# A study on conversion and storage of sustainable energy using aquatic civil structures

Author

E. E. Juffermans

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## Colophon

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**E. E. (Eva) Juffermans** (Author)
University of Twente.
Bachelor Civiele Techniek

Campuslaan 45
7522NG Enschede

e.e.juffermans@student.utwente.nl
+31 6 422 449 06

**P. (Paulien) Hoogvorst MSc** (Daily supervisor)
Witteveen + Bos
Industrile automatisering & duurzame energie

Van Twickelostraat 2
P.O. Box 233
7400 AE Deventer

paulien.hoogvorst@witteveenbos.com
+31 6 192 908 35

**Dr. Ir. A. G. (Bram) Entrop** (UT supervisor)
University of Twente.
Construction Management & Engineering

Drienerlolaan 5
P.O. Box 217
7500 AE Enschede

a.g.entrop@utwente.nl
+31(0)53 489 6860

## Preface

This is a study on conversion and storage of sustainable energy using aquatic civil structures. This report is the final result of my bachelor thesis project in Civil Engineering. Commisioned by Engineering and consultancy bureau Witteveen + Bos inquiries have been performed for the group Smart Infra Systems within a period of 11 weeks from May to July 2017 in Deventer. I am very grateful for the cooperation and ambience with and from Witteveen + Bos, especially from Paulien Hoogvorst and Johan Kornet.

Many thanks to my supervisor from the University Bram Entrop for trying to make sense of unstructured reports and support in the process. To Izak Hanse, Bas van Haaren and my parents my sincerest gratitude for digging through my text looking for improvements. Also special thanks to Emiel van Druten, Peter Suijdendorp and Herman Meester from Witteveen + Bos for enthusiastic responses to my research and help with collecting data.

For me this research is the link between two fields of study I very much enjoy: civil engineering and sustainable energy or hopefully my bachelor and master.

Eva Juffermans
Deventer, July 2017

# Abstract

The objective of this research is to gain information on possibilities concerning conversion and storage techniques in aquatic civil structures. Specifically on those techniques that use water in (a part of) the process.

Using the scientific method, conversion and storage techniques are investigated on several conditions to get an overview of plausible techniques to implement in aquatic discharge structures. The conditions consist of the impact of the technique on the water balance and function of the structure, the total cost of operation including the installation cost, maintenance cost and payback time and performance measured by the peak power and capacity. An hypothesis is formed based on the techniques that rated best in the criteria analysis: "Electrical energy can be converted and stored using hydro power and pumped hydro storage in existing structures that dispense superfluous water". This is tested using two test locations with different discharge systems: Sluis Sambeek in the Meuse and the Waaiersluis in the Hollandsche IJssel. From these tests can be concluded that the research does not support the idea of profitable conversion or storage of energy in existing aquatic discharge structures due to strong constraints on the water balance. This does not mean a definitive no to hydro power in aquatic civil structures, but another approach should be wielded to make the possibilities more cost efficient. An example of such an approach could be a life cycle analysis on hydro power components.

# Contents

# 1 Introduction

The discussion on sustainable energy sources has truly started during the last decades. However, a large part of the problems remain unsolved. Engineering bureau Witteveen+Bos is well aware of this problem, designing solutions to large projects on water, infrastructure and other landmarks. Encountering the consequences of environmental change and limited resources on everyday basis in design constraints, questions on how to level the extremes in sustainable electricity supplies emerged. Regarding conversion and storage of sustainable electricity, several solutions among which the application of electricity storage for traffic purposes (like lighting systems and traffic regulators) or heating facilities were considered. The most promising solution appeared to be storage using aquatic civil structures due to the present level of expertise in the field by those involved and the possibilities those systems would provide. The involvement of water creates additional solutions, offering a broader set of sustainable techniques to resolve the issue.

## 1.1 Background

When pursuing sustainability in the use of energy, the 'Trias Energetica' can give guidance in approaching this goal. Internationally employed since 2001 by A.G. Hestnes (former president of the 'International Solar Energy Society') it contains a roadmap to sustainable design (see Figure 1) (Entrop & Brouwers, 2009). In the second step, use of renewable energy, an obstacle can be exposed. Renewable energy resources are characterized by extremes in supply of electricity, as their sources are not enforceable in the amount of power they provide. For example with the use of photo-voltaic panels or wind turbines, whenever solar radiation or wind respectively is strongly present or absent, these extremes are incited. The net load (calculated by subtracting the forecasted electricity production from the forecasted demand) does not follow these extremes: while the net load peaks during the evening and is relatively low during the day, Photo Voltaic panels (PV-panels, also known as solar panels) peak during mid-day (Denholm, O'Connell, Brinkman, & Jorgenson, 2015). See for example Figure 2 showing net load and electricity production from solar radiation and wind on a day in March in the state of California. According to this graph there is a risk of overgeneration around 12pm, meaning there would be more electricity generated than can be used at that moment. In 2013 California Independent System Operator (CAISO) made a projection on the developement of the net load towards 2020 (California Independent System Operator, 2016). The already large differences in net load and the overgeneration risk will likely extrapolate in the upcoming years due to the increasing capacity of PV-panels during mid-day. This is also known as the 'Duck curve'(see Figure 3). This projection was recently confirmed by energy consultant ScottMadden (Vlahoplus, Litra, Quinlan, & Becker, 2016) reading even higher extremes than predicted .

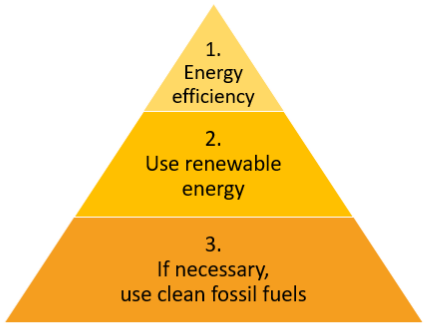


**Figure 1:** The Trias Energetica

A solution should be found to properly distribute these amounts of overgenerated electricity over the demands, instead of letting this energy go to waste. For example, one can find energy consumers like heavy industry and connect them to a network including sustainable sources. Excess in sustainably generated electricity can be a substitute for the non-sustainable electricity used previously and generation of non-sustainable energy could be decreased. Tentatively, the demand of those consumers will not be inferior to the

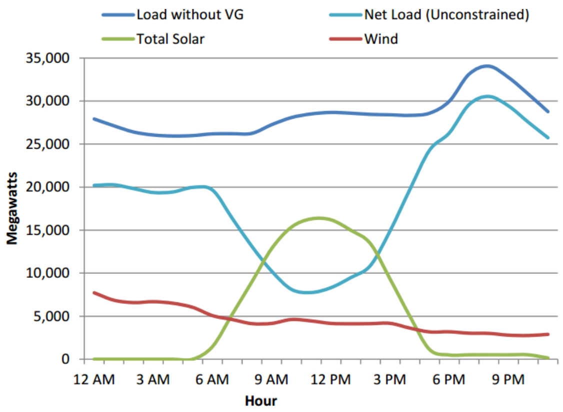


**Figure 2:** Energy profile of March 29th 2013 in California. Reprinted from Denholm et al., 2015, p.14

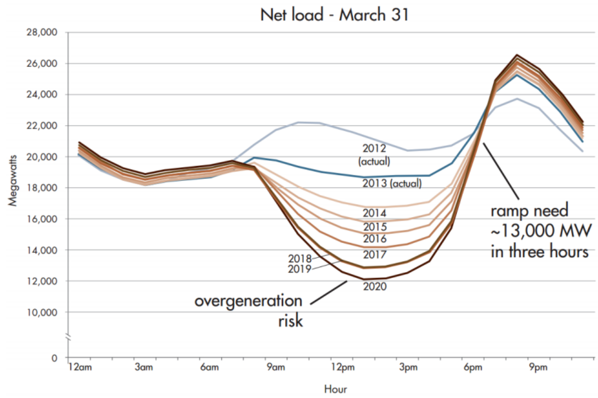


**Figure 3:** CAISO's Duck curve: Daily energy load profile in California. Reprinted from Denholm et al., 2015, p.3

capacity of sustainable sources. The downside of this option is that the energy often needs to be transported a long path coming from the source, which causes major losses of energy due to resistance of the cables. Moreover, when considering smaller energy networks like neighbourhoods with average house holds, these heavy consumers might not be present in a suitable range. Besides, when all energy sources have been converted to be sustainable, this solution will not suffice.

Another option could be to store energy generated during mid-day hours for later use. The most common method of storing energy is in chemical batteries. After many years this process has been improved, but an efficiency up to 90% seems to be the limit (Anton & Sodano, 2007). Even with an efficiency of 90% the life cycle of a chemical battery is unsustainable. Storing energy in potential and kinetic energy of water, also known as 'Pumped hydro power', is a mature, sustainable method of storing energy used in Australia, USA, Switzerland and many other countries (Paish, 2002). Although large scale applications require more head difference than present in the Netherlands, small or micro hydro power might form a solution for Dutch generation and storage.

When using potential and kinetic energy of water for storing and regenerating electricity a necessary element is the existence of water in a controlled environment. This element can be found in all aquatic civil structures. Of these structures a potential source for generation of electricity may lie in those that discharge superfluous water. When dispensing superfluous water, potential energy is set loose and transformed into kinetic energy. Possibly techniques can be found to efficiently access and use this energy.

**The problem statement is:** *"Generation of sustainable electricity does not align with the demand of electricity consumers creating an environment in which sustainable electricity could go amiss."*

## 1.2 Structure of this report

In Chapter 2 the setup of this research will be explained. The research objective will be set, research questions to accomplish this objective will be constructed and elucidated with an approach following the hypothetico-deductive method, also known as the scientific method, indulged very often in scientific research (Ayala, 2016). After exploring the layout, both conversion and storage techniques are investigated on several conditions to get an overview of plausible techniques to implement in aquatic discharge structures in Chapter 3. When this is clear, two test locations are chosen (Chapter 4) and the most promising conversion and storage techniques will be implemented in these situations in Chapter 5. The results will be analysed and the research will be concluded with an answer to the main research question in context of possible reservations. Recommendations to follow-up research and viable projects will shed some light on practical consequences of this research at the end in Chapter 9.

## 2 Research setup

### 2.1 Research objective

With this research the options will be investigated for integrating energy conversion and storage techniques in civil structures that discharge superfluous water. These options could for example be present in sluices or weirs. Primary focus will be electricity and dammed water as energy carriers, because electrical energy will be both the supplying carrier (from the surrounding network) and the final carrier to enable consumers of the network to easily access and use the energy. In Figure 4 an overview of the positioning of this research can be found. Thermal energy will not be investigated due to the short amount of time available for this research and the absence of prior knowledge on critical subjects like exergy and efficient use of thermal energy. This is a possibility for further investigation to be conducted by a thermal energy expert.

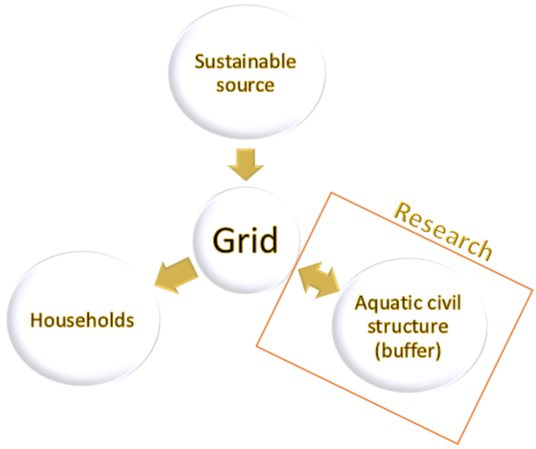


**Figure 4:** Research demarcation

**The research objective is:** *"To integrate energy conversion and storage in aquatic discharge structures using electricity and dammed water as energy carriers."*

### 2.2 Scope

The research will be done while keeping applications in the Netherlands in mind. This limits the scope by creating several issues. As a result the difference in altitude in the environment will be relatively low and when building up a volume of water as storage method this will form a restriction. The dimensions of the volume are limited to increase in surface (length and width) as opposed to depth causing restrictions in finding possible areas which are non-existent in areas with more altimeters. Additionally the water balance in most situations in the Netherlands is on a tight schedule of discharge and pumping due to the many polders and deltas in the Netherlands. This might not be compatible with discharge and pumping volumes needed for storing or converting energy.

Another important issue will be the changes needed to implement the desired techniques in real situations in the Netherlands. The operational techniques used in the Netherlands are not designed to facilitate energy conversion or storage systems. When the current operational techniques should be replaced entirely, it is questionable how profitable such a project would be in both environmental and financial aspects. The emissions and materials necessary to facilitate such a project might diminish the positive effects of clean energy. It is also quite possible that no financial support can be found for projects with a long payback period in ratio to the profit since this research will probably result in small scaled solutions.

An output of relative small scale solutions is assumed because the potential of kinetic energy in Dutch rivers and waterways can estimated by the formula $E_{kin} = \frac{1}{2}mv^2$. This equals a potential of $E_{kin} = \frac{1}{2}\rho Q v^2$ per second expressed by means of flow rate. The mean flow rate of the Rhine at Lobith, representing the highest flow rate of the rivers of the Netherlands on average, is 2300 m$^3$/s and the mean velocity at that point is approximately 1 m/s (Meulen, Joziasse, Meurs, Ham, & E., 2008). This results in a potential of $E_{kin} = \frac{1}{2} \cdot 1000 \cdot 2300 \cdot 1^2 = 1550000 J/s = 1550 kW$ for the largest river in the Netherlands (neglecting efficiency of conversion techniques and assuming all water can be used). Compared to the energy needed to contribute to the national grid, this is a potential for local grids (US Department of Energy, 2002). If the profits outweigh the costs, it is desirable to implement such measures.

## 2.3 Research questions and methodology

The research objective can be achieved by answering the main research question:

*"Can electrical energy be converted and stored using existing structures that dispense superfluous water?"*

This question can be split in research to two separate subjects: conversion techniques and storage techniques. Although their application is tightly linked when aiming for high efficiency, they can first be investigated separately to better understand their relation and possibilities in aquatic discharge structures. After this they need to be evaluated together and tested on actual situations.

The process is described by three subquestions as listed below:

1. How can electricity be converted using dispensation of superfluous water?

2. How can electricity be stored using aquatic structures that dispense superfluous water?

   The disadvantages and advantages of both options will be tested on the criteria proposed in Section 2.2 and a decision will be made on the most suitable techniques.

3. How can storage and conversion of electricity be implemented in aquatic civil structures that dispense superfluous water in the Netherlands?

By use of the hypothetico-deductive method, illustrated in Figure 5, these questions will be answered. With help from the first two sub-questions a hypothesis will be deduced as to which techniques show the most potential considering the circumstances described in the scope. With this information a prediction can be made on suitable techniques for aquatic discharge structures which will be tested with a theoretical experiment using the test locations in Chapter 5 (sub-question 3). According to the results of the last sub-question the hypothesis is supported or should be revised. The next step, on whether more research should be done confirming the hypothesis (perhaps a pilot project) or on the question to which techniques are best used in aquatic civil structures, will be discussed in Chapters 9 and 7.

