Netherlands

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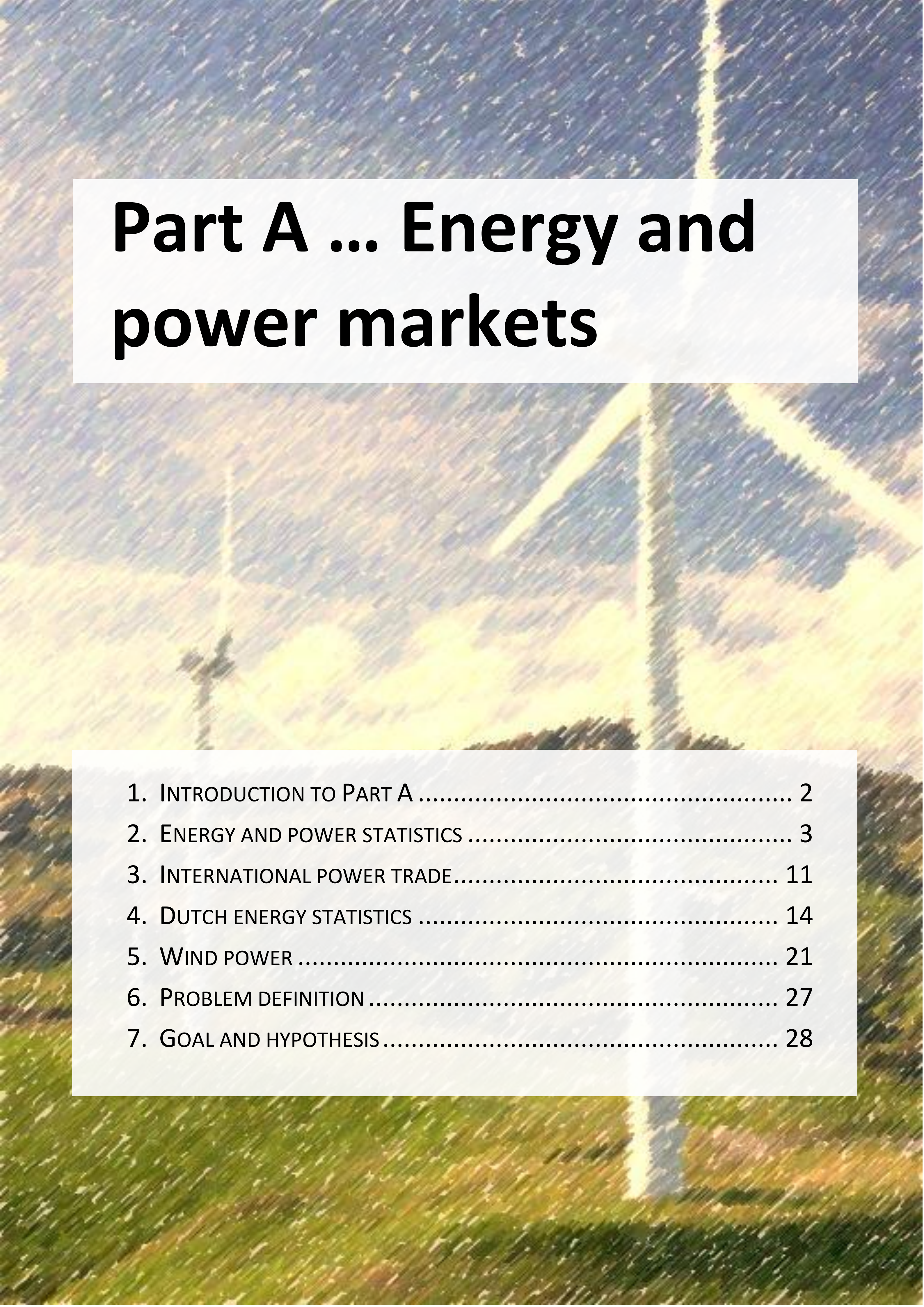

Part A … Energy and power markets

1. Introduction to Part A

The energy market is changing rapidly. While the fossil fuels are dominating globally, the sounds of opposition are increasingly stronger, emphasizing the negative side-effects that the fossils bring along. The call from society for a cleaner, renewable, more independent way of energy is becoming increasingly stronger. At the same time the industry is pointing at the problems of the alternative sources of energy.

Energy generation from *renewable energy sources (RES)*, namely wind, sun and biomass, offer a clean, decentralized way of producing energy that is widely available. The generation from RES is increasing in recent years and this trend will continue.[2] A major issue with energy from RES is that they are heavily dependent on availability, meaning there's only energy when the wind is blowing within certain limits, regardless of demand. This is called the intermittency of RES. This intermittency may prevent the further penetration of RES and lower the reliability of the system.

At the same time, utility companies are trying to cope with the large fluctuations coming from the demand side. This turns out to be a tough job as it is difficult to manage a system with conventional fossil fueled plants that lose a lot of efficiency in the process of turning on and off. Perhaps there are better ways of dealing with these demand variations.

An insight into the energy market is needed to determine when demand takes place, what the nature of the supply is and what kind of mechanisms are used to manage the imbalance between supply and demand. Questions on how this imbalance is treated now and how the rise of RES will affect this imbalance are imminent in the creation of solid energy system. Recognizing the real problems (the so-called *problem behind the problem*) and identifying the desired situation are core results of this analysis.

The following research questions form the base of the analysis performed at Part A:

a. What are the energy market trends on different scales; from a global scale to the Netherlands and how large is the rise of the renewable energy sources?
b. Why is Europe investing in renewables and decreasing its fossil fuel dependency?
c. What is the role of European power trade and can it be considered an option for the imbalance?
d. How large is the variability of renewables and how does it affect their reliability?
e. What are the characteristics of the Dutch energy market, from the supply and demand side and how will this change with a possible increase in the share of renewables?

At the end of this section the problem as well as the goal should be formulated clearly with a thorough understanding of the main processes surrounding these topics.

[2] REN21, 'Renewables 2011 Global Status Report', 2011

2. Energy and power statistics

The following subjects are discussed in this chapter:

2.1 The global production and consumption

Trends in the global energy market are important to create a background. The world energy demand is largely supplied by fossil fuels with the shares of oil, natural gas and coal offering an 81.8% of the global consumption in 2010. Though their relative share in the total energy consumption is diminishing, their absolute numbers are rising especially in the developing countries, which can be accounted to the increase in total energy output; +1.8% in 2012 (see *Figure 1*).[3] The global trends can be split up in trends for developed and undeveloped nations. For developed nations, total energy output is steady despite the growth of economies and productivity. This can be accounted by the increasing efficiency and demand side management. In contrast, the output of developing nations and cheap fossils is increasing rapidly.

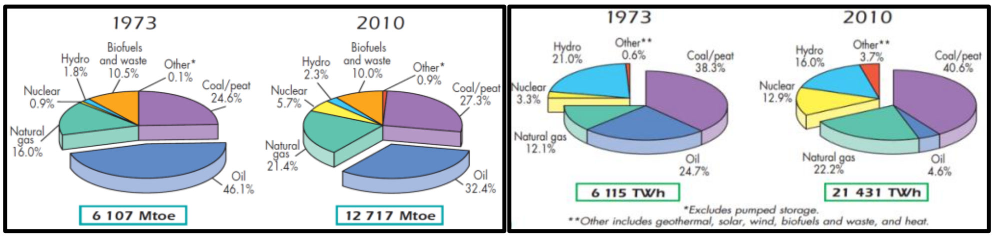

Figure 1 … (left) Share of fuels in energy production in 1973 and 2010 and (right) share of power production by fuel (IEA, Key World Energy Statistics, 2012)

Oil is still the largest consumed energy source, with a global share of 32.4% in 2010. Looking at the share of oil from 1973 till 2010, a significant reduction is visible from 46% to 32%, and there is a reduction for 13 years consecutively. This reduction is balanced with a combination of sources: hydropower and coal (small share), altogether with increases in nuclear energy and natural gas.[4]

Coal (either hard or soft coal/lignite) has a share of 27.3% in 2010. While oil is dropping constantly, the share of coal increased in 2012 with 2.5%, outputting a share of 29.9%. Coal is especially popular in the developing nations such the rise of 10% in China, whereas Europe shows a decrease of 1.1%.

Natural gas shows a similar increase, with a share of 21.4% in the production in 2010. The same shift of consumption from Europe to Asia is observed as for coal; while Europe's dropped by 10% in 2012, China and Japan increased respectively 21% and 10%. With this increase, global consumption rose 2.2%.[5]

[3] BP, Statistical Report of the World of Energy, 2013
[4] BP, statistical review of world energy full report, 2012
[5] BP, statistical review of world energy full report, 2012

Renewable energy sources (RES) are grouped together and are a combination of solar, wind, geothermal, hydro, and some forms of biomass energy. In 2010, about 16.7% of the energy consumption could be allocated to RES, with 8.5% coming from traditional biomass (mostly for heating) and 3.3% from hydropower. The modern RES have a share of 4.9%, with 3.3% for solar/geothermal, 0.9% wind/PV and 0.7% biofuel. Looking at the power market, RES accounts for 19% of which 16% comes from hydropower (see *Figure 1*). The growth in RES is largely triggered by Europe, where wind energy rose 25.8%.[6]

Nuclear energy was rising till the 2000's, stagnated the last decade and is now diminishing, with 4.3% in 2011. The 2011 tsunami in Japan affected nuclear energy significantly; this event emphasized the disadvantages and affected the public view a lot. This resulted in the stop of the Japanese nuclear power program and triggered a global ripple effect with large decreases in e.g. South Korea and Germany (Figure 2). This ripple didn't affect France, who increased its dependency on nuclear sources to 41%.[7]

Figure 2 … Drop in nuclear power generation (BP, Statistical Review …, 2013)

Global energy consumption is expected to rise till 2030 ranging from 35% to 60%. The current differences in trends between developed and undeveloped nations will maintain, as developing nations are expected to rise 65% and developed nations will diminish their output due to increasing efficiencies, despite the 50% growth in their economies.[8,9,10]

2.2 Views on fossil sources

The discussion surrounding fossil sources is a controversial one. Considering reasons in favor of- and against fossil fuels can contribute to a more systematic analysis of the discussion *(see Table 1)*.

Support for fossils		Opposition for fossils	
Costs	One of the most competitive costs per kWh for power generation as well as efficiency regarding heat	**Pollution**	Generation with fossil sources creates many byproducts that are negative for environment and health
Functionality	Many possible applications, such as fuel for transportation, generation of electricity, heat and as a in the production of plastic	**Global warming**	One of the by-products, CO_2, is causing global temperatures to rise. Carbon costs have been introduced to lower the levels of CO_2 in the air.
Technology	The technology is proven and perfected. Much experience and knowledge is present	**Energy availability**	Caused by the geographic distribution, the energy needs to be transported in order to be available, a process with many uncertainties
Flexibility	In creation for power, the extracted fuel can be applied wherever, whenever with flexible amounts	**Energy dependency**	Fossil fuels are extracted in certain geographic locations, which makes people dependent on these places
Reliability	Despite the doubts surrounding availability, no chronic problems concerning extraction or transportation are faced, and there has been no large economic stagnations due to unavailability	**Diversity of generating capacity**	The current portfolio of nations is heavily based on fossil fuels, which makes them very dependent and less flexible
		Price dependency	Since not accessible to everyone, the few can determine market price
		Depletion	Fossil fuels are limited in stock, leading to problems concerning sustainability

Table 1 … Advantages and disadvantages of fossil fuels

[6] REN21, Renewables 2012, 2012
[7] BP, statistical review of world energy full report, 2012
[8] BP, Energy Outlook 2030, 2013
[9] ExxonMobil, Outlook for Energy; A View to 2030,
[10] IEA, World Energy Outlook 2012, 2012

2.3 The depletion of fossil fuels

A popular RES promotion statement is the depletion of oil, gas and coal supplies. There are numerous studies by varying parties who oppose a nearing depletion however the majority estimates it to happen within this century (*see Figure 3*). The main uncertainty lies in data about current reserves. One estimate uses a modification of the Klass model[11] on the current known reserves, and predicts that there is enough oil, gas and coal to last respectively 35, 37 and 107 years.[12] While each study shows a different life span, the main ranges are in that order of magnitude and suggest a shift from oil and gas towards coal, as coal reserves are more abundant and it's a cheap source to generate energy.

These estimates increase the doubt on the sustainability of fossil fuels. This doubt alone is triggering a large opposition for these sources, claiming that an investment in these sources is short-termed thinking. Governments and businesses can consider the economic benefits of fossil fuels as not justifying the disadvantages, doubt and the public opinion.[13]

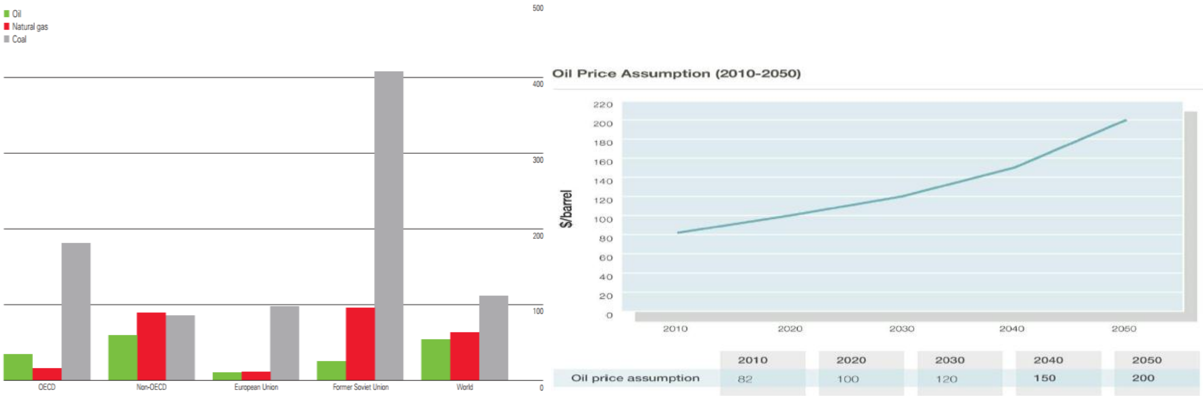

Figure 3 … (left) Fossil fuel reserves-to-production (R/P) ratio at end 2011 (OECD are developed nations) (BP, statistical review of world energy full report, 2012) and (right) Oil price development estimations 2010-2050 (EREC, RE-Thinking 2050, 2012)

A more detailed look into the known reserves shows that especially former Soviet Union nations are blessed with high coal reserves while Europe struggles generally with low reserves (*see Figure 3 left*). Stimulated by low reserves, fossil fueled Europe is venturing towards the alternative sources. If it doesn't, the continent will become increasingly dependent on imports to power its wealth. Combined with increasing difficulty in extraction, the scarcity of fuel will lead to an increased price (*see Figure 3 right*).

Shale gas has revived the discussion about the uncertainty of reserves. This natural gas extracted from the shale rock is especially in North-America a resource that is considered a great deal. However both in America as well as in Europe, the approach has been very careful and critical, with doubts about the benefits as well as the large reserve estimations.[14] Academic circles also point out that shale gas in Europe is deeper and harder to extract.[15] A careful approach is required mainly due to the many unknowns, uncertainties and the early stage the studies are in. Therefore, any predictions and estimations in this stage cannot be very reliable and basing all hopes on shale gas is rather wishful thinking.

[11] The Klass model is a form of diffusion model that is widely used to predict life expectancies in econometrics
[12] S.Shafiee, When will fossil fuel reserves be diminished, 2008
[13] C. Pauly, A visions for fueling Europe on Renewables, Spiegel.de, 2013
[14] N. Ahmed, Shale gas won't stop peak oil, but could create an economic crisis, The Guardian, 2013
[15] NOS, Hoogleraren tegen schaliegas, NOS.nl, 2013

2.4 Main European trends

Europe in the last decade can be characterized by a shift from fossil fuels to alternative energy sources. Since 2000, there's a steady drop in the supply and consumption of oil, gas and coal. The total energy production has decreased with 7.4% in between 2005-2010 (*see Figure 4*), which is largely a sign of increasing efficiencies and energy saving actions. [16]

While nuclear energy has stagnated in the last decade, the rise of RES is clearly visible in both the production and consumption. Overall, the share of wind power and *photovoltaic* (PV) power in 2011 was respectively 7% and 2% of the total electricity demand.[17,18] This doubling doesn't mean much because the share has been very low overall.

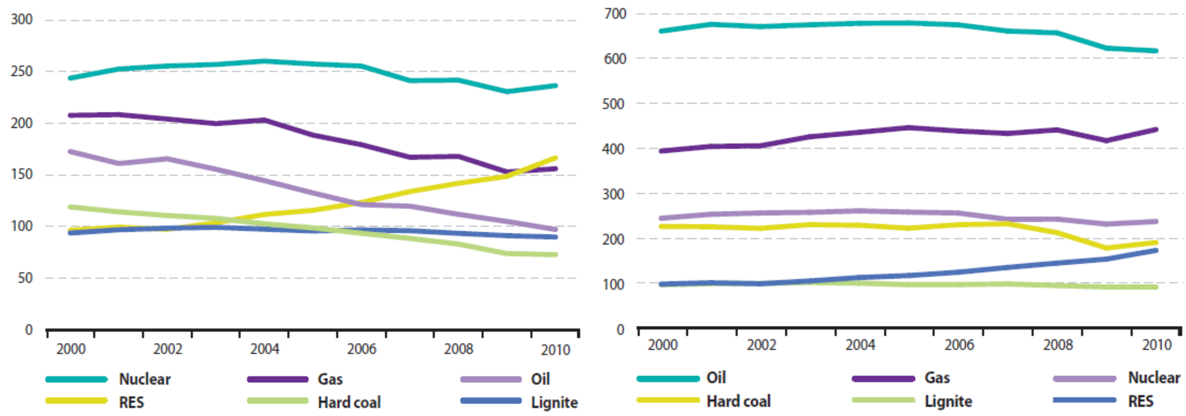

Figure 4 … (left) Primary energy production and (right) consumption by fuel, EU-27 (Mtoe), 2000 - 2010 (Eurostat, 2013)

Europe as a whole has a large dependency on oil, i.e. Europe relies largely on oil imports. The dependency has risen from 75% to 85% in between 2000-2010. For the same period, the dependency on gas has risen from 49% to 62% and coal from 43% to 58%. The high import of fossil fuels is due to low production values, which in turn can be appointed to the low reserves for fossil fuels (*see §2.3*).

Coal consumption had been steadily dropping in the last decade until last year, when it started to grow again with about 2%. This is likely due to the high oil and gas price and the low coal prices in this year and this is expected to continue.[19]

A distinction from the global profile is that Europe produces both more RES (20%) and nuclear energy (28%) than each fossil fuel. Even though its share is declining, Russia remains the important energy producer for Europe; the biggest exporter of oil and gas, while 2nd in coal. Norway is a notable producer inside Europe as the 2nd producer of gas (49%), oil (49%) and RES (6%).

[16] Eurostat, Energy Indicators for 2012, 2013
[17] EWEA, 'Wind in power annual statistics', 2012
[18] EurObserv'ER, 'Photovoltaic Barometer', 2012
[19] Energy Digital, High natural gas prices lead to increased demand for coal in Europe, Oilprice.com, 2012

2.5 Regional differences inside Europe

Regional differences are interesting for the overview of the current energy situation inside Europe. This analysis will be done looking at the large players in the European market and their respective energy balance. The main energy producers are Norway, France, Germany and the UK with respectively 24.9%, 16.8%, 15.5%, and 16% of the total energy production in the EU-27. Largest consumers are Germany, France, UK, Italy and Spain with respectively 19%, 13%, 12%, 11% and 8% of the total energy consumption. Norway is the largest energy exporter of energy while Germany the largest importer.

The consumption of oil is high everywhere, with peaks in Greece, Ireland, and Portugal, with 52%, 51%, 50% of their total consumption. It is interesting to see these countries are indeed suffering because of the high oil price.[20] The use of oil is specifically low in the Scandinavian countries and central European countries such as Hungary and Czech Republic, staying way below 30%.

Germany has a relatively mixed energy profile, with apart from oil (34%) and gas (22%), an even spread among nuclear, RES, coal and lignite (11% each). Lately, Germany is investing a lot in wind and solar energy (now 11%) whiles the share of nuclear has plummeted *(see Figure 2)*. Many RES projects are planned and there are days that 50% of the power comes from wind and solar only.[21]

France on the other hand is continuing its large investments in nuclear energy. Already 41% of the energy (13% average in EU-27) and 75% of the power came from nuclear sources in 2010.[22] Together with oil (31%) and gas (16%), there isn't much diversification in their energy profile. Together with some investment in RES to reach targets set by the EU, France continually expands its share in nuclear energy.

The UK is characterized by a high fossil fuel consumption, with natural gas (40%), oil (35%) and coal (14%) supplying 89% of the total consumption. With almost no RES (3%), the profile is similar to Ireland, Belgium and the Netherlands, with both high gas shares and very low RES input. The remainder in the UK is supplied with nuclear energy (8%). However, very recent plans to increase the share of RES have been put forward, with the ambitions of becoming the largest offshore wind supplier in the world.[23]

The Scandinavian countries have generally high shares in RES, with an average of 30% of the energy consumption. Denmark has chosen for a mix of oil (26%), coal (20%) and gas (23%), while Sweden and Finland chose nuclear energy (29% and 16%). Norway almost exclusively consumes RES (35%), oil (41%) and gas (19%).

Central Europe displays diverse profiles, with large roles for nuclear energy in Czech Republic, Hungary and Switzerland (16%, 16% and 25%). There is high RES consumption in Austria (26%) due to hydropower possibilities, whereas coal has a large share in the Czech Republic (42%). In Eastern Europe, biomass is large for heating, especially in the Baltic States (34%) and Romania (16%). Coal is huge in Poland (42%) and Macedonia (45%) and overall, the Eastern European countries show shares of oil well above EU-27 average of 35%, with the exception of Bulgaria, which shows a preference for nuclear (22%).[24]

[20] G. Tverberg, The devastating economic impact of constantly high oil prices, Oilprice.com, 2012
[21] T. Smedley, Goodbye nuclear power: Germany's renewable energy revolution, The Guardian, 2013
[22] EnergyPub, France Energy Profile, Speroforum.com, 2007
[23] The Crown Estate, UK Offshore Wind Report, 2012
[24] Eurostat, Energy Indicators for 2012, 2013

2.6 Policies regarding RES

The EU is continually supporting further advancement of RES, e.g. with a new resolution in favor of coupling the windmills on the North Sea.[25] A target was set in 2000 to have 22% RES consumption by 2010. Currently, the share is 12-13% and it is clear that these goals have not been met. This suggests that these targets are not strict and are perhaps not seriously pursued by members.[26] The current goal is an average of 20% renewable energy consumption by 2020 (the member specific targets are in *Figure 5*).[27]

The current goals are however more realistic. Firstly, the combination of growth in academic knowledge with public awareness had led to a situation where there's acceptance for RES projects, sustainability and opposition against fossil fuels. In some nations, this translates into policy through subsidy and support; however not in entire Europe.[28] Financial difficulties may be one of the reasons. As economic growth isn't as expected, nations are drawn by the lower costs of fossil energy.[29] Despite economic hardships, the EU pushes for strict deficit control,[30] yet desires large investments from members to reach the 20% 2020 targets; this is rather inconsistent.

Businesses are drawn to cheaper fossil energy as well. Recently, Royal Shell stated [31] that it is retreating from the wind energy market because:

"to create a gas plant it costs only 15% of the total amount needed for a wind farm with similar capacity."

This short-term thinking of governments and businesses is the main reason for a relatively low RES share. However, with new policies and projects, the shift in thinking is visible in the recent growth in RES investment. Many countries are en route of reaching the EU 20% targets, whereas others (Ireland, UK, France and the Netherlands) still have a long way to go.

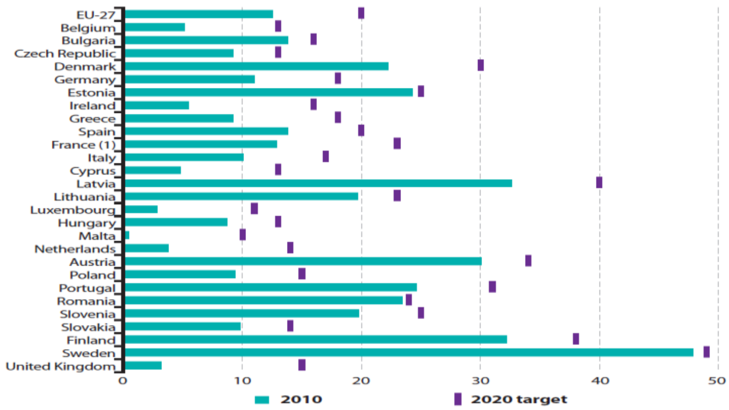

Figure 5 … Share of renewable energy in gross final energy consumption compared to EU targets (Eurostat, 2012)

[25] G. Ten Den, Resolutie tot koppelen windmolenparken Noordzee, Change Magazine, 2009
[26] EU Commission for Renewable Energy, 'Energy Targets by 2020', 2011
[27] EU Commission for Renewable Energy, 'Energy Targets by 2020', 2011
[28] B. Schievink, Kabinet gaat subsidie op zonnepanelen niet opnieuw invoeren, Tweakers.net, 2013
[29] Economist.com, Taking Europe's pulse, The Economist.com, 2013
[30] FME, CPB verwacht begrotingstekort van 4,6 procent voor 2013, FME.nl, 2012
[31] VOZT, Offshore Windenergie, VOZT.nl, 2010

2.7 Roadmap 2020-2050

Future estimations as far as 2050 have been developed by various parties. Because of the uncertainty in future predictions, a lot of sources are considered to increase the reliability of the analysis. Depending on the analysis, the roadmaps can be split in three categories:

- **Estimation** based upon trend lines and future scenarios in energy demand
- **Policy studies** that focus on the feasibility in favor of a certain goal
- **Targets** that are set by organizational bodies, mostly national or larger authorities

In the developed world, the energy demand is actually dropping due to improved energy efficiency policies and technologies (*see Figure 6*). The total energy consumption in 2050 in Europe will therefore remain largely unchanged and will be around 80 Exajoule per year.

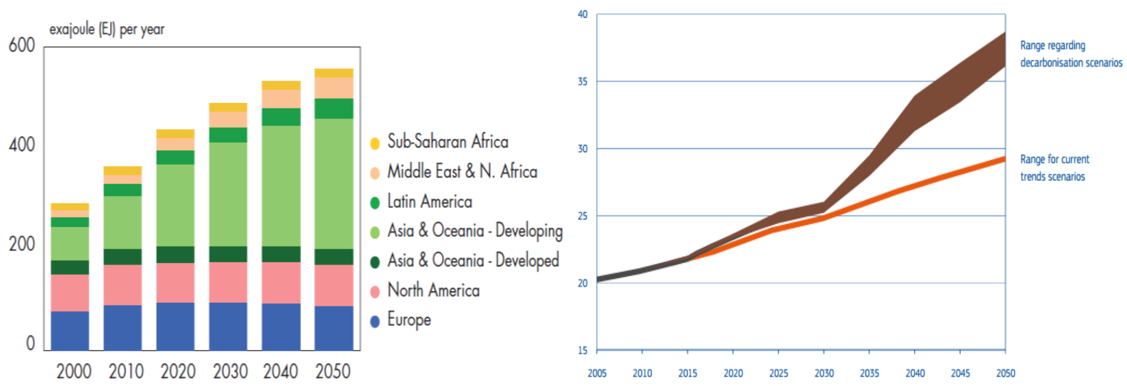

Figure 6 ... (left) Final energy consumption by region (Shell, Energy Scenarios 2050, 2008) and (right) Share of electricity of total energy in current trend and decarbonization scenarios (% of final demand on vertical axis) (European Commission, Energy Roadmap 2050, 2012)

The share of electricity in the total energy demand is growing rapidly (*see Figure 6 right & Table 2*). This is because more appliances are using electricity in their functioning. Expected is that once the new generation 'clean' cars kick off, the increase will be significant; the most competitive technologies in the race as dominant car technology are electric cars and hydrogen fuel celled batteries, which both require electricity to be charged.[32]

Year	Share of electricity in the total energy demand
2020	23%
2030	25-26%
2040	27,5-35%
2050	30-40%

Table 2 ... Future share of electricity in the total energy demand

The EU targets for 2050 are to reduce the carbon emissions by 80%, with leads to the target of enhancing renewable energy to 75% in 2050, with 97% of the electricity coming from RES and not further developing nuclear energy (*see Figure 7*).[33]

[32] P. Fairley, Will electric vehicles finally succeed?, MIT Technology Review, 2010
[33] European Commission, Roadmap 2050, 2012

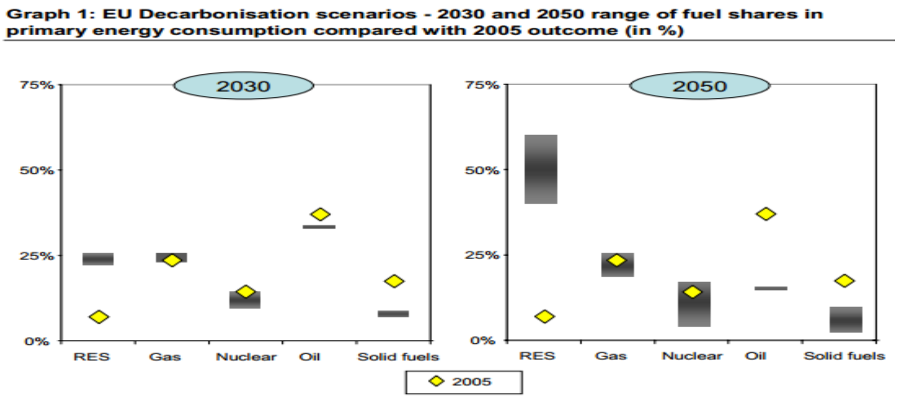

Figure 7 … EU decarbonization scenarios (European Commission, Roadmap 2050, 2011)

A summary of the analyzed sources is visible in *Table 3*. Based upon the share of electricity in the total demand of energy (*see Table 2*), some target and predictions are transformed.

Year	% of energy	% of power	Source	Category
2020	14%	70%*	European Commission, Roadmap 2020 (for Netherlands)	Target
		35%	Dutch Government, Rijksoverheid.nl	Target
		39.2-39.8%	Energiekonzept, 2010	Target
	25%	96%-100%*	EREC, RE-Thinking 2010	Policy study
2030		65-67%	EC, Energy Roadmap 2050, 2012	Target
	36%	100%*	EREC, RE-Thinking 2050,2013	Policy study
		50%	BP Energy Outlook, 2012	Estimation
		50%	European Climate Foundation, Power Perspectives 2030, 2012	Estimation
2040		65%	EC, Energy Roadmap 2050, 2012	Target
	27-50%	100%	Energiekonzept, 2010 (for Germany)	Target
		100%	EREC, Scenario 2040, 2010	Policy study
2050	19%	48%-63%*	EREC, RE-Thinking 2050, 2013	Policy Study
		80%	P.Chefurka, World Energy to 2050, 2007 (only modern RES without hydro	Estimation
	100%	100%	Energiekonzept, 2010 (for Germany only)	Target
	40-60%	97%	WWF & OMA & Ecofys, The Energy Report, 2011	Policy study
	35%	60%	EC, Energy Roadmap 2050, 2012	Target

*Table 3 … Overview targets and predictions 2020-2050 (the percentages marked with * are translated from the energy demand using Table 2)*

It should be noted that the large part of current RES is biomass and wind energy, each about 38%-57% of the current electricity consumption. Biomass as a source is barely growing,[34] while wind power will triple its capacity by 2020.[35] A similar trend is visible for PV. Taking into account these factors, the share of electricity coming from variable sources (mainly wind and PV) will become about 36% in 2030.

[34] Shell, Future Scenarios 2050, 2012
[35] Windenergie.nl, Rijksoverheid, 2011

3. International power trade

The EU is striving for a more united Europe with an integrated energy market. With its policies it is continually promoting market competition and is liberalizing the European Energy market. Recently it has founded ACER, an EU-backed institution which aims to unify energy policies in member states.[36] With the liberalization, production becomes independent of transport, e.g. creation of TenneT in the Netherlands. Production is done by commercial utility companies that also aim on maximizing profit. Excess generated energy in the form of electricity has become a commodity that is traded like consumer goods.

The electricity is transferred through the existing European energy grid, e.g. Dutch people can buy cheap nuclear power from France, or clean hydropower from the Norwegian mountains (*see Figure 8*). Increased cooperation is visible throughout entire Europe and new infrastructure is steadily constructed.

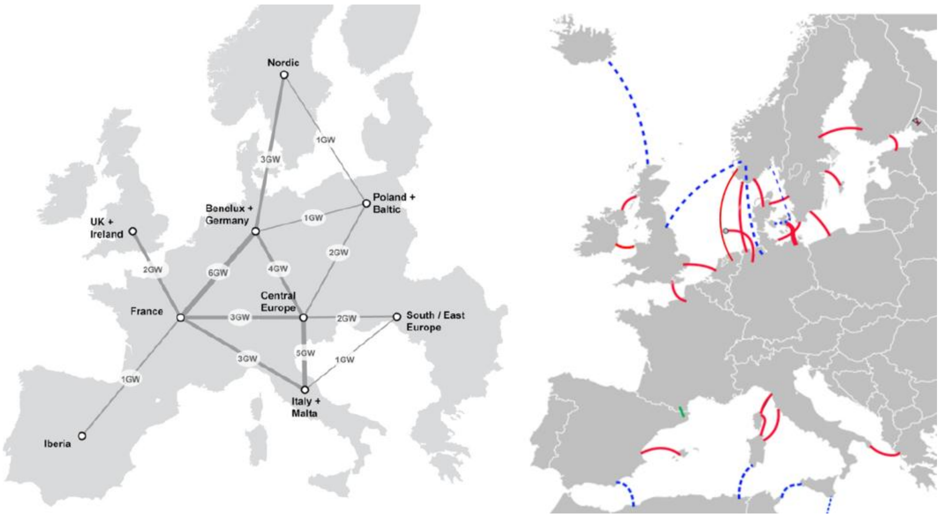

Figure 8… European energy grid (OMA, Roadmap 2050, 2010 (left) & Wikipedia (right), 2012)

Relevant is the link between Norway and the Netherlands, the NorNed, through a 700 MW submarine cable. During the day Norway provides the Netherlands with hydropower, while the Dutch provide power gas fired power during the night to pump water back up the high mountains and to power the electric common heating systems in Norway.[37] A second NorNed line was planned; however Statnett (Norwegian transmission operator) has delayed this till 2021 having currently no interest in a second NorNed cable. Plans to further increase the capacity between Norway and Germany (NorGer) have not been delayed.[38]

There are many similar exchanges between bordering countries and there are plans to create a fully integrated European power grid, which will profit from the geographic conditions. The scale of the plans differs; while some look regionally, others use a wider scope (*see Figure 9*). Before a grid unification is desired, some barriers have to be crossed. The current infrastructure already has insufficient capacity, e.g. Germany's inability to transport Northern Germany's power southward.[39] Laying this infrastructure costs significant amounts of capital and expands the maintenance costs. Other problems are increased

[36] European Commission, Single market for gas and electricity, EC.Europa.eu, 2013
[37] Euromonitor International, Heating Appliances in Norway, Euromonitor.com, 2013
[38] F. Straver, "Statnett herziet strategie interconnectoren", Energeia, 2011
[39] Reuters, Germany subsidizes cheap electricity for its neighbors, Reuters.com, 2013

transport losses and the increase in regional dependency; with increased cross border exchange, nations will trust their neighbor when demand cannot be met.

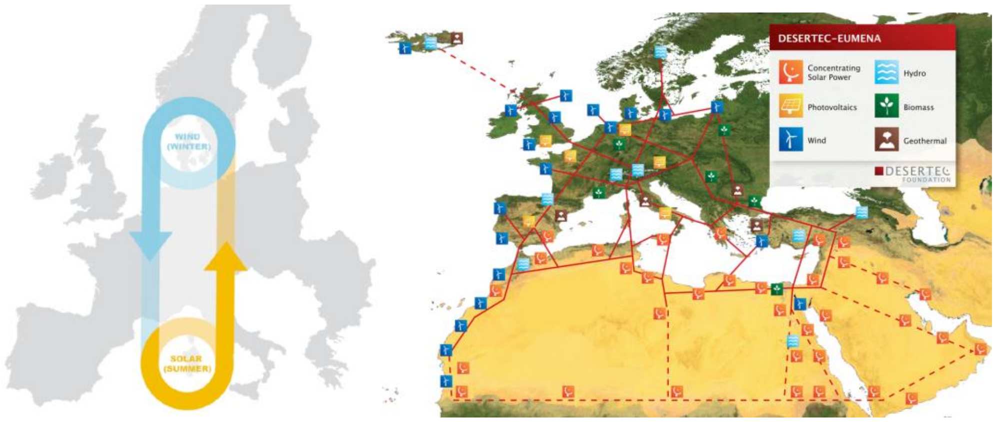

Figure 9 … (left) Future ambitions regarding an (extended) European energy grid (OMA, Roadmap 2050, 2010) and (right) DESERTEC Foundation, 2013)

With the increase of RES, it will be harder to get this energy ‘somewhere else’, since climates operate on continental scale rather than national (*see Figure 10*). No guarantees can be given and it isn’t hard to imagine a scenario where this energy is simply not available at the neighbors. Trust is laid on the free market mechanism; however there’s no insight into what the European gap between supply and demand is and whether the market will function as rapidly to ensure no blackout. The plans of liberalization are overall discouraging energy independence of regions and countries.

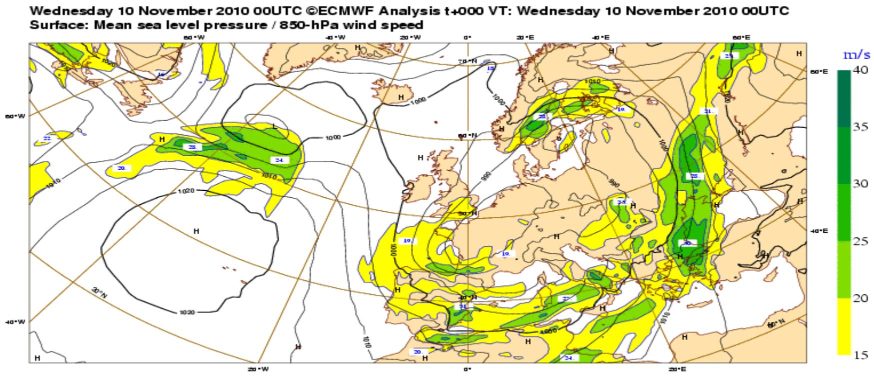

Figure 10 … Analysis of the wind regimes on October 10th, 2010 (HPC-CH, 2010)

One important note in this respect is that the ideas consider the technical workout, not considering much of the sociologic, economic and political aspects of the solution. The political issue comes down to dependence. Some plans stretch out to regions such as Northern Africa and the Middle East that are politically unstable.[40] Even within Europe these problems may arise[41], challenging the dependency that is ought to be created. Looking at the plan to use Northern Europe’s wind energy to power the south in winter (*see Figure 9 left*), a situation may arise of consequetive low wind speeds for months. This will lead to several allocation problems and eventually influence the trust in the system. This exemplifies the risks of such large-scale collaborations on primary needs.

The market responded on the liberalization with large utility companies generating large portions of the European electricity. Privatized utility companies no longer have the sole goal of providing the society

[40] BBC News, Arab Uprisings, BBC.co.uk, 2013
[41] BBC News, Eurozone Crisis Explained, BBC.co.uk, 2013

with energy, but also profit maximization for their share-holders. In 2009, the top 7 utility companies produced 50% of the total electricity of the EU-27. The list is led by EDF-group, which produced 20% of the total European supply using largely nuclear power (*see Table 4*).[42] These companies will increasingly support crossborder transmission in between their operating regions, stimulated by the liberalization of the market. This will happen regardless of what the most efficient situation is.

Several trade markets have been created, serving different time scales, from yearly to monthly (e.g. ENDEX) to day-ahead (e.g. APX Spot) and hour-ahead markets (e.g. APX Intraday). The hour-ahead market offers a close match between generation and consumption in terms of time, while seasonal differences are balanced at the long-term market.

Utility companies in Europe	Yearly production (TWh) (2009)[43]	Share of EU-27 market	Operates countries in Europe (* signifies the base country) :
EDF-group	652	19,6%	FR*, UK, AU, BE, DE, HU, IT, NL, PL, SL, ES, SE, CH
E.On Group	216	6,5%	DE*, UK, SE, IT, ES, FR, NL, HU, CR, SL, RO, RU
Vattenfall	175	5,3%	SE*, DN, FI, DE, NL, PL, UK
Enel Group	170	5,1%	IT*, BG, FR, HE, RU, RO, SL, SP
RWE Group	169	5,1%	DE*, NL, BE, UK, HU, SL, CR, PL, TR
GDF Suez Europe	141	4,2%	FR*, BE, NL, UK, DE, IT
Iberdrola+Scottish	92	2,8%	ES*, UK*, IR
Total	1615	48.6%	
(AU = Austria; BE = Belgium; BG=Bulgaria; CH=Switzerland; CR=Czech Republic; DE = Germany; DN= Denmark; ES=Spain; FI=Finland; FR = France; HE=Greece; HU = Hungary, IT = Italy; IR=Ireland NL=Netherlands; PL=Poland; RO=Romania; RU=Russia; SE=Sweden; SL=Slovakia; TR=Turkey; UK = United Kingdom;			

Table 4 … Largest utility companies in Europe (Annual reports 2010 of EDF (Electricity de France), E-On, Vatenfall, Enel, RWE, GDF Suez, Iberdrola+Scotish Power)

[42] EDF, Annual Report 2011, 2012
[43] PricewaterhouseCoopers, European Carbon Factor, Enerpresse, 2010

4. Dutch energy statistics

The following subjects are discussed in this chapter

4.1 Dutch energy balance

The Netherlands is characterized by an energy profile heavily dominated by oil and natural gas, which account for respectively 39% and 42% of the total consumption. With the addition of coal (10.4%), the Dutch share of fossil fueled energy is 91%; among the highest in Europe (*see Table 5*). What's remarkable is that the Dutch import of oil is nearly 150% more than consumed. This oil is stored in large silos around ports (hence the high bunker value) and exported when prices are high. Oil is imported the most.

Subjects			Unit	Total energy	Total coal and coal products	Total oil and oil products	Natural gas	Renewable energy	Nuclear energy	Trash and other energy bearers	Electricity	Warmth
Energy supply		Total energy supply	PJ	3287	344	1278	1373	136	39	55	62	-
		Extraction	PJ	2699	-	63	2406	136	39	55		
		Import	PJ	10099	.	8418	783	-			116	-
		Export	PJ	8521	.	6379	1812	-			54	-
		Importbalance	PJ	1578	.	2039	-1029	-			62	-
		Bunkers*	PJ	719	-	719	-	-				
		Supply mutation	PJ	-271	.	-105	-4	-				
Energy transfer	Input energy transfer	For electricity/CHP**	PJ	979	241	23	507	104	39	32	14	20
		For fuel and wamth	PJ	3326	127	3147	27	16		5	2	2
	Production energy transfer	For electricity/CHP**	PJ	585							368	217
		For fuel and wamth	PJ	3273	110	3128	8	-				27
Energy use	Total energy use	Total energy use	PJ	3287	344	1278	1373	136	39	55	62	-
	To balance post	Balance electricity/CHP**	PJ	394	241	23	507	104	39	32	-353	-197
		Balance fuel and warmth	PJ	53	16	19	19	16		5	2	-24
		Energetic final use	PJ	2153	20	713	763	16		18	401	222
		Non-energetic final use	PJ	687	67	524	84				12	
	To sector	Energy sector	PJ	548	251	124	404	52	39	0	-243	-78
		Industry (no energy sector)	PJ	.	.	.	.	.	.	.	.	.
		Transport	PJ	481	-	474	1	-	-	-	6	-
		Private households	PJ	.	.	.	.	.	.	.	.	.
		Agriculture, fishing & service	PJ	.	.	.	.	.	.	.	.	.
		*Bunkers are import of fuel through for international ships and aircrafts and is not calculated in the Dutch energy balance										
		**CHP = combined heat and power										

Table 5 … Energy balance for 2012 in numbers (CBS, 2013)

Natural gas is 89% of the total production. About half, 55% is consumed nationally, while 45% is exported, making it the largest energy source for production and consumption. Nearly all exports are of natural gas.

RES accounts for only 4% of consumption, among the least in Europe. This 4% is split into 0.81% wind energy and 3.22% biomass. RES is accountable for 10%, in the power production which is shared by 4.10% wind power and 5.85% power from biomass.[44] Biomass is used for heating and 36% for power generation.

Coal consumption has risen from 9.4% in 2011 to 10.5% in 2012, due to the low price of coal and rises in the oil and natural gas price.[45] This rise combined with the relative instability of the oil price is leading to an increase in the use of coal, which is among the heaviest polluters.[46]

[44] CBS, 2013
[45] CBS Statline, 'Wereld Olieprijs en Wereld Steenkoolprijs', 2013
[46] Mishra U.C, Environmental impact of coal industry and thermal power plants in India, Journal of Environmental Radioactivity, 2004

4.2 RES targets and their feasibility

The share of RES in the Netherlands is very low, ranking 4th from the bottom in Europe when it comes to the share of RES generation (*see Figure 5*). Considering the high demand from society,[47] this seems rather strange, but the reality is more complex.

Coming from a low share of RES energy and having less natural potential for renewable energy development, the EU has specified a lower target for the Netherlands of 14% rather than the 20% by 2020.[48] The Dutch government is more optimistic and has declared renewable energy ambitions of 16%.[49] To create a feeling for the magnitudes, a quick calculation for the required windmills for 2020 is under assumption that energy consumption will be the same in 2020 and a 14% share of RES, supplied with only 3 MW wind turbines with 30% capacity factor.[50] This quick calculation shows that an additional 7700 turbines are needed by 2020. Considering a market price for wind power of $1.3 million/MW,[51] the total investment required is $3.3 billion. Developments that will affect this price are increase of other RES, development in turbine technology and reduction in price/MW.

So how feasible are the targets of 14% and 16% by 2020? Based on data of RES from the last 20 years, a trend line is generated. This analysis shows that when using a 2nd order polynomial for the growth curve (which is optimistic), the share of RES generation will rise up to 9% by 2020 (*see Figure 11*). More detailed analysis could be made by adding data of planned projects. This analysis shows that the Netherlands won't be able to get even near the 14% EU-target with the same pace of growth. More extensive analyses report the same conclusion.[52]

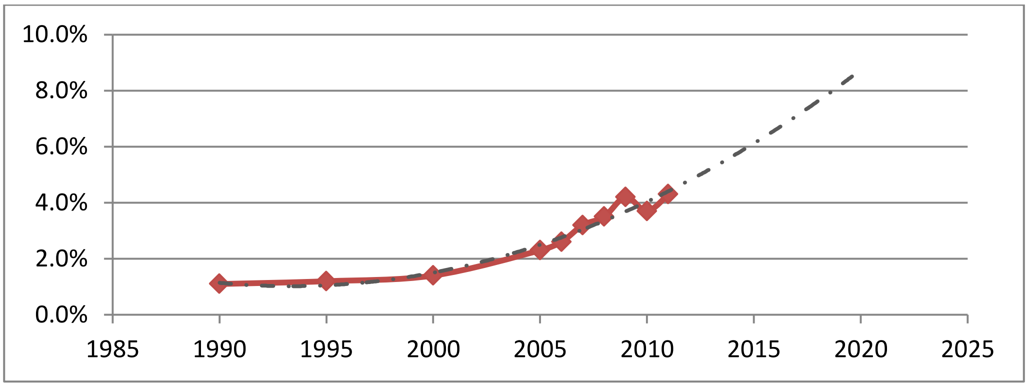

Figure 11 … Share of RES in total consumption data (red line) with 2020 forecast (dashed line) (red line data from CBS, Hernieuwbare Energie in Nederland, 2012)

[47] NatuurenMileu.nl, Ook Henk en Ingrid willen schone Noordzeestroom, NatuurenMillieu.nl, 2013
[48] EU Commission, Renewable Energy Roadmap, 2007
[49] Rijksoverheid, Duurzame Energie, Rijksoverheid.nl, 2013
[50] ECN, Energietechnologiën in het kader van transitiebeleid: factsheets, 2004
[51] Vesta, 2013
[52] Planbureau voor de Leefomgeving, Wissels Omzetten, 2013

4.3 Low RES utilization and future problems

The reason for the low RES utilization in the Netherlands is in essence a combination of low motivation to invest in RES and a high preference for fossil fuels. As the Dutch economy is heavily reliant on fossil fuels (*see §4.1*), a lot of turnover is realized in the trade of oil and the export of gas. The higher capital cost for investing in RES rather than for fossil fueled sources (both for initial investment and costs per kWh),[53] decreases the interest in RES.

In fact, the Dutch dependence on fossil fuels is so high, that the imminent energy transition will become very difficult for the Netherlands (*see §2.3*); a worrying situation.[54] This transition may be a forced one, as the predictions state that by 2022, the Netherlands should be importing their largest energy and export product: natural gas.[55] The Dutch economy profits largely from the consumption and trade of fossil fuels, namely the export of natural gas and trade in oil. Up to 50 billion, or 20% of the government budget can be allocated to energy related activities. There is a lack of insight into the economic consequence of this transition and making this transition too quickly will cause a lot of economic damage. Different energy development scenarios must be analyzed and considered in order to prepare a smooth transition.[56]

It is highly likely that part of this transition has to be realized by a growth in RES. It is therefore remarkable that there's still very little installed RES capacity. The main reasons for this are summarized as:

- There's barely any hydropower potential in the Netherlands, due to the small height differences
- There is only limited land available for biomass creation. Used for heating purposes mostly, biomass is competitive with natural gas in many countries.
- Grid capacity lacks to open possibilities for decentralized power generation, e.g. wind farms.[57]
- There's relatively low governmental support for implementation of RES. Varying goals and disruptive policies continue to plague development. Compared to Germany, Spain and Denmark, whose governments actively support RES through policy, subsidies and attention, the Dutch government seems rather passive. The current stakes in fossil fuels and lobbying has no doubt an influence in this political choice.[58]

Despite the image the summary sketches, the Netherlands does have a lot of potential in wind energy. This potential is onshore as well as offshore around the North Sea, where the highest European average wind speeds are measured.[59,60] Other countries around the North Sea are expanding their capacities to utilize this potential, while the Netherlands lacks due to reasons mentioned above.

Solar energy was only 0.1% of the power consumption in 2011 but is rapidly expanding with the price drop in PV panels.[61] While the potential for solar energy is great, it remains an expensive option among the RES as the technology is still developing with industry products reaching efficiencies around 15%.[62] Extensive studies prove that 4000 MW capacity is possibly by 2020.[63]

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[53] C. Douwes, Offshore Windenergie, VOZT.nl, 2010
[54] Nu.nl, Wetenschap bezorgt over energieakkoord, Nu.nl, 2013
[55] R.Kleiburg, Visie op toekomstige energiemarkt', ECN, 27/11/2012
[56] TNO, Naar toekomstbestendig energiesysteem nederland, 2013
[57] Rabobank Food and Agribusiness Research, Rabobank Report Q2 Renewables, 2013
[58] Nu.nl, Nederland mist collectief leiderschap, Nu.nl, 2012
[59] Trouw, Noordzee onbenut voor duurzame energie, EuropaNU.nl, 2012
[60] European Environment Agency, Europe's onshore and offshore wind energy potential, 2009
[61] B. Heerema, Zonne-energie, Tegenlicht.vpro.nl, 2013
[62] PVPakket.nl, Zonnepanelen kopen, PVpakket.nl, 2013
[63] W. Simons, KEMA: in 2020 4000 MW aan zonne-energie in Nederland, Energiebussiness.nl, 2011

4.4 Future Dutch power market

The Dutch government has no post-2020 energy policy. Therefore European predictions (*see §2.7*) are used to determine Dutch power market expectations. The Netherlands consumes about 3.5% of the total EU-27 consumption. Inside the EU-27, apart from no growth in supply, there is no large distribution difference of power expected and this value is assumed to be the similar in 2050. To give meaning to the relative numbers of RES, the various estimated absolute numbers are used (*see Table 6*).

Year	Annual power demand EU-27 (TWh)	Annual power demand Netherlands (TWh)	Source
2020	3443-4393	120.5-153.8	*EREC, RE-Thinking 2050,2013*
	3100-3400	108.5-119	*Eurel, Electrical Power Vision 2040 EU, 2013*
2030	3886	136	*Energynautics, E Grid Study 2030-2050, 2011*
	3616-3702	126.6-129.6	*EREC, RE-Thinking 2050,2013*
	4100	143.5	*OMA, Roadmap2050, 2010*
	3400-3550	119-124.3	*Eurel, Electrical Power Vision 2040 EU, 2013*
2050	4543	159	*Energynautics, European Grid Study 2030-2050, 2011*
	3491-4987	122.2-174.5	*EREC, RE-Thinking 2050,2013*
	4800	168	*OMA, Roadmap2050, 2010*
	4000-4050	140-141.8	*Eurel, Electrical Power Vision 2040 EU, 2013*

Table 6 … Future power demand in Europe and the Netherlands

4.5 Power generation and transmission

Leading the liberalization trend in Europe, the Netherlands has since 2008 split the generation and transmission of electricity. European commercial companies handle most of the Dutch power generation (*see Chapter 3*). The total installed power capacity in 2013 is equal to 20.564 MW.[64] Transmission and distribution is handled by TenneT. This commercial company is responsible for a continuous power supply and expansion of the infrastructure where required. TenneT also provides cross-border transmission. The Netherlands is net exporter of energy since 2009,[65] with Germany the largest contributor in this trade of energy. The Dutch benefit from the NorNed cable that is used to the fullest. Despite its operation at full capacity, an expansion has been delayed by Norway (*see Chapter 3*).

The longer the transport, the greater are the losses. The transport and distribution losses were around 4% in 2010, which is low compared to Europe and the world average (8.3%).[66] To put things in perspective, the losses in the 580 km submarine NorNed cable are 3.7%.[67] With this cable, the Netherlands nearly doubles its total transmission and distribution losses.

[64] TenneT, Installed capacity, 31/05/2013
[65] CBS, Nederland sinds oktober 2009 netto-exporteur van elektriciteit, CBS.nl, 2010
[66] The World Bank, Electric power transmission and distribution losses (% of output), Worldbank.org, 2013
[67] J.E.Skog et al., The NorNed hvdc cable link, 2010

4.6 Power load curves

The power load curve is a graph that displays the consumed amount of electricity along a certain time period. Although it displays the power curve, it can provide a good indication of the consumed energy. The Dutch consumption ranges about 5 GW throughout a typical day. Around the year, the output varies between the extremes of 8 – 18 GW. It is hypothesized that consumption is more in winter, with shorter days and more electrical heating required. The statistics prove this distinctively with a change of about 20% in the use of electricity *(see Figure 12*).

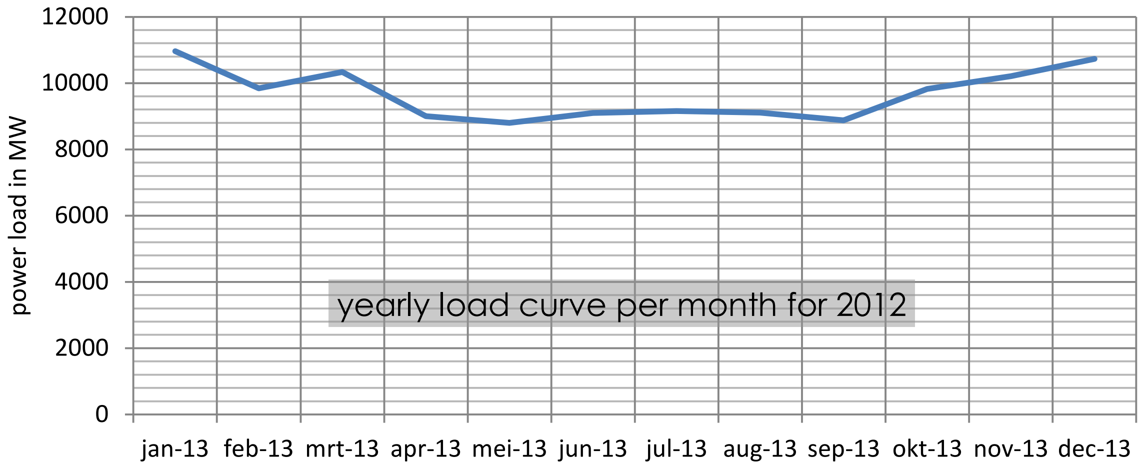


Figure 12 … Yearly load curve per month for 2012 (ENTSO-E, Extracted on 13-6-2013)

This difference is because of the colder temperature and shorter days. Even though most of the heating happens with natural gas, there is still a significant amount of electrical heating. A shorter day means the light will be turned on earlier and on a social level, people spend much more time inside, making more use of appliances. Looking at the daily variation for a month, a distinctive saw-tooth profile is visible due to the differences in weekdays and weekends (when most people aren't working) (*see Figure 13*). The more detailed hourly curve for a week shows a very typical load curve, signifying the large fluctuations between day and night (*see Figure 14*).

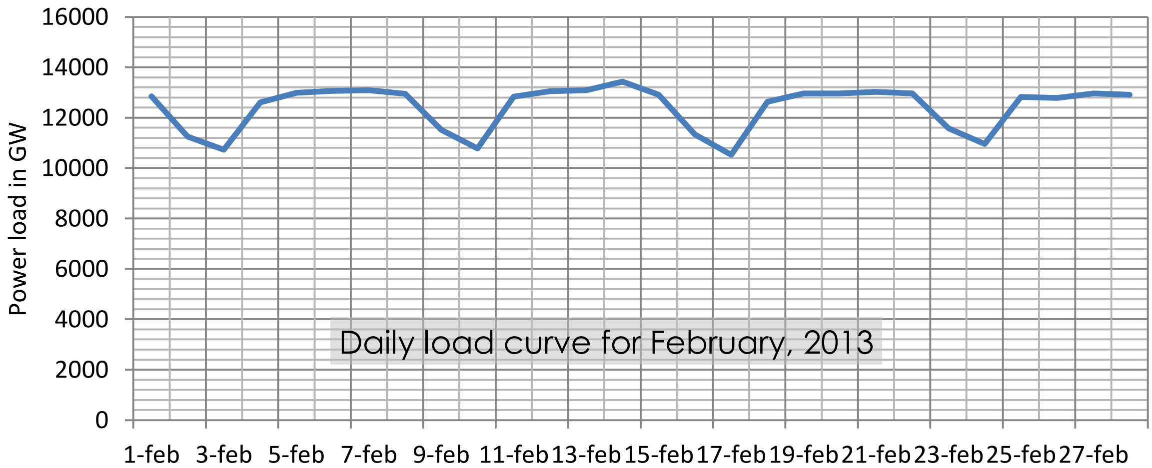


Figure 13 … Daily load curve for February, 2013 (ENTSO-E, Extracted on 13/6/2013)

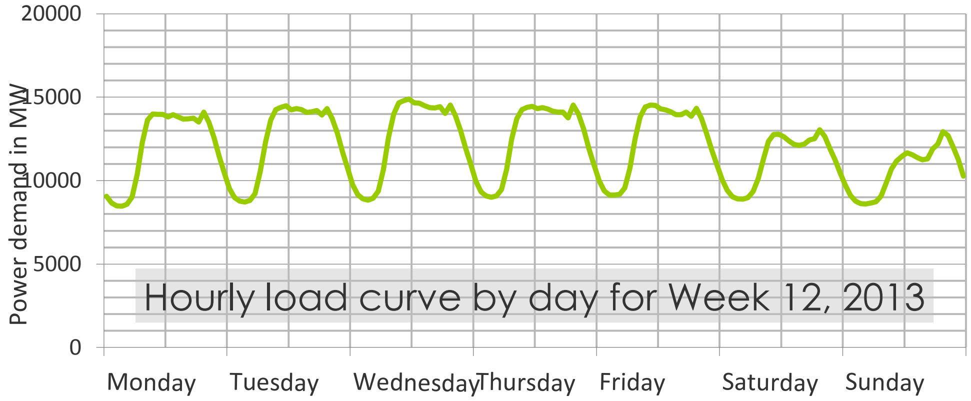


Figure 14 … Dutch daily load curve for week 12, 2013 (ENTSO-E, 2013)

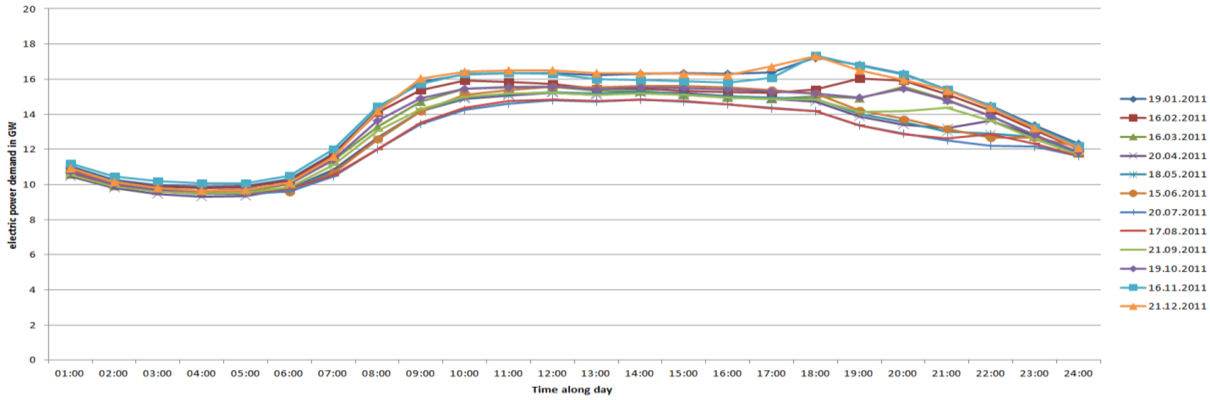


Figure 15 … Hourly electricity load curve for the Netherlands in 2011 (ENTSOE, Statistical Yearbook, 2011)

Zooming in on an hourly load curve for a day shows a very typical profile (*see Figure 15*). The mentioned seasonal differences are also visible in *Figure 15*. In winter, the graph presents a sharp peak after office hours (17:00-19:00) due to people coming home after work and turning on their appliances. In summer, this peak comes later at around 22:00 in August. This is due to the long daylight and warmer temperature as people spend more time outside. Throughout the entire year, the nightly values between the hours 23:00 – 05:00 show very little variability in demand.

