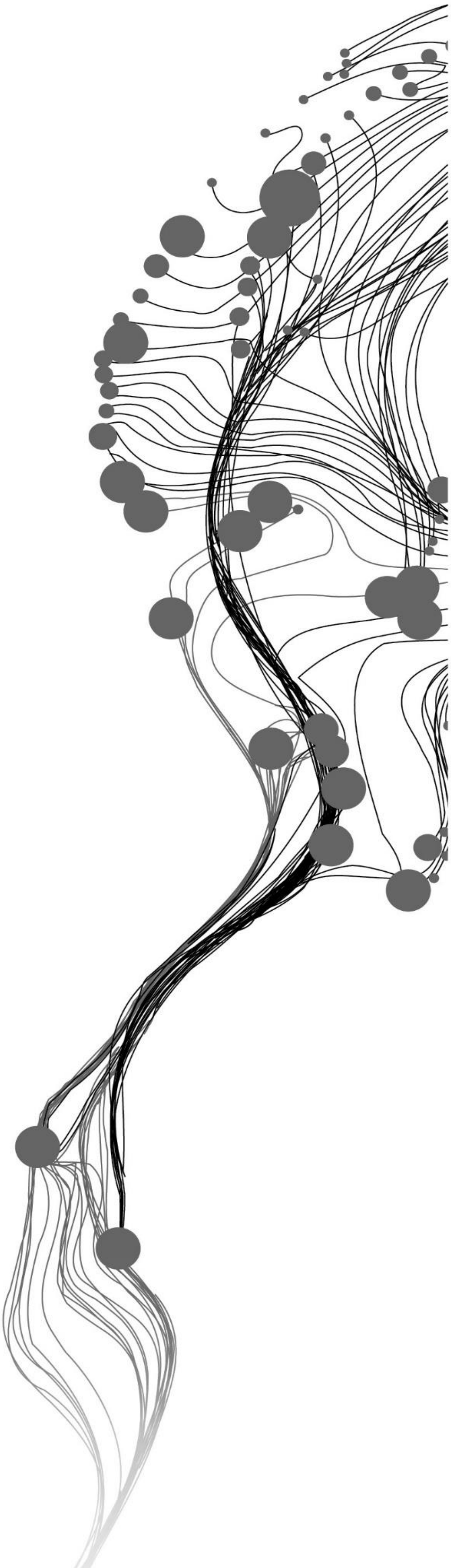
External limitations to Reverse Electrodialysis

MILA LUNA VAN DRUTEN
June 2023

SUPERVISORS:
Dr. Ing. M.J.M. Penning de Vries
Dr. Ir. C. van der Tol



External limitations to Reverse Electrodialysis

MILA LUNA VAN DRUTEN
Enschede, The Netherlands, May 2023

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.
Specialization: Spatial Engineering

SUPERVISORS:
Dr. Ing. M.J.M. Penning de Vries, department of Water Resources
Dr. Ir. C. van der Tol, department of Water Resources

THESIS ASSESSMENT BOARD:
Prof. dr. B. Su
Dr. W.D.B. Warbroek

ABSTRACT

Reverse Electrodialysis (RED), a promising renewable energy technology for capturing osmotic power, has the potential to be scaled up to commercial viable levels. This study explores the impacts of external factors on the RED process, specifically on the study area on the Afsluitdijk in the Netherlands. The research identifies a substantial domestic demand for renewable energy. The availability of (fresh) water, the salinity gradient and the water temperatures are analysed as the physical limiting factors. These physical factors showed a more beneficial situation for RED production in the winter months in terms of water availability, but a more suitable salinity gradient and water temperature in the summer months. Societal forces, such as water management and energy demand, play a major role in promoting renewable energy sources and were shown to be inherently intertwined with the status of the physical factors. This study considers future changes of the external limitations based on Delta scenario predictions, showing particularly promising results in terms of water availability under the most extreme climate change scenarios. Despite considerable uncertainties, the findings clearly highlight the potential for upscaling RED under all predicted scenarios.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Meeting the increasing energy demands of a growing global population in a sustainable manner requires more renewable energy sources (Moomaw, 2011). A mix of several renewable energy sources is needed to replace fossil fuels, production- and energy security wise. One of the challenges of the energy transition is that most of the currently developed energy sources, for example solar-, wind- and tidal energy, are produced at limited times. Osmotic power or saline power, which is based on the energy that is released as a consequence of mixing two units of water with different salinity levels, could be added to this mix. This technology is not limited to certain production times, has no significant operational hazards and releases no CO_2 (Nazif et al., 2022; Kleiterp, 2012). This form of energy generation, oftentimes called 'Blue Energy', is still under development and not yet operational at a commercial scale.

Theoretically, the energy potential of salinity gradient energy is the second largest energy source in the world and could be produced anywhere where two waterbodies with different salinity levels meet (Moreno, 2018). Approximately 1.4 to 2.6 TW of energy could be produced with Blue Energy based on the fresh water flow into the oceans from the world's major rivers, which would cover the current global electricity demand or about 16% of the current total energy consumption (Nazif et al., 2022). Because of the continuity of the hydrological cycle, the energy production is renewable (Mei & Tang, 2018). Renewable energy sources are replenished at a higher rate than they are consumed, according to the United Nations, and is therefore key to addressing the climate crisis (United Nations, n.d.).

Currently, there are two methods at nearly commercially viable level to generate Blue Energy: Pressure Retarded Osmosis and Reversed Electrodialysis (RED). This research will focus on the latter, of which the technology will be explained in the following chapter. A RED trial power plant located at dyke Afsluitdijk in the Netherlands has the ambition to scale up to a commercially viable production level of 200 MW – so the question arose what limitations are in play that prohibit them from producing even more, and what effects will this scaling up process have? The technical potential of RED has been thoroughly researched (including Tufa et al., 2018, Moreno et al., 2018, Nazif et al., 2022, Mei & Tang, 2018, Kang et al., 2022, Daniilidis et al., 2014), but its impacts on the broader socio-economic and environmental systems has not. Similarly, research on the limits to RED imposed by external physical and social factors is minimal. Now that the commercialisation of RED seems near, it is important to research to what extent the interactions between surrounding systems and the powerplant influence its production capacity. Therefore, this research will focus on the external limitations that influence the RED energy potential, to see if the technique would be considered relevant in the broader socio-environmental sense.

1.1. Technology

The RED technology makes use of a salinity gradient to harvest energy. A short description of the technology is described to provide some background information.

Electrical energy can be generated by mixing waters with different salinities, leaving only brackish water as the rest product (Moreno et al., 2018). Simply put -- when two solutions, one with a higher salinity gradient than the other, alternatingly flow through compartments, the salt particles will strive for maximum entropy, meaning the salt will want to distribute itself over the water volume. By separating the water with a lower salinity and water with a higher salinity by ion-selective membranes (meaning they only let either cations or anions through), the osmotic flow can be converted into an electric current (Kleiterp, 2012). So, while the feedwaters are flowing through the compartments, the molar free energy gradient causes the cations and anions to move through the membranes, as depicted in Fig. 1. During this osmotic flow, the ions flow in the direction of the anode or the cathode, depending on their charge. This leads to a negatively charged anode compartment and a positively charged cathode compartment. This eventually results in an electron being transferred via the external electric circuit (Kleiterp, 2012; Moreno et al., 2018). The difference in potential accumulates during the process and can be transformed into an electrical current by connecting to an external load (Moreno et al., 2018).

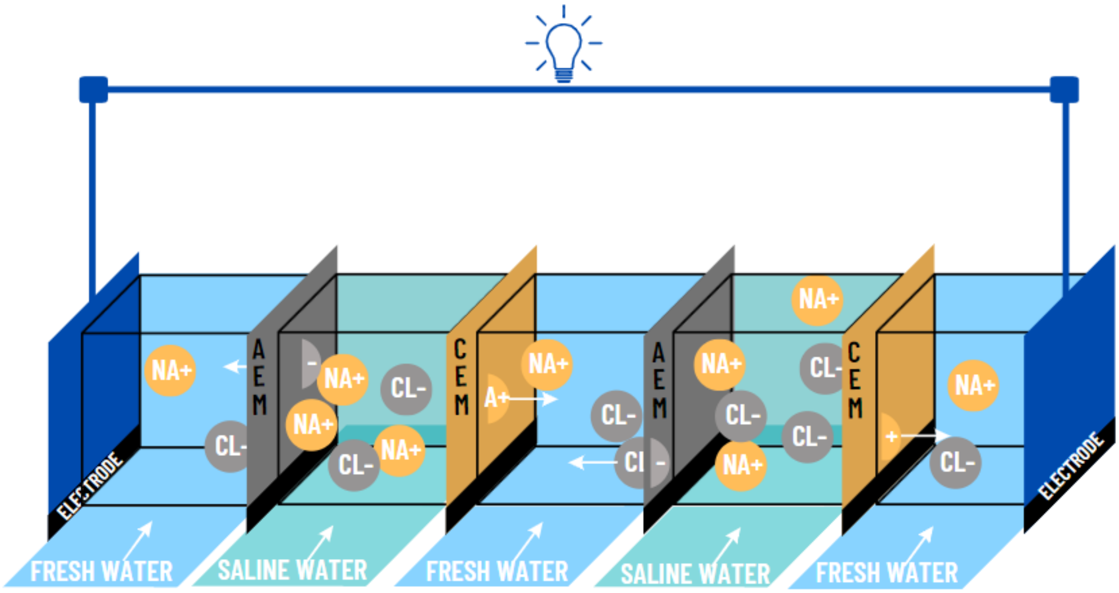


Fig. 1: The RED technology. Fresh (accommodating few Na+ and Cl- ions) and saline (accommodating more Na+ and Cl- ions) water flow alternately through the compartments, which are divided by cation (CEM) and anion (AEM) exchange membranes.

During the process, the feedwaters – which are volumes of water with the different salinities in the compartments - become brackish. Since under natural circumstances the mixture of saline water and fresh water would also result in brackish water, this rest water can safely be returned to the sea.