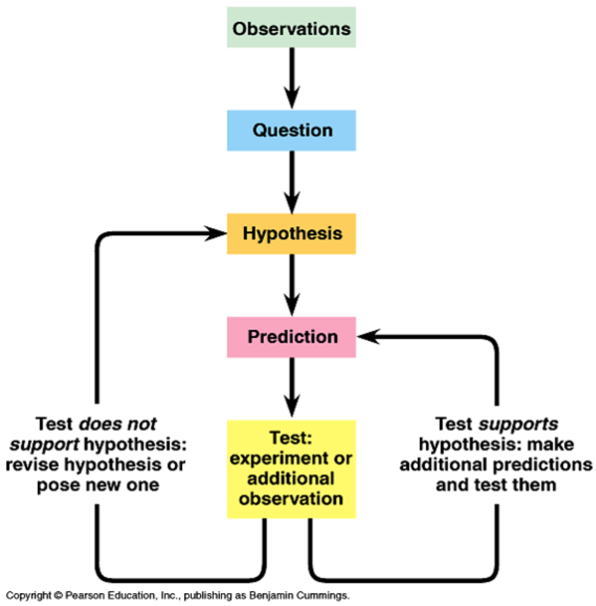


**Figure 5:** The hypothetico-deductive method. Reprinted from MacLeod, 2017, slide 32.

# 3 Conversion and storage of electricity

To answer the first two research questions posed in Section 2.3 the possible techniques will be elucidated and evaluated on several criteria. These criteria will be alleged and categorized in the first section. After setting the framework the techniques will be discussed and in the last section of this chapter an analysis is performed on both the conversion and storage techniques. With the analysis high potential techniques can be distinguished.

## 3.1 Criteria of selection

The conversion and storage techniques will be compared on several criteria to determine which techniques are better applicable in civil discharge structures. This is executed by comparing the advantage the technique offers when operating with the disadvantage of the investment needed, considering the circumstances that the impact of the technique will create.

- *Impact*; the effect of implementing a conversion or storage technique in a water lock will be measured by two aspects: the impact on the water balance and on the (original) function of the lock. The effect on the water balance will be measured by percentage of deviation of the local and total[1] volume flow rate in $m^3/s$. The impact on the original function will depend on the primary goal the original structure had, in which two categories can be distinguished: navigation and retaining water. The impact on the first category will be measured by percentage of delay in passage in minutes, the impact on retaining water by percentage of deviation in head in meters.
- *Total Cost of Ownership (TCO)*; an estimation of the TCO should indicate the financial benefit of the technique that is to be implemented. Aspects of the TCO are installation and maintenance costs, the revenue from supplied electricity measured in Euro and deducible from the first aspects, payback time.
- *Performance*; the total power (kW), maximum capacity (kWh per year) and efficiency should be as high as possible. The first goal will be electricity supply for the structure itself and when this amount can be exceeded, supply for the local grid is considered.

The criteria for consideration of conversion and storage techniques need to be measurable and comparable to extract conclusions. The criteria are made comparable by use of the rating scale of Likert (1932). This measurement method provides an attitude scale towards degrees of approval with the questionnaire materials and has often proved itself in research papers. A study on review of scale developments (Hinkin, 1995) has shown that up to five point scaling the coefficient alpha reliability increases. Reliability of scaling methods using more than five points level off. Therefore, a five point scaling system is applied. All criteria have been given values for each rating relative to each other, where a very positive rating corresponds with much potential for local grid supply and a very negative rating with few potential for even supporting the energy supply of an average lock system (see Table 1).

The impact is scaled to a commonly used method of design for safety in waterways, the project 'Veiligheid Nederland in Kaart' (Projectbureau VNK, 2013). When implementing conversion techniques, the flow rate will often slow down due to extraction of energy from the water resulting in a decrease in head. With a deviation of the head higher than 10%,

[1] The local *and* volume flow is considered. The flow might accelerate in a certain spot (local) due to concentration of the flow through a tight area. This may cause negative effects like erosion and impact on navigation. A deviation in total volume flow rate may contribute to flooding or drainage of the surrounding water level.

**Table 1:** Rating of criteria

| Rating: | - - | - | -/+ | + | ++ |
|---|---|---|---|---|---|
| Impact | | | | | |
| Water balance (% of $m^3/s$) | ≥20 | 15 | 10 | 5 | 0 |
| Function of the water lock (% of m or min) | ≥20 | 15 | 10 | 5 | 0 |
| TCO | | | | | |
| Installation cost (€/kWh) | ≥2000 | 1000 | 500 | 250 | ≤100 |
| Maintenance cost (€/kWh/year) | ≥200 | 100 | 50 | 25 | 0 |
| Payback time (years) | ≥40 | 30 | 20 | 10 | ≤5 |
| Performance | | | | | |
| Power (kW) | 0 | 25 | 50 | 100 | ≥200 |
| Capacity (MWh per year) | 0 | 100 | 200 | 400 | ≥800 |

industrial navigation might not be possible depending on the waterway causing extra costs for dredging. The same is assumed for the flow rate (the relation between flow rate and head is not lineair, but they are strongly related). The time to lock ships in larger navigation lock amounts to approximately 15 minutes (Provincie Flevoland, 2017). A deviation of a few minutes is acceptable although not preferable and set to the rating +/-.

The total cost of ownership is scaled to the performance criteria. The installation costs that are higher than those that would correspond to the ++ rating of power and capacity are set to the – rating, costs that are lower than those that would correspond to the – rating of power and capacity are set to ++ and the installation costs corresponding to the +/- rating of power and capacity are set to +/-. Similarly, the maintenance costs are processed. The rating of payback time is based on several case studies in sustainable energy for moveable bridges and locks (Bierling, 2015) and the assumption that most renewable energy systems have a life span of a maximum of 40 years. Costs of replacement of the technologies after lifespan and subsequential revenue and payback times have not been taken into account. The revenue is estimated using the present price categories from www.apxgroup.com of €40/MWh When knowing the installation, maintenance and revenue, the payback time can be estimated.

The electricity consumption of a household in the Netherlands is on average 3000 kWh/year (CBS, 2016). The electricity consumption of large lock structures is about 300 MWh/year (Rijkswaterstaat; Personal communications, 2017). Complemented by an advising report of Frontier Economics to the ministry of economic affairs (2015) and the research report of Bierling, a range on possibilities for power and capacity has been deployed. The values are strongly related to the TCO, and should be examined in relation to the respective criteria.

## 3.2 Conversion techniques

Currently many techniques using several different sources are in some phase of the process from research to competing on the energy market. The ones listed below have been filtered to techniques using water in (a part of) the process. They are sorted by source of energy.

### 3.2.1 Hydro power

Hydro power is a conversion technique using the pressure of water (from velocity or head) to drive some sort of turbine. In the turbine the gyration of the rotor is converted to electricity by making changes in the surrounding magnetic field inducing an alternating or direct current.

*Impact*

The impact on the water balance from implementing hydro power can be minimized by homogenizing the original flow rate distribution (over time) with the flow rate exhaust from the turbine(s). Locally the flow rate will increase with the ratio of the width of the river to the width of the turbine entrance. Common crossflow turbines have an entrance width of 0.2 m on average (Chaurette, n.d.), compared to large rivers and canals in the Netherlands of 100 m in width this results in a ratio of 500. Erosion of the waterway can be protected from this acceleration by monitoring the exhaust of the turbine and when encountering high speeds arrangements could be made to reduce the exhaust flow, for example by facilitating a stilling basin.

The impact on the function of the lock depends on the application. When using discharge of the lock to convert energy, discharge times need to be estimated in advance. When obstructing passage of navigation or deviating too far from the desired discharge rate the flows should be separated or it should be possible to bypass the turbine. Consequences of deviation from the flow rate could for example include: obstruction of industrial purpose navigation causing issues in economic and transportation equilibria.

*TCO*

The total cost of ownership can be estimated assuming the potential power would be around 15 000 kW and capacity around 60 000 MWh (hypothetical case in between the calculated power output of paragraph 'Performance' below). This is performed using a study from the energy research centre (ECN) on characteristic numbers for small hydro projects (Beurskens & van Sambeek, 2003). Installation costs are dependent on the current situation of implementation. Assuming the use of an existing structure, following the scope of this research, the installation costs would be between €1000 and €1500 per kW, adding to a total of $1250 \cdot 15000 =$ €18 750 000. Maintenance can be estimated to 2% of the installation costs per kW each year, resulting in €375 000 per year (Lako & Wakker, 2009).

The price of electricity varies greatly over day and year, for present price categories see www.apxgroup.com. Assumed is an average of €40 per MWh resulting in a revenue of about €2 400 000. This suggests a payback period of approximately 8 years.

*Performance*

The source of pressure defines the maximum power output and two sources can be discerned: kinetic energy and potential energy.

Kinetic energy, also known as 'run-off-the-river' power, is abstracted from the natural velocity of the river by placement of a turbine in the river stream. The maximum power output can be derived from the basic formula of kinetic energy, $E_{Kin} = \frac{1}{2}mv^2$, as shown in Equation 1.

$$P_{Kin} = \frac{1}{2}\rho Q v^2 \eta \tag{1}$$

Where: $P$ is the potential power output in $W$.
$\rho$ is the density of the water in $kg/m^3$.
$Q$ is the flow rate of the water in $m^3/s$.
$v$ is the velocity of the water in $m/s$.
$\eta$ is the dimensionless efficiency of the turbine.

Potential energy is converted by placing a turbine at the base of a head difference in water and aiming a flow pressurized by the head difference at a turbine. Potential energy of the water is transformed to kinetic energy and to work done on the blades. The maximum power output from potential energy can be derived from the basic formula for potential energy, $E_{Pot} = mgh$, as shown in Equation 2.

$$P_{Pot} = \rho Q g h \eta \tag{2}$$

Where: $g$ is the standard gravitational acceleration of 9.81 in $m/s^2$.
$h$ is the difference in head before and after the obstruction in $m$.

In both equations it is assumed that the flow rate will remain the same (instead of decreasing due to friction losses) and that the water flowing through a certain point in the river can exclusively be directed through turbines and used for conversion of energy.

The potential power output from each source is equal when the ratio of velocity versus head is $0.051v^2 = h$. The mean head at weirs in the largest rivers of the Netherlands (Rhine and sub rivers and Meuse) is between 2 and 3 meters (Meulen et al., 2008). To match the potential in power from potential energy, the velocity would need to meet values of at least 7 m/s. A multiplication as such would have consequences for the water balance. The potential energy will therefore be used to calculate the potential for hydro power, with the Meuse and Rhine/Waal as examples. The Rhine has a mean flow rate of 2300 $m^3/s$, the Meuse 290 $m^3/s$ and a mean head of 2 m is used for the Rhine and 3 m for the Meuse (although in reality this strongly depends on the location).

This forms a potential for the Rhine of $1000 \cdot 2300 \cdot 9.81 \cdot 2 = 45126\eta\, kW$ peak power. Assuming the turbine could run 50% of the time (due to differences in flow rate), the potential capacity would be $45126 \cdot 365 \cdot 24 \cdot 0.5 = 1.98 \cdot 10^8 \eta\, kWh$ per year. For the Meuse in a similar calculation: $1000 \cdot 290 \cdot 9.81 \cdot 3 = 8535\eta\, kW$ and $8535 \cdot 365 \cdot 24 \cdot 0.5 = 3.74 \cdot 10^7 \eta\, kWh$. This amount is not entirely accessible due to turbine efficiencies of 70-90% (Nasir, 2014), friction losses, unwanted deceleration of the flow rate and the inability to guide the entire stream through a turbine. Assumed is that 75% of the flow rate can be guided through turbines, with 80% efficiency, this means approximately 60% of the total amount is accessible. This results in a final estimated power of 27 076 kW and 118 591 MWh per year for the Rhine and 5 121 kW, 22 430 MWh per year for the Meuse.

#### 3.2.2 Wave energy

A relative novelty to capturing energy from water are the techniques to convert energy from temporal elevation of the water level. On short intervals varying from several seconds to minutes (also known as waves) this originates for a relatively small amount in the gravitational pull from the moon and for an irregular but larger result from a wind or vessel induced pressure gradient. For this analysis wind induced waves have been left out of the scope since wind induced waves reduce greatly in size before encountering civil discharge structures due to blocking of the wind by shore, vessels and decrement of depth of the water.

*Impact*

The impact of wave capturing techniques is positive. Drivers or pressure pads along the side of waterways adds to protection of the shore by forming a physical boudary to erosion of water, wind or objects tempering the surface. The impact on water balance and function of the lock is non-existent.

*TCO*

A study on energy from waves along shore estimates the installation costs for piezo electric materials or drivers alongside the shore at a maximum of €200 per running meter (van der Wal, de Jong, & Weller, 2010). Exact numbers on maintenance costs are unclear. Assumed is that by use of drivers or piezo electric materials relatively much maintenance is needed due to the impact of algae or damage to the performance of the systems. The revenue on vessel induced wave energy would be approximately €120/m considering the performance of drivers (the best perofrming technique, see 'Performance') 3000 kWh/m$^2$. The amount is a hypothetical case between the potentials of the Meuse and Waal. To make the technique profitable, the maintenance costs should be below €120/m per year or lower. When maintenance costs of €80/m could be established, the payback period would be approximately 15 years. Assumed is the same price per MWh as hydro power and that the vertical length of the area of potential energy is utilized fully by the chosen technique.

*Performance*

The available amount of energy from waves can be calculated using the Airy wave theory, also known as linear wave theory, from George Beddell Airy (1801-1892) describing the time averaged wave induced energy per unit horizontal area by addition of potential and kinetic energy (Holthuijsen, 2007). The potential energy of a wave is the potential energy of the water column including the wave, minus the potential energy of the water column excluding the wave as illustrated in Figure 6. This can be described by the following intervals:

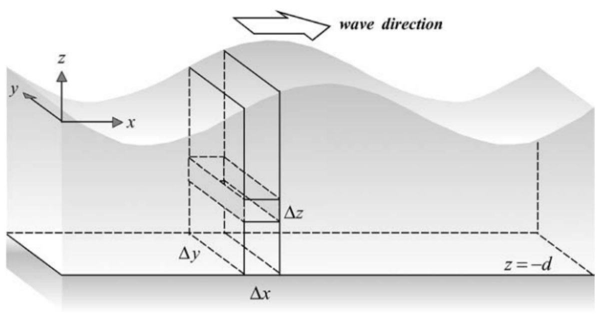


**Figure 6:** A water column in the $x, y, z$ field used to calculate the wave energy. Reprinted from Holthuijsen, 2007, p.131.

$$E_{pot} = \int_{-d}^{\eta} \rho g z \, dz - \int_{-d}^{0} \rho g z \, dz = \int_{0}^{\eta} \rho g z \, dz \tag{3}$$

Where:
- $E_{pot}$ is the energy of a wave over area $\Delta x \Delta y$ in $J/m^2$.
- $d$ is the water depth in $m$.
- $\eta$ is the surface elevation in $m$.
- $\rho$ is the density of the water in $kg/m^3$.
- $g$ is the standard gravitational acceleration of 9.81 in $m/s^2$.
- $z$ is the coordinate in z-direction in $m$.

The result of this integral expressed in terms of wave amplitude $a$ is:

$$E_{pot} = \frac{1}{2}\rho g\eta^2 = \frac{1}{4}\rho g a^2 \tag{4}$$

The kinetic energy of this wave can be expressed as $\frac{1}{2}\rho\Delta x\Delta y\Delta z u^2$ with $u^2 = u_x^2 + u_z^2$. Under the conditions from the linear wave theory this can be abbreviated as:

$$E_{kin} = \frac{1}{4}\rho g a^2 \tag{5}$$

Describing the kinetic energy per unit horizontal area. The total wave energy density is then $E_{pot} + E_{kin}$:

$$E_{wave} = \frac{1}{2}\rho g a^2 \tag{6}$$

The available amount of power that theoretically could be extracted (provided the efficiency of all conversion systems is 100%) is defined by multiplying the wave energy with the group velocity:

$$P_{wave} = E_{wave} \cdot c_g = c \cdot n \cdot \frac{1}{2}\rho g a^2 \tag{7}$$

Where: $P_{wave}$ is the power of a wave in $W/m^2$.
$c_g$ is the propagation velocity of a group of waves in $m/s$.
$c$ is the phase speed of a wave in $m/s$.
$n$ is a dimensionless ratio $\frac{1}{2}\left(1 + \frac{2kd}{sinh(2kd)}\right)$.