The relation between demand and consumption is very strong. To show the distinct character of this profile, the demand curves from New England, USA are examined. This region is very similar to the Netherlands in terms of population (15 million), general lifestyle, environment and climate. Their power demands are very similar to the Netherlands (*see Figure 16 left*). The curve displays a few trends:

- In the morning there is the highest elevation change due to the start of the day, in between 5:00 and 8:00 hours. This transition from low to high demand is called the *morning ramp*. A lot of extra capacity is required in these hours as there is a shift of 5 GW in demanded capacity.
- Later in the day (around 18:00 – 22:00 hours), the maximum value of power is reached. This is called the *peak demand*. This is a time of high price and stress on the system. Power systems are mostly designed on this value, as demand is high and generation rises in a short time span. The extra capacity is reached with *peak units,* with quick response characteristics that come with high costs. Around the peak demand, energy demand is very fluctuating (*see Figure 16 right*). The five-minute peak demand shows higher required capacities. This is due to lack of detail in the hourly load curve. This difference is rather important when designing the capacity.

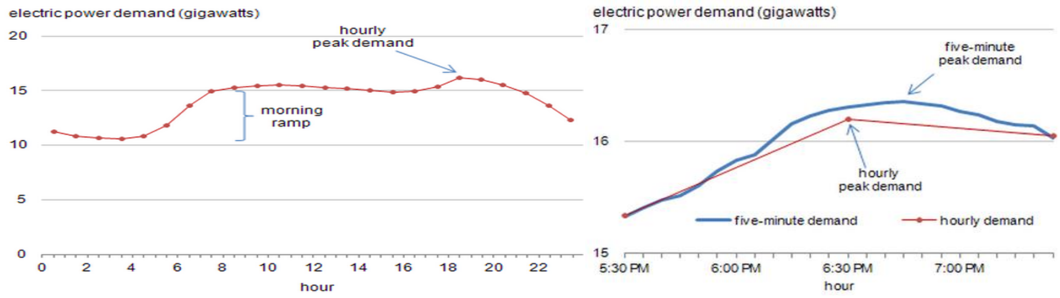


Figure 16 … (left) Electricity load curve for New England, USA for 22/10/2010 and (right) Detailed peak load curve for New England, USA for 22/10/2010 (EIA, Electric load curve New England, 2010)

With the liberalization of the European energy market, electricity is open for trade on power trade markets. These display the fluctuations in the price per MWh for different future time periods, i.e. months, days, hours. One expects the prices to follow demand and supply. Data shows however that price fluctuations are varying more radical than consumption and demand. A lot of factors are influencing the power price, so the exact reason cannot be given and depends on each case (*see Figure 17*).

Figure 17 … Daily load curve displaying the load along the week 21 in 2013 (APX Group, 2013)

The fluctuation is visible throughout the month and the price does go down with low demand, however is not consistent each time (*see Figure 17*). Especially towards the end of the month, the price follows the load almost precisely, which confirms the strong correlation.

Figure 18 …Monthly load curve for the Netherlands including the price variance for May 2013 (APX Group, 2013)

5. Wind power

The following subjects are discussed in this chapter:

5.1 Introduction to wind power

Wind power is a mature technology of which the first applications date back to the 4th century BC. Along the line, development progressed rather slowly until the current stage at which a typical turbine has an output of 3 MW and a cost price of $4.1 cents per kWh.[68] Future developments are mostly in terms of capacity and rotor size (*see Figure 19*). The history, future prospects and the current global share of the technology have been analyzed of which the findings are reported in *Appendix A*.

Wind is created from the imbalance caused by the sun's radiation. From this perspective, wind power is actually a derivative of solar energy. More information about the fundamentals of wind has been incorporated in *Appendix B*.

The preference for wind power in this report above solar power in the Netherlands comes from the high potential and the fact that the technology is mature and is already applied world-wide for decades, while solar power is still in the early development phase. Nevertheless, the development of solar power is rapid and as the unit prices are decreasing, it is increasingly becoming an interesting investment.[69] While the nature of the energy source is different, the way in which it affects the energy system is the same. Relevant is that solar power displays a similar variability and increasing the share of solar will increase the imbalance between supply and demand.

Because of its potential, wind power is the main target and this energy source will be examined further (*also see §2.7 and §4.3*).

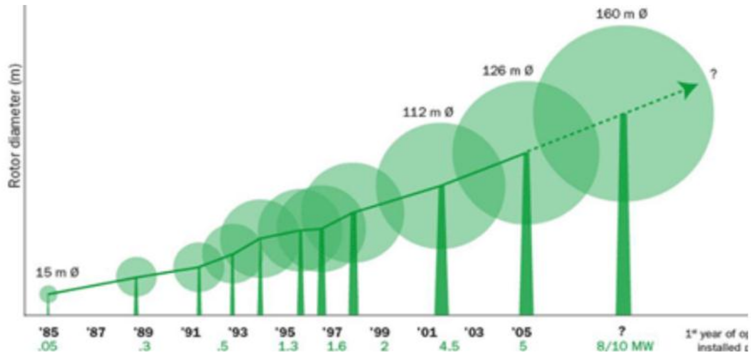


Figure 19 … Trends in turbine design (J. Beuskens, ECN, 2012)

[68] J. Conca, Is the answer, my friend, blowing in the wind?, Forbes.com, 2012
[69] DOE NREL, Solar Market Report, 2012x

5.2 Dutch wind power

The amount of turbines in the Netherlands was 1882 by the end of 2011, which combined a power capacity of 2000 MW (average of 1.1 MW per turbine). Together these turbines produced 18% of the Dutch electricity production.[70] The distribution of the wind turbines is primarily in the North-west (*see Figure 20*). This is because of the relatively high average wind speeds.

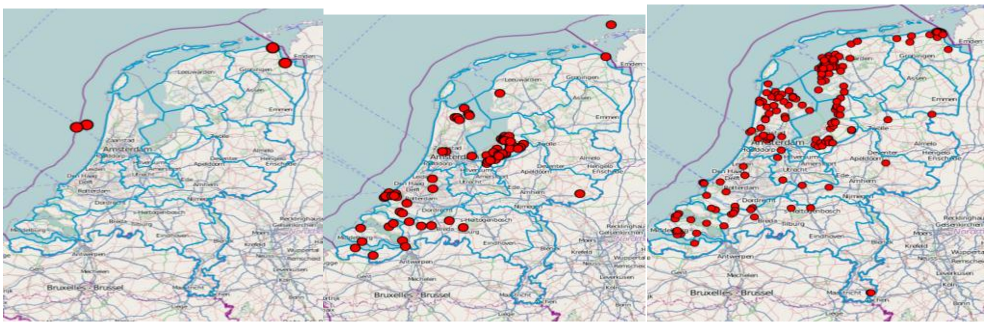


Figure 20 ... Current wind energy projects in the Netherlands from left to right, >50 MW (1st), 10-50 MW (2nd), 1-10 MW (3rd) (Rijkswaterstaat, www.w-i-n-d.nl, 2012)

When analyzing wind power potential, ground wind speeds are interesting, however with modern windmills reaching up to 90m (*see §5.1*), measurements at 100 m height are more relevant (*see Figure 21*). The areas with high potential are the north-west of the Netherlands, reaching over the North Sea (*see Figure 22 left)*. In fact, this potential is high when compared to the rest of Europe (*see Figure 22 right*). Despite its lower potential, Spain has relatively more installed wind capacity than the Netherlands.

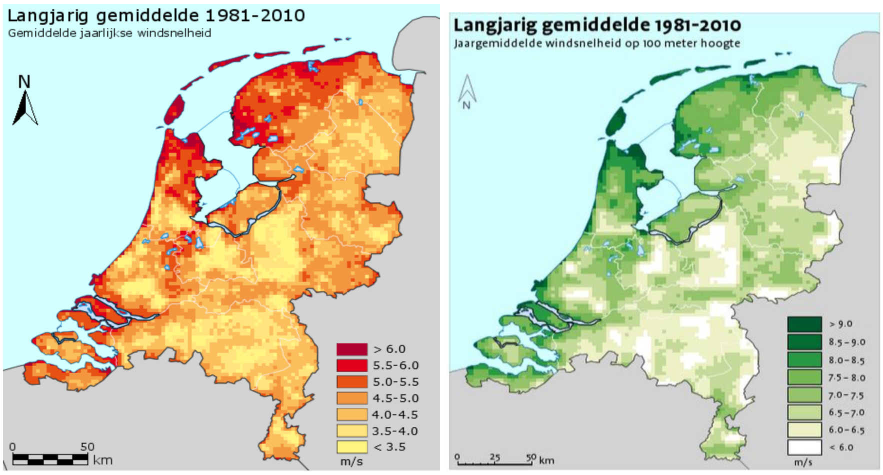


Figure 21 … Long-term average wind speeds 1981-2010, ground speeds (left) and at 100m (right) (KNMI, 2012)

The largest Dutch wind farm is 23 km offshore; the Prinses Amaliapark. With an installed capacity of 120 MW supplied by 60 Vestas V80 turbines of 2 MW, this park produces 435 GWh in a year (a very high capacity factor of 0.414), enough to supply 120.000 houses of power. The project was financed by a banking consortium meaning there is trust in annual turnover that is high enough to pay off debt, without the need to offer shareholders added assurances. This is a large change in the wind power industry.

[70] CBS, Hernieuwbare energie in Nederland 2011, 2012

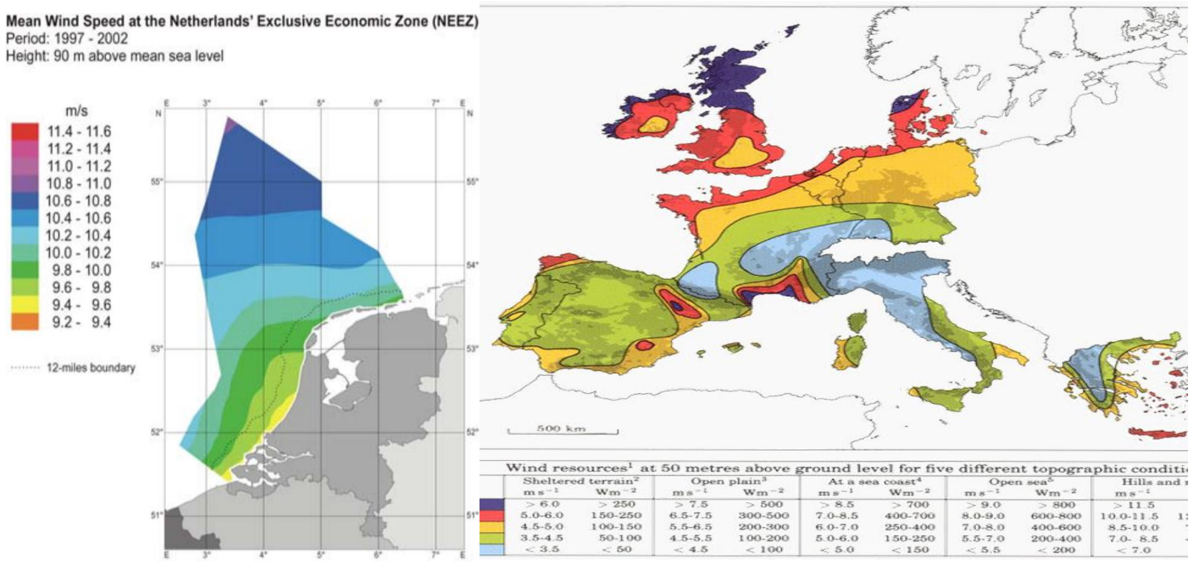


Figure 22 ... (left) Mean wind speeds at the Netherlands' Exclusive Economic Zone (Energy Research Center Petten, 2004) and (right) Wind speed averages in Europe (KNMI, 2012)

Another large project is OWEZ, also an offshore wind farm. It consists of 36 Vesta V90 turbines with each 3 MW creating 108 MW of installed capacity, enough for 100.000 households. The project is said to have costs around 200 million euros, including government subsidies. The tendon was given to Royal Shell and Nuon, who contracted much of the engineering work to a consortium led by Ballast Nedam. After the pilot, Shell backed out of wind power because it claimed that it is cheaper to invest in natural gas.[71]

The largest wind park on land is the Delftzijl Zuid, with a capacity of 75 MW. The park dates back to 2008 and uses Enercon's E-71 turbines that generate 2-2.3 MW each, with 30 turbines in the farm.

The current Dutch ambitions are to reach 6000 MW of wind power by 2020 in order to meet the 14% EU-goal and the 16% is has targeted itself.[72] Offshore farms are preferred because onshore wind power is facing opposition due to visual blockage and lower efficiency. For the total North Sea, a potential capacity of 135 GW is deemed feasible.[73] To meet the targets, several large projects are planned, among which the most noteworthy is the Windpark Noordoostpolder. With 48 turbines of 3.6 MW and 38 turbines of 7.5 MW (!), installed capacity will be 458 MW, four times larger than the current largest. A subsidy of €916 million is aimed for filling in the gap between cost price for this project (€9.6 cent/kWh) and power price (€6-7 cents/kWh).[74] Construction on the first 48 turbines has commenced recently and is expected to be finished in 2015.[75] Similar to this, there are other plans waiting approval. A recent plan states that large amounts of investment will be made on wind power and negations have started.[76]

[71] C. Douwes, Offshore windenergie, VOZT.nl, 2010
[72] Rijksoverheid, Meer duurzame energie in de toekomst, Rijksoverheid.nl, 2013
[73] Windspeed, Roadmap 2030, 2013
[74] Windkoepelnop.nl, Windpark Noordoostpolder, Windkoepelnop.nl, 2013
[75] Nu.nl, Ballast Nedam bouwt mee aan windmolenpark Noordoostpolder, Nu.nl, 2013
[76] E. Van der Schoot, 'Fortuin in Molens', De Telegraaf, 30/05/2013

5.3 Wind of Change: Denmark

Denmark may be an interesting role-model for the Netherlands. Denmark contributes to the world of wind energy with companies that develop turbine technology like Vesta, the largest wind turbine producer in the world. Not too many years ago, it undertook drastic changes and made a transition to decentralized power production. Therefore, Denmark is a very interesting reference case, also because of the many resemblances to the Netherlands in terms of climate (wind regimes), political system, economy and life standards.

The change in Denmark towards a wind powered country started in 1971, when the public and political will was put forward to push from a centralized energy market to decentralization by RES (*see Figure 23*). This created a situation in 2011 in which 28% of the Danish power demand came from wind, with targets of 50% by 2020 and 100% by 2035.[77]

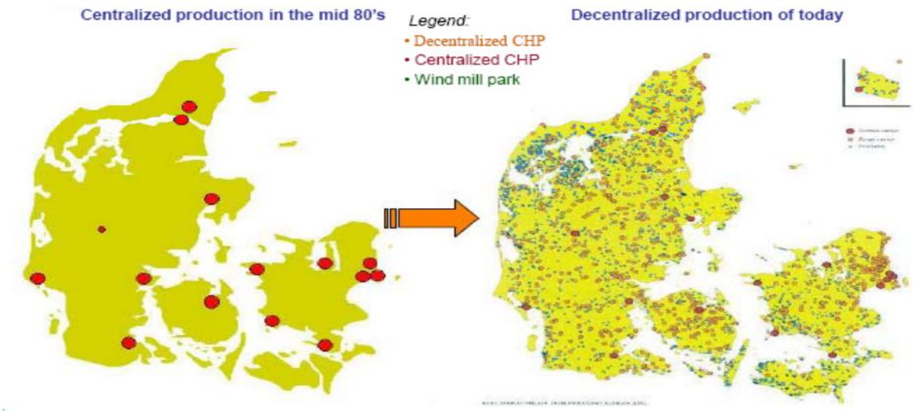


Figure 23 … Transition of Denmark from a centralized to a decentralized energy production (A.Holmsgaard, 2010)

The change from a centralized supply to a decentralized one meant the construction of lots of wind farms. Since the wind regimes ruling in Denmark are very similar to the one in the Netherlands, Danish wind power records can serve as a reference when designing for the Netherlands. The Danish wind data are displayed in *Appendix B*. Based upon these data; the following conclusions have been drawn:

- The average capacity factor of offshore Danish turbines was 44.9% in 2012
- With 871 MW of installed offshore capacity, they produced 19.457 GWh of electricity. [78]
- During low variability, the turbines operated at a capacity factor of 20% or lower utmost 3 days in 91% of the cases *(see next paragraph for more about capacity factors)*
- The capacity factor values range between 10% and 70%
- There is a very strong relation between the wind power supply and the spot price
- The spot price rose disproportionally, up to 400% of the average at times of very low wind output
- When wind output was low, the generation using Combined Heat Plants (CHP) was very high and so was the spot price

[77] S.Cha, Evaluation of Energy Storage System to Support, Danish Island of Bornholm Power Grid, 2012
[78] Energynumbers.info, Capacity factors at Danish offshore wind farms, Energynumbers.info, 2010

5.4 Performance of a wind system

When analyzing the potential of an area as a wind farm site, the most important characteristics are the wind speed and duration. A minimum wind speed of 21 km/h is required to create an efficient wind farm.[79] The performance of a wind power system is largely dependent on the response of the conversion system to the wind velocity variations. This is illustrated with the load curve (*see Figure 24 left*).

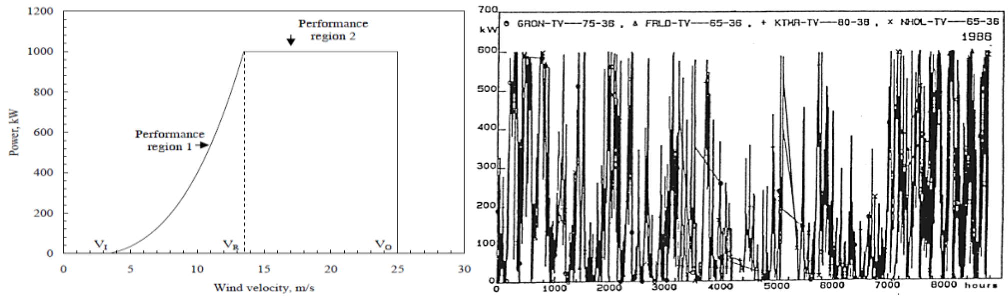


Figure 24 ... (left) Ideal power curve of a pitch controlled wind turbine of 1 MW (S.Mathew, Wind Energy, 2006) and (right) Typical 'saw' profile for the generation of a wind turbine (J. Halkema, Windmolens Fictie en Feiten, 1998)

This means that high wind speeds don't nessecarily lead to high output and may actually stop the turbine to prevent damage. There is an optimum wind speed for each turbine and the output is dependent on the match between turbines and wind regime. Typically, the ouput curve has many fluctuations (*see Figure 24 right*). The capacity factor (C_f) gives the ratio of power actually produced over a period of time with respect to the power it could have produced if the machine had operated at full capacity:

$$Capacity\ factor \qquad C_f = \frac{E_T}{T * P_R}$$

- In which E_T is the produced energy, T the measured time and P_R is the total capacity.

Guidelines for design values for C_f are around 0.2 - 0.3 for onshore turbines and 0.4 for offshore turbines.[80] To acquire more relevant values for the Dutch region, the Danish data have been analyzed (as large amounts of data are not present for the Netherlands), which can be found in *Appendix B*. The results show that their offshore turbines displayed an average C_f of 0.45 in 2012 and 0.39 along their lifetime. With 871 MW of installed offshore capacity, they produced 19.457 GWh of electricity in 2012.[81]

The C_f is commonly averaged over the year, even though it fluctuates throughout the year depending on the wind (*see Figure 25*). For the Netherlands, wind power output is particularly interesting in the winter; generating up to 20% more power.

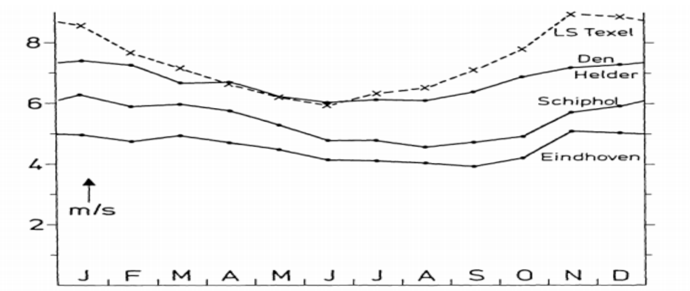


Figure 25 ... Yearly wind speeds of the monthly averages on 4 different stations (KNMI, Weerklimaat in Nederland, 1959)

[79] AWEA, 2010
[80] ECN, Energietechnologiën in het kader van transitiebeleid: factsheets, 2004
[81] Energynumbers.info, Capacity factors at Danish offshore wind farms, Energynumbers.info, 2010

5.5 Wind variability compared to demand

With conventional power generation, output is adjusted as far as possible to demand, using a combination of turning plants on and off, adjusting capacities and using peak generation units for quick response. Because there is no mechanism to turn on the wind or to increase its capacity, this might pose a problem in the future with larger penetration of wind power. It might coincidentally be true that the wind power generation curve mimics the demand curve, outputting high power when demand is high. This is dependent on the regional wind climate. For wind farms in the UK, analysis shows that there is indeed a positive correlation between wind supply and demand, although a very weak one (*see Figure 25*). The curve shows that when demand is high, the capacity factor is also high. Since the wind regime of the UK and the Netherlands are similar, a similar correlation may be true for the Netherlands.

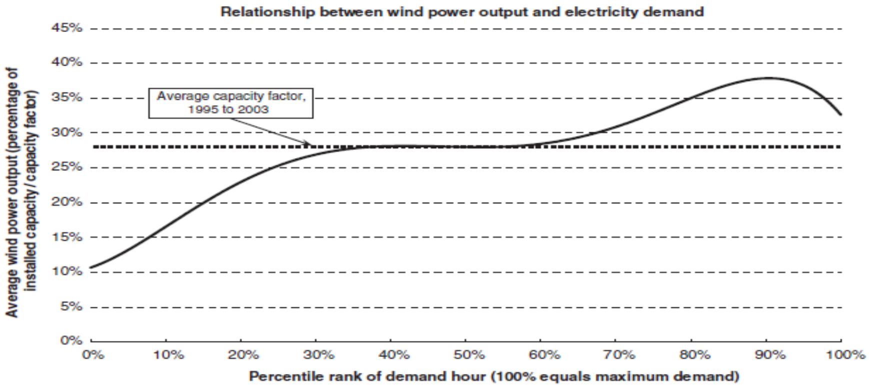


Figure 26 … Relationship wind power availability & power demand (S.Graham, Characteristics of UK wind resource, 2005)

5.6 Views on wind power

Advantages	Disadvantages
Wind energy is clean; GHG emission only with construction.	**Visual pollution** of with windmills that reach 90 meters in height
Low location dependency. The EU imports 52.7% of its energy; of which mostly coal (58.4%), oil (84.3%) and natural gas (62.4%).[82] To decrease this foreign dependency, wind power offers an alternative with its high potential sites for generation (*see §5.2*). Capital spent on exploitations in politically unstable nations can be directed into growth of the domestic energy market, creating more jobs and encouraging the economy.	Wind energy is not always readily available, as it does not always blow as fast. **The problem of intermittency and variability forms a large disadvantage** which will be attempted to be solved within this report. The consequence of intermittency is that no reliable energy system can be built. Even with a well-designed energy storage facility, when the wind doesn't blow for a time longer than the storage capacity, no energy is available for the market.
Fuel is free for wind turbines and in the operation phase, there are only maintenance costs. The market price of wind energy ranges between 5-7.5 cents/kWh, already a very competitive price.	The height and rotors form an obstruction and **possible danger to birdlife**. Analysis of the bird deaths shows that the share caused by wind mills is insignificantly low.[83]
Wind is a renewable and sustainable source of energy. There is an unlimited supply of wind and offers a clean, guild-free solution.	**Too much noise** by large windmills are causing opposition, despite most of the complaints being social and psychological factored [84]
It is ethical, in a market with good labor rights and transparency. This is in sharp contrast with the fossil fuel markets. The coal industry is marked by hard labor, low rights and collapsing mines, whereas the oil market with its oil spills, [85] monopoly abuse, [86] low labor rights and low environmental awareness.[87]	**Grid capacity has to be expanded** because windmills are located far away from settlements. Large-scale plants need little infrastructure, whereas a wind park stretches hundreds of meters and is placed at the location with best wind generation. This introduces **losses in transportation** and **extra grid infrastructure costs**.

Table 7 … Summary of wind power discussion

[82] Eurostat, 'Energy Indicators', 2012
[83] J. Layton, Do wind turbines kill birds, HowStuffWorks.com, 2010
[84] S. Chapman, Much angst over wind turbines is just hot air, Sydney Morning Journal, 2011
[85] The Guardian, BP oil spill, The Guardian, 2013
[86] R.James Woolsey, 'How to break both oil's monopoly and OPEC's cartel', 2008
[87] Amnesty International, 'Nigeria: petroleum, pollution and poverty in the Niger delta', 2009

6. Problem definition

In this section, a conclusion is drawn based upon the analysis performed above. This conclusion is also the formulation of the problems that are identified in the analysis of the energy and power markets. The problem is found to be multi-faceted, which is why it required very extensive research.

The analysis shows that fossil sources hold a very strong position in the global market despite the strong arguments opposing its use. As a cheap source of energy, they are especially utilized in developing nations whereas their share drops steadily in the developed nations. Overall, the depletion of the sources is imminent and will cause the fuel price to rise significantly, making alternative sources more attractive.

Especially in Europe, the call for alternative sources is high. Even though the total energy consumption is not growing due to increased efficiency and power management, European countries are increasingly trying to lower their fossil fuel dependency. This is visible in targets (set by the EU and national governments) and in future energy market studies. While there are differences in strategy to realize this, Europe will overall continue to be characterized by the strong growth of renewable energy sources (RES).

This will pose large problems for the Netherlands, which is heavily reliant on fossil sources for its consumption and economy. The utilization of RES is very low due to mentioned reasons and it is highly unlikely that it will fulfill either the EU or its own goals. However, the government is pushing for investments to increase the share of RES and initiate the transition from fossil sources. This growth of RES in the Netherlands has to be coupled with a strong expansion of wind power capacity. Out of the RES, wind power shows the highest potential for the Netherlands due to the high wind speeds. The current wind farms confirm this potential, with especially offshore wind farms providing high capacity factors. The research proves that wind power alone is insufficient in offering a reliable power system because of its variable nature; apart from the seasonal differences, wind speeds could be very low up to three days.

Analysis concludes that there are high fluctuations in demand in especially the hourly curve along a day and that this is causing high power prices on the hourly markets. This is because these peaks are balances by conventional plants which require a certain temperature to perform most efficiently and are therefore less suitable for situations with high fluctuations. The increase in RES will result in an increase of daily fluctuations and an increase of the current problems.

To summarize, the main problem is the imbalance in supply and demand. This is causing a lot of loss of efficiency for utility companies as they cannot provide a steady load. Because there is no controlling mechanism or buffer in the system, these problems are simply solved by generation at a higher rate. With the increased penetration of variable energy sources, of which mainly wind power is relevant for the Netherlands, this imbalance is likely to increase. With the increase in variability, it will be increasingly difficult to balance this with conventional units, who are limited by their nature of operation.

7. Goal and hypothesis

To face the problems, a change in the energy balancing is required. The following strategies are presented with their drawbacks and an assessment is made of which strategy to pursue further in the next part.

1. Increasing international transmission lines, allowing more energy trade

This strategy has too many uncertainties and it is too risky since it is concerning primary needs. The uncertainties and problems with this strategy are widely discussed in Chapter 3.

2. More energy management from demand side

The development of efficient products and industries plays a key role; however solely relying on this strategy is naïve, because of many factors such as consumer lifestyle choices that cannot be influenced.

3. Increased flexibility of conventional energy plants

With the increased penetration of RES, more plants will become back-up plants that will generate when demand is high and the RES performs insufficiently. The problem with this strategy is the rise of energy prices as these back-up units are only operated incidentally. In the transitional phase from a fossil fuel dominated energy system to a renewably dominated system, this strategy will play a significant role. However, when designing a future system, one doesn't need to rely on fossil fuels. As the plants will get older and start to deteriorate, they will slowly be placed outside the system.

4. Energy storage

The problem definition is concluded with a desire for a buffer system; a system that can regulate the imbalance between demand and supply. Temporary storing this energy in a storage device, the excess produced energy that is variable in nature is not wasted and be used later during peak hours. This will lead to a great increase in efficiency and less waste of primary energy. Storage will open up the door to wind power and similar variable sources. The goal is to create the link between supply and demand. One needs to find a solution for the cases where the demand and supply are put together, but don't seem to be match. At these periods, energy storage will kick in and compensate the difference (*see Figure 27*).

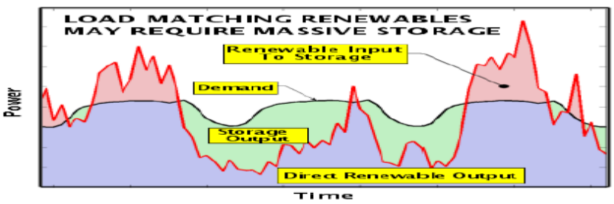
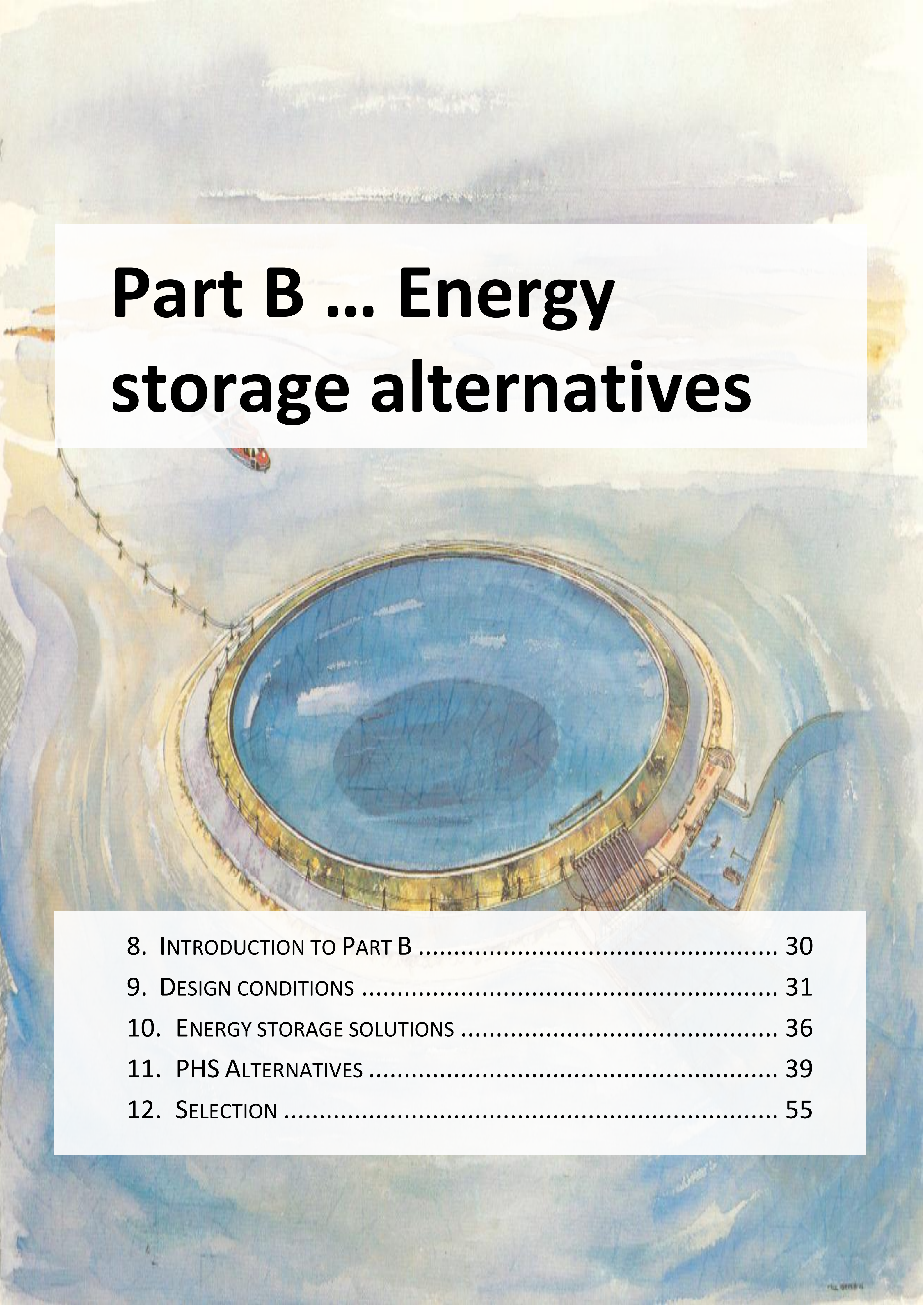


Figure 27 … The goal of energy storage (A. Shakouri, Trade offs in renewable energy solutions, 2011)

It is hypothesized that energy storage should be the preferred strategy. The following research question will be the foundation of the research that is performed:

"How to solve the problem of imbalance between supply and demand with a rise of renewable energy sources with a variable character and offer a clean, safe, dependable, cost-efficient way of large-scale energy storage for (a large part of) Netherlands that can be integrated into the current power grid?"

To analyze this broad question, it is divided into sub-questions which are presented in the Introduction of each part. As the analysis takes place, new questions will arise which require specific answering.



Part B … Energy storage alternatives

8. Introduction to Part B

In Part A, the problems are identified and a first step towards the solution is made by formulating the goal towards creating an energy storage solution. The imbalance between demand and supply leads to large differences between production and power consumption. The consequence is a system with high uncertainty that is difficult to manage. Demand comes from consumers and their behavior can be predicted to a high degree and supported with statistical data, a close approximation can be made. This demand is heavily influenced by day and night rhythms, culture and regulations (e.g. free weekends) and is highly uncontrollable in nature.

This section starts by identifying the characteristics of the desired situation. What is the required amount of balancing from the demand and supply side, what are the characteristics of the desired system? These design criteria will be set and the desired situation will be quantified so that a suitable solution can be looked for. The goal and the solution will be defined in more detail as the options and alternatives regarding energy storage are investigated. Each technology has its pros and cons and it will be the design criteria that determine the suitability of a specific technology.

The following research questions form the base of the analysis performed at Part B:

a. How would an energy storage system function in the Netherlands and what are the primary design criteria to fulfill these functions?
b. What methods of energy storage are there? What are the main advantages/disadvantages with the current methods? Which method of storage is applicable in the Netherlands?
c. What is the most preferable method of storage in terms of applicability and how can this method be optimized to function in the Netherlands?

The result of this section should be a clear understanding of the criteria for an energy storage solution, a stated preference for a certain storage technology and possibly the first impressions of how such a system should be shaped.

9. Design conditions

The following subjects are discussed in this chapter:

9.1 Benefits of energy storage

Basically, storing energy enables you to output energy whenever demand is high and also serves as a solution against the variability of wind by limiting the unexpected and uncontrolled output of energy.

There are other benefits for storing energy like the obvious resource-management advantages; the energy that is being generated is not 'wasted'. Another is that the market system can be exploited to create benefits; saving can be done when demand is low and thus the price, while generation occurs when demand is high and thus the price (*see §4.6*). This offers net benefits over the collection and distribution of energy (this is further explored in *Chapter 19.3)*. From this perspective, with only the peak-balancing, energy storage could be beneficial regardless of whether coupled with wind power.

As displayed in Dutch hourly load curves, peaks on which generating utilities are designed, are momentary and these peaks are up to 33% higher than average consumption (*see §4.6*). To design a system of national energy generation based upon the peak is a waste of capital, since they will be operational only for a limited amount of time. Another problem with the peak-based design is that fossil fuel based plants perform less efficiently by being turned on and off.[88] In summary, the benefits of energy storage are:

- Higher share of primary energy utilization
- Better utilization of the base load
- Fuel costs savings
- Having more control on the regulatory system of energy production
- Lowering of the installed thermal production output

9.2 Preliminary system boundaries

System boundaries are used to set certain geographic borders in which solutions will be looked for. As incorporated in the main question (*see Chapter 7*), a solution is looked for (a large part of) the Netherlands and the emphasis is a large-scale solution (*see §9.6*), which is why in this initial stage, the system boundaries are the whole Netherlands, including its waters (*see Figure 28*). The pink shade in *Figure 28* indicates borders of the land area, whereas the red line does this for the Dutch waters, which is close to the internationally agreed borders with the bordering nations.

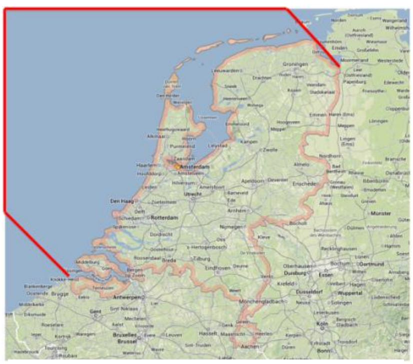


Figure 28 ... Initial system boundaries (Google Maps, 2013)

[88] Fossil fueled plants usually operate using the heat generated by burning the fuel. For the plant to operate on an efficient level, this heat has to reach a certain value. The losses are mainly caused in reaching these temperatures.

9.3 Preliminary stakeholder's analysis

It's important to identify different parties that have influence and relevance on an energy storage solution (*see Table 8*). Their interests are guiding in creating a system with a primary function of serving society.

Group	Stakeholder	Interest	Influence	Relevance
Government	European Union	Realization of EU-targets for RES	Low	Low
	National government	Meeting EU-targets, national prestige, minimal costs	Very high	Medium
	Province (regional government)	Regional prestige, minimal costs, high benefits	High	High
	Municipality (local government)	High safety local citizens, life quality, land value, cheap power, no loss of land, increased risk, improved economy	High	Very high
	Adjacent municipalities	Increased risk, cheap power	Medium	High
	Rijkswaterstaat	Increased maintenance of civil structures	High	High
	Ministry of Finance	Minimal costs, improved economy	Medium	Medium
	Ministry of Defense	Low risk	Low	Low
Industry	TenneT (transmission company)	Improved power management	High	Very high
	Power generation companies	Efficient generation, high management, more RES options	Very high	Very high
	Agriculture & Fishery	No loss/hindrance of land/ fishing area	Low	Low
Public and commerce	National citizens	National prestige, cheaper power	Low	Low
	Local citizens	High land value, improved economy	Medium	Very high
	Recreationists and tourists	Quantitatively and qualitatively improved recreation	Low	Low
	Environmental organizations	No loss of natural habitat, protection of environment	Medium	Very high
	Commercial sector (e.g. businesses)	Business opportunities	Low	Low
Project	Engineering, construction firm	Increase in work, maximum profit	Medium	Very high
	Workers	More jobs, good working conditions	Low	Very high

Table 8... Initial stakeholders analysis

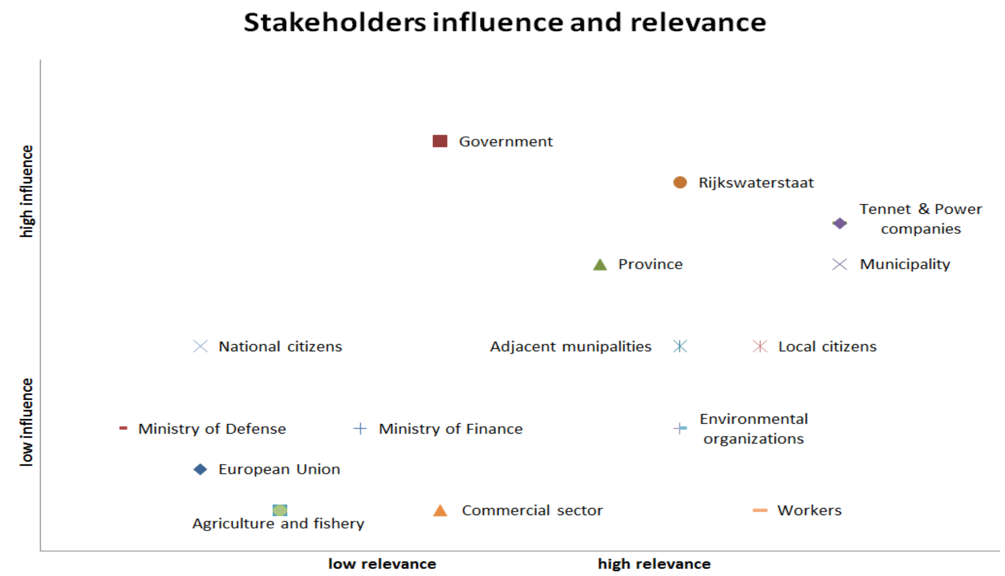


Figure 29 ... Stakeholders influence and relevance graph

The major stakeholders of importance and relevancy are: TenneT, utility companies, Rijkswaterstaat, the corresponding municipality, province and government. Especially their wishes are considered when creating a solution. This means the solution should comprise a system that **lifts the national prestige and local life quality, while improving power management and efficiency and creates a durable system at low costs with high benefits and more possibilities for RES.**

While doing so, the preference is that the solution combines this with nature and recreation while having low risks and little local interference and improves business opportunities and employment rates.

9.4 Wind power balancing function

The design criteria for the wind power balancing function are determined using statistical data presented in *Appendix B* for the wind power situation in Denmark. Already in Part A, the high similarities between the Danish and Dutch systems are discussed and explained that this data is used because of its large abundance and availability. The wind power balancing function will only define a required storage capacity for the energy storage system. The key findings of this analysis has been reported in *§5.3*

It was found that utmost 3 days the wind power performed below a critical level of C_f of 0.2. This has been observed for 90% of the cases and is set as the design criteria. This means that the energy storage system that is designed should be able to cope with a low power performance of $C_f = 0.2$ for 3 days.

For the current situation and the 2020 scenario, the installed wind capacity is used to determine the required storage capacity. Because there are no specific targets for the Netherlands beyond 2020, the European targets are used as a reference and scaled accordingly (*see Table 3 and Table 6*). The average value of all sources is used as the representative value for that scenario. This scaling is done in the same way that the EU has specified 14% RES in 2020 compared to the average of 20% by 2020 for Europe.

The calculation for the future scenarios of 2030 till 2050 is performed as shown in *Figure 30* and the targets are displayed in *Table 9.*

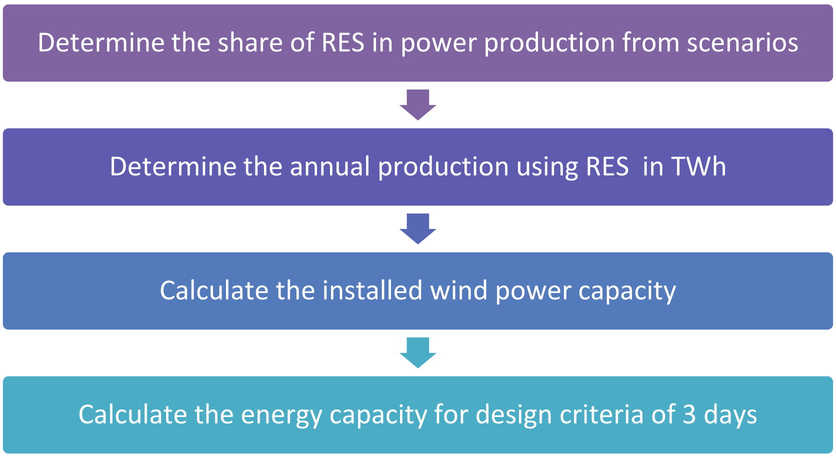


Figure 30 ... Defining the energy storage capacities for the wind power balancing function

Year	Estimated % of RES in power	Generation coming from RES [TWh]	Installed wind power [MW]	Required energy capacity [GWh]
2013			2000	4.8
2020	(35)	(44)	6000	14.4
2030	57	74	10000	24
2040	75	100	13650	33
2050	86	130	15650	38

Table 9 ... Required energy storing capacity of system for the wind balancing function

9.5 Peak-demand balancing function

Apart from regulating the variable input from wind power, energy storage can also be used for peak shaving purposes. This part of the problem is widely discussed in *Part A*. The energy storage solution must be designed based on the worst scenario, when the variation of demand is highest. To determine when this occurs, the Dutch load curves are analyzed (*see §4.6*) for different time periods:

- Along a year, this peak is reached in winter, namely January
- Along a month, there is no distinct peak
- Along a week, this peak is reached in the middle of the week, namely Wednesday
- Along a day, this peak is reached after office hours, namely between 17:30 - 21:00

Based on the findings above, for each month of the year, one day with the maximum load profile is chosen and analyzed. Due to the availability of the data, this is done for the year 2011.[89] It should therefore be noted that the analysis is unable to figure out extremes that occur on a scale of multiple years. The choice not to consider only January (the yearly peak month) is because the variance with the peak is essential and not the absolute number. This is defined according to:

- *Base load,* which will be covered by conventional units. This is defined as the average between 10:00-17:00, after the morning ramp, during which units operate steady at high efficiency
- *Peak loads,* the difference between the base load and the extreme values along the day (note: this is not the extreme value minus the mean, so there can be multiple peak loads in a day)

A simple algorithm is created and calculated that does the following:

- makes the separation between *base load* and *peak loads (the peak load at only a specific hour)*

$$Base\ load = mean\ value\ (time_{ref})$$
$$Peak\ load\ = i - Base\ load$$

- sums up the <u>positive</u> peak loads to acquire the total energy storing capacity required

$$Required\ storage\ capacity = \sum_{t=00:00}^{24:00} (for(peak\ load(i) > 0))$$

- calculates the extreme value of the defined peak loads which the system should provide

$$Required\ power\ capacity = maximum(peak\ loads)$$

In which $time_{ref} = 10:00 - 17:00$, i = corresponding value at a specific time between *00:00 -24:00*

An example of the physical meaning of the algorithm is shown for *12 December 2011* in *Figure 31* in which the blue curve is the hourly load values and the red line indicates the base load. The area in between the red and blue curve gives the total required energy capacity whereas the maximum minus the base load gives the total required generating capacity. The full results for all analyzed data are displayed in *Table 10*.

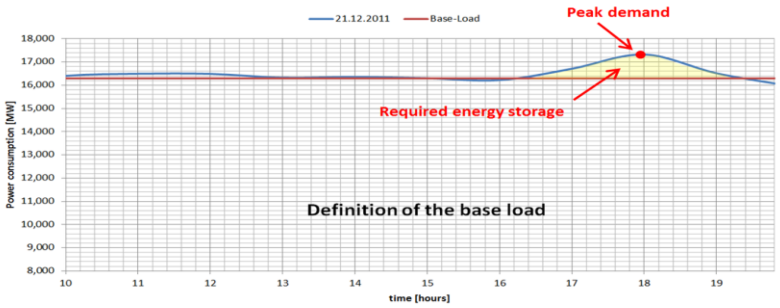


Figure 31 ... Definition of the base load for 12 December 2011 (Data from ENTSOE, 2013)

[89] ENTSOE, 2013

Date	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	Storage Capacity (GWh)	Generation Capacity (MW)
19.01.2011	14,265	15,834	16,257	16,333	16,328	16,217	16,287	16,345	16,298	16,365	17,214	16,826	16,293	15,422	14,484	1,64	919
16.02.2011	14,108	15,369	15,905	15,825	15,726	15,467	15,463	15,344	15,248	15,206	15,419	16,031	15,913	15,140	14,208	1,56	463
16.03.2011	13,284	14,729	15,440	15,554	15,556	15,330	15,318	15,108	14,940	14,886	15,020	14,910	15,580	14,843	13,905	1,76	259
20.04.2011	12,665	14,160	14,885	15,053	15,227	15,090	15,236	15,226	15,024	14,856	14,713	13,861	13,414	13,197	13,645	0,37	130
18.05.2011	12,560	14,173	14,957	15,155	15,244	15,181	15,282	15,160	15,015	14,960	14,860	14,027	13,547	13,030	12,880	0,31	140
15.06.2011	12,576	14,180	15,105	15,378	15,570	15,517	15,606	15,595	15,535	15,391	15,173	14,226	13,731	13,163	12,655	0,46	134
20.07.2011	12,021	13,445	14,269	14,619	14,797	14,716	14,816	14,708	14,560	14,350	14,190	13,363	12,912	12,503	12,191	0,47	175
17.08.2011	12,021	13,510	14,372	14,750	14,851	14,771	14,824	14,762	14,559	14,341	14,170	13,347	12,872	12,619	12,874	0,47	153
21.09.2011	13,058	14,283	14,984	15,164	15,232	15,096	15,181	15,118	14,941	14,874	14,829	14,155	14,192	14,368	13,651	0,29	130
19.10.2011	13,630	14,914	15,442	15,538	15,564	15,431	15,537	15,497	15,417	15,283	15,199	14,942	15,451	14,776	13,922	0,18	75
16.11.2011	14,462	15,714	16,321	16,342	16,291	16,000	15,967	15,867	15,815	16,079	17,346	16,780	16,279	15,418	14,445	2,84	1260
21.12.2011	14,185	16,026	16,405	16,496	16,490	16,328	16,360	16,304	16,221	16,711	17,322	16,515	15,968	15,357	14,375	1,71	950

Table 10 ... Storage requirements based on the peak shaving function of the storage solution (Data gathered from the European Network of Transmission System Operators for Electricity (ENTSOE))

The values in *Table 10* are marked green when they are below the base load and red when they exceed the base load and thus require the energy storage device to come in action.

From the results, the requirements of the energy storage device are defined as the extreme values, displayed in *Table 11*. It can be seen that the required energy storage function is far less than the requirement defined by the wind power balancing, which is normative for the energy storage capacity.

Required duration of operations	Required energy storage	Required generating capacity
6:00 hours	2.84 GWh	1260 MW

Table 11 ... Required design criteria based upon the peak-shaving function

9.6 Large-scale vs. small-scale solutions

One of the key discussion points when choosing an energy storage system is whether to choose lots of small-scale solutions or a few large-scale solutions. A comparison of advantages between both options can provide more insight in the selection (*see Table 12*).

Small-scale solution	Large-scale solutions
Flexibility in capacity upgrade	Larger efficiency due to losses of one solution
Easier to adjust to changes	Larger efficiency due to lower number of units
Low primary investment costs	Overall lower cost per kWh: since some costs are fixed for each unit; fewer units means lower costs
Lower threshold for realization	Simpler regulatory system
More reliable system due to spread of risk	Lower maintenance costs
	Lower operational costs

Table 12 ... Advantages comparison between small-scale and large-scale solutions

Currently, RES are less competitive compared to fossil fueled sources. This comparison is based upon the costs per kWh to serve it to a customer. The comparison in *Table 12* shows that the cost per kWh is lower using large scale solutions. The lower costs per kWh combined with the other economic advantages, gives large-scale solutions the decisive edge in this particular situation.

10. Energy storage solutions

10.1 Overview of energy storage alternatives

Now that the design criteria have been defined for the system of energy storage, a suitable technology can be sought to fulfill these criteria. The detailed analysis of all the energy storage techniques is performed and can be found in *Appendix C*. Here, a summary of the results is presented with an overview which displays the technologies, the advantages and disadvantages. The overview is displayed in *Table 13.*

10.2 Selecting a suitable energy storage solution

There are many ways to store generated energy. In between these possibilities, there are lots of similarities. An initial method to thin down the possibilities is based upon the required storage time and scale. Some possibilities are suited for conditions where power is needed in minutes and requires quick access times. Like this, there are other characteristics that ensure a most efficient way of storage. The main focus of this assessment is on storage solutions that are suited for the two functions of wind power balancing and peak-shaving defined in *Chapter 6*.

Based upon a comparison of the variety of energy storage solutions, a preference for a specific method can be made depending on the conditions and wishes (*see Table 14*). The determination will first be made by elimination of methods. The first criterion is the desire for a large-scale solution (e.g. > 100 MW). Only the following storage solutions are suitable for this criterion:

- Underground compressed air energy storage (U-CAES)
- pumped hydropower storage (PHS)
- cryogenic energy storage (CES)

Out of these options, the only proven technology seems to be PHS, as CAES and CES are technologies under development and haven't proven their performance (*see Table 14*). CES has no major real-life applications and pilot projects of CAES have proven its very low efficiency. The alternative systems should be kept in mind when comparing the developed system for energy storage.

Pumped hydropower storage (PHS) is considered to be the most suitable.

Type	Storage by	Generation by	Advantages	Disadvantages
Pumped hydro-electricity storage (PHS)	Pumping water to higher elevation	Releasing water from high elevation to charge turbines	- Fit for large scale storage - Proven technology - Flexible - Rapid response	- Very dependent on geographic conditions - High primary investment
Compressed air energy storage (CAES)	Pushing compressed air into a cavity	Releasing the compressed air to charge a gas-fired turbine	- Fit for large scale storage - Use of existing cavities	- Low efficiency - Low experience
Flywheels and similar mechanical storage	Accelerating a rotating heavy mass around an axis	The heavy mass will keep on rotating for some time, utilization of the mass during this period	- Very quick response - High energy density - High efficiency	- Expensive - Short availability - Only for small-scale
Chemical storage alternatives	Reversing the generation process	Using the electron flow between anode and cathode	- Experience with some types - Flexible system - High energy density	- Promising types for large scale still under development - Expensive for large-scale
Hydrogen fuel cells	Reversing the generation process with power input	anode (the fuel) and cathode (the oxidant) react with one another inside an electrolyte	- Clean (water as output) - High energy density - Flexible system - Fit for large scale	- Expensive for large-scale - Low efficiency - Expensive
Electrical systems	Saving between two electrodes separated by insulating material	Releasing the saves energy	- Very high efficiency - Quick recharge - Very high energy density	- Still in development - Expensive for large scale
Thermal storage, mainly Cryogenic Energy Storage (CES)	Using energy to create cryogenic fluid	Fluid used in cryogenic heat engine	- Low costs - Fit for large-scale use	- Low efficiency - Under development
International power trade (see Chapter 3)	Sending excess energy into market	Buying energy from market	- Increased cooperation - “Buy as your use” (less waste in investments - Fit for large-scale use	- Increased dependency - Possible unavailability - High price during peak hours - Investment in grid capacity

Table 13 ... Overview of the analyzed energy storage technologies

Summary of energy storage technologies.

	Efficiency (%)	Capacity (MW)	Energy density (Wh/kg)	Run time (ms/s/m/h)	Capital ($/kW)	Capital ($/kWh)	Response time	Lifetime (Years)	Lifetime cycles	Self discharge (per day)	Maturity	Charge time	Environmental impact	Thermal needs
Mechanical storage														
CAES underground	70–89	5–400	30–60	1–24+ h	800	50	Fast	20–40	>13,000	Small	Commercial	Hours	Large	Cooling
CAES aboveground	50	3–15		2–4 h	2000	100	Fast	20–40	>13,000	Small	Developed	Hours	Moderate	Cooling
Pumped hydro	75–85	100–5000	0.5–1.5	1–24+ h	600	100	Fast	40–60	>13,000	Very small	Mature	Hours	Large	None
Flywheels	93–95	0.25	10–30	ms-15 m	350	5000	Very fast (<4 ms)	~15	>100,000	100%	Demonstration	Minutes	Benign	Liquid nitrogen
Electrical storage														
Capacitor	60–65	0.05	0.05–5	ms-60 m	400	1000	Very fast	~5	>50,000	40%	Developed	Seconds	Small	None
Supercapacitor	90–95	0.3	2.5–15	ms-60 m	300	2000	Very fast	20+	>100,000	20–40%	Developed	Seconds	Small	None
SMES	95–98	0.1–10	0.5–5	ms-8 s	300	10,000	Very fast (<3 ms)	20+	>100,000	10–15%	Developed	Minutes to hours	Moderate	Liquid helium
Thermal storage														
CES	40–50	0.1–300	150–250	1–8 h	300	30		20–40	>13,000	0.5–1%	Developing	Hours	Benign	Thermal store
HT-TES	30–60	0–60	80–200	1–24+ h		60		5–15	>13,000	0.05–1%	Developed	Hours	Small	Thermal store
Chemical storage														
Pb-acid battery	70–90	0–40	30–50	s-h	300	400	Fast (ms)	5–15	2000	0.1–0.3%	Mature	Hours	Moderate	Air conditioning
Na–S battery	80–90	0.05–8	150–240	s-h	3000	500	Fast (ms)	10–15	4500	~20%	Commercial	Hours	Moderate	Heating
Ni–Cd battery	60–65	0–40	50–75	s-h	1500	1500	Fast (ms)	10–20	3000	0.2–0.6%	Commercial	Hours	Moderate	Air conditioning
Li-ion battery	85–90	0.1	75–200	m-h	4000	2500	Fast (ms)	5–15	4500	0.1–0.3%	Demonstration		Moderate	Air conditioning
Fuel cells	20–50	0–50	800–10,000	[illegible]-24+ h	10,000		Good (<1 s)	5–15	>1000	Almost zero	Developing	Hours	Small	Varies

Table 14 … Comparison of the variety of energy storage methods (A.Evans, Assessment of utility energy storage for increased RES penetration, 2012)

11. PHS Alternatives

11.1 Introduction

In the previous chapter, the decision is made in favor for *pumped hydropower storage* (PHS). PHS can be realized in a variety of ways; since high elevation PHS isn't possible for the Netherlands, one can either go underground or expand the reservoir surface. The alternatives are grouped accordingly, with each group presenting several alternatives that are very distinct; they either use a different technique or emphasize a specific case and geographic situation.

The alternatives in *Group 0* are not really considered as an option, but are defined as to compare and test the other alternatives. Their function as a reference is explained at the respective section.

The alternatives in Group 1 mainly focus on low-head hydropower and benefit from the large surface of a reservoir to store and generate required amounts of power. The first Dutch concept of low-head hydropower storage was proposed in the Plan Lievense. Dating back to 1979, ir.Lievense came up with a plan to create an artificial lake with a water level difference relative to the surrounding water body. The head difference is used to generate and store energy. The original plan was finished in 1981 and had two major updates: the creation of the Valmeer in 1986 and the creation of the Energie Eiland in 2007. Both these plans will be considered here and finally, a smaller scale variant for a storage island is considered that requires little adjustments; a silt depot called: 'De Slufter'.

The alternatives in Group 2 are based on the same principles as normal PHS with the exception that it uses subsoil spaces to acquire the height difference. The benefit of underground PHS (UPHS) is that not much terrain is required above ground, which is preferable in the densely populated Netherlands. It does however require a subsurface reservoir to which the water can be released and pumped back from. This is either a subsurface cavity to be constructed or an existing cavity that is fit for storing water.

A primary selection is made based upon a Multi Criteria Analysis (MCA). The alternatives are detailed to such a degree that a qualitative selection can be made. The results of this chapter should be a preference for a certain alternative. An overview of the alternatives:

11.2 Group 0: The reference alternatives

11.2.1 Alternative 0.1: Doing nothing

Figure 32 ... The smoke coming from a peak-unit plant in the Ruhr area in Germany

Concept and evaluation

Not doing anything could possibly be the best solution. With no solution, the current problem remains unsolved with increased future consequences. The current problems have widely been discussed in *Part A* (*see Chapter 6)*. Since no investment is required, this is the cheapest alternative at first glance. No additional value is created and the problem is not solved and may even worsen. One may be missing the benefits a solution brings along. This may come in the form of costs (e.g. yearly fuel savings) or in terms of convenience, such as risk reduction and improved conditions. For a fair comparison, the benefit should be transformed into monetary terms, which is not always possible, e.g. what are financial benefits of improved convenience? The primary decision must be based upon more than monetary units. This alternative checks the additional value created by the other alternatives.

11.2.2 Alternative 0.2: European Energy Market

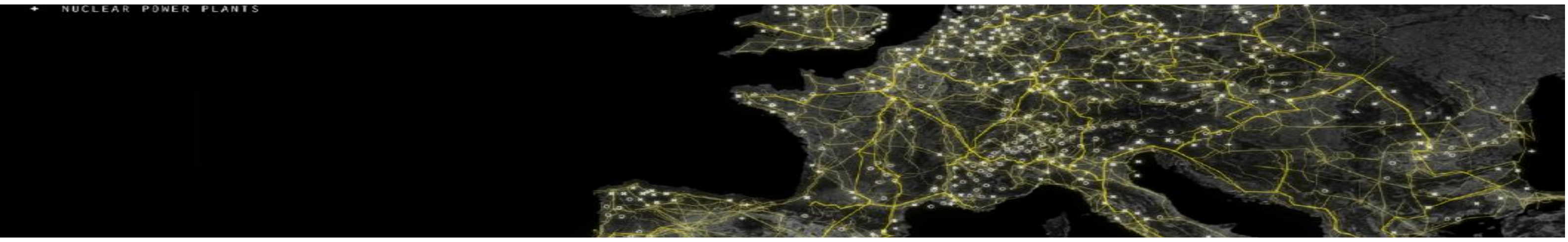


Figure 33 ... A possible future scenario of the European Grid (OMA, Roadmap 2050, 2010)

Concept and evaluation

This alternative serves as a reference because many organizations highly value this option. It has been discussed widely in *Chapter 3*. To summarize, the main problems are concerning the reliability. The peak demand of the Netherlands coincides with its neighbors, which means that the power will be unavailable or the price will be very high during these hours. Increased penetration of RES will increase the fluctuations of the supply curve. Since climatological events take place on a scale that affects most of Western-Europe, every nation will be out of power once the intermittency of the RES kicks in. The grid capacity needs to be expanded if more cross-border trade is going to happen, since countries are already facing problems with their own grid.