Because of their easy accessibility and availability, seawater and river water are most commonly used in the RED procedure. But fresh water has a relatively high electrical resistance compared to water with a higher salinity, which dictates the conductivity of the cells. Using brackish water as the low-salt solution and brine water as the high-salt solution has been shown to increase productivity in the REApower project (Tedesco et al., 2015). However, these solutions are not abundantly accessible and available, which is a limiting factor in the production capacity of the powerplant since the potential power generated is linked to the amount of water that is going through the plant. Lakes or seas which are not fed by freshwater rivers, for instance the Dead Sea or Lake Urmia in Iran, are becoming increasingly saline and therefore interesting for RED purposes, if less saline water (e.g. sea water, as fresh water is in short supply there) is available in the region.

RED, as a rule of thumb, has a gross production capacity of 1 MW per 1 m^3/s mixed water flow with a continuous flow (Herman et al., 2020). The RED plant's capacity can therefore be calculated by multiplying the theoretical production capacity with the fresh- and saline water flow, but is then technically limited by internal factors, such as the membrane characteristics and fouling. Membrane characteristics indicate how much energy can be generated per membrane area. These membrane characteristics can decrease over time due to usage by the osmotic process (Kleiterp, 2012). Fouling, which essentially indicates the pollution of the system, is considered one of the key bottlenecks for the production capacity of RED. Nazif et al. (2022) described that without anti-fouling measures, the power density of the RED systems could be diminished by more than 80% from the theoretical potential to the practically obtained power density. That is why pre-treatment of the feedwaters is a crucial part of the production process. The composition of foulants, such as colloids, natural organic matter, monovalent- and multivalent ions and micro-organisms, in both the fresh- and the saline water determine how much pre-treatment is necessary (Zhang et al., 2019). Pre-treatment of water is capital-intensive and therefore influences the costs of the expansion of the powerplant (Nazif et al., 2022).

In recent years, many academic papers have been published on RED, focusing on process analysis, optimization, stack designs, membrane designs, fouling, modelling and hybrid applications (including Tufa et al., 2018, Moreno et al., 2018, Nazif et al., 2022, Mei & Tang, 2018, Kang et al., 2022, Daniilidis et al., 2014). The technical challenges of the powerplant are still, and have been so far, the major limiting factor in the upscaling process of the RED technology to a commercial level. REDstack, one of the major pilot sites in the world and the powerplant this research will focus on, states that they have optimized the technology towards commercial readiness levels. Therefore, this research will focus on external limiting factors and leave the internal technicalities that are involved in the upscaling outside of the scope of this research.

1.2. Study area

Although the RED technology is not yet commercially viable, it has grown significantly over the last few years towards readiness level and has been tested in pilot trials under different real world environments (Tamburini et al., 2019). One of those pilot plants was the previously mentioned REApower project, where the result of mixing brackish water (~0.18% NaCl equivalent) from the shore in Trapini, Italy and saturated brine water (~23.4-29.2% NaCl equivalent), retrieved from adjacent saltworks, was a power output of 330 kW (Mei & Tang, 2018). Another pilot site, which this research will focus on, has been in function since 2014 in the Netherlands, called REDstack.

Theoretically, about 3000 MW of energy can be generated with Blue Energy in the Netherlands, which could cover 10 percent of the national energy demand (Rijksoverheid, 2012). The RED "REDstack" trial plant is located on the Afsluitdijk, which divides the freshwater (0.2-0.5% NaCl) IJsselmeer lake from the salt water (~2.8%) Waddenzee sea, both which REDstack uses as feedwater (Nazif et al., 2022; Mei & Tang, 2018). REDstack aims to scale up to a production capacity of 200 MW, after having overcome all practical obstacles over the years. At the moment, the pilot plant has a maximum production capacity of 50 kW (Budde, 2021). Current research focuses on internal optimization, such as the creation and efficiency of nano-membranes, the efficiency of stacking in a circle instead of a cube and the combination of the RED technology with other technologies, e.g., water treatment. Nazif et al., (2022) describe the major limitations of the commercialization of RED as the low-power density, membrane fouling and lack of cost-effective ion exchange parts of the membranes.

The IJsselmeer area, where the REDstack powerplant is based, exists of multiple individual lakes, which are increasingly considered to be connected to one another and the surrounding land, instead of being isolated units (Van Riel et al., 2021). The main functions of the lake area, enforced by water management, are to ensure the water safety, sustainably act as a fresh water- and drinking water buffer and to balance the demands of water management and -usage functions with its role as a robust ecosystem (Van Ginkel et al., 2022). The fourth main function applied to the lake area, as stated in the agenda for 2050, is to significantly contribute to the energy transition of the Netherlands (Ministerie van Infrastructuur en

Waterstaat, 2018). To what extent they want to contribute, is not quantified. The fresh water in the IJsselmeer has been increasingly efficiently managed since its creation to an exactness of 1 centimetre (Lammens et al., 2008; Zandvoort et al., 2019). The in- and outflow of the lake varies during the seasons and is artificially manipulated to maintain a certain ground water level in the surrounding areas ensuring the maintenance functions of the lake (Van Riel et al., 2021).

A bottleneck analysis in 2018 by Mens et al. (2020) showed that the risk of full utilization of the water buffer of the IJsselmeer would happen more frequently than the former calculated risk of once in the 50 to 100 years, due to a changing demography and climate change (Mens et al., 2021). The IJsselmeer must first and foremost be used as a freshwater buffer and flood defence mechanism, other demands on the fresh water come second. To what extent a demand on fresh water by the RED powerplant affects the system, potentially leading to a wicked situation, will be elaborated on in the following chapter.

1.3. Wickedness

Reducing greenhouse gas emissions is both a stakeholder consensus and knowledge problem in itself, and even more so if the proposed intervention were to influence the freshwater buffer of a country. Policy makers worldwide are trying to reduce the greenhouse gas emissions by seeking more technical knowledge and trying to create public understanding. Most of these measures require structural change of industries by means of incentives and compensations. Nevertheless these policy debates are notorious for being fragmented and for involving a lot of stakeholder disagreement, since it often impacts peoples' lives severely (Head, 2014). A significant attribute of a wicked problem is that it is often not solvable by a 'solution' in the sense of one technical intervention or application of knowledge (Head, 2014), but rather, as Rittel and Webber (1973) described, social issues in modern society depend on political judgement rather than scientific certainty.

The energy transition can be considered one of these problems, congested with stakeholder disagreement and without a straightforward solution. Therefore, only interventions can be suggested that might attribute to solving a part of this wicked problem or gather more knowledge to map the various competing interests. The RED powerplant intervention makes use of universally scarce fresh water, which might lead to another wicked problem in itself – namely a fresh water shortage. The sixth goal of the Sustainable Development Goals (United Nations General Assembly, 2015) is to "Ensure availability and sustainable management of water and sanitation for all". It is therefore clear that the water management of the fresh water in the IJsselmeer lake should prioritize the needs of the population over a private company, such as REDstack, that also demands fresh water. Besides that, the IJsselmeer area serves more socio- and environmental purposes, which all put conflicting demands on the area. If RED energy would demand a large portion of the freshwater supply, it undoubtedly conflicts with other demands. As will be described in this research, REDstack will mostly use fresh water that does not serve other purposes, except during times of fresh water shortage or other extremes – which is when the wickedness arises. On the other side, renewable, sustainable and potentially low-cost electric energy is also needed to sustainably develop the growing population -- in the Netherlands as well as abroad. A changing climate makes the situation even more wicked, since it might affect the physiological characteristics of the area and affect the socio-ecological demands and their prioritization by governance actors.

This research aims to decrease the wickedness of the situation by casting some light on the possible contribution of RED energy into the Dutch renewable energy mix. This will be done by examining the external influences that limit the production capacity of a RED powerplant. Research shows that this is a promising greenhouse gas emission free and renewable energy technology. Whether or not this technology will be received well by involved stakeholders depends on its benefits, e.g. energy production capacity, and its drawbacks, e.g. its demands on resources. Changes in the systems due to the changing climate may influence the interaction between the surrounding socio-physical systems and the powerplant, which could influence the way the upscaling process is received by stakeholders. Most research on RED is focused on the internal technical challenges, which leaves a knowledge gap on the external socio-physical influences that impact the technology's potential. In summary, the purpose of this study is to decrease the wickedness of the situation by clarifying both the socio- and the physical influences on a RED plant.

1.4. Aim

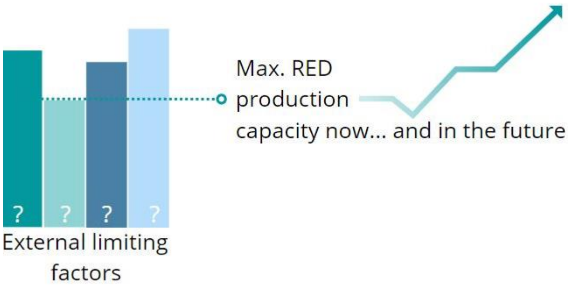


Fig. 2: The overarching concept of this research

This research will quantify the external limitations to the scaling up potential of a RED power plant at the Afsluitdijk. How much energy can be generated using RED presently and in the foreseeable future, given the societal and physical circumstances, will be the main research question of this thesis. The aim is to investigate if the Dutch society can benefit from investing in the upscaling process of the RED powerplant, using the following (sub)research questions.

Research question:
How much energy can be generated using RED presently and in the foreseeable future, given the societal and physical circumstances?

Sub questions:
What is the current renewable energy gap?
What are the quantified limits of RED at the Afsluitdijk imposed by external physical factors?
What societal factors are limiting the application of RED in the Netherlands?
What are the expected changes to the external physical limiting factors in the future, under different emission scenario's?