An equation from (Permanent International Association of Navigation Congresses, 1987) based on an analysis of nine empirical studies on wave height (Sorensen, 1997), can be used to calculate the maximum wave height:

$$h_{max} = A\text{"}d\left(\frac{S}{d}\right)^{-0.33}F^{2.67} \tag{8}$$

Where: $h_{max}$ is the maximum wave height in $m$.
$A$" is a dimensionless coefficient accounting for vessel properties.
$S$ is the distance from the origin of creation in $m$.
$F$ is the ratio of flow inertia to the external field $\frac{v}{\sqrt{gd}}$ or Froude number.

With the wave height, the propagation speed $c$ can be estimated based on the wave height from empirical data on the IJsselmeer (Effing, 2005). This value is set to 6 m/s which is slightly lower than the propagation speed at very shallow depth of $c = \sqrt{gd} = 6.9$. This corresponds with the Froude value which in shallow waters should be greater than 0.7 and in this case is $\frac{v}{\sqrt{gd}} = 0.56$ or 0.60 depending on the respective speed of the vessel.

Coefficient A" equals 0.8 for conventional inland vessels and their speed is on average 14 km/h (van Ommeren, 2011), for recreational navigation A" is 0.25 and the speed varies. Recreational navigation speed is estimated on 15 km/h to account for an average of smaller speedboats and larger, slower recreational navigation.

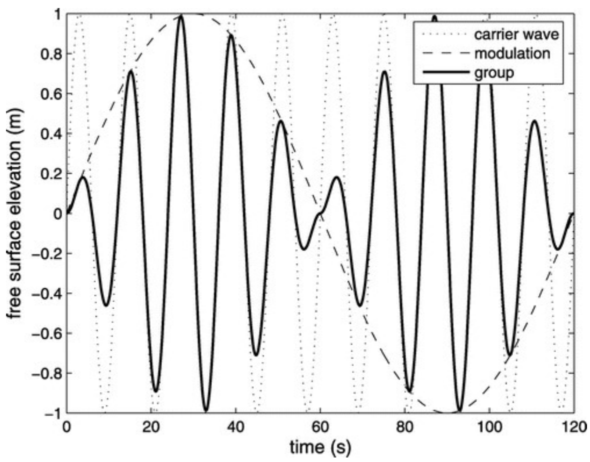


**Figure 7:** Wave pattern of a group of waves. Reprinted from Soldini et al., 2013, p.64.

A group of waves is assumed to have a pattern of maximum wave height at the highest point, surrounded by waves at 80% of the maximum wave height, 60%, 40% and 20% along each side, illustrated by the bolt black graph in Figure 7.

Most waterways in the Netherlands appropriate for industrial navigation purposes like the Rhine, Meuse and many large channels, are monitored by Rijkswaterstaat and kept to certain design requirements on fairway profile conditions (Rijkswaterstaat, 2011). The minimum depth is 4.9 m and the average distance from the side of the vessel to shore is 14.1 m ($0.5W_t + 0.5\Delta_w - 0.5W_d$, see Appendix A CEMT-VI). Furthermore, a report of Adviesdienst verkeer en vervoer and CBS (2003) provides general numbers for recreational and industrial passages. Of the larger rivers in the Netherlands, the Meuse and Waal or 'boven Rijn' form high potential with much passage. In table 2 the potential energy of vessel-created waves in the Meuse and Waal have been calculated for one side of the river (with the most potential, i.e. the most vessels passing on the respective side).

**Table 2:** Potential power of vessel induced waves in $kWh/m^2$ per year

| | Meuse | | Waal | |
|---|---|---|---|---|
| | Industrial | Recreational | Industrial | Recreational |
| | 1 997 | 298 | 10 828 | 2 830 |
| Total: | 2 295 | | 13 658 | |

The efficiency of conversion of tidal power is depend on the technique used and only preliminary research is currently available.

By use of drivers the power output is estimated by (van der Wal et al., 2010) on approximately 0.5 kW on average. Considering a wave period of 3.9s, based on the research of (Effing, 2005), and 23392 vessel passages (based on the Meuse, amount of industrial and recreational passages on the northern/eastern side of the river) the capacity would be 760 kWh/year. Sub sequential the efficiency equals $760./2295 \cdot 100 = 33\%$. For the Rhine 160915 vessel passages is used to result in a capacity of 5230 kWh/year

For piezo electric materials the efficiency is estimated in a research from Anton and Sodano (2007) to be 3%, yielding a capacity of 69 kWh/m$^2$ for the Meuse and 410 kWh/m$^2$ for the Rhine.

Because of the better estimated performance of drivers, this technique will be compared in the selection of techniques.

#### 3.2.3 Tidal Energy

Elevation of the water surface also occurs on larger intervals of approximately 12 hours. This is induced by the gravitational pull from the moon and sun causing respectively high and low tide and spring and neap tide.

*Impact*

The impact of tidal energy techniques is large on the global water balance due to relying on storage of large volumes of water to provide an outflow through a turbine. The largest issue would be how salt or brackish water could easily be stored without heavily impacting the surrounding (sweet water) environment. The function of the water lock however, bears close to no impact from such techniques.

This impact could be minimized by using an existing environment similar to tidal storage circumstances like the Schelde in Zeeland, the openings between the Dutch islands or the Ems river. Since those possibilities do not include civil discharge structures (yet) these will not further be included in this research.

*TCO*

The installation costs for a turbine strongly depends on the application. The costs for the fabrication of a storage facility would be very large considering the options of a concrete bunker or excavation of some sort of lake. The latter is disregarded due to salinization of the environment.

At www.familyhandyman.com and www.concretenetwork.com an approximation of concrete costs of 90\$ per cubic yard is advised which equals about €100/m$^3$. To estimate the costs of a concrete storage environment, a price of €120/m$^3$ is assumed, including 10% spilling and 10% extra for special finishing for submerged concrete exposed to salinity. Assuming an area of 1000 m$^2$ (f.e. a river or channel 200 m in length and 5 m in width or a basin of 1 km by 1 km) and considering an amplitude of 0.7 m with a capacity of 0.06 Wh/m$^2$ surface area (see next paragraph), this solution would have a capacity of 0.06 kWh. With no maintenance costs and no installation costs regarding the turbine or implementation of the materials, the payback time would amount to 50 million years.

*Performance*

The power of tidal energy can be calculated with a similar approach as hydro and wave energy: the total energy is the potential plus kinetic energy (Gorlov, 2001).

When implementing such techniques considering a basin for storage, the tidal velocity will be close to zero, therefore the kinetic energy is negligible and the total energy can be calculated by integrating over the vertical coordinate of the lifted volume:

$$E_{Tidal} = Ag\rho \int z\,dz = \frac{1}{2} g\rho A H^2 \tag{9}$$

| | | |
|---|---|---|
| Where: | $E_{Tidal}$ | is the tidal energy in $J$. |
| | $A$ | is the surface of the lifted volume in $m^2$. |
| | $g$ | is the standard gravitational acceleration of 9.81 in $m/s^2$. |
| | $\rho$ | is the density of sea water of 1035 $kg/m^3$. |
| | $z$ | is the vertical coordinate of the lifted volume in $m$. |
| | $H$ | is the head of tide in $m$. |

This is the energy generated in one period of high tide - low tide - high tide taking 12 hours and 25 minutes in the Netherlands. A study from Ecofys (van de Berg, Geurts, & Stolk, 2010) shows that a tidal amplitude of 0.7 m is the optimum for inland applications, where a lower amplitude would tend towards a non-beneficial amount of energy conversion and a higher amplitude to large surcharge of the payback period due to high installation and maintenance costs. This would result in a potential power of $\frac{1}{2} \cdot 9.81 \cdot 1035 \cdot 0.7^2 \cdot A = 2.5$ kW/m$^2$ $2488 \cdot \frac{1}{12.42 \cdot 3600} = 0.06$ Wh/m$^2$ surface area.

When using turbines to use tidal velocity the power from potential energy becomes negligible. According to Gorlov (2001), using turbines to extract power from a free unconstrained flow can be calculated with Equation 10.

$$P_{Tidal} = \frac{1}{2} \rho A v^3 \tag{10}$$

With $v$ as the tidal velocity in $m/s$ and $A$ the upstream area of rising water from the turbine in $m^2$. In the Netherlands the tide varies from around 3 m in Zeeland to 1 m around Den Helder and back to 3 m when going east to Delfzijl (Watersportalmanak, 2017). When considering a lake or large waterway with a small opening to sea, this could form a high potential source.

### 3.2.4 Blue Energy

Blue energy is the name for all techniques using salinity difference to extract energy from water. The two most commonly employed techniques are pressure-retarded osmosis or 'PRO' and reverse electro-dialysis or 'RED'. There are other forms of extracting energy from salinity difference like applications of electric double-layer capacitors, Faradaic pseudo capacitors and abiotic nano fluids, but they are still under developement (Jia, Wang, Song, & Fan, 2014). In several years these might be worthwhile.

*Impact*

The impact of blue energy systems on the water balance would be minimal at structures that form a barrier between salt and sweet water. The output of the systems could be guided back to its respective origin and the brackish water should be led to the salt water side. Considering the never ending supply of salt water, this would have minimal effect on the salt concentration (especially in tidal areas) and the salinization would have no effect on the sweet water environment.

The impact on the function of the lock for guard locks would be at risk to a certain extend. When the function is to make an absolute division between salt and sweet water, a problem might occur in the extraction of sweet water. Since the sweet water is partly mixed with salt water, the amount of discharge to the sweet water source will be less than the original amount (small for PRO systems and none for RED). This should be taken into account. Implementation by combination of the streams to the lock is not practical. The flow rate of sweet water is about 700 mL/min which would cause the locking function to delay by a very large amount of days.

*TCO*

Information on the costs of PRO and RED systems is not publicly available. The system's preliminary results are insufficient to review the technique as an option for civil discharge structures for now.

*Performance*

PRO uses the pressure difference of salt and sweet water to drive a turbine. Sweet water is directed aside from salt water separated by a membrane only permeable by water (not by any dissolved substances). This induces a flow from sweet to salt water to alleviate the low pressure in the sea water tube. The added water causes the pressure to rise and this pressurized water is leaded through a turbine to generate electricity, illustrated in Figure 8. Theoretically this pressure difference is about 23 ATM under normal circumstances (20°C and 3,5% difference in salinization), equivalent to the potential energy of a 231 m dam (Jia et al., 2014). However, the power density is strongly dependent on the properties of the membrane used. A pilot project from the company Statkraft generated roughly 1 W per $m^2$ of membrane division. Graphene membranes, consisting of a hexagonal honeycombed lattice with $sp^2$-bonded atoms, potentially form a large improvement over the currently existing membranes in mechanical strength and thickness. Statkraft

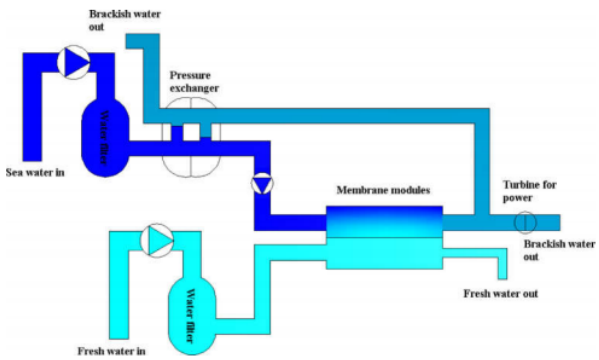


**Figure 8:** Construction of pressure-retarded osmosis electricity generation. Reprinted from Jia et al., 2014, p.93.

has chosen to discontinue its investments in the project in 2014 because the goal to make the technology competing on the market has proved to be too difficult for now (Stattkraft, 2013).

RED systems use the different ion solutions of sweet and salt water to create a current from one solution to the other. Membranes dividing two different solutions flowing in the opposite direction are only permeable by either cathodic or anodic ions, illustrated in Figure 9. The positive and negative ions in the salt water move in opposite directions to the sweet water due to the respective filter of the membranes, thereby creating a current when the outer sides are connected by a circuit. By stacking multiple layers of salt and sweet water on top of each other, a circuit is created of multiple small 'batteries' each adding an even amount of power to the circuit.

The maximum power output of RED systems can be described by Equation 11[2].

$$P_{max} = \frac{(V^0)^2}{4R_{stack}} \tag{11}$$

The company REDstack is the leading research facility on RED systems in the Netherlands. Currently a project on the Afsluitdijk near Harlingen is the world's first 'real world' feed water operated plant, see also www.redstack.nl. A lot of progress has been made over the last few years, but considering the necessary amount of water needed to flow through all stacks the technique is not ready for small scale plants implemented in locks. Since the product of RED is only brackish water, the generated power is generally considered to be limited most by the available amount of fresh water. Possible locations in the Netherlands are therefore limited to the Afsluitdijk and perhaps in the province of Zeeland. The results on REDstack's project may shed some light on the possibilities. For this research the potential of blue energy is insufficient.

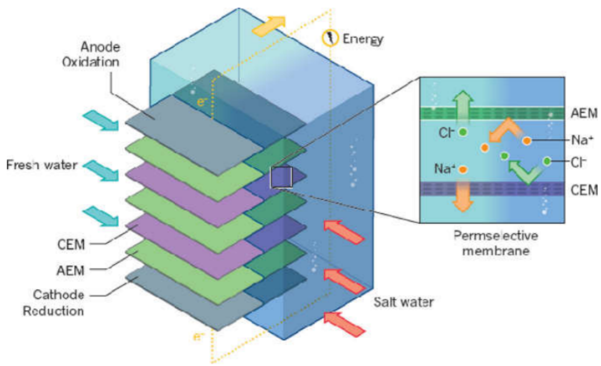

**Figure 9:** Construction of reverse electro-dialysis electricity generation. Reprinted from Jia et al., 2014, p.95.

#### 3.2.5 Aquatic biomass

Aquatic biomass can be divided in two main categories, breeding micro algae and breeding seaweed. The latter is mainly used for cultivating nourishment. In the '80s and '90s experiments on harvesting energy have been conducted, but due to issues on rinsing the biomass and damage to the breeding environment in harsh weather the technique could not compete with the low oil prices (van de Berg et al., 2010). Since then other experiments have been conducted and although there is potential in projects at sea, none have proven competitive with other energy sources.

The breeding systems used to cultivate micro algae can be divided in open systems (exposed to open air) and closed systems. Currently projects with open systems are trying to find solutions to the relatively low biomass concentrations, sensitivity of the system to other organisms like competing algae or animals feeding on algae and lack of control on the temperature among other things. These issues do not (or in lesser intensity) occur in closed systems.

Basically all algae cultivations need light, carbon dioxide, nutrients, water and a mild temperature. Closed systems like bubble columns, horizontal tube reactors or flat plate

[2] This equation is further elucidated in Appendix B

reactors can easily control these substances. There are many variations on the above mentioned systems, elucidated in the book 'Duurzame Energietechniek' (Ouwehand, Papa, Entrop, & de Geus, 2017) and the article (van de Berg et al., 2010).

*Impact*
Closed systems barely interact with civil discharge structures. The only factor they have in common is the water flow and the amount needed for cultivation is far below 1 $m^3/s$. The impact on the environment however, is in contrary to the previous renewable sources, not zero. The process of cultivating algae is in need of light, nutrients and controlled temperature, all produced by using electricity (or other power sources) and emitting exhaust fumes in production and/or transportation.

*TCO*
A project in Spain, Jerez with a volume of 85 $m^3$ and a area footprint of 1000 $m^2$ demanded an investment of €200/$m^2$, a total demand of €200 000. An example of a project in Spain, Almria is a six unit photo bio-reactor with a cultivated volume of 30 $m^3$ and area footprint of 600 $m^2$. A study from Ecofys (van de Berg et al., 2010) compared this to the potential outcome in the Netherlands, resulting in a revenue of 109 GJ per year. The installation and maintenance costs of such a scale have not been explicitly calculated, but assumed is 50% of the installation costs for maintenance. In comparison with the project in Jerez, the investment costs is assumed to be similar since the maintenance is slightly lower in proportion to the scale (less algae will probably need less nutrients and carbon dioxide) but the lower scale usually results in higher investment costs in proportion to up-scaled projects. With investment or installation costs of €200/$m^2$ and maintenance costs of 50%·€200/$m^2$, results in maintenance costs of €60 000 per year and installation costs of €120 000. The revenue of 98.8 GJ/year (or 27 444 kWh/year) equals €1 097 per year assuming an energy price of €40 per GWh (see Section 3.2.1). The revenue of this project does not become beneficial overtime considering the maintenance costs are a factor of 60 higher than the revenue.