To provide more reliability in the system, a controlling body within the EU is suggested that monitors the power production and distribution and can make an early warning when the system is nearing a black-out. Overall, there are many uncertainties regarding international power trade. These uncertainties lower the effectiveness of this solution, creating high risk regarding availability and price fluctuations.

11.2.3 Alternative 0.3: Traditional PHS

Figure 34 ... Seneca Pumped Hydro Storage Plant near Pennsylvania, USA (Wikipedia, 2010)

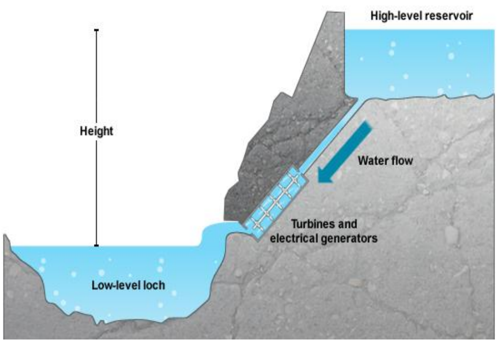
Concept

Characteristics that are valid for traditional PHS will to a very high degree also be valid for the other alternatives that utilize the same principle. The advantages and disadvantages have largely been discussed in *Chapter 10*. As a reference, this alternative elaborates the principle idea and theory.

Some 127.000 MW of PHS capacity was installed globally in 2009, with an expected growth rate of 60%, the capacity by 2013 should be around 203.000 MW.[90] Due to the flat topography, the Netherlands has low potential for hydropower. Therefore, only a handful of plants are installed near rivers with 38 MW installed capacity in total.[91] Traditional pumped hydropower is therefore very difficult.

Theory

Traditional PHS comprises of two reservoirs: one upper and one lower (*see Figure 35 left*). Excess energy is pumped in the form of water to the upper reservoir and released when energy is needed, powering a turbine in between. While there is no working example of PHS in the Netherlands, it's not entirely a new concept. There are applications abroad[92] and the concept is predominantly based upon proven hydropower technology (*see Figure 35 right).*



PHES Plant	Country	Power Capacity (MW)	Storage Capacity (MWh)	Pipe Length (m)	Minimum Head (m)	Maximum Head (m)	Generating Flow Rate (m^3/s)	Pumping Flow Rate (m^3/s)
Yagisawa	Japan	240	1368	483	53	112.5	83.2	77.3
Revin	France	760	3600	969	211.2	242.4	70	55
Shin-Takasegawa	Japan	1280	8832	2792	202.7	264.4	155.5	100.6
Mingtan	Taiwan	1600	10720	4443	340.5	410.8	77.4	57

Figure 35 … (left) Scheme of PHS (BBC, 2013) and (right) Reference PHS (TCPS, PHS Tech: International Experience, 1996)

By pumping water to a higher elevation, essentially the potential energy of the water is raised. The energy potential of water at any given height is formulated as

[90] E.Ingram, Worldwide Pumped Storage Activity, 2010
[91] Milieu Centraal, Waterkracht, MillieuCentraal.nl, 2010
[92] Wikipedia, Vianden Pumped Storage Plant, Wikipedia,org, 2013

$$E_{pot} = mgh = \rho Vgh = \rho Ahgdh \qquad [Joule]$$

- m = mass [kg]
- g = gravitational acceleration [m/s^2]
- h = hydraulic head [m]
- dh = thickness of the upper reservoir [m]
- V = volume of water [m^3]
- ρ = density of water [kg/m^3]

Considering this equation, the system will benefit disproportionally in a situation where the upper level of the reservoir is heightened while maintaining lower level (rise of *h* and *dh*). It has therefore the preference to increase the height. The same effect is true for the power. The power is formulated as:

$$P = E/t = \rho Ahgdh/t = \rho gHQ\eta \qquad [\text{Watt}]$$

- Q = flow in [m^3/s] (the flow rate is dependent on the size of the turbine and *penstock*
- η = efficiency [-]

Traditional PHS is very dependent on geographical characteristics, which means that the feasibility first starts with the search for a potential location. The most important attributes are the following:

- How much water is flowing in and out of the system, i.e. more water leads to more energy
- The geographical conditions to store the water, both for the creation of the upper as lower reservoir, i.e. the larger the reservoir, the more power
- The elevation difference and the water free fall height that can be realized, i.e. higher elevation difference leads to more energy production
- The costs required to realize the previous two points, i.e. larger facilities lead to higher costs

The following points should also be taken into considerations when designing such a structure:

- The expected amount of evaporation considering different water levels in the reservoir
- The expected average energy costs and generation
- The geological specification of the site, such as data of soil characteristics, leakage possibilities, earthquake statistics, foundation possibilities
- Sediment flow and the expected accretion as a result
- Direct losses or negative effects as a consequence of the PHS, e.g. loss of agricultural land, movement of people, constructions, etc.
- Other possible functions that can be realized, e.g. recreation, irrigation, naval functioning
- The ecological effects e.g. influence in water flows, water levels, environment etc.

Generally speaking high up the mountains the flow areas will be small, the amount of water is little, the water drop will be high and the reservoirs will be deep but small. In lower areas, the water and sediment amount will be higher, the water level difference lower and the reservoirs shallow but stretched. This leads to the distinction between low-head and high-head waterpower. It should be clear that the Netherlands is predominately a place for low-head waterpower (*see Figure 35 right*). A reference PHS plant is the Ludington PHS plant in the USA. The characteristics, costs and performance have been added to *Appendix F*.

11.3 Group 1: Storage Islands

11.3.1 Alternative 1.1: Plan Lievense

Figure 36 … Sketch of the original Plan Lievense

Concept

The idea of the Plan Lievense is the creation of an upper reservoir enclosed by dams. The original plan bases its design mainly on the peak shaving function, although it also incorporates a wind power regulatory system. The reservoir consists of a circular island forming the upper reservoir in a PHS system. The lake or sea around it is used as the lower reservoir. Generation and storage happens by letting the water flow and pumping it back up from the surrounding. The benefits in terms of costs come from fuel cost savings and were estimated to be fl1.2 billion annually.

More detailed

The circular shape is due to the favorable ratio of perimeter and surface. Phased development is made possible through the creation of three compartments; each holding an 800 MW turbine (*see Table 15*). Along the years, the plan has been updated several times in which different hydraulic heads are considered. The original plans consist of a hydraulic head of 70m, which is later reduced to 40m.

Capacity	Size reservoir	Original costs (in Dutch guilders)/Estimated today's costs[93]
800 MW	30 km^2	fl. 1.9 billion / €1.66 billion
1600 MW	55 km^2	fl. 3.1 billion / €2.70 billion
2400 MW	165 km^2	fl. 5.6 billon / €4.88 billion

Table 15 ... Three different capacities for the Plan Lievense (Begeleidingscommissie Voorstudie Plan Lievense, Wind Energie en Waterkracht, 1981)

Three locations are identified as potential sites (*see Figure 37 left*):

1. In the Markermeer attached to the Houtribdijk
2. At the shore near the Brouwersdam
3. In the North Sea far off the coast

The height of the dam ring depends on the chosen hydraulic head. The crest width of the Markermeer solution is 7m, enough to place small road on top.

[93] Internationaal instituut voor sociale geschiedenis, De waarde van de gulden/euro, IISG.nl, 2013

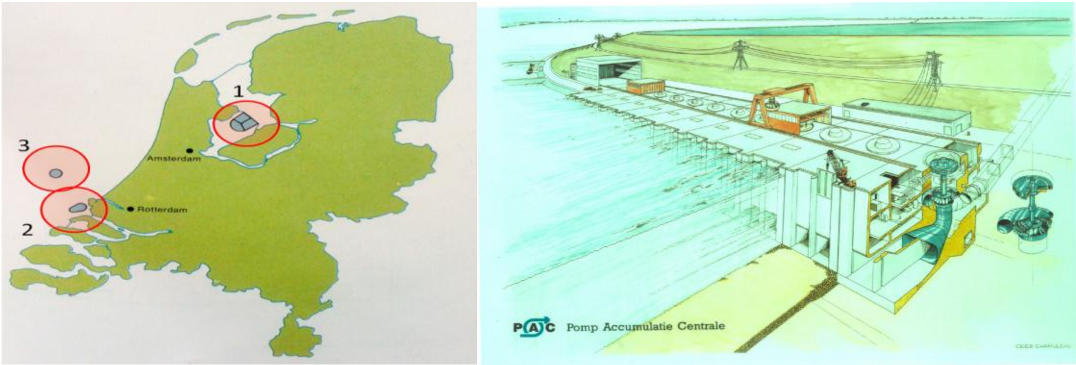


Figure 37 … (left) Possible locations for the upper reservoir and (right) Overview of the turbine and the reservoir of Plan Lievense (Begeleidingscommissie Voorstudie Plan Lievense, Wind Energie en Waterkracht, 1981)

The width in the other two options is 60m, significantly larger due to the dune shaped profile instead of a steep dam. The estimated ground moving works are projected to be up to 1 billion m^3 of sand, of which around 300 million m^3 sand for the dams and dunes, depending on the size of the reservoir. Since space is not a major restriction for the North Sea location, a surface area of 40 km^2 is deemed possible. Turbines operate with an estimated efficiency of 80%. The design safety of the dam ring at the Markermeer solution is much higher because of the large possible consequences in case of a breach. The design criteria are ten times higher than proposed in the Delta norm. The other locations share the same safety requirements as the Delta norm. Plan Lievense has been updated and reshaped in many ways, such as the new Afsluitdijk.[94] In this plan, a similar dam ring is proposed at the Afsluitdijk, utilizing the height differences in between the North Sea and the IJsselmeer. Each variant uses the same concepts and ideas developed in the original Plan Lievense, though with some modifications to e.g. the dam height and power generation capacity.

Evaluation of Plan Lievense

A point of criticism against the alternative is in terms of safety. The creation of a water reservoir with a water level of +70m NAP in the original plan, and +40m NAP in updates, raises concerns. These concerns are amplified by the proximity of Amsterdam at the Markermeer solution, and the proximity of Rotterdam at the Brouwersdam solution. The risk of failure is defined as the probability of failure times the consequence. As a solution for the safety concerns, the plan offers to decrease the probability of failure at this location by tenfold. The concerns revolve mostly around the consequences, which leads to a low safety feeling and makes the alternative at this location prone for intentional destruction such as acts of terrorism. The North Sea site has therefore the preference.

The main barrier for the realization has probably been the high primary investment costs. Although based upon existing technology, the creation of such an island is still unique in the world and its feasibility is unproven meaning there is some uncertainty regarding the practical efficiencies and effectiveness in the power grid. This uncertainty combined with large required investments lower the feasibility of the concept.

[94] Rijkswaterstaat, Natuurlijk Afsluitdijk, 2010

11.3.2 Alternative 1.2: Energy Island

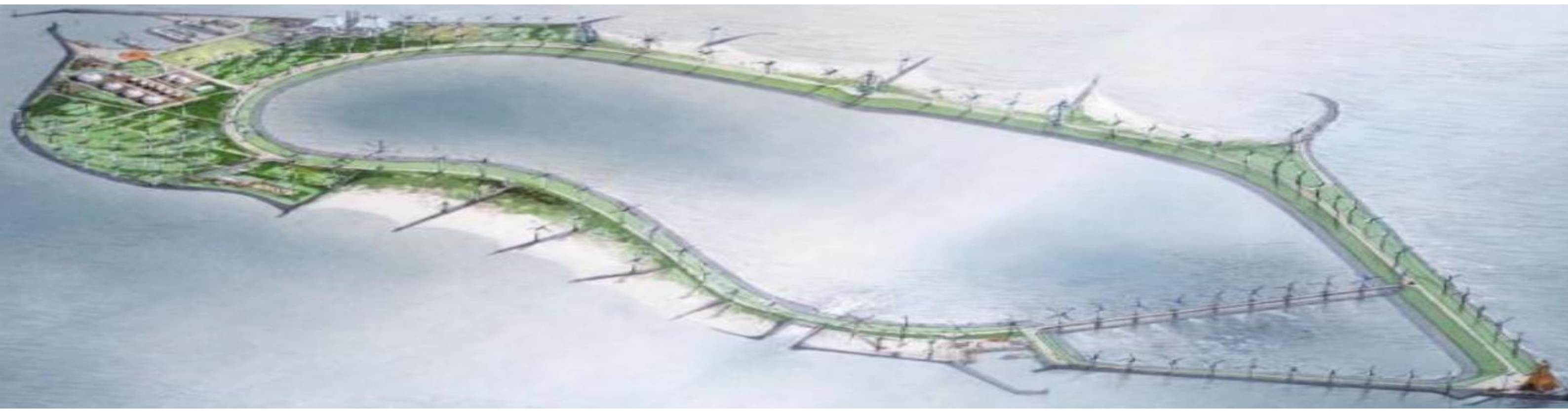


Figure 38 … Sketch of the Energy Island

Concept

Based largely on the principles and ideas of the original Plan Lievense, this alternative develops the idea of an island in the North Sea. The significant concept difference with the Plan Lievense is the creation of the "Valmeer" concept. This solution creates a lower reservoir and lets water from the surrounding water to flow in; a reversed PHS-system. The idea is combined with multiple other functions, among which an LNG terminal, agriculture, tourism, wind farms, water sports and housing. This is to increase its feasibility and justify the high investment costs.

More detailed

The goal of the island is to store energy at night so that the base load plants can operate at a higher efficiency and supply the peak-demand by day so that expensive peak-demand units are not required. With the increased penetration of wind power into the grid, the variable output can be balanced using this solution. The entire island stretches 6 x 10 km in size and a reservoir of 40 km^2 gives a capacity of 20 GWh. Using 16 turbines of 125 MW each, these turbines can produce 1500 MW of power for 12 hours. The water level in the reservoir varies from -40m to -32m NAP. The reservoir will be closed off from the water using surrounding slurry walls that reach the deep clay layer at 40 meters below sea level. Therefore, the island is placed on top of a large clay layer to prevent inflow of ground water. The entire area will in this way be closed off from any in- or outflow of water. The costs to create the island are calculated to be around €2.45 billion of which 1/3 account for the civil engineering works whereas 2/3 can be allocated to the pumps and other electro-technical work.

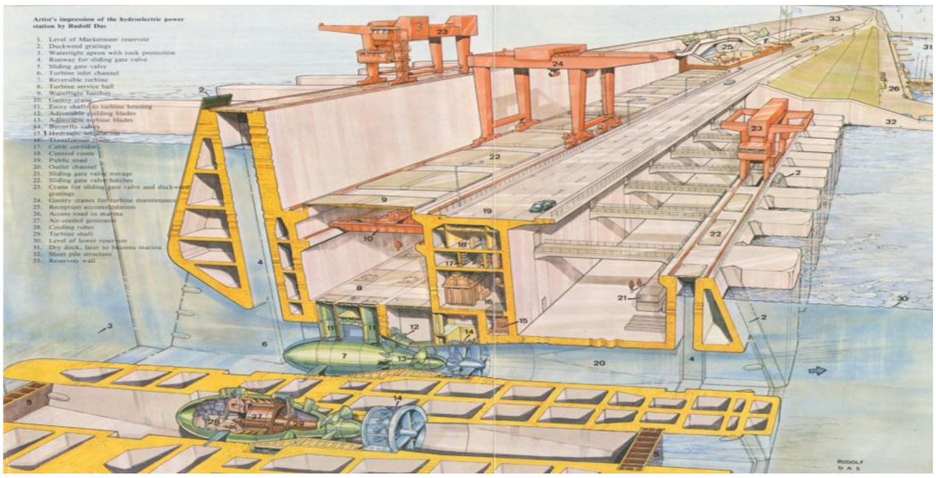


Figure 39 ... Detailed drawing of the turbine cross-section

The energy capacity of the system is derived in *Appendix G* to be

$$E_{cap} = \frac{1}{2}\rho g A(h_0^2 - h_1^2)$$

Here ρ is the density of water, g is the gravitational acceleration, A the surface area and h_o and h_1 the lowest and highest reservoir level, relative to the mean water level outside the reservoir. The flexibility of the formula is predominantly given by the surface area A as well as the chosen heights of h_o and h_1. The results of some experimenting are displayed in *Table 16* (*see Appendix C for the MAPLE models*).

Situation	Surface area reservoir (km^2)	h_o (m)	h_1 (m)	Energy capacity (GWh)
Small island	5	-20	-10	2.09
Medium island	15	-30	-20	10.46
Large island	30	-40	-30	48.83

Table 16 ... Calculations of the energy capacity

The surface area of the reservoir is a factor that can easily be increased upon available water space. This increase in the surface area will increase the costs, because a larger island will be required. The elevation differences play a significant role in the equation because of the disproportional increase. Therefore the preference is to create a high dam. However, this height is restricted by practical issues and cost considerations. Previous experiences with dredged islands prove that large islands up to 50 km^2 are possible. Although a vertical expansion is preferable theoretically, a horizontal expansion may be the preference practically. A balance between height, surface and costs will lead to the optimum design.

Evaluation of the alternative

The energy storing capacity of 20 GWh is very high for current purposes which make this plan sustainable for the future. The power generation capacity of 1500 MW is high enough to have a large input into the grid and supply an adequate portion of the peak-demand.

The construction of an island of 6 x 10 km is rather controversial. This controversy is increased with the large investments required to realize this option. A project of this scale touches lots of stakeholders, of which especially the environmental organizations will be strongly opposed. While the primary analysis shows possible cost-effectiveness, realizing this alternative will be unique in the world and is therefore considered a risky investment. For this reason, especially policy makers and organizations that don't profit directly from such a solution will be cautious to invest.

Looking at technical uncertainty, there is much unknown regarding the clay layer which is supposed to be uniformly present for at least ten meters. Analysis of the CPT data shows that throughout the entire area, there is a lot of variance in soil characteristics and material type.[95]

[95] DinoLoket, 2013

11.3.3 Alternative 1.3: The Slufter

Figure 40 … Location of the Slufter on the map (Google Maps, 2013)

Concept

This alternative explores the idea of using existing sites for the application of low-head PHS. At the Maasvlakte of the Port of Rotterdam, there is silt depot, called “De Slufter”, which is used for the storage of contaminated silt from the port area. This is quite a large depot and at first site this depot resembles the drawings of the Valmeer idea (*see Figure 41 left*). This has been the primary incentive to look further into this option.

Without much alteration, this depot can be transformed from a silt depot into an energy storage solution. With the addition of turbines, it can be used to generate and store power similar to the concepts in the alternatives Plan Lievense and Energy Island; by pumping and releasing into the surrounding North Sea.

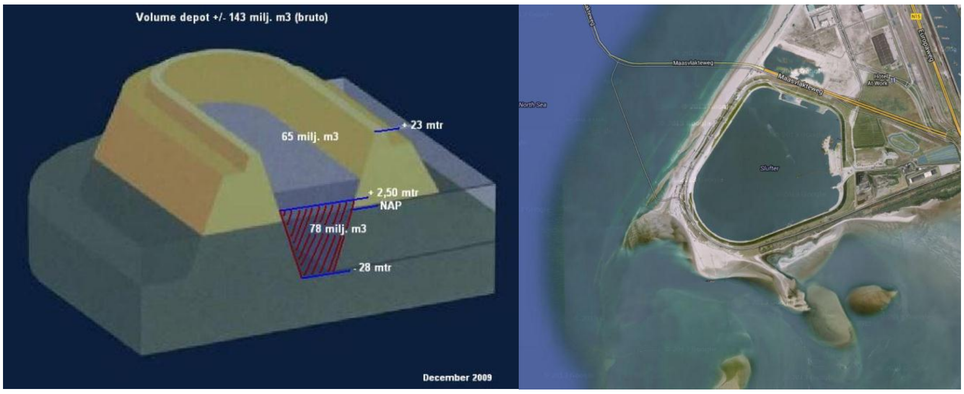


Figure 41 … (left) Sketch profile of the Slufter (DeSlufter.com, 2009) and (right) Aerial view of ‘De Slufter’ (Google Maps)

More detailed

De Slufter was constructed in 1987 in response to the large polluted soil that was being dumped into the North Sea. Sedimentation is a natural process in the slow-flowing waters of the Port of Rotterdam and constant dredging is needed to keep these areas accessible for large ships. In many cases this silt is polluted and contains contaminants that cannot be dumped directly into the sea. For this reason the depot was constructed southwest of the Maasvlakte. The company Boskalis Dolman is responsible for the operation and maintenance of the depot. Their contract has been extended till 2014. About 3 million m^3 of dredged sediment was brought to the depot a decade ago and this number is diminishing significantly.

The site is suitable as it is close to the industrious Port of Rotterdam and close to possible future offshore farms. This means the power storage will be close to power consumption and generation, a preferable position, which minimizes transmission losses. Plus, given the location, the required grid infrastructure is likely to be present, which saves investment for grid infrastructure.

The depot has a depth of -28m NAP and height of +23m NAP and can hold 143 million m^3 of silt, leading to an average surface area of 2.6 km^2. The Slufter can be used for energy storage in a variety of ways. One example, using the direct Valmeer concept, one can vary the depth between -28m and -18m NAP, which will give a total energy storage capacity of

$$E = \frac{1}{2}\rho g A(h_0^2 - h_1^2) = 5.4 * 10^{12}\, J \sim 1.5\, GWh$$

Applying 4 turbines of 125 MW each, gives a power generating capacity of 500 MW that will be able to produce for 3:30 hours. This number is barely enough to fulfill a peak demand shaving function. The major advantage of this alternative is that it utilizes already an existing construction that will create much more value/benefits when used for this function. Transforming the depot into a storage solution will not require much investment, making it economically more viable.

Aside from the silt storage functions of the Slufter, together with its surroundings, it can combine recreational functions. The present high wind speeds make it an ideal spot for windsurfing and other water sports.[96] There is a beach for recreational purposes and a small fishing association.[97] These functions can be maintained within the alternative. In fact, it should be sought to expand these functions to increase the feasibility and create more public acceptance. The geographical conditions are somewhat favorable. Since the inflow of water needs to be prevented, the reservoir needs to be closed for groundwater. Soil data suggests an impermeable layer starting from a depth of -45 m NAP.[98] However, this layer is a mixed layer, so detailed data is required to determine the characteristics of this layer.

Evaluation of the Slufter

Data about the Maasvlakte and its surroundings is abundant, which lowers the uncertainties. The depot needs to be improved for energy storage, which requires investment in turbines and optimizations to the depot. However, relative to the creation of an entirely new island, these investments will be very low.

The concern about this alternative is the uncertainty with the subsoil and the relatively small energy capacity, making it less fit for national storage. With the presence of the Maasvlakte 1 and 2, expansion to the northern and western side is restricted, but not on the eastern and southern side of the Slufter. Another major issue is the current function of this land, with the depot containing 78 million m^3 of contaminated silt (at a level of +2m NAP). Where is this large amount of silt going to be left and what about the annual deposits? For options that consider double functionality, the presence of the silt will largely decrease the depth and potential for storage. From a juridical, political and planning point of view, it should be examined what chances and consequences there are for this function change. Not much expectation into this can be given at the moment, increasing its uncertainty. Another possible point of criticism is the relative proximity of a large water elevation to the port and city of Rotterdam. The application of the Valmeer concept reduces much of the flooding concerns because in case of a breach, the flood wave will enter the reservoir and the reflecting wave will reach the shores. It is expected that this reflecting wave will largely be damped out, forming low risk for the shore.

[96] Surfed.nl, Slufter Surf Forecast, Surfed.nl, 2010
[97] SVV de Slufter, Strand vis vereniging, Svvdeslufter.nl, 2010
[98] DINOloket, Dinoloket.nl, 2013

11.4 Group 2: Underground Pumped Hydro Storage

11.4.1 Alternative 2.1: UPHS in existing cavities

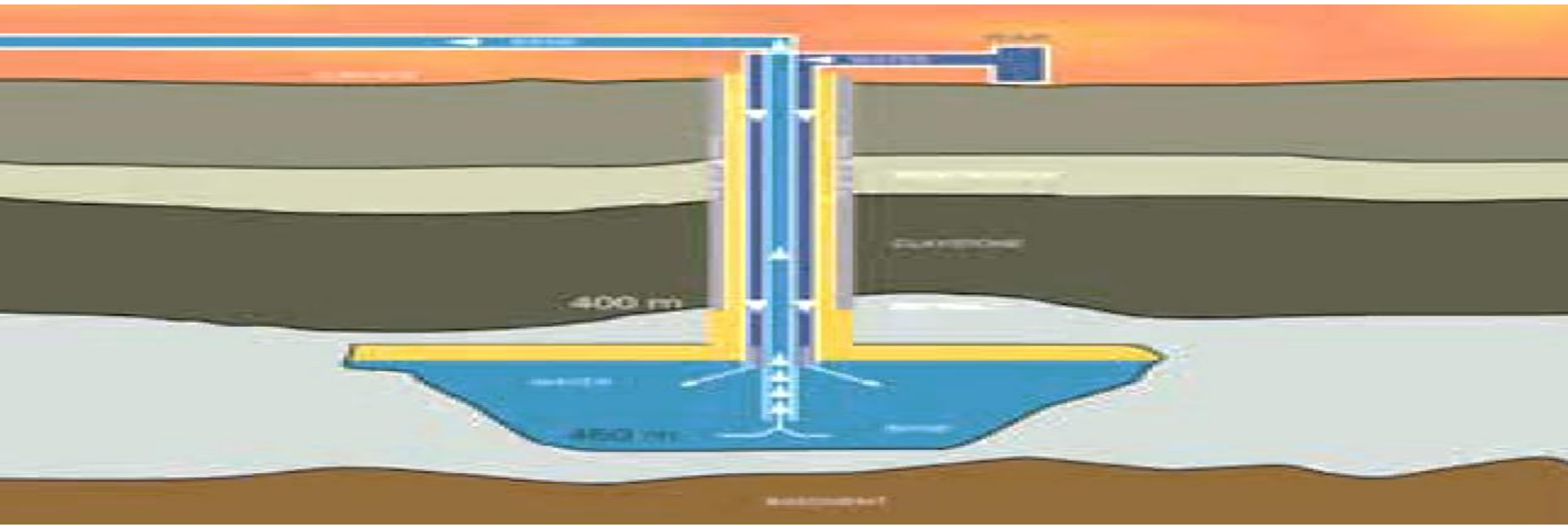


Figure 42 … Cross-section of a cavern with a possible system of energy storage (Grondboor en Hamer, Zoutspecial, 2010)

The concept

This alternative works by pumping water up and releasing it into the sub-surface reservoir when generating. The application of UPHS requires a subsurface reservoir. This can either be newly constructed or existing cavities can be modified for this application. The last option is considered for this alternative to save primary investment costs. A primary assessment of the geographic data displays two main areas where such large subsoil places are present:

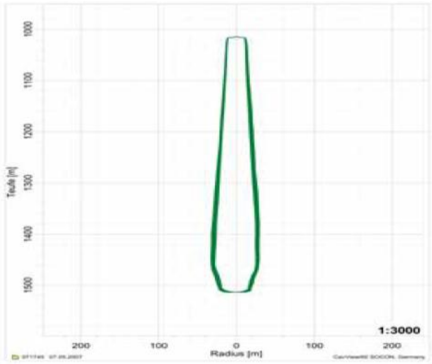
- Depleted salt caverns in the north-east of the Netherlands
- Old mine shafts in the province Limburg

Depleted salt caverns

The cavities surrounding the Dutch provinces Groningen and Drenthe are promising for this alternative. Large cavities were left after salt was extracted along the years. These cavities are surrounded by rock salt, which makes them highly impermeable and suitable for this purpose. This is why these cavities are also interesting for storing gas and oil.[99] The subsoil spaces stretch up to 1600 m deep which makes them ideal for large-scale storage (*see Figure 43*). Large modifications are required before these can be used as UPHS plants. The strength and stability of the hollow spaces must be ensured for this purpose. Areas are required to house the turbine and generator houses. Above the ground, there should be significant space in the surroundings to construct the upper reservoir.

For simplicity, the assumption is made that the level in the upper and lower reservoir remains steady. This is justifiable due to the large reservoir area and the large hydraulic head (in the order of 500 m – 1500m) relative to the variation caused by varying reservoir levels (in the order of +/- 30 meters). Quick calculations using the basic PHS formulas (*see §11.2.3*) show that a cavity as displayed left in Figure 43 can hold up to 12 GWh of energy, large enough for large-scale applications.

[99] Eneco Gasspeicher, Gasopslag in zoutcavernes, Eneco.nl, 2009



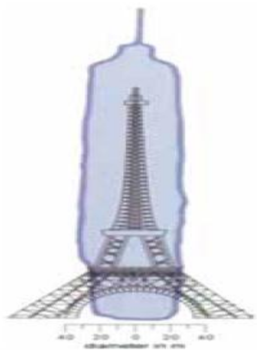


Figure 43 ... (left) Vertical cross section (sonar measurement) of a cavity near Winschoten, Groningen (right) cross section of another salt cavern compared to the size of the Eiffel Tower (300m) (Akzo Nobel Industrial Chemicals B.V., 2010)

Mineshafts in Limburg

Another possibility is to use mineshafts in Limburg for storage. These mineshafts provide access to large depths and large enough. Dutch mines can be split into state mines and private mines. Among these two, the state mines are significantly larger. Most of them are no longer used and their shafts are closed off, like the Hendriks State Mine.[100] The Hendriks State Mines consists of four shafts, three in Brunssum and a ventilation shaft in Nieuwenhagen. The fourth shaft is the largest, with a depth of 1058m and a diameter of 6.7m. These shafts were constructed some decades ago and it is expected that their condition are not up to the current standards.

For the construction of the reservoirs, Limburg is particularly interesting. In this province high elevations can be found; potential sites for the upper reservoir. The soil conditions are preferable for the creation of a lower reservoir underground; they consist of solid rock which will be hard to cut through, however will be beneficial for the stability.

Evaluation

It is very difficult to determine a qualified subsoil space for this application. The space should have no leaks and the inflow of groundwater into the system must be minimal. Relative to the mines, the impermeability of the salt caverns can be ensured to some degree. The second uncertainty is concerning the stability and strength of these cavities. Primarily not constructed for the use of storage, they cavities are old and have very different norms to oblige to. The stability and strength of the salt cavities with the extracted rock salt is very arbitrary. This leads to many uncertainties.

Apart from this, there are more general UPHS uncertainties regarding the control and management of the subsoil part of the structure. Fractures, seismic activity, leakages in- and out of the system and difficulty in constructing the subsurface spaces seems to be main points of opposition. The seismic activity of the Northern areas is worrying and could possibly lead to consequences such as damage or leakage.[101]

[100] Wikipedia, Schacht (mijnbouw), Wikipedia.nl, 2013
[101] NOS, Schade door bevingen Groningen, NOS.nl, 2013

11.4.2 Alternative 2.2: OPAC Limburg

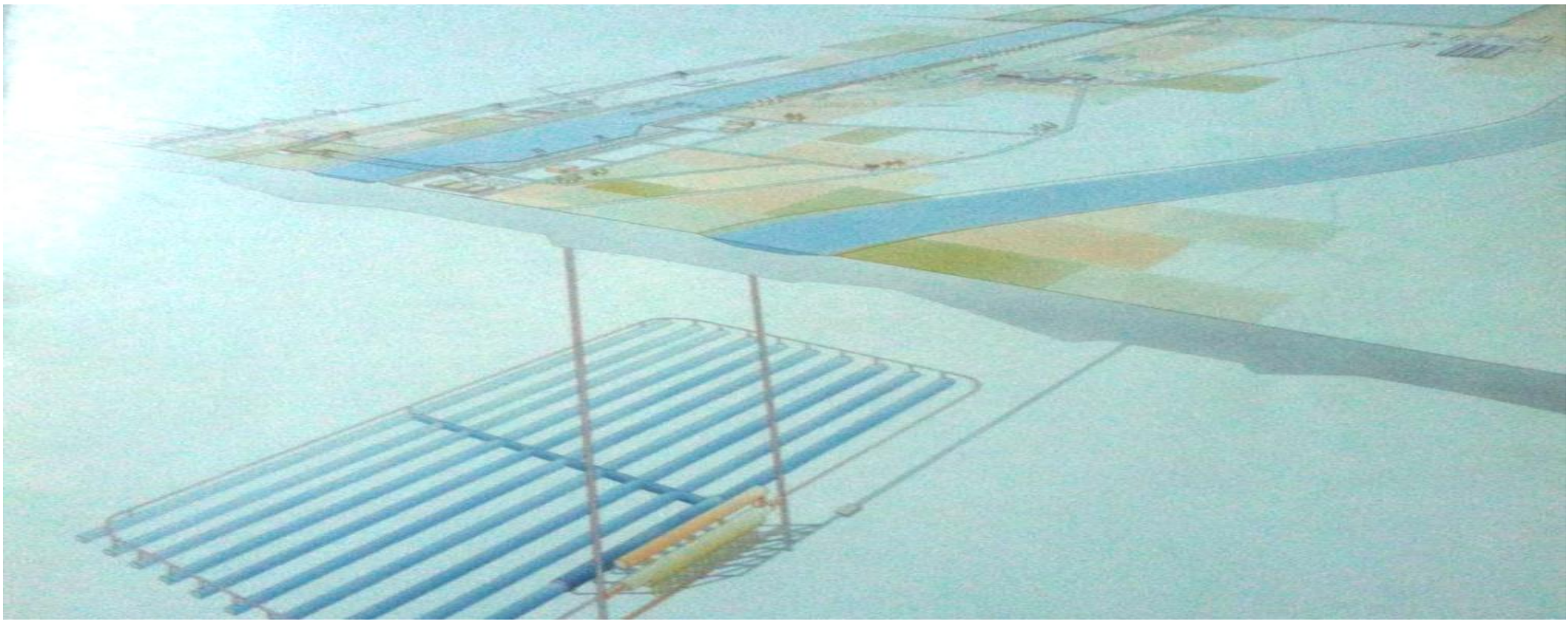


Figure 44 … Sketch of a UPHS plant (De OPAC Groep, OPAC in kort bestek, 1988)

Concept

This plan has been previously considered to create a UPHS plant in Limburg. In this alternative, a reservoir is created underground and above ground. At night, the storage is utilizing the unused cheap base load generated from these primary sources to pump the upper reservoir full and during the day, it is generating to balance the expensive peak load. This will make the storage profitable. In order to reach this goal, the design is based upon the daily load curve of 2000 (this plan dates back to 1988). Three alternatives have been considered, of which one has been picked and further optimized (*see Table 17*).

Storing capacity (GWh)	Generation capacity (MW)	Costs [Dutch guilders] (price in 1985)
5	400	fl. 1.4 billion
8	1400	fl. 2.5 billion
20	2000	fl. 4.3 billion

Table 17 … Alternative designs for the OPAC plant

More detailed

Whether a place is suitable for underground storage depends on geographic conditions. The following conditions are favorable for an underground reservoir:

- Low lateral variations in the soil along relatively large distances
- Low presence of karst topography, which is an indicator for the level of groundwater flow
- Determination of the thickness of layers, as uniformity is preferable
- Presence of an impermeable layer, otherwise additional modifications are needed
- Low presence of large geological cracks in the surrounding area
- Low seismic activity

Based upon these criteria, the province of Limburg has been found fit for the UPHS solution. The choice for Limburg is based on the large amounts of geographic data is available and the presence of a limestone layer. This limestone layer showed low groundwater flow and little fractures. The underground reservoir is placed near the small town Geulle, which is on the river Meuse (“Maas”) north of Maastricht. The location for the upper reservoir is just south of the underground reservoir, in between Geulle and

Maastricht. The total surface of the upper reservoir for 8 GWh is 0.5 km^2. To reduce visual hindrance, the reservoir is slightly buried, with the dikes raising 2 meter above ground level. To prevent leaking, membranes have to be used as soil enclosure. This location has been chosen with a large emphasis on future expansion of the system up to 40 GWh. The proximity of the business area is preferable due to the available grid connections.

The design seeks to use proven construction methods to lower the uncertainties; for the underground reservoir, either a tunnel boring machine (TBM) or “drill and blast”-method is considered, of which the first one is deemed preferable. All the drilled soil can be recycled in the construction of the upper reservoir or the greater construction industry. The total construction time will take 10 years and will costs approximately fl. 2.5 billion Dutch guilders, of which the underground works account for 80% of the total costs. With a design lifetime of 50 years, the plant is estimated to operate with an efficiency of 77%. The application of Francis-turbines should ensure this rate.

An important aspect of the design is the connection between the reservoirs. For this purpose, three shafts are needed, one for the water and two for ventilation. A risk analysis points out that the consequences of potential calamities at either the upper- or lower reservoir are manageable. The plan therefore recommends that the feasibility study has been sufficient and the UPHS plant can be constructed. With this, the ball is tossed to the political and market players.

Only the alternative with 8 GWh storage capacity and 1400 MW generation capacity has been optimized in terms of technical design. Of this alternative, the underground reservoir is placed 1400 meter below ground level. The fluctuating water volume is approximately 2.4 million m^3.

Evaluation

While the study takes away a lot of the uncertainties of the technical design in operational phase, not much is mentioned about the construction of the project. The technical uncertainties revolve mainly around the construction of the lower reservoir. The construction is conceptually clarified and much uncertainty remains on how to manage a TBM underground with the sharp corners of the design. No strength and stability calculation have been displayed in order to show that a 1400 m subsurface construction is feasible. Also not much is mentioned about the consequences in case of leakages and how they are to be controlled.

Since 80% of the costs are allocated to the construction of the lower reservoir, the constructional uncertainties lead to high financial risk. Generally speaking, the primary investments are relatively high and these uncertainties don’t provide a higher feasibility.

11.4.3 Alternative 2.3: Gravity power

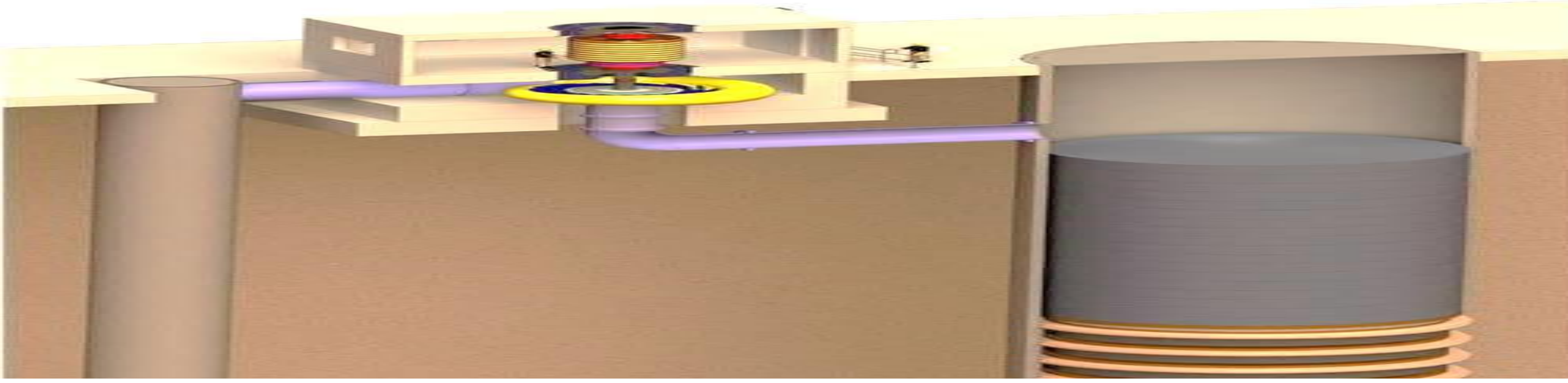


Figure 45 … Top scheme of gravity power (gravitypower.net, 2013)

Concept

The gravity power idea is an innovation from the similarly named Gravity Power.[102] The idea is to drill a hole into the soil, fill it with a liquid and put a large, heavy piston on top. Excess energy can be used to lift the heavy piston to a higher elevation inside the tube. When power is needed, the piston is simply dropped and the liquid will charge a turbine.

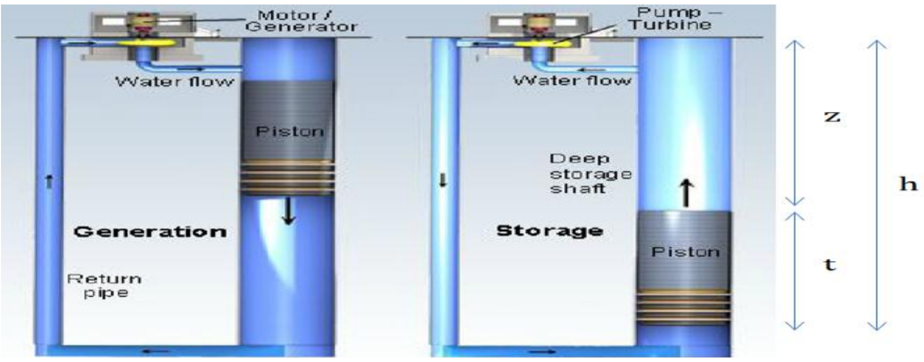


Figure 46 … Scheme of Gravity Power (gravitypower.net, 2013)

More detailed

The piston is used to generate pressure on the water body causing the turbine to flow. For this concept, the energy storage can be derived from the basic equations of potential energy (*see §11.2.3*)

$$E = \frac{1}{4}\pi d^2(\rho_{piston} - \rho_{water}) * g * t * z * \eta$$

- d = hole diameter
- ρ_{piston} and ρ_{water} are respectively densities of the piston and water
- t and z > the piston and water body thickness
- η = total efficiency

A model is created to play around with the parameters and their influence on the energy capacity *(see Appendix D*). Primary assumptions are made for the parameters and further optimized considering specially designed construction techniques. The results range from conservative estimations to “the best case situation” (*see Table 18*). The common diameter that can be found for the borehole is around 1-1.5 meter, while they range till 3m.[103] Considering new developments, holes with a diameter of 4m are

[102] Gravity Power, 2013
[103] Kulichikhin, N. I., and B. I. Vozdvizhenskii, “Razvedochnoe burenie”, Moscow, 1973

possible.[104] Radical ideas are to use a tunnel-boring machine (TBM) to drill a vertical hole in the soil that can range up to 6 m. The feasibility of this construction method is explained in general terms in the previous alternative.

Situation/ Variable	Diameter borehole (m)	Density piston (kg/m^3)	Thickness piston (m)	Total height (m)	Efficiency (-)	Energy capacity (GWh)
Primary	3	3200	100	500	0.7	0.0015
Optimized	4	3200	300	700	0.7	0.0045
Best Case	15	3200	1000	2000	0.7	0.75

Table 18 … Energy storage capacities under changing variables

The height leads to a quadratic increase in energy capacity, so the depth should preferably be as deep as possible, restricted by technical and economic factors. The Dutch soil characteristics are not very favorable for deep boreholes; deep layers from the Miocene (depth 100-600 m) and the Jura (depth 600-1500 m) are built up from clay, lose sand and peat.[105] Based on this data and the economic feasibility,[106] these aspects remain the strongest uncertainty in the technical design. The heavier the piston, the more energy can be generated. Looking at material densities and their prices per m^3, it seems feasible to apply heavy concrete (2700-3200 kg/m^3) with the combination of water (1000 kg/m^3). The piston needs to be flexible enough to move up and down, yet there should be no space between the piston and the wall; it is difficult to realize a situation where the water doesn't leak in between the piston and the wall. This is expected to be the main contributor to the losses (assuming a loss of 20%). Considering power losses of the turbine and generator (together 10%), the total efficiency is estimated to be 70%. Calculation based on favorable primary assumptions show a potential energy capacity of up to 0.75 GWh.

Mineshafts in Limburg

The fourth shaft of the Hendriks mine (*see §11.4.1)* can be used for gravity power. The main difference is that the shaft will thus be used for storage whereas UPHS used it as a connection between the upper and lower reservoir. With a depth of 1058m and a diameter of 6.7 meter, this mine could thus be able to storage an amount of up to 0.044 GWh with the use of a 500m thick piston.

Evaluation

The capacity shows a high sensitivity to the diameter and the height; small changes can lead to massive improvements. While the technique is promising, it may be better suited for regional or local balancing. The combination with the mineshafts is promising since the mine shafts are no longer used and the shape is suitable for this application. The condition of the mineshaft is however unknown, which is the largest uncertainty. Many uncertainties regarding risks, possible construction techniques and costs surround the technique. Overall, the technique is considered to highly experimental and not suitable for large-scale storage. This is empowered by the lack of practical proof (not even a pilot project) of the theoretical possibilities.

[104] FAO, Large diameter wells, FAO.org, 2010
[105] Geologie van Nederland, Dwarsdoorsneden, GeologievanNederland.nl, 2013
[106] J. Bourna, Stroom uit stoom door water van 4000 meter diepte op te pompen, Trouw, 2012

12. Selection

12.1 Multi Criteria Analysis

12.1.1 Introduction

A *Multi Criteria Analysis* (MCA) is used to define a value to the alternatives. An MCA is a method to attempt to evaluate the value of different alternatives in a rational and objective way. The objectives are organizing, increasing the transparency of decision making and supporting decision makers in their choice. The analysis is based upon different criteria, which are determined using the stakeholder's analysis and design criteria (*see §9.3*). A detailed explanation of the chosen criteria is given in *Appendix E.*

Because each criterion has varying importance, a *weight matrix* is performed to obtain the *weight factor*. For example; visual obstruction is important to people neighboring the solution. Depending on their potential influence on the entire project, one can judge whether this criteria is more important than others. Like this, each criterion is compared to the other, of which the results can be found *Appendix E.*

12.1.2 MCA results

The valuation for each alternative and criterion happens on a scale from 1-10; a high number indicating high performance. Even though an MCA seeks to create an objective decision tool, judgments in this stage are largely based on preliminary knowledge and estimations, which contain a large subjective character. Therefore, extensive sociologic analysis on the wishes and position of the stakeholders is recommended.

The results of the MCA are presented in *Figure 47.* The Storage Islands score generally higher than the UPHS options. The reference alternatives Group 0 serve their purpose as a reference as for some cases doing nothing actually is preferable option.

The values are especially sensitive to criteria with a high weight factor, namely *costs, reliability, economic benefits, risks and power performance*. Variations of 1 step wouldn't make or break any alternative, but larger variations can especially have strong influence on the alternatives for the mentioned criteria.

Alternative	***0.1 NO***	***0.2 EEM***	***0.3 PHS***	***1.1 LIEVE***	***1.2 EI***	***1.3 SLUF***	***2.1 UPHS***	***2.2 OPAC***	***2.3 GP***
MCA Value	***4.3***	***5.4***	***4.1***	***5.2***	***5.8***	***6.0***	***4.5***	***4.5***	***5.4***

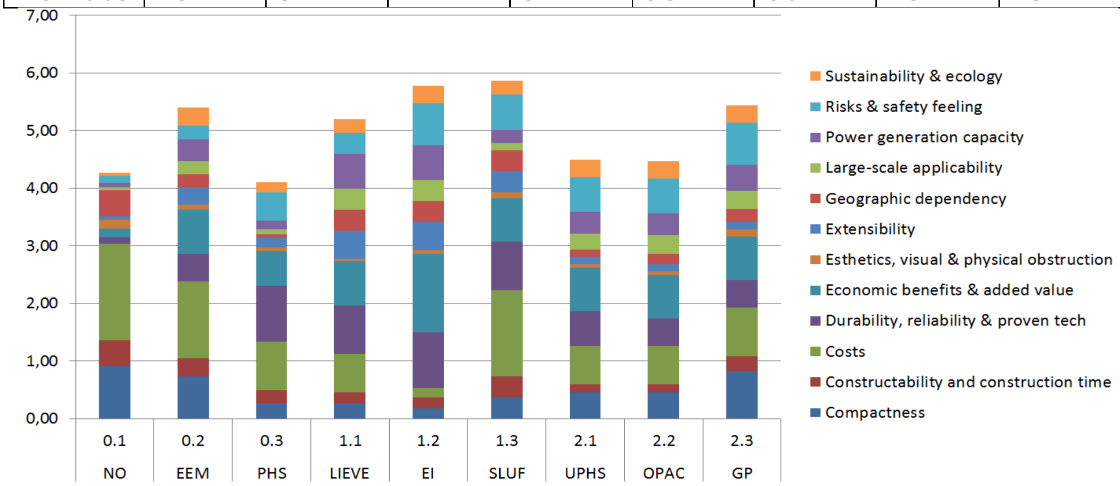


Figure 47 … MCA results for each alternative

12.2 Selection of alternative

The most promising alternatives are the Energy Island, the Slufter and Gravity Power using mineshafts. The Slufter scores the highest because it's an alternative that doesn't require a lot of investment or construction time and performs reasonable for other aspects. The Energy Island scores high due to the added value it creates in combination with the large capacity. The downsides are the high construction costs and time and difficult methods for building. Gravity Power also scores high because of the utilization of existing mines. This saves a lot of costs and construction time and gives the mines a new purpose. The value would drop a lot if the mines prove to be not suited for this function.

The selection is partly based upon the MCA. The values displayed a distinct preference for The Slufter, while its value is very close to the Energy Island and Gravity Power. Despite not a winner by much, the Slufter seems rather interesting. Compared to the Energy Island, it shines by its feasibility and low investment costs. Compared to Gravity Power, it is far more suitable for large-scale application and is based upon proved technologies with fewer uncertainties.

The selection has a minor subjective character as the MCA does not convince with a strong preference for one alternative. Out of the alternatives, Plan Lievense and the Energy Island are ideas that are investigated to some degree, whereas Gravity Power has been the topic of another recent graduate thesis.[107] In between all the options, the concept of low-head PHS is never investigated further using existing environments and a smaller scale that the Slufter offers. This could be promising as the evaluation of other Storage Islands proved to be negatively affected by the high investment costs.

The Slufter's relatively smaller scale (compared to the other Storage Islands) and existing suitable 'shape' is something that holds a lot of potential for this application and the MCA result confirms this. The uniqueness, innovation and ingeniosity of the Slufter combined with the practical possibility, its potential and economic feasibility and room for creativity is something that calls for a focus on this alternative. This alternative deserves therefore to be worked out in more detail.

[107] R. Imambaks, Gravity Power, 2013

Part C … Technical detailing Slufter

13. Introduction to Part C

In the previous part, an extensive study has been performed to the criteria that define the solution. The first step towards a solution was made by identifying the technologies that are used for the storage of energy. These have been tested according to the desired goal and design conditions which resulted in a preference for Pumped Hydropower Storage (PHS). Since traditional PHS is realized in elevated areas, the principle of PHS was transformed and made suitable for the low-lying Netherlands. This resulted in the qualitative design and consideration of several alternatives. These alternatives were tested with a multi criteria analysis that resulted in a preference for the Slufter, a slip depot in the Maasvlakte. This produced the highest value and confirmed the potential in which the high feasibility and low investment costs were decisive factors.

Now that the location and general concept of the solution is known, a deeper analysis can be performed that will be the foundation of the technical design of the Slufter. Is it really possible to realize such a solution at that location?

The following research questions form the base of the analysis performed at Part C:

a. What are the characteristics of the Slufter and its environment?
b. How should the design criteria be adjusted for the smaller scale of the Slufter?
c. How can the Slufter alternative be further optimized to enhance the benefits of the system?
d. What are the technical and constructional challenges in realizing the Slufter and which risks should be assessed?
e. What is the performance of the system when operational, how can it be integrated into the power grid and what are the yearly benefits from power trade and fuel savings?

At the end of this section the primary design of the Slufter should be clear and the main challenges should be addressed or discussed. The financial and functional benefits of the system should be quantified in order to make a comparison with the current way of demand side balancing.

14. The Slufter analysis

The following subjects are discussed in this chapter

14.1 Detailed system boundaries

The system boundaries are further specified for the solution and chosen in a way that the consequences of the construction to the surrounding areas can be overseen (*see Figure 48).* Rather than a national approach, the boundaries are specified down to the western port area of Rotterdam. A wider area has been selected as a boundary than the Slufter (found at the center of *Figure 48)*. This has two reasons:

- In *Part B*, the preliminary assessment showed that the storage capacity may be insufficient for national demand. Therefore, more surface area may be required for an expansion.
- Any action and changes in the shoreline in the area is not without consequences. Choosing the boundaries wider than the Slufter gives insight into these problems.

Figure 48 … System boundaries defined with the red box (Google Maps, 2013)

14.2 Environment around the Slufter

Located south of the Maasvlakte, the Slufter is surrounded by the North Sea in the south, west and east. With the construction of Maasvlakte 2 (which is due in 2014) a large part of the western border will be occupied by the port (*see Figure 49*). The Maasvlakte 2 is a large land creation project meant to increase the capacity of the Port of Rotterdam. On the Maasvlakte 2, there will be several container terminals as well as bulk good storage places for oil, gas and coal. This will be an area of high economic value.

Even though never meant to be a recreational beach, the Slufter Strand is a very popular beach on the western side. It offers both a clean beach and sea without facilities besides a parking place. It is particularly an interesting spot for wind- and kite surfers due to the high wind speeds.[108] Since the construction of the Maasvlakte 2, the beach is used for equipment storage and has not been accessible. When construction works finish, most of the southern part of the beach will be re-opened for public.[109]

Eastwards of the Slufter, there is the Oost-Voornse Meer. This lake is a buffer in between the port and Voorne and is a popular place for swimming and lake recreation with a lot of facilities. South-east of the Slufter at the shore of West-Voorne, there is Rockanje, one of the most popular and well developed recreational beaches in the area. It is part of the greater natural zone of West-Voorne and part of the Natura2000.[110] The nature in this area is improved as compensation for the construction of the Maasvlakte 2 (*see Figure 50 1st*). Any action in this area is therefore problematic.

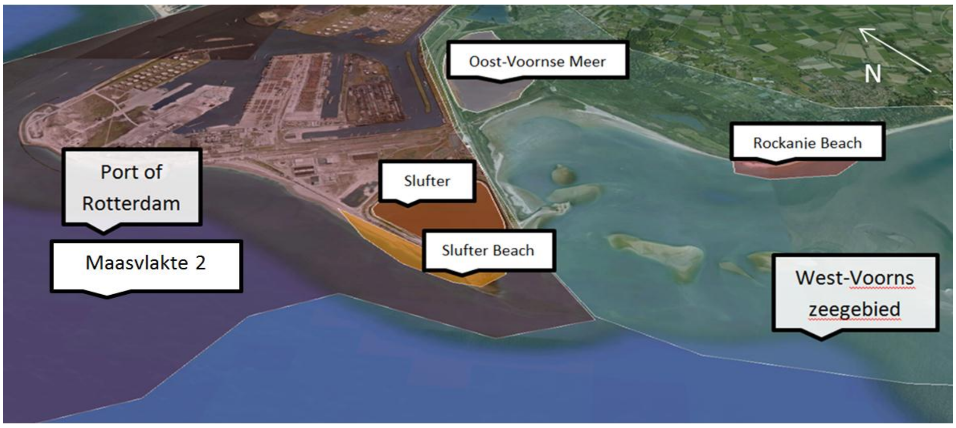


Figure 49 … Perspective overview of area with indicated areas (Google Maps, 2008)

The area indicated in red in *Figure 50 2nd* suffers from bad water quality and continuous natural nourishment from the sea. As the flow for water at the Dutch shore is mainly from south to north, the water flowing into this inlet loses speed and settles the sediment, more about this in the next paragraph. The area borders a Natura2000 area at the coast of West-Voorne. In this area, there are no villages or cities and the area is protected under the Natura 2000 guidelines *(see Figure 50 3rd).*

Figure 50 … (left) Natural area of West-Voorne and (right) zone 1 is nature with limited recreation, zone 2 with some recreation and zone 3 with high recreation (Gemeente Westvoorne, Bestemmingsplan Westvoorne Zeegebied, 2013), (3rd) Natura2000 area: Voornes Duin (Natura2000, 2013)

[108] Port of Rotterdam, Havenkrant, June 2009
[109] Maasvlakte 2, Slufterstrand dit jaar nog grotendeels open, Maasvlakte2.com, 2009
[110] Natura2000, 2013

14.3 Morphological analysis around the Slufter

In this section, the morphological situation around the Slufter is analyzed. There seems to have been a lot activities going on along the years that have influenced the morphology of this area. This is mainly the construction of the first Maasvlakte and the closing of the Haringvliet.

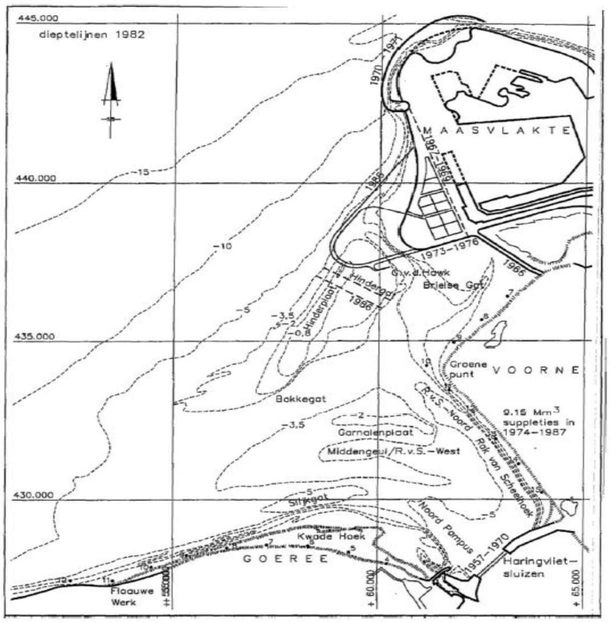


Figure 51 … Old overview of activities surrounding the Maasvlakte (Waalstra, 1977)

The closing off of the Haringvliet has led to a structural shoaling in the area enclosed by the Slufter and West-Voorne. The morphological effect of the construction of the Maasvlakte 2 will be very little on the entire Haringvliet inlet.[111,112]

On the short-term, no structural erosion is expected in the area between the Slufter and West-Voorne, instead it is expected that the area will be filled up more in the coming years.[113]

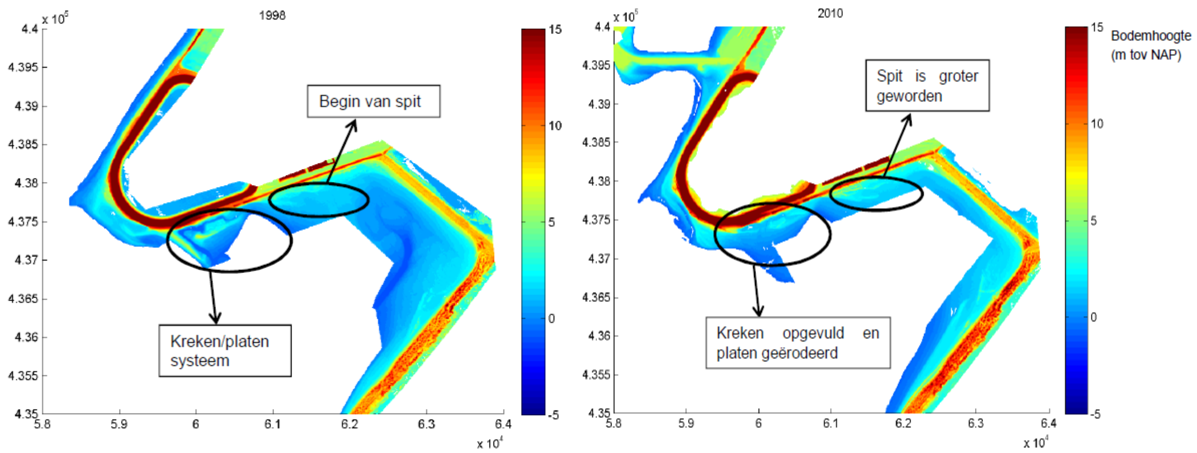


Figure 52 … Lidar bathymetrie 1998 and 2010 (Deltares, Ontwikkeling Kliferosie Slufterdam 2013)

[111] Roelvink, 1998
[112] Waalstra, 1997
[113] Deltares, Ontwikkeling Kliferosie Slufterdam, 2013

Important sediment movements are displayed in *Figure 53* and *Figure 54*. These images illustrate the results of modeling and confirm the primary hypothesis that the area in between the Slufter and West-Voorne is subject to sedimentation. The wave-dominated sediment transport occurring at the western border of the Slufter is no longer an issue because of the construction of Maasvlakte 2 which is now located there. Furthermore, the sedimentation taking place at the south border of the Slufter should be considered as an area that requires constant nourishing. The local sedimentation there will be unaffected by the construction of the Maasvlakte 2.

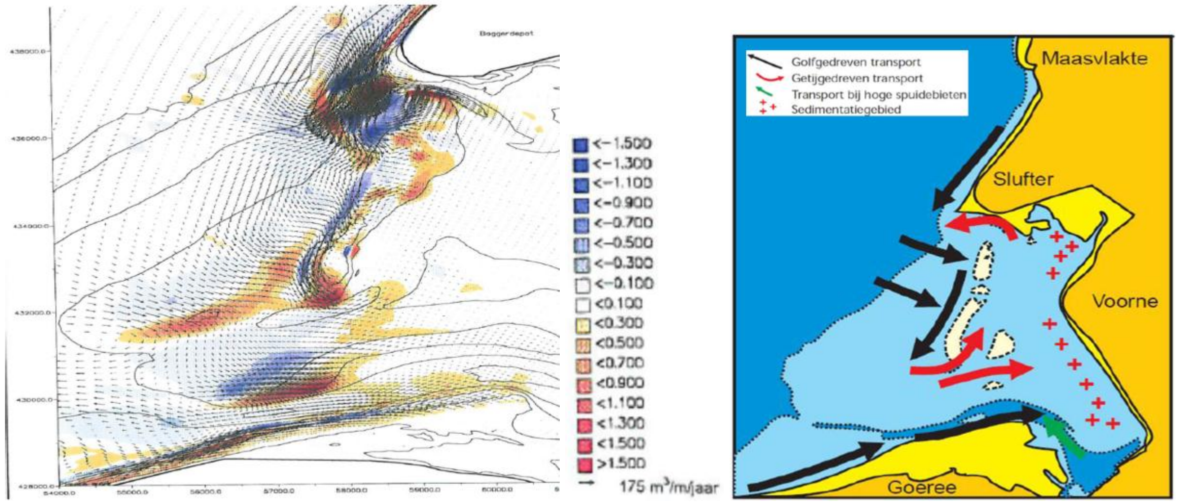


Figure 53 ... (left) Modeling the bathymetry changes in the area (Roelvink, 1998) and (right) Important physical processes in the area (golfgedreven = wave dominated, getijgedreven = tide dominated hoge spuidebieten = high purge values, sedimentatiegebied = sedimentation area) (Stam, 2002)

Figure 54 ... Accretion visible in the area east-ward of the Slufter

14.4 Detailed stakeholders analysis

The stakeholder's analysis created in *§9.3* is further detailed now that the location of the solution is further specified (*see Table 19 and Figure 55*).