2. METHODOLOGY

To what extent the Dutch society would benefit from a scaled-up version of the REDstack powerplant depends on the benefits and drawbacks of the plant -- now and in the future. The societal and physical limitations should therefore be researched. This is a research that includes a clear technical engineering and governance aspect, and a subtler – but nonetheless most important - spatial aspect, which presents itself in the spatial circumstances that create the physical and societal limitations, including a water balance, meteorological impacts and downscaled climate projections. This research will be conducted in the following order:

1. The context in which the limitations are set will be described based on academic literature studies. Whether or not there is a societal need for RED energy forms the base for the first sub question, therefore the energy demand context is described first. Similarly, the context in which the physical limitations are set, based on academic studies, as well as their connection to RED power output are described afterwards. This literature study will form the base on which conclusions can be drawn from the results. This step can be seen as phase 0 (see Fig. 3), as it lays the groundwork on which the other phases can build.
2. The Dutch demand for renewable electrical energy is determined, by calculating the current gap between the demand for energy (fossil fuels and renewable energy) and the supply potential of renewable energy. The size of this gap, in MW, will be used as a guideline for the societal demand on new renewable energy sources. This gap could potentially be closed by RED energy, if the production capacity allows. This is visualized as phase 1 in Fig. 3.
3. The physical limiting factors for the energy production of RED are quantified, by researching the available volume of feedwaters, the salinity of the water, the composition of the water and the temperature on monthly basis. Together with step 4, these limitations are visualized as phase 2 in Fig. 3.
4. The societal limiting factors are analysed by performing a stakeholder analysis, estimating their demands on the IJsselmeer lake, and looking at strategic governmental documents to examine the plans for the lake area in the near future. As stated above, this takes place in phase 2, as depicted in Fig. 3.
5. After listing the current physical and societal limitations, a prognosis of the availability of these necessary RED variables can be created, using the KNMI and the Delta scenarios. Afterwards, the Delta scenarios applied to the study area will be examined. The prognoses will be enhanced by forecasts described in academic literature and strategic documents. This is visualized as phase 3 in Fig. 3.

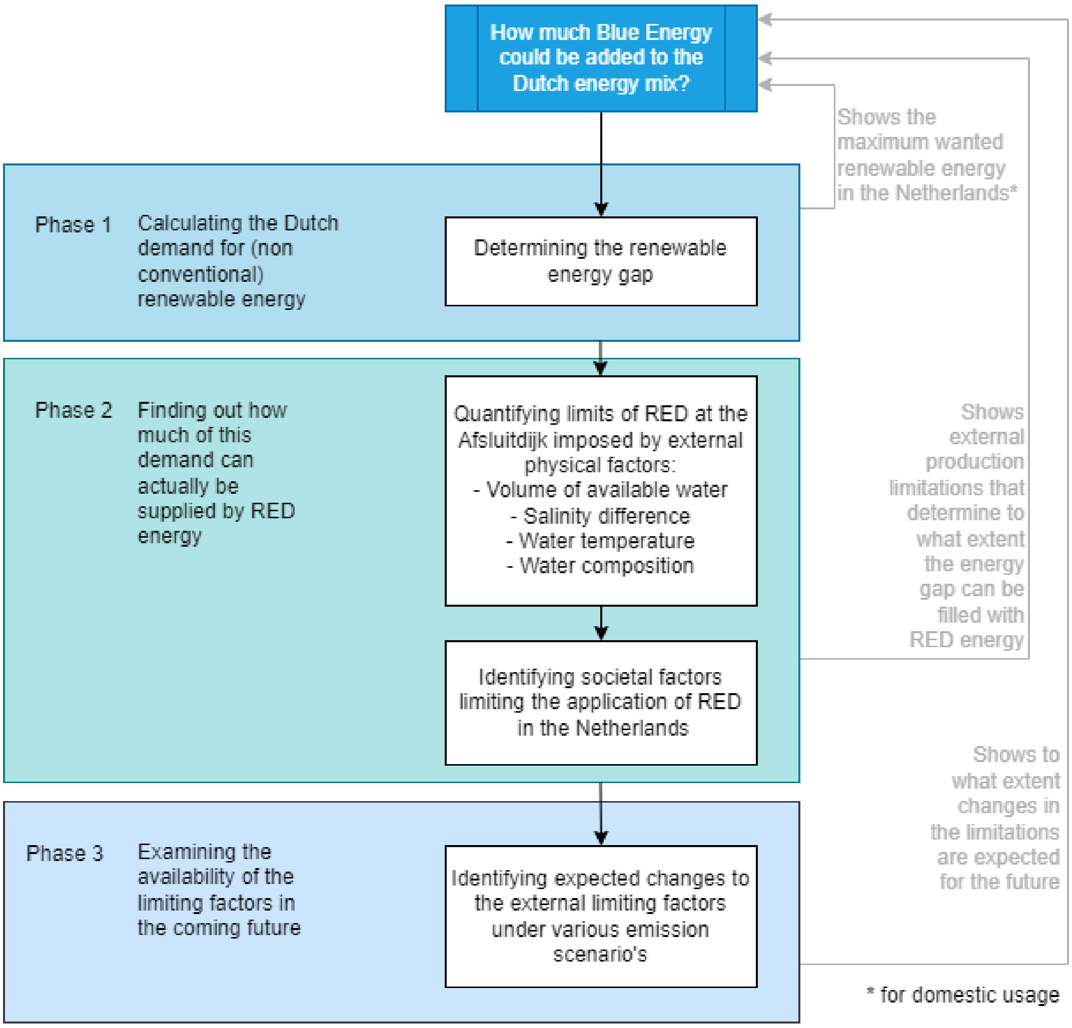


Fig. 3: Methodology flowchart.

2.1. Data

To execute this research, data from multiple sources were retrieved, which are described below.

2.1.1. Energy gap

The demand for renewable energy is quantified by calculating the difference between the actual usage of non-renewable energy and renewable energy, which indicates the energy required to replace all currently used non-renewable energy by renewable energy. This analysis does not take energy prices into account but simply looks at the difference between the actual energy use and consumption.. For the term ‘renewable energy’, the definition used by the Central Bureau of Statistics (CBS, 2023) is used, stating that it consists of energy produced from wind, water, sun, ground and biomass sources that are replenished. It is calculates as the sum of gross electricity production from renewable energy sources; the gross production of sold heat from renewable sources; end use of energy retrieved from the ground, air, sun and biomass. Non-renewable energy sources consist of energy retrieved from non-replenishable sources, such as fossil fuels and nuclear power. Since energy can be transported internationally, data on Dutch energy generation might not necessarily show the domestic demand for energy. Therefore, data on Dutch energy usage will be used to determine the energy gap. Given the losses of energy when transported over a large distance, it is assumed that domestic production of renewable energy is preferred over importing it –

meaning there is a direct link between the energy gap and the demand for locally produced renewable energy.

Electrical energy cannot substitute all energy demands, and RED provides renewable electrical energy. Therefore both the total energy gap (including electrical energy) and the electrical energy gaps are analysed, to show a holistic picture of the demand for renewable electrical energy. The formerly (chapter 3.1) discussed planned electrification of the entire Dutch energy system, should be kept in mind when looking at the total energy usage for future reference, as a lot of the now non-electrical energy demands are expected to transform into electrical energy demands in the near future.

Using the most recent 10 years of available data (ranging from 2010 to 2020), the gap between energy demand and renewable energy supply was visualised using CBS based Klimaatmonitor (Klimaatmonitor, n.d.) and EUROSTAT data (EUROSTAT, 2022). Klimaatmonitor provided open source yearly data on energy usage, split into total energy usage and electrical energy usage, per province. After investigating the demand and supply per province in the Netherlands, it seemed a more logical choice to look at the country as a whole. As it is quite a small country, energy can fairly quickly be (re)distributed from its production source to its usage location. EUROSTAT provided open source monthly data on energy usage in the Netherlands per category. Using the data from January 2016 to September 2022, the data was transformed to the unit TJ.

2.1.2. Physical limitations

Data used for the physical limitations has been derived from Rijkswaterstaat (waterinfo.rws.nl) (Rijkswaterstaat, 2021) and the Royal Dutch Meteorological Institute (KNMI), as well as research papers that were conducted in the name of the Dutch government. Data on the discharged water from the Afsluitdijk, the salinity levels of the Wadden Sea and the IJsselmeer and the water temperatures of both waterbodies were downloaded from Rijkswaterstaat (Rijkswaterstaat, n.d.). The datasets range from 1-1-1990 until 31-12-2019. The choice to work with 30 years of data was based on the Guide to Climatological Practices (WMO, 2018), which recommends using a 30-year reference period to determine climatological trends.

The physical limitations analysis uses a monthly timestep. Mean monthly data was deemed the right temporal option for the following calculations, to remove errors from the datasets, ignore daily variability and to incorporate the delay time of the discharged water from the river to the Afsluitdijk,. The choice to work with the mean of multiple measurement points, to make an estimation of the status around the location of REDstack, was based on several factors: there were almost no measurements (for all physical factors) taken at the Breezanddijk, where REDstack is located, so taking the mean of multiple closely located measurement points is assumed to give the closest result. Secondly, by taking the mean of multiple sources, potential errors and faults of measurement points are smoothened out, making the values more reliable.

2.1.2.1. Water volume

The Rijkswaterstaat data was retrieved from above stated timeseries for the measurement points Den Oever and Kornwerderzand. The daily data was recalculated to mean monthly discharge in m^3/s.

2.1.2.2. Correlations water balance

Fig. 4: Map of lake IJsselmeer, showing the measurement points used to calculate the correlations in the water balance. Map is retrieved from Bing satellite images in QGis.

The correlations discussed in the Background Literature Studies (chapter 3.2.1) were calculated using the following methodology. The 30 years of daily discharge data was taken from measurement points Kornwerderzand and Den Oever - which are the two discharge points on the Afsluitdijk - and on measurement point Olst, which has data on the discharge of the river IJssel. The unit was in m^3s^{-1}. Similarly, the same 30 years of precipitation and evaporation data were downloaded from KNMI (KNMI, 2016) Since there were no measurement points in the lake itself, all the measurement points surrounding the lake were selected. That meant for precipitation Swifterbant, Tollebeek, Lemmer (Gemaal Buma), Oudemirdum, Makkum, Kornwerderzand, Den Oever, Krileroord, Medemblik, Hoogkarspel and Enkhuizen were selected, and for evaporation Stavoren, Marknesse, Lelystad, Berkhout. The data on precipitation was measured daily at 08:00 and the evaporation was measured daily at 00:00, both in millimetres. Using Python, the mean daily millimetres of precipitation and evaporation could be calculated and converted to m^3/s, using the following formula:

$$P_{\text{Ijsselmeer}} = P * A_{\text{Ijsselmeer}}$$

Equation 1: used to calculate the precipitation over lake Ijsselmeer.

$$E_{\text{Ijsselmeer}} = E * A_{Ijsselmeer}$$

Equation 2: used to calculate the evaporation over lake Ijsselmeer.