*Performance*
After cultivating a certain amount of algae, the culture can be harvested by separating the algae from their habitat using a centrifuge. Afterwards they are dried resulting in powder which can be used as fuel. The hypothetical project in the Netherlands produces an annual amount of 5.2 ton powder. A recent study on the caloric value of biomass (zyuuran & Yaman, 2017) shows a caloric value of approximately 19 MJ/kg. The study from Ecofys has used 21 MJ/kg, so the amount of 109 GJ/year from their study is adjusted to 98.8 GJ/year. The power of the system is theoretically 98.8 divided by $365 \cdot 24 \cdot 60 \cdot 60$ considering a 24/7 maintenance and operation of the system, which is 3.13 kW.

## 3.3 Storage techniques

Similar to the conversion techniques, the storage techniques have been filtered to those using water in (a part of) the process. Below the two hydro storage forms are elucidated and described on each criterium.

### 3.3.1 Pumped hydroelectric storage

Pumped hydro electric storage or 'Pumped hydro' is a form of mechanical energy storage using pressure from potential energy of water and converting the energy to electricity by use of turbines.

*Impact*
Pumped hydro has a large impact on the flow rate, it's the main parameter that is altered. The deviation could easily exceed 20% depending on the situation.

The impact on the function can be high if the lock is a scouring lock. In such situations the water balance is usually tight which is the reason for existence. The impact on navigation locks is minimal. The function will require a certain amount of water for each lock cycle, but when comparing this to the flow rate of a turbine it is negligible.

*TCO*
Considering the costs involved to implement pumped hydro in navigation locks, the only investment would be in turbines. These costs are similar to those before mentioned in section 3.2.1, but will require slightly less payback time due to the more efficient use of the turbine.

*Performance*
Potential energy storage in civil discharge structures can use an upstream lake (or river or channel) to store water. The weir is already in place, but to generate electricity turbines will need to be installed.

The performance of the system will depend on the dimensions of the available basin and efficiency of the turbine. The same parameters for calculations of turbine power will be used as in Section 3.2.1. The capacity however, will be calculated taking the basin into account. The effect on the capacity will be that in times when the flow rate exceeds the design rate for the turbine, water can be impeded (to certain amounts) extending the operation time of the turbine.

Rijkswaterstaat has provided flow rate distributions over the last few years of measuring point Sambeek in the Meuse (Personal Communications, 2017). The normative high water level or 'Maatgevende Hoogwaterstand' for the Meuse is based on a recurrence time of 1/1250 years and amounts to 3800 $m^3/s$ (van Schrojenstein Lantman, 2004). When designing a turbine with peak performance on the average flow rate of 277 $m^3/s$, the flow rate is lower than the design flow rate in 1864 days over 10 years, illustrated in Figure 10. That is 66% of the time in which the turbine could perform better. When stocking water between the weir and the previous weir upstream, the exceeding amounts in wet periods could (to certain extend) be used in dry periods. The weir of Sambeek raises to a height of 10.85 m+NAP. A discharge amount of the mean flow rate raises the water level to 10.88 m+NAP upstream and each year a peak in discharge occurs in the late winter. Since the mean flow rate already causes the weir to overflow, the turbine should be designed to perform best on a lower flow rate.

A linear increase of the power of the turbine from zero to maximum power corresponding to a flow rate from zero to design rate is assumed. With a flow rate from design rate

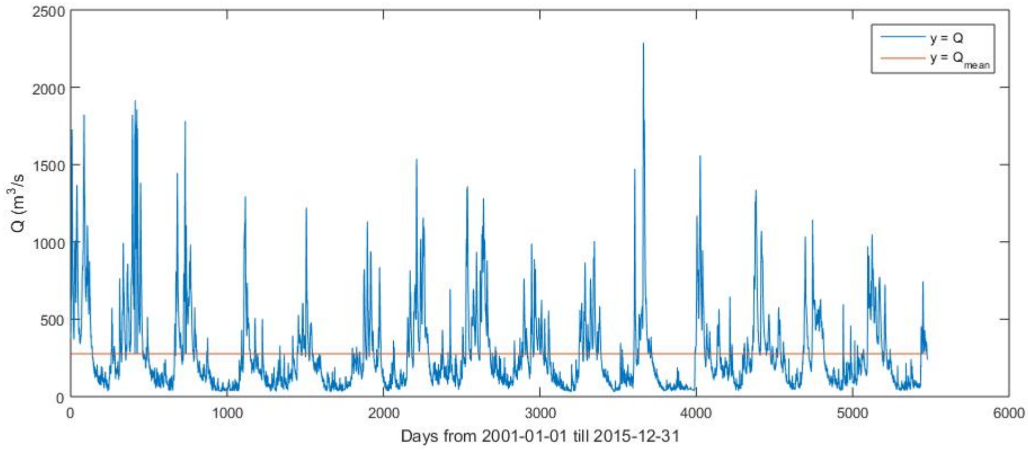


**Figure 10:** Flow rate at Sambeek in the Meuse from 2001-01-01 till 2015-12-31.

to weir design rate a constant maximum power is assumed. With a design flow rate of 277 $m^3/s$ and head of 2.77 m the capacity equals $1000 \cdot 277 \cdot 9.81 \cdot 2.77 \cdot 0.8 \cdot 241 \cdot 24 \cdot 0.5 = 17414$ MWh/year. An example is calculated with a design flow rate of 230 $m^3/s$. The turbine peak power would amount to $1000 \cdot 230 \cdot 9.81 \cdot 3.02 \cdot 0.8 = 5.45$ MW. The turbine is shut down during the entire period the flow rate is higher than the weir design rate of 277 $m^3/s$. The capacity of the system would be $5.45 \cdot (213 \cdot 0.5 + 28) \cdot 24 = 17596$ MWh/year. Due to linearisation of the turbine power below design flow rate, this is not completely accurate, but it indicates towards benefit of a study on design flow rate for the turbine and improvement of the original capacity of the turbine.

#### 3.3.2 Hydrogen storage

Electricity can be stored by use of hydrogen. The technique stores power using fuel cells and regenerates electricity by converting chemical energy back to electricity or using hydrogen in a combustion engine or turbine, illustrated in Figure 11. Production of hydrogen with electrolysis is by the chemical reaction of Equation 12 at the cathode and Equation 13 at the anode. After that it can be stored in liquid or pressurized gas form (Huggins, 2010).

$$H_2O + e^- = \frac{1}{2}H_2 + OH^- \tag{12}$$

$$H_2O = e^- + \frac{1}{2}O_2 + 2H^+ \tag{13}$$

For very large systems with very long duration applications underground (pressurized) storage of hydrogen deserves consideration, but provision for the local grid and lock structures is not profitable. Storage as a compressed gas in high pressure tanks (340-680 atm) and hydride storage are more profitable for this scope with pressurized gas as most profitable technique (Schoenung, 2001) (Hua et al., 2011). This category is investigated.

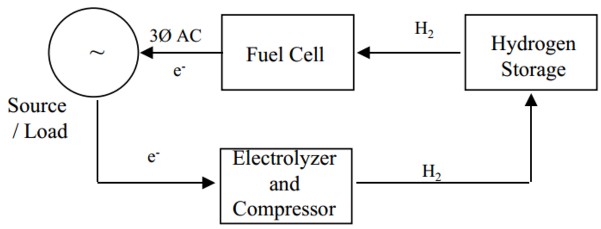


**Figure 11:** Hydrogen energy storage system using fuel cells. Reprinted from (Schoenung, 2001, p.8).

*Impact*

The impact on the flow rate as well as the function of the lock is non-existent. If water is needed at all, it is only needed for the first charge cycle to sustain electrolytic production of hydrogen. Discharging the battery or reversing the reaction reproduces water, so it could be used again. The steam reforming process of producing hydrogen is more cost efficient and therefore more often used technique for hydrogen production. The plant consumes a large area and can be connected to a large grid.

*TCO*

In an article on the combination of solar and wind power with hydrogen storage (Shakya, Aye, & Musgrave, 2005), a project with a capacity of 25 185 kWh estimated total capital costs of €340 000 with a lifespan of 25 years. The maintenance costs of the storage amount to 30% of the total capital costs $340000/25185 \cdot 0.3/25 = e0.16$/kWh/year. The installation costs are €149 090. The revenue is €40 296/kWh/year resulting in a payback time of slightly below 4 years.

*Performance*

According to Schoenung (2001) the performance of pressurized hydrogen gas is within the range of 700 to 1500 kW and 100 to 10 000 GWh per lifespan. The efficiency of discharge via fuel cells is 0.59% and discharge via combustion 0.44%.

## 3.4 Selection of techniques

The rating discussed in Section 3.1 is applied to all conversion and storage techniques listed in Sections 3.2 and 3.3. The score of each technique is based on a five point rating scale from – to ++, listed in Table 3, and is deduced from the information listed in the previous sections. With this information a judgement can be made on the best conversion

**Table 3:** Rating of conversion and storage techniques

| | | Impact | | TCO | | | Performance | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Water balance | Function | Installation | Maintenance | Payback time | Power | Capacity | Total |
| Conversion | Hydro power | -/+ | -/+ | - | + | + | ++ | ++ | 5+ |
| | Wave energy | ++ | ++ | ++ | - | + | - - | + | 5+ |
| | Tidal energy | - - | ++ | - - | - - | - - | ++ | - - | 6- |
| | Blue energy | -/+ | -/+ | N/A | N/A | N/A | N/A | N/A | 0 |
| | Aquatic biomass | ++ | ++ | ++ | -/+ | - - | - - | ++ | 4+ |
| Storage | Pumped hydro | - | - | -/+ | -/+ | ++ | ++ | ++ | 5+ |
| | Hydrogen | ++ | ++ | ++ | ++ | ++ | ++ | ++ | 14+ |

and storage technique for aquatic civil structures.

Two best techniques tied with a score of five above average or nineteen out of twenty-eight points for conversion: hydro power and wave energy. Comparing the two techniques, wave energy scores much better on impact while hydro power excels at performance. When considering the three criteria as one each, instead of by each component the score of hydro power is -/+, +, ++ for impact, TCO and performance and the score of wave energy is ++, -/+ or + and - or -/+ respectively. The slightly down-graded components of wave energy in comparison to hydro power favors the result of the best conversion technique in hydro power.

The best storage technique according to the rating scale is hydrogen storage. However, this technique should not be implemented in aquatic discharge structures. The only component where water from the Dutch waterways could play a role is the process of producing hydrogen. The amount of water involved in this process is not very voluminous and should be treated before ready to produce hydrogen. A good location for a hydrogen storage plant could be near or implemented in a water treatment plants. Closer to a larger grid connection would also be advantageous. Taking into account the implementation of hydro power as conversion technique, storage of energy by pumped hydro will be part of the design process when optimizing turbine design to the water balance.

With the answer on the first two sub-questions a hypothesis can be phrased:

*"Electrical energy can be converted and stored using hydro power and pumped hydro storage in existing structures that dispense superfluous water"*

This hypothesis will be tested using two locations representative to aquatic civil discharge structures. The locations will be chosen in the next chapter.

# 4 Test locations

To be able to answer the main question and achieve the goal of this research, a few existing situations will be investigated to test the applicability of conversion and storage techniques. These situations will be determined by conditions derived from both compatibility with the restrictions that are encountered and optimization of the resulting power output. The first and second condition ensure compatibility with restrictions posed in the scope (see section 2.2), the third optimizes the resulting power output.

- *Adaptability of operational techniques*; the properties of mechanisms used to discharge and lock the water should be accessible and (to a certain extend) adaptable to changes. They can help in the storage and conversion process when flows are already separated (or otherwise directed beneficial to the energy density), but also oppose the possibilities when (part of) the available water volume is needed to proceed with the primary functions like navigation and regulation of the water level.
- *Flexibility of the water balance*; when energy is extracted from speed or pressure of water, firstly the water is directed to a smaller space to increase energy density. Afterwards the remains are redirected to the original flow. This affects the surroundings by corrosion and temporal deficits and surplus. The water balance in the chosen situation should be flexible, able to cope with water level and speed fluctuations.
- *Scale*; the potential for each situation can partially be assessed in advance by reviewing the physical dimensions of the lock system and water flow rate. When considering smaller constructions with fewer discharge, the potential will likely be smaller than in sizeable systems with a large dispensation of water.

Depending on the situation the solution could be used to ensure an energy neutral structure or function as a storage system for sustainable energy from local electricity networks if the scale of the solution proves to be substantial.

## 4.1 Conditions

To determine which situations are practical and representative, a short evaluation has been made on the previously discussed conditions: adaptability of operational techniques, flexibility of the water balance and scale.

**Adaptability of operational techniques** In the Netherlands there are many different types of gates used to lock water. In Appendix C a list of different gates has been included. In these types a general pattern can be found. They all dispense using one (or more) of the mechanisms listed below (Glerum & Vrijburcht, 2000) (US Army Corps of Engineers, 1995a) (US Army Corps of Engineers, 1995b):

- Lock culverts (see Figure 12)
  These tubes form a water transportation system circumventing the gates of the lock. Due to the concentrated flow through the tubes, turbines could form potential in these mechanisms.
- Gate openings or valves (see Figure 13, marked green)
  Gate openings are sliding lids opening vertically or horizontally to let the water through the doors. They are operated mechanically due to large pressure.
- Moving gate (see Figure 13, marked orange)
  Moving gates are smaller doors within the lock gates revolving around a vertical or horizontal axis. They are either mechanically operated or use head pressure of the water that is to be displaced to open.

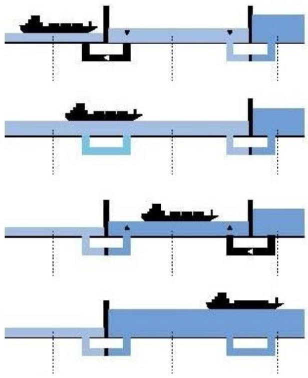

**Figure 12:** Example profile intersection water lock with lock culverts

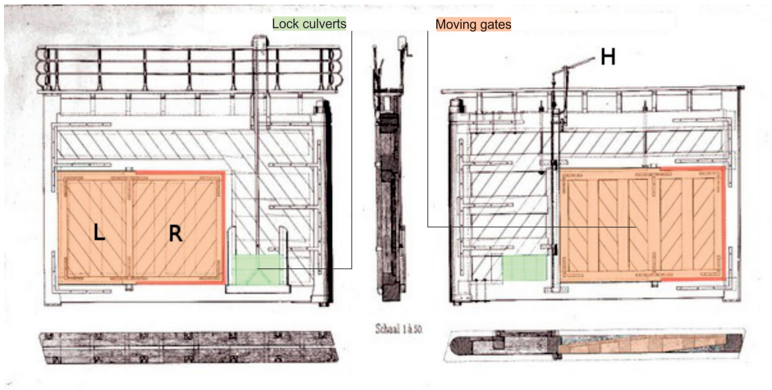


**Figure 13:** Frontal intersection lock gate with valve openings and a moving gate

Of these mechanisms two will be investigated in a currently existing scenario from the Netherlands. Firstly inquiries shall be made on gate openings (or valves). These types of dispensation are most common in the Netherlands. When finding a sustainable application for these types, it would be applicable to many situations in the Netherlands. Secondly lock culverts will be investigated. These types are less common than gate openings, but form a high potential for turbines due to separation of the water from the rest of the system: more spacious solutions will be applicable and the impact on the river dynamics will be lower. Moving gates will not be investigated due to the large amount of changes needed to facilitate conversion and storage techniques and their relatively low presence in locks in the Netherlands.