Group	Stakeholder	Interest	Influence	Involvement
Government	European Union	Checking EU-targets for RES	Low	Low
	Dutch state	Meeting EU-targets, national prestige, providing national service and safety, increased benefits	Very high	Medium
	Province of Zuid-Holland	Regional prestige, providing regional services, having high economic, living and settlement climate for the province	High	High
	Municipality of Rotterdam	High safety citizens, life quality, land value, cheap power, no loss of land, increased risk, improved economy	High	Very high
	Stadsregio Rotterdam	Improved economic, living and settlement climate of the Rotterdam and surrounding	Low	Medium
	Adjacent municipalities of Westvoorne, Brielle, Westland, Maassluis	Improved economic, living and settlement climate of specific municipality	Medium	High
	Rijkswaterstaat (Min. of Infrastructure)	Increased maintenance	High	High
	Ministry of Finance	Budget maintenance, improved national economy	Medium	Medium
	Ministry of Defense	Safety of citizens, avoidance of terrorism	Low	Low
	Hoogheemraadschap van Delfland	High water quality, lowering risk for pollutions	Medium	High
Industry	Tennet (power transmission operator)	Improved power management	High	Very high
	Utility companies (e.g. Nuon, Essent, Eneco)	More efficient generation due to improve management, more RES possibilities	Very high	Very high
	Agriculture & Fishery	No loss/hindrance of land/ fishing area	Low	Low
	Boskalis Beheer Slufter (exploiter)	Economic interests	Medium	High
	Port of Rotterdam	High economy port area, port services and safety	Very high	Very high
	Companies operating at/with the port	High economic opportunities	Very low	Low
Commerce	Hospitality industry (hotels, catering and tourism sector	Business opportunities	Low	Low
Public	Regional citizens & power consumers	National prestige, cheaper power	Very low	Low
	Local citizens	High land value, improved economy	Medium	Very high
	Recreationists and tourists	Quantitatively and qualitatively improved situation for recreation	Low	Low
	Environmental organizations (mainly Greenpeace, Natuurbehoud, WNF, Stichting Noordzee, Natura2000, Zuid-Hollands Landschap	No loss of natural habitat, protection of environment	Medium	Very high
	ANWB (travelers association)	Tourism facilities maintained and expanded	Low	Medium
	Recreatieschap Voorne-Putten-Rozenburg	Preservation of ecology and landscape		
	Stichting Duinbehoud (dune protection)	Preservation of dune landscape	Low	High
Project related	Engineering, construction companies	Increasing in work leads to higher revenues	Medium	Very high
	Employers & workers	More jobs, good work conditions	Low	Very high

Table 19 … Detailed stakeholder analysis

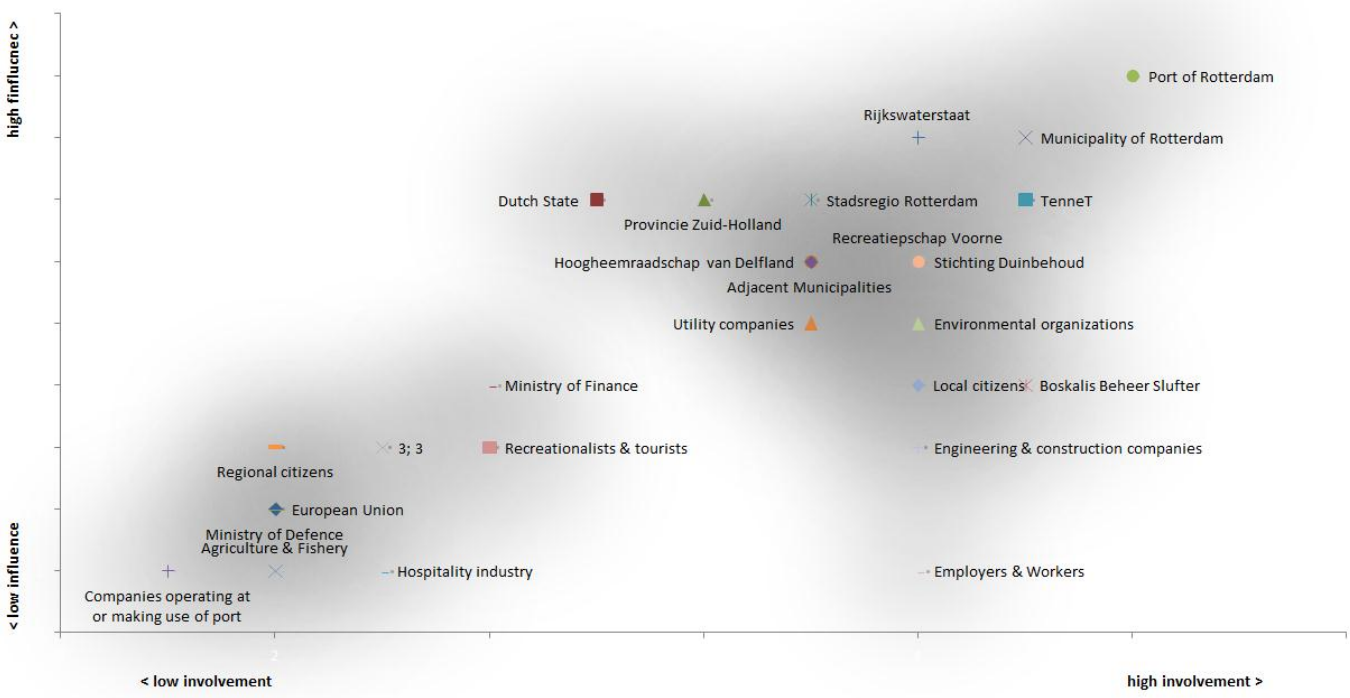


Figure 55 … Detailed stakeholder analysis

The analysis is different from the previous as it adds more location specific stakeholders, such as the Port of Rotterdam, the specification of the municipalities and all of the surrounding environmental organizations. The stakeholders which occupy the right upper black blur have a prominent role at some point in the project. When designing a solution, the wishes and demands of these parties should be taken in consideration. When designing, the solution should focus on the following points to not conflict with the interests of prominent stakeholders:

- No interference with the port activities, improve the reputation of the port and of Rotterdam
- Contribute to the improvement of the local and regional economy
- Keep the total costs relatively low
- Preserve the natural state of the area or create a landscape of similar natural value
- Improve the possibilities for RES
- Provide a situation in which the energy costs are possibly cheaper
- Preserve a high quality of the surrounding in terms of land value and life standards

Furthermore during the design process, the following point should be tried to implement or not be hindered in all phases along the lifetime of the solution

- Provide a contribution for reaching the RES-targets set by the EU
- Improve the prestige and image of the Netherlands
- Provide a contribution to the employment
- Preserve the dune landscape as well the recreational function of the Slufter beach
- Preserve the overall safety in the area, controlling possible safety risks
- Offer possibilities for local business and tourism development

14.5 Sustainable Rotterdam

14.5.1 Ambitions of Rotterdam

The development of Rotterdam centers around two main ambitions: economy and sustainability. The economic ambitions are largely shared with the ambitions of the Port of Rotterdam, the largest contributor to the regional economic productivity, see *next paragraph*.

The sustainability ambitions can be recognized in the creation of the Rotterdam Climate Initiative.[114] This program aims to reduce the CO_2-emissions of Rotterdam with 50% by 2025. This is achieved by a variety of the program and projects. These projects and programs prove that the city is taking genuine steps to reach these ambitions.

It is therefore safe to say that the general idea of the Slufter is in line with the ambitions of Rotterdam.

14.5.2 Ambitions Port of Rotterdam

The Port of Rotterdam largely shares the ambitions of Rotterdam. The future plans show that the main concerns are economy and sustainability. The economic concerns focus on the shift of the global economy towards other centers in the world, predominantly caused by the growth of developing nations. Improved port efficiency and developing the port as a hub for innovation and bio based economy are the main actions to improve economic conditions. This can be achieved by the collection of CO_2 and the investment in hydrogen fuel cell plants.

Within the economic ambitions is the ambition to be the leading port in Europe regarding energy; the Energy Port. This is accompanied by the desire to become the hub for natural gas aside from oil and coal. The other desires focus on developing technologies, such as utilizing coal plants for the capture and storage of carbon and thus becoming the CO_2-hub. Improved investment in wind power and biomass will ensure power generation from renewables, as efficiency is increased further.[115]

The economic ambitions are in line with the sustainability ambitions. More efficiency will lead to less power consumption and creating possibilities for hydrogen fuel will decrease emissions. The Port of Rotterdam wants to be the most sustainable port in the world by 2030.

With these ambitions comes the goal of the Port of Rotterdam to become the international leader in innovation and development regarding ports. This will ensure the flexibility and sustainability of the port and is in line with the Dutch ambition of being an economy based upon knowledge.[116]

It is therefore safe to say that the general idea of the Slufter is in line with the ambitions of the Port of Rotterdam. Especially the creation of the energy-hub and the sustainability wishes of the port are directly contributed by the realization of the conceptual idea that is energy storage. The proximity of the port to the storage location is beneficial for the industry located at the port area.

[114] Rotterdam Climate Initiative, Wat doen we al, ClimateIniative.net, 2012
[115] Port of Rotterdam, Rotterdam Energy Port, PortofRotterdam.com, 2012
[116] Port of Rotterdam, Havenvisie 2030, 2011

14.6 Specifications of the Slufter

14.6.1 Technical specifications

The Slufter is a depot that is surrounded by dams that physically separate the stored silt from the environment. The average surface area enclosed by the dams is 2.62 km^2. The perimeter that encloses the depot is 5.5 km long. The surrounding dams are 51 meters high; the crest at +23m NAP and toe at -28m NAP (*see Figure 56*).[117]

Figure 56 … (left) Schematization of the profile of the Slufter (www.slufter.com, 2009) and (right) Cross-section location (Google Maps, 2013)

The dams have an inner slope of 1:3, which means that the inside width of the dams is 150 meter at the bottom. Assuming a uniform dam width, the surface area at the bottom of the depot is 2.31 km^2, while the upper surface area is 2.93 km^2. This makes the average surface area 2.62 km^2.

The outer slopes of the dams changes per section. The south-western section has a slope of 1:5, making the width on the outer edge 250 m, while the south-eastern section has a slope of 1:4 to 1:5, with a width varying from 200-250 m.

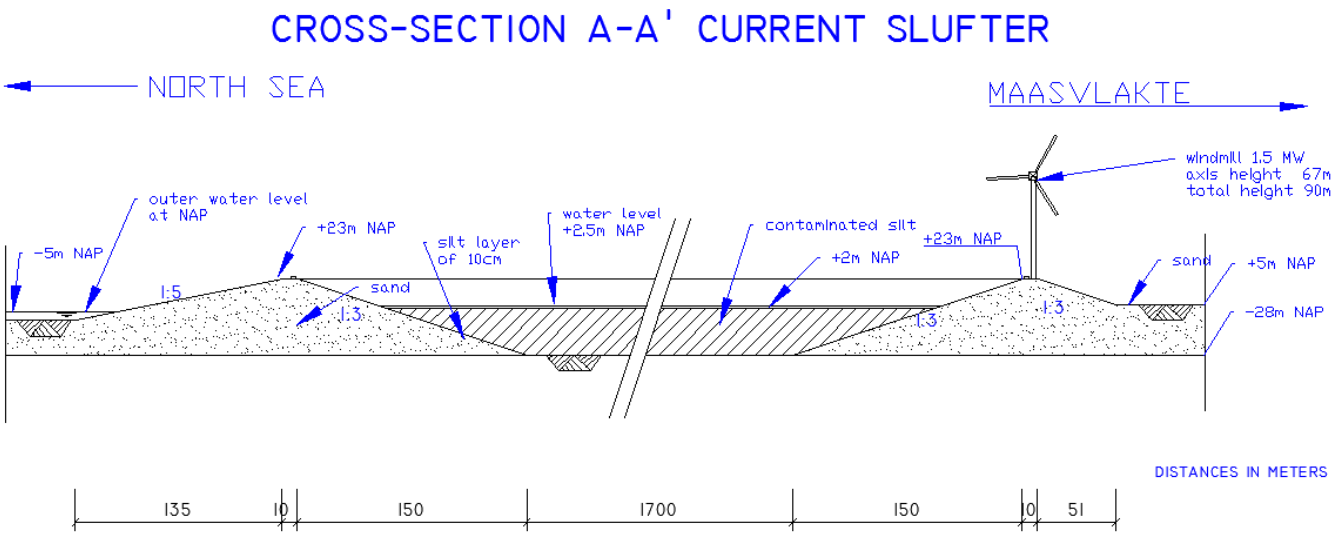


Figure 57 … Cross-section A-A' of current Slufter

[117] While there are small deviations in the height as well as in the depth throughout the area, the maximum deviations are about 1 meter and therefore it is safe to assume a uniform height and depth.

The cross-section of the Slufter in its current state is visible in *Figure 57*. The cross-section was taken halfway along the long edge of the Slufter (*see Figure 56).*

The dams are entirely built up from sand, which is abundant in the area. To prevent the possibility of contamination, the inside of the depot has been covered with a layer silt of 10 cm with a density of 11 kg/m^3 and very low permeability. No other measures have been taken to prevent leakage of contaminations. As it seems highly unlikely that this is sufficient, it can be assumed that there is some flow of contaminated water out of the depot. Even though it is not known what the degree of leakage is, it has not lead to any major environmental pollution problem since its construction in the 1980s.

14.6.2 Silt storage specifications

A full general analysis is performed providing a thorough background into the case of contaminated silt, the yearly input, possible locations and recycling possibilities. This analysis is presented in *Appendix Y*.

The Slufter is currently full for 50% of its capacity; this translates to 78 million m^3 of contaminated silt. This is predominantly silt of class 3 but also contains class 4 contaminations (*see Appendix Y as to what these classes mean*). This silt has very low permeability as it is used to make the bottom of the Slufter water-sealing by application of a 10-cm thick layer.[118]

The Slufter contains silt collected from the port area which is the result of the flow from the Rhine (*Rijn)* and Meuse *(Maas)* rivers. This is predominantly silt of Class 3, meaning that the silt requires processing before it can be released into the environment. As previously mentioned, the inflow of contaminated silt has decreased a lot and the yearly input of silt into the Slufter is now about 0.6 million m^3 silt *(for yearly input trends, see 14.7)*.

While originally designed for class 3 material, the acceptance of class 4 material to the Slufter has been commissioned on 11 September 1996. The motive for this change of function is the construction of the Maasvlakte 2. Another depot at the Maasvlakte area designed for class 4 contaminated materials, the Papegaaienbek, needed to be cleared for this. All of the silt stored inside the Papegaaienbek has then been moved to the Slufter and dumped inside by opening the top of the class 3 layer, placing the class 4 material and reclosing the top with class 3 material (*see Figure 58*). The Papegaaienbek has been constructed in 1986, close to the Slufter, and its main function was depositing heavy contamination in the lower river areas.[119] The capacity of this depot was 1.2 million m^3 and the depot was full when it was decided that the silt was going to be placed in the Slufter.[120]

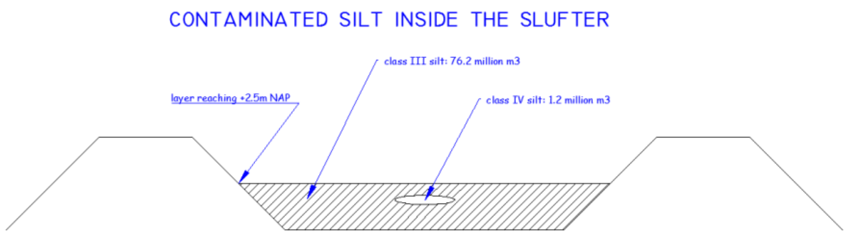


Figure 58 … Contaminated silt inside the Slufter (not on scale)

[118] Rijkswaterstaat, Herziening acceptatiecriteria en het scheiden van zand in het depot de Slufter, Milileu-effectrapport, 1998
[119] Commissie voor de haven, Slufter/Herziening acceptatiecriteria, BDS.Rotterdam.nl, 1996
[120] Mosmans, Normering slibdepots zijn zelf 'bagger'?, Mosmans.com, 2000

14.6.3 Slufter subsoil

The layers under the Slufter are mixes of mainly sand with silt. At 45 meters depth the formation of Pieze-Waalre starts; a formation that contains a lot of clay layers (*indicated in orange, see Figure 59 first*).

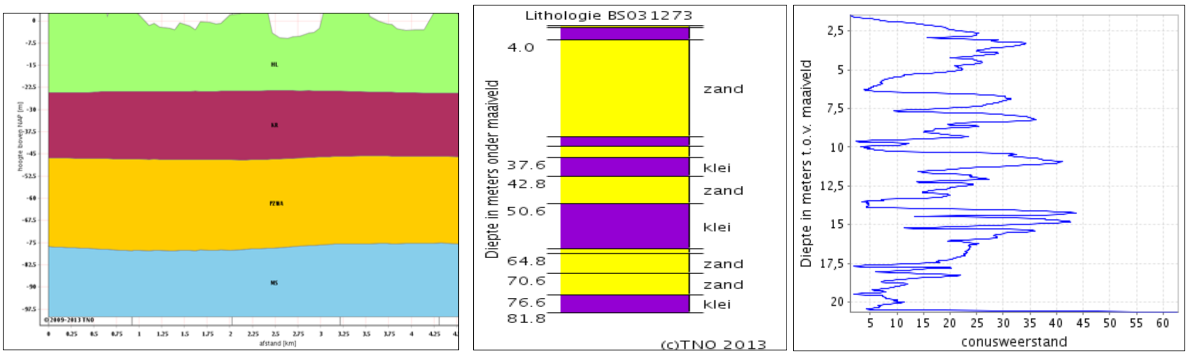


Figure 59 … (first) Overview of formations underneath Slufter and (second) Within the formation there's a lot of variation with detailed results at random point 100 meters south of Slufter and (third) random CPT taken inside Slufter (TNO, 2013)

Due to the construction of the Maasvlakte and Maasvlakte 2, a lot of soil data is available in the area. However, since not required for the Maasvlakte, these data do not cover the deep soil, particularly sub-30 meters, which is interesting for locating a water-enclosing layer. A few subsoil tests can be found right next to the Slufter that indicate a very mixed layer of sand and clay, confirming the nature of the Pieze-Waalre formation (*see Figure 59 second*). The sand has varying characteristics but displays an average density of 16 kN/m^3 (*see Figure 59 third*).

The data indicates the presence of a clay layer of 5 meters thickness at 37 meters depth and an even ticker layer of 15 meter starting at 50 meters depth. The first thick clay layer could be sufficient to function as a water-sealing layer, however its presence throughout the surface area of the Slufter is not guaranteed. As for the 15-meter one, even if not the same thickness everywhere, this layer has a higher likelihood to function as water-sealing.

14.7 The future of the Slufter

The water quality in the flow areas of the Rhine and Meuse rivers is strongly improved in recent years.[121] This is leading to less flow of contaminated water and soil into the Rotterdam port area and with less contaminated water flowing into the system, less contaminated soil is arriving each year to the Slufter. This decrease has been rather linear since 1988. Following this trend, the silt input will stop around the year 2014 (*see Figure 60*), the same year on which the current contract of operation and maintenance with Boskalis Dolman ends.[122, 123]

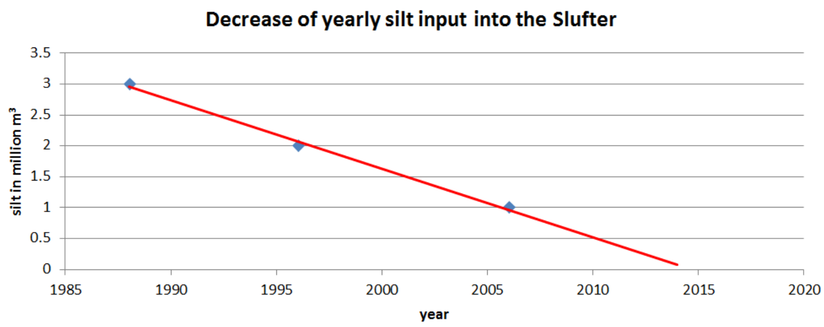


Figure 60 … Decrease in the yearly silt input into the Slufter with a linear interpolation in red (Bijeenkomsten uit het verleden, Baggernet.info, 2006)

The Port of Rotterdam is therefore looking for other possible functions for the Slufter. Among their considered options, an energy storage solution is also mentioned.[124] This coincidence of the ambitions of the Port of Rotterdam and the analysis done in this report is rather promising, confirming that the thought process is in line with the ambitions of the Port of Rotterdam. As a stakeholder with large influence and large involvement to the project, this contributes to the feasibility (*see §14.4 for the full stakeholder's analysis*).

Among the other considered options, there is the generation of power with other methods, such as biomass from algae, osmosis plants, wind and solar power. Wind and solar power can be combined with an energy storage solution. Considerations like osmosis plants and biomass from algae are highly experimental. Besides power generation, the area could be used for nature, e.g. bird nesting areas.

Another point in favor of a function change is the relative low ground prices that the municipality gets for the Slufter, which has been troubling the municipality. Being a depot full of open, contaminated silt, it isn't the most attractive of places to be.[125]

A quick evaluation of the future alternatives shows a lot of promise for the energy storage solution presented. Many of the future ideas for the area can be combined although they require more analysis to be deemed feasible.

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[121] G Zwolsman, Waterkwaliteit van de Rijn en de Maas bij (extreem) lage afvoeren, 2005
[122] Port of Rotterdam, Baggeren als economische motor voor de Rotterdamse Haven, Bijeenkomst uit het verleden, 2006
[123] De Slufter homepage, 2013
[124] Port of Rotterdam, Havenvisie 2030, 2011
[125] Rechtbank Rotterdam, Zaaknummer: C-10-398044 - HA ZA 12-255, Rechtspraak.nl, 2013

14.8 Windpark Slufter

On top of the dam surrounding the Slufter reservoir, 17 windmills of Siemens with 1.5 MW are operated by Eneco and Nuon (*see Figure 61*). The windmills have an axis and total height of 67 m and 90 m above ground level. With a capacity of 25.5 MW, the yearly production is 91.500 MWh, which provides 26.250 households of their power demand. The farm capacity factor is 0.41, significantly higher than the average of 0.3 *(see §5.4 for wind power fundamentals and capacity factors)*.[126] The local wind speeds are relatively high at 9.2 m/s (33 km/h) and have a dominant wind direction of WSW (*see Appendix B for the analysis of normative wind direction in the area*).[127] Due to the high wind speeds, the park is one of the most profitable ones in the Netherlands.[128] Therefore Eneco and Nuon are investigating the possibility of placing high capacity turbines of up to 8 MW.[129] Placing windmills on top of a dam which contains contaminated silt is rather controversial because of the increased risk for failure of the dam due to failure of the windmill. Nonetheless, the Port of Rotterdam and Rijkswaterstaat allowed the realization, meaning that they consider the risks manageable and highly value the contribution to their image.

*Figure 61 … (left) Overview of the Windpark Slufter (right) A wind turbine assembling at Windpark Slufter (**Eneco, 2006**)*

14.9 Potential for regional balancing

14.9.1 Scale reduction

Since the surface area of the Slufter is relatively small, the energy capacity that can be stored may be insufficient to supply the national demand. Therefore, a regional solution such as the province of Zuid-Holland could be a more suitable. Should the Slufter perform higher than expected, the coastal provinces Zeeland and Noord-Holland can be incorporated. These provinces are obvious choices, as the growth of wind power will mainly come from offshore wind power (*see §5.2 for more about future wind power plans)*. Another option is the close proximity of Noord-Brabant. Depending on the performance of the created solution, these areas can be regarded for fulfilling the role of regional balancing. Despite being significantly smaller, the benefits of a large-scale are still maintained (*see §9.6 for the benefits of a large-scale solution*).

With a smaller scale alternative, the likelihood of realization is higher, even though it is a unique idea and despite there being no working examples around the world. The goal is to provide a system that is can provide a peak-balancing and the wind power balancing for the province of Zuid-Holland and perhaps more provinces. To determine the regional demand and output, educated assumptions are made in the following paragraphs. Where the required data is missing, the national trends are used as a guideline.

[126] Siemens, Ons duurzaamheids portfolio, Siemens.nl, 2010
[127] KNMI, 2013
[128] EcoEdges, Een windmolenpark dicht bij huis; hoe werkt het?, EcoEdges.com, 2013
[129] Dichtbij, Kijkje in de windmolen op De Slufter, Dichtbij.nl, 2013

14.9.2 Regional peak-shaving function

The regional demand for power in Zuid-Holland is significantly higher than the national average per province. Since no clear numbers about the power consumption per province can be found, the power demand of the province has to be estimated using reference data; the population and the GNP. The relation between power demand and GNP is not so obvious, but actually forms an accurate indication of power demand.[130]

Being a part of the Randstad area, Zuid-Holland has a high population density. The population is 3.5 million, 22% of the national population. The province is characterized as the heart of the national economy and industry, with a lot of large cities and the Port of Rotterdam, one of the largest ports in the world. Due to this, a disproportional high number of 22% of the GNP is accountable to this province.[131]

To obtain the regional demand and required capacity, the national values are multiplied with the share which is determined using the population and GNP (*for national values, see §9.5*). Due to the lack of data and the estimation using references, the obtained value is multiplied with an uncertainty factor of 1.1, allowing for this approximation to have an accuracy of 10%. For the case of Zuid-Holland, the required power output becomes 305 MW and the power storage capacity 0.69 GWh. The same is applied for the bordering provinces of Zeeland, Noord-Holland and Noord-Brabant (*see Figure 62*). Note that the primary objective is to facilitate Zuid-Holland and this is the main design criteria.

Figure 62 … The share of population, GNP and the required power output and capacity for the coastal provinces around the Slufter (CBS, 2013 & Wiki-foundation, 2012)

[130] Cifter A. & Ozun A., Multi-scale causality between energy consumption and GNP, 2007
[131] Rijksoverheid, Nationaal Strategisch Rapport 2012, 2012

14.9.3 Regional wind balancing function

The calculation of the required regional wind balancing function is done in the same way using the national values (*see §9.4 for national values*). The base of the calculation is the installed wind capacity per province. These values are than scaled using the national values.

The current distribution of wind capacity is known, as is the distribution in 2020.[132] First, the current share per province is calculated, then the share in 2020. The trend that is seen from 2013 to 2020 is continued for the province until 2050. This estimation is multiplied by a factor of 1.2, which means the accuracy of the calculation is within 20%. This is a rather devious method of calculation, but since there aren't future ambitions per province after 2020, this is deemed to give reasonable estimates for the required wind balancing capacity per province.

An example calculation is performed for Zuid-Holland, after which the other provinces are calculated analogously. Zuid-Holland has an installed capacity of 260 MW, 10% of the national capacity. The province wishes to increase their capacity to 720 MW by 2020. [133] The ambitions for 2030 and 2050 are a continuation of this trend. These ambitions will be realized by 300 MW in the port area, 200-300 MW in the Randzone Goeree-Overflakkee and another 200-300 MW elsewhere.

The scenarios are calculated using the national trends while taking into account that the share of the coastal provinces will grow disproportionally high because of the investments in offshore wind farming *(see §5.2 for these developments*). This growth will be in the order of 10% until 2030.[134]

The required energy storage is calculated and displayed in *Table 20.*

Area	Year	Installed wind power (MW)	Required storage estimation (GWh)
Zuid-Holland	2013	260	0,62
	2020	720	1,73
	2030	1770	4,25
	2050	3541	8,60
Zeeland	2013	205	0,49
	2020	500	1,20
	2030	1230	2,95
	2050	2460	5,97
Noord-Holland	2013	430	1,03
	2020	1030	2,47
	2030	2500	6,00
	2050	5000	12,14
Noord-Brabant	2013	82	0,20
	2020	420	1,01
	2030	800	1,92
	2050	1600	3,88

Table 20 … Required storage capacity for wind balancing for different scenarios

[132] Agentschap, Windenergie beleid per provincie, Agentschap.nl, 2013
[133] Agentschap, Windenergie beleid per provincie, Agentschap.nl, 2013
[134] ATO, Offshore windenergie in Nederland, 2010

15. The Slufter alternatives

The following subjects are discussed in this chapter:

15.1 Introduction to Slufter alternatives

In the previous chapter, the Slufter and its environment are further analyzed so that the alternative can be further optimized. These optimizations are done to improve the performance of the Slufter in terms of functionality, integration in the area, management of contaminated silt and additional value. Which optimization is worth investing in? This is researched in this section with the use of defined alternatives, which are a combination of several optimizations.

The improvement ideas are only limited by creativity; using calculations where needed, the potential of the ideas is quickly discovered and more detailed if promising. The full report of ideas and considerations can be found in *Appendix H*. An overview of the considerations and their result is presented in *Table 21*.

The evaluation shows distinct preference for certain ideas. It is important to realize that not every idea can be combined with another. Therefore, apart from the base option of simply placing turbines, four different alternatives are proposed as combinations of ideas to maximize the positive effects. To make a somewhat equal comparison between alternatives, the output rate is chosen as measure of performance.

#	Consideration/ideas	Result
1	Increasing height of the surrounding dams	There is balance between the costs of the heightening and the extra power gained. This analysis shows that the height of the dams could be improved up to +40m NAP
2	Increasing the depth inside the Slufter	Analyzing the subsoil and the danger for bursting shows that the depth could be further increased from -28m to -31.5m NAP, an increase of 3.5 meter
3	Splitting the reservoir in two sections	- Because higher elevations are possible, this leads to a quadratic growth in power generation. Even though the reservoir will be split in half, the loss of energy storing capacity is outweighed by the disproportional growth in power output - The upper reservoir should be placed towards the south to minimize risk - There are no capacity benefits in creating unequal sizes due to the linked reservoirs
4	New reservoir	The analysis presents a possibility for doubling the size at the east-side of the Slufter
5	Choosing the right slice of fluctuating water	This is a balance between energy storage capacity and guaranteed power generation capacity, depending on the dimensions of reservoir and height of dams
6	Wind setup in the reservoir	The fetch length is relatively small that when considering the longest span of the reservoir, the total setup because of (extreme) winds is only 2.5 cm; insignificant
7	Solving the double functionality of energy and silt storage	- If the dam is split in two, the silt can be placed in the upper reservoir - The silt has low permeability which means it could be utilized for the dam core - The silt can be used for the water-enclosing slurry walls (reduction of 0,5 million m^3) - Transferring the silt and full recycling are very difficult due to the large amounts - The silt is aligned the sides at a 1:10 slope, opening depth for power generation

Table 21 ... Considerations for optimization and their results

15.2 Alternative 1A: Current

Figure 63 ... Aerial view of the Slufter (Portofrotterdam.com, 2013)

Concept and contaminated silt management

The idea is that the Slufter will operate as the upper reservoir and the surrounding waters as the lower reservoir. To store the energy, the water will be pumped from outside to fill the reservoir and released back into the sea in order to generate energy (*see Figure 64*). The only physical change is the placement of reversible turbines. Basically the contaminated silt can remain as it is. The silt management is more extensively discussed in the next alternative and is the same as for this one. To limit seepage through the dam, one can use a variety of ways of which the slurry wall is chosen in the initial design,

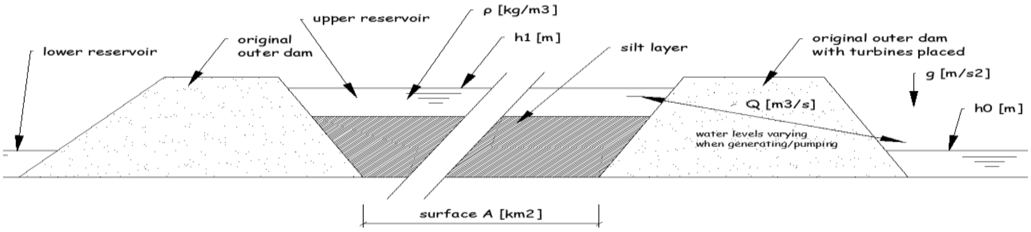

Figure 64 ... Conceptual sketch Alternative 1B (not on scale)

Power performance, turbines and costs

Due to the very low head difference, the performance of the turbines is not very high. The most optimum turbines found have a maximum output capacity of 20 MW (*Pedreira Dam in Brazil, see Appendix F*). The total energy storage capacity and generation capacity are given by (*see Figure 64 , for derivations, see Appendix G, all the parameters have been introduced in §11.2.3):*

$$E_{cap} = \frac{1}{2}\rho g A(h_1^2 - h_0^2) \qquad \text{and} \qquad P_{max} = \rho g Q h \eta$$

To ensure a minimal power output, the water level inside the reservoir will be fluctuating from +23 m to 15m NAP (*Why? -> see §15.1*). This gives a storing capacity of 1.18 GWh with a maximum output 20 MW per turbine. This means that to supply the province of Zuid-Holland, a minimal of 16 turbines are needed. This is quite high and it should be figured out whether this is feasible practically. With these turbines, the peak generation will be 320 MW, providing power for 8 hours and 23 minutes.

The costs can be split into the civil engineering costs and the electro-technical costs (*see Table 23 and Appendix U for cost references*).

Activity	Costs in million euro's
Placing of slurry walls to prevent water leakage	€ 100
16 x 20 MW turbines incl. casing	€ 700
Total	€ 800

Table 22 ... Rough estimate of costs for Alternative 1A

15.3 Alternative 1B: High

Concept and contaminated silt management

The idea is the same as Alternative 1A (*see Figure 64*), however in Alternative 1B the outer dams are heightened to achieve a higher power output and a dam core is placed to control losses. The heightening could be justified over the current situation since the increase in the height has a strong influence in the storage capacity as well as the power capacity, while coming at low costs.

This alternative combines the silt management function with energy storage. Only the top height is required for generating power which means the lower parts can be maintained with the stored silt *(see Figure 64)*. Since the water is in open contact with the silt, it could mix and leak out contaminants during turbine activity. By placing a filter layer on top of the silt, this mixing is limited. The contaminants could also seep into the outer dams and find their way into open water.

The seepage of the water from inside the dam may be a problem. To limit seepage, a number of techniques can be applied such as slurry walls or the construction of a dam core. The latter is chosen for this alternative in the primary design.

Technical details

As the previous alternative offers too little hydraulic head to provide an adequate power output, the dams are heightened from +23m to +40m NAP with the reservoir level at +39m NAP. This heightening is applied for the entire surrounding dams and from the outer sides, so that the dam is built up from the North Sea and Maasvlakte, not from inside. This is because of two reasons:

- the surface area of the Slufter is guaranteed (which is required to supply a storage requirement)
- because the dam is filled with silt, the construction is made difficult from the inside (i.e. one has to remove the silt, heighten the dam and replace the silt)

With the assumption of a uniform dam profile, the volume of sand that is required for the heightening is equal to (*see Figure 65):* $19.7 * 10^6 \sim 20\ million\ m^3\ sand$

In between the current dam and the heightening, a filter layer of 1 m of silt is applied. The silt inside the Slufter is used for this because of its low permeability. The contaminated silt is readily available and trapped between the two layers; it will not form any pollution risk. The water may be able to flow underneath the filter layer; it should be calculated how much the flow is before taking action.

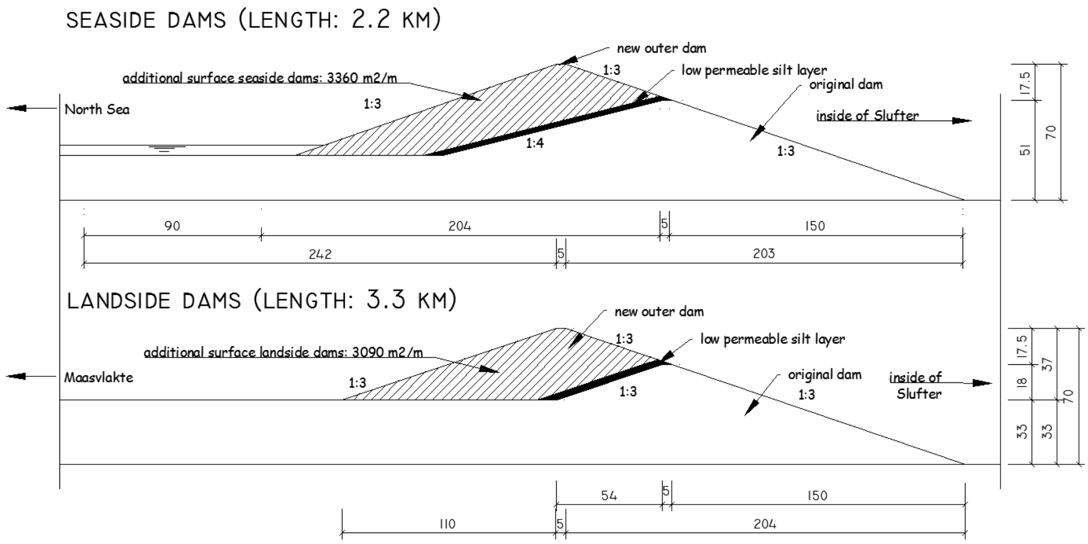

Figure 65 ... Sketches of old dam and new outer dams without a core

Power performance, turbines and costs

The total energy storage capacity and generation capacity are given by (*see Figure 64, for derivations, see Appendix G, all the parameters have been introduced in §11.2.3)*

$$E_{cap} = \frac{1}{2}\rho g A(h_1^2 - h_0^2) \quad \text{and} \quad P_{max} = \rho g Q h \eta$$

To ensure a minimal power output, the water level inside the reservoir will be fluctuating from +40 m to 30m NAP (*Why? -> see §15.1*). This gives an energy storing capacity of 2.03 GWh. The chosen turbines are based upon the Alqueva dam, but scaled and optimized for this hydraulic head (*see Appendix F*). The maximum power generation will be 125 MW per turbine and 75 MW when the water level hits +30m NAP. In order to supply the province of Zuid-Holland, a minimum of 3 turbines are needed. With these turbines, the generation will vary in between 375 - 225 MW, providing power for 7 hours and 55 minutes under full capacity, enough to cover the peak of the day. Their placement will be on the south-eastern side of the Slufter because of the relatively sheltered position and the higher constructability due to easier access.

The costs can be split into the civil engineering costs and the electro-technical costs (*see Table 23 and Appendix U for cost per unit values*). The core costs are estimated to be about the same as a slurry wall in this phase.

Activity	Costs in million euro's
Heightening of outer dams	€ 150
Placing impermeable core walls to reduce seepage	€ 100
3 x 125 MW turbines incl. casing	€ 375
Total	€ 625

Table 23 ... Rough estimate of costs for Alternative 1A

15.4 Alternative 2: Valmeer

Figure 66 ... 3D-model sketch of Alternative 1B

Concept and contaminated silt management

The conceptual idea is the same as before, except the Slufter will operate as the lower reservoir and the surrounding waters as the upper reservoir. The water will be pumped to the sea to 'charge' and released back to generate energy (*see Figure 67*). The benefit is that the dam failure risk is reduced since the reservoir is lower than the surroundings. The physical changes consist of increasing the depth and the placing the reversible turbines. Without danger for surface rapture, the depth can be increased to -31m NAP to increase the hydraulic head *(see §15.1)*.

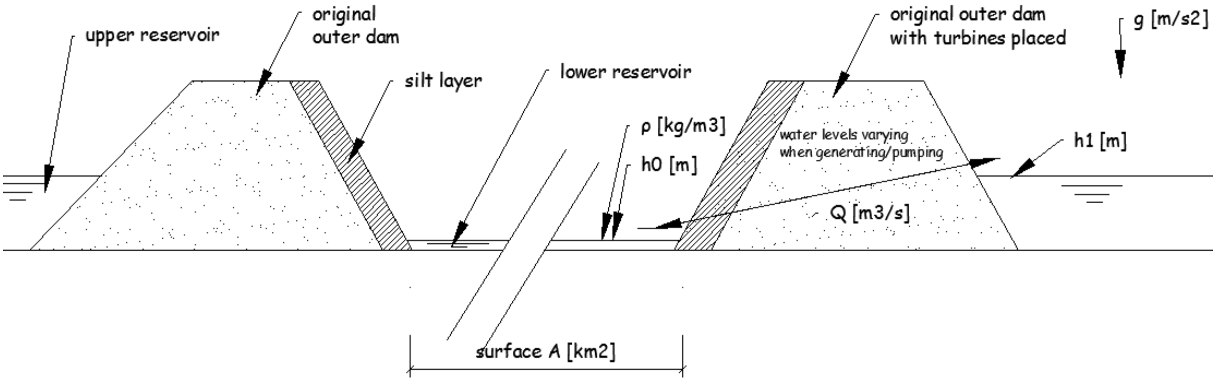

Figure 67 ... Conceptual sketch alternative 1B (not on scale)

The largest issue with this alternative is the silt which is currently stored in the Slufter. In order to profit from the depth, this silt has to be removed, which is a problem due to the amount *(see §15.1).* The majority of the silt will have to be transferred to other places where possible. To work out this alternative further, it is assumed that 50% of the silt can be transferred to other locations, leaving 35 million m^3 in the Slufter. Since it is desirable to maintain the height as much as possible, the remaining silt will be stacked on the sides. This strategy will ensure that the hydraulic head is guaranteed, but will reduce the surface area. Pushing the silt to the sides, the layer thickness along the sides equals 77m and reduces the surface area to 2.25 km^2. Practical issues may arise when trying to stack this silt on the sides. While the top layer is expectedly very muddy and slushy, the bottom layers should be more consolidated over the years. Besides, it will be unable to make the silt remain at the same slope as the dam, and therefore a lot of surface area will be lost. Should this turn out to be the preferred alternative, more analysis into this problem is required.

Technical details

The current depth of the Slufter is -28m NAP. Without the risk of bursting, the depth can be increased to -31.5 m NAP. This deepening can only be done once the silt has been removed. This requires dredging of

$$surface\ area * thickness > \ 2.6 * 10^6 * 3.5 = 8.3 * 10^6 \sim 8.3\ million\ m3\ of\ soil.$$

The turbines will be placed on the south-eastern section (*indicated in Figure 66*). This area is sheltered from the sea and is accessible through land, which will have a positive influence on the constructability. With the assumption that 50% of the silt is transferred, this means that 35 million m^3 of silt will need to be recycled or moved.

Power performance, turbines and costs

The total energy storage capacity and the power output with varying Q and h is given by (*see Figure 67, for derivation, see Appendix G, all parameters are already introduced in §11.2.3)*

$$E_{cap} = \frac{1}{2}\rho g A(h_0^2 - h_1^2) \qquad \text{and} \qquad P_{max} = \rho g Q h \eta$$

The water level inside the reservoir will be fluctuating from -31 m to -20 m NAP (*Why? -> see §15.1*). This gives a storing capacity of 0.97 GWh. Utilizing slightly lower performing turbines; the power output will vary between 79.4 MW and 55.4 MW per turbine. In order to reach a power output that can supply Zuid-Holland, 4 turbines are placed. The maximum capacity will then be 320 MW and the minimum capacity 221.6 MW. The turbines can operate for 2 hours and 55 minutes under full capacity, which is short compared to the other alternatives.

The costs are split into the civil engineering costs and the electro-technical costs while the costs for the transfer of the silt are not included because the uncertainty regarding this strategy. The costs for the electro-technical by far outweigh the civil engineering costs (*see Table 24 and Appendix U for cost references)*.

Activity	Costs in million euro’s
Transferring part of the silt	€ 100
Pumping the silt to the sides	€ 100
Deepening of reservoir	€ 67.2
Placing of slurry walls to prevent water leakage	€ 100
4 x 80 MW turbines incl. casing	€ 500
Total	€ 867.2 ~ 870

Table 24 ... Rough estimate of costs for Alternative 1B

15.5 Alternative 3: Split

Figure 68 ... 3D sketch model for Alternative Split

Concept and contaminated silt management

The idea for this alternative is to place a separating dam inside the Slufter that will create an upper reservoir on the south side and a lower reservoir on the northern side. The benefit is that the full dam height as well as the depth can be utilized for the hydraulic head. The system will pump water to the upper reservoir to 'charge' and release it to the lower reservoir to generate power (*see Figure 69*). The physical changes consist of the construction of a separating dam and heightening of the outer dams of the upper side. The separating dam will be placed inside the Slufter, splitting it into two equal sections.

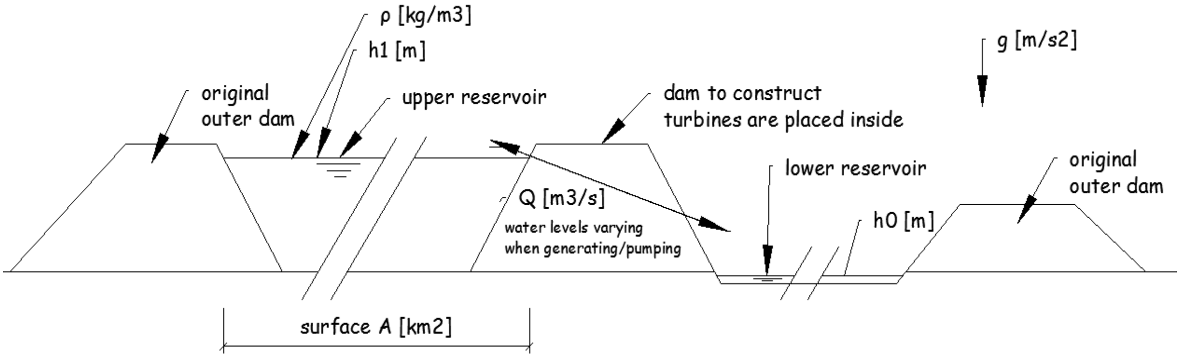

Figure 69 ... Conceptual idea sketch of Alternative 2 (not on scale)

The silt will be recycled and transferred to other destinations as much as possible. It is assumed that this will be about 10%, and the remaining silt will be around 65 million m^3. These will be placed in the upper reservoir and will stack to a height of 50 m. There is a possibility to use the silt in the construction of the separating dam.

Technical details

The dams surrounding the upper reservoir will be raised from +23m to +40m NAP, which means that the newly constructed dam will be 68 m high, of which about 35m above ground level. In the primary analysis, it is assumed that this will be an earth dam; this type is cheap and suitable for construction of such heights.[135] For the parts that need to be heightened, which span 1880 m, an estimated 1.5 million m^3 soil is required. Because windmills are placed on the western and northern dams, the upper reservoir will be facing the south (*see §14.2*). This will also be beneficial in terms of risk. A possible source of sand is the surrounding dam of the lower reservoir, which no longer requires a height of +23m NAP. However, this would require additional work to remove and replace the windmills which are currently placed on top of the western dams. The depth of the lower reservoir can be increased from -28m to -31m NAP, with the dredging works requiring 4.2 million m^3 of soil. This dredged material can also be used in raising the surrounding dams. The lower reservoir is made less permeable with the construction of surrounding slurry walls until -50m NAP and for the upper reservoir either a slurry wall or an impermeable core can be constructed of which the first one is chosen.

The real problem lies in the realization of this alternative. Since the depot is already filled with silt and the dam cannot be built on top, the construction of a 70m high dam with 427 meter width at the bottom is very difficult (considering a slope of 1:3). Ideally, the silt would be removed, the dam would be built and the silt would be pumped back into the upper reservoir. However, pumping large amounts of silt, storing it somewhere and pumping it back are activities that trouble the construction due to logistical problems and long duration. These practical problems will have to be solved if this is the preferred alternative.

Power performance, turbines and costs

The total energy storage capacity and the power output with varying Q and h is given by (*see Figure 69, for derivations, see Appendix G, all the parameters have already been introduced in §11.2.3)*

$$E_{cap} = \frac{1}{2}\rho g A\left((h_0^2 - h_1^2) - (h_0 - h_1)^2\right) \quad \text{and} \quad P_{max} = \rho g Q h \eta$$

To ensure a certain power generation capacity, the water level in the upper reservoir is altered from +40 m to +20m NAP, giving a storage capacity of 1.67 GWh. The maximum power that can be generated is 129 MW per turbine. When the water approaches the lower limit, generation will be significantly lower, about 76 MW. In order to supply the required amount of power for Zuid-Holland, at least 3 turbines are required. The total capacity of the turbines will be 387 MW for the upper limit and 228 MW for the lower limit. Should the turbines be maximally loaded until lower limit, it would last about 5 hours and 35 minutes. This is more than sufficient to cover the duration at which the peaks occur during the day.

The costs are split in civil engineering costs and electro-technical costs *(see Table 25 and Appendix U for cost references)*

Type of activity	Activity	Costs in million euro's
Civil Engineering	Dredging lower reservoir	€ 33.8
	Heightening dams	€ 20.2
	Construction of separating dam	€ 200
	Placing of slurry walls to prevent water leakage	€ 100
Electro-technical	3 turbines incl. casing	€ 375
Total		€729 ~ 730

Table 25 ... Rough estimate of costs Alternative 2

[135] Karkeh dam, Islamic Republic of Iran, 2013 (this dam features an earth dam of 127 meters high

15.6 Alternative 4: Greater

Figure 70 ... 3D sketch model for Alternative 3

Concept and contaminated silt management

This is a solution for the relatively low storage capacity. It solves this by expanding the surface area of the current reservoir significantly on the eastern side that is enclosed by the Slufter and West-Voorne. A new reservoir will be dug here which will operate as the lower reservoir and the Slufter as the upper reservoir. The silt can thus remain in the Slufter and will form an impermeable bottom for the upper reservoir.

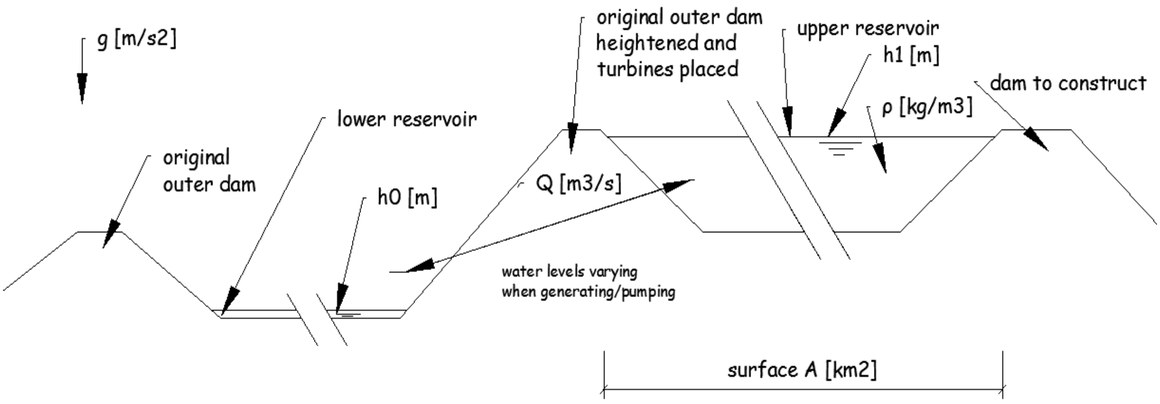

Figure 71 ... Conceptual idea sketch of alternative

Technical design specifications

The location of the expansion has been chosen eastward of the Slufter. This area is designated for nature development, but is suffering from accretion (*see §14.3 and Figure 54*). Along the edges of the reservoir, the nature development can continue. The current eastern dam of the Slufter will become the dam separating the reservoirs and the location of turbines. The hydraulic head is chosen as in Alternative 3, +39m NAP which requires dams of +40 m NAP surrounding the Slufter. The new reservoir will have a depth of -31m NAP (*see §15.1)*. The required excavation is 93 million m^3 and part of this can be used for the heightening of the Slufter dams, which requires about 20 million m^3 (*see §15.3*). To make the new reservoir less permeable, it's closed off with slurry walls of 50m depth into the impermeable layer. To make the Slufter less permeable, either slurry walls or an impermeable core can be constructed with the heightening (because naturally the dam width will also expand).

Power performance

The total energy storage capacity and power output varying by Q and h is given by (*see Figure 71, for derivations, see Appendix G, all the parameters have already been introduced in §11.2.3)*

$$E_{cap} = \frac{1}{2}\rho g A\left((h_0^2 - h_1^2) - (h_0 - h_1)^2\right) \quad \text{and} \quad P_{max} = \rho g Q h \eta$$

With a hydraulic head varying from +39m to +20m NAP, the storage capacity will be 3.48 GWh, double the amount of the other alternatives. Since the hydraulic head is the same as in *Split Slufter*, so will the power output; 129 MW at the upper limit to 76 MW at the lower limit. Since the reservoir is larger, additional turbines can be used to utilize more power. Since the requirement is to balance Zuid-Holland, the same 3 turbines are used which generate between 387 MW - 228 MW, doing this for 12 hours and 41 minutes. This value is a lot more than is required and it should be considered to utilize more turbines that will serve more people or balance a larger area.

Costs

This alternative does require more civil engineering work than other alternatives and despite the larger scale, costs are not significantly higher than they are compared to the other alternatives (*see Table 26 and Appendix U for cost references*).

Type of activity	Activity	Costs in million euro's
Civil Engineering	Buying off extra piece of land	€ 100
	Lowering depth lower reservoir	€ 67.2
	Heightening dams upper reservoir	€ 54
	Placing of slurry walls to prevent water leakage	€ 150
Electro-technical	3 turbines incl. casing	€ 375
Total		€746.2 ~ 750

Table 26 ... Rough estimate of costs for Alternative 3

15.7 Selection using cost-benefit analysis

15.7.1 Introduction

Cost-benefit analysis is based upon the economic principle of willingness-to-pay or to accept. The valuations are based on the willingness to pay of the potential gainers for the benefits they will receive as a result of the chosen alternative and the willingness of potential losers to accept compensation for their losses. A project is desired when the benefits (i.e. value) are high compared to the losses (i.e. costs).

Ultimately, the choice between the alternatives will be based upon the value/costs-ratio. This ratio ensures that the best value is created for that specific amount of costs, and thus chooses the alternative that turns costs into value most efficiently. The value will again be determined using an MCA. The costs for the different alternatives are estimated using key figures. This method provides a rough estimation of the costs of the alternatives relative to one another. With both the values and cost per alternative known, a value/cost-ratio can be calculated, which will form the end of the cost-benefit analysis.

15.7.2 Multi Criteria Analysis

The different stage in the selection procedure demands slightly different criteria to be used. The set of criteria are once again explained in *Appendix E*. The alternatives considered are:

Alternative	1A	1B	2	3	4
Name	*Current*	*High*	*Valmeer*	*Split*	*Greater*

For a description of an MCA and how it works, see *§12.1* and *Appendix E*. Based on a weight matrix, the importance of each criterion has been defined. The choice and meaning of each criterion and the clarification concerning the given relative values are in *Appendix E*. The strong points of each alternative and the values are displayed in *Figure 72*.

Each alternative displays distinct specialties, for example, the Valmeer performs relatively well with visual blockage as it is the only solution that creates a lower reservoir. However, since the hydraulic head is limited, the energy and power capacity remain relatively small. Similar statements can be made about the other alternatives based upon *Figure 72*. The Greater Slufter alternative creates most value.

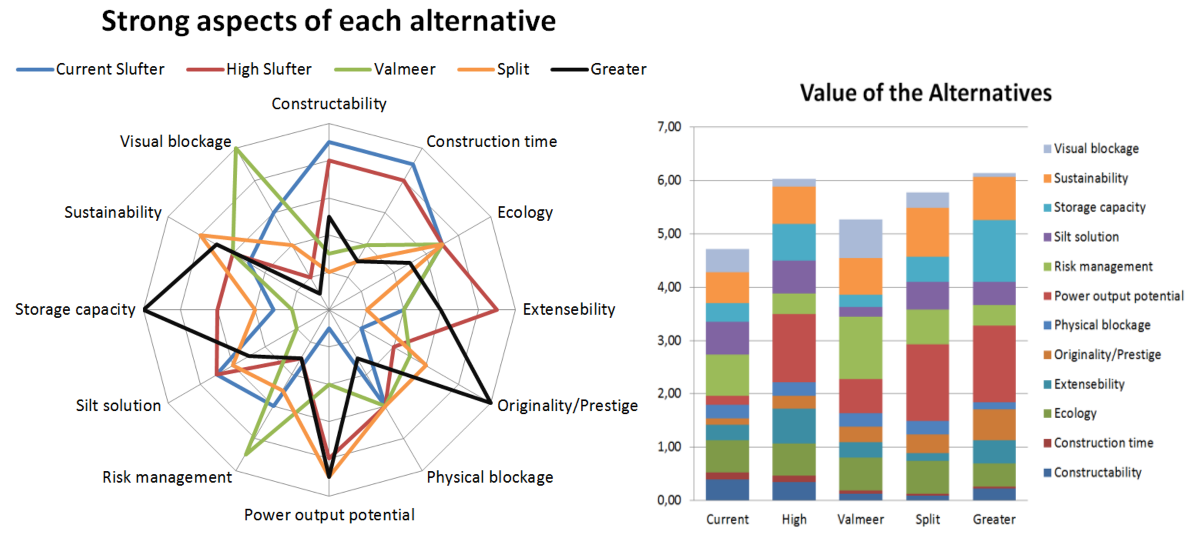

Figure 72 … MCA results graphically

15.7.3 Selection

Using the MCA, a set of values has been appointed to the alternatives and costs have been calculated in the description of the alternatives (*see Table 27*). With the two variables determined, the cost-benefit ratio for each alternative is can be calculated as (*see Figure 73*):

$$Cost\ benefit\ ratio = \frac{Value}{Costs} * Scale\ factor\ of\ 10^\wedge 8$$

A high ratio means that the value is high compared to the costs and that for every unit of value the accompanied costs are the lowest among the alternatives. It means the best alternative utilizes every euro spent to the fullest for the creation of value. The cost-benefit ratio shows that *Alternative 1B: High Slufter* has the highest cost-benefit ratio.

Alternative	Current	High	Valmeer	Split	Greater
Primary costs (in million)	€800	€625	€ 870	€ 730	€750
Value (-)	4.71	6.03	5.28	5.78	6.14
Ratio	**59%**	**96%**	**61%**	**79%**	**82%**

Table 27 … Total costs and value of the alternatives side by side

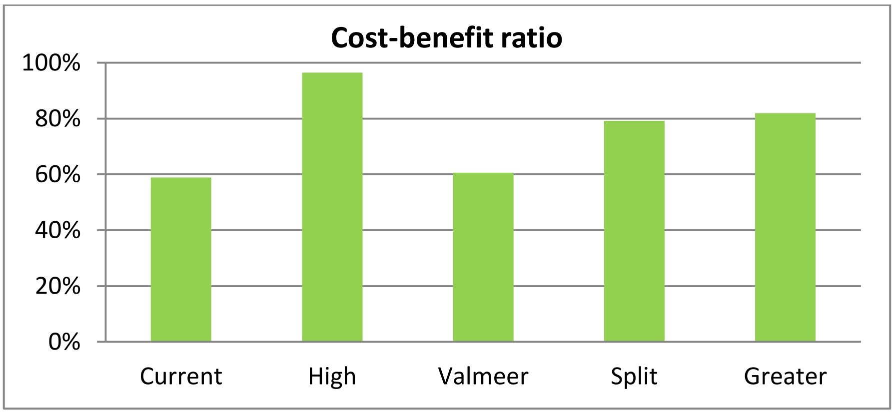

Figure 73 … Cost-benefit ratio of the alternatives side by side

15.7.4 Evaluation

The High Slufter performs excellent when creating value for the costs. The plan excels by its simplicity, making most of the current situation and is a compromise between the alternatives of Greater and Split. The cost-benefit ratio is very sensitive to the power capacity. An increase in the power output potential has a positive effect on the valuation as well as the costs as fewer turbines are required to meet the same targets. Another strong aspect is the storage capacity, which is why the Greater alternative scores rather high despite its high costs. Sustainability and risk management are factors to which the ratio is also sensitive for. The ratio suggests a high dependence on the costs. While this is true, costs are in fact a representation of the amount and complexity of the work that is required. This combined with the low power output is why the Valmeer alternative fails to impress.

A large addition to the performance is the specification of the turbine. The Greater and Split alternatives cannot profit much from the significantly higher hydraulic head. Mentioned otherwise, the optimized turbines used in the High Slufter perform really well when compared to the original Alqueva turbines. This has a large influence in the value, which translates to lower costs because not so many turbines are required. A similar story can be told for the current Slufter. As the ratio shows, it is certainly worth spending the extra money on the civil engineering works since the gain from it is significantly higher than the other alternatives. The High Slufter is therefore chosen to be worked out.

16. Technical design

The following topics are discussed in this chapter:

16.1 Introduction to technical analysis

With the highest cost-benefit ratio, *Alternative 1B: High Slufter* has been chosen to be further worked out. The potential of this alternative combined with the low investments required have resulted in a high cost-benefit ratio. The technical work-out revolves around the design of the heightened dam, the placement of the turbine and the integration of the system in the national power grid. The design process is a cyclic process (*see Figure 74*) that requires the analysis of the current situation and proposals for improvements (*PLAN*); executing the proposed improvements (*DO*); checking based upon the goal whether the situation has improved (*CHECK*); adjusting according to the check (*ACT*). To improve readability and effectiveness in the report, only the relevant parts of this process are presented with corresponding calculations.