Where $P_{\mathrm{Ijsselmeer}}$ stands for the total precipitation on lake Ijsselmeer [m^3/s], P stands for average precipitation rate per m^2 in [m^3/s] and A stands for the area [m^2]. $E_{\mathrm{Ijsselmeer}}$ stands for the total evaporation on lake Ijsselmeer [m^3/s], E stands for average evaporation rate per m^2 in [m^3/s] and A stands for the area [m^2]. Since precipitation *(P)* and evaporation *(E)* are usually expressed in mm/day, they were transformed from mm/day to $m^3/m^2/s$ by multiplying it by (1000 divided by 86400 seconds/day). With all variables set at the same unit scales, the correlations between the variables could be investigated. Again, the temporal resolution was set at monthly timestep to ignore the delay time of the water, smooth out daily variability and to average random errors in the data sets.

2.1.2.3. Water salinity

Using Rijkswaterstaat data, the same source as was used for the volume of water, the same 30 years of data on 'Salinity surface water' were downloaded for the closest measurement point to the Afsluitdijk. As water salinity data was not consistently provided for many measurement points and included many errors, especially in the IJsselmeer, only few measurement points were used that provided the most consistent data in the variable 'Salinity Surface Water'. Given the spatial and temporal variability of salinity in the Wadden Sea, taking the monthly mean from various measurement points was decided to give the most adequate results to be appointed to the Breezanddijk – the location of REDstack.

Fig. 5: Map of lake IJsselmeer, showing the location of the measurement points used to calculate the salinity levels.

The measurement points in the Wadden Sea that were used are Doove Balg West, Marsdiep Noord and Vliestroom providing 30 years of surface water salinity, and the ones in the IJsselmeer were measurement at points Andijk, Houtribhoek, Ketelmeer West, Steile Bank and Vrouwezand, which provided the most reliable data available in the IJsselmeer. The measurements for the IJsselmeer only started in 2006, therefore the climatic dataset was insufficient as climate data record (at least 30 years of data). The unit used is Practical Salinity Unit or PSU, which is used to define salt concentrations in water, which is indicative to salt in gram/kg (or liter) water.

2.1.2.4. Water temperature

To determine the seasonal variability of the feedwaters temperature, data was again downloaded from Rijkswaterstaat and measurement points were chosen that have a coverage of most of the 30 years and are located closest to the REDstack powerplant.

Fig. 6: Map of lake IJsselmeer, showing the location of the measurement points used to calculate the temperature levels.

For the Wadden Sea, the measurement points Breesem boei 1, Doove Balg Oost, Doove Balg west, Doovebalg midden, Harlingen, Harlingen havenmond west, Harlingen voorhaven, Kornwerderzand buiten, Westkom / Scheurrak were chosen.

For the IJsselmeer the points Andijk, Breezanddijk binnen, Den Oever, Kornwerd and Kornwerderzand were chosen. Data between the years 2000 and 2002 and the year 2003 were missing. Some of the measurement points provided data for every ten minutes, giving an overload of information. In addition to comparison objectives, that is why the monthly mean measurements were again calculated.

2.1.3. Societal limitations

The data that is needed for the social limitations was derived from literature, based on (strategic) documents on the water management of the IJsselmeer, to find the societal demand on the water in the lake. Academic literature was used to perform a stakeholder analysis, an energy landscape analysis and to discuss water- and non-water related societal limitations.

2.1.4. Forecasts

The datasets used to create the forecasts are based Rijkswaterstaat data and on KNMI and Delta scenarios. KNMI used the fifth climate assessment of IPCC, the global model projections of CMIP5 and observed Dutch climate features and trends to construct the meteorological climate scenarios with the in-house models EC-Earth and RACMO2 (Van den Hurk et al., 2014). The normal climate was calculated from two 30-year observations, ranging from 1951-1980 and from 1981-2010. Using IPCC emission scenarios RCP 4.5, 6 and 8.5, they created two main scenarios G (moderate) and W (warm). Within the main scenarios KNMI presented L (low), H (high) and WHdry, based on the changes in airflow throughout the seasons. 'High' changes lead to high air pressure during the summer months over Western Europe and more frequent low-pressure systems with more west wind during the winter months.

The KNMI scenarios were combined with socio-economic scenario studies of the national institutions for planning, *Plan Bureau Nederland* and *Centraal Planbureau.* Their scenarios were called the WLO'15 socio economic development scenarios.These datasets were then used to analyse the expected changes in the national water systems, using the National Water Model (NWM). The NWM covers a country wide surface- and sub-surface water system, integrates societal users and water demanders, and can be used for scenarios and adaptation options. Important to mention is that it is commonly accepted by policy makers, water managers and modellers – giving it legitimacy (Prinsen et al., 2015; Hunink et al., 2018). The so-called model train that was used consists of several individual but connected models, called *Landelijk Hydrologisch Model* or LHM (the national hydrological model consisting of meteorological and hydrological models), LSM (using SOBEK), LSM-LT (LSM light) and LTM (based on LSM-LT). The input data consisted of meteorological data (based on the KNMI scenarios). Input data for the National Water Model consisted of river discharges under different KNMI scenarios. KNMI and Deltares used various hydrological models (GRADEinstrumentarium 2, HBV, SOBEK and Precipitation-Runoff model) to simulate the effects of the KNMI climate scenarios on the river Rhine and the river Meuse. The resulting data consists of a 100-year datasets (ranging from 1911 to 2010) for each scenario on weather (precipitation, evaporation and temperatures) and river discharges (discharge, water levels, salinization), based on the formerly mentioned river discharge models. The scenario 100 year datasets do not represent the historic observations but is tweaked to be able to show the prognoses (Hunink et al, 2018).

The results from the Delta scenarios could be retrieved from Informatiepunt Leefomgeving (2018), where the datasets "LSM-LT" were downloaded for the REF2017 and all scenarios (S2050, D2050, R2050 and W2050). With these datasets, the discharge from the Afsluitdijk could be derived, showing the reference data used for the model train, as well as the resulting scenarios for the time period between 1912 - 2012. The downloaded data consisted of various different files with daily data, divided into maps per year. Therefore, for each individual scenario including REF2017, the "WABES" datasets (showing discharge results) were extracted and then combined to show daily data of each scenario over the whole 100 year period. Afterwards, the measurement points Lorentzsluizen (Kornwerderzand) and Stevinsluizen (Den Oever) were filtered out, and afterwards the daily values were summed to show the daily Afsluitdijk discharge over the whole time period, per scenario. Then, the monthly mean was calculated for comparison purposes.

Table 1: Data summary.

Variable	**Source**	**Unit**	**Temporal resolution**	**Alteration**	**Time span**
(Renewable) energy	Klimaatmonitor Rijksoverheid (n.d.)	TJ	Year		2010 – 2020
(Renewable) energy	EUROSTAT	TJ	Year		2016 - 2022
Discharge Afsluitdijk	Rijkswaterstaat (2021)	m^3/s	Monthly mean	Discharge Den Oever + Discharge Kornwerderzand	1990 – 2019
Discharge Olst	Rijkswaterstaat (2021)	m^3/s	Monthly mean	Calculated from daily data	1990 – 2019
Precipitation	KNMI (2016)	m^3/s	Monthly mean	Mean taken from multiple measurement points. Transformed daily data into monthly mean and recalculated to m^3/s.	1990 – 2019
Evaporation	KNMI (2016)	m^3/s	Monthly mean	Mean taken from multiple measurement points. Transformed daily data into monthly mean and recalculated to m^3/s.	1990 – 2019
Water temperature	Rijkswaterstaat (2021)	^oC	Monthly mean	Mean taken from multiple measurement points. Transformed daily or 10 minute data into monthly mean.	1990 – 2019
Surface water salinity	Rijkswaterstaat (2021)	PSU	Monthly mean	Mean taken from multiple measurement points. Transformed daily data into monthly mean.	1990 – 2019 for Wadden Sea, 2006 – 2019 for IJsselmeer

Discharge Afsluitdijk Scenarios	Informatiepunt Leefomgeving (2018)	m^3/s	Monthly mean	Transformed daily data into monthly mean.	1912 – 2012

2.2. Ethical risks and considerations

An ethical concern to keep in mind is that not all demands on fresh water are equally well represented and heard in policy making processes. Those who might need it most might not have the means to make their demands heard. Similarly, ecosystem and species demands might not be fully represented either. Prioritizing the different freshwater demands is an ethical process in itself: The methodology to decide who has the most just claim on the limited resource, is a specific area of research that goes beyond the scope of this thesis.

The biggest risk of this research appears to be the time and resources spent on doing research on the external limitations, while the internal technical challenges might hamper the technology from becoming commercially viable at all. However, it is still important to do this research now to see if it is at all interesting to upscale the powerplant, for many hours and research might be spared if the answer is ‘no’. Risks in performing the research lie in the availability of the data. Since no interviews and or personal data will be obtained, there are no ethical risks there. The data that will be used is freely accessible Dutch governmental and European commission data.

Lastly, climate projection prognoses always come with many uncertainties. There is uncertainty about the future levels of anthropogenic emissions and natural events, uncertainty linked to model imperfectness of climate process representations, uncertainty involved in the knowledge about climatic conditions and accuracy about calibration and validation data, and lastly, difficulty in representing variability in long-term projections (USAID, 2014). The process of getting the prognoses for the IJsselmeer area includes several steps, which all come with approximations, assumptions and uncertainties. Albeit being created by trustworthy institutes with plenty of good resources, it should not be forgotten that uncertainty could have crept into models, for example by incomplete physics depictions, inaccuracies, shortcomings etcetera (van den Hurk et al., 2014). The last and perhaps biggest risk with forecasting is the assumption that historically observed climate relationships will carry into the future. The outcomes should therefore not be interpreted at face value, but together with the technical documentation of all included assumptions and limitations.