**Flexibility of water balance** As mentioned earlier corrosion and temporal deficits or surplus will be the main disadvantages when energy is extracted from pressure of water. All waterways in the Netherlands are on a relative tight schedule of discharge and pumping due to the chance of flooding in all areas with few elevation. This controlled environment is even more present in channels than in (canalized) rivers due to the low range in flow rate. Channels are therefore excluded from the potential locations for testing conversion and storage techniques.

**Scale** To optimize the possible amount of conversion the discharge of water should be increased for either potential energy or kinetic energy. Translated to river properties this means either a large pressure head or large velocity.

Of the possible operational techniques, gate openings are used most often in the Netherlands and when implementing conversion or storage in such discharge techniques, there would be many possibilities to mimic the design. Disregarding channels as potential locations the rivers Rhine and Meuse have the largest flow rate, head and speed forming a large scale possibility (see 3.2.1). In the Rhine river three different lock structures are very suitable for hydro power: Hagestein, Amerongen and Driel. In Hagestein a hydro power station is already running, empowering all three the lock structures (Utrechtse Stichting voor het INdustrieel Erfgoed, 2016). In Amerongen and Driel a slightly altered design would have a high probability of succeeding. Since this does not pose any new potential, these possibilties have not been taken into account. In the Meuse the lock with the largest head is Sluis Sambeek with a head of 3.25 m (Hensen, 2017). This lock is a part of four different locks in the Meuse that all have the same poiree-stoney locking system, the others being Linne, Roermond and Belfeld (Verduijn, 2015). When succesfully implementing conversion and storage techniques in Sambeek, the design could be implemented to the other locks as well.

Of the situations that could be exemplary for the use of lock culverts, three of the larger water locks in the Netherlands using this technique are compared: the 'Sluis III' in the Wilhelminakanaal, the 'Noordersluis' in IJmuiden and the 'Waaiersluis' in Gouda. These three are all situated in a channel since lock culvert discharge systems do not exist in the rivers of the Netherlands. Of these situations the first two are both under renovation. Therefore the 'Waaiersluis' in Gouda (in the 'Hollandse IJssel') has been chosen as test location.

### 4.2 Chosen locations

The chosen test locations are reviewed more fully and an overview is presented below.

**Sluis Sambeek** River: Meuse

This water lock complex in the river Meuse is situated below Boxmeer, near Sambeek (see Figure 14) and is in utilization since 1929. The water flow in the Meuse at this point is between 60 $m^3/s$ and 2200 $m^3/s$, the mean head is 2.8 m (Rijkswaterstaat, Personal Communication, June 2017).

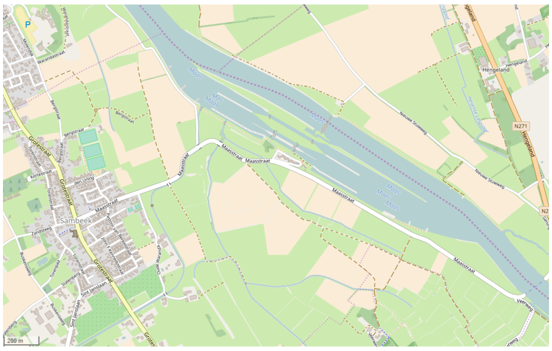

**Figure 14:** Plan of Sluis Sambeek. Reprinted from https://www.openstreetmap.org

**Figure 15:** Situation photo Sluis Sambeek. Reprinted from http://www.debinnenvaart.nl

The complex contains three navigation locks and a scouring sluice (see Figure 15). The scouring sluice is located on the north-east side of the river. It consists partially of a Poiree barrier, a frame with thirteen gaps in which three vertically aligned partition boards of 4.85 m wide and 1.56 m tall control the flow area for each gap. The other part of the scouring sluice are Stoney gates: two gates of 17 m wide in which an upward sliding lid controls the flow area (Rijkswaterstaat / Afdeling Multimedia Rijkswaterstaat, n.d.). In the south-west half of the river a navigation lock of 260 m in length by 16 m in width grants passage to larger barges and two smaller navigation locks of 142 m in length and 16 m in width form additional passage capacity for smaller ships. The blueprints of the situation can be found in Appendix D.1.

**Waaiersluis Gouda** River/canal: Hollandsche IJssel

The Waaiersluis is a monument located in Gouda (Rijksdienst voor het Cultureel Erfgoed, 2000) and forms a barrier between the canalized part of the Hollandsche IJssel and the unconstrained river since 1854 (see Figure 16). The canalized Hollandsche IJssel functions as navigation route and storage basin for neighbouring polders. The lock system functions primarily as scouring sluice, secondarily as navigation passage (Boerboom, 2014) (see Figure 17). Characteristics between the two parts of the Hollandsche IJssel are a flow rate of 10.1 $m^3/s$ and a difference in head of -1 to 1 m on average between the tidal currents on the west side and the standard water level of 0.55 m +NAP on the east in the channel (Hoogheemraadschap De Stichtse Rijnlanden, 2017) (Rijkswaterstaat, Personal Communication, June 2017).

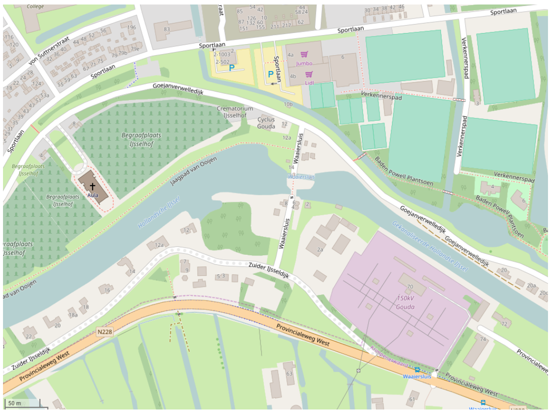


**Figure 16:** Plan of the Waaiersluis. Reprinted from https://www.openstreetmap.org

**Figure 17:** Situation photo Waaiersluis. Reprinted from http://rijksmonumenten.nl

The water lock is managed by 12 doors of which 2 steel doors on the south side are meant for scouring. The other 10 doors regulate the water level in the navigation lock: two times two smaller mitre gates for low tides, two times two higher mitre gates for high tide and two wing gates for locking high pressure (fast) flows. When a fast stream is passing through the lock, the pressure is used to close the gate when needed by opening the culverts and with that pushing the larger door open by filling the wing gate chamber. The blueprints of the situation can be found in Appendix D.2. The mitre gates are used in normal circumstances, but used to be operated by hand which made closing the doors too heavy in high water flows. The wing gates would be operated at such times.

# 5 Implementation

In the analysis of techniques, Section 3.4, a hypothesis was phrased with regard to application of conversion and storage in existing structures: "Electrical energy can be converted and stored using hydro power and hydrogen storage in existing structures that dispense superfluous water". This will be tested using the lock systems selected in the previous chapter. Possibilities on implementing the techniques in each system will be discussed and examples on implementation will be presented for each lock system. The possibilities will be analysed in Chapter 6.

## 5.1 Sluis Sambeek

Design properties of hydro power will be discussed regarding gate openings as operational techniques and relative large flow and head for the Netherlands. This also means implementing part of the principle of pumped hydro storage to optimize turbine power and capacity. All properties on the current situation of Sluis Sambeek discussed below originate from Rijkswaterstaat / Afdeling Multimedia Rijkswaterstaat (n.d.) and personal communication with Rijkswaterstaat (2017) unless otherwise indicated.

*Power*

The first choice regarding implementation of hydro power is between a free flow turbine and a pressurized turbine or stated differently, between kinetic and potential energy. The ratio between potential and kinetic energy equals $0.051v^2 = h$ (see Section 3.2.1). With a mean head of 2.77m for Sluis Sambeek and an equal efficiency of both turbines a velocity of 7.38 m/s should be matched or exceeded. The velocity in the current situation when the weir is down is 1070 $m^3/s$ divided by the profile area of the complete weir at 10.8 m+NAP (see Appendix D.1 and (Rijkswaterstaat / Afdeling Multimedia Rijkswaterstaat, n.d.)) is $\frac{1070}{120 \cdot 4.7} = 1.9$ m/s, almost a factor 4 too few. Matching the potential power with kinetic power could also be accomplished by larger efficiency of the free flow turbine or larger operational time, but a factor 4 is highly unlikely to achieve.

The flow and head for which the turbine should have the highest efficiency, the design flow and head, can be calculated by optimization of $h \cdot Q \cdot t$. Q and h are related, the time t is the time the combination of $Q \cdot h$ is available in days over a period of 15 years (2001-2015). The design flow rate and head is calculated with the computer program Matlab, see Appendix E. The turbine will not be in use when flow rates higher than 1070 $m^3/s$ occur. At those times the weir is let down on the bottom of the river and the head difference is 0. This is approximately 8 days per year. The design flow is 208.8 $m^3/s$, the design head is 2.95 m and during 159 days out of the year the turbine can produce on peak power. The potential power without energy losses is $P = \rho \cdot g \cdot Q \cdot h = 6.04$ MW.

Due to friction in the pipeline to the turbine energy losses occur, which can be translated to head loss. These losses can be estimated with the design of penstock (or pipelines). The length of the penstock should be as low as possible so the turbine should be implemented close to the weir near the bottom of the river. The ideal place to decrease friction losses would be just behind the weir at the bottom. However, navigation has to be able to easily pass over the Poiree valves of the weir. When considering the 4.68 m of the weir height the turbine could only have a maximum diameter of around 0.5 m taking industrial vessels of 3.5 m draft into account. This is too small for turbines and excavating a part of the river bed would very likely sludge. Implementation behind the Stoney valves is considered. This would be possible since the Stoney valves stay upright during flooding of the weir. The turbine would be protected from navigation. However, since the Stoney valves control the volume flow through the weir the pressure head would be close to impossible to capture in a pipe at that location. The eastern side of the river is the final possibility. By placing a pipe circumventing the Poiree valves the water can be led to a few meter downstream, where the turbine would have no hinder of the Poiree frame when putting the weir down. By installing the turbine in the side embankment of the river, it could be placed approximately 30 m downstream from the weir, which is where the reinforcements of weir end. A penstock length of 30 m is presumed. The internal penstock diameter can be estimated using Equation 14 and the minimum tickness with Equation 15 with a manning coefficient of 0.014 for an uncoated cast iron pipe (Nasir, 2014). The internal penstock diameter is 621 mm with a minimum thickness of 4 mm.

$$D_p = 269 \cdot \Big(\frac{n_p^2 \cdot Q^2 \cdot L_p}{H_g}\Big)^0.1875 \tag{14}$$

$$t_p = \frac{D_p + 508}{400} + 1.2 \tag{15}$$

Where: $D_p$ is the penstock diameter in $mm$.
$n_p$ is the dimensionless manning coefficient
$Q$ is the design flow rate in $m^3/s$.
$L_p$ is the penstock length in $m$.
$H_g$ is the design head or gross head in $m$.
$t_p$ is the minimum penstock thickness in $mm$.

The head loss can than be calculated using the Darcy-Weisbach equation (Equation 16, (Brown, 2002)).

$$h_l = f_D \frac{L_p}{D} \cdot \frac{v^2}{2g},\ with\ Q = \frac{\pi}{4} D^2 v,\ so\ h_l = f_D \frac{8L}{\pi^2 g} \cdot \frac{Q^2}{D^5} \tag{16}$$

Where: $h_l$ is the head loss in $m$.
$f_D$ is the Darcy friction factor of $\frac{64}{Re}$
$D$ is the penstock diameter in $m$.
$v$ is the average speed in the penstock in $m/s$.
$g$ is the gravitational acceleration coefficient of 9.81 in $m/s^2$.

The friction coefficient equals $\frac{64}{Re}$ with $Re = \frac{vl}{\nu}$. The kinematic viscosity $\nu$ is 1.6438 $\cdot 10^{-6}\, m^2/s$ which means that $f_D = 1.02 \cdot 10^{-6}$ for water of approximately 1°C. The head loss is then 0.35 m, resulting in a nett head of $2.95 - 0.35 = 2.60$ m.

Knowing the nett head, the rated power can be estimated with Equation 2: $\eta \cdot 1000 \cdot 9.81 \cdot 208.8 \cdot 2.6 = 5.3\eta$ MW, $\eta$ being the turbine efficiency. The rated capacity equals the rated power times the amount of time the turbine has the respective power output. The efficiency of a turbine is partially dependent on the percentage of design capacity that is led through the turbine and varies per turbine type, see Figure 18.

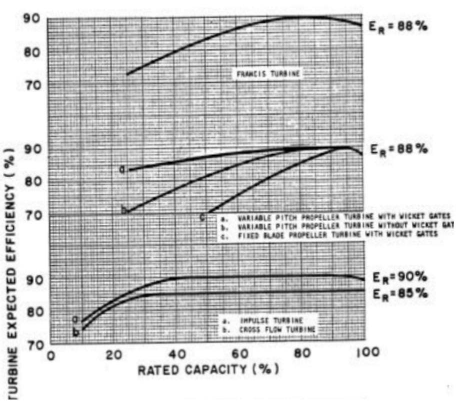


**Figure 18:** Efficiency curve over the rated capacity (%). Reprinted from (Sangal et al., 2013, p.426).

Relying on research on multi criteria analysis for turbines based on flow rate and head (Williamson, Stark, & Booker, 2014) a propeller turbine is chosen since the propeller with draft tube

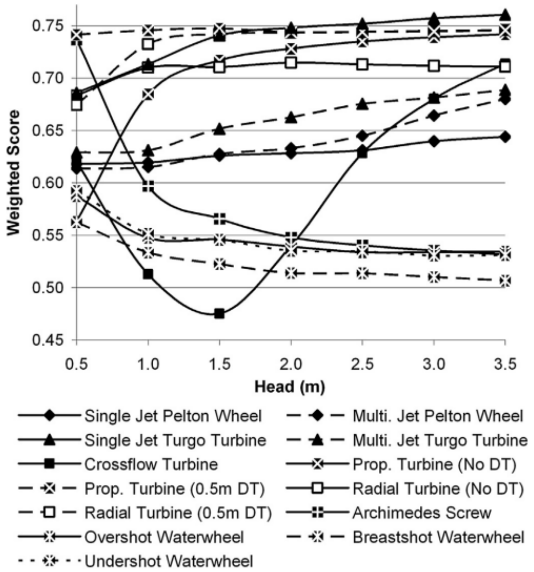


**Figure 19:** Weighted scores of 13 different turbines over head, 'DT'= draft tube. Reprinted from (Williamson et al., 2014, p.48)

| Criterium | Weight |
|---|---|
| Power density | 0.30 |
| Full flow efficiency | 0.25 |
| Part head/flow efficiency | 0.20 |
| Civil works (adjustment environment) | 0.15 |
| Maintainability and servicability | 0.05 |
| Modularity | 0.05 |

**Table 4:** Weighted criteria used in the multi criteria analysis.

is not applicable when implementing the turbine in the embankment as proposed. The weights and aspects of the analysis can be found in Table 4.

Subsequently the efficiency curve for the rated capacity calculation is modelled to match curve b of the middle curve group in Figure 18. A relation of the form $\eta = 0.9 - 0.2 \cdot (E_p - 1).^2$ for $E_p>0.3$ and $E_p<1.3$ is used. In this equation $E_p$ is the percentage of rated capacity of the maximum rated capacity. Calculated with Matlab (see Appendix E) resulting in a total rated capacity of 27.5 MWh per year.

For this situation, the flow rate that is directed into the turbine has to be controlled. When reaching higher values than the design flow rate, the flow rate is cut to the value of the design flow rate to optimize turbine efficiency. This means that a large part of the available flow rate is often unused (discharged through the weir), illustrated in Figure 20. Addition of another turbine would add a rated capacity of 5.25 MWh per year and addition of a third turbine would add a rated capacity of 1.67 MWh per year, see Appendix E.