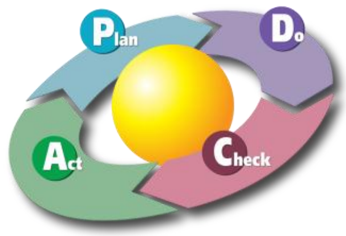

Figure 74 … Cyclic nature of design and test process according to the Deming Quality Circle

The reservoir size is relatively small, which means it is not subject to a lot of processes that do affect large lakes and reservoirs. These are aspects like the astronomical tide and short waves. As calculated in *Appendix H*, wind setup is negligible inside the reservoir as the fetch length is very small. Because the dams are 40 meters above sea level, sea waves and overtopping of the dam from outside are no issue. The flow along the bottom of the dam may cause erosion and in time could challenge the stability of the toe; the profile should be chosen wide enough that toe instability is not an issue. Therefore, most of the loads and dangers come from the inside. Part of the technical analysis is the effect of the rapidly fluctuating water level on stability. This is a very specific issue for this case as the reservoir level will be fluctuating in a matter of hours. The result of this section should be a technical design of the system that ensures strength and stability or discussed the main issues.

16.2 Dam sections

16.2.1 Reconsiderations Alternative 1B High Slufter

The upper reservoir water level will be +39 m NAP, which is 35 meters above ground level.[136] This height is realized with an upgrade of the current dams. To make the dam impervious, an impermeable core is designed for which the silt inside the Slufter may be used. Especially the bottom layers are largely consolidated and suitable because of its low permeability.[137] It has prior been used inside the Slufter to limit the outflow of contaminants from inside the Slufter.

To minimize the slope angle of the dam and thus the volume that it occupies, a material with a high angle of friction is preferable. Slope angles of 1:2 are possible for rock-fill dams,[138] however for the Netherlands, rock is not readily available and importing is a very expensive option. Materials that are available are sand and silt. The dam fill is therefore executed with sand. Due to the lower repose angle of sand, the dam slope is 1:3 with a crest of 10m wide.[139] There aren't many large earth dams, but even far larger sizes are certainly possible. [140]

The expansion of the dam affects the energy storing capacity positively because the dam is expanded on the outer side, so from sea side. This means there is no occupation of surface area inside the dam; instead, the surface area at the top becomes slightly larger (*see Figure 65)*. With the expansion, the crest moves 54m seawards and the perimeter at this point is 5.84 km. With a current top surface area of 2.82 km^2, this means that the surface area at the top becomes

$$expansion: shift\ towards\ sea * perimeter\ at\ that\ point\ \rightarrow 54 * 5839 = 315000\ m^2 \sim 0.32\ km^2$$

$$new\ surface\ area\ at\ top = old\ surface + expansion\ \rightarrow\ 2.82 + 0.32 = 3.14\ km^2$$

With a slope of 1:3, the surface area at the lower limit of +30m NAP can be calculated. With a difference of 10m, the width at the lower point is reduced with 30m at each point along the perimeter of 5.65 km. This means the surface area the lower limit becomes (similar to the calculation above)

$$reduction\ relative\ to\ total\ area: 30 * 5651 = 169521\ m^2 \sim 0.17\ km^2$$

$$surface\ area\ at\ lower\ limit: 3.14 - 0.17 = 2.97\ km^2$$

For more information on the specifications of the Slufter and the initial Alternative 1B: High Slufter, *see §14.6* and *§15.3.* As the reservoir surface is higher than initially anticipated, the amount of turbines is raised to 4 instead of the 3 in the initial alternative. The benefits of this raise are discussed in *Chapter 19*.

16.2.2 Splitting the sections

The heightening of the dams is from +23m to +40m NAP, a difference of 17 meter. The heightening of the dams will occur by expanding the dam from the outer sides. This has the following reasons:

- the reservoir size is not limited because of the dam width expansion
- expanding inside the reservoir needs more soil due to the high reservoir height (*see Figure 67)*
- expanding inside the reservoir is troublesome because of the silt which has to removed first

Three different sections are defined along the perimeter of the Slufter (*see Table 28 and Figure 75*). The separation is made based upon the current cross-sectional dam profile.

[136] Based upon surrounding ground level height (Dinoloket, 2013)
[137] Rijkswaterstaat, Herziening acceptatiecriteria en het scheiden van zand in het depot de Slufter, Milileu-effectrapport, 1998
[138] Paul D.K., Seismic safety analysis of a high rock-fill dam subjected to severe earthquake motion, 2010
[139] Rijkswaterstaat, MER IJsseloog, 2006
[140] NASA, Earth Sciences Web Team Tarbela dam, NASA, 2010

	Section	Length [km]
#1	North Sea Dam	1.28
#2	West-Voorne Dam	1.14
#3	Maasvlakte Dam	3.42
	Total	5.84

Table 28 … Different dam sections named after their neighboring area

For each section a primary design is made that varies in terms of height levels and dam slopes. These initial dimensions are based upon guidelines, tested and further optimized. The calculations mostly focus on the West-Voorne dam as this section is normative in terms of height and slope (*see §16.2.4*).

Figure 75 … Different dam sections (#1 red = North Sea dams, #2 blue = West-Voorne dams, #3 Maasvlakte dams)

16.2.3 North Sea Dam

The North Sea Dam is located along the southern edge of the Slufter bordering the North Sea. This particular part of coast is therefore subject to tough sea conditions. This has been taken into regard in the design by making typical dune profile for this part. The slope is high (1:3.5) at the upper part of the dam while they are low (1:6) at the lower parts.

Currently, the Slufter Beach is present there. With the expansion, the coast will be 200 meters from the Slufter towards the sea. Already this stretch of beach is about 200 meters (*see Figure 76*), meaning that most of the upgrade will be required in the height.

Figure 76 … Close up of the southern dams of the Slufter (Google Maps, 2013)

The cross-section is presented in *Figure 82.* The additional required volume of sand is dependent on the additional surface area (*GREEN*) minus the area that is removed *(RED)* for the core construction that can be recycled (*see Figure 77):*

$$surface\ area = left\ green\ part + right\ green\ part - red\ part \rightarrow 650 + 2740 - 380 = 3010\ m^2$$

$$total\ volume\ sand = \ surface\ area * length \rightarrow \ 3010 * 1280 = 3852800 \sim 3.85\ million\ m^3$$

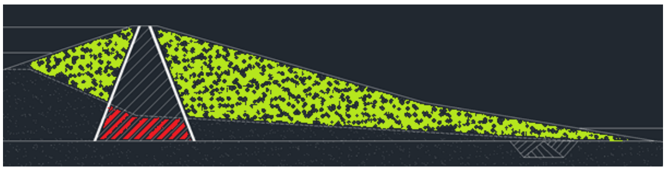

Figure 77 ... Additional surface area of sand indicated in green (the striped section is the core)

16.2.4 West-Voorne Dam

The West-Voorne dam is located at the east-side of the Slufter, facing the West-Voorne coast. This section isn't subject to heavy sea conditions as the North Sea dam (*see §14.3)*. This area is rather quiet and calm with some sedimentation happening in between the Slufter and West-Voorne (*see Figure 78 and §14.3*).

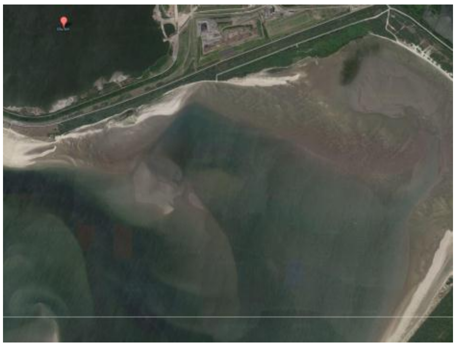

Figure 78 ... The area in between the Slufter and West-Voorne

The slopes are chosen to be steeper here (1:3) since on this section the turbines will be installed. Because the area is not subject to heavy sea conditions, this is the perfect location to place the turbines and realize a steep slope. The slope of 1:3 is based upon the internal friction angle of sand and reference projects.[141] In the current specifications, the slopes of this side are also steeper than on the North Sea side.

The cross-section is presented in *Figure 82.* The additional required volume of sand is equals the additional area (*GREEN*) minus the removed area *(RED)* for the core that can be recycled (*see Figure 79*):

$$surface\ area = left\ green\ part + right\ green\ part - red\ part \ \rightarrow 650 + 2756 - 150 = 3256\ m^2$$

$$total\ volume\ sand = \ surface\ area * length \rightarrow \ 1140 * 3256 = 3711840 \sim 3.70\ million\ m^3$$

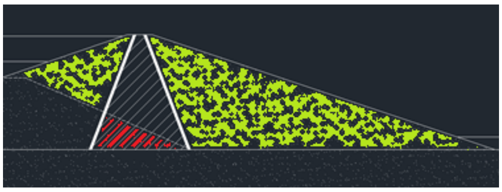

Figure 79 ... Additional surface area of sand indicated in green (the striped section is the core)

[141] Rijkswaterstaat, MER IJsseloog, 2006

16.2.5 Maasvlakte Dam

The Maasvlakte Dam is mainly located at the west, north and east side of the Slufter, attached to the Maasvlakte, which has a ground level of +5m NAP. Northward in the bordering area, there is the Maasvlakteweg, a road connecting the Maasvlakte 2 with the port area. This road is in the way of the dam expansion. Since nothing is located next to this road, the road is moved 100 meters northward (parallel to current road) together with any pipelines or other underground lines. On the south side a road stretches along the Slufter edge, the Noordzeeboulevard, which will be removed. On the other sides, there are no major hindrances as the outer dam moves about 100 meters more inland *(see Figure 82)*.[142]

Figure 80 ... The bordering area in between Slufter and the rest of Maasvlakte where red area indicates the hindrance on the northern section

The slopes are chosen in line with the current dams, at 1:3. This slope is based upon the internal friction angle of sand and reference projects.[143] Due to the lower height difference, the dam width is smaller. The cross-section is presented in *Figure 82.* The additional required volume of sand is equals the additional area (*GREEN*) minus the removed area *(RED)* for the core that can be recycled (*see Figure 81*).

$$surface\ area = left\ green\ part + right\ green\ part - red\ part \ \rightarrow 650 + 1687 - 361 = 1976\ m^2$$

$$total\ volume\ sand =\ surface\ area * length \rightarrow\ \ 1976 * 3420 = 6757920 \sim 6.76\ million\ m^3$$

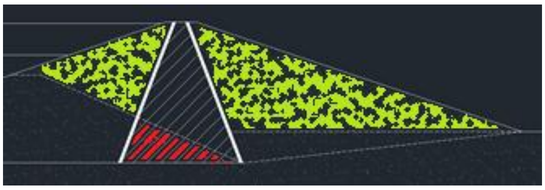

Figure 81 ... Additional surface area of sand indicated in green (the striped section is the core

16.3 Total volume of sand

All the specific surface areas, their length and the total required sand volume have been calculated *(see Table 29).* The total required amount of sand for the upgrade is 14.5 million m^3.

	North Sea Dam	West-Voorne Dam	Maasvlakte Dam	Total
Surface area [m^2]	3010	3256	1976	8242
Length [km]	1280	1140	3420	5840
Required volume [million m^3]	3.85	3.70	6.76	14.31 ~ **14.5**

Table 29 ... Summarized required sand volume

[142] This has been confirmed during a site visit
[143] Rijkswaterstaat, MER IJsseloog, 2006

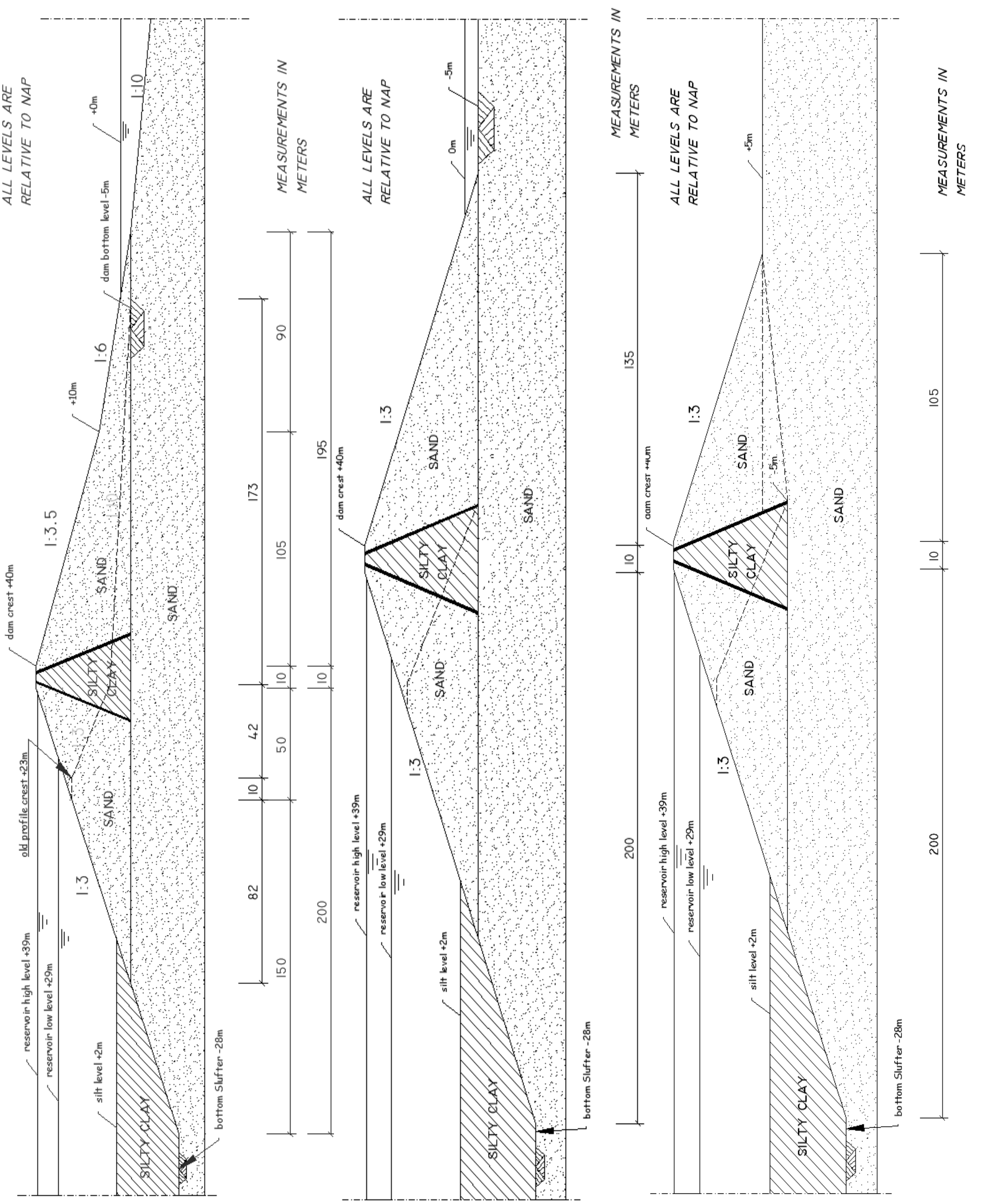

Figure 82 … Cross-sections from top to bottom: North Sea Dam; West-Voorne Dam and Maasvlakte Dam

16.4 The core

The main function of the dam is to form a separation between the water levels and between the contaminated silt and the sea. The dam fill sand has a high permeability and therefore, an impervious core is placed inside the dam and is identical for each section (*see Figure 82*). The primary functions of the core are control the seepage of the groundwater through the dam and increasing the stability. Because the groundwater will flow through the dam, this may cause some erosion of the core material, especially due to the small particle size of these soils. Therefore a filter is placed in between the sand and the silty clay to limit this. The core dimensions have been derived from guidelines (see *Figure 83)*.[144] The slopes on both edges are chosen to be slightly lower than 3:1 and the width at the crest is chosen to be 5 meters. This means that with a height of 45 meters, the width is 15 meters on each edge, giving a total width of 40m *(see Figure 83)*. The required amount of core material is then

$$core\ material = cross\ section\ area * perimeter \rightarrow 1075 * 5840 = 6278000\ m^3\ \sim 6.3\ million\ m^3$$

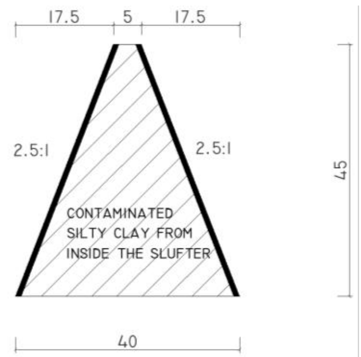

Figure 83 ... Core dimensions as defined in the technical design

A possible material for the use of the core is the silt which is stored inside the Slufter. The use of the silt inside the reservoir makes the problem (*"the contaminated silt"*) to be part of the solution ("*the new dam*"). The silt is actually a mixture of clay and has low permeability.[145] Already a thin layer of silt is being used at the boundaries of the Slufter to limit the outflow of contaminated silt *(see §14.6.2)*, which proves the water-sealing quality. Other benefits are the wide availability, the close proximity and the recycling of contaminated silt. The preference is to use silt from deeper levels inside the Slufter. This soil will have a higher consolidation and will be preferable for the stability and the constructability. Quantitatively, not much can be said about the consolidation and settling characteristics of this material because this is very dependent on detailed soil analysis. That the Slufter is still not full is in fact a combination of the reduced yearly input and the high consolidation of the material. Therefore, a strong recommendation goes out for more analysis in this regard in order to say more.

Should the silt in the Slufter not be qualified by for example very low internal friction or too high consolidation characteristics, other sources can be used for the core construction. One alternative is to use clay layers in the surrounding areas. The subsoil analysis shows that the soil in the surrounding area consists of many clay layers. The criteria for the core material are high internal repose angle, low permeability and high consolidation degree. Other options consist of the placement of slurry or sheet pile walls. For the further detailing, it is assumed that the lower layers of contaminated silt fulfill the criteria.

[144] US Army Corps of Engineers, General Design and Construction Considerations for Earth and Rock-Fill Dams, 2004
[145] Rijkswaterstaat, Herziening acceptatiecriteria en het scheiden van zand in het depot de Slufter, Milileu-effectrapport, 1998

16.5 Stability analysis using GeoStudio

16.5.1 Introduction

The software package *GeoStudio 2012* by *GEO-SLOPE International* is used in order to perform the flow analysis through the dam and slip circle stability analysis. It is a *Finite Element Method* (FEM) software package that is build up from several modules in order to analyze geo-technical issues. The modules which are used for the analysis of the dam are

- SEEP/W for the analysis of the groundwater flow through the dam
- SLOPE/W for the analysis of the slip circle stability of the dam

In total, thirteen different analyses have been performed using *GeoStudio 2012* to get an understanding of the problem (*see Figure 84*). The focus of the model has been the West-Voorne dam, which is normative in terms of slope and height.

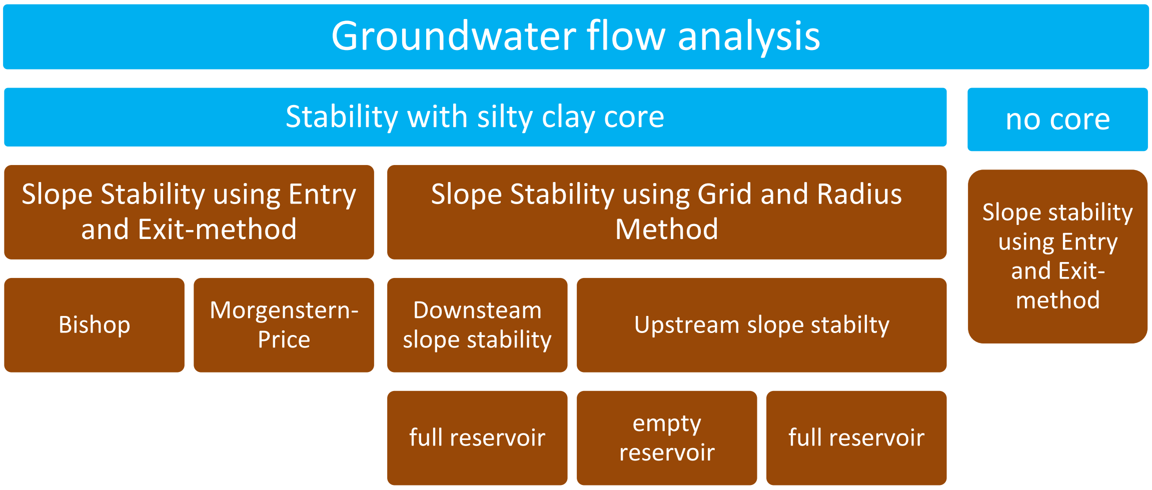

Figure 84 … Sequential analyses that have been performed (blue indicating SEEP/W and brown SLOPE/W)

The analyses in SEEP/W and SLOPE/W are performed consecutively, as the flow line is required for the stability analysis. Most of the research is on the downstream slope of the dam, since it is expected that this side will be normative. For the upstream side the normative situation occurs when the reservoir is full and the sea level is at an extremely high level of 4.5 meter with a return period of 1/10.000 (*Dutch coastal design criteria*).[146]

[146] A. Sterl et al., Extreme North Sea storm surges and the changing climate: an ensemble study, KNMI, 2010

16.5.2 Analyzing the unconfined flow through the dam

Using SEEP/W

The goal of this analysis is to get an understanding of the groundwater flow through the dam and the effect of the core on this flow. Using the SEEP/W module, one can analyze what the unconfined flow is through an earth dam. In this model, the core consists of a silty clay material found in the Slufter.

Geometric model, boundary conditions and materials

The technical design acts as a reference on which the geometric model is based. The geometric model is inserted using dimensions and slopes from the cross-section (*see Figure 85).* Three different materials are specified in the analysis; dam fill sand, silty clay core and subsoil sand. The relevant characteristics for this analysis, the hydraulic conductivity and the volumetric water content, can be found in *Appendix J*. These are inserted as curves and are based upon specimen analysis found for silty clay material.[147]

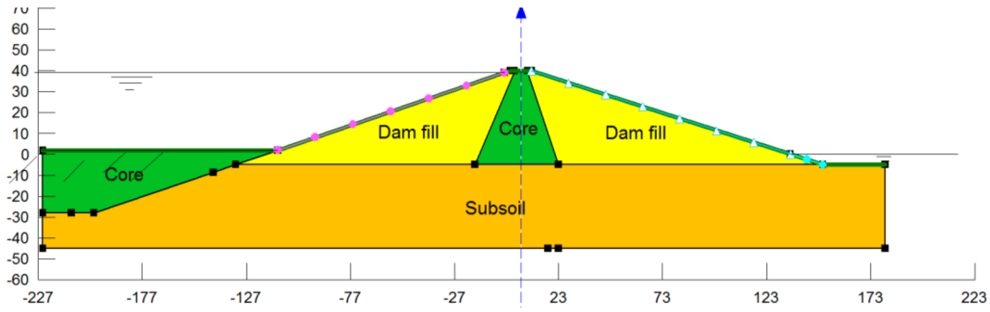

Figure 85 … Geometric model as used in SEEP/W (axis values in meters, y = 0 is at 0 m NAP and x=5m is center of dam)

The hydraulic condition on the left side of the dam is the hydraulic head of +39m NAP. This boundary condition is applied at the left slope starting from the top of the silt level to the crest level (*see pink dotted line in Figure 85*). On the right ride two different hydraulic conditions have been defined; first is the lower water level that runs from -5m to 0m NAP (*indicated in light blue in Figure 85*). Above this line until the dam crest, is the so-called *Potential Seepage Face* (*indicated with the green line with white triangle dots in Figure 85*). The *Potential Seepage Face* boundary is used for the solver to locate the position of where a potential seepage face might develop. In this case, this is the whole downstream area until the water level at NAP.

Calculation

The analysis is done using a *Steady State* situation with an iteration amount of 500 (which provides a well balance between accuracy and computation time). The *Direct Equation Solver* is used to solve the equations. To determine the flow of water through the dam, a *Flux line* is introduced into the geometric model (*the dashed blue arrow through the dam center, see Figure 85*). This *Flux line* is the line where the solver calculates the total flow potential through the dam. Despite not considering a transient mode, this solution gives a great indication of the total seepage volume.

Results

The result of the flow map shows the distinct presence of the core (*see Figure 86*). The arrows are vectors that indicate the flow in that specific point. The points indicate the direction of the flow whereas the sizes of the arrows indicate the amount of flow.

[147] GEO-SLOPE International, SEEP/W Version 5 User Manual Appendix A: Hydraulic conductivity, 2001

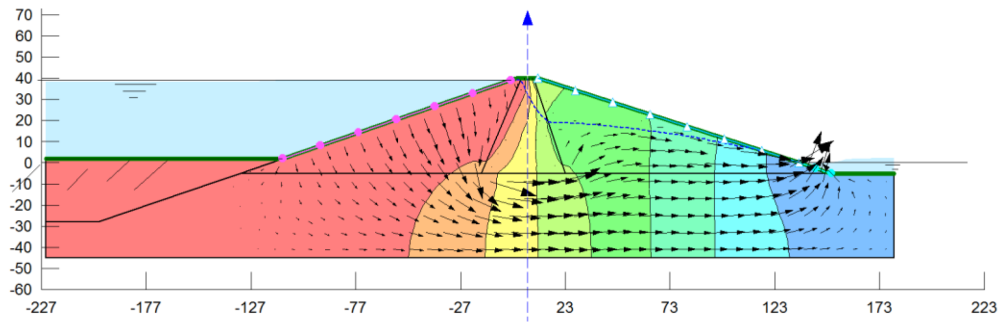

Figure 86 ... Result of the flow patterns (contours indicating head pressure)

Due to the presence of the core, the groundwater flows under the core towards the seepage point which is located at the sea level. At this site, there are large amounts of flows looking at the arrows and this could form a potential problem for the toe. The vectors can be replaced by so-called *flow lines* that illustrate the path of the groundwater flow starting from the upper reservoir side all the way to the seepage point. The flow lines show a flow through the dam which cannot be seen in the vector display (*see Figure 87*). The reason is that this flow is very little and the vectors are sized relative to one another, they are virtually invisible in *Figure 86*.

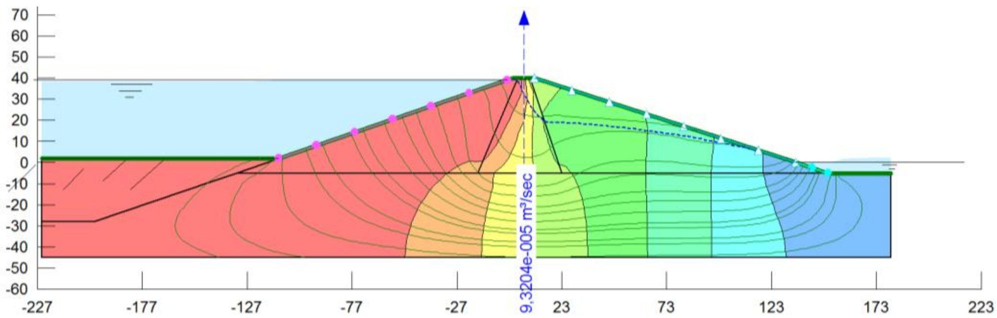

Figure 87 ... Flow lines and flux label

The flux going through the dam is displayed in *Figure 87*. The flux label indicates that the amount of flux is 9.3204*10^{-5} m^3/sec. The total seepage values are:

$$flow = flux\ cross\ section * perimeter\ \rightarrow$$

$$9.3204 * 10^{-5} * 5840 = 0.544 \frac{m^3}{sec} \sim 47030 \frac{m^3}{day} \sim 0{,}1\%\ of\ fluctuating\ water$$

$$head\ drop\ due\ to\ seepage = \frac{flow}{surface\ area} \rightarrow \frac{47030}{3.14 * 10^6} = 0{,}015\ m \sim 15\ mm/day$$

To compensate this loss each day, the turbines have to pump up this loss:

$$T_{pumping} = \frac{flow}{amount\ of\ turbines * pump\ capacity} \rightarrow \frac{47030}{4 * 170} = 69\ seconds$$

If the turbines pump up water for another minute, the seepage losses would be accounted for a whole day under the assumption that the water level is maintained throughout the day (which signifies the extreme case). The daily losses are only 0.1% of the fluctuating water volume, which is very low.

To create more understanding of the model behavior, graphs of the developing water pressure, water flux gradient, and velocity of the water in the x- and y-gradient have been computed and can be found in *Appendix J*.

16.5.3 Analysis of confined flow through a dam without core

In order to assess the importance of the core as a limiting factor on the water losses, the core material is changed into dam fill sand material (*see Figure 88*). Apart from this change, all other values are kept the same as this is only a comparison for the seepage with and without a core. It is the hypothesis that this model will have a larger flux through the dam. This can be accounted to the low hydraulic conductivity.

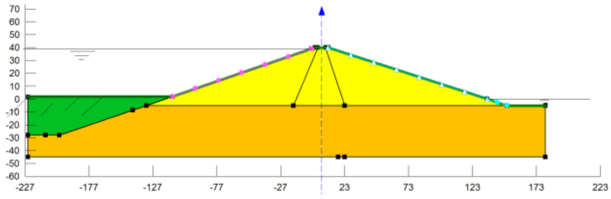

Figure 88 … Geometric model without a core

As there is no core, the groundwater flows directly towards the surface seepage point slightly above the sea level (*see Figure 89*). The vectors are showing high amounts of flow just under the crest. This is because there a convergence towards the surface seepage point. The pressure head lines are moving more regularly as the flow is not hindered by the presence of the core.

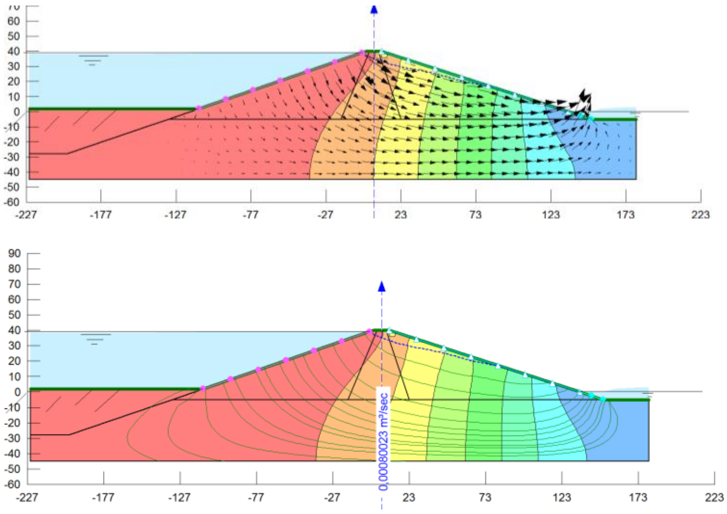

Figure 89 … Groundwater flow through the dam without a core

The flux running through the cross-section of the dam without the core is 8.0*10^{-4} m^3/sec. The hypothesis was correct however a ten-fold increase in flow is surprising. The total flow out of the reservoir due to seepage, the water lowering in a day and the time required to pump the loss is

$$flow = flux\ cross\ section * perimeter \ \rightarrow$$

$$8.0 * 10^{-4} * 5840 = 4{,}672\frac{m^3}{s} \sim\ 403660\frac{m^3}{day} \sim\ 1\%\ of\ fluctuating\ water$$

$$head\ drop\ due\ to\ seepage = \frac{flow}{surface\ area} \rightarrow \frac{403660}{3.14 * 10^6} = 0{,}13\ m \sim 130\ mm$$

$$T_{pumping} = \frac{flow}{amount\ of\ turbines * pump\ capacity} \rightarrow \frac{403660}{4 * 170} = 593\ seconds \sim 10\ minutes$$

The losses without a core add up to 1% of the total volume per day. Even though 10 times as high, this is not a significant amount. If the turbines pump up water for another 10 minutes, the seepage losses would be accounted for a whole day under the assumption that the water level is maintained throughout the day (which signifies the extreme case). Not constructing a core does reduce efficiency of the system, but the seepage values are not devastating.

16.5.4 Slip circle stability

Introduction, geometric model and materials

The stability analysis will be done with the flow analysis as parent, i.e. first the flow analysis is performed, upon which the stability is check with that steady state flow situation through the dam. These two alternative calculation methods are explained as they are used in the analyses.

- *Entry and Exit Method*
- *Grid and Radius Method*

Two different methods will be checked; the method of *Bishop* and the method of *Morgenstern-Price*. The background information about the two methods is given in *Appendix* J. They consist basically of a limit equilibrium situation in which the slip stability is safe when

$$stability\ demand\ \rightarrow\ F = \frac{strength}{load} = \frac{shear\ resistance}{weight\ of\ the\ soil} > 1$$

The geometric properties of the model are the same as they have been calculated for the flow *(see Figure 90*). The hydraulic conditions come from the previous model and were inserted into the model according to the maximum and minimum state of the water level. For the stability analysis, additional material characteristics are required such as the unit density, cohesion and angle of repose. The material model is modeled as Mohr-Coulomb and the chosen parameters can be found in *Table 30.* The soil characteristics have been chosen based upon the expected soil conditions and educated estimates.[148]

Material	Unit density (kN/m^3)	Cohesion (kPa)	Phi (°)
Dam fill	16	3	31
Core fill	16	34	25
Subsoil	17	1	35

Table 30 … Material properties for slip circle analysis GeoStudio

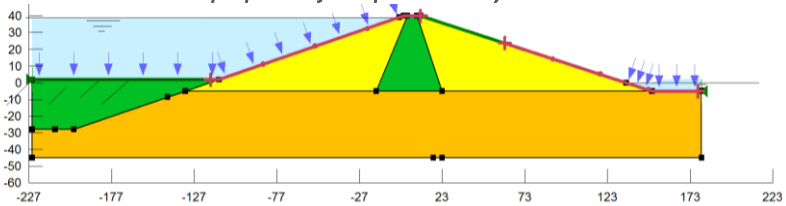

Figure 90 … Geometric model in GeoStudio for the slip circle stability calculations

Calculation

The *Entry and Exit Method* is used to model the stability of the slope. The *ranges* are defined at the top and bottom of the slope (*see Figure 91*) and have been chosen broad not to exclude any possible slip circle due to computation power limitations. If computation power is really an issue, it should be considered whether it is possible to restrict the accuracy rather than range of analysis. From an engineering perspective, it is safer to know all possibilities of failure rather than the accuracy of failure.

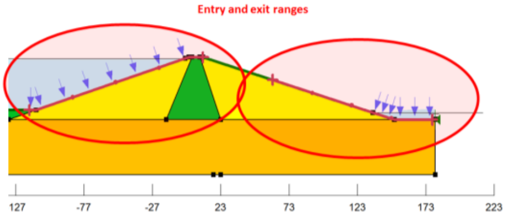

Figure 91 … Entry and exit ranges for the Entry and Exit Method

[148] Rijkswaterstaat, Herziening acceptatiecriteria en het scheiden van zand in het depot de Slufter, Milileu-effectrapport, 1998

Results

The analysis is initially performed using a Morgenstern-Price method of calculation. The program calculates thus the possible slip circles and the corresponding safety factor (*see Figure 92*).

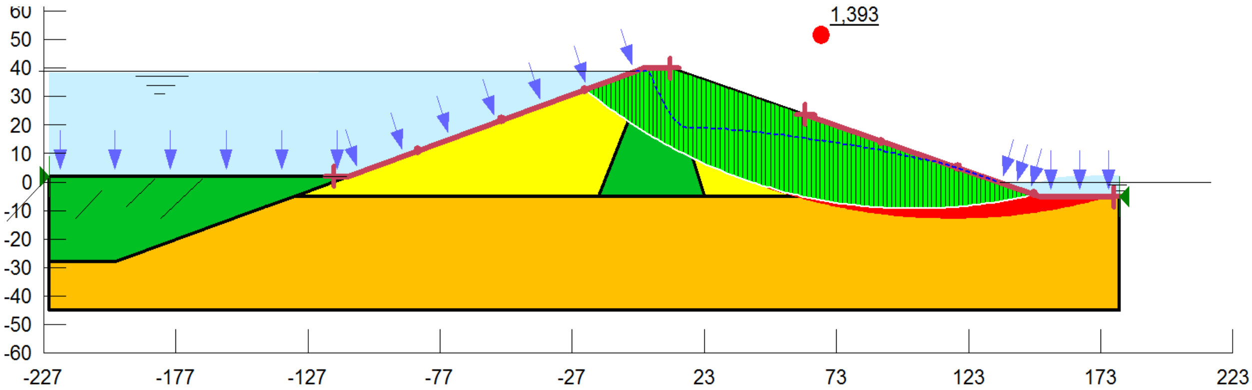

Figure 92 ... Critical slip circle using the Morgenstern-Price analysis

The critical slip circle has a safety factor of 1.393 for the Morgenstern-Price analysis. This means that even for the critical slip circle, the safety factor is relatively high. The properties of the sliding body mass are:

Parameter	**Value**
Method	Morgenstern-Price
Factor of Safety	1,393
Total Volume	3.518,8 m³
Total Weight	56.547 kN
Total Resisting Moment	3,8167e+006 kN-m
Total Activating Moment	2,7393e+006 kN-m
Total Resisting Force	17.886 kN
Total Activating Force	12.846 kN

Sometimes it's more helpful to think in terms of a failure zone as opposed to the location of specific slip circle. A safety map is drawn on the map to indicate a zone where slip circles with very similar factors of safety could develop (*see Figure 92 in red*). The safety map has a range until a stability factor of 1.443, which equals an increment of 0.50.

Without changing any of the values, the analysis is performed once again using the Bishop method. The results for the Bishop method are very similar to the one of Morgenstern-Price (*see Figure 93*).The safety factor is however slightly lower than this is for the Morgenstern-Price analysis; a value of 1.354. Being only a fraction lower, the stability factor is still very high indicating a high stability of the slope against slip circle sliding and this specific failure mechanism. The Bishop method does produce a slightly different safety map (*see Figure 93*). Graphs showing the development of the shear resistance, mobilized shear, total normal stress, effective stress and the pore water pressure are attached in *Appendix J*.

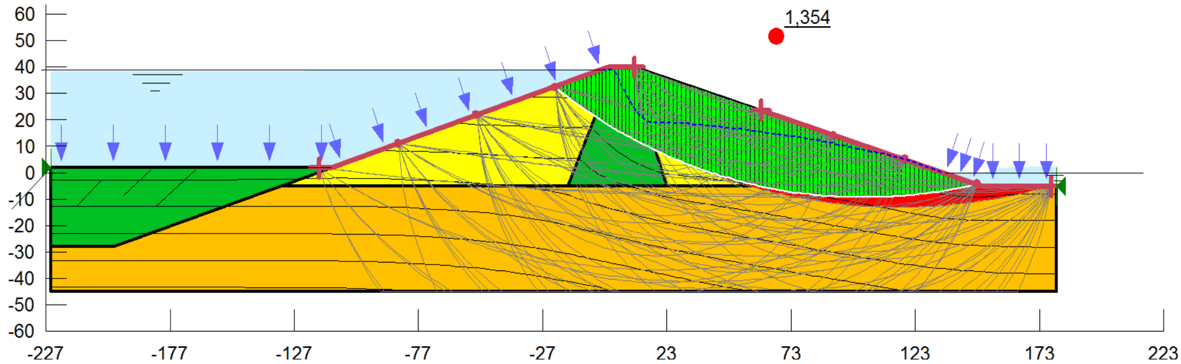

Figure 93 ... Slip circle analysis using the method of Bishop

Grid and radius method

The analysis is further detailed with the *Grid and Radius Method.* This analysis presents an alternative to the before used *Entry and Exit Method.* The method of approximating the safety factor is the *Morgenstern-Price Method*. Only the calculation method is changed to Grid and Radius whiles the rest remaining exactly the same. For more information about the geometric model and the materials, see *Figure 85* and the explanation there. The calculation is still performed after the flow modeling, which is where the hydraulic conditions come from.

The Grid and Radius Method uses a grid of possible radius points to test multiple slip circles. The grid size can be limited because the range of point location is known somewhat. The solver is then used to determine the exact location and the critical slip circle safety factor. The grid has been purposefully chosen to be quite large (*see Figure 94*), because of the high reservoir level which can cause a variety of possible slip circles, far greater than for a normal slope.

The results are promising also for the *Grid and Radius Method* (*see Figure 94*). The critical slip circle safety factor is 1.382, which is very similar to the values obtained at the *Entry and Exit Method*. The slip circle that is formed is however a different one, which proves the essence of this method. The safety map is drawn in *Figure 94* which proves that the potential slip circles are around the critical slip circle.

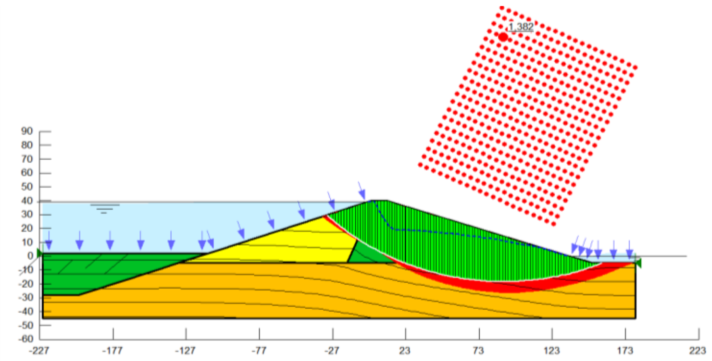

Figure 94 … Critical slip circle and safety map for the Grid and Radius Method on the core model

16.5.5 Stability analysis for the dam without a core

The SEEP/W model without a core is now put to a stability calculation using the Morgenstern-Price method. The Bishop method is not tested for this case, as the previous model already displayed very similar results. The geometric model is the same as the flow analysis *(see Figure 88)*.

The solver has computed the critical slip circle with its corresponding stability factor *(see Figure 95)*. The critical safety factor displays a value of 0.996. As explained before, any value below 1 means that the load is larger than the resistance. This means that the stability is not guaranteed for this case. The safety map provides a range of possible slip circles that might form in the range of 0.996 till 1.046 *(see Figure 95)*. This is called *the critical zone*, an area for which the stability is not guaranteed.

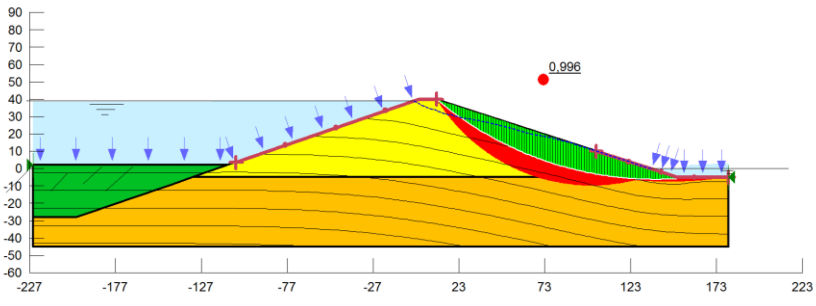

Figure 95 … Safety map and critical slip circle for the dam without core

Further enhancing the analysis with the Grid and Radius method shows that especially the toe of the dam is subject to instability *(see Figure 96)*. This is because of the high flow nearing the toe *(see Figure 89).*

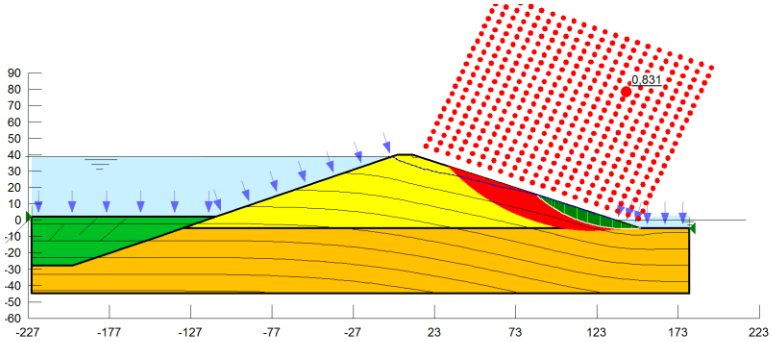

Figure 96 … Critical slip circle and safety map for the Grid and Radius method on the no core model

16.5.6 Calculation of the upstream slope full reservoir

Introduction and modeling

The left side of the dam is expected to be strong enough, especially with the water level being as high as it is. This hypothesis will be tested in this section. The model details are again the same, no adjustments are required there. The model is tested according to the *Grid and Radius* method. The only change is in the calculation method; the characteristics are changed from a *Left-to-Right* to a *Right-to-Left* calculation.

Results

The results support the previously mentioned hypothesis that the left-hand side is indeed deemed to be far more stable compared to the right side of the dam (see *Figure 97*). The Grid and Radius Method provides a critical slip circle with a safety factor of 3.464. This is a very high value and confirms that on this side of the slope, no instability issues are expected.

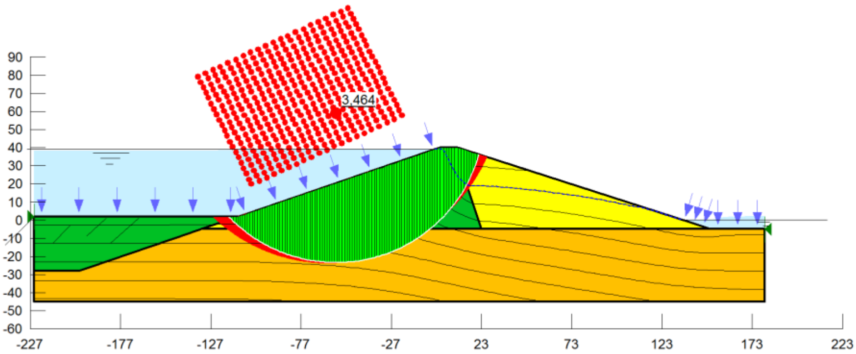

Figure 97 … Grid and Radius Method applied on the left-side of the dam

16.5.7 Calculation of the upstream slope empty reservoir

The situation is analyzed for which the water in the reservoir is emptied and the sea level is experiencing its 1/10.000 probability of a high water level of 4.5 meter. [149] The model is the same with only the hydraulic conditions changing. The water level is modeled as a phreatic water line. The grid size is expanded more downwards as the water level is introduced (*see Figure 98*).

[149] A. Sterl et al., Extreme North Sea storm surges and the changing climate: an ensemble study, KNMI, 2010

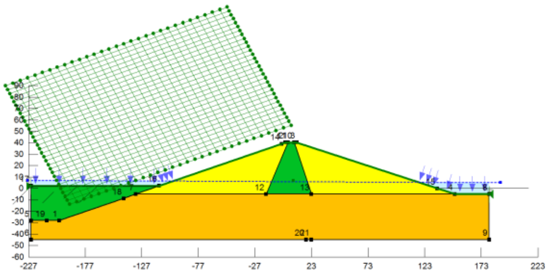

Figure 98 … Model of Grid and Radius method analysis of the upstream slope during extreme situations

This situation does produce a lower safety factor corresponding to the critical slip circle. The reduction is actually quite significant, with the slope losing almost half of its stability. Nonetheless, this won't have much consequences as the margins at which this slope is guaranteed are very high. In this extreme situation, the critical slip circle still produces a safety factor of 2.122 (*see Figure 99).*

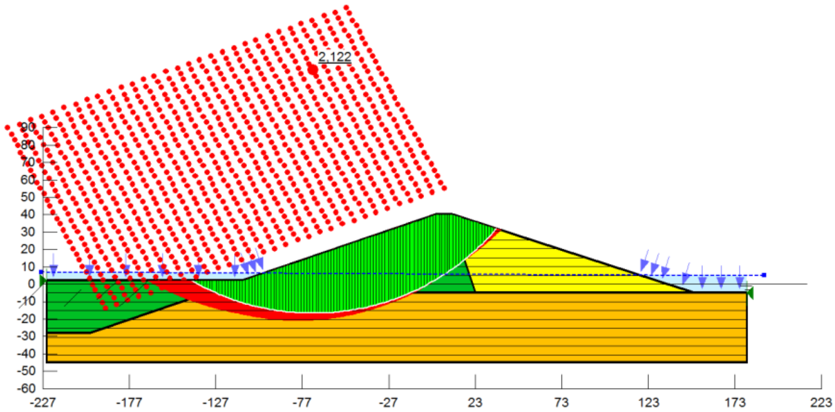

Figure 99 … Critical slip circle for the extreme water level in combination with an empty reservoir

16.5.8 Concluding remarks on the GeoStudio modeling

The GeoStudio 2012 analyses produced great understanding in the physics of the dam and its weak points. This is mainly because the model allows for experimenting and playing with many variables. The Morgenstern-Price method produced very similar results as the Bishop's method did. Therefore, the following analyses have been performed in the Morgenstern-Price method only. The *Grid and Radius* and the *Entry and Exit* methods also produced similar results although it seemed as if the analysis could be done with more overview and understanding with the *Grid and Radius* method. Therefore it seemed as if this method produced more reliable results and was easier to use and understand what was going on. This method therefore has the preference.

The flow modelling resulted in a preference for the core model as opposed to the no core version. With a 10 fold decrease of the seepage values, the presence of the core is significant. However, even considering the no core values, the seepage values are not very high and seem to be manageable.

This cannot be said concerning the stability as the no core model resulted in a safety factor below 1. This is due to the instability near the toe because of the high flow velocities. The stability of the model with core is satisfied with varying margins for all the extreme situations that the model has been tested for.

The hypothesis that the upstream slope stability is stable is confirmed, although results for the extreme sea level produced safety factors which were surprisingly low compared to the high reservoir level situation.

16.6 Stability with fast lowering water level using PLAXIS

16.6.1 Introduction

The PLAXIS 2D 2011 software package is used to analyze the deformations, flow, stability and the pore pressures in the dam. The highlight in this analysis is the effect of the very fast lowering of the reservoir level on the dam stability. The package is intended for Finite Element Method (FEM) calculations for 2D-analysis of deformation and stability in geotechnical issues. With the Plaxis software, seven additional aspects regarding the stability and the performance of the dam are analyzed (*see Figure 100*).

Figure 100 … Analyses performed using PLAXIS

Only the West-Voorne dam is tested because of the normative design (*see §16.2*). The calculations are performed under the assumption that sea level is steady. Only the first model (CCM) is explained detailed, since much is the same; any ambiguities should be therefore checked with the first analysis. Material properties have been tried to be consistent to the GeoStudio analyses. There are differences as Plaxis requires other (more extensive) specifications that have been based upon educated guesses.[150] Especially for the core this difference can be large; the core material is modeled as Undrained B type in Plaxis where-as GeoStudio doesn't make this difference. The difference in the results may (apart from the sheer different nature of the software) be influenced by material differences.

Parameter	Symbol	Silty clay	Dam Sand	Subsoil Sand	Unit
General		BLUE	GREEN	YELLOW	
Material type	Model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	-
Drainage type	Type	Undrained B	Drained	Drained	-
Soil weight above water	γ_{unsat}	16	16	17	kN/m^3
Soil weight below water	γ_{sat}	18	20	21	kN/m^3
Parameters					
Young's modulus	E'	1.5*10^3	2.0*10^4	5.0*10^4	kN/m^2
Poisson's ratio	v'	0.35	0.33	0.3	-
Cohesion	c'_{ref}	-	3.0	1.0	kN/m^2
Undrained shear strength	$s_{u;ref}$	5.0	-	-	kN/m^2
Friction angle	φ'	-	31	35	°
Dilatancy angle	ψ	-	1.0	5.0	°
Young's modulus inc.	E'_{inc}	300	-	-	kN/m^2
Reference level	y_{ref}	30	-	-	m
Undrained shear strength	$s_{u;inc}$	3.0	-	-	kN/m^2
Reference level	y_{ref}	30	-	-	M
Flow					
Flow data set	Model	Hypres	Hypres	Hypres	-
		Van Genuchten	Van Genuchten	Van Genuchten	-
Soil		Subsoil	Subsoil	Subsoil	-
Soil coarseness		Very fine	Very fine	Very fine	
Horizontal and vertical permeability		1.0*10^{-4}	0.25	0.01	m/day

Table 31 … Material properties as defined in the Plaxis analysis

[150] PLAXIS Reference Manual Appendix: Material properties, 2011

16.6.2 Centered Core Model (CCM)

Geometric model, boundaries and boundary conditions

First a dam under normal conditions is constructed with a center core made out of the silt inside the Slufter. The dam is analyzed using a *Plain strain model* with *15 nodes*. The geometric model is generated using the technical design as a reference and is displayed in *Figure 101.*

The horizontal boundaries are chosen to be sufficiently far away from the dam, at about 100 m on each side. This distance ensures that the effects can be seen inside the model computations. The bottom vertical boundary is enclosed by the clay layer that can be found at -50m NAP. It is assumed that his layer is a water enclosing layer and is modeled accordingly (*see §14.6.3*). The top vertical boundary is enclosed by the dam. All boundaries for the dam points are not restricted so that the dam can deform in all directions in the x,y-plane (*see Figure 101*). The possible movement of the points is one of the goals of this analysis. The subsoil boundary conditions for each point are chosen like:

- For the subsoil bottom, movements for the *points (5,6)* both x- and y-direction are restricted. The points have therefore been chosen to be at a sufficient depth from the bottom of the dam
- On the sides, the *points (4,8,7,11)* are restricted only in the x-direction. The points have therefore been chosen to be at a sufficient distance from the toes of the dam

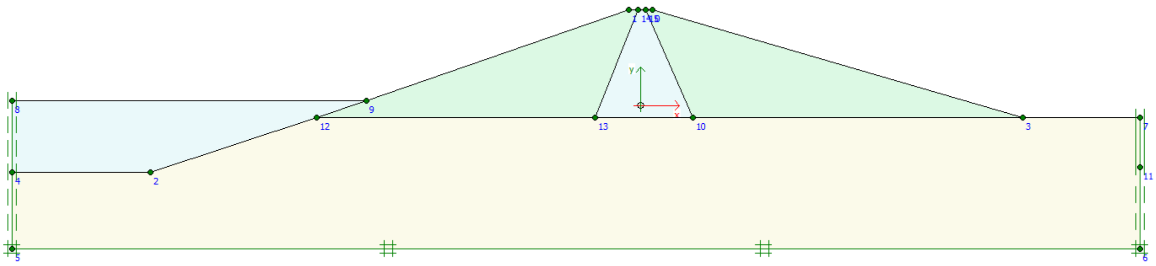

Figure 101 … Geometric model and boundary conditions

Mesh

The global coarseness of the mesh is generated with *Fine* quality and has been further refined for the respective clusters of the dam. These areas are the dam and its core, as well as the connection areas with the silt in the Slufter. The generated mesh with appointed materials is displayed in *Figure 102.* Determining the suitable coarseness of the mesh is a rather difficult process. Creating a mesh as detailed as possible is the preference, since this models the reality more closely. Very fine detail in the mesh requires however a lot of computation time. With a trial-and-error method, a suitable coarseness for the mesh has been defined. This trial-and-error method consists of performing the same calculations with two mesh types: one very fine and another slightly coarser. If the results are more than 10% affected with the use of a finer mesh, than the preference would be to use the finer mesh.

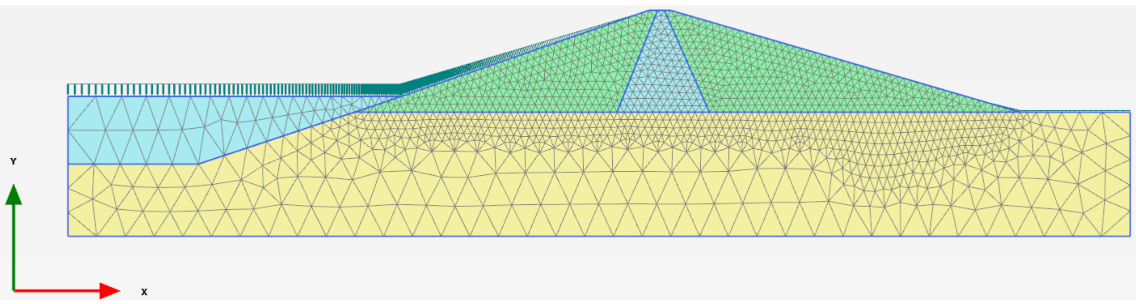

Figure 102 ... Centered core geometric model

Calculation phases

Nine different calculation phases are defined in the PLAXIS Model (*see Figure 103*).

Initial phase	• The dam as build in in the geometric model
Phase 1	• High reservoir level
Phase 2	• Fast lowering of high reservoir level
Phase 3	• Slow lowering of high reservoir level
Phase 4	• Low reservoir level
Phase 5 till 8	• Stability calculations for Phase 1 till 4

Figure 103 … The calculation phases to model the effect of a rapid lowering of reservoir level

- **Initial phase**: Here the calculations are performed using the *Gravity loading* calculation method. The upper water level is put inside the reservoir and the lower one at the sea level (*see Figure 104)*. With the hydraulic conditions defined, the initial pore water pressures are calculated using a steady state groundwater flow.
- **Phase 1 High reservoir level**: In this phase, the Initial Phase is calculated as a *Plastic Undrained* model. This increases the detail of the stress field. The third and fourth phase both start from this standard situation (i.e. a dam with a reservoir level at 39 m) and the water level. This phase models a steady high water level in the reservoir.
- **Phase 2 Fast lowering of reservoir level**: Continuing from Phase 1, the water level is dropped by 10 meters in a matter of hours. Instead of a steady-state calculation, a transient groundwater flow calculation is used to model the change of groundwater flow during the drop. The chosen time interval is 0.25 day (6 hours). The calculation method is *Consolidation (EEP)*. The drop in water level is signified linearly with h(t) in *Figure 104*, according to:

$$h(t) = y_0 + \Delta y * t/\Delta t$$

  - $y_0 = 40$ m (top water level)
  - $\Delta y = -10$ m (signifying a drop of 10 meters)
  - $\Delta t = 0.25$ day ~ 6 hours

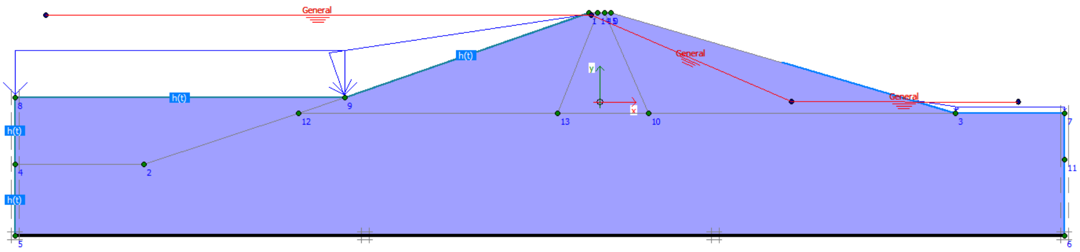

Figure 104 … Drop in hydraulic head level for Phase 2

- **Phase 3 Slow lowering of reservoir level**: The third phase is exactly the same as the second one, except for a longer time interval of the linear water level drop. Whereas in Phase 2 the 10 meter drop occurred in 6 hours, in this phase the drop is 5 days.
- **Phase 4 Low reservoir level:** This is the situation in which the lower limit of the water level is reached. This simulates the long-term behavior of the dam at this lower reservoir level. Similar to Phase 1, a steady state calculation is done for the water pressure distribution (*see Figure 105*).

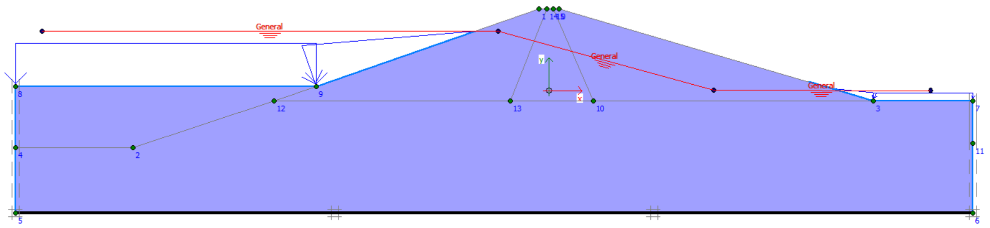

Figure 105 … Water conditions for the lower limit of the reservoir in Phase 4

- **Phase 5 till 8 Safety calculations**: In Phase 5 till 8, safety calculations are performed for the corresponding Phases 1 till 4. For example, Phase 5 is a safety calculation of Phase 1, Phase 6 of Phase 2 and so on. This safety calculation is a phi-c reduction method. For more info about this method, *see Appendix K*. This method is a limit equilibrium state calculation method that calculates the safety factor by balancing the strength versus the load. In this way, it is similar to Bishop's method. Similar to the safety factor, PLAXIS displays the development of Msf.

Results

Apart from considering the static situation of the high water level and the stability of the lower reservoir level, it is interesting to see what the influence of the fast drop in water level is. This is a problem which is very specific for this situation, as the water level drops quite significantly in a short amount of time. The analysis is performed by looking at the active pore pressure, the deformation of the mesh and the stability during the phases. The pore pressures for the high water level are displayed in *Figure 106 Phase 1*. The high water level in the water reservoir is leading to high pressures right under the reservoir. This is due to the large height of the water body. In the dam, this high water level leads to mainly pressure and a slight suction on the opposite slope. The profile of the pore pressure along the dam in Phase 2, when the water level is dropped in a linear way by 10 m, is visible in *Figure 106 Phase 2*. As the water level drops, the pressure profile changes. Because the drop happens relatively quickly, the effects are somewhat 'delayed' inside the dam. For the sandy material, the effect kicks in rather quick due to the high permeability, but for the core this is not true. This introduces high variance of pressures and leads to more suction on the downstream slope as well as on the upper part of the upstream slope. In Phase 3, the time interval of 6 hours is made longer to see the difference in pressure profile and the effect of this rapid lowering. The time interval is chosen to be 5 days and the difference is visible in the pore pressure curve for Phase 3, *see Figure 106 Phase 3*. The water level lowering in the reservoir echoes throughout the dam. For a rapid one, the water line lacks behind due to the core. However, considering longer periods of time (in this case 5 days), the pressure that is built up in front of the dam is slowly declining and the result shows that the water level inside the dam is much lower. The result of the lowered water level is analyzed in Phase 4. The trend in the curves continues and the pore pressure along the dam for Phase 4 is displayed In *Figure 106 Phase 4*.

The most visual change of how the lowering affects the dam is in terms of the deformations (NOTE: the deformations are scaled). At Phase 1, the deformations are somewhat limited (*see Figure 107 Phase 1)*, however after Phase 2, the rapid lowering of the water level, the deformations are significantly higher (*see Figure 107 Phase 2*). The locations where the deformations take place are mainly at the core, which is highly compressible. The trend is continued in Phase 3 and Phase 4 (*see Figure 107 Phase 3 and Phase 4*). The deformations are quite significant. The difference between the high reservoir level (+39m NAP) and the crest of the dam (+40m NAP) is only 1 meter, which is barely sufficient to counter the deformation, especially considering added safety factors. It should therefore be considered to either lower the high reservoir level or heighten the crest level.