3. BACKGROUND LITERATURE STUDIES

Before diving into the quantification of the physical limitations and the analysis of the energy demand and societal limitations, the context of these factors is discussed. Using academic literature, the background information on the current context is illustrated, as well as the relationship of the physical limitations to the power output of the plant.

3.1. Energy Gap

The first external limitation to the production capacity of Reverse Electrodialysis that is discussed in this thesis is the renewable energy demand. After all, there is little need to invest time, energy and money in an intervention if nobody is interested in its output. In this research, the demand for renewable energy is estimated by the gap between renewable energy usage and the total energy usage in the Netherlands.

To do so, data on Dutch energy usage from the Dutch Central Bureau of Statistics (CBS, 2023) and the EUROSTAT (2022), the European commission's bureau of statistics, were gathered for the ten most recent available years, from 2010 – 2020. It should be noted that the war in Ukraine, which had a big impact on the Dutch energy system, started after the timeseries ended. As stated before, this was the most recent available data, so those recent changes fall outside the scope of this research.

The primary contributor to climate change continues to be the rising CO_2 emissions, of which 70% of these emissions are linked to energy consumption (Sun et al., 2021). Therefore, the energy sector plays a key role in addressing climate change and the sustainable development goals. Kadoshin et al (2000) stated that the energy consumption can be divided into four main complex and interrelated factors: population growth, living standards improvement, scientific technologies development and the individual country's unique conditions. Acheampong (2018) showed the one-directional causal relation between energy consumption and economic growth, as well as the causal relation between energy consumption and carbon emissions.

Over the last decade, globally, there has been an astounding evolution of renewable energy, growing the installed renewable capacity and significantly increasing the number of renewable energy sources (Ahmad & Zhang, 2020). Simultaneously, energy demand increases rapidly too. Between 2012 and 2040, the global primary energy requirements will increase by 37%, according to Ahmad et Zhang's forecasts (2020). The growth in energy requirements will mostly come from non-OECD nations, meaning countries which are not part of the Organisation for Economic Co-operation and Development (OECD). According to their global forecasts for 2040, about two-thirds of these requirements will be accounted for by renewable sources and nuclear energy sources, while one third will be accounted for by oil, coal, and natural gas (Ahmad et Zhang, 2020). Yao et al (2019) found in their research that for worldwide OECD economies, an increase in human capital is correlated with a significant decrease in non-renewable fossil fuels consumption and an increase in renewable energy consumption. However, the Netherlands and Australia are outliers in this finding, as human capital seems to reduce renewable energy consumption in our cases.

On a national scale, the current Dutch Government agreed upon the following emission reduction targets, which are in line with the European climate goals: a greenhouse gas reduction target of at least 55% for 2030 (compared to 1990), 80% for 2040 and greenhouse gas neutral by 2050 (Scheepers et al., 2022). This means a drastic and lengthy process of changing the energy system, which must include a reduced energy demand, energy production using biomass and renewable energy and an increased electrification of the system (Ros et al., 2011). In order to analyse current energy usage and predict future energy demand, energy models are often used. Besides that, they can be used to identify future energy saving measures and help assess the factors that influence the final energy consumption the most (Martinez-Soto & Jentsch, 2019). Similarly, scenario studies can help us get an idea of how the future may look like. For the energy transition, these scenarios can be quantified by modelling the integrated energy system.

The Dutch Ministry of Economic Affairs and Climate Policy invested in such research, which was conducted by TNO. This scenario study of the integrated Dutch energy system, modelled by TNO's OPERA model, examines two scenarios in which the Dutch can achieve the EU climate goals: called 'Adapt' and 'Transform'. The set targets are only achievable if, amongst others, electricity acquires a bigger share in the energy mix (Scheepers et al., 2022). In their scenarios, the electricity demand grows significantly, from 110 TWh in 2022 to 300 – 500 TWh in 2050. This growth is not only due to electrification of the energy functions in end user sectors, such as electrified production processes in the industry, usage of electrical transportation and usage of electrical applications such as electrical heat pumps. This growth also depends on the growth of industrial hydrogen demand and domestic sustainable hydrogen production (Scheepers, 2022). The mentioned growth in electricity production capacity is modelled to come from maximizing the potential production capacity of wind- and solar energy, as well as the development of an international electricity trade system with Germany, Belgium, the United Kingdom, Norway and Denmark (Scheepers, 2022). In TNO's 'Transform' scenario, the final energy consumption declines between the years 2030 – 2050, due to the assumption that behavioural changes will lead to lower energy demands.

Similar to climate prognoses, energy scenario studies are associated with large amounts of uncertainty and therefore the chances are high that society and technologies will develop differently than described. On the other side, the insights of the scenario studies can help policy makers, developers and other interested parties get a better understanding of roles certain technologies may play in future energy systems and show how current energy transition decisions may develop over time. The TNO scenarios are created to be plausible within the current Dutch system, but system shaking developments are also worth researching. For example, the energy demand pattern of the Netherlands is expected to reverse in seasons. For example, according to Hekkenberg et al (2009), the electricity demand pattern in the Netherlands is expected to resemble the patterns in South European countries, where there is a electricity demand peak in the summer rather than the winter. Due to global warming, the demand for cooling applications during the summer months increases, which might lead to a shifting balance between the currently high electricity demand for heating and low electricity demand for cooling. If so, that shift will impact the electricity generation capacity, maintenance and electricity prices.

In summary, we do not know what the future will hold, but we do know that the energy transition has started in the Netherlands and will likely change the way the energy system currently works. To determine the demand for renewable energy, specifically for RED energy, we should therefore look at the current energy characteristics and at expected future energy developments. It can be concluded that there is a growing demand for more renewable energy, endorsed by national and international agreements.

3.2. Physical limitations

The biggest hurdles for RED consist of membrane fouling, the cleaning process of the feedwaters and membranes and lowering the production costs for the membranes (Sharma et al., 2022), but these challenges are outside the scope of this research. Instead, this research focuses on the factors determining RED performance.

The available feedwater streams and internal efficiency of the process are major factors in determining the technical limitations of the RED process (Daniilidis et al., 2014; Nazif et al., 2022). This means the external limitations directly linked to the performance of the RED powerplant are the availability of the feed stream in volume, the properties of the water – the temperature, ionic composition and concentration- and the availability of energy that is needed to power the powerplant (Tristán et al., 2020). The same list was described by Roldan-Carvajal et al. (2021), who used the water volume, salinity, composition and temperature to calculate the theoretical salinity gradient potential. Placed within a larger social and ecological context, other stakeholder claims on the resources compete with the needs of the RED powerplant and can therefore also be considered limiting factors.

3.2.1. Volume

Reverse electrodialysis power capacity is technically limited by the available amount of water for the energy production (Daniilidis et al., 2014). In the case of REDstack, the available water comes down to the fresh water from lake IJsselmeer and the more saline water from the Wadden Sea. At this moment, seawater is not considered to be a limiting factor, given the vast amounts available. So, the RED plant at the Afsluitdijk production capacity therefore mainly depends on the average flow rate of the IJsselmeer water into the Wadden sea (Daniilidis et al., 2014). This dependence on the lake demands a description of its socio-technical context.

Lake IJsselmeer is the most significant freshwater buffer of the Netherlands. The main functions of the IJsselmeer area can be summarized as 1) flood defence, 2) fresh-water buffer and distribution and 3) a robust ecological network (Van Ginkel et al., 2022). The national government is the responsible party to ensure these functionalities. These tasks include the maintenance of the basin storage (In Dutch '*Komberging*') as a flood defence mechanism, maintaining the freshwater buffer if a meteorological drought or insufficient water influx takes place, and ensuring the ecological functions of the area as part of the European Natura2000 and Dutch nature and ecological networks (*Natuurnetwerk Nederland, Kaderrichtlijn Water, habitatfunctioning for flora and fauna*) (Van Ginkel et al., 2022). By managing the water level of the lake, the lake provides a structural availability of 400 million cubic meters of buffered freshwater (Nationaal Deltaprogramma, 2020b). This water is used for drinking water purposes, agriculture, industry and nature conservation. Besides water buffering, the lake is used for recreational purposes, shipping, fishery, transport, sand extraction and has historic- and nature values (Nationaal Deltaprogramma, 2020b; Van Ginkel et al., 2022). All of which will be discussed more thoroughly in chapter Societal Limitations (4.3).

The water level of the IJsselmeer lake has been managed since its creation, currently manageable up until an exactness of 1 centimetre (Van der Ham, 2007). This precision water management is possible as the largest source of inflow is manageable at the weir at the Rhine, as well as the outflow at the discharge points at the Afsluitdijk (Buitelaar et al., 2015.). Discharge of this fresh water takes place at two locations at the Afsluitdijk, at Kornwerderzand and at Den Oever, under free gravitational fall (Arcadis, 2022). That means discharge is only possible if the water level of the IJsselmeer is higher than that of the Wadden Sea, which usually takes place during low tide in a time period called the 'discharge window'. This discharge window is expected to get smaller with sea level rise, which is why pump installations are soon to be installed at the Afsluitdijk (Arcadis, 2022).

During the winter period, the flood defence function of the IJsselmeer area is most important, and during the summer months the buffer function (Van Ginkel et al., 2022). The most recent determination of the seasonal water levels was in 2018, where the Administrative Board IJsselmeer area, consisting of the central government, the provincial government, the regional water authorities, municipalities and PWN3 (Rijkswaterstaat, 2018) set the ranges for November to February at -0.4 to -0.05 meter NAP (the Dutch water level measurement unit, which comes down to the average water level of the North Sea), at -0.4 to -0.1 meter NAP for the months October and March and at 0.3 to -0.1 meter NAP during the rest of the year (Arcadis, 2022). There is a window for variability, for example during dry or wet periods. By making use of discharging under free fall and the new pump capacity, the lake water level ranges are set to last up until the year 2050 (Nationaal Deltaprogramma, 2020b). After 2050, the average winter water level is allowed to rise 10 to 30 centimetres with the seawater level. This flexible water level management results in a structural availability of 400 million cubic meter freshwater buffer (Nationaal Deltaprogramma, 2020a). While this water level variation is needed to ensure the flood safety -including the maintenance of the surrounding dykes - and freshwater buffer functions, the yearly water level trend that is created is the antipode of natural seasonal water level variation, leading to conflicting ecological requirements (Van Ginkel et al., 2022).