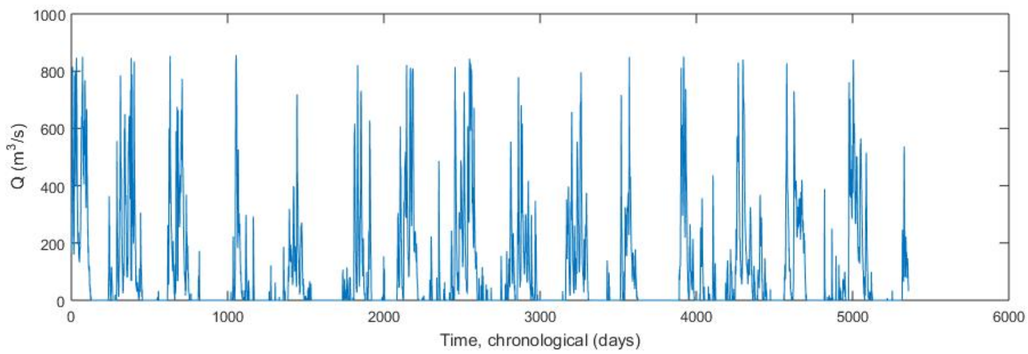


**Figure 20:** Unused flow rate over time (2001-2015).

*TCO*

In an economic analysis of micro hydro plants in the low head range (<50 m) (Aggidis, Luchinskaya, Rothschild, & Howard, 2010), a general relation is derived between the total project cost (TCO), the power of the site and the head. The relation is based on 50 real life small hydro plants and matches the empirical data suprisingly close, illustrated in Figure 21. This relation is described by Equation 17.

$$C_{project} = 25000 \cdot (P/H^{0.35})^{0.65} \qquad (17)$$

| | | |
|---|---|---|
| Where: | $C_{project}$ | is total project cost in £. |
| | $P$ | is the power in $kW$ |
| | $H$ | is the head in $m$. |

For Sluis Sambeek the TCO equals $25000 \cdot (\frac{5438}{2.95^{0.35}})^{0.65}$ = £5.24 mln which equals €5.84 mln.

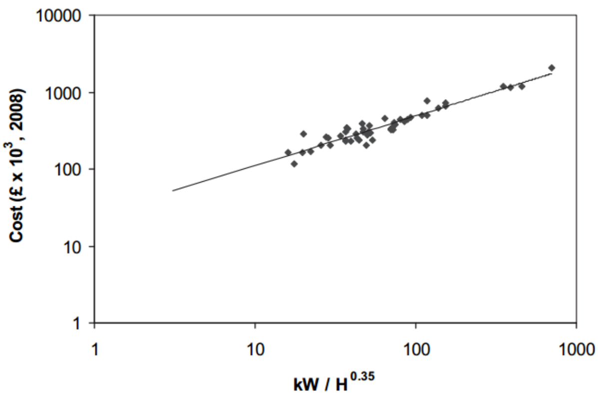


**Figure 21:** Empirical relation between the total project cost, power and head of micro hydro plants.

*Impact*

The design of hydro power in Sluis Sambeek is matched to the actual flow rate. The discharge needed for the turbine is guided through a pipe on the eastern shore and returned to the river at approximately 30 m after extraction at the weir. The total water balance is therefore unaffected. The local water balance is not entirely unaffected due to the increased velocity of discharge from the turbine. This will cause erosion of the embankment at the discharge point which has to be avoided. To accomplish this a stilling chamber could be constructed at the outlet or the outlet could be made to reach further into the flow of the river. With enough space between the embankment, river bed and outlet, the impact on the local water balance will also be negligible. A stilling chamber would be less fragile to outer forces like navigation, animals or currents but would involve more costs, for an extension of the outlet vice versa.

The impact on navigation and guarding the water level is also very low. The deviation of navigational locking in minutes due to implementation of hydro power is zero. This also holds for the deviation of the water level upstream and downstream in m.

## 5.2 Waaiersluis

The design properties of hydro power will be discussed regarding lock culverts as operational techniques and a small flow rate and head for the Netherlands. All properties on the current situation of the Waaiersluis discussed below originate from Hoogheemraadschap De Stichtse Rijnlanden (2017) and personal communication with Rijkswaterstaat (2017) unless otherwise indicated.

*Power*

The available head for the Waaiersluis can be calculated by subtracting the level of the discharge point (at the middle of the diameter of the lock culverts) from the mean water level at the channel. This equals $0.55 - (-0.5) = 1.05$ m. The value of the flow rate of 10.1 $m^3/s$ is set and the lock culverts are approximately level with the water height in the channel. From that is deduced that the head between the channel and the discharge point is $\frac{1}{2}d = 0.3$ m. The relation $0.051v^2 = h$ between potential and kinetic energy for the Waaiersluis then equals $0.051v^2 = 0.3$. The minimum velocity to match the potential energy is 2.4 m/s. Discharge is currently done using the scouring lock next to the Waaiersluis. When scouring through the lock culverts of the wing doors of the Waaiersluis, the discharge velocity at 10.1 $m^3/s$ equals $\frac{10.1}{\pi \cdot 0.6^2} = 8.9$ m/s. This is almost four times as high as the minimum velocity, so a flee flow turbine will be implemented.

The required flow rate of 10.1 $m^3/s$ cannot constantly be discharged due to the tidal differences at the western side of the lock. This means that the flow rate is higher at low tide and zero at high tide. For each tidal cycle of 12 hours and 25 minutes, the average discharge is 10.1 $m^3/s$. The flow rate during low tide is subsequently $10.1 \cdot 2 = 20.2$ $m^3/s$, resulting in a velocity of 17.9 m/s. The potential power without energy losses is then $P = \frac{1}{2}\rho Q v^2 = 3.22$ MW.

The best place for a turbine is at the beginning of the lock culvert at the channel. Theoretically it could also be placed at the end of the lock culvert from the channel to the wing gate, but then the whole wing gate chamber should be redesigned increasing the installation cost sharply. Even if that would not be an issue, the cultural and architectural value of the monument prevent that possibility (Rijksdienst voor het Cultureel Erfgoed, 2000). It is also unnecessary, because whether the turbine is at the end of the pipe or at the beginning, the friction losses and subsequently power loss is equal.

The friction losses can be calculated using Equation 16, expressed in the equivalent head loss. The length of the lock culvert from the channel to the wing gate chamber is 15.898 m (see blueprint in Appendix D.2). The equivalent head loss is then $h_l = f_D \frac{L_p}{D} \cdot \frac{v^2}{2g} = 4.4 \cdot 10^{-4}$ m. This can be translated to velocity loss with the relation $0.051v^2 = h/$. The reduction in velocity is 0.093 m/s resulting in a nett velocity of 17.8 m/s. Knowing the nett velocity the rated power can be estimated by: $P = \frac{1}{2} \cdot 1000 \cdot 20.2 \cdot 17.8 \cdot \eta = 3.20\eta$ MW.

Using the multi criteria analysis of Elbatran, Yaakob, Ahmed, and Shabara (see Section 5.1) the choice of turbine is set to the Archimedes screw. From Figure 18 an efficiency of 0.9 is deduced (the impulse turbine curve).

With all static conditions available the final power and capacity can be calculated: $P = \frac{1}{2}\rho Q v^2 \eta = \frac{1}{2} \cdot 1000 \cdot 20.2 \cdot 17.8^2 \cdot 0.9 = 2.9$ MW and the capacity is $P \cdot t = 6.3$ GWh.

*TCO*

The economic analysis of (Aggidis et al., 2010) is also used for the situation in the Waaiersluis. The equivalent head at a velocity of 17.8 m/s is 18.7 m. The equation $C_{project} = 25000 \cdot (P/H^{0.35})^{0.65}$ then equals $25000 \cdot (\frac{2.9 \cdot 10^6}{18.7^{0.35}})^{0.65} = £203$ mln which equals

€225 mln.

*Impact*

The impact on the global flow rate is zero. This is obligatory since the water level in the channel needs to be at a constant level of 0.55 m+NAP at all times. When deviating from this level the sweet water supply will be too low (resulting in salinization of the environment) or the water level in the surrounding polders will be too high causing agricultural water damage and damage to basements of houses and other buildings. The impact on the local flow rate is higher since the velocity is sharply increased, but since this is in a controlled environment (within the wing gate chamber) the damage to the river bed will be negligible.

A study should be made on the relation between navigational locking and scouring. Depending on the variable need for locking, the choice could be made to make an adapted schedule for locking to accommodate maximum capacity. Another option could be to give way to navigation locking and obtain a lower capacity of the turbine.

## 6 Analysis of the test locations

In the Netherlands opportunities present itself in the implementation of hydro power in civil discharge structures with valves and lock culverts.

*Comparison to hypothesis and first estimation*
The hypothesis "Electrical energy can be converted and stored using hydro power and pumped hydro storage in existing structures that dispense superfluous water" is partially disproven. Storage using pumped hydro is not possible at the test locations considering the design constraints of flow rate and water levels in the Netherlands. The part describing conversion is not proved invalid. It does come with a lot of constraints. For example the set flow rate and water level, but also the importance of navigation and the gaps in knowledge on the working of renewable techniques. The latter might be resolved in the near future due to rapid evolution of renewable energy, but is still a significant obstacle in capacity calculations among others.

In both test locations the resulting power output and capacity is much lower than estimated in the criteria analysis. This is caused by the lack of estimation of energy loss in the first estimation, but also by the constraints of the specific locations that were chosen. It would be interesting to know whether this would also be the case with the other technologies presented and if there are locations in the Netherlands with less heavy constraints.

The impact on the function and water balance has evolved positively, resulting in close to no impact. This was necessary for implementation. Exceeding this principle constraint would have large consequences like economical and material damage.

The TCO of the first estimation of hydro power is -€82.5 mln considering a life span of 50 years (Suwanit & Gheewala, 2011). The TCO of location Gouda deviates most from this estimation with a TCO of €255 mln (a deviation of 400%). Location Sambeek has a TCO of €5.24 mln (a deviation of 106%). Both locations are non-profit designs.

The score of the criteria analysis for the final situations can be found in 5.

**Table 5:** Rating of current design situations.

| | Impact | | TCO | | | Performance | | |
|---|---|---|---|---|---|---|---|---|
| | Water balance | Function | Installation | Maintenance | Payback time | Power | Capacity | Total |
| Sluis Sambeek | ++ | ++ | - - | - - | - - | - - | - - | 6- |
| Waaiersluis | ++ | + | - | - - | - - | + + | + + | 2+ |

*Comparison of test locations*
The performance of the Waaiersluis is much higher than that of Sluis Sambeek, but the Waaiersluis might decrease in performance when the navigational funtion of the lock is accomodated primarily. Furthermore the installation costs of the Waaiersluis will probably be relatively lower than that of Sluis Sambeek since the penstock is already in place at the Waaiersluis.

# 7 Conclusion

The main question 'Can electrical energy be converted and stored using existing structures that dispense superfluous water' can be answered with the analysis in the previous chapter. This research does not support the idea of profitable conversion or storage of energy in existing aquatic discharge structures due to low rating on either impact or TCO. Considering the capacity needed to provide for the electricity demand of the lock system in Sluis Sambeek is a little under 300MWh (Personal Communication, Rijkswaterstaat (2017)), the design of the Sluis Sambeek is for 9.2% self providing. The exact electricity demand of the Waaiersluis has not been provided, but considering the scale in ratio to Sluis Sambeek the Waaiersluis will be self providing and probably be able to provide for part of the surrounding demand. The overall conclusion is: The outcome of the analysis confirms the possibility of conversion used in existing structures, but does not confirm the possibility of storage in existing structures.

# 8 Discussion of the results

The sensitivity of the conclusion is influenced by many assumptiones and generalizations. The logic validity of assumptions, extrapolations and generalizations is invalid. For example the generalization of the total project cost, the conclusion that Equation 17 describes the relation between cost, head and power is inductive reasoning. This is logically invalid, since the conclusion might not hold for all cases. All standard ratings for the criteria analysis (Table 1) are based on assumptions. Even though most of them are verified by one or more sources, this is probably the weakest point of the research. Especially the impact, for which the values are often within a certain range of possibilities in the criteria is subject to uncertainty. The overal rating is set to equal weight for all components, but an inaccuracy already occured in comparing the first two techniques: when rating the 3 main values equal, the result can be different from rating all subvalues equal. Of the techniques that have not been chosen for implementation these techniques might form other possibilities . . . The filter on possible locations is very quickly narrowed down by including lock culverts. Although the potential of decreasing installation and maintenance costs is high, the occurance in the Netherlands is very low. The total potential for lock culverts in the Netherlands is subsequently also low, so this choice should perhaps be reviewed. Adding to a positive review could be the output of the situation which is rather high. In calculating the design flow and head of the turbine(s) for Sluis Sambeek, the time that $Q \cdot h$ is lower than the value for peak production is completely neglected. This is not neglected for the rated capacity and power, but a small error is present in those values due to calculations based on the design flow and head. Depending on the efficiency distribution of the turbine, taking this into account could alter the design properties. Making the choice of turbines an iterative process and recalculating design properties including efficiency distribution will improve the estimation of optimal design properties. With a better estimation the power and capacity would increase (the power and capacity is underestimated).

# 9 Recommendations for further research

Further research should be conducted to extend the support for this conclusion and to investigate potential of techniques in other circumstances. The criteria analysis should be extended and adapted by means of a stakeholder analysis in weighting. The impact should be made better measurable, the performance could be extended with the efficiency of the technique and a TVO (total value of ownership) should replaced TCO including immaterial benefits. Considering the largest impediment on implementing the test situations is finance and TCO it is recommended to extend the research especially on this topic. A manufacturer should be contacted in such a study to further specify the specific design conditions and have a custom made design. When measuring the suitability with for example a TVO including environmental goals, addition to company values and other immaterial value the comparison might turn out differently and potential can be found in other techniques. The filter on techniques using water could be reconsidered. In civil structures in general might be large potential for storage by use of f.e. flywheels or superconductors. Subsequent goals for research can be found: when provided with energetic data on the Waaiersluis a research on implementing conversion and/or storage techniques should be done to level supply and demand in the local grid. Another goal could be to make the whole lock system sustainable and look at the design of an energy efficient lock. A design in the Netherlands for tidal energy could be investigated using f.e. the river Ems Possible locations for pumped hydro in the Netherlands could be investigated specifically (so suitable location would not be discarded due to constraints for other designs than pumped hydro). A research could be done on life cycle of turbines to improve costs.