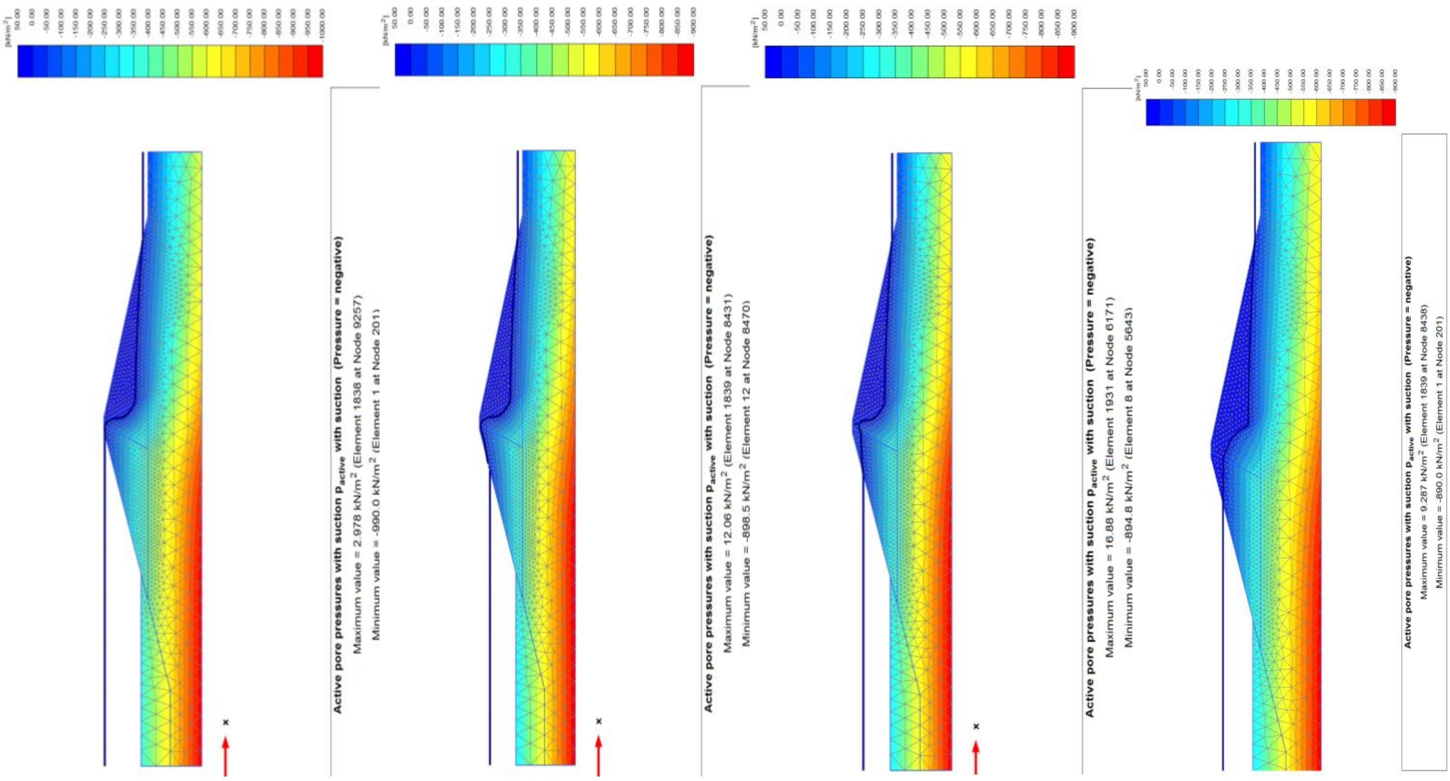

Figure 106 ... Active pore pressure in Phase 1 till Phase 4

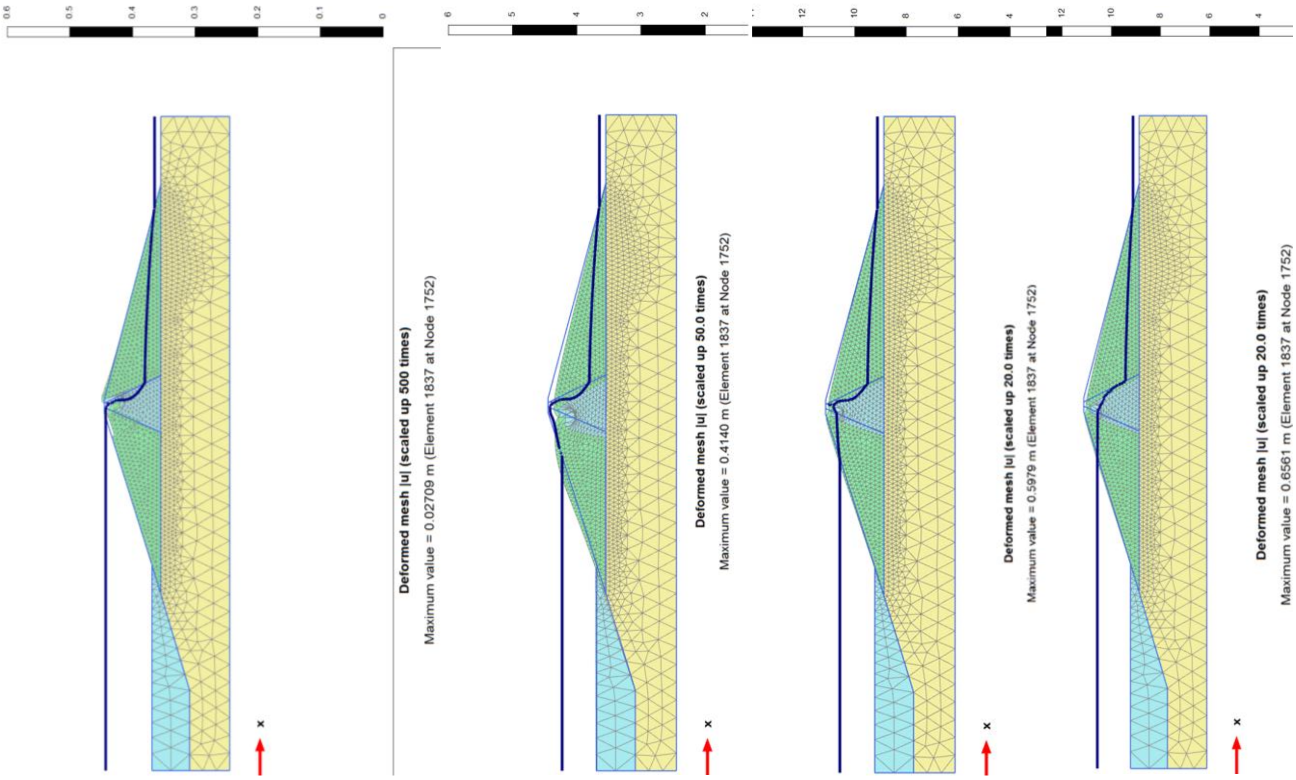

Figure 107 ... Deformations in Phase 1 till Phase 4

Stability

The safety factors for each phase are displayed in *Table 32*.

Phase	Situation	Stability Factor
Phase 5 (Safety calculation of Phase 1)	High reservoir level	1.765
Phase 6 (Safety calculation of Phase 2)	Fast lowering	1.270
Phase 7 (Safety calculation of Phase 3)	Slow lowering	1.505
Phase 8 (Safety calculation of Phase 4)	Low reservoir level	1.685

Table 32 … Stability factors for each phase

The reduction of stability during Phase 2 is substantial and this analysis has proven that the fast reduction has a large influence on the stability of the system. Whereas a conventional analysis may point out that the dam has a stability factor of 1.765, during the transitional phase from a high reservoir level to a lower one, the stability drops significantly to 1.27. The development of the safety factor with the deformation is displayed in *Figure 91*.

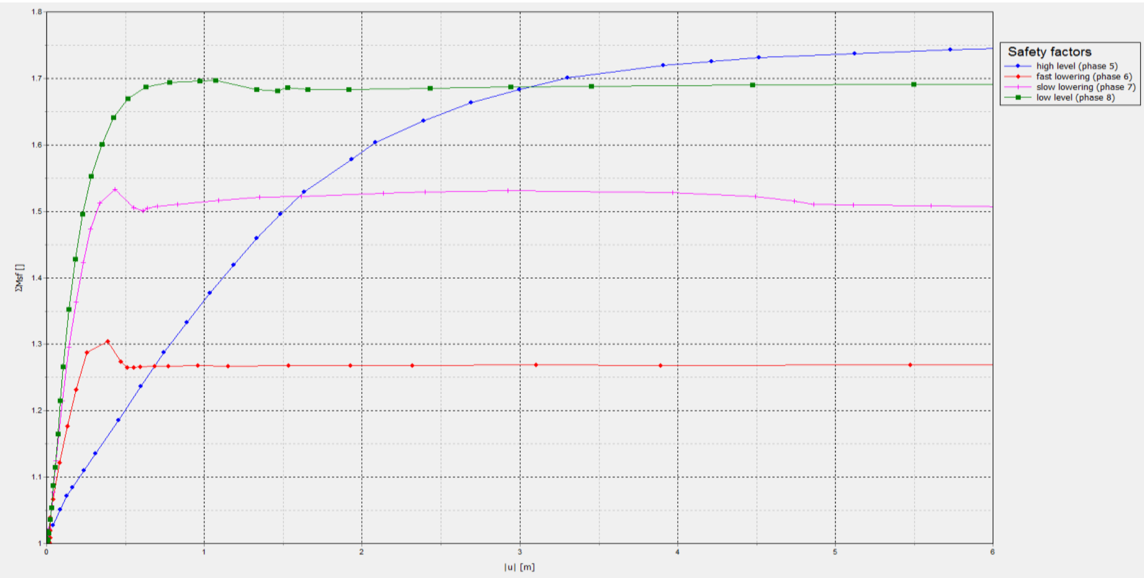

Figure 108 … Safety factor for each phase varying as the deformation increases

16.6.3 No Core Model (NCM)

Geometry and calculations

The reasons to place a core inside a dam is to limit the flow of groundwater and increase the stability of the dam. To analyze whether this is really required in this situation, a model without a core is analyzed; the No Core Model (NCM). For the analysis, the model is adjusted slightly by changing the material of the core into Dam Fill Sand, with which the program makes no more distinction between the core and the material surrounding it (*see Figure 109*). The same calculation phases, boundary- and hydraulic conditions are applied as in the previous cases; see *Figure 101 till Figure 105*.

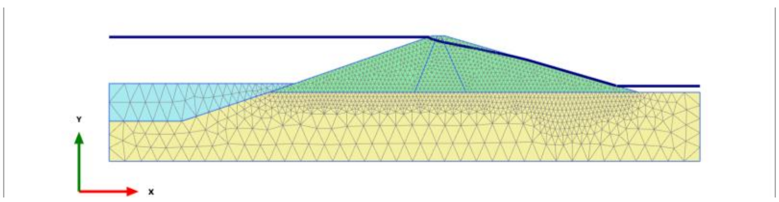

Figure 109 … Generated mesh for the no core model

Results

As expected, the dam collapses already in Phase 1 at which the high reservoir level is calculated. Analysis of the groundwater flow shows large amounts of groundwater flowing through the dam and leaving the dam near the toe (*see Figure 110*). The $\sum M_{stage}$ at the end of an uncompleted calculation step shows which part of the force imbalance is applied before the calculation failed. This is a measure of the safety factor for directly failing calculations. This value is for this model is $\sum M_{stage} = 0.45$.

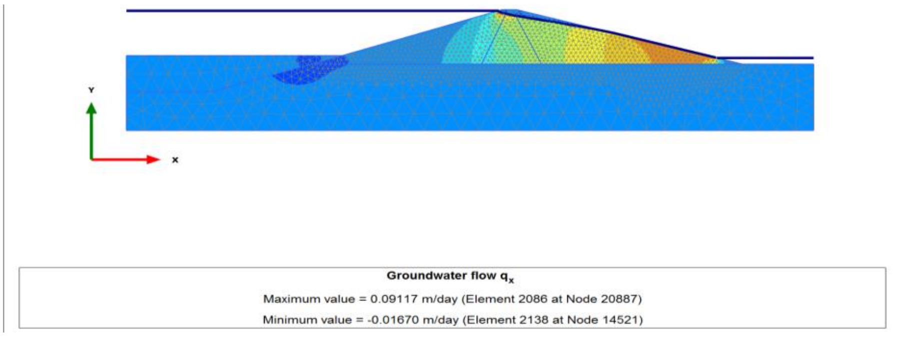

Figure 110 … Groundwater flow in the x-direction for NCM

Further evaluation displays the true culprit and reason for collapse. The analysis can be performed by looking at several data curves, all leading to the same conclusion (see *Figure 111*). The dam slides along the line that is visible along the figures and this is causing failure. It is confirming that this analysis presents the same results as GeoStudio 2012 for the dam without core.

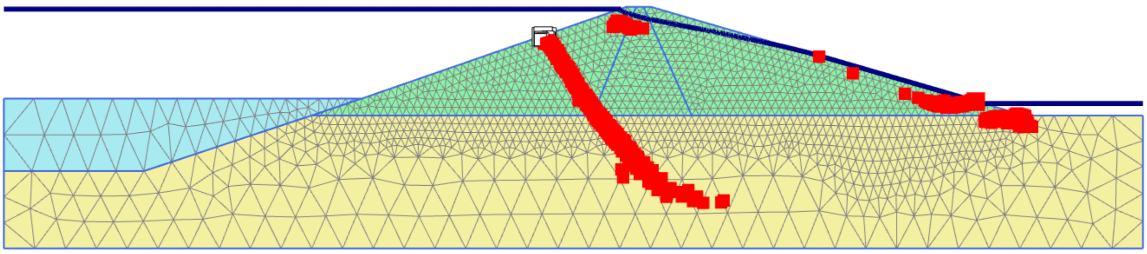

Figure 111 … Plastic points development for NCM indicated with red squares

16.6.4 Alternative core models

The CCM has been analyzed and the results have been evaluated. One problem with the CCM is that it requires some excavation of the current dam in order to place the core. The next step is trying to make improvements in the model as to aid the construction process. Two alternative cores are considered:

- the Line Core Model (LCM)
- the Shifted Core Model (SCM)

16.6.5 Line Core Model (LCM)

Geometry and calculation

In essence the same geometric model is used. The only alteration is the change of core shape. The model with the new core and mesh is presented in *Figure 112*. No other changes are made to any of the boundary conditions or hydraulic conditions; they are the same as in CCM, *see Figure 101 till Figure 105*.

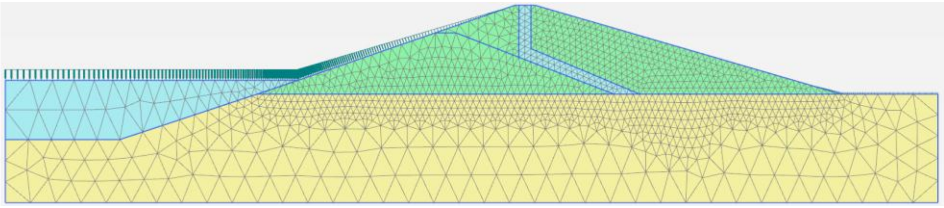

Figure 112 … Generated mesh Line Core

Results

Evaluating the calculations produces stable results for all the considered phases. However, for Phase 2, this stability factor is very close to 1. The stability factor M_{sf} at Phase 1 is 1.46 and at Phase 2 this drops to 1.06, which is significantly lower than the CCM and the figures display a potential weak point of this core model (*see Figure 113*). Stability is the major issue looking at the plastic points formation as wells as the strains, they all form a possible sliding line along which the dam could fail.

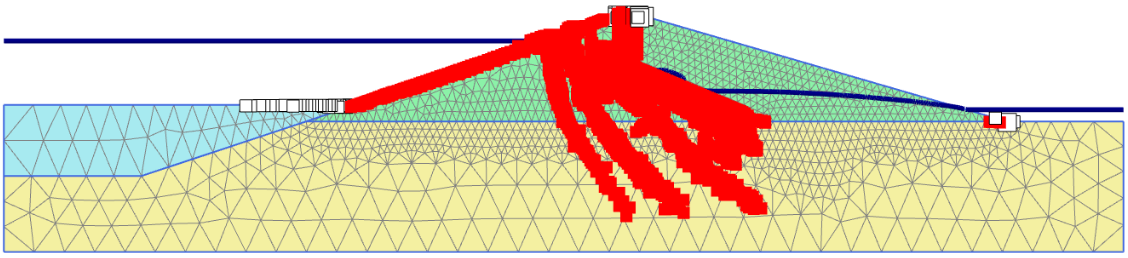

Figure 113 … Plastic points LCM in Phase 2

16.6.6 Shifted Core Model (SCM)

The other alternative core that is modeled is the Shifted Core Model (SCM). The goal with this model is to create a core that satisfies all criteria of stability and minimizes the removal of current soil. The model, its boundary conditions and the created mesh are displayed in *Figure 114*. The hydraulic conditions remain unchanged and can are visible in the CCM description in *Figure 101 till Figure 105*.

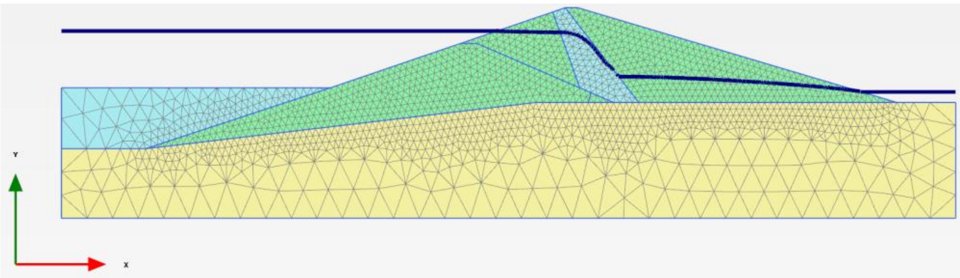

Figure 114 … Generated mesh with the SCM

Results

The results of SCM show a similar profile as the LCM with a low stability at Phase 2. While providing stability factor of 1.498 at Phase 1, this drops to 1.08 at Phase 2. The deformation is significantly higher (up to double) and this is caused mainly by the direct contact of the water with the core (*see Figure 116*). The pore pressure has an abrupt change when it reaches the core, unlike what was seen in the CCM (*see Figure 106*). This is because of the reversed angle the core has with respect to the core of CCM. As opposed to following the surrounding pressure lines, the pressure line changes shape. This is the cause of some other problems as the plastic points and strains. These problems are clarified in *Figure 116*. While it may look like there is no problem, the figure demonstrates that there are very high strains at the border of the core and the sand.

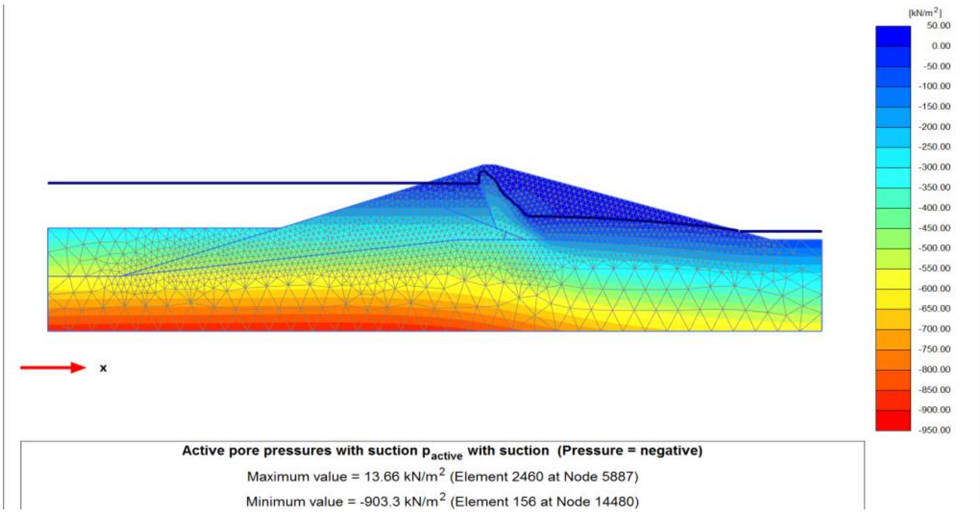

Figure 115 ... Active pore pressure for SCM for Phase 1

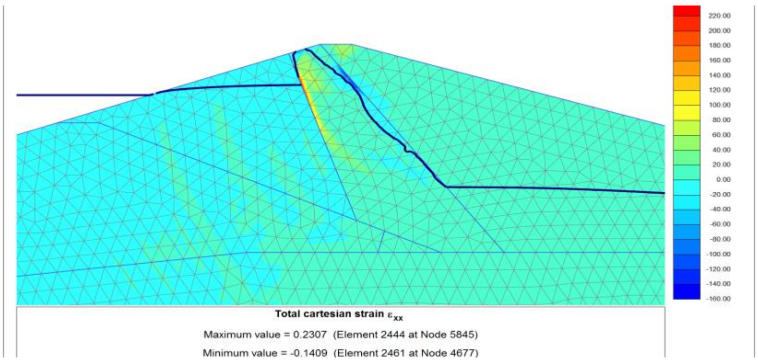

Figure 116 ... Strains for SCM in Phase 2

16.6.7 Concluding remarks on the effect of lowering reservoir level

The effect of the fast lowering reservoir has been thoroughly analyzed and experimented with the use of several different core models. The deformations and the effective stress distribution can be viewed on the basis of the results of phases 1 to 4. Here, attention is focused on the variation of the safety factor of the dam for the different situations.

Regardless of which core model is analyzed, the drop of stability because of the fast lowering water level is substantial and requires the dam to have a high initial stability factor. To exemplify this, the CCM model shows a stability factor of 1.79 for the high reservoir level which dropped to 1.27 in Phase 2.

Three different dam core designs have been tested for the defined calculation phases. The alternative that performed best was the original CCM. This model performed best in the flow of the stresses and keeping the deformations low. This is mainly because of the downward sloping side core. These results are in contrast to the other two alternatives, the SCM and LCM, which are largely alterations of the core to maximize construction ease. They both showed distinct weak spots, potential slide circles and therefore proneness to failure. The results is a weak stability factor for Phase 2, both not reaching values above 1.1, so not even 10% safety margin. Both alternatives utilize a core slope that should be mirrored along the vertical axis to provide a smooth transfer of stress. When the mirroring happens, it essentially loses all constructability benefits and thus leads to the CCM. Since stability overrules construction ease, the choice falls on the CCM.

16.7 Turbine housing and connecting penstocks

16.7.1 Francis turbines

The turbines that are chosen to be used in the alternative are Francis turbines that base their design on the Alqueva turbines but have been optimized for the Energy Island plan, which utilizes a lower head. The characteristics and performance of these turbines are laid out in *§19.2.1*. In this section, the turbine related constructions are analyzed. The design of the turbines as well as the related construction is not the main focus of this research, but their integration and feasibility aspects are analyzed nonetheless.

16.7.2 Flow velocity inside penstocks

Each turbine has one penstock connecting the high water level inside the Slufter to the turbine house which is placed at sea level. These should have a flow capacity which is equal or higher than the water flow capacity of the turbines. By dimensioning them with a slightly higher flow capacity, it is ensured that this part of the system is not the bottleneck. When the turbines are generating power, the flow through the turbines is in the range of 230 - 345 m^3/s, varying by hydraulic head. When the pumps are active to pump up the water back into the reservoir, the maximum flow is 170 m^3/s. This means that 345 m^3/s is the flow value per turbine for which a penstock has to be designed. The inlet and outlet of the penstocks are streamlined as much as possible ($\mu = 1$). The flow speed through the penstock is then given by

$$U_{penstock} = \frac{Q}{A} = \frac{Q}{1/4\pi D^2} \sim \frac{1.274\,Q}{D^2}$$

- U = flow speed [m/s]
- Q = flow [m^3/s]
- A = surface area penstock
- D = inside diameter of the penstock

For the initial design, the speed of the water is calculated using the maximum speed of the water given the hydraulic head. The initial diameter of the penstock is calculated using this speed and the formula above:

$$maximum\ flow\ speed \rightarrow U_{maximum} = \sqrt{2g\Delta h} = \sqrt{2 * 9.8 * 45} = 27.5\ m/s$$

$$diameter\ penstock \rightarrow 27.5 = 1.274 * \frac{345}{D^2} > D = 3.85 \sim 4\ meters$$

16.7.3 Losses

The assumption is made that the losses at the inlet and the outlet are negligible due to the relatively smooth transition. Also the bends and corners are performed smoothly in order to keep these losses at a negligible level. One loss source that could be play a significant role is the wall friction due to the large length of the penstocks of 140m. The head loss as a result of the flow is calculated using the Colebrook-White formulation. This formula is chosen because of its appliance for high Reynolds numbers which are expected here. The total head loss is calculated using Colebrook-White, however, written in another form:

$$Colebrook - White\ equation\ friction\ coefficient \rightarrow \sqrt{f} * \left[-2\log\left(\frac{\frac{e}{D}}{3.7} + \frac{2.51}{Re_{pipe} * \sqrt{f}}\right)\right] = 1$$

$$total\ loss\ of\ head\ due\ to\ friction \rightarrow H_{fric} = f * \frac{U^2}{2g} * \frac{L^2}{D}$$

- f = friction coefficient
- D = inner diameter pipe
- e = Colebrook-White roughness coefficient[151], 0.015 mm

[151] Flowserve, Cameron Hydraulic Data Book, 2000

- Re_{pipe} = Reynolds number of the pipe[152], $Re = \frac{UD}{v}$
    - v = kinematic viscosity, assumed at 10 degrees[153], 10^{-6} m^2/
- Length of the penstock, L = 140m

This is an iterative calculation, which is executed in *Microsoft Excel 2010* (see *Appendix V for Excel-sheet*). The hypothesis that the flow would be in the turbulent regime is proven and signifies the importance of this analysis. The calculations are done for the maximum volume of 345 m^3/s. For the initial design, this results in H_{fric}= 30.91 m, an immense loss. To reduce this significantly, the diameter is incrementally raised in order to see the effect, *see Table 33*. A small increment reduces the hydraulic head losses significantly, but this drop decreases with every increment. Changing the diameter also results in a more expensive structure. The diameter is therefore limited at 8 meters, for which the head loss is 0.96 m, just below 1 meter. This is only true for the flow at the top level. To illustrate this, the loss is only H_{fric}= 0.4 m for a flow of 250 m^3/s.

Parameter	Diameter	Flow speed	Friction factor	Head loss	Pressure loss
Symbol	D	U	f	H_{fric}	ΔP
Unit	[m]	[m/s]	-	[m]	[kPa]
Iteration #1	4	27.47	0.023	37	303.97
Iteration #2	5	17,58	0.023	10.15	99.60
Iteration #3	6	12,21	0.023	4.08	40.03
Iteration #4	7	8,97	0.023	1.88	18.52
Iteration #5	8	6,87	0.023	0.96	9.46
Iteration #6	9	5.43	0.023	0.54	5.3

Table 33 ... Hydraulic head loss due to pipe wall friction at the maximum flow of 350 m^3/s

The choice is made for a penstock of 8 meters diameter. This value is consistent with the turbine specifics (*see Appendix N for characteristics*), which feature a runner diameter of 8.8 meters. This massive 8 meters diameter forms a problem where the penstock hits the sea level. The local water level does not exceed 5 m depth. This can be solves with a combination of dredging and flattening of the penstock at the end (so that the surface remains the same but the height is less). The amount of flattening and/or dredging is dependent on the specific depth at that site. The turbine placement is moved more towards the sea where the depths are slightly larger (*see Figure 117*). More about the integration is in the following sections.

Figure 117 ... Seaward move of turbine placement (Google Maps, 2013)

[152] Prof.dr.ir.J.A. Batjes, Vloeistofmechanica, 2002
[153] Prof.dr.ir.J.A. Batjes, Vloeistofmechanica, 2002

16.7.4 Turbine housing

The reversible turbines will be placed on the outer side of the dams. While the design of the turbine housing is outside the scope of this report, real-life examples are displayed in which the placement of the turbine and the function in terms of shape and size are similar to the turbine system proposed here.

The first example is the derived from Plan Lievense (*see §11.3.1* and *Figure 118*). This plan consists of comprehensive ideas for the turbine housing design and dimensioning. The same designs are later used in the Energie Eiland concept (*see §11.3.2*).

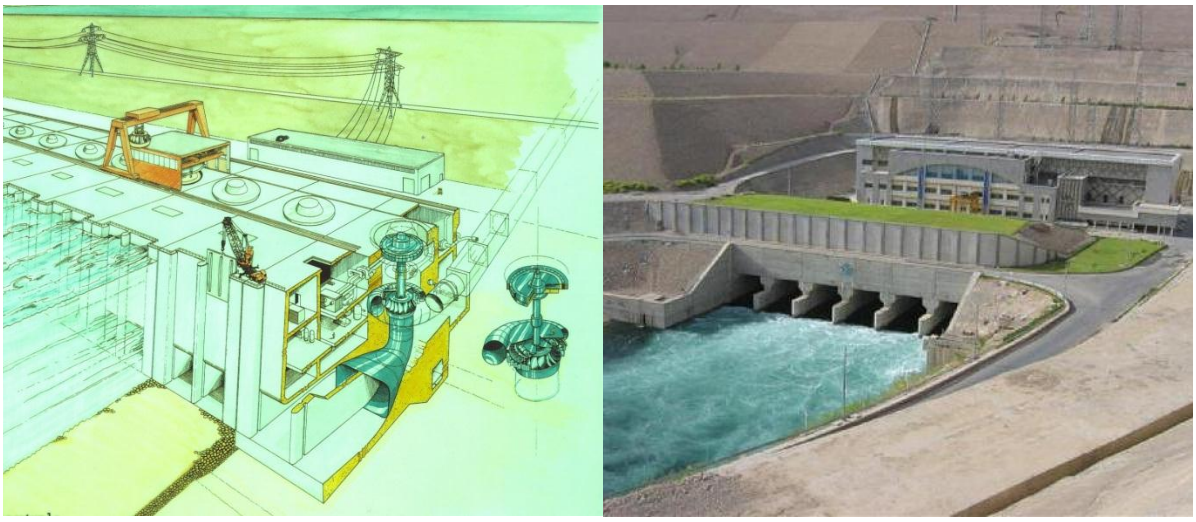

Figure 118 ... (left) Sketch of the turbine houses (Ingenieursbureau Lievense, Energie Eiland, 2006) and (right) Turbine housing for the Karkheh Dam in Iran (Industcards.com, 2012)

While the Plan Lievense turbine houses have not been realized, the next example has: the Karkheh dam in the Islamic Republic of Iran in 2001. The turbines offers similar capacity and the turbines houses have been realized in a very similar manner as is proposed here (*see Figure 118*). The width of the opening at the lower level is 30 meters and the power capacities of the turbines are 520 MW.[154] Another similarity between the Karkheh Dam and the Slufter is the use of an earth dam; the Karkheh uses a wide mix of different soils among which gravel, which has a higher internal friction angle than sand and allows steeper slopes. Nonetheless, the height of the dams of the Karkheh Dam is also significantly higher than is proposed in this plan, 127 m compared to 45 meters.[155]

16.7.5 Integration with the dam

The turbines will be placed in the section of the West-Voorne dams (*see Figure 117*). It is expected that the dam fill material is sufficiently strong that it can support the weight of the penstocks. The penstocks have a high stiffness in order to resists local deformation of the dam.

The turbine housing is placed at the toe of the dam. This should be taken in account in the design of the turbine housing as the load of the dam will be on top of it. Placing the turbine housing inside the dam has some benefits since the length of the penstocks is less and therefore the total loss of energy due to friction. Placing the turbines at the lower part also means that it is easily accessible in case of a malfunction or maintenance works. The cross-section of the West-Voorne Dam at the location of the turbines is displayed *in Figure 119*. The penstocks are placed between the current dam and the expanded part. This way, they utilize the head difference and require the minimum amount of work. This process is more detailed in

[154] Industcards, Hydroelectric power plants in Iran, Industcards.com, 2012
[155] S.R.Tafti, A. Shafiee and M.M.Rajabi, The influence of clay core composition on the permanent of embankment dams, 2008

Chapter 17. In the penstock opening areas (*see Figure 119 and Figure 120*) additional measures have to be taken for the surrounding soil. When starting and stopping the turbines/pumps, the generated flow is very high and could lead to local erosions near the dam toe. This could in time endanger the stability of the turbine housing and the dam itself. It is important to make sure this failure mechanism does not appear, so the soil at the bottom will have local strengthening that will have a length reaching until the outside of the turbulent zone of the penstock inlet. The inlet/outlet should be designed so that the water flow into the penstocks is smooth without much turbulence. This has already been pointed out during the consideration of the head losses and is also applicable here. With less turbulence in this area, less soil erosion will occur.

To reduce the seepage along the penstocks, a seepage barrier is placed and designed according to the Dutch building norm (NEN3651:2012). This states that if the penstock is crossing a non-primary embankment, the placement of seepage barrier is sufficient. While not valid for this situation, more strict rules suggest the placement of this seepage barrier inside clay box of at least 1 meter in front of the barrier. Since the penstock goes through the clay core dam, this clay box necessity is also fulfilled.

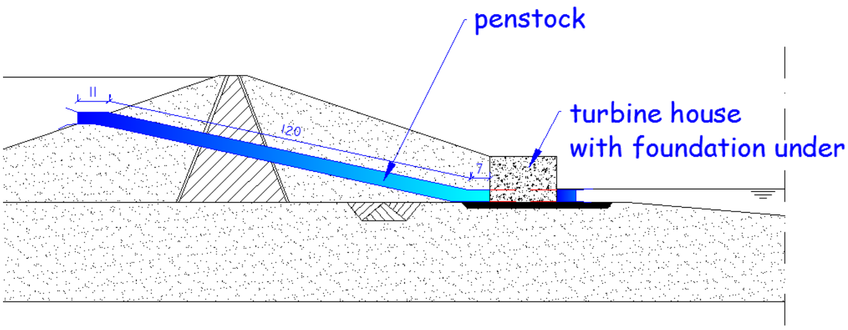

Figure 119 … Placement of the turbines and penstocks with respect to the dam design

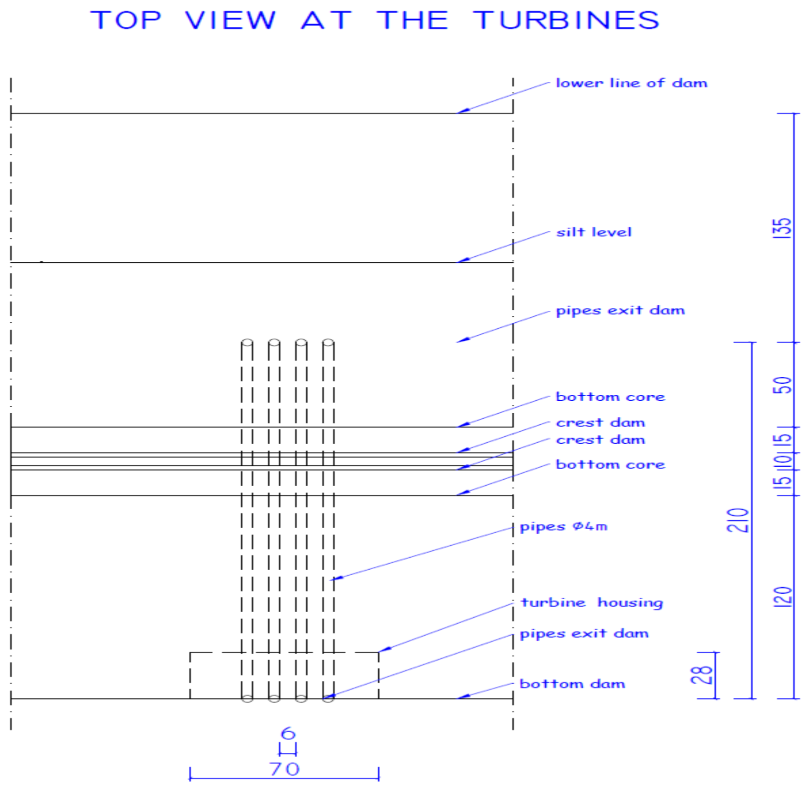

Figure 120 … top view of turbine placement

16.8 New Windpark Slufter

16.8.1 Strategies for the new Windpark

Currently, 17 windmills are operating to produce 25.5 MW of peak-capacity with one of the highest capacity factors in the Netherlands (*see §14.8 for more about this wind farm*). As the expansion takes place on top of the current dams, the windmills will need to be removed. Three possible alternatives are proposed for the new Windpark, after which a preference for one alternative is explained.

Removing the Windpark

An option is to remove the wind farm and not replace it. Placing wind turbines on top of a 35 meter high dam would drastically increase visual pollution and could be left out. Then there is the aspect of risk. In case of a dam breach, the bordering area of the Maasvlakte could be flooded (*see §14.8*). The placement of the wind turbine enhances this risk, e.g. the failing nacelle could potentially damage the dam due to its weight.

Re-placing the current turbines on top of the higher dam

This option considers re-placing the turbines on the new dams. Whether this alternative is an option depends on the technical feasibility; the new dam should be able to resist the added weight of the turbine. For this, the PLAXIS models of *§16.6* are recalculated with the distributed load on top *(see next paragraph).* This load consists of the foundation plus the turbine. The foundation dimensions are estimated from *Figure 121 left*; a circular foundation with 8m diameter and 2m thickness.

$$Weight_{foundation} = area * thickness * concrete\ weight \rightarrow \frac{1}{4}\pi * 8^2 * 2 * 24 = 2411\ kN$$

Because detailed information about the Siemens turbines on top of the dam is missing, the turbine weight is estimated using a reference turbine: the GE 1.5 MW from General Electronics *(see Figure 121 right)*.

Weight	GE 1.5 MW
Nacelle [kN]	550
Rotors [kN]	350
Tower [kN]	700
Foundation [kN]	2411
Total [kN]	4011
Weight/surface [kN/m²]	80

Figure 121 … Foundation of a 2 MW wind turbine (Pelegroup.co.uk, 2004) and (right) weight specs of the GE 1.5 MW

The placement of the turbine could be problematic due to placement of the core material. This core material is very easy to compress and is located right under the foundation of the windmill.

Upgrading the Windpark with higher capacity turbines

Another proposed alternative is to place turbines of higher capacity. This idea follows from the high efficiency of the current Windpark. With a capacity factor reaching up to 0.4, this is the perfect place to place high capacity turbines. This option is considered now by the operating utility companies (*see §14.8*). High capacity turbines proposed in the Windpark Noordoostpolder (*see §5.2)* could be utilized for this project as well. These turbines are significantly larger and heavier than the current ones. Should this be the desired option, the model would have to be re-run in order to assess whether it is safe to place these turbines. This is proposed as a recommendation.

16.8.2 Modeling of CCM with windmill on top

Introduction

This analysis will calculate whether it is feasible to re-place the windmills on top of the dam after the expansions in size. The load of the windmills is modeled for that particular part of the cross-section with a distributed load on top of the dam. This distributed load comes from the weight of the windmills and its foundation which transfers to the dam. This load is calculated to be 80 kN/m^2 with added safety factor for the permanent load. Two different analyses have been performed in order to experiment with the load of the windmill.

1. Distributed load on designed dam
2. Distributed load on designed dam with smaller core

Distributed load on designed dam

The geometric model is taken from the analyses performed in *§16.6* and added with the distributed load (*see Figure 122*). Note that the distributed load is only placed on top of the Dam Fill Sand and not on the Silty Clay Core material. This is because the distributed load is not placed upon a plate as it is in reality, however directly on the dam on the different sections. If the load would be applied on top of the core material, which is highly compressible, this would give an incorrect modeling of what will take place: once the core is deformed slightly, the sand which has a higher compressibility will take over the load. The distributed load is not modeled on top a plate because the plate deformation is not the goal in these analyses, only whether the dam can withstand the load.

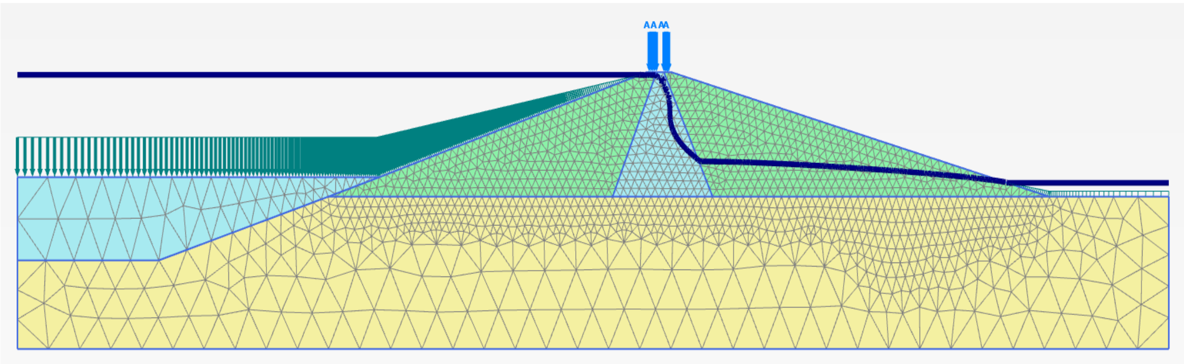

Figure 122 ... Geometric model with the distributed load

Results

The effect of the load on the stability is checked for the various calculation phases 1 till 8 (*see Table 34 and Figure 123*). This is because this load is permanent and will also act when the reservoir level is dropping quickly. This is considered to be the worst-case scenario.

The stability is expectedly lower than it is for the situation without load. Since the margins at Phase 1 are quite high, the situation with load offers no danger to the stability. However, the hypothesis that the fast lowering of the reservoir level could potentially lead to problems is true. The safety factor drops to 1.068 at Phase 6 (corresponding to the fast lowering phase), which is close to the critical balance of 1. The safety margin is too low to be considered safe. The same is true for Phase 7 and 8, although to a lesser extent.

Phase	Situation	SF with no load	SF with load
Phase 5 (Safety calculation of Phase 1)	High reservoir level	1.765	1.572
Phase 6 (Safety calculation of Phase 2)	Fast lowering	1.270	1.068
Phase 7 (Safety calculation of Phase 3)	Slow lowering	1.505	1.131
Phase 8 (Safety calculation of Phase 4)	Low reservoir level	1.685	1.129

Table 34 ... Stability factors for each phase with and without distributed load on top for CCM

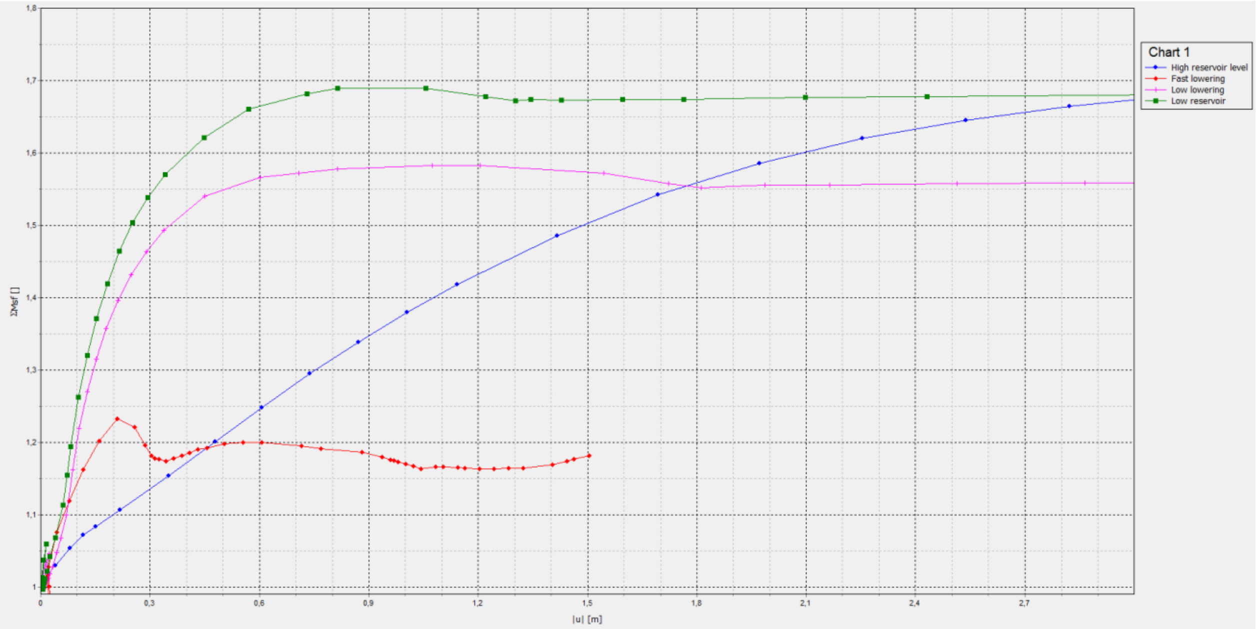

Figure 123 … Stability factor for CCM

Together with the drop in stability, the load is causing higher deformations at the top. As a consequence of the load, the two sections of Dam Fill Sand push down the core material further. This is causing large deformations for Phase 1 at which the high water level also pushes down. The other deformations seem to be controlled. The deformations of the model have been attached to *Appendix K.*

16.8.3 Distributed load on dam with smaller core

The stability factors presented for the previous model are too low to be considered safe. Therefore the model is slightly adjusted to test the effect on the stability. This change consists of the narrowing the core at the top so that the forces find their way quicker into the dam fill sand section of the dam. These parts have greater load bearing capacity. In the previous model, it seemed that the dam fill sand section takes on the distributed load and exerts it directly on the core. To limit this, it is analyzed what the influence is when the core is narrowed down and the hypothesis will be tested. No other alterations are made as far as the boundaries, boundary conditions, hydraulic conditions and calculation are concerned.

Since the load is only applied on the Dam Fill Sand section of the crest, this section is enlarged by decreasing the width of the core near the crest (*see Figure 124*).

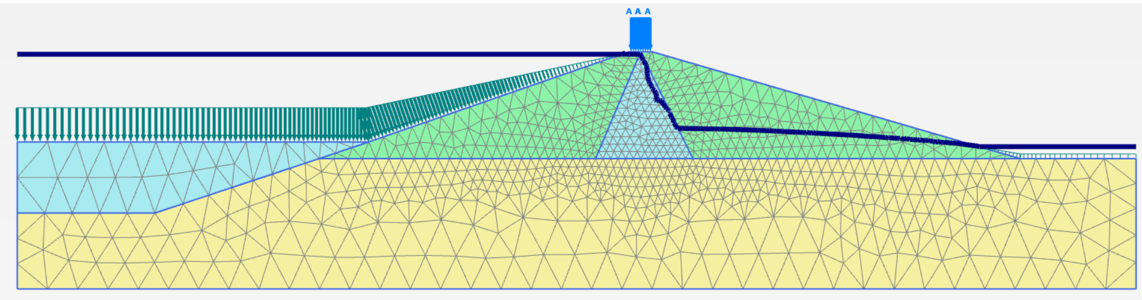

Figure 124 … Model with smaller core

Results

The alteration is successful because the safety factors of the corresponding phases have increased (*see Table 35*).

Phase	Situation	SF with no load	SF with load	SF with load and smaller core
Phase 5	High reservoir level	1.765	1.572	1.641
Phase 6	Fast lowering	1.270	1.068	1.184
Phase 7	Slow lowering	1.505	1.131	1.4
Phase 8	Low reservoir level	1.685	1.129	1.588

Table 35 ... Stability factors for each phase with and without distributed load on top for the smaller core

Each phase is showing higher safety factors than the previous model. The hypothesis has been proven and the model stability has been improved. The stability factor for Phase 6 is higher, but not really convincing of its stability. The factor safety of is below 1.2 for the fast lowering, which is still very low.

The deformations are lower than they are for the previous model which is promising. A larger part of the Dam Fill Sand is resisting the deformation introduced by the distributed load which is causing much less deformations and a better stress distribution overall. The deformations images have been added to *Appendix K*.

16.8.4 Concluding remarks on the placement of the windmill on top

It is shown that the original model has some complications when dealing with the added distributed load. The complications are mainly at Phase 6 when the reservoir level is lowered quickly. The stability factor drops to a value which is very close the critical value of 1.

The model with the smaller core that is introduced to improve this stability performs better. In this sense the thought process and hypothesis have been proved and the introduction of the model has been beneficial in the understanding of how the model works. Still, the stability factors of the smaller core model are not convincing as they remain below 1.2.

The smaller core model performs well at this analysis. However, because the model is smaller at the crest, this will influence the groundwater flow when the reservoir is high. This influence will be unfavorable as the width is smaller; the chance of the water passing over the core is higher. This could be a major problem. Therefore, this model can only be considered a recommendation for this analysis and a proof the hypothesis above. To say more, it should be further analyzed.

No convincing recommendation can be given at this moment as to the possible of placing windmills on top. Therefore the strategy of not replacing the windmills is chosen with the recommendation for more analysis. There are potential constructions possible which could make it possible such as

- Placing a vertical pile foundation under the windmill
- Placing sloping pile foundations in the dam to support the windmill

These possibilities should be analyzed further to quantify their potential.

16.9 Connection to national and European grid

The Slufter requires a high capacity cable to allow the connection with the grid. Since the generated power is far higher, the peak generation capacity of 375 MW is normative for the design of the connection cables. Depending on this value, it can be calculated how many 380 kV cables are required. The choice of a 380 kV cable comes from the vicinity of the port area and Maasvlakte. Analysis of the power grid lines surrounding the Maasvlakte area shows the vicinity of a 380-400 kV transmission line (*see Figure 125*).

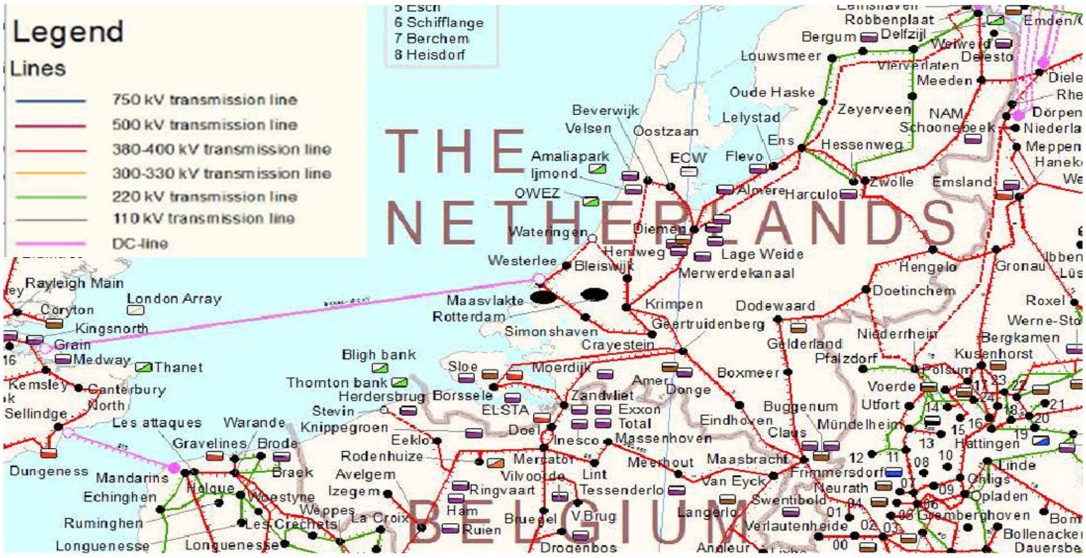

Figure 125 ... Power grid infrastructure of ENTSO-E Map 2012, ENTSO-E, 2012

There is a large coal plant of 1200 MW at the Maasvlakte of E-On. With a minor extension and possibly an upgrade of capacity, the cable connecting this plant to the grid could be utilized by the Slufter as well.

What is furthermore interesting is the proximity of the international power line with the United Kingdom (UK). Especially since the UK is currently expanding its wind power capacity significantly (*see §2.5*). At night, the UK can either turn down their wind turbines or keep them operating in order to power the water turbines of the Slufter. The presence of this line could offer possibilities for close cooperation with the UK

Figure 126 ... Location of the coal plant and the required extension (E-On, Locatie Maasvlakte, 2013)

16.10 Filter on top of the silt layer

In order to prevent the mixing of the contaminated silt layer with the water, a filter is placed on top of the silt layer. The top silt layer inside the Slufter is very muddy in contrast to the lower parts which are largely consolidated. Since the particle size is very small, these particles can easily get picked up by the flow during turbine activity. These particles contain many contaminants and could damage the surrounding nature. Ergo, the filter does not have to be water-sealing; it needs to limit the very top level erosion. A geometrically closed filter is fit for this application. The idea behind this type of filter is that the particles of the base material get stuck inside the larger particles used for the filter material. The filter layer should have larger permeability than the base layer so that there is no building up of local pressure. The choice upon determining the right filter layer depends on three criteria:[156]

- Stability between filter layer and base layer: $\frac{d_{15F}}{d_{85B}} < 5$
- Higher permeability of filter layer than base layer: $\frac{d_{60}}{d_{10}} < 10$
- Internal stability $\frac{d_{15F}}{d_{15B}} > 5$

The application of these criteria results in two boundaries in between which the result is supposed to be chosen. A particle size of 0.004 mm is assumed from the classification of the material as silty clay (*see §14.6.2*). Assuming a gradation of this material with a ratio $d_{85}/d_{15} = 2$, gives a range of around d_{15}= 0.003 mm and d_{85}=0.006 mm. The stability rule and permeability rule gives

$$d_{15F} < 5 * d_{85B} = 0.03\ mm$$

$$d_{15F} > 5 * d_{15B} = 0.015\ mm.$$

The d_{15} value of the material should be in between 0.015 and 0.03 mm. For the internal stability rule, the d_{60}/d_{10} = 10 ratio is assumed to be about the same as d_{85}/d_{15}= 15. This means that coarse silt to very fine sand with a d_{15} value of 0.02 mm and a d_{85} of 0.1 mm will be suitable as material for this filter layer

16.11 Evaporation out of the system

The evaporation of water out of the reservoir is a net loss of water that reduces the efficiency of the system. Without going into much detail about the several computation methods to calculate the evaporation, reference data is taken elsewhere in the Netherlands.[157] Since climatological aspect play a large role in the evaporation, the use of this data can be justified. The net loss due to evaporation in the province of Friesland was calculated for each season (*see Table 36*). The dominant season is summer, during which the evaporation is 4.65 mm/day.

Season	Spring	Fall	Summer	Winter
Evaporation [mm/day]	2.7	1.6	4.65	0.67

Table 36 ... Reference evaporation values for the open waters in Fryslan (FutureWater, Berekening Verdamping, 2006)

For the upper reservoir this means a daily evaporation of

$$daily\ evaporation = evaporation/day * surface\ area \rightarrow 4.65 * 3.14 * 10^6 = 14601\ m^3\ per\ day$$

Because this seems significant, this is put into perspective: the daily fluctuating water mass is in the order of 30 million m^3. Compared to these fluctuations each day, the evaporation of this is only 0.0047% of this value; an insignificant loss. Daily, the pumps will have to pump for an additional 20 seconds to account for this loss. The order of these losses is really small and will be balanced somewhat by the precipitation.

[156] G.J. Schriereck, Bed Bank and Shoreline Protection, 2004
[157] FutureWater, Berekening openwaterverdamping Fryslan, 2006

17. Construction method

An overview of the main construction activities that are discussed are

17.1 Introduction to construction method

The technical design that is analyzed must be able to be built in a rather easy way. In this section the different possibilities for construction will be explained. All the activities that are required are identified with their corresponding estimated duration. With all the activities in sight, a concept planning can be made for the realization of the technical design.

The result of this section should be a clear understanding of all the necessary steps in order to go through the construction. While smaller activities may require more detailing, it should be clear how to the construction process progresses in general and that solutions are presented for large problems regarding constructability.

17.2 Site preparations

17.2.1 Clearing, stripping and grubbing

The project starts with clearing all non-required objects from the site, such as the removal of vegetation, boulders, fences, small buildings and other structures close to the site. There are no large hindrances that need to be taken care of *(see Figure 127)*. Stripping is the removal of all topsoil of the dam. The top soil is heavily affected by external factors such as wind and weather so that the characteristics of the topsoil could be different because of mixing soils. Grubbing is the removal of organic material, such as roots and plants. Any organic material that is still on the outer dam surface may influence the behavior of the expanded dam. Therefore, this step is essential to guarantee stability and durability.

17.2.2 Removing the windmills

Before any heightening of the dam may occur, the windmills which are currently on top of the Slufter have to be removed. There are 17 windmills placed at certain distances throughout the entire dam except for the southern section (*see Figure 127*). Disassembly of the wind turbine goes according to the following steps: [158]

1. Remove the rotor blades (*see Figure 128*)
2. Remove the nacelle with the gearbox and generator
3. Remove the top part of the tower (*see Figure 128*)
4. Depending the different parts the tower is built up from, repeat the last step

Figure 127 … Position of the 17 windmills on top of the Slufter (Google Maps, 2013)


Figure 128 … (left) Rotor disassembled from tower and (right) disassembly of the tower in parts (Mlife.com, 2008)

Disassembly of a turbine can be done very quickly. Utilizing one crane, it will maximally take one week to disassemble all. Storing the units can be done in vacant areas of the Maasvlakte 2.[159] Since storage is only required during construction, this is justified and future plans of the Maasvlakte 2 area aren't hindered.[160]

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[158] NRELPR, Short time lapse of a 1.5 MW wind turbine installation at the National Renewable Energy Laboratory, Youtube.com, 2009
[159] B. Kuipers, Is het erg als de Maasvlakte 2 voorlopig voor een deel leeg blijft, Erasmus Univeristy Rotterdam, 2012
[160] Port of Rotterdam, Projectorganisatie Maasvlakte 2: Monitoringsplan aanleg Maasvlakte 2, Maasvlakte2.com, 2008

17.2.3 Re-routing Maasvlakteweg and Noordzeeboulevard

The road on the northern side of the Slufter is the Maasvlakteweg. When the expansion on the northern side is to be considered, this road must be placed more towards the north where sufficient space is available. The re-rout will take place by first constructing the new road in order to keep the function and the accessibility. This new road is placed about 100 meters more upwards. The move should also consider any pipes and cables. Once finished, the old road can be demolished and its material recycled. The same process goes for the Noordzeeboulevard, which will be built after finishing the dam expansion.

17.2.4 Dredging the inner area in between West-Voorne and the Slufter

As the area enclosed by the Slufter and the West-Voorne coast is increasingly getting clogged by the sediment (*see §14.3*), this area needs to be dredged to ensure that large amounts of water can be extracted. Also the penstocks will pump and flow out into this section. To ensure a certain depth for the placement and operation of the penstocks, some local dredging may be required (*see Figure 129*). This dredging will not be a problem because this is not a Natura2000 area and the wildlife between the Slufter and West-Voorne is focused more towards the Oost-Voornse Meer.

Figure 129 … (left) Area clogged by sediment; needs to be cleared because of the turbine placement and (right) location of temporary storage site where the dredged sand can temporarily be stored (Google Maps, 2013) (Google Maps, 2013)

17.2.5 Temporary storage site for the dredged material

Large amounts of dredged soil will need to be stored temporarily before it is distributed to the location where the dam construction is ongoing. The availability of the Slufter Strand (the beach), is also used during the construction of the Maasvlakte 2, where the beach was used as a temporary site to store equipment etc. (*see Figure 129)*. This stretch of land can also be used as a dump site for the dredged material. There are no large spatial limitations here, so a further detailing is not required at this stage.

17.3 Phased construction along the length

The upgrading the dams will be done in several phases. This will be beneficial in terms of costs and allows for the re-use of the temporary sheet piles to create a building site. Since work cannot commence everywhere at the same time, this phased construction will not hinder the total construction time. The construction will be split in four phases (*see Figure 130*):

1. West-Voorne Dam and part of the Maasvlakte dam (in blue)
2. Northern part of the Maasvlakte dam (in red)
3. Western park of the Maasvlakte dam (in green)
4. North Sea dam (in orange)

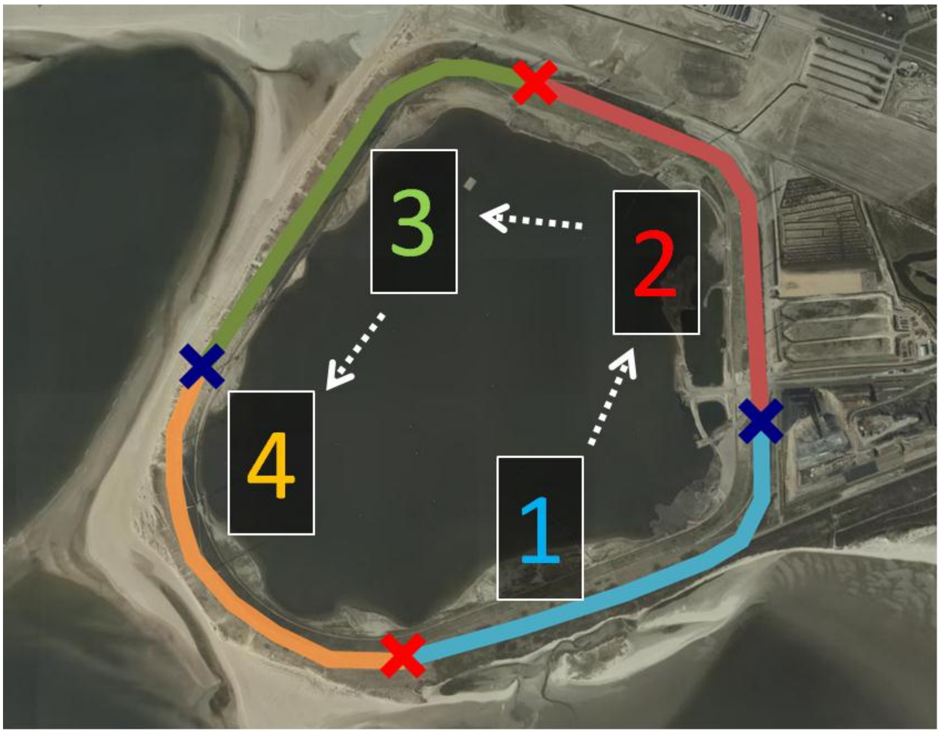


Figure 130 ... Placement of the sheet piles, numbers indicating sections, X marks indicating sheet pile borders (ArcGis, 2013)

The construction is started at section 1 because the turbine will be placed there. Since the construction of the turbines housing and connections may take some time, this is the start of the construction. Then the sheet piles are moved to part 2 and so on following the circle. The North Sea dam is chosen to be built last because this is where the sand will be dumped and spread out during the construction of the different phases. The sheet piles sections are marked with the X in Figure 130. After the construction of the initial part of the dam, they can be moved to the next section as the construction of the rest of the dam continues. Since there is a lot of possibility for overlap of the different activities and sections, the construction will not be halted by these activities.