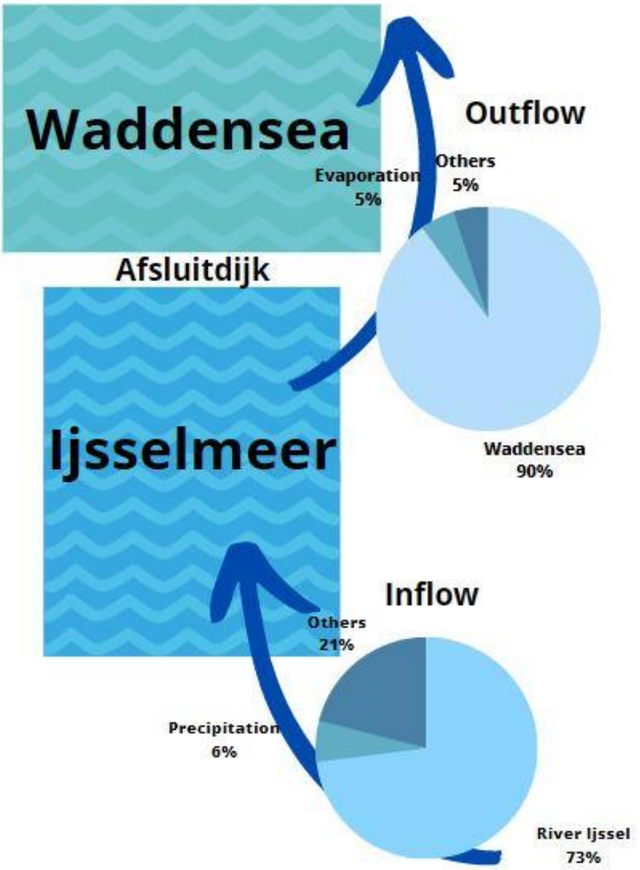


Fig. 7: A simplified water balance of lake IJsselmeer, showing the influxes and outfluxes in percentages.

A quick overview of the water balance of the IJsselmeer is as follows. On average, 16 billion cubic meters of water flow into the IJsselmeer yearly (Nationaal Deltaprogramma, 2020b), of which 73% flows in from the river IJssel, 6% comes from precipitation and the remaining water comes from different sources, such as the Markermeer (4%) and Zwarte Water (9%) (Buitelaar et al., 2015). About 90% of the outflowing water is being discharged at the Afsluitdijk into the Wadden Sea, 5% of the outflow consists of evaporation and the remaining 5% is discharged into the Markermeer (3%) or discharged into the surrounding region and/or used for drinking water. Currently, if weather conditions do not allow for free fall discharge from the Afsluitdijk for a long period, multi peak levels (in Dutch *meerpeilpieken*) of water can accumulate and lead to a higher water level than preferred, up to 25 centimetres over the whole lake (Buitelaar et al., 2015). Pumping capacity, like the REDstack powerplant, could help mitigate these multipeak levels, as they do not depend on the discharge window. During extremely wet periods, the surplus water that needs to be discharged at the Afsluitdijk can accumulate to 3200 m^3/s (Buitelaar et al., 2015) – creating an extra societal demand for REDstack to increase their production capacity.

As the water that leaves the Afsluitdijk will become brackish, and can therefore no longer be used for fresh water purposes, it is assumed that the water has served all fresh water demands during its retention time in the lake. The disposal of the fresh water into the sea could therefore mean that it can be considered fresh ‘rest water’, without other conflicting demanders. This argument will be elaborated on in chapter Societal Limitations (4.3). For this study, this fresh discharge water from the Afsluitdijk into the Wadden Sea is considered usable for RED purposes. The total volumetric availability of this discharge water will be treated as the limiting factor of fresh water availability.

In order to show how the variables in Fig. 7 relate to the discharge from the Afsluitdijk, the correlations between the variables were calculated. The purpose of this calculation was to give a more in-depth picture of the water system of the IJsselmeer. The lake was simplified to the following model (Fig. 8) for these calculations:

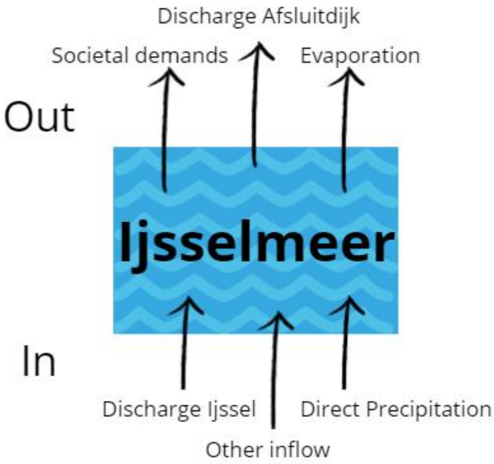


Fig. 8: Simplified water balance of lake IJsselmeer, on which the correlations were calculated.

Using Pearson’s R, the correlations between the discharge of the Afsluitdijk and the inflow variables are as follows. The highest correlation could be found in the relationship between Discharge Olst + Rainfall (calculated to 100 percent according to their contributions from literature) ~ discharge Afsluitdijk + evaporation (calculated to 100% according to their contribution found in literature). However, the correlation between the discharge from the river IJssel (Discharge Olst) and the discharge from the Afsluitdijk also had a significant Pearson’s R of 0.83. A visualization of the correlations can be seen in Fig. 9. A heatmap of the correlations of all variables can be found in Appendix 1, as well as a scatterplot showing the values of Discharge Afsluitdijk and Discharge Olst.

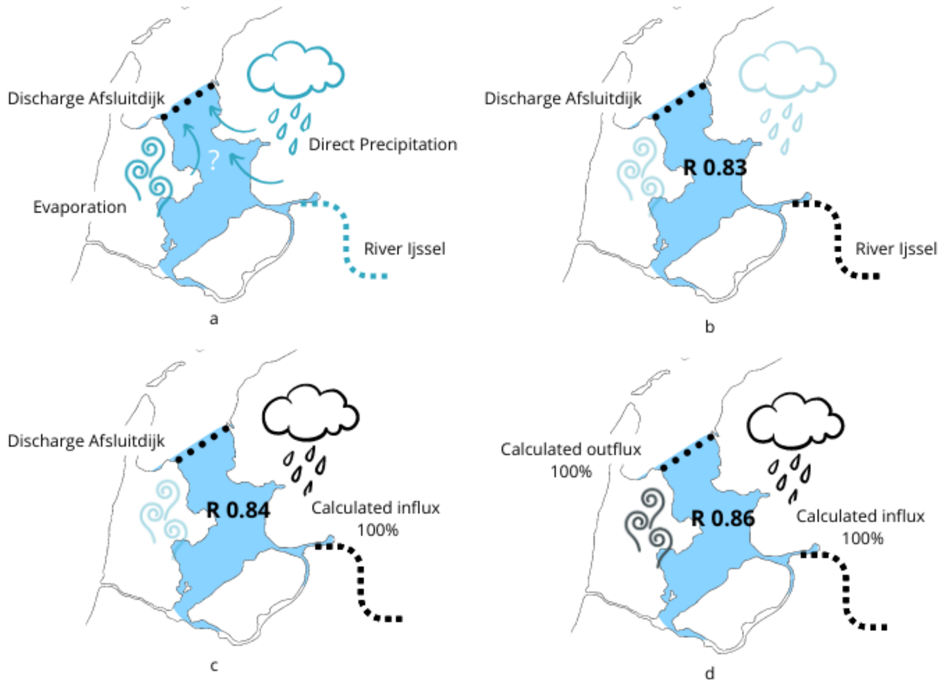


Fig. 9: Visualization of the discussed correlations. Figure a) showing the investigated variables. b) Showing the Pearson coefficients of the discharge of the river IJssel and the discharge of the Afsluitdijk. c) Showing Pearson coefficients of the calculated 100% influxes of the system and the discharge of the Afsluitdijk. The 100% influx was calculated from the discharge of the river IJssel and the influx of direct precipitation over the lake, divided by their proportional contribution to the total influxes (which is 79%, see Fig. 4) and then times 100%. d) Shows the Pearson coefficients of the calculated 100% influx ((Discharge IJssel + direct precipitation)/79*100%) and the calculated 100% outflux ((Discharge Afsluitdijk + evaporation)/95*100%). The proportional contributions used are shown in Fig. 4.

3.2.1.1. Relationship to power output

The quantified relationship between volume of water and power output of a RED powerplant depends heavily on the internal set up of the powerplant, as will be the same with the salinity and temperature. However, the relationship between the volumetric water availability and the power output is discussed and tested in academic literature, as well as described by REDstack. As mentioned before, REDstack uses the rule of thumb of 1 m^3/s of fresh water mixed with 1 m^3/s of salt water generates 1 MW under real life conditions. In theory, it could even generate up to 1.8 MW (Kleiterp, 2012). Research by Roldan-Carvajal et al. (2021) showed that the theoretical salinity gradient potential depends on various local factors: the salinity, temperature, flow rate of both input waters and the composition. They found that the potential for the Magdalena River mouth in Colombia is between 1.3 MJ/m^3 and 1.6 MJ/m^3. With a discharge of 5000 m^3/s in high discharge season (with 1.6 MJ/m^3), that translates into 5000 m^3/s = (5000 · 1.6 MW=) 8000 MW. So, 1 m^3/s of water can generate 1.6 MW, which is quite a bit more than at the Afsluitdijk. In Mei & Tang (2018), the research showed that in theory, approximately 0.8 kWh can be generated with 1 m^3 of fresh water, which translates to 0.8 · 1000 W · 3600 seconds = 2.88 MW. According to Veerman (2009), 1.76 MJ can theoretically be generated by 1 m^3 of sea water and 1 m^3 of river water. Pintossi et al (2021) made the bit more conservative statement that these units of water could generate 1.7 MJ. Using these references, the conservative estimation by REDstack seems like lower-boundary estimate for this research.