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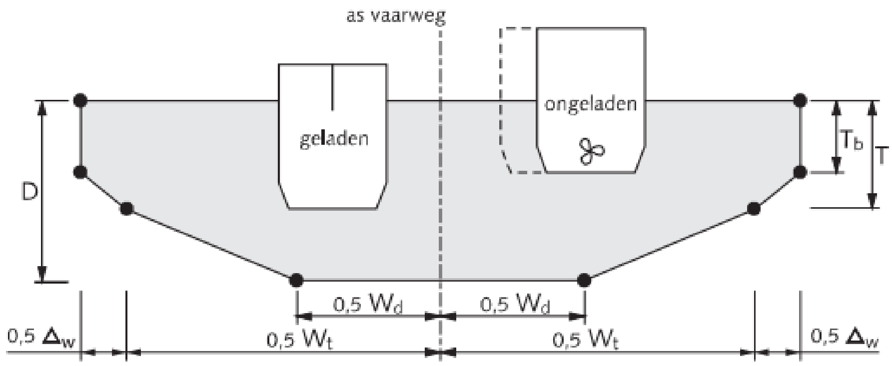
# Appendices

## A Richtlijn Vaarwegen 2011 - Minimum vaarwegprofiel voor rechte vaarwegen




<table>
<tr><th rowspan="3">klasse</th><th colspan="5">minimum vaarwegprofiel (m)</th></tr>
<tr><th rowspan="2">diepte D*</th><th colspan="2">breedte</th><th colspan="2">zijwindtoeslag $\Delta_w$</th></tr>
<tr><th>Wt</th><th>Wd</th><th>landstreek</th><th>kuststreek</th></tr>
<tr><td colspan="6">normaal profiel</td></tr>
<tr><td>I</td><td>3,1 - 3,5</td><td>20,4</td><td>10,2</td><td>2</td><td>4</td></tr>
<tr><td>II</td><td>3,5 - 3,6</td><td>26,4</td><td>13,2</td><td>3</td><td>6</td></tr>
<tr><td>III</td><td>3,5 - 3,8</td><td>32,8</td><td>16,4</td><td>4</td><td>8</td></tr>
<tr><td>IV</td><td>3,9 - 4,2</td><td>38,0</td><td>19,0</td><td>5</td><td>11</td></tr>
<tr><td>Va</td><td>4,9</td><td>46,0</td><td>22,8</td><td>5</td><td>11</td></tr>
<tr><td>Vb</td><td>5,6</td><td>46,0</td><td>22,8</td><td>9</td><td>18</td></tr>
<tr><td colspan="6">krap profiel</td></tr>
<tr><td>I</td><td>2,9 - 3,3</td><td>15,3</td><td>10,2</td><td>3</td><td>5</td></tr>
<tr><td>II</td><td>3,3 - 3,4</td><td>19,8</td><td>13,2</td><td>4</td><td>7</td></tr>
<tr><td>III</td><td>3,3 - 3,5</td><td>24,6</td><td>16,4</td><td>5</td><td>10</td></tr>
<tr><td>IV</td><td>3,6 - 3,9</td><td>28,5</td><td>19,0</td><td>7</td><td>15</td></tr>
<tr><td>Va</td><td>4,6</td><td>34,0</td><td>22,8</td><td>7</td><td>15</td></tr>
<tr><td>Vb</td><td>5,2</td><td>34,0</td><td>22,8</td><td>12</td><td>24</td></tr>
<tr><td colspan="6">enkelstrooksprofiel</td></tr>
<tr><td>I</td><td>2,9 - 3,3</td><td>10,2</td><td>5,1</td><td rowspan="6">nader te bepalen</td><td rowspan="6">nader te bepalen</td></tr>
<tr><td>II</td><td>3,3 - 3,4</td><td>13,2</td><td>6,6</td></tr>
<tr><td>III</td><td>3,3 - 3,5</td><td>16,4</td><td>8,2</td></tr>
<tr><td>IV</td><td>3,6 - 3,9</td><td>19,0</td><td>9,5</td></tr>
<tr><td>Va</td><td>4,6</td><td>22,8</td><td>11,4</td></tr>
<tr><td>Vb</td><td>5,2</td><td>22,8</td><td>11,4</td></tr>
</table>

* = gegarandeerde nautische diepte excl. marge voor onderhoud

# B Power output of reversible electro-dialysis

$$P_{max} = \frac{(V^0)^2}{4R_{stack}} \tag{18}$$

$$V^0 = N(\frac{2\alpha_{av}RT}{zF} ln\frac{a_c}{a_d}) \tag{19}$$

$$R_{stack} = \frac{N}{A}(R_{aem} + R_{cem} + \frac{d_c}{\kappa_c} + \frac{d_d}{\kappa_d}) + R_{el} \tag{20}$$

Where:

| | |
|---|---|
| $P_{max}$ | is the maximum power output in $W$. |
| $V^0$ | is the potential difference over the stack in $V$. |
| $R_{stack}$ | is the sum of resistance over the membrane pairs $\Omega$. |
| $N$ | is the number of membrane pairs. |
| $\alpha_{av}$ | is the average membrane perm-selectivity in $V$. |
| $R$ | is the gas constant of 8.314 in $\frac{J}{mol\,K}$. |
| $T$ | is the absolute temperature in $K$. |
| $H$ | is the electrochemical valence. |
| $F$ | is the Faraday constant of 96485 in $\frac{C}{mol}$. |
| $a_c$ | is the activity of the concentrated solution in $\frac{mol}{L}$. |
| $a_d$ | is the activity of the diluted solution in $\frac{mol}{L}$. |
| $A$ | is the effective membrane area in $m^2$. |
| $R_{aem}$ | is the anion exchange membrane resistance in $\Omega m^2$. |
| $R_{cem}$ | is the cation exchange membrane resistance in $\Omega m^2$. |
| $d_c$ | is the thickness of the concentrated compartment in $m$. |
| $d_d$ | is the thickness of the diluted compartment in $m$. |
| $\kappa_c$ | is the concentrated compartment conductivity in $S/m$. |
| $\kappa_d$ | is the diluted compartment conductivity in $S/m$. |
| $R_{el}$ | is the electrode resistance in $\Omega$. |

# C List of various gates used in locks worldwide

Below an overview of worldwide common gates for locking water is presented (Glerum & Vrijburcht, 2000) (US Army Corps of Engineers, 1995a) (US Army Corps of Engineers, 1995b).

- Gates sliding horizontal, illustrated in Figure 22 by a rolling gate.
  Rolling gate
  Sliding gate
- Gates rotating on a horizontal axis, illustrated in Figure 23 by a Tainter gate.
  Tainter gate
    With counter weight
    Without counter weight (or sector gate)
  Tumble gate
- Gates sliding vertical, illustrated in Figure 24 by a lift gate.
  Drop gate
  Lift gate
  Double leaf lift gates
- Gates rotating on a vertical axis, illustrated in Figure 25 by wing gates.
  Mitre gate
  Standing Tainter gate
  Single pivot leaf gate
  Wing gate
  Drum gate
  Hinged crest gate
- Others
  Bulkhead gates; these gates are actually weirs or walls with movable or removable sections, illustrated in Figure 26.

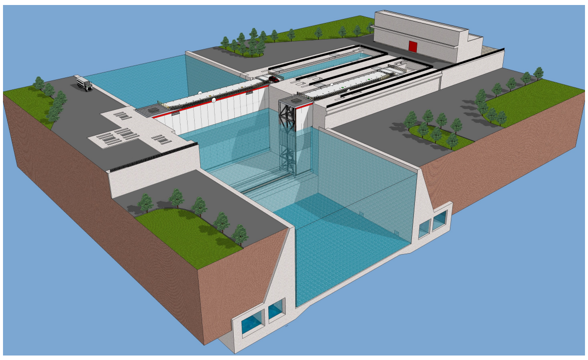


**Figure 22:** Rolling gate. Reprinted from http://www.nationalestaalprijs.nl

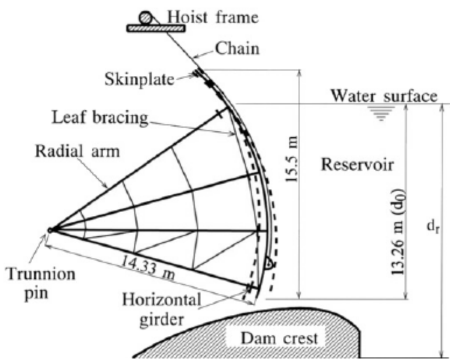



**Figure 23:** Tainter gate. Reprinted from https://www.researchgate.net

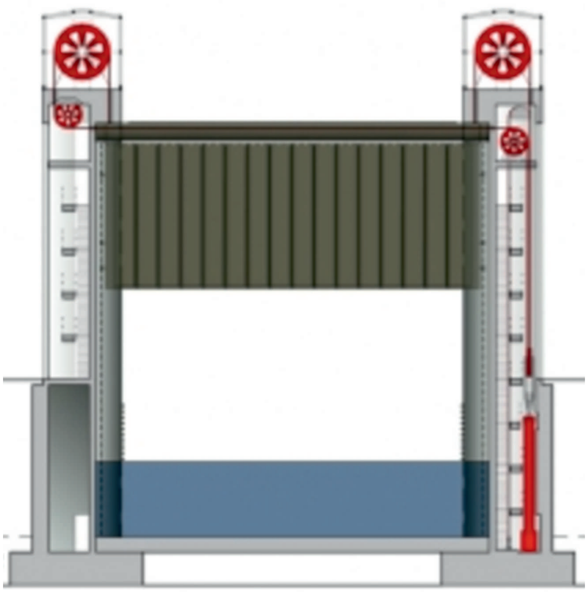


**Figure 24:** Lift gate. Adapted from http://www.debinnenvaart.nl

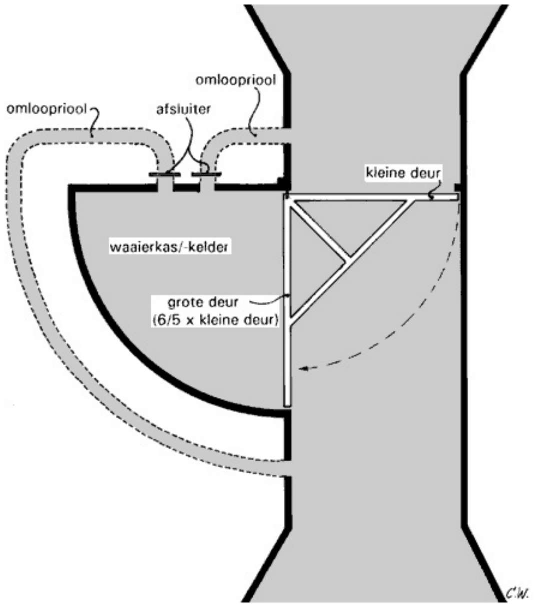



**Figure 25:** Wing gate. Reprinted from http://goudawaterstad.eu

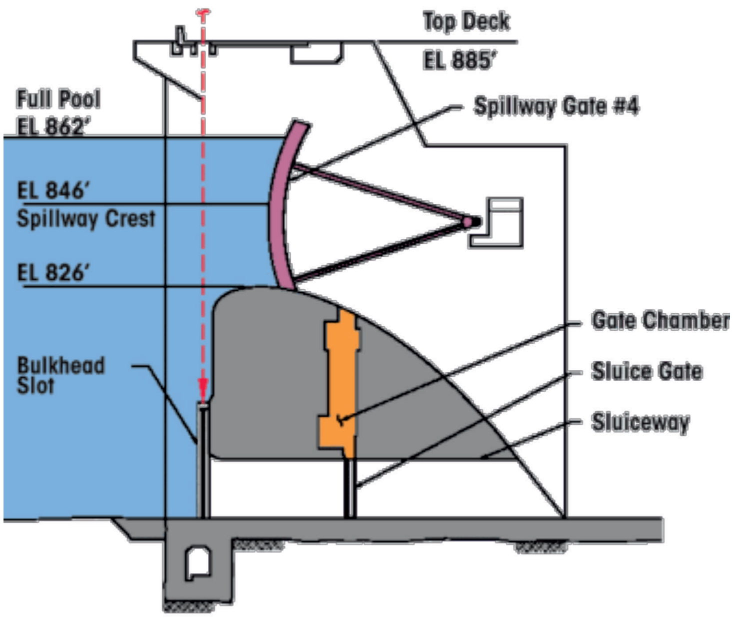
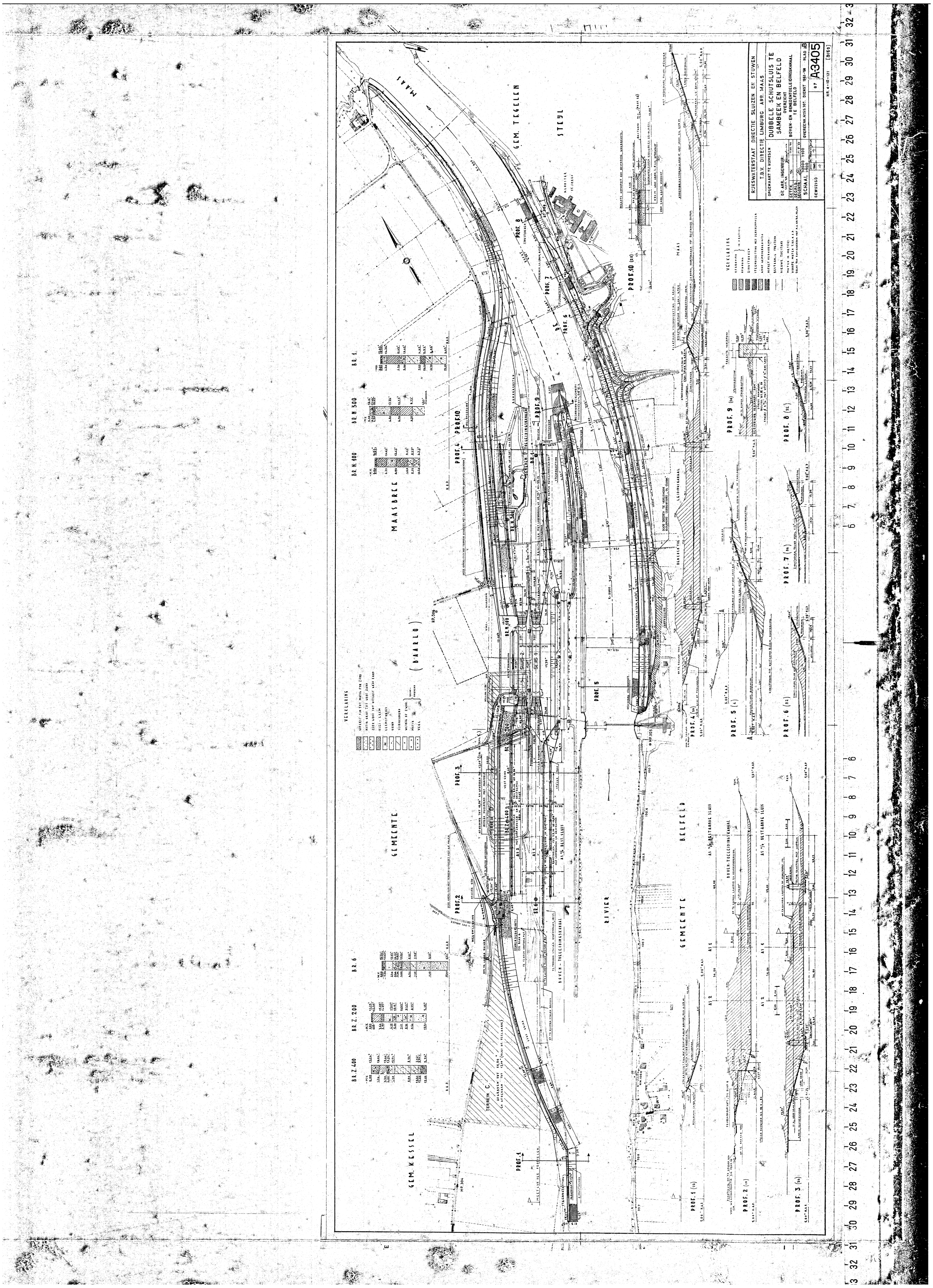