17.4 Creating a building site

17.4.1 Introduction

Two temporary sheet piles are needed for the construction; one on the dam side and one on the sea side (*see Figure 131*). The ground retaining sheet pile *(displayed on the left in Figure 131*) has the primary function to withhold the soil pressure as well as the water pressure. The sheet pile is anchored into the back soil with 2 anchors. These sheet piles are extensively calculated using PLAXIS 2D 2011 (*see §16.6*). The length of sheet pile that is required is the ¼ of the perimeter that it is enclosing *(see previous paragraph)*, which equals to 1500 meters. The amount of anchors is not lessened by this, since they cannot be re-used but will remain in the soil. The sheet piles are driven into the soil using a pile driver.

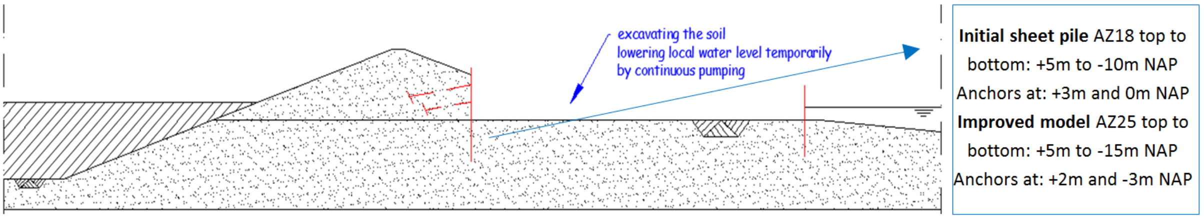


Figure 131 ... Temporary sheet piles construction

17.4.2 Modelling the temporary ground retaining walls

The ground retaining wall is modelled using PLAXIS. The full analysis of the sheet piles is in *Appendices X*. An initial model and an improved model have been calculated:

- First, using initial design choices, the sheet pile is modeled with top to bottom from +5m to -10m NAP (ground level at -5m NAP). The sheet pile is supported by two anchors at +3m and 0m NAP.
- The model is optimized by going deeper to -15m NAP, changing the sheet pile wall from AZ18 to AZ25 and re-positioning the anchors for better moment distribution , at +2m and -3m NAP

The two models in their ultimately deformed state are displayed in *Figure 132*. The model is not only improved in terms of deformations, but also in the moment distribution of the sheet pile *(see Figure 133).*

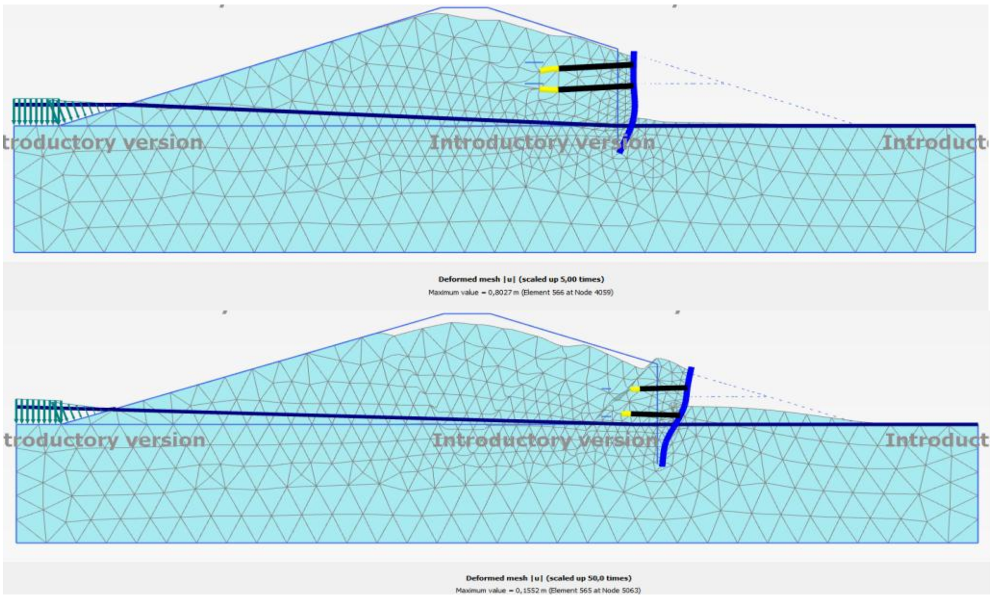


Figure 132 ... (upper) deformed state for the initial model and (lower) deformed state for the improved model

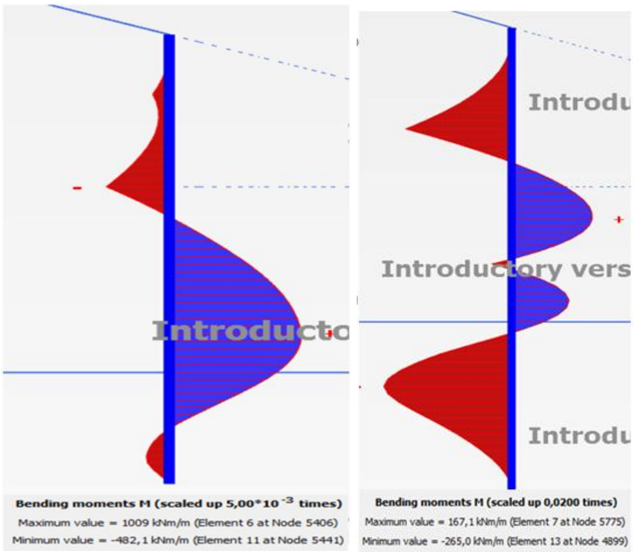


Figure 133 ... (left) sheet pile moment distribution in the initial model and (right) moment distribution in improved model

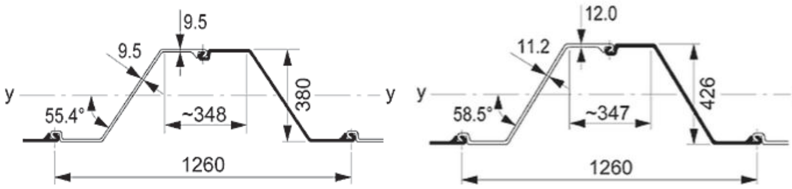


Figure 134 ... AZ18 vs. AZ25 (ArcelorMittal, 2013)

Concluding remarks on the sheet pile analysis

The improved model performs substantially better than the previous model, reducing the deformations, improving the overall stability *(see Figure 135)* and reducing the moments in the sheet pile and thus allowing for a cheaper sheet pile for construction. The maximum bending moment in the sheet pile is 267 kNm/m. The sheet pile that is chosen was the AZ-18 (from ArcelorMittal), which was improved to the AZ-25 in the improved model. Even with the smallest steel grade, which is S240, the maximum bending moment resistance is 589 kNm/m, which is way above what is 265 kNm/m. Considering this wide safety margin, it should be considered whether there is still room for further optimization by choosing a smaller profile.

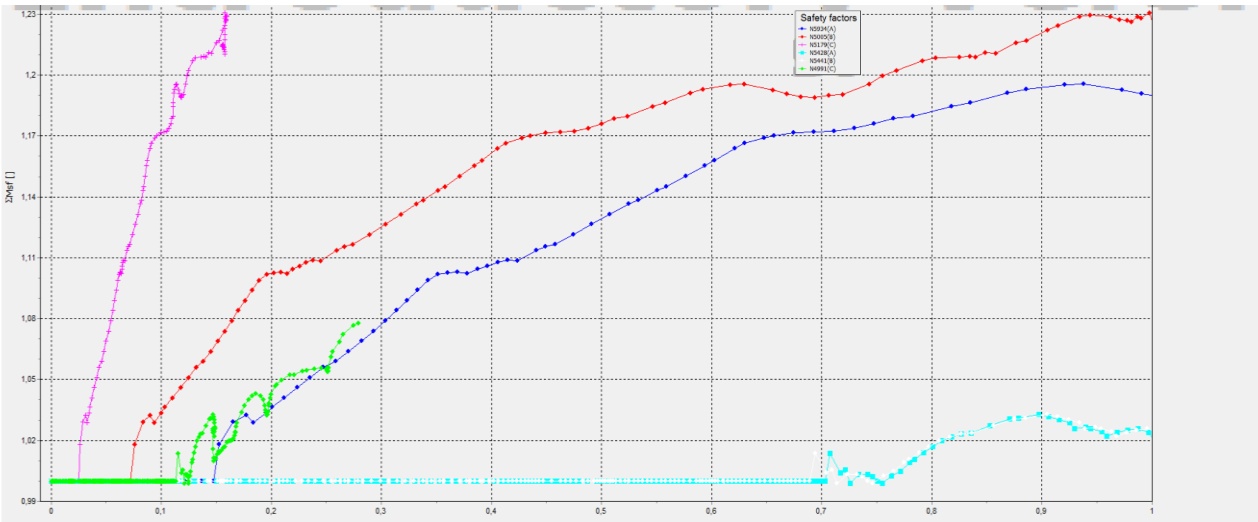


Figure 135 ... Safety factors chancing with displacement (stability curves of points A, B, C (top to bottom) for the improved model (top three curves) and the initial model (lower 3 curves note: one is in white))

17.4.3 Water-retaining sheet pile

The water-retaining sheet pile (*displayed on right of Figure 131*) has the primary function of with-holding the direct flood of water into the excavated area. This is water height of 5 meters, although this changes along the area and it is doubted whether this is really necessary. Also due to its lower complexity, the pile will not be thoroughly analyzed.

It could even be considered to pump all the water in the area in between the Slufter and West-Voorne.

17.4.4 Lowering the groundwater level

Now that the building site is closed off from both sides, the local water level must be dropped in order to start construction of the dam. This is difficult to assess, because the depths along the shore are very fluctuating. If there is need for lowering the water level, this is done using temporarily draining using pumps. Once the lower part of the dam is constructed, the drainage can stop. The area that needs to be drained is rather large, but the amount of lowering is not.

There will be a groundwater flow from the surroundings into this temporary basin as well. In this stage this is perceived as being limited but does require more analysis.

17.5 Sand source

The total volume of sand for all the construction works will be in the order of 14.5 million m^3. To put these volumes in perspective: for the construction of the First Phase of Maasvlakte 2, a volume of 240 million m^3 sand is required, which makes this only 6% of the scale of the Maasvlakte 2. Because of the scale of the dredging works, the Maasvlakte 2 is an interesting reference project for the dredging part of the Slufter. From extensive research a suitable area for sand collection is found (*see Figure 136)*. The choice for sand collection areas for the Maasvlakte 2 is based upon two factors: [161]

- supply qualitative sand fit for construction of land
- relative close proximity to the project

Both criteria are valid for the Slufter and due to the location of the Maasvlakte and the possibilities to dredge this site from the sea; the sand collection areas used for the Maasvlakte 2 are also suitable places for the Slufter dam expansion. Since the required sand is only 6% of the required sand of the Maasvlakte, it is expected that the amount of sand is present. Some assumptions are made for the source (*see Table 37).*

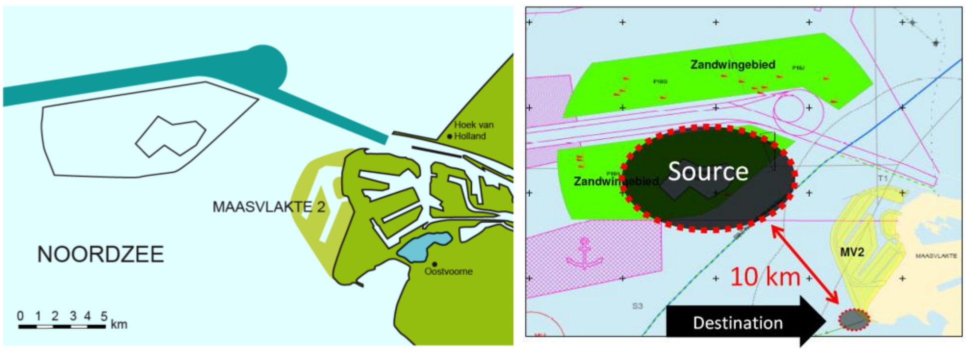


Figure 136 … Map showing the sand collection area for the Maasvlakte 2

Characteristics source	value
Depth of the sand	20-30 m
Distance to project site	Approximately 10 km

Table 37 … Relevant characteristics of source

[161] Maasvlakte2, Zorgvuldige selectie zandwinlocatie en hergebruik zand, Maasvlakte2.com, extracted on 2013

17.6 Dredging methodology

The dredging methodology will consist of several steps and is partly cyclic (*see Figure 137*).

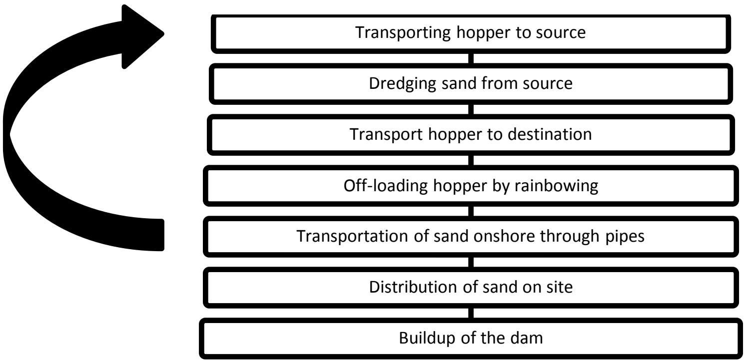


Figure 137 … Dredging methodology

The required amount of sand from the source is 14.5 million m^3. During the dredging process, a lot of the dredged soil will be lost due to many reasons; this is estimated around 20% of the total, meaning that the total should be taken 17.4 million m^3.[162] A trailing-suction-hopper-dredge (TSHD) will be used because of its wide array of applicability and its suitability to dredge to a depth of approximately 30 meters (*see previous paragraph*). To optimize the calculations, a dredging vessel is chosen: the *Volvox Olympia* of *Van Oord Dredging and Marine Contractors (see Appendix M for characteristics)*. Two similar sized TSHD's will be used, utilizing in total three ships. An operational scheme is created for these three ships (*see Table 38*). The loading, off-loading, transport times and supplementation speed are determined as follows:[163,164]

- The loading time is 25 minutes, with added margin: 30 minutes, ship capacity is 4870 m^3
- The transport time is 30 minutes (*see Figure 136*)
- The off-loading time is about 20 minutes, estimated 30 minutes with margin
- Each cycle consists of 5 steps, with each step taking 30 minutes > total cycle time is 2.5 hours
- So every cycle (2.5 hours), the transported material is 14610 m^3 or 5844 m^3/hour

Step	Loading at source	Transport	Off-loading at destination	
1	#1 #2 #3			
2	#2 #3	#1		
3	#3	#2	#1	Cycle 1
4		#1 #3	#2	= 2.5
5	#1	#2	#3	hours
6	#2	#1 #3		
7	#3	#2	#1	
8		#3 #1	#2	Cycle 2
9	#1	#2	#3	= 2.5
10	#2	#1 #3		hours
11	#3	#2	#1	so on…
Ships	Ship #1 #1	Ship #2 #2	Ship #3 #3	

Table 38 … Scheme for dredging

[162] Dr.ir. S.A. Miedema, Dredging processes the loading process of a Trailing Suction Hopper Dredge, 2012
[163] Dr.ir. S.A. Miedema, Dredging processes the loading process of a Trailing Suction Hopper Dredge, 2012
[164] Volvox Olympia (Van Oord B.V., 2013) see *Appendix M*

17.7 Off-loading by *rainbowing* and distribution

The TSHD has a draught of 7.2 meter (*see Appendix M*), which means it cannot approach very near the coast. Instead, it can only reach the red line indicated in *Figure 138*. The safe depth the ship can reach is about 100 meters from the Slufter dam. From this distance, the ship can rainbow the sand onto shore.[165]

Figure 138 ... (left) Bathymetry of the area close to the Slufter (Deltares, Ontwikkeling Kliferosie Slufterdam 2013) and (right) Expected dump sites by means of rainbowing

The sand will be rainbowed into the dump zone and will be transported using a pipe system hooked on power pumps. Corresponding with the phased construction scheme (*see §17.3*), the sand is first transported to the 1st drop zone. After the required amount has been dropped, that section of the pipe system is taken apart and the sand will reach the 2nd drop zone. This process will continue until all sites have sufficient sand to build up the dam. After the 4th drop zone, the last drop zone is the same as the initial dump zone (*see Figure 138*). At the drop zones the sand will be used to construct the dam by more detailed equipment like dump trucks, bulldozers and scrapers.

A pump station is installed to pump the sand to locations as far as 1 km (the other side of the Slufter); the sand which already contains a high degree of water. The sand at the location will be drained in order to ease the construction and improve the constructive properties. There is no need to construct the entire pipe system in once, since the assembly of the pipe system is quick and easy and because the arrival of sand is limited by the TSHD's. The construction of the pipe system is therefore done in phases (*see §17.3*). The following steps are distinguished in accordance with the phased construction:

1. Construction of the pipe length until 1st drop zone (constructed 'against the clock')
2. Pump incoming sand onto the 1st drop zone (in the meanwhile start constructing dam)
3. Partly disassembly of pipe system until 2nd drop zone and assembly towards the 3rd drop zone
4. Pump all incoming sand onto the 2nd drop zone (construction of West-Voorne dam starts)
5. Disassembly remaining pipe system at 2nd zone and full assembly towards 3rd drop zone
6. Pump all incoming sand on the 3rd drop zone
7. Repeat step 3 for the 4th and 3rd drop zone and drop of all sand into 4th drop zone
8. Disassembly of entire pipe system, removal of pump station and rainbowing of sand into dump zone

Further optimization of this process is possible depending on the power of the pump station and the requirement of placing additional drop zones to further enhance the construction process

[165] Volvox Olmpia, Vimeo.com, 2012 (video showing operation of Volvox Olympia)

17.8 Core material source

The contaminated silt inside the Slufter is used for the construction of the core (*see §16.4 and §14.6.2*). Because of the higher consolidated degree, this material will be extracted from the lower levels (detailed soil analysis is required to determine this depth). To maintain the material characteristics as much as possible, this material will not be dredged but simply dug out. This digging can be done by placing the equipment on top of the current dam and digging from there. The equipment can then move along the length with the construction. Since the location of the material is very close to the site, this can be justified. It can be considered to automate this process with a similar system as the bucket-chain-excavator since the extraction depth and dam distance is the same along the length (*see Figure 139 right*).

The digging will be done parallel to the pumping of sand and will be done close to the section of dam core that is being constructed. This way, the transport length of the core material and the required equipment is kept at a minimum. The digging process is done constantly as the dam core gets higher. Before used for the construction, the core material is drained to improve its constructive qualities.

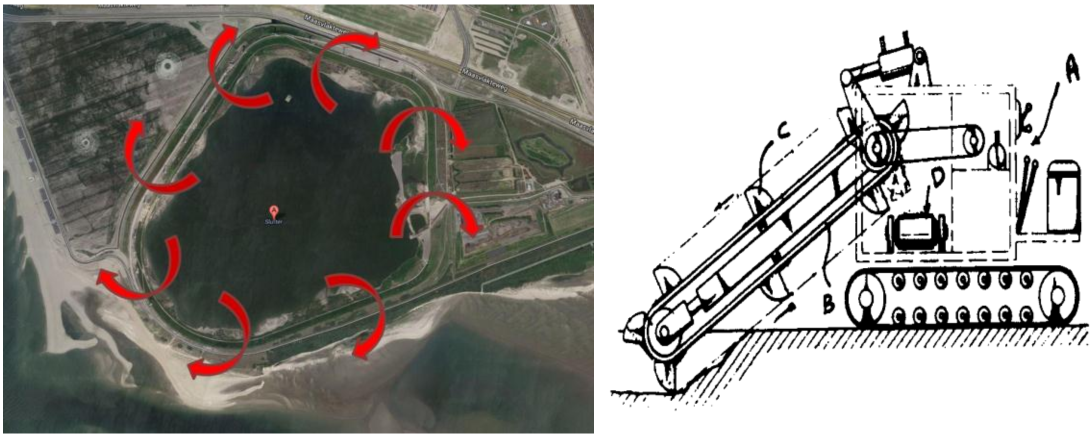


Figure 139 … (left) Pumping of the silty clay material from the inside to the outside of the dam and (right) Example of bucket wheel excavator (USPTO.gov, 2013)

17.9 Construction of the dam

The construction of the dam starts together with the construction of the core and the turbine housing (*see §16.7).* The construction method is explained for the West-Voorne dam for the cross-section with the turbines and penstocks (*see Figure 140)*. Other cross-sections have a similar method without the penstock and turbine housing. The penstocks will be placed on the dam until the dam has reached a slope in which the core material doesn't simply slide off under the steep angle. Assumed is that a slope of 1:10 is feasible for the core material. Should it be difficult for the core material to maintain any slope, this material can be supported by further deposition of sand from both sides, until the core is horizontal. The build-up of the dam will be done incrementally, meaning that the build-up of core material goes along with the build-up of the surrounding sand. This way, the steep slope of 3:1 for the core can be maintained with the constant support of the sand as the dam gets higher.

With each increment a thin layer of soil is placed on top of the previous layer. This layer is than compacted using rollers. The goal density of the fill and clay material is around 1600 kg/m^3. To achieve this level of density, vibrating rollers are used for the sand fill and smooth wheeled rollers for the core.[166]

[166] T. Stephens, Manual on small earth dams, 2010

17.10 Constructing the turbine housing and penstocks

The turbine housing is constructed on the outer bottom of the dam. The sequential process has been explained in *Figure 140*. The penstocks will be placed on top of the current dam along the slope until they reach the crest of the current dam. On top of these, the dam fill will be placed which will make the penstocks part of the dam. The construction of the turbine house is as straightforward as the construction of any concrete structure. Since the turbines are large items, they will have to be lowered into the construction using a crane upon the finalization of the turbine housing construction. This has to be taken into account during the construction process. The chosen crane is the same as the one to re-place the windmills on top (*see §17.11*) can be used for this, since a turbine will weigh in about 170 tons.[167] The construction of the turbine housing can start as soon as the building site is created and the local water level dropped. This is simultaneous with the construction of the dam core. The construction of the turbine housing does not hinder any other construction process and is therefore not restricted to any strict deadline. The penstocks will come prefabricated onto the site in segments. These segments will be placed onto location after which they will be joined and made watertight.

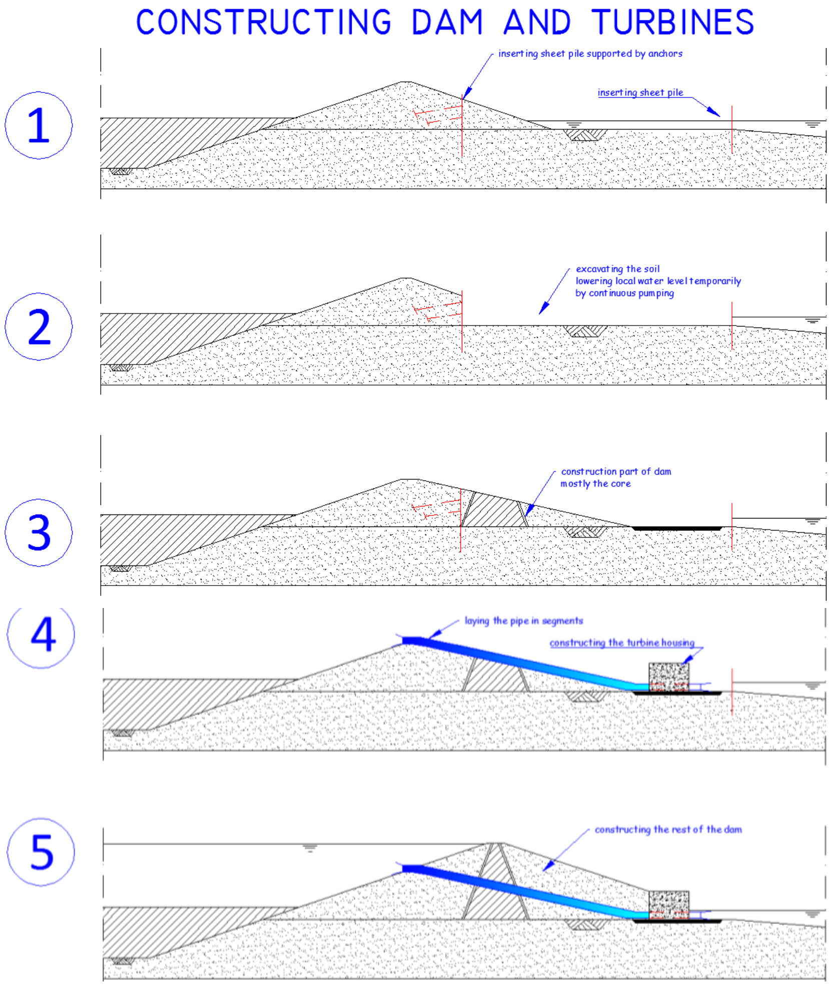


Figure 140 ... Construction method turbine, pipes and rest of dam

[167] K. Bonsor, How hydropower plants work, HowStuffWorks.com, 2011

17.11 Re-placing the windmills

Although some remarks have been placed for the placement of the windmills back on top in terms of the stability of the dam, especially during the fast lowering of the reservoir level *(see §16.8.2*), a quick insight is given to how this should be done.

Placing these windmills could be problematic because of the high elevation of the Slufter. Searching for a suitable crane results in many possibilities, among which a suitable one is presented (*see Figure 141*). This particular crane has the carrying capacity to carry the separate parts as well as the capacity to reach heights of up to 56m.

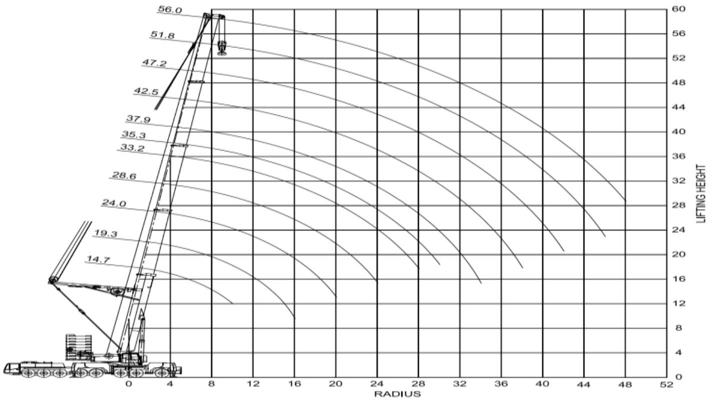


Figure 141 ... Mammoet mobile crane DEMAG AC 500-1 ***(Mammoet, 2013)***

The lifting crane would approach the landside windmills easily from the outside of the dam. For the seaside bordering dams, a barrage ship could be used to put the windmill and crane on top. Another possibility is using a ship crane. The advantage is that a ship crane can gain relatively easy access to the site. This easy access only applies to the southern section and it should be a ship with suitable draught properties. It is expected that a land crane would be cheaper and more efficient, because a ship of this scale would require more mobilizing costs and it would not be worth it for only placing the southern windmills.

17.12 Initial fill of the reservoir

Once the construction is finished, the reservoir can be filled using the four pumps. The volume of water required to fill up the entire reservoir is equal to

$$V_{reservoir} = average\ surface\ area * upper\ level \rightarrow \frac{3{,}14 * 10^6 + 2.51 * 10^6}{2} * 39 = 110\ million\ m^3$$

With a pumping capacity of 170 m^3/s for each turbine, it will take

$$T_{initial\ pump} = \frac{V_{reservoir}}{amount\ of\ turbines * pump\ capacity} \rightarrow \frac{110 * 10^6}{4 * 170} = 161764\ s \sim 45\ hours$$

This initial pumping requires a lot of power which is in the order of €300.000, negligible compared to the construction costs (*see Chapter 18.2)*.[168] After filling, the Slufter is ready for operation.

[168] Calculated with a hourly price of €40 per MWh

18. Planning & Costs

The following subjects are discussed in this chapter:

18.1 Planning

The realization of the construction project in terms of time is put out in the planning. It is rather preferable to have the construction built as soon as possible. Having a fast construction period has the following advantages:

- Sooner functionality
- Sooner creation of benefits
- Lower costs due to less rent building up
- Shorter occupation of the area
- Shorter period of hindrance to the surrounding

Motivated by creating an optimized construction period, a tight planning is created for the construction method. The construction costs are dominated by the rent of the TSHD (*see Chapter 18.2*). Therefore, it has been the aim to try to keep up the rental period of the TSHD's at a minimum, while trying the keep up with the rest of the construction. The critical line gives the normative time duration and these activities have a higher priority. Any delay of these activities will lead to a delay of the entire project; in order to control these risks, some margins have been added to their duration.

Construction starts in March 2nd 2015 and is planned to finish on December 16th 2015. This is a total construction time of

$$301\ days \sim 39\ weeks \sim 10\ months$$

The total project including the permit applications and the public awareness campaign stretches a year. The GANT-diagram of the project planning with the critical line indicated in red is displayed in *Figure 142*. The description of each activity can be found in *Appendix S*.

The following assumptions are made:

- The dredging is happening 24 hours a day, 5 days week (maintenance is possible in the weekends)
- For the other construction sites, a working day consist of 12 hours
- A work week is 5 days, starting from Monday till Friday
- Construction starts on March 2nd 2015 (three months after the silt depot contract ends)
- The duration of permits and licenses takes 3 months (should this take longer in reality, then the construction date should be fixed and permit application should start earlier)
- Vacations and holidays are neglected

18.2 Costs

18.2.1 Construction costs

The conventional method of calculation is short-sighted in terms of adding the full costs of a construction project. Especially when dealing with comparisons between RES and fossil fueled plants. Without going much into this discussion, a reference to *Appendix Q* is made out for more about this.

The indicative costs for the realization of the construction are determined for the project. They are dependent on the technical design, construction method and the planning. The costs have been calculated using indicative values obtained in literature and reference projects. By splitting up the activities and defining their sub-costs, a higher accuracy is obtained. The construction costs overview is displayed in *Table 39*. The detailed description of each cost-post can be found in *Appendix U*.

Energy projects are usually rated using the price per unit of power. This way they can be compared to one another in a more objective way. The total costs for the Slufter are nearly €580 million. With a power capacity of 470 MW, the investment price per unit is

$$costs\ per\ unit\ of\ power = \frac{primary\ costs}{peak\ capacity} \rightarrow \ \frac{580.000.000}{470} = \ 1.234\ million\ €/MW\ or\ 1234\ €/kW$$

This is significantly higher than fossil fuel alternatives, but a conclusion on the basis of the primary investments would be too short-sighted. Ergo, the unit price of the full lifetime of the project is presented in *Chapter 19*.

18.2.2 Maintenance and operation costs

The costs for hydropower systems like the Slufter are mainly dominated by the construction costs. The system requires no fuel to operate, apart from the power required to pump the reservoir back up (which is integrated into the power trade system, see §*19.2*). The operational costs are therefore limited to maintenance to electro-mechanical parts. The operational cost for hydropower systems are very low at €0.66 per kWh.[169] The total operational costs depend on the kWh produced in a year. Considering that the Slufter is operational fully along the year, the yearly MWh production of the Slufter is calculated. This number is reduced by considering some possible downtime of the system (e.g. for maintenance) and some other efficiency issues (the technical efficiency is incorporated in the storage capacity)

$$2{,}16\ GWh/day\ \sim\ 788400\ MWh/year$$

$$considering\ operational\ time\ of\ 90\%\ \rightarrow 788400 * 0{,}9 = 709560\ MWh\ per\ year$$

$$total\ cost = cost/kWh * yearly\ generation\ \rightarrow 0{,}66 * 709560 = 469309 \sim €\ 0.5\ million\ per\ year$$

This is significantly less than the operational costs for conventional power generation units. As mentioned before, a lifetime comparison offers a more objective view (see *Chapter 19*).

[169] IEA ETSAP, Technology Brief: Hydropower, 2010

18.3 Sensitivity of planning and costs

18.3.1 Cost sensitivy

The final costs will be sensitive to uncertainties in the cost estimations. The costs are split in to the civil engineering costs and the electromechanical costs (namely the turbines). The turbine costs are determined using recent reference data of turbines with similar and even larger capacity and confirmed with multiple reference project to ensure a high accuracy.

Three activities account for nearly 75% of the total civil engineering costs:

- Renting the TSHD (50% of the costs)
- Sheet pile works (13% of the costs)
- Rent of ground moving works such as bulldozers, scrapers etc. (8% of the costs)

Renting the TSHD has been determined using data from *Van Oord Dredging and Marine Contractors*. Their TSHD, the *Volvox Olympia*, has been used as a reference for the other utilized two ships. The rental costs have been directly verified (given this project description) and therefore offer a high accuracy.

The costs for the sheet pile works has been estimated using an average of the several sources *(see Appendix F and U).* By looking at multiple sources in the Netherlands, a higher accuracy is obtained.

The rental cost of the ground moving equipment has a high level of accuracy since the values have been directly obtained from a supplier of such equipment. An uncertainty in this regard is however the amount of equipment required. This is based upon the average handling speed of such equipment, which is a value which is very project-dependent. Therefore, a medium level of accuracy is obtained for this activity.

Concluding, the cost sensitivity analysis shows a high level of accuracy because of the reliable sources of information. Like mentioned before, the costs are very dependent on the duration of the construction works, which requires a sensitivity analysis of the planning.

18.3.2 Planning sensivity

The planning sensitivity is qualitatively assessed using the critical line in the Gant-chart *(see Figure 142)* and the activities mentioned above are related to see how the planning affects each activity costs. The following activities are considered:

- Permits and licenses: a wide range has been chosen here with a an advice to start earlier (possibly already in the engineering phase) with the procedures if problems are expected
- Site preparations: not much can go terribly wrong here, a slow process can be speeded with labor
- Assembly pipe line system: straight-forward task that consists of putting the parts together
- Pumping the required sand: this task depends heavily on the input of the dredging team. As the dredging is subject to lots of external factors that could influence its activities, some uncertainty is expected with regard to this. This is however buffered by incorporating margins for each step of taking the sand, transporting and dropping and by the fact that the onshore pumping starts delayed with respect to the sand dredging activities. This delay is another buffer incorporated in the planning. Using these buffers, the high accuracy is maintained.
- Finalizing and placing a filter layer: these are activities that are uncertain but have a small part in the total planning. Any delay is therefore not with large consequences, which allows less accuracy.

ID	Task Name	Duration	Start	Finish
1	**Preparations**	**80 days**	**Thu 1-1-15**	**Wed 22-4-15**
2	Permits and licenses	42 days	Thu 1-1-15	Fri 27-2-15
3	Public awareness campaign	30 days	Mon 19-1-15	Fri 27-2-15
4	Site preparation	30 days	Mon 2-3-15	Fri 10-4-15
5	Re-routing Maasvlakteweg	30 days	Mon 2-3-15	Fri 10-4-15
6	Reserving working space	30 days	Mon 2-3-15	Fri 10-4-15
7	Removal windmills	8 days	Wed 1-4-15	Fri 10-4-15
8	Placing sheet piles Phase 1	7 days	Mon 13-4-15	Tue 21-4-15
9	Lowering local water level	1 day	Wed 22-4-15	Wed 22-4-15
10	Assembly pipe system	3 days	Mon 13-4-15	Wed 15-4-15
11	**Dredging**	**132 days**	**Wed 15-4-15**	**Thu 15-10-15**
12	Enough for Phase 1	33 days	Wed 15-4-15	Fri 29-5-15
13	Enough for Phase 2	33 days	Mon 1-6-15	Wed 15-7-15
14	Enough for Phase 3	33 days	Thu 16-7-15	Mon 31-8-15
15	Enough for Phase 4	33 days	Tue 1-9-15	Thu 15-10-15
16	**Executiong Phase 1**	**120 days**	**Thu 16-4-15**	**Wed 30-9-15**
17	Foundation of turbine housing	7 days	Thu 23-4-15	Fri 1-5-15
18	Constructing turbine housing	90 days	Mon 4-5-15	Fri 4-9-15
19	Placing penstock	2 days	Thu 3-9-15	Fri 4-9-15
20	Placing turbines inside housing	2 days	Mon 7-9-15	Tue 8-9-15
21	Excavation part of old dam	10 days	Thu 23-4-15	Wed 6-5-15
22	Half-way construction dam	18 days	Thu 7-5-15	Mon 1-6-15
23	Pumping the required sand	33 days	Thu 16-4-15	Mon 1-6-15
24	Finising dam	18 days	Mon 7-9-15	Wed 30-9-15
25	**Preparations Phase 2**	**8 days**	**Tue 2-6-15**	**Thu 11-6-15**
26	Re-placing sheet piles	7 days	Tue 2-6-15	Wed 10-6-15
27	Lowering local water level	1 day	Thu 11-6-15	Thu 11-6-15
28	Assembly pipe system	3 days	Tue 2-6-15	Thu 4-6-15
29	**Executiong Phase 2**	**45 days**	**Fri 5-6-15**	**Thu 6-8-15**
30	Pumping the required sand	33 days	Fri 5-6-15	Tue 21-7-15
31	Excavation part of old dam	10 days	Thu 11-6-15	Wed 24-6-15
32	Half-way construction dam	17 days	Thu 25-6-15	Fri 17-7-15
33	Finising dam	17 days	Wed 15-7-15	Thu 6-8-15
34	**Preparations Phase 3**	**8 days**	**Mon 20-7-15**	**Wed 29-7-15**
35	Re-placing sheet piles	7 days	Mon 20-7-15	Tue 28-7-15
36	Lowering local water level	1 day	Wed 29-7-15	Wed 29-7-15
37	Assembly pipe system	3 days	Wed 22-7-15	Fri 24-7-15
38	**Execution Phase 3**	**45 days**	**Mon 27-7-15**	**Fri 25-9-15**
39	Pumping the required sand	33 days	Mon 27-7-15	Wed 9-9-15
40	Excavation part of old dam	10 days	Thu 30-7-15	Wed 12-8-15
41	Half-way construction dam	17 days	Thu 13-8-15	Fri 4-9-15
42	Finising dam	17 days	Thu 3-9-15	Fri 25-9-15
43	**Preparations for Phase 4**	**8 days**	**Mon 7-9-15**	**Wed 16-9-15**
44	Replacing sheet piles	7 days	Mon 7-9-15	Tue 15-9-15
45	Lowering local water level	1 day	Wed 16-9-15	Wed 16-9-15
46	Disassembly pipe-system	1 day	Thu 10-9-15	Thu 10-9-15
47	**Execution Phase 4**	**45 days**	**Fri 11-9-15**	**Thu 12-11-15**
48	Pumping the required sand	33 days	Fri 11-9-15	Tue 27-10-15
49	Excavation part of old dam	10 days	Thu 17-9-15	Wed 30-9-15
50	Half-way construction dam	17 days	Thu 1-10-15	Fri 23-10-15
51	Finising dam	17 days	Wed 21-10-15	Thu 12-11-15
52	**Finalizing**	7 days	Fri 13-11-15	Mon 23-11-15
53	Construction of small road on top	15 days	Tue 24-11-15	Mon 14-12-15
54	Placing the windmills on top	17 days	Tue 24-11-15	Wed 16-12-15
55	Placing a filter on top of the silt	14 days	Tue 24-11-15	Fri 11-12-15
56	Filling up the reservoir	1 day	Tue 24-11-15	Tue 24-11-15
57	Connection with national grid	5 days	Tue 24-11-15	Mon 30-11-15

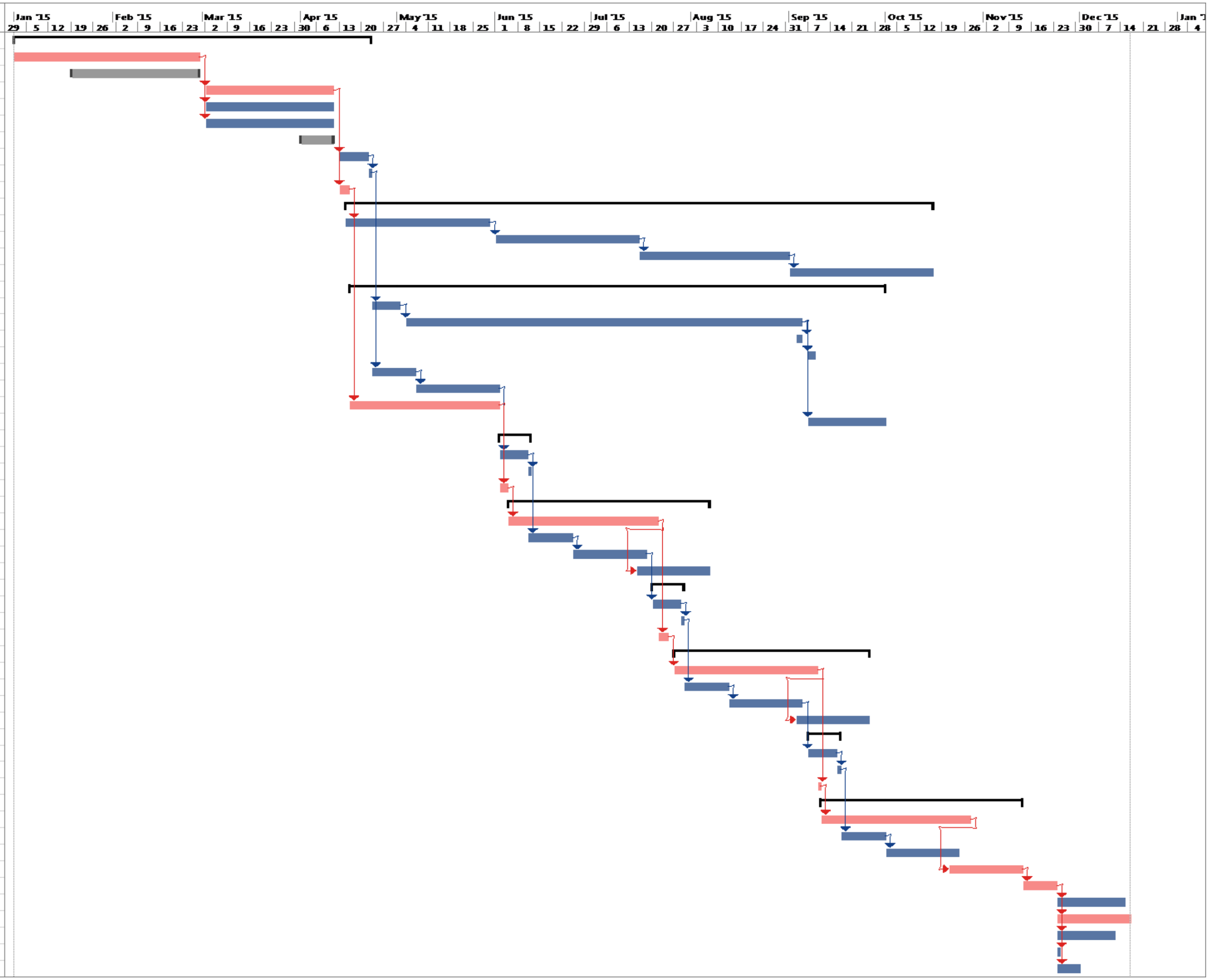
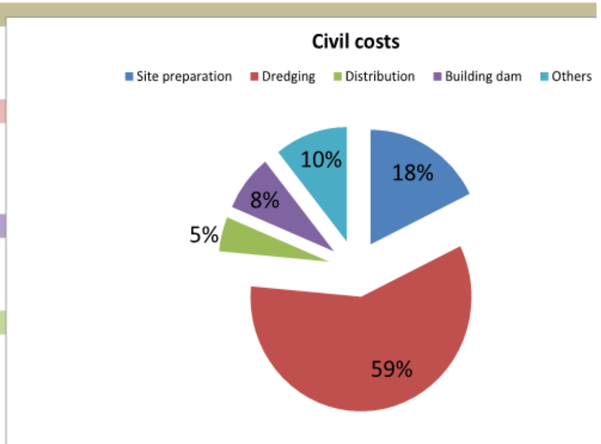


Figure 142 … Gant-chart of constructional plan

Costs of Project Slufter

Activity	Costs/week	Amount required	Time required (weeks)		Total	relative		Comments	
Site preparation				€ 17.826.500,00			18%		notes
Groundretaining sheet pile	€ 3.100,00	1820	1		€ 5.642.000,00	6%		costs per meter incl. placing and anchoring	Costs that are spent once have a required set at 1 week
Water retaining sheet piles	€ 2.325,00	1500	1		€ 3.487.500,00	3%			
Anchoring	€ 1.200,00	3000	1		€ 3.600.000,00	4%		costs per unit	
Pile driver	€ 19.250,00	4	26		€ 2.002.000,00	2%			
Re-routing Maasvlakte weg	€ 2.050,00	1500	1		€ 3.075.000,00	3%		costs per meter incl. destruction of old road	
Cranes to remove windmill	€ 10.000,00	1	2		€ 20.000,00	0%			
					€ -	0%			
					€ -	0%			
Dredging				€ 59.100.000,00			59%		
Mobilizing TSHD	€ 1.300.000,00	3	1		€ 3.900.000,00	4%			
De-mobilising TSHD	€ 1.500.000,00	3	1		€ 4.500.000,00	4%			
Renting TSHD	€ 650.000,00	3	26		€ 50.700.000,00	50%			
					€ -	0%			
Distribution				€ 4.914.000,00			5%		
Renting pipe system	€ 39.000,00	1	26		€ 1.014.000,00	1%		required length 1 km	
Renting pump station	€ 75.000,00	2	26		€ 3.900.000,00	4%		Booster station III	
					€ -	0%			
					€ -	0%			
					€ -	0%			
Building dam				€ 8.028.800,00			8%		
Bulldozers, scrapers, etc	€ 3.088,00	100	26		€ 8.028.800,00	8%			
					€ -	0%			
					€ -	0%			
					€ -	0%			
Others				€ 10.748.000,00			11%		
Labor	€ 3.000,00	100	10		€ 3.000.000,00	3%		amount in months	
Management	€ 5.000,00	10	26		€ 1.300.000,00	1%			
Site office, management	€ 24.000,00	1	26		€ 624.000,00	1%			
Renting storage spaces	€ 200.000,00	1	26		€ 5.200.000,00	5%			
Monitoring	€ 24.000,00	1	26		€ 624.000,00	1%			
					€ -	0%			
					€ -	0%			
					€ -	0%			
					€ -	0%			
					€ -	0%			
Construction costs subtotal					**€ 100.617.300,00**	**100%**	**17%**		
Turbines									
125 MW Turbine	€ 70.000.000,00	4	1		€ 280.000.000,00	71%			
Penstocks	€ 5.000.000,00	3	1		€ 15.000.000,00	4%			
Turbine housing	€ 100.000.000,00	1	1		€ 100.000.000,00	25%			
Electo-mechanical costs subtotal					**€ 395.000.000,00**		**68%**		
Profit + Risk	*(the percentages are calculated*			12%	€ 59.474.076,00		**10%**		
Finance	*using the sum of the subtotals,*			1%	€ 4.956.173,00		**1%**		
General expenses	*not of the final total)*			4%	€ 19.824.692,00		**3%**		
Total					**€ 579.872.241,00**		**100%**		



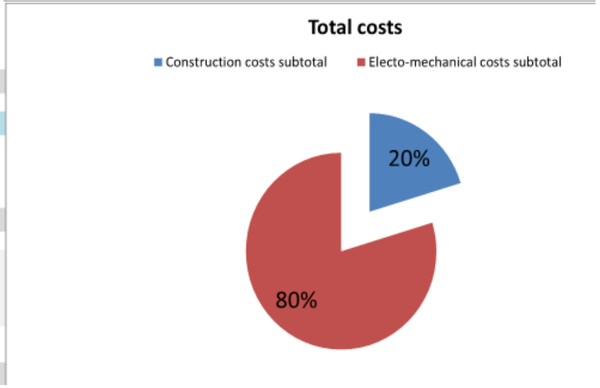


Table 39 … Construction costs split into civil costs and electro-mechanical costs

19. Operation, benefits & payback

The following subjects are discussed in this chapter:

19.1 Introduction to operation and benefits

The next phase of analysis is the operational phase, in which the Slufter will provide its primary functions of peak balancing and energy storing. To show the practical application of the PHS-system with 4 turbines, different scenarios are defined. Economic benefits from grid integration are discussed in *Chapter 19.3*. The goal of this chapter is to see what the possibilities are for the integration of the Slufter in the power grid, its operation within the current system and the benefits it can generate by applying smart strategies.

19.2 Grid integration

19.2.1 Turbine characteristics

To acquire characteristic turbine data, one can specifically design a new turbine designed for this particular case or use turbines that have proven technical feasibility and operation experience. The turbines that are used are the proposed turbines for the Energie Eiland-plan and are based upon the Alqueva Dam turbines in Portugal (*see §11.3.2 and Appendix F and N*). The turbine type is the Francis turbine, which is applicable for the given low head differences, its wide use and very high efficiency.[170] The optimized Alqueva turbines range the hydraulic head from 30 to 40m and have a peak-output of 125 MW. The turbine displays a relation between flow and head which is favorable for this specific case (*see Figure 143*). With the chosen turbine and its characteristics, the power generation of the system over time is calculated in detail using an extensive model: the *Power Generation Model* (*PGM, see Appendix O*).

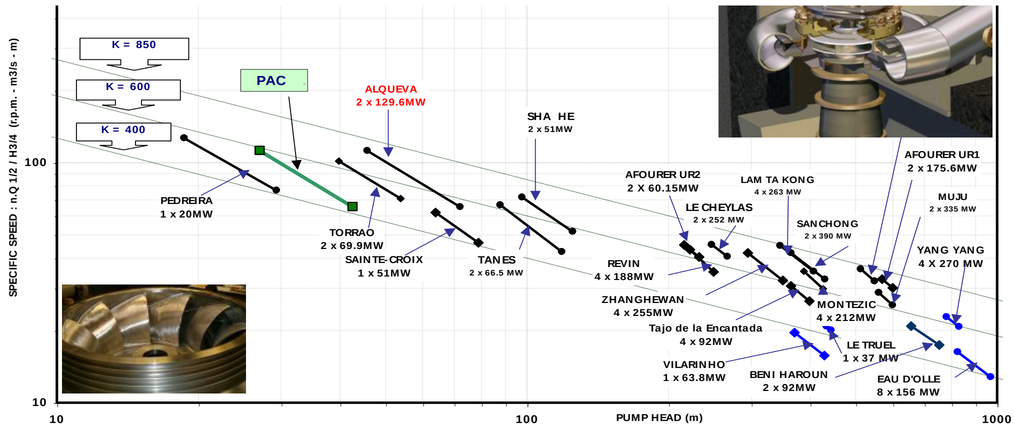


Figure 143 … Reference turbines with their corresponding characteristics (Alstom, 2005)

[170] Jan Vreeburg, Pumps and pumping stations, TU Delft, 2010

19.2.2 Efficiency of the system

The efficiency of the system is dependent on the efficiency of the individual parts. As the real-life efficiency depends on a multitude of factors (e.g. imperfections in material, design, losses, etc.), they are rather difficult to determine beforehand. Therefore, an estimated is made based upon references. [171,172]

By splitting the efficiencies into parts, a higher accuracy is achieved for the total efficiency (*see Table 40*). The sum of the partial efficiencies lead to a total estimated system efficiency of 78%. The efficiency for generation is independent on the pumps so when determining their performance, this has to be reduced from the total efficiency. The generation efficiency is dependent on the Francis turbines, motor and generator, equal to 90%.

Component	Efficiency
Francis turbines	95%
Pump	85%
Motor	98%
Generator	98%
Total	78%

Table 40 … Efficiency of the system

19.2.3 Power generation model

To simulate how the system can operate along a day a model has been created; *the Power Generation Model (PGM)*. Along with constants (i.e. water density and gravitational acceleration), the input is:

- Surface area of reservoir varying by depth (due to sloping, surface becomes less as level drops)
- Upper and lower limit of the water level
- Flow/head-characteristics (Qh-curve) and pump capacity of the applied Francis turbine
- Number of turbines
- Efficiency of the system and its specific parts, losses of hydraulic head (e.g. penstock friction)

With this data, the model can be run and the following results are calculated:

- Specific power generation curve along the time, hydraulic head or flow (for different scenarios)
- Flow through the turbines at any given time, hydraulic head and power (for different scenarios)
- Hydraulic head variation and reservoir depletion speed and time
- Reservoir filling time, fluctuating water amount
- Total energy capacity as integral of power generation curve (this is the net value)

The model is created under the following assumptions:

- The water is perfectly distributed over the amount of turbines
- The turbine characteristics are based upon the chosen turbine, however the Qh-curve is scaled from the Alqueva turbines (*see Appendix F and N for information about both)*
- The pump capacity of the chosen turbines are derived from the Alqueva turbines
- The efficiency of the system is constant
- The characteristics of the turbine are only guaranteed in between 30 and 40m hydraulic head

The power generation throughout the day can be controlled and is thus subject to the power generation strategy. The model has about been perfected for two scenarios:

1. Maximum output
2. Fixed output

The Maximum output scenario is a situation in which the Slufter performs at full capacity. It is interesting to see what the limits of the PHS is, how long it can operate at full capacity and what the power output distribution is.

The Fixed output scenario is a situation in which the output of the Slufter is controlled in order to balance it inside the national grid. This scenario shows the usefulness of the system under a controlled output.

[171] Lievense en KEMA, Plan Energie Eiland, 2006

[172] Alstom, Francis hydro power plants, Alstom.com, extracted on 2013

19.2.4 Pumping an 'empty' reservoir full

Through experimentation with the model, the fluctuating water level of the reservoir has been further optimized to fluctuate between +39m and +31m NAP. These levels provide the best balance in terms of generation and charging time (*see results below*) using 4 turbines.

The previous lower level was set at +29m NAP which required a pumping time of 12 hours and 50 minutes. This is deemed to be too long if the goal is to balance daily. The model results are presented with the new fluctuations. The net energy storing capacity with the new boundaries is 2.16 GWh and the fluctuating water volume is 24.6 million m^3 of water. The total pumping time of the reversible turbines is

$$T_{pumping} = \frac{fluctuating\ volume}{amount\ of\ turbines * pump\ capacity} \rightarrow \frac{24{,}6 * 10^6}{4 * 170} = 36141\ sec\ \sim 10\ hours$$

The pumping is done linearly and *Figure 144* shows the amount of pumped volume over time (blue curve with diamond markers) and the reservoir level (green line with triangle markers).

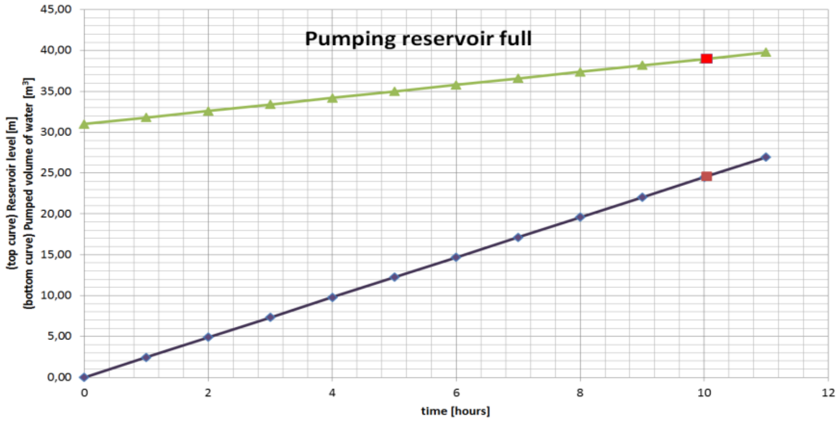


Figure 144 … (top curve in [m]) showing the reservoir level with red dot indicating a full reservoir and (bottom curve in [m^3]) showing the pumped water volume with the red dot indicating a full reservoir (Note: two scales on vertical axis)

19.2.5 Maximum output scenario

This situation shows the maximum capacity of the system if all 4 turbines where to utilize the full hydraulic head at that moment. This scenario is not far-fetched since the Slufter's primary function is to balance the peak-demand; when a lot of power is demanded in a relative short amount of time. Depending on the availability or production costs of other peak-units, the grid controller may choose to completely drain the Slufter first, before putting other units in action. The model shows that the lower level of the reservoir is reached after 6 hours, which is more than sufficient to gap the peak period (*see Figure 145*). During this time, there is no certain fixed power output, but the output changes with the lowering water level.

When the reservoir is still full, the change of power output is larger than it is after some time. This is caused by the characteristics of the turbine and is a direct consequence of the Qh-curve. The power output fluctuates between 468 – 269 MW with an average of 357 MW (*see Figure 146*). This is quite significant and with this power output, the storage solution would become a mediocre power generator nationally.[173] Because the turbines are working at maximum capacity, the hydraulic head drops quickly. As time passes, the hydraulic head drops because of the high flow of water. Because the water level drops, the power that can be generated drops as well: the power curve shows a steep slope.

[173] ECN, Monitoring Nederlandse elektriciteitscentrales, 2005

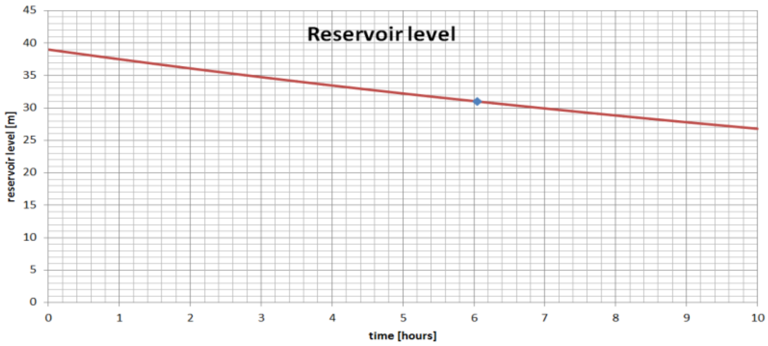


Figure 145 … Change in reservoir level [m] with blue dot indicated the lower reservoir limit

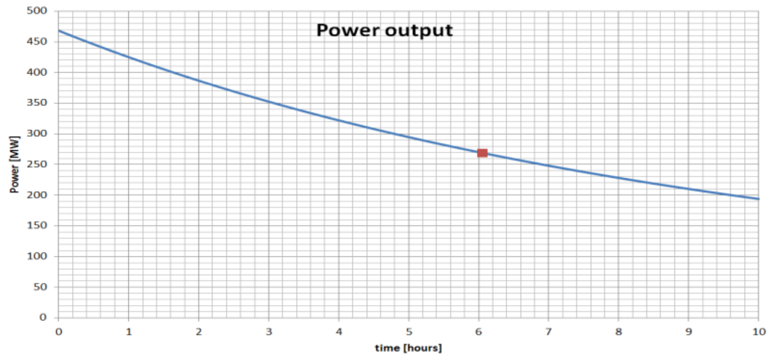


Figure 146 … Change of maximum power output [MW] with red dot indicating lower reservoir limit

19.2.6 Fixed output scenario

This situation shows a controlled and regulated Slufter. The output is kept steady as long as possible until the system cannot generate this fixed rate any longer due to insufficient head. This scenario is close to reality as the transmission company (*TenneT for the Netherlands*) would be interesting in providing a portion of the power using this system, while adjusting other units accordingly. Other peak-generation units are mostly gas-turbines that prefer a steady rate rather than a constantly varying one.

The steady rate is kept at 350 MW which is competitive value when compared to large power plants.[174] With this fixed output rate, the system generates power for 6 hours and 30 minutes. By rolling back the maximum power output at the start, however requiring this for a longer period, the generation time is extended by half an hour (*see Figure 147*). The power output stays steady at 350 MW until a certain point where there simply isn't enough flow through the turbines. At this point the turbines back down a little. The power ranges between 350 – 269 MW with an average of 331 MW (*see Figure 148*).