To quantify the available volume of fresh water, this research will focus on the discharged water from the Afsluitdijk, based on historic, current and predicted data. These calculations are based on the assumption that REDstack could use all the discharged water to generate energy.

3.2.2. Salinity

Contrary to the volumetric relationship to REDstack's power output, the relationship between the salinity levels of the feedwaters and the power output is not straight forwardly quantifiable. In academic literature, where the vast majority of studies has been at laboratory scale using synthetic saline feedwaters (Pawlowski et al., 2020), multiple theories exist that describe the optimal salinity gradients. In practice, it appears that the optimum salinity gradient for maximum power output is inherently determined by the powerplants internal set up. Since REDstack was not able to share their salinity – power output relationship nor the temperature – power output relationship, these relationships will be estimated using academic literature. This research will work with these academic descriptions, knowing that it can only estimate the power output of the REDstack powerplant and not quantify the relationship, which is what would have been preferable.

Rijkswaterstaat stated that the yearly mean maximum salinity level is 150 mg/l in the IJsselmeer (Rijkswaterstaat, 2021). Usually, half of the total salt influx in the IJsselmeer flows from the IJssel into the lake (Van Ginkel et al., 2022). About 23% gets into the lake via the sluices in the Afsluitdijk, the rest mostly seeps in from regional water systems. During dry periods, the amount of salt influx through the Afsluitdijk - either through the sluices or through leakage - increases severely. Together with an increase in evaporation of the lake, this may lead to lake salinity levels exceeding the set maximum levels. The current way to counteract high salinity levels is fresh water dischargement. Van Ginkel et al. (2022) calculated that once every 2 to 3 days, 70 – 90 m^3/s should be discharged from the Afsluitdijk to counteract the salinity increase. That makes the Afsluitdijk's discharge a water demander as well. Although the more saline water is not optimal for RED fresh feedwater purposes, there is no reason to assume that this water cannot be discharged through REDstack as well as through the currently used sluices. As long as dischargement is possible, the salinization of the lake is limited to low lying erosion pits and the transport channels near the Afsluitdijk (Nationaal Deltaprogramma, 2020b). However, if dischargement is no longer possible, the low lying high salinity water will slowly mix with the rest of the lake's waters. Due to the large volume of water in the lake, the mixing process is slow, as is the process of desalinizing the water after the chloride concentrations limits have been exceeded – which took up to six months after the dry summer in 2018 (Nationaal Deltaprogramma, 2020b). Salinity levels even remained high until spring 2019 (Bestuurlijk Platform IJsselmeergebied, 2020). Therefore, the main strategy is to prevent salinization rather than to salvage it.

The Wadden Sea can be described as a low-lying tidal coastal region, with a shallow body of water, tidal flats, wetlands and an intertidal ecosystem (Gerkensmeier & Ratter, 2018). The Dutch Wadden Sea's salinity levels are influenced by both anthropogenic and natural drivers, creating a spatial-temporal dynamical play of salt fluxes. On the one side, saline North Sea water enters the Wadden Sea, on the other side, fresh IJsselmeer water is discharged into the Wadden Sea. The water is moved primarily by predictable tides and less predictable wind, pushing the salinity and fresh water clusters into different directions, depending on the time, speed, direction and duration of the events (Donatelli et al., 2022). Combined with the seasonal variability of the fresh water dischargement, all these influences lead to a sea with a highly spatial and temporal variance in salinity levels, even showing high-salinity and low-salinity clusters that relate to sporadic events, such as an abnormal amount of water being discharged from the Afsluitdijk or extreme winds (Donatelli et al., 2022). Anthropogenic influences had an direct effect on the salinity levels of the sea, as was demonstrated in Van Aken (2008). Based on historic events when large hydraulic works were implemented, the salinity levels at Marsdiep over a time period between 1861- 2003 could be divided into subperiods. First, the period before the Afsluitdijk was developed and lake IJsselmeer still belonged to the Zuiderzee, started with a salinity level of 31.5 PSU in 1861 but decreased with about 0.25 per 10 years. The second one, after the implementation of the Afsluitdijk starting in 1933, but before a weir was installed in the river Rhine, letting the river IJssel discharge naturally, with a mean salinity level of 29.6 PSU. The third period was after said weir was installed in 1972, making the discharge of the river IJssel manageable and increasing the discharge by 40%. That period showed a mean salinity level of 28.7 PSU (Van Aken, 2008). All in all, the salinity level in the Wadden Sea depends heavily on the amount of water being discharged from the Afsluitdijk, which in turn depends on the societal demands – which will further be discussed in chapter Societal Limitations (4.3).

3.2.2.1. Relationship to power output

The salinity gradient plays a Janus-esque role, on the one hand it is the electromotive driving force for Reverse Electrodialysis, on the other hand also contributes the overall internal resistance (Mei & Tang, 2018). According to Vermaas et al. (2012), the net power density, which is the power per membrane area, depends on the membrane potential, the resistances and the power needed to pump the feedwater through the system. The resistances are the ohmic resistance, the boundary layer resistance and the resistance created by changing concentrations. RED membranes work best with lower salinity gradients, that appear in nature, rather than higher gradients, such as the combination of brine water with freshwater, due to the permselectivity (Daniilidis et al., 2014). The permselectivity is the ability of the membranes to filter the ions. With high salinity gradients, the flux of salt has a bigger impact on the permselectivity than the water flux, while at a lower salinity level, the water and the salt flux form a similar effect on the permselectivity.

The equations that form the base for RED power generation can be found in the literature, amongst others in Ortiz-Imedio et al. (2019) and Tufa et al. (2018). The Gibbs energy of mixing equation can be used to calculate the amount of energy that is released after a process where two streams of water with a salinity difference are mixed (Dandiilidis et al., 2014). The actual energy efficiency is however limited by internal factors, such as the ohmic losses in the stacks and the transport of co-ions and water through the membranes (Dandiilidis et al., 2014). As the salinity gradient varies spatially through the stacks, the electromotive force over the membranes varies too (Tufa et al, 2018). As a lot of knowledge on internal settings and properties, such as the stack geometry, flow velocity, membrane properties, temperature, and channel thickness and length (Tedesco et al., 2015, Tufa et al., 2018) is needed to work with these formulas - which was not shared -, this paper can only base the relationship between salinity and power output on rough estimates and assumptions. In case the needed information on internal settings is acquired, further research using these equations is recommended.

So, in general, a greater salinity difference between the two feedwaters enhances RED performance. On the other side, membrane permselectivity decreases with more concentrated high salinity feedwaters, which limits power generation. As REDstack has optimized their internal system with the available salinity gradient, using the Wadden Sea water with a salinity at about 28 g/liter and IJsselmeer water at about 0.2 to 0.5 g/liter, their system efficiency is expected to drastically reduce if the salinity gradient would increase considerably, due to the increased internal resistance (Jang et al., 2020). Especially the low salinity feedwater, in this case derived from the IJsselmeer, is highly associated with the Ohmic losses and therefore limiting the power output (Tufa et al., 2018). In the reverse situation, a smaller salinity gradient results in a reduced electromotive force, but also in a lower internal resistance that could result in a higher power output.

The optimal salinity gradient depends on factory settings, therefore, a consensus has not been reached in the academic world on quantified optimal values. For example, Mei & Tang's research (2018) considered a river water and sea water combination, and their power density in W/m^2 ranged between <1 to 2.3 W/m^2. In another laboratory study, performed by Altiok et al. (2021), the power density was most strongly and positively impacted by an increase in the high salinity feedwater's salinity level. Contrarily, Zoungrana et Cakmakci (2021) argue that the feedwater with the lower concentration has a far higher sensitivity and impact on the power output than the high concentration feedwater. In addition to that, Ortiz-Martinez et al. (2020), argue that the low concentration feedwater can be a major contributor to the internal resistance. The optimal concentrations in Zoungrana et Cakmakci's research (2021) were between 4 to 6 mM for the low salinity feedwater and between 600 to 684 mM for the higher concentration feedwater. A study at REDstack at the Afsluitdijk showed that the ionic composition of the used feedwaters during their 30 day experiment were typically at 342.5 mM Cl^- (+- 37.6) and 283.8 mM Na^+ (+- 32.6) for the Wadden Sea, and 2.7 mM Cl^- (+- 0.2) and 2.3 mM Na^+ (+- 0.2) for the IJsselmeer (Simoes et al., 2022). In Ortiz-Martinez et al.'s model research (2020), the optimal NaCl concentration for a 550 mM high concentration, corresponding with the average seawater salinity, was 20 mM NaCl for the lower concentration feedwater.

Without the needed information on the powerplants' set up, no quantifiable conclusion on the relationship between salinity gradient and power output can be drawn. However, assuming that the REDstack set up is optimized for the currently occurring salinity gradient range in its feedwaters, it can be argued that large changes in the salinity gradient are most likely not beneficial for the power output of the plant. The benefits of an increase in the driving force by a higher salinity gradient might outweigh the disadvantages of an increased internal resistance, but there is at time of writing no way of quantifying this tipping point.

3.2.3. Temperature

According to Sharma et al. (2022), the operating temperature also plays a crucial role in the optimization of the RED process. The temperature of the feedwaters, in the study area derived from the IJsselmeer and the Wadden Sea, have a substantial effect on the potential energy generation (Sharma et al., 2022). Warmer feedwater results internally in an increase in the obtained power density and a decrease in the stack resistance, as well as an increase in the conductivity (Nazif et al., 2022). Similar to the relationship between the salinity gradient and the power output, the relationship of the feedwater temperature and the power output is also unquantifiable without knowledge on the internal REDstack set-up. Academic literature will therefore once again be used to make an estimation on the effects temperature change will have on the power output.