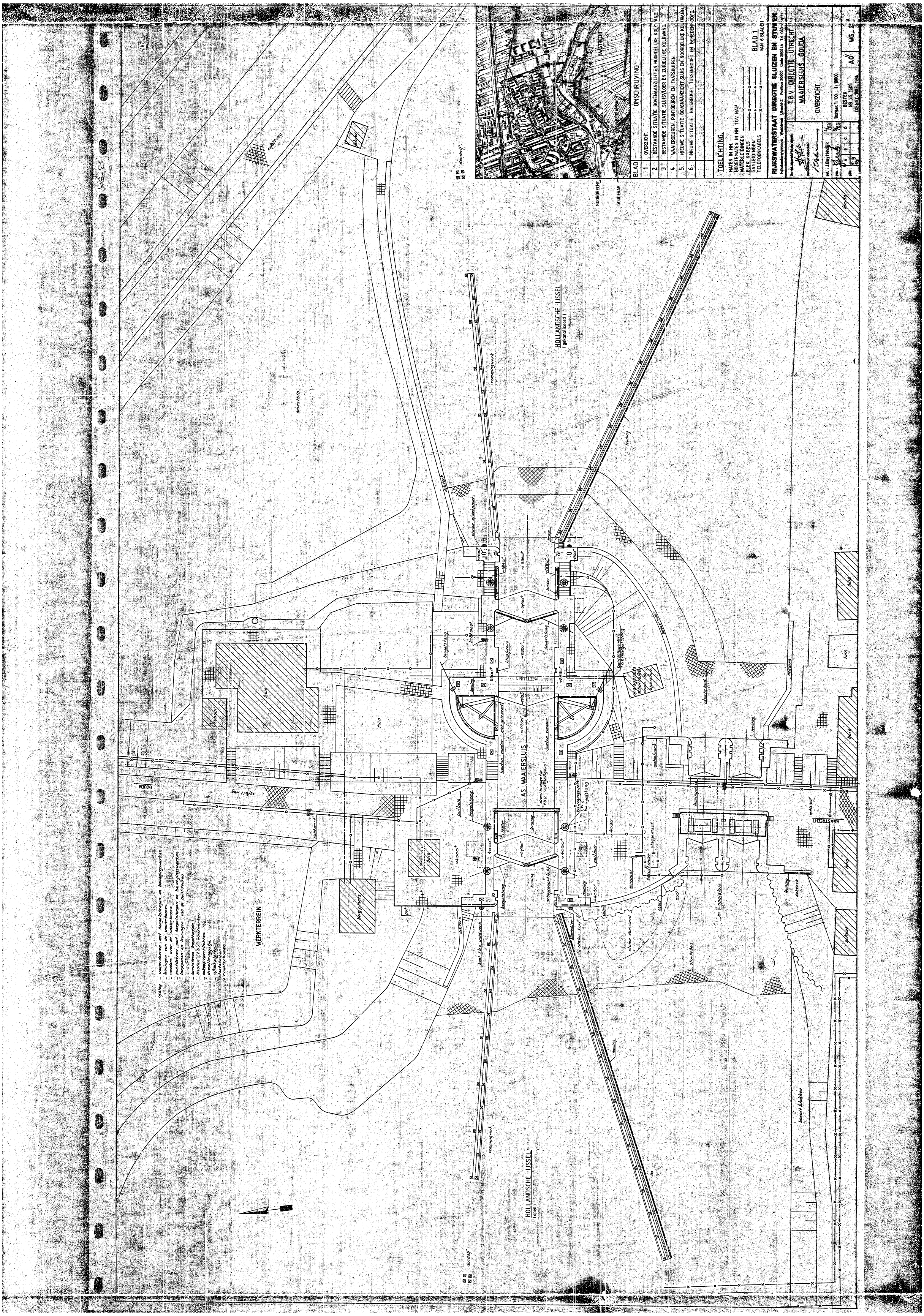

**Figure 26:** Bulkhead gate. Reprinted from http://www.hydroworld.com

# D Blueprints of test locations

## D.1 Sluis Sambeek



## D.2 Waaiersluis Gouda



# E Matlab script Sluis Sambeek

## Contents



```
clear, clc
close all
```

## Load data

```
%Matrix(5478x2) Number of the day of the month, Flow rate Venlo 2001-2015 in m3/s
Qvenlo = load('qvenlo2.txt');
%Matrix(5478x2) Number of the day of the month, Water level upstream of the weir in cm+NAP
Hbov = load('hsambov2.txt');
%Matrix(5478x2) Number of the day of the month, Water level downstream of the weir in cm+NAP
Hben = load('hsamben2.txt');
```

## Rearrange vectors, correction of data gaps

```
%setting data gaps from -999 to value previous index
Hbovmean = mean(Hbov(:,2));
kb = find(Hbov(:,2) == -999);
for i = 1:length(kb)
    Hbov(kb(i),2) = Hbov(kb(i)-1,2);
end
Hbovmean = mean(Hbov(:,2));
%setting data gaps from -999 to value previous index
Hbenmean = mean(Hben(:,2));
k = find(Hben(:,2) == -999);
for i = 1:length(k)
    Hben(k(i),2) = Hben(kb(i)-1,2);
end
Hbenmean = mean(Hben(:,2));
%setting data gaps from -999.99 to Q mean (too many gaps to substitute previous value)
Qmeanv = 276.6406; %manually adjusted Qmean untill this value equals Qmeanv (rule 34)
k = find(Qvenlo(:,2) == -999.99);
for i = 1:length(k)
    Qvenlo(k(i),2) = Qmeanv;
end
%creating vector Qmean
Qmeanv = [1:5478]';
for i = 1:5478
    Qmeanv(i) = mean(Qvenlo(:,2));
end
Qmean = Qmeanv(1) %creating constant Qmean
%creating vector Q with flow rate 1070 and 200 m3/s
Q1070(1:5478,1) = 1070;
Q200(1:5478,1) = 200;
%head difference in m
h = (Hbov-Hben)./100;
hmean = mean(h(:,2))
```

```
Qmean =

  276.6406
```

```
hmean =

    2.7761
```

### Calculations

```
%amount of days over 15 years with a flow greater or smaller than a respectively b
a = 1070;
b = 200;
daysgreater = Qvenlo(:,2)>a;
daysgreaterc = sum(daysgreater);
daysfewer = Qvenlo(:,2)<b;
daysfewerc = sum(daysfewer);

%Flow distribution vector
Qdist = sort(Qvenlo(:,2));

%Velocity at Q = 1070 m3/s
v_Q1070 = 1070./(120.*4.68);

%Optimum of Qht / calculation of design flow rate
k = find(Qvenlo(:,2)<1070);
Qh1 = Qvenlo(:,2).*h(:,2);
Qh1070 = Qh1(k);
for c = 1:length(Qh1070)
    daysqhgreater(:,c) = Qh1070>Qh1070(c);
    daysqhgreaterc(c) = sum(daysqhgreater(:,c)); % Amount of days Q*h is available
end
Qht = Qh1070.*daysqhgreaterc'; % Qht, Q*h*'amount of days Q*h is available'
Qhtdist = sort(Qht); % Distribution of Qht
index_opt = find(Qht==max(Qht));
Qx1070 = Qvenlo(k,2); % Chronological flow rate without values exceeding 1070 m3/s
hx1070 = h(k,2); % Chronological head corresponding to Qx1070
Hbovx1070 = Hbov(k,2); % Chronological water level upstream corresponding to Qx1070
Qdesign = Qx1070(index_opt) % Design flow rate in m3/s
hdesign = hx1070(index_opt) % Design gross head in m+NAP
Hdesign = Hbovx1070(index_opt); % Design water level upstream in cm+NAP

%Power, capacity and rated capacity
rho = 1000; % Density of water
g = 9.81; % Gravitational acceleration
hlfactor = 8.091222.*10.^-6; % Head loss factor from the Darcy-Weisbach equation.
for i = 1:length(k)
    if Qx1070(i) > 208.8
        Qx1070t(i,1)=208.8;
        Qx1070rest(i,1)=Qx1070(i)-208.8;
    else Qx1070t(i,1)=Qx1070(i);
         Qx1070rest(i,1)=0;
    end
end
Qht = Qh1070./Qx1070.*Qx1070t*24; %Q*h*t per day
hl = hlfactor.*Qx1070t.^2; % Head loss
hnet = hx1070-hl; % Netto head
Capacity1 = Qht./hx1070.*hnet; % Capacity in kWh per eta*rho*g
E_r = Capacity1./(Qht(index_opt)); % Rated capacity per eta*rho*g
eta = 0.9-0.2.*(E_r-1).^2; % Turbine efficiency
for i = 1:length(k)
    if eta(i) > 1.3
        eta(i)=0;
    elseif eta(i) < 0.3
        eta(i)=0;
```

```matlab
    else eta(i)=eta(i);
    end
end

Capacity = Qht./hx1070.*hnet.*rho.*g.*eta;
Capacityrated = sum(Capacity)./15./1000 % Total rated capaciy in kWh per year

Power = Qdesign.*hdesign.*g.*rho*0.9./1000 % Turbine power in kW
Powergem = sum(Capacity)./length(Capacity)./1000; % Average  power of the turbine

for i = 1:length(k)
    if Qx1070rest(i) > 208.8
        Q_turbine2(i,1)=208.8;
        Qt2rest(i,1)=Qx1070rest(i)-208.8;
    else Q_turbine2(i,1)=Qx1070rest(i);
        Qt2rest(i,1)=0;
    end
end

Capacity_turbine2 = Capacity./Qx1070t.*Q_turbine2;
Capacityrated2 = sum(Capacity_turbine2)./25./1000 % Total rated capaciy in kWh per year

for i = 1:length(k)
    if Qt2rest(i) > 208.8
        Q_turbine3(i,1)=208.8;
        Qt3rest(i,1)=Qt2rest(i)-208.8;
    else Q_turbine3(i,1)=Qt2rest(i);
        Qt3rest(i,1)=0;
    end
end

Capacity_turbine3 = Capacity./Qx1070t.*Q_turbine3;
Capacityrated3 = sum(Capacity_turbine3)./25./1000 % Total rated capaciy in kWh per year
```

```
Qdesign =

  208.8000


hdesign =

    2.9500


Capacityrated =

   2.7549e+07


Power =

   5.4383e+03


Capacityrated2 =

   5.2494e+06


Capacityrated3 =

   1.6668e+06
```

## Graphs

```
%{
%Plotting the flow rate over time including Q200, Qmean, Q1070 and Qdist
figure()
x = [1:5478];
plot(x,Qvenlo(:,2),x,Q1070,x,Qmeanv,x,Q200,x,Qdist);
ylabel('Q (m^3/s)')
xlabel('Days from 2001-01-01 till 2015-12-31')
legend('Q','Q_{1070}','Q_{mean}','Q_{200}','Q_{distribution}')

%Plotting Qht
figure()
x = [1:5478];
plot(x(k),Qht,x(k),Qhtdist);
ylabel('Q*h*t (m^2)')
xlabel('Time, chronological for Qht, amount of days in 15 years Q*h*t is available for Qhtdistr (days)')
legend('Qht','Qht_{distribution}')

%Plotting unused flow rate
x = [1:length(k)];
figure()
plot(x,Qx1070rest)
ylabel('Q (m^3/s)')
xlabel('Time, chronological (days)')
%legend()

%}
```

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# F Transcripts of interviews

## F.1 Emiel van Druten - Brainstorm hydro power

<table>
<tr><td>Emiel van Druten</td><td>Subject: Brainstorm possibilities hydropower</td></tr>
<tr><td>Time & date interview: 17/05/2017, 15:30h</td><td>Report date: 18/05/2017</td></tr>
<tr><td>Location: Office Witteveen + Bos,<br>Deventer – SP, 4th floor</td><td>Reported by: Eva Juffermans</td></tr>
<tr><td colspan="2">Participants</td></tr>
<tr><td>• E. (Emiel) van Druten MSc</td><td>• E.E. (Eva) Juffermans</td></tr>
<tr><td colspan="2">Emiel van Druten is employed at Witteveen + Bos in the PMC ‘Gebiedsontwikkeling’, focussing on energy and sustainable development. His Master Thesis was on pumping stations and he offered to help and brainstorm on ideas and solutions for hydropower in water locks.</td></tr>
<tr><td colspan="2">Minutes</td></tr>
<tr><td colspan="2">After elaborating on the research questions and chosen locations, Emiel explains about a project he was on concerning a feasibility study in small hydropower in Sierra Leone in 2016. They analysed several locations, their potentials, enhancing possibilities and turbine options.<br>In discussion on which turbines might be fit for the locations in the Netherlands he mentions a few aspects of calculations on potential and, in addition, practical focal points to the business case.<br>Mentioned turbines (with a diameter of 1m in mind and considering a very low head):<br>- Kaplan: Not suitable, applicable at a minimum head of about 20-25 m.<br>- Streamdriver (company: Voith): Used in calculations in Sierra Leone, applicable at a minimum head of 2 m, smallest option: intersection of 1.380 m (data sheet on turbine received).<br>- VLH turbine: minimum diameter of 3.150 m (table of electrical output per head per turbine type received.<br>- Fishflow Buisvijzel: combined pump and turbine, efficiency rate of 0.92 % when considering (mechanical) pumped hydro storage (both storing and regenerating electricity)<br>Storage potential of hydropower:<br>In storing electricity by use of pumped hydro storage, necessary data are the dimensions of the upstream (and downstream) river (or canal) and ‘Peilbesluiten’ which is a decision of Rijkswaterstaat on the water level of restricted areas.<br>Business case:<br>When considering the potential in terms of companies who want to invest in the technology, current alternatives are very important (does it outweigh the current systems?). For example when looking at energy storage instead of using electricity from the grid, the price ratio between peak supply and low supply can be compared to the ratio of efficiency of the technology in electricity storage. When the price ratio is lower than the efficiency of conversion, it is cheaper to just draw electricity from the grid than to store it. An extension to this statements is that robustness of the alternative should also be taken into account: once the technology is installed, it is more robust than the electricity price (which is dependent on economics and supply and demand) and could therefore be favourable. When needed, market results of electricity prizes on year basis can be provided by Emiel. Week, day and hour overviews can be found at apxcres.com/marketresults.</td></tr>
</table>

## F.2 Peter Suijdendorp - Water balance in the Netherlands

| Peter Suijdendorp | Subject: Water balance in the Netherlands |
|---|---|
| Time & date interview: 14/06/2017, 11:00h | Report date: 14/06/2017 |
| Location: Office Witteveen + Bos,<br>Deventer – SP, 5th floor | Reported by: Eva Juffermans |
| **Participants** | |
| • Ir. P.J. (Peter) Suijdendorp | • E.E. (Eva) Juffermans |
| Peter Suijdendorp is employed at Witteveen + Bos in the PMC 'Smart Infra Systems', focussing on integration of mechanical engineering in infra systems. As a group leader on integration of mechanical installations and with experience from inspections of (water) infra structures his knowledge on water balance and integration of systems can be valuable for this research. | |
| **Minutes** | |
| Water management in the Netherlands is working on an optimal solution to the many different risks we face. Discharge in water is on a tight schedule in roughly two periods. The first situated around spring, when water is melting in the mountains of the Swiss Alps (often in combination with long lasting rain) and the flow rate in the four main rivers (Meuse, Waal, Rhine [Nederrijn and Lek], and IJssel) is increased. The second occurring around the end of August up and until September, when rainfall in short periods of time is very intense and the total amount of discharge is not as much a problem as the required discharge capacity per second. In these periods, discharge capacity increases swiftly (especially for the river Meuse), due to canalization of the rivers by previous removal of floodplains.<br>In summer, management on discharge of water is reversed, when relative drought is challenging and water needs to be retained. Ample greenhouse farming or urbanization contribute to the rapid reduction of groundwater levels. When the water supply is low, the water balance is kept high enough for navigation to function properly by pumping water upstream. This is often brackish water from remote deltas by lack of other resources. Furthermore, fall in groundwater level causes lowering of the ground level. These phenomena create environmental, economic and agricultural problems. The problems will probably be augmented by the effect of climate change. The rise of the sea level and intensification of rainfall will contribute to larger extremes in discharge and retainment.<br>In wet periods water retention basins and other controlled inundation areas are very important. One of the current solutions is in the form of the project 'Ruimte voor de rivier' covering multiple applications of increased storage capacity around the river environment. This project is not only active in the Netherlands, but also started in many regions in Germany. It requires collaboration between multiple countries covering the river basin of the Rhine.<br>Another element to be considered is the controlled environment in the Netherlands. The Rhine and sub rivers are blocked by moveable dams to control the discharge capacity, causing the water flow to be split more regularly between the IJssel (to replenish the fresh water basin 'IJsselmeer') and the Waal (added navigation purposes). Here management requires cooperation and consultation between the countries situated along the Rhine as well. | |