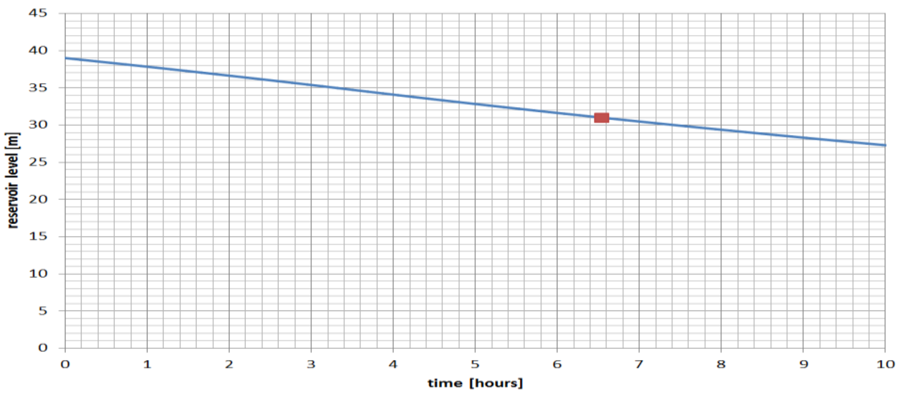


Figure 147 … Change in reservoir level [m] with blue dot indicated the lower reservoir limit

[174] ECN, Monitoring Nederlandse elektriciteitscentrales, 2005

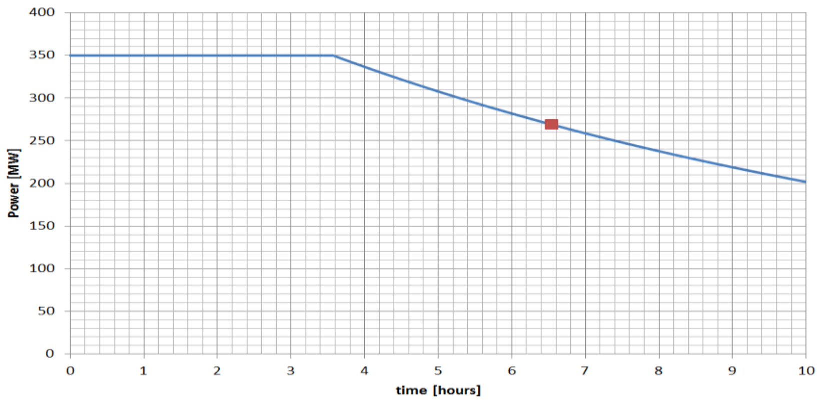


Figure 148 … Change of maximum power output [MW] with red dot indicating lower reservoir limit

19.2.7 Evaluation and feedback to regional demand

The model provides insight into the possible integration into the grid. As the power capacity drops with the reservoir level, careful planning is required to supply a certain power output for a certain time. Two scenarios have been experimented with which both shows promising results. The power capacity as well as the storage capacity of the system is quite higher than initially expected. While only two scenarios are presented here, a large amount of strategies can be applied with the storing system. The high flexibility, the relative high efficiency combined with a fast startup time makes this an increasingly promising energy storing solution.

The system has an annual power output of 709.560 MWh (*see §18.2.2*). A regular household is utilizing an average 3440 kWh per year.[175] This means that the amount of households that the Slufter will annually serve is equal to

$$\frac{yearly\ generation}{average\ consumption\ per\ household} \rightarrow \frac{709560 * 10^6}{3440 * 10^3} = 206268 \sim 200.000\ households$$

This number does not portray the real potential of the Slufter and rather underestimates its importance. This is because the main function of the Slufter is to provide the peak load and therefore the power capacity is normative when assessing the amount of households it is serving. Considering the Maximum Output Strategy, the Slufter produces an output of 470 MW. This is enough to fulfill the peak generation demands of entire Zuid-Holland, Zeeland and about half of Noord-Holland *(see §14.9.2).* With its peak balancing function, the Slufter is serving

$$peak\ balancing\ function \sim 5\ million\ people$$

Looking at the wind storage capacity, the system performs less adequately *(see §14.9.3).* Creating a system with 2.16 GWh of storage capacity, it is capable of fulfilling the current national energy storage demands. This is because there is very low storage demand since the share of RES is still low. Looking at 2020, the Slufter would be able to barely fulfill the demands of Zuid-Holland and Zeeland. Further down the line, as soon as 2025, the Slufter will be incapable of providing Zuid-Holland's demands. Possible expansion plans are therefore included in this report (*see Chapter 21.4)*.

[175] Nibud, Energie en Water, Nibud.nl, 2013

19.3 Power trade benefits

19.3.1 Integration into the power system

The Slufter will be integrated into the Dutch power system where it will operate to provide a balancing function for the peak power demand as well as a storing function for the variable wind power. The performance of this grid is simulated by the development of the PGM in the previous section. This model is expanded with the Benefit Model (BeM) to incorporate hourly power prices. The model is explained in *Appendix O*; here only the results and finding are discussed.

As the Slufter will operate on a daily basis, the hourly power market is relevant. On this market, the prices per MWh vary per hour along a full day (the markets have been analyzed in *Part A*). By utilizing a smart strategy of buying and selling with correct timing, the Slufter can create benefits. First the power prices will be analyzed and strategies only based upon the prices are defined, not regarding the capabilities of the Slufter. Later, capabilities of the Slufter are taken into respect to define a specific operation strategy.

19.3.2 Power prices

The power prices fluctuate highly throughout a day. The data used to base a strategy on are hourly power prices from the European Energy Exchange (EEX), of which the hourly trade is done on the *ELIX*. Hourly power prices are taken for varying dates along 2013 (*see Table 41 and Figure 149*). Especially for power markets it is relevant and more accurate to take recent data, because of the high market volatility. It should be noted that the data set shows does not regard (smaller) variations along a week and month.

	Wed,	Wed,	Wed	Wed	Wed,	Thu,	Wed	Wed	Thu	Thu	Wed	Wed,		
hour	10-okt-12	7-nov-12	12-dec-12	9-jan	10-feb	10-mrt	8-apr	14-mei	8-jun	13-jul	11-aug	10-sep	Unit
1	36,22	17,86	37,63	37,95	31,84	28,73	28,4	32,68	27,89	28,58	37,55	34,96	€/MWh
2	32,1	14,83	35,61	38,01	29,66	24,54	22,23	30,1	23,46	27,38	35,42	33,79	€/MWh
3	29,69	12,91	32,98	35,71	27,83	19,59	15,17	27,77	21,04	24,66	32,02	30,42	€/MWh
4	28,22	14,78	31,71	33,27	25,5	16,98	12,13	25,48	16,54	21,2	29,86	29,08	€/MWh
5	30,01	9,7	31,21	33,21	25,37	16,46	12,95	25,01	14,05	23,17	30,55	29,06	€/MWh
6	34,3	20,75	35,46	36	29,78	20,06	25,11	27,09	15,09	28,3	34,01	32,27	€/MWh
7	47,95	43,67	48,94	43,85	44,74	34,4	39,91	28,3	19,08	49,78	51,56	48,88	€/MWh
8	63,63	53,28	65,52	60,94	60,31	43,98	54,63	31,33	21,51	62,99	62,99	62,64	€/MWh
9	64,27	53,67	66,75	63,27	62,22	46,38	55,01	37,66	26,35	67,19	67	64,76	€/MWh
10	64,06	54,97	65,79	61,89	58,08	44,97	55,88	42,7	31,6	68,19	66,03	66,01	€/MWh
11	61,98	53,03	64,76	61,18	51,25	38,96	55,96	43,5	36,01	67,48	65,01	65,05	€/MWh
12	61,09	54,69	65,5	61,55	46,92	34,03	55,95	43,98	37,05	67,48	64,07	64,99	€/MWh
13	56,3	53,23	63,11	60,42	38,73	27,91	54,14	42,51	36,23	63,17	59,9	61,97	€/MWh
14	53,32	52,67	62,32	60,07	32,86	20,02	52,06	38,76	32,02	63,09	56,92	61,92	€/MWh
15	52,62	52,43	63,13	59,95	32,41	22,52	52,11	36,52	30,84	60,82	56,48	60,01	€/MWh
16	49,48	48,77	63,87	58,14	32,16	27,68	51,14	35,19	29,76	60,38	56,03	58,8	€/MWh
17	50,09	51,24	66,41	58,9	35,08	30,22	49,99	36,47	29,28	59,94	56,29	54,03	€/MWh
18	53,75	59,94	70,57	64,05	45,22	37,02	53	41,12	32,02	61,99	61	54,94	€/MWh
19	64,25	66,07	68,39	66,01	56,96	45,25	56,96	45,66	38,1	67,43	64,55	60,05	€/MWh
20	80,57	62,58	65,05	63,09	62,54	53,81	62,06	51,01	50,1	72,98	73,99	66,03	€/MWh
21	61,95	52	60,46	57,57	56,06	46,02	56,95	46,02	42,35	66,18	65,93	60,26	€/MWh
22	53,11	48,88	52,23	48,3	42,01	36,72	47,1	38,87	34,4	60,15	58,36	51,08	€/MWh
23	46,69	45	53,24	45,64	35,1	36,67	45,44	38,07	34,57	59,3	53,1	47,25	€/MWh
24	38,47	36,88	43,17	41,55	30,39	33,84	42,02	33,05	30,99	45,81	42,7	37,11	€/MWh

Table 41 ... Hourly power prices for varying dates along the year (EEX, 2013)

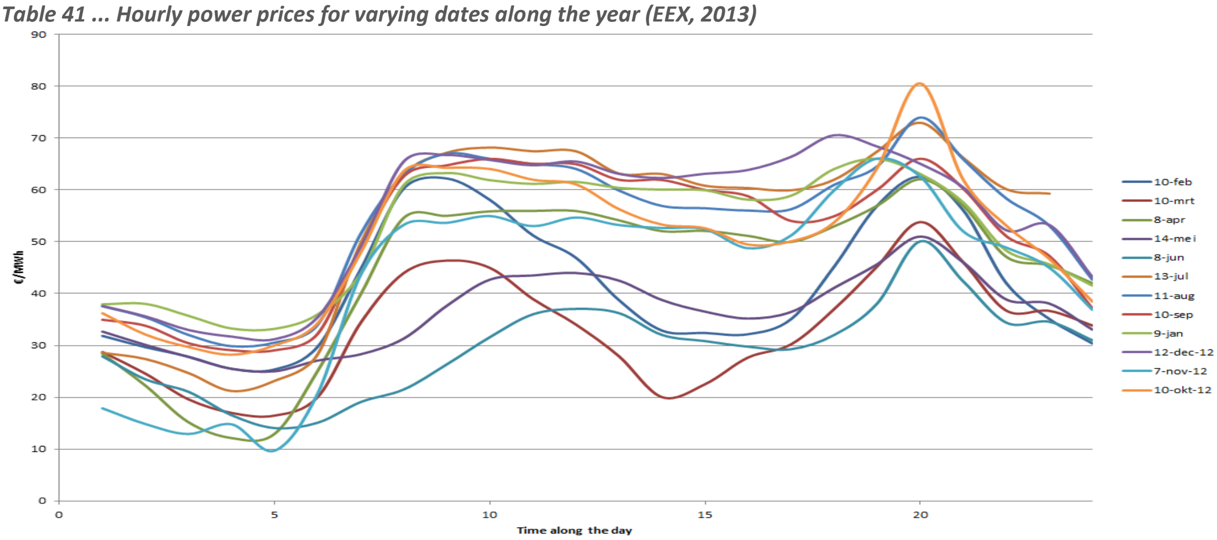


Figure 149 ... Graphical representation of the values in Table 41

Because this set of data can be very incidental rather than typical, the interest should be more towards finding trends and verifying those using alternative sources. From this data, these trends are visible:

- Distinction between summer and winter profiles: summer showing only one major drop and one rise whereas winter shows two major drops and rises
- Difference between extremes ranges from 26 till 52 €/MWh, an average 40 €/MWh difference
- The summer months have a higher total average power price than the winter months
- In the summer, the morning ramp comes later and the evening drop comes earlier than in winter; summer curves are more concentrated in the mid-day than winter curves
- Summer curves display the highest peaks: maximum of 74 €/MWh between 19-20h on 10/8/2011
- Minimum of 12 €/MWh on 8/4/2011 between 3-4h

This data set is compared with a data set taken of the APX Power NL Hourly (the Dutch hourly power market, because of the lack of data, the European markets are used). This data is only available for 1 day ahead, so in order to get a sufficient amount of data to test the hypothesis, these prices are registered every day starting from 9th of October going till the 23rd, 2013. This data is used to verify the results and evaluate the resemblance of the Dutch power market to the European power markets. This comparison results in a confirmed hypothesis; APX displays similar trends as in ELIX (*see Appendix W*).

19.3.3 Power Trade Strategy

Buying and selling, also known as the trade of power, is an important way to make the Slufter generate economic benefits. A smart strategy can result in a profit in the long run. The main focus of any trade strategy is to **buy when cheap and sell when expensive;** the same goes for trade in power. Now the test values have been verified (*see previous paragraph*), the strategy can be based upon them. Due to the seasonal changes explained above, the strategy will performs differently in the summer and winter. Every hour, it must be assessed whether to buy or sell power (*see Figure 150*).

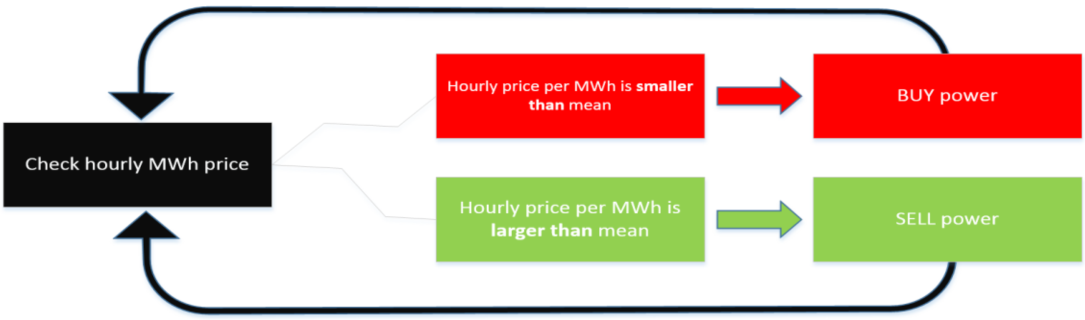


Figure 150 … Cyclic hourly power market strategy

The difference between the low and high power price provides the profit for that specific day. The data set is used to analyze this further and determine when the power should be bought and sold. Since the Day-Ahead markets publish hourly power prices for the next day, this strategy can easily be applied in practice by defining a schedule of buying hours and selling hours and executing them on the next day.[176]

19.3.4 Maximum Profit Strategy

The goal of this section is to create a strategy in which the Slufter makes maximum profit. This strategy relies heavily on the assumption that power price and demand are strongly dependent. This hypothesis is proven for this data set, with both curves investigated into more detail (the results can be found in

[176] See daily power markets on EEX.COM and APX.COM

Appendix P). The findings show a very strong relation between price and demand. The general idea of the Maximum Profit Strategy is a continuation of the Power Trade Strategy, but optimized for profit (*see Figure 151*). The sample data set to test the strategy is the same as *Figure 152*, in which the "SELL" (green) and "BUY" (red) zones have been indicated (from the Slufter's perspective).

Figure 151 ... Maximum Profit Strategy

	Wed,	Wed,	Wed	Wed	Wed,	Thu,	Wed	Wed	Thu	Thu	Wed	Wed,	
hour	10-okt-12	7-nov-12	12-dec-12	9-jan	10-feb	10-mrt	8-apr	14-mei	8-jun	13-jul	11-aug	10-sep	Unit
1	36,22	17,86	37,63	37,95	31,84	28,73	28,4	32,68	27,89	28,58	37,55	34,96	€/MWh
2	32,1	14,83	35,61	38,01	29,66	24,54	22,23	30,1	23,46	27,38	35,42	33,79	€/MWh
3	29,69	12,91	32,98	35,71	27,83	19,59	15,17	27,77	21,04	24,66	32,02	30,42	€/MWh
4	28,22	14,78	31,71	33,27	25,5	16,98	12,13	25,48	16,54	21,2	29,86	29,08	€/MWh
5	30,01	9,7	31,21	33,21	25,37	16,46	12,95	25,01	14,05	23,17	30,55	29,06	€/MWh
6	34,3	20,75	35,46	36	29,78	20,06	25,11	27,09	15,09	28,3	34,01	32,27	€/MWh
7	47,95	43,67	48,94	43,85	44,74	34,4	39,91	28,3	19,08	49,78	51,56	48,88	€/MWh
8	63,63	53,28	65,52	60,94	60,31	43,98	54,63	31,33	21,51	62,99	62,99	62,64	€/MWh
9	64,27	53,67	66,75	63,27	62,22	46,38	55,01	37,66	26,35	67,19	67	64,76	€/MWh
10	64,06	54,97	65,79	61,89	58,08	44,97	55,88	42,7	31,6	68,19	66,03	66,01	€/MWh
11	61,98	53,03	64,76	61,18	51,25	38,96	55,96	43,5	36,01	67,48	65,01	65,05	€/MWh
12	61,09	54,69	65,5	61,55	46,92	34,03	55,95	43,98	37,05	67,48	64,07	64,99	€/MWh
13	56,3	53,23	63,11	60,42	38,73	27,91	54,14	42,51	36,23	63,17	59,9	61,97	€/MWh
14	53,32	52,67	62,32	60,07	32,86	20,02	52,06	38,76	32,02	63,09	56,92	61,92	€/MWh
15	52,62	52,43	63,13	59,95	32,41	22,52	52,11	36,52	30,84	60,82	56,48	60,01	€/MWh
16	49,48	48,77	63,87	58,14	32,16	27,68	51,14	35,19	29,76	60,38	56,03	58,8	€/MWh
17	50,09	51,24	66,41	58,9	35,08	30,22	49,99	36,47	29,28	59,94	56,29	54,03	€/MWh
18	53,75	59,94	70,57	64,05	45,22	37,02	53	41,12	32,02	61,99	61	54,94	€/MWh
19	64,25	66,07	68,39	66,01	56,96	45,25	56,96	45,66	38,1	67,43	64,55	60,05	€/MWh
20	80,57	62,58	65,05	63,09	62,54	53,81	62,06	51,01	50,1	72,98	73,99	66,03	€/MWh
21	61,95	52	60,46	57,57	56,06	46,02	56,95	46,02	42,35	66,18	65,93	60,26	€/MWh
22	53,11	48,88	52,23	48,3	42,01	36,72	47,1	38,87	34,4	60,15	58,36	51,08	€/MWh
23	46,69	45	53,24	45,64	35,1	36,67	45,44	38,07	34,57	59,3	53,1	47,25	€/MWh
24	38,47	36,88	43,17	41,55	30,39	33,84	42,02	33,05	30,99	45,81	42,7	37,11	€/MWh

Figure 152 ... Sample data tested for the strategy testing (red indicating BUY power to charge the Slufter, green is SELL)

19.3.5 Results

Pumping the reservoir happens when prices are low (*red zones in Figure 152*). The lowest sequence of prices is chosen on the Day-Ahead market and pumping is done accordingly. The pumping happens with a constant flow, which will require more power as the reservoir level is higher. The pumping time is calculated with the PGM to be 10 hours. These 10 hours have to be distributed over the low price range using the BeM. Likewise, power generation is performed as the opposite process of pumping. Power generation happens at maximum capacity, for which the PGM calculated a time of 6 hours. The strategy is applied on the sample data and generated the results in *Table 42*.

	Costs to pump		Revenue from generation		Profit	
10-okt-12	€	80.950,52	€	134.430,73	€	53.480,21
7-nov-12	€	57.365,06	€	121.557,27	€	64.192,21
12-dec-12	€	86.583,95	€	142.306,54	€	55.722,58
9-jan	€	84.842,22	€	133.146,28	€	48.304,06
10-feb	€	66.440,41	€	116.526,06	€	50.085,65
10-mrt	€	50.043,36	€	100.352,41	€	50.309,06
8-apr	€	62.008,57	€	123.314,96	€	61.306,39
14-mei	€	64.333,47	€	97.046,68	€	32.713,21
8-jun	€	47.106,79	€	85.163,95	€	38.057,16
13-jul	€	78.746,99	€	147.410,23	€	68.663,24
11-aug	€	87.078,82	€	144.625,32	€	57.546,50
10-sep	€	80.588,56	€	140.129,30	€	59.540,74
MEAN VALUE	€	70.507,39	€	123.834,14	€	53.326,75

Table 42 ... Results of the Maximum Profit Strategy applied on sample data

19.3.6 Evaluation of the power trade benefits

The results of the PGM + BeM are promising for the performance of the system and the possibility to obtain revenues. The results show a daily profit ranging from €32.000 to €70.000; an average of €53.000. This mean value is representative for a time period of a year in which the total profit will be

$$profit = daily\ profit * year\ (90\%\ runtime) \rightarrow\ 53000 * 329 = €19.345.000$$
$$\sim €\ 19.35\ milion\ per\ year$$

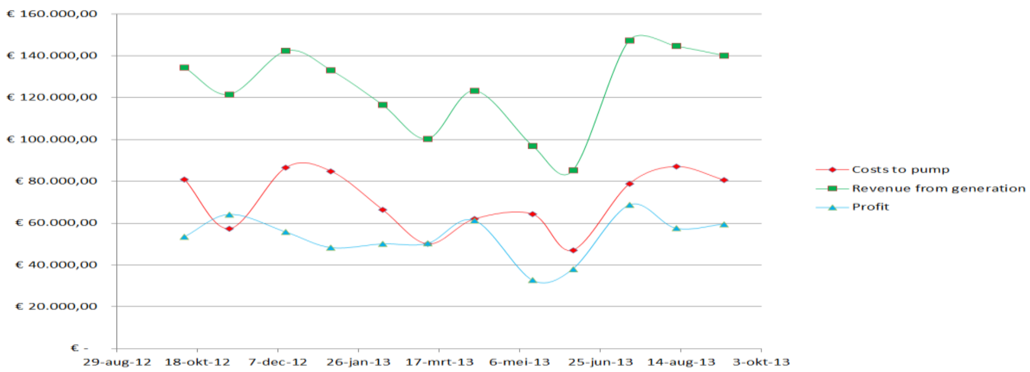


Figure 153 ... Graphical representation of the results (the lines in between the markers are only indicative)

This value is of course very dependent on power price development so to obtain a more reliable value, the analysis should be supplemented with a detailed historic analysis and the implementation of future power price scenarios. This is a recommendation for further analysis. This calculated value shows the potential of energy storage on the scale of the Slufter. The fluctuations on the Day-Ahead market are large and will increase with the rise of RES due to their variable character. For this reason, the future benefits from power trade are more promising than these numbers.

19.4 CCGT alternative and fuel cost savings

The current power units used for peak balancing are Combined Cycle Gas Turbines (CCGT). Due to increasing demand and high material costs, investment costs has risen from 2002 till 2009 from 600 to 800 €/kW.[177] The rise of cost is tempered by the economic crisis and the cost today remains about 800 €/kW. A CCGT unit with similar specification of the Slufter providing 450 MWp requires an investment of

$$Investment\ costs\ CCGT = costs/kWh * peak\ power \rightarrow\ 800 * 470 * 10^3 = €\,376\ million$$

Considering investment costs only means that CCGT-units are about 35% cheaper than the Slufter. To make a fair comparison, lifetime costs and benefits have to be considered. While the investment costs of CCGT units are significantly lower, the generation costs are higher than for the Slufter which could make the Slufter a better option in the long run. The development of gas prices is crucial in this comparison. Generation costs for CCGT units range at €48-60 per MWh, of which €22-33 per MWh for fuel.

In *§18.2.2*, the annual output of the Slufter is calculated to be *709560 MWh*. The Slufter is pumped during the night when efficient power units are used for power generation. Among them are coal plants which provide a cheap way to power the Slufter. The fuel costs for a coal plant are in the range of €11-18 per MWh.[178,179,180] Compared to CCGT units, the net benefit of using a coal plant ranges between €4-22 per MWh; typically 13 €/MWh. The fuel savings from using the Slufter rather than CCGT-units are

$$Fuel\ savings\ = yearly\ generation * saving\ per\ MWh\ in\ € \rightarrow\ 709560 * 13 = 9.224.280$$
$$\sim €9.2\ million\ per\ year$$

[177] Other reference prices are also obtained from this source, IEA ETSAP, Gas-fired power, Technology Brief, 2010
[178] IEA, Executive Summary, IEA.org, 2010
[179] IEA ETSAP, Coal-fired power, Technology Brief, 2010
[180] Note that this is on average, the nightly price should be lower, meaning the final results is underestimated

19.5 Pay-back period

19.5.1 Results

The application of the conventional method of cost calculation is somewhat troubling as it doesn't provide a fair comparison between fossil fueled plants and clean plants. Basically, it comes down to the fact that the negative side-effects caused by fossil fueled plants are not factored into the equation. The discussion is further explained in *Appendix Q* and forms a side-note to the applied method of cost-comparison.

With the use of an expenditure model the costs of the project along the entire lifetime will be looked upon. All the expenses and benefits have already been defined and calculated; now remains to see their development over a longer period under the influence of the economy. The model assumptions together with the full model are presented in *Appendix R*.

Mainly the choice of a time-preference value is discussable in this analysis. The time-preference (discounting rate) factors in indicators such as interest rate, inflation etc. The discussion can be raised by the fact that these indicators are also dependent on the energy price. The real question is rather: high much higher will the interest rate be with respect to the energy price growth? [181] The US Department of Commerce presents a detailed method for choosing a time-preference rate when dealing with energy projects. This method results in a relative time-preference rate of 1.1% (*see Appendix R for assessment*).

The payback period for the Slufter for a relative time-preference of 1.1% is 30 years (*see Figure 154*).

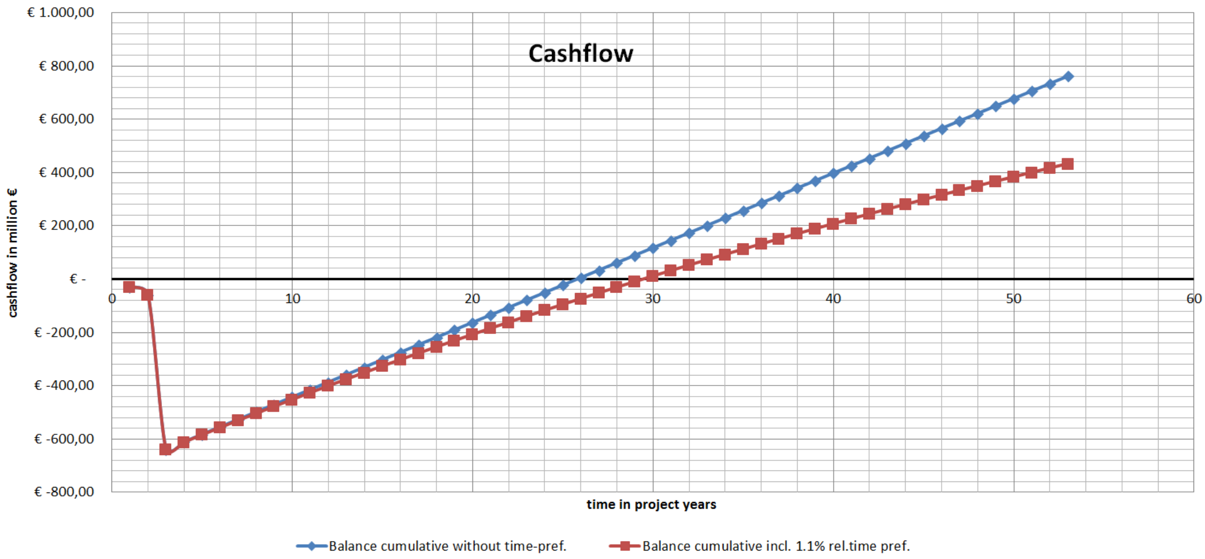


Figure 154 … Cash flow during the project lifetime of the Slufter

[181] USA Dep. Of Commerce, Energy price indices and discount factors for life-cycle analysis, NIST Handbook, 2013

19.5.2 Levelized energy costs

The investment costs are calculated to be 1234 €/kW (*see §18.2.1*). Now the costs over the lifetime of the Slufter can be levelized using the *Levelized Energy Costs* (LEC). The LEC is the price at which the electricity must be generated to break even over the lifetime of the system, in other words;

$$LEC = \frac{\sum_{t=1}^{n}(I_t + M_t + F_t)/(1+r)^t}{\sum_{t=1}^{n} E_t/(1+r)^t}$$

- I_t = investment cost [€]
- M_t = operation and maintenance [€]
- F_t = fuel expenses [€]
- E_t = energy produced over lifetime [MWh]
- r = time preference rate = 2 %
- n = lifetime of system (a value of 40 years is taken to compare with CCGT)

Since this system does not produce energy but rather stores and re-generates it, the comparison with conventional power plants is not valid unless the power source to store the energy is included in the comparison. Nonetheless, the addition of the investment and the storage facility per unit of generation can be computed so that regardless of the power source, the cost per unit prices can be calculated. The values are calculated using the Expenditure Model, which produces an added LEC of

$$LEC_{add} = 21.40 \frac{€}{MWh}$$

This is the additional costs that the system introduces to any power source unit price. The system powers itself using the cheap prices during the nightly hours, where it stores power for an average value of 32.64 €/MWh.[182] With this addition, the total LEC becomes

$$LEC_{total} = LEC_{add} + LEC_{storing} \rightarrow 21.40 + 32.64 = 54.0 \sim 54\ €/MWh$$

Compared to CCGT units which have generation cost ranging from €48-60 per MWh, this price is pretty competitive since is offers other benefits as being a clean option and reducing the energy dependency.

[182] Calculated using the Benefit Model presented earlier (this value includes the efficiency)

20. Risk analysis

The following subject are discussed in this chapter

20.1 Introduction to the risk analysis

In this chapter, the risks involving the project are analyzed and assessed. The main focus of this risk analysis will be the Slufter dam in operational stage. The design and engineering part is not significantly different from other projects, of which sources can be found in literature. Before talking about risk, it is defined as the chance that an activity may happen multiplied with the impact of that action:

$$risk = probability * consequence$$

Within this definition, the main focus is managing undesired actions. The probability is usually defined as the chance of possible failure and is based on statistical data, e.g. the probability dike failure in the Netherlands is 1/100.000 years. The consequence is usually quantified in monetary units, e.g. the damage of an earthquake is given by the total value of the houses and infrastructure destroyed. This is not without controversy, i.e. how much is a person worth? The analysis is performed using the RISMAN method. As the steps are executed, the method will explain itself and prove its purpose.

20.2 The goals of the risk analysis

The goal in the risk-assessment is to create an overview of the possible risks and assess which ones have priority in risk-management. The goal is divided into the three different project phases and is defined as:

1. In the planning phase: a streamlined project description, plan of action, activities and deadlines
2. The construction phase: performed efficiently and without problems, within the given deadlines and budgeting with no unexpected events and guaranteeing structural safety
3. In the operational phase: the system should be able to perform the operational activities without issues and maintain a high efficiency while guaranteeing structural safety

The main focus of this analysis will be the operational phase. The detailing of the risk assessment should be sufficient so that one has a clear understanding what the largest risks are and what is causing them. Quantifying them is outside the scope of this analysis and requires more technical analysis.

The risks in the constructional phase are quickly mentioned. These surround the sheet pile works such as failure due to exceedance of soil resistance, plastic behavior of steel, anchor failure, instability anchoring, Kranz-instability, soil fracture, macro-instability, deformation of sheet pile, not working water-sealing connections of the sheet piles, damage to surrounding during placement of the sheet pile. There could be other (more planning oriented) risks such as weather problems during dredging works and pump station malfunctions. These are relatively small issues that require further detailing and handling in a later stage of the project. The analysis moves with the operational phase.

20.3 Mapping the risks

20.3.1 Failure tree operation

This phase in the analysis is important because the hypothesis is that most structures fail not because the wave was too high, but fail because of a failure mechanism that is not regarded. Without trying to prove this hypothesis, the full spectra of the failure mechanisms for the Slufter during the operational phase are identified. Failure is defined as the occurrence of excessive deformation or erosion that causes an uncontrolled release of water from the Slufter reservoir or surrounding structures. The failure mechanisms are therefore the interesting parts.

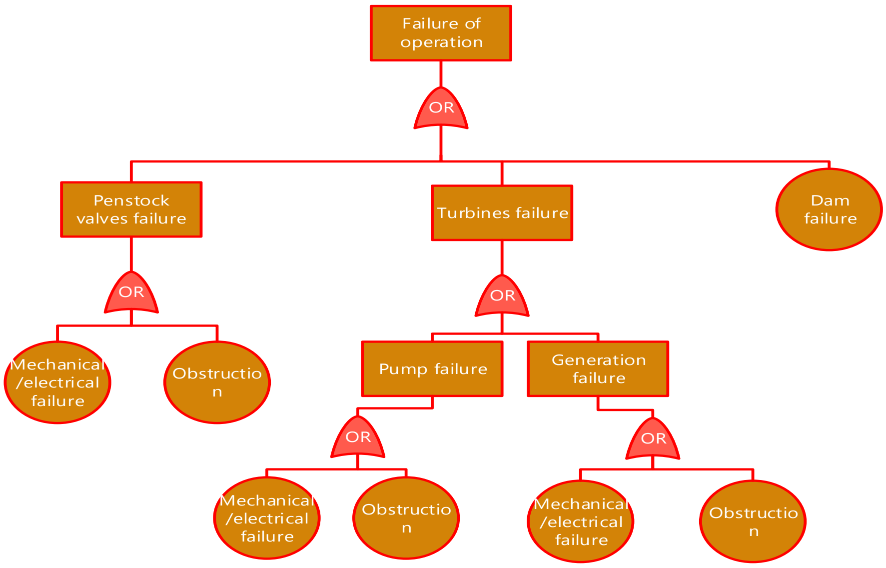


Figure 155 … Failure tree for the system operation

20.3.2 Failure tree for the dam

The turbines and penstocks risks are not considered into much detail in this risk analysis. The focus is the failure of the dam. The failure tree for the Slufter has been further expanded for the dam in *Figure 157*. The possible failure mechanisms for the dam are grouped in four categories *(for more information about each group and a description how it could lead to failure, see Appendix T)*. In the technical design, most of the mentioned risks have been limited.

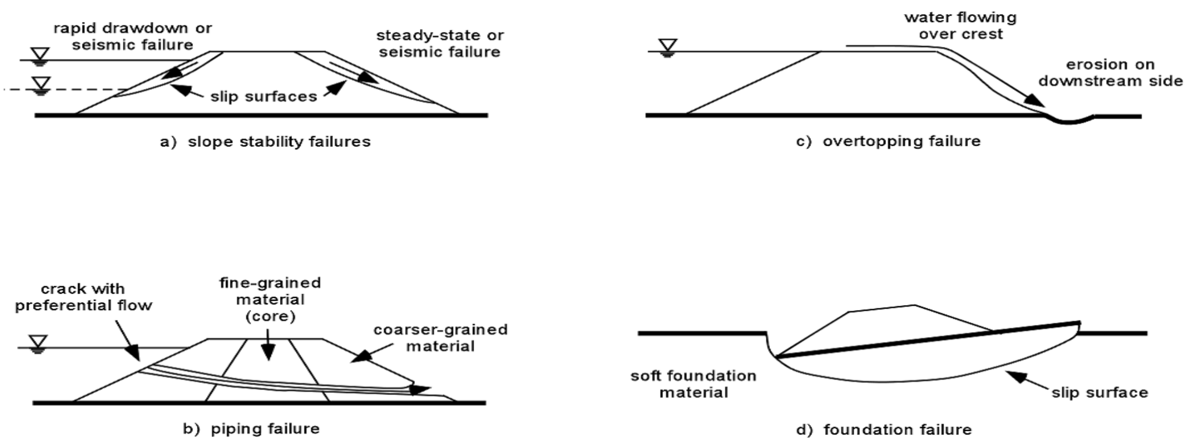


Figure 156 … .The four categories of failure mechanisms (J.Weijers and M. Tonneijck, Flood Defences, 2009)

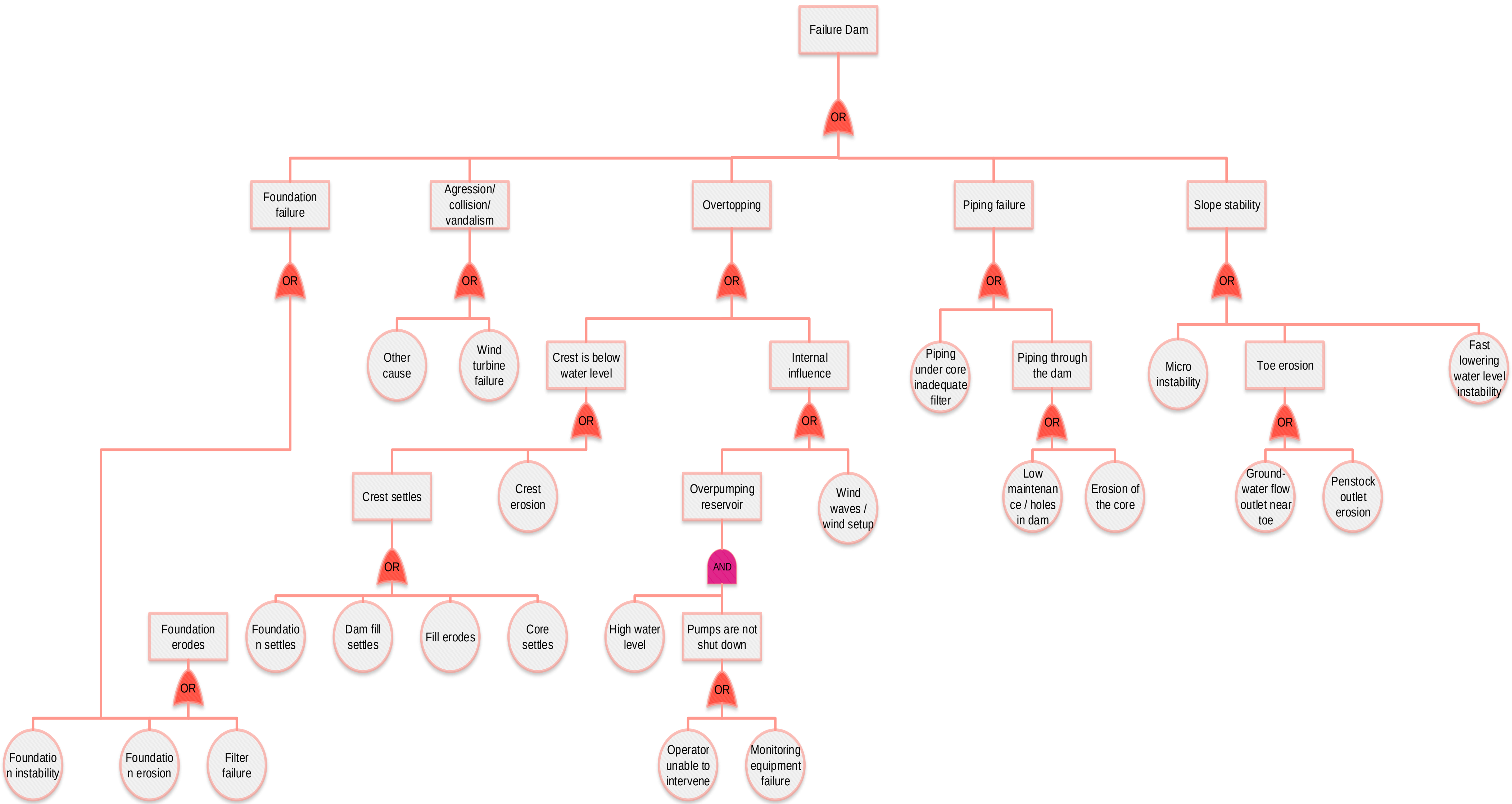


Figure 157 … Failure tree for the dam failure

20.4 Consequences of a dam failure

20.4.1 Introduction

To say anything about the consequences of the dam collapse, information is required about the surrounding areas, the flow of water and the velocity of the initiated flood wave. Information about the surrounding areas consists of determining the economic value of the surrounding areas. As three-quarters of the Slufter is surrounded by the North Sea, this applies to the Maasvlakte (*see Figure 158*). In 2008, the area of the port and the industry provided a gross input into the Dutch economy of €15 billion. If half of this is earned at the Maasvlakte near the Slufter, this is an economic value of €7.5 billion yearly.[183]

Figure 158 ... Environment of the Slufter (OpenStreetMaps.nl, 2013)

The flow and emptying time of the reservoir is estimated through a steady opening. As the flow goes through the opening, the water level drops and so does the flow. A primary calculation will be made with a steady flow rate to get an indication of the order of magnitude. In the most unfavorable situation, the breach width is five times the height of the dam, about 140 meters (initially, the breach width will be less, however it will develop in time).[184] This is further simplified by considering a 2-dimensional situation. The time to empty the reservoir is then calculated by

$$flow\ duration\ till\ empty\ Slufter = \frac{V_{t=0}}{Q_{t=0}} = \frac{A_o}{\mu A}\sqrt{\frac{\Delta z_{t=0}}{2g}} = \frac{3.14 * 10^6}{0.6 * 140} * \sqrt{\frac{35}{2 * 9.8}} = 49951\ s\ \sim 14\ hours$$

Factoring in the lowering of the reservoir level in the calculations will increase the emptying time, meaning this simplification presents an extreme value. When the breach has occurred, the first action could be to open the turbines valves to lower the reservoir level. The PGM is used to further calculate the flows running through the turbine opening by means of extrapolation of the results (*see Figure 159*). Since the curve is decreasing exponentially, the bottom of the reservoir is reached at 55 hours.

The opening of the turbines does have a role in lowering the reservoir level, but is simply insufficient. It should therefore be considered to create an opening valve facing the North Sea. Similar to the function of spillways for hydropower dams, this opening can help lower the reservoir level in a short amount of time than through the dam breach opening. This option will remain a recommendation to be analyzed further.

The literature does not supply a lot sources when dealing with the wave propagation of dam break into an area. Mostly, they analyze a river dike breach. Sources are found nonetheless, among which the following

[183] Maasvlakte2, Rotterdam de belangrijkste haven van Europa, Maasvlakte2.com, extracted on 2013
[184] Dam Safety Office, Prediction of embankment dam breach parameters, USBR.gov, 1998

sources present methods that are applicable here: *Fraccarollo and Toro,*[185] *Tingsanchali & Rattanapitikon*[186] and *Jovanovic & Djordjevic*[187] (*see Figure 160*). For the analysis of the flood wave and its destructive power that is a consequence of the dam breach, above mentioned sources are referred to.

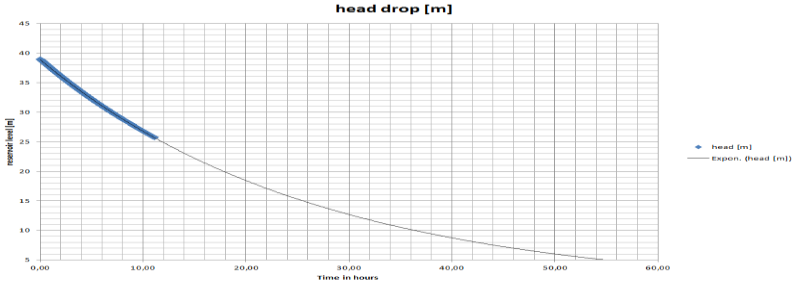


Figure 159 … Time required emptying the reservoir through the turbine opening

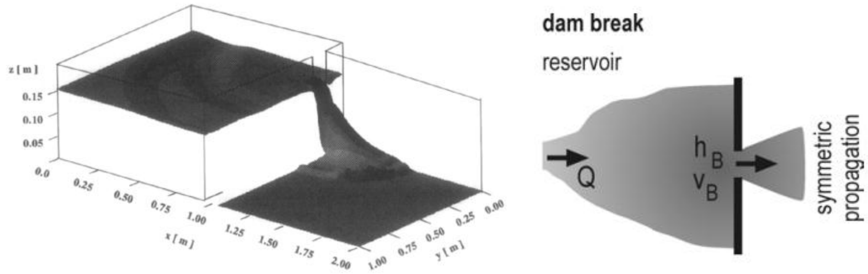


Figure 160 … Image of the numerical model performed

20.5 Monitoring and automatic back-up system

Most of the risks identified in the fault tree (*see Figure 157)* are risks related to the technical design, which have been limited with the calculations in *Chapter 16*. However, new problems and new failure mechanisms may arise during any phase of the project.

Therefore, both the construction works as well as the operational phase have to be monitored closely. By monitoring, it will be possible to further manage these risks. By looking for early signs of a failure mechanism and adjusting the monitoring systems to these specific places, the state and situation of the dam will be well-known. With an early warning system for a lot of failure mechanisms, it will be able to fix the problem.

The pumping activities rely heavily on the operator. To limit the human influence on the system, an automatic back-up systems is created that will stop the turbines from pumping once it exceeds a certain reservoir level. The system can also be set to automatically flow the water out of the turbines once a breach has been monitored.

For both the construction phase and the operational phase, an extensive monitoring plan has to be realized. This plan will contain what, how, where and by whom the measurements will be made, how the data will be stored and presented. For every measurement, it should be considered what the expected value is and what the boundary value is during extreme conditions.

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[185] L.Fraccarollo and E.F.Toro, Experimental and numerical assessment of the shallow water model for two-dimensional dam-break type problems, Journal of hydraulic research, 1995

[186] T.Tingsanchali and W.Rattanapitikon, 2-D mathematical modeling for dam break wave propagation in supercritical and subcritical flows , 25th IAHR Congress for Hydraulic Research, 1993

[187] Jovanovic M. and Djordjevic D., Experimental verification of the MacCormack numerical, Advances in Engineering Software Vol. 23, 1995

21. Environment and expansion

The following subjects are discussed in this chapter:

21.1 Introduction to environment and expansion

In this section, a qualitative analysis is made for the environmental consequences of the transformation, followed by a short identification of possibilities of adding value to the energy storing function. At the end of this chapter it should be clear what the negative effects on the environment might be, coupled with some ways to compensate these and increase the value of the system.

There are lots of possibilities for creating and expanding the nature around the Slufter. Actually, being a reservoir with a varying water level, The Slufter can easily be combined with any form of nature. Some ideas had been identified in the creation of additional value in and around the Slufter which is in line with the future vision of the Port of Rotterdam (*see Table 43 and Figure 163*).

21.2 Contaminated silt management

With the application of energy storage for the Slufter, the future function of storing silt will be lost. A dual functionality is not possible because of the possibility of water flowing in and out of the system that is contaminated by mixing with the silt. The Slufter will still function as storage place for the current stored silt. The current amount of silt is 73 million m^3 (*see §14.6.2*), of which a part will be used in the dam core. The amount of silt which is used is equal to 6.3 million m^3 (*see §16.4*). This reduces the amount of silt to 67 million m^3 and causes the silt level to drop by

$$drop\ of\ silt\ level = \frac{used\ volume\ of\ silt}{surface\ area\ at\ that\ height} \rightarrow \frac{6.3 * 10^6}{2.62 * 10^6} = 2.4\ meters$$

The current level is at 2.5 meters NAP, which means the new level, will be at NAP. Since there is no hydraulic head difference between the sea-level and the silt level, there will be low natural flow to outside the dam. However, with the addition of a water layer that is 39 m thick, this will enhance the vertical and horizontal seepage of the contaminants. To speak quantitatively about this, groundwater models should be created and calculated what the increased seepage is, which is a recommendation.

By constructing the filter layer on top of the silt (*see §16.10*), the silt will be separated from the water inside the reservoir. The filter will ensure that the silt will remain inside the reservoir, not causing any contamination to the surroundings by direct in- and outflow of water.

The choice to utilize the Slufter for energy power essentially means that it cannot be used any more for additional storage of silt. The yearly input of contaminated silt is little and can be stored at other possible locations which are explored in *Appendix Y*.

21.3 Morpholical changes in the area

The area surrounding the Slufter will remain largely unchanged apart from the additional space requirement for the heightening of the dams.

The turbines are placed towards the southern side of the West-Voorne Dam *(see Figure 117)*. Here, they will be generating high flow values with the pumping and generation. Therefore, the surrounding area needs to be dredged until a certain depth. This dredging needs to be done repetitively, as the areas will continue to accrete because of the morphological conditions *(see §14.3)*. Because it is very local, no drastic change in the environment is predicted as a result of the dredging or the flow.

21.4 Plans for expansion

21.4.1 Introduction of expansion plans

Power balancing will be an increasing necessity in the future. With the increase of power from renewable energy sources, the need for power storage capacity will increase (*see §9.4)*. In this section it will be explored how the designed Slufter can cope with the growth in demand for power balancing.

Power balancing comes from both sides: supply and demand. The future of power generation is characterized by renewable energy sources, which increase the variable character of power supply (*see Part A*). For as well as the near future and further, power demand remains rather steady. Despite a rise in demand from industry and people, this is largely countered by increase in efficiency and cuts on power waste. The need for additional power balancing comes therefore mostly from the supply side, largely accountable to the variable energy sources. With the increase of wind power utilization for the Netherlands and the variable character of the wind, storage has to increase significantly in order to present wind power as a reliable energy source.

21.4.2 Expanding the Slufter to the Greater Slufter

The expansion of the storage capacity is very simple in concept; a larger reservoir will result in a larger storage capacity. Plans for a larger reservoir have already been presented in the alternatives with the Greater Slufter (*see §15.6*). With some modifications to the design, this alternative is presented here as a feasible option for expansion. The idea is to expand the size of the upper reservoir using the area that was indicated in the Greater Slufter. Because of the turbine placement, the new reservoir area is slightly adjusted. With the new reservoir, the size is expanded from 3.14 km^2 to 6.28 km^2. The energy storage capacity would doubles by this, from 2.16 GWh to 4.32 GWh. Depending on the demand for power capacity, additional turbines can be added near the current proposed placement. The largest activity is the creation of the dam surrounding the reservoir. This will have the same shape and size as was designed in Greater Slufter, *see Figure 161*.

Figure 161 ... Expansion of the Slufter (adjusted from the design of alternative 3, expansion indicated in red)

Silt from the Slufter will be dredged to the new reservoir to make the bottom of the new reservoir equally water-sealing. The silt management will remain unchanged with the silt remaining in the Slufter, covered with a filter to prevent mixing with the water. The dams are built in the same manner as the Slufter dams will be built up, see *Chapter 15.7.4*.

By removing the dam in between the two reservoirs, one large system can be created. However, the new reservoir can also operate parallel to the Slufter once new turbines are placed. This offers more flexibility.

21.4.3 Even further down the timeline...

It may be very much so, that doubling the power storage capacity is insufficient to cope with the balancing demands. Therefore, additional expansions plans are presented. This expansion will happen through so-called *expansion by compartments* strategy (*see Figure 162*). The compartmenting starts off with the creation of the Slufter for energy storage. The next expansion doubles the size (*red area in Figure 162)*. With future demands rising, a third compartment could be added (*purple area in Figure 162)*.

The areas that are chosen are suitable, especially considering the future. The clogging of the inlet has been discussed in the analysis. Further on in the future, this area will no long be underwater, offering possibilities for other functions for the area. The third compartment may be problematic; although it is not inside a Nature2000 area, the area is right next to it. Most of these points are discussed in *Chapter 14.* The expansions take place in the same manner that previous expansion is planned.

Figure 162 ... Expansion by compartments strategy for the future of the Slufter

21.5 Possibilities for creation of additional value

Value creating activity	Description	Feasibility
Habitat for bird-life	Because of the space, calmness and food, the area is a popular place for birdlife. These birds can be given a place to rest using so-called floating islands inside the reservoir. A pilot project, with an island created from FlexBase, has already been successful.[188] The island needs to be fixed with anchors so that it doesn't float away during turbine activity.	The pilot project proves its function by realizing these islands. Using this relatively cheap way, added value can be created to the storage device.
Development of the Slufter beach	Despite having no facilities, the Slufter Strand is now a popular place for visitors *(see §14.2)*. After the construction, this again can serve its purpose as a recreational site.	The sand is present since this dam section consists of a dune profile on the outer slope
Floating windmills	Inside the reservoir, there is sufficient space for floating windmills. This option is preferable because of the high wind power potential *(see §14.8).* Since these mills have a height of around 60-90 meters, the fluctuating water level will have no influence.[189]. This idea could be an alternative to the current windmills.	The current windmills have the highest C_f -factor in the Netherlands (*see §14.8*). Placing windmills are therefore guaranteed to be operating at high efficiency
Water sports around the Slufter	The surroundings of the Slufter are already a popular place for a variety of water sports, such as windsurfing, kite-surfing, sailing and wake-boarding (*see §14.2)*. This function is very dependent on the availability of the former proposed beach	High winds are present which is a requirement for some watersports, while the other sports can be practices without requirement

Table 43 … Possibilities for additional value creation in and around the Slufter

Figure 163 … Possibilities for additional values visualized

[188] DuraVermeer, Officiële ingebruikname Flexbase drijvend vogeleiland in De Slufter, DurvaVermeer.nl, 2008
[189] F. Bierboer, Dubbele Energie-eiland, De Ingenieur, 2012

22. Conclusion & Recommendations

22.1 Conclusion

While many engineering problems start off with a detailed problem description coming from the client, this case required a deeper search of the '*real problem behind the problem'*. This problem is found to be the power imbalance between supply and demand. From demand side this is the highly fluctuating daily peak-demand which is balanced by conventional fossil generation units. These are not optimal for this purpose because they lose a lot of their efficiency in the process of heating up and are rather expensive. From the supply side, the upcoming modern renewable energy sources offer a highly varying supply and therefore lose a lot of their reliability.

This is the situation in which the Slufter as an energy storage unit comes into play. It surpasses alternatives in many scale levels because it's a large scale solution, based on proven PHS technology and utilizing the full environment to minimize costs. The solution is clean as it uses water for its generation and flexible in operation as it can be powered by any energy source. In the current operation strategy, it is powered using the cheap nightly power which mostly comes from coal. With the rise of RES in the future, this may very well be dominated by wind power in order to utilize the RES potential in the Netherlands. Thus, it can aid in the penetration of wind power because its implementation increases the reliability of a wind power system.

The technical feasibility is promising, although more analysis is required into the soil characteristics and especially the settlement of the core. Flow analyses show that while constructing a core limits the seepage up to 10 times, even without an impermeable core, seepage is not significantly high. The core (CCM) is however preferred when considering stability in the many considered extreme static cases. A rather unique feature of the dam is that it is subject to extremely fast (down to 6 hours) fluctuations of water. This reduces the stability of the CCM by 30% while a steadier lowering leads to only 15% loss of stability. This fast lowering is why two other analyzed core models, the SCM and LCM, which are easier to construct, perform significantly worse in terms of stability. While the CCM does stay stable with a windmill on top, the margin in the fast lowering phase is too low to be recommended. An attempt of optimization by making the core smaller at the top has been successful at providing better stability; however, especially considering added settlements of the windmill, this requires more analysis.

The performance in terms of peak-balancing is solid as it provides a high output of 470 MW with 4 turbines, enough to supply the peak-balancing needs of Zuid-Holland, Zeeland and a large part of Noord-Holland. The wind power balancing with 2.16 GWh is enough to last Zuid-Holland till 2025. Plans for phased expansion of the power and storage capacity are offered as future demand changes. These expansions can be realized in the area between the Slufter and Voorne, an area that is increasingly clogging up with sediment. The simulated daily operation of the system in the fluctuating energy market is highly profitable; with the Maximum Profit Strategy, the annual profit is €19.3 million by sheer buying power in the night and selling during the day. As the Slufter is a replacement for the CCGT units operating now, the fuel required for these plants is saved, which results in an annual €9.2 million savings. These are only the savings when considering direct fuel costs and without the secondary effects of fossil fueled plants (such as carbon costs or pollution mitigations).

The detailed planning and costs are confirming the primary estimates as it costs nearly €600 million to build the construction plan in 10 months. With the annual benefits added and annual maintenance costs reduced, the pack-back period is 30 years, although this number is sensitive to market developments and economic conditions. All in all, the system is proving to be promising economically as well.

The Slufter shows high potential for the application of energy storage through PHS because it incorporates the current function of silt storage in the new situation. It profits from the current function that boasts high surrounding dams and a thick consolidated impermeable silt layer below to minimize the civil engineering costs. The concept fits perfectly into the desires and image of Rotterdam and the Port of Rotterdam that seek a new function for this area and fits in their future sustainability and energy ambitions. If coupled with the ideas for the added creation of value, such as the Slufter beach, the birdlife habitat and floating windmills, it could gain easy public support. People would rather see a water reservoir that provides them with a service and aids the penetration of renewable energy than a place to hide away contaminations and worry about this area's future for centuries.

22.2 Recommendations

Based upon the analysis performed, some recommendations are put together for future study. The amount of recommendations is kept limited to really emphasize the core recommendations.

22.2.1 Expanding technical analysis with detailed soil analysis, consolidation and windmills

The following characteristics should be verified for each soil type:

- Hydraulic conductivity
- Volumetric water content
- The assumption that the material is anisotropic
- Permeability (follows from the hydraulic conductivity and volumetric water content)
- Soil unit weight above and below water
- Soil cohesion
- Internal angle of repose / internal friction angle
- Young's modulus
- Poisson's ratio
- Undrained shear strength
- Dilatancy angle
- Young's modulus inclined
- Undrained inclined shear strength

With this data, the technical analysis should be expanded by analyzing the settlements and consolidation of the core. After, the design can be optimized for the placement of windmills. As the most efficient wind farm in the Netherlands, the continuation of the Windpark Slufter will add a lot of value to the Slufter.

22.2.2 Increasing power and storage capacity

It should be considered to add more water turbines as this will concentrate the generation more with a higher capacity for a shorter time. This fits the peak demand function better, however comes with higher costs. The choice therefore depends if the costs can be justified by the additional benefits.

The Slufter in its current form offers a limited amount for power storage that is suitable to supply Zuid-Holland till 2025. This is heavily dependent on the expansion of RES in the Netherlands. Primary ideas for expanding the reservoir have been incorporated in the plan; however require more analysis. As these sections don't feature the environment the Slufter profits from, how will the technical design looks like and what construction methods will be considered. Will the costs make up for the added benefits?

22.2.3 Optimizing the benefits and pay-back period

The Power Generation Model (PGM) and the Benefit Model (BeM) are two tools developed that incorporate some analysis on the market fluctuations. This can be expanded by more statistical analysis spanning multiple years and considering local deviations.

The same research is proposed for the economic development. The benefits and thus pay-back period are very sensitive to market changes and the time-preference rate. While a scenario has been chosen in this research, this can be expanded with multiple scenarios that are based on market research.

22.2.4 Risk management

Quantitative analysis on the probability of failure, the consequences and thus the risks are essential because of the 35 meter high dam that is close to the Maasvlakte area that is worth billions to the Dutch economy. The risk analysis performed in this research maps the risks and qualitatively assesses them and the consequences. This can be further expanded by the proposition of measures to mitigate the risks.

A suggestion is the creation of 'spillway' inside the North Sea dam that can be opened in case of an emergency. This spillway has to be designed so that the water flowing into the Maasvlakte remains limited due to the opening of this spillway. It should be assessed whether this option is feasible.

22.2.5 Sociologic analysis for empowering the Stakeholders analysis and MCA's

The multi criteria analyses (MCA's) are used as a decision making tool in the choice of the alternatives. While meant to be a tool to make an objective choice, the value judgments display a strong subjective character because the demands and wishes of the stakeholders for the criteria are guessed. To limit this, the MCA could be supported with an extensive market and sociologic analysis that gives insight into the valuation of the criteria.

22.2.6 Groundwater analysis with regard of contamination

In the current situation, the flow of contaminants into the surrounding area has been limited *(see §14.6.2*). With the placement of a water layer of 39 meters, the contaminated soil underneath the Slufter will be put under an increasingly high pressure that could enhance the flow of contaminants into the sub-layers and the environment, especially for the Class 4 material coming from the Papegaaienbek. This analysis can be performed by simulating the groundwater flows in the new situation. With the modeling of the groundwater flow in the new situation, some quantitative values of the flow can be given and this risk can be assessed.

Abbreviations

Abbreviations that can be found here are made *cursive ('italic')* in the paper (alphabetical ordered)

- **EU** … European Union
- **BeM** … Benefit Model
- **CES** … cryogenic energy storage
- **CCM** … Centered Core Model
- **CCGT** … combined cycle gas turbines
- **C_f** … capacity factor
- **EEX** … European Energy Exchange
- **GHG** … greenhouse gases
- **GWH** … gigawatt hour
- **KWh** ... kilowatt hour
- **LCM** … Line Core Model
- **LEC** … levelized energy costs
- **MCA** … Multi Criteria Analysis
- **MWh** … megawatt hour
- **NAP** … Normaal Amsterdams Peil
- **NCM** … No Core Model
- **PGM** … Power Generation Model
- **PHS** … pumped hydropower storage
- **PV** … photovoltaic
- **RES** … renewable energy sources
- **SCM** … Shifted Core Model
- **TSHD** … trailing suction hopper dredger
- **U-CAES** … underground compressed air energy storage

Glossary

Terms that can be found in the glossary are made *cursive ('italic')* in the paper (alphabetical ordered)

carbon price … price based upon the carbon content of fuels (P. Hoeller, OECD, 2§10)

capacity factor … value for the variability obtained by dividing the generated power and turbine capacity

energy … the amount of work of heat delivered (IPCC, 'AR4-SP, Annex 1', 2007)

fossil fuels … are fuels formed by natural processes such as anaerobic decomposition of buried dead organisms. The age of the organisms and their resulting fossil fuels is typically millions of years, and sometimes exceeds 650 million years (P.Mann, Giant oil and gas fields of the decade 1990-1999, 2009)

global warming … the rise of global temperatures of 1 degree or more over the course of at least a century (IPCC, 'AR4-SP, Annex 1', 2007)

greenhouse gases … greenhouse gases are gases that contribute to the warming of the earth. The main mechanism is the trapping of the sun's radiation (as illustrated IPCC report IV, 2007)

intermittency - the extent to which a power source is unintentionally stopped or unavailable (frequently used as if it were synonymous with variability, which is the extent to which a power source may exhibit undesired or uncontrolled changes in output (G.Sinden, Assessing the Costs of Intermittent Power Generation, 2005)

penstock … is either a sluice or gate used to control the flow of water, or a pipe used to carry water to a turbine (The Free Dictionary,2013)

primary energy … is an energy form found in nature that has not been subjected to any conversion or transformation process. It is energy contained in raw fuels, and other forms of energy received as input to a system. Primary energy can be non-renewable or renewable (The Encyclopedia of Earth, 2011)

renewable energy source (RES) … sources from which energy is obtained that is from the continuing or repetitive currents of energy occurring in the natural environment and includes non-carbon technologies such as solar energy, hydropower, wind, tide and waves and geothermal heat, as well as carbon-neutral technologies such as biomass (IPCC, 'AR4-SP, Annex 1', 2007)

wind energy … the transfer of the kinetic energy in moving air to electrical energy or mechanical energy (Wind Energy, Encyclopedia Britannica, 2013)

pumped hydropower storage … hydropower with the possibility to pump the water back up

Slufter … silt depot used for contaminated silt, located at the Maasvlakte near Rotterdam

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The end, thanks for reading!