3.2.3.1. Relationship to power output

In several modelling and laboratory studies, it appeared that an increase in temperature enhances the productivity of the process (REApower, n.d., Mehdizadeh et al., 2019, Benneker et al., 2018, Tristán et al., 2020, Avci et al., 2018). In Mehdizadeh et al.'s (2019) pilot scale set up, increasing the temperature of the solutions had a positive influence on the maximum gross power output, the resistance of the solutions and the membranes and eventually, the net power output. Feedwater temperature influences the electromotive force and conductivity of the solutions, as well as the membranes (Mei & Tang, 2018). According to the Nernst-Haskell equation, the ionic diffusion enhances with an increasing temperature, as the viscosity of the feedwaters decreases. Therefore, ions can more easily move through the solutions, and that means the conductivity increases (Mehdizadeh et al., 2019). If there is a temperature gradient between the feedwaters, meaning one is warmer than the other, a thermos-osmotic flux might be established, in addition to the osmotic flux based on the salinity gradient (Benneker et al., 2018). However, the gross power density increases even further if both feedwaters are warmer, as the benefits of enhancing the ionic diffusion outweighs the benefits of the thermos-osmotic flux. With increased temperatures, the Ohmic resistance declines, resulting in the total maximum gross power density increase up to 38% when heating the stream waters from 20°C to 40°C, in a 4 cell RED stack set up (Benneker et al., 2018). The non-Ohmic resistance, on the other hand, increases with an increase in temperature, as the capacitive effects of the solutions get higher, creating a larger salinity gradient in the direction of the flow (Benneker et al., 2018).

Extremely high water temperatures – about 60 °C -- on the other hand, negatively influence the permselectivity (Mei & Tang, 2018, Sharma et al., 2022) and may lead to membrane material degradation (Benneker et al., 2018). Since it is highly unlikely that the Wadden Sea nor the IJsselmeer would heat up to these temperatures, these side effects will not be researched further. However, seasonable variations in water temperatures could have considerable effects on the power output (Mei & Tang, 2018). It should be noted that not all academic papers report a positive relationship. Hossen et al. (2020), for example, stated that they found no statistical relationship between conductivity and water temperature, after a real life pilot study with different temperatures in the United States of America. The majority of the research papers does, however, report this relationship.

It can be concluded that overall, the general idea is that the warmer the water, the higher the energy output for RED is. Since it is not favourable to heat up the feedwaters, seasonal changes determine the natural water temperatures and therefore the feedwater temperatures. It is assumed that this temperature does not change significantly within the powerplant.

3.2.4. Interconnection

An important conclusion, based on the academic background studies, is the inherent interconnectedness of the external factors – the physical factors amongst themselves as well as with the societal factors. This interconnection is important for this research, as well as for further research and potential implementation plans. The limitations will be researched independently in this research, but it is important for future reference that these factors influence each other heavily.

The limiting factors are connected in several ways. To name a few, the level of precision on the water management of lake IJsselmeer, based on societal needs from the lake, does not merely influence the volumetric amount of water that is being discharged from the Afsluitdijk, it also influences the salinity levels of both the IJsselmeer and the Wadden Sea. As described, salinity levels in the lake are managed for societal demands, with the main desalinization measure being discharging the fresh water into the Wadden Sea, called flushing as discussed in chapter 3.2.2 and will be discussed further in chapter 4.3. The Wadden Sea's salinity level reacts to this discharged volume of relatively fresh water, in return. The salinity levels of the lake should be managed to be able to deliver to the societal needs, for example drinking water and irrigation water. The amount of water that can be used for societal needs depends on the volumetric availability of water in the lake, as does the volumetric volume of water that is being discharged from the Afsluitdijk. The water temperature is naturally linked to the salinity levels, with the water temperature influencing the density of the water, and the salinity and water density sharing a positive relationship. Air temperature therefore influences the water temperature and the salinity levels, directly by influencing the potential evaporation, and indirectly by altering the water temperature. Many more connections can be detected, for this research the notion of the interconnection will suffice.

In conclusion, the interconnection implies that by proposing an intervention that alters one of the factors, the other factors will likely also be influenced.

4. RESULTS

The demand for non-conventional renewable energy technologies will be researched in this chapter, by calculating the gap between the current electrical energy demand the Netherlands and the current production ability of renewable energy in the Netherlands. This gap could be filled by RED produced energy. Physical and societal factors that limit the maximum production capacity are quantified and discussed in this chapter.

4.1. Energy gap

The ambition in the Netherlands is to emit no greenhouse gasses by 2050, which makes a shift to more renewable energy usage imperative. To what extent there is a demand for RED energy in the Netherlands, depends on the demand for (renewable) energy and the current renewable energy supply. The calculated results are shown in Fig. 10.

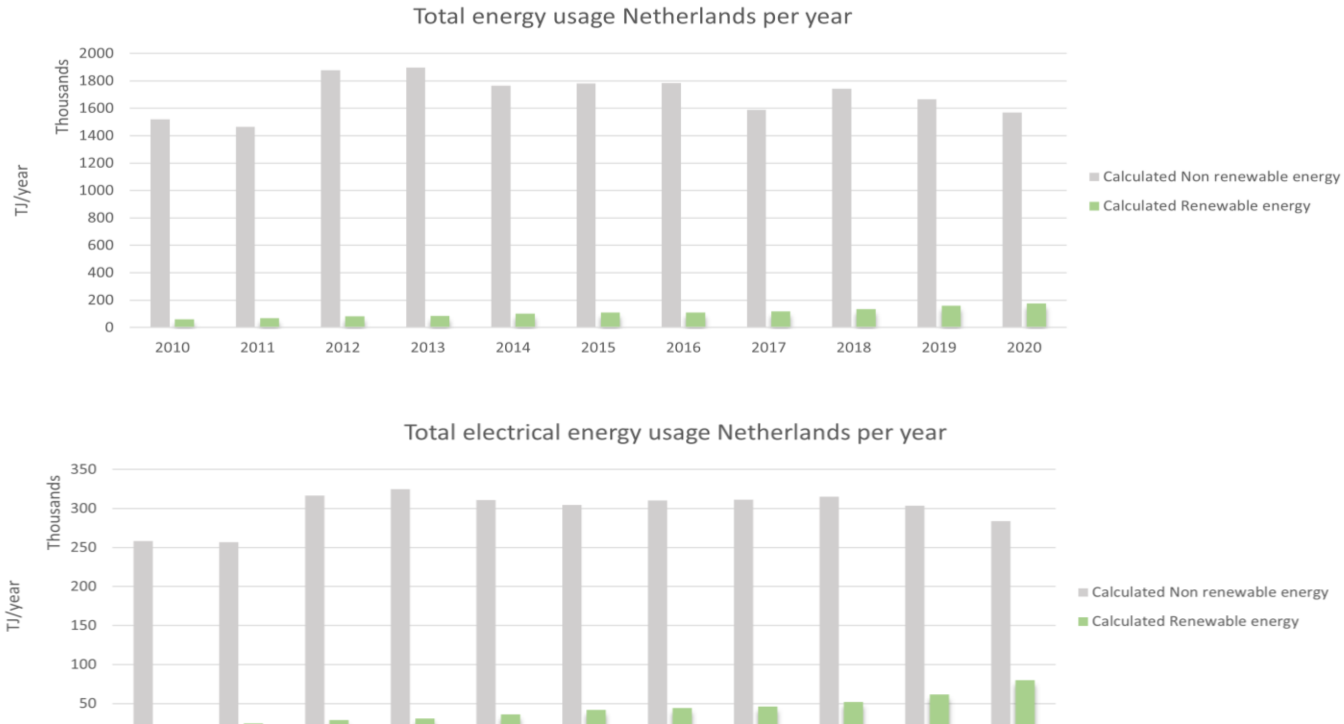


Fig. 10: The Dutch energy gap for total energy usage and electrical energy usage, based on data from CBS.

Fig. 10 shows a slow but steady increase in the amount of renewable energy usage, accompanied by a decline in usage of non-renewable energy. The total energy demand increased by 10.63% between the years 2010 and 2020. In other words, the total energy usage per year varies, but a consistent growth of renewable energy usage can be detected. The consistent growth of the amount of used renewable electric energy can be seen in the lower panel of Fig. 10. It is apparent that the total usage of electrical energy is increasing. What catches the eye is the gap between non-renewable and renewable energy usage, which gets smaller as the years progress, but remains considerably large. The largest difference between the non-renewable and renewable total energy was in 2013, which was nearly 2 million TJ. The energy gap between the total electric energy usage and its renewable counterpart is a factor of 10 smaller than that of the total energy usage.

In 2020, the most recent year, the energy gap consisted of $1.39 \cdot 10^6$ TJ/year for the total energy usage. For the electrical energy usage, it consisted of $2.04 \cdot 10^5$ TJ/year, for the same year. Converted to GW - by dividing the number by the seconds per year to TJ/s, and then multiplying it by 10^9 to GW - that means that there was a total renewable energy demand of 44 GW or 6.5 GW of renewable electrical energy in 2020. Althoughthis is a simplified calculation is, that does not take context into account, this number illustrates an aim for renewable energy production – and can be seen as the Dutch societal demand for renewable energy, such as RED.

Using EUROSTAT monthly data on energy usage in the Netherlands, available from January 2016 to September 2022 in TJ, the seasonal differences in used energy sources can be determined. The main categories are displayed in Fig. 11, showing:

- combustible fuels (consisting of the sum of renewable and non-renewable combustible fuels, coal and manufactured gases (excluding biofuel portion), natural gas and oil and petroleum);
- wind (consisting of the sum of on- and offshore wind);
- solar (consisting of the sum of solar thermal and solar photovoltaic);
- nuclear fuels;
- other fuels (which are set at zero).

Fig. 11 shows an overall higher energy usage during the winter months and a lower total energy usage during the summer months. The growing contribution of renewable energy sources to the total energy usage over the years is also visible in the graph, mirrored by a declining total energy usage of non-renewable energy. Nuclear fuels show a very steady contribution to the total energy mix, in contrast to the solar energy usage – which displays a wave like contribution throughout the annual cycles. The contribution of wind energy shows a more capricious annual cycle, but a higher contribution during the winter months and a slightly lower contribution during the summer months can be observed. Other fuels do not appear to play a role in the Dutch total energy usage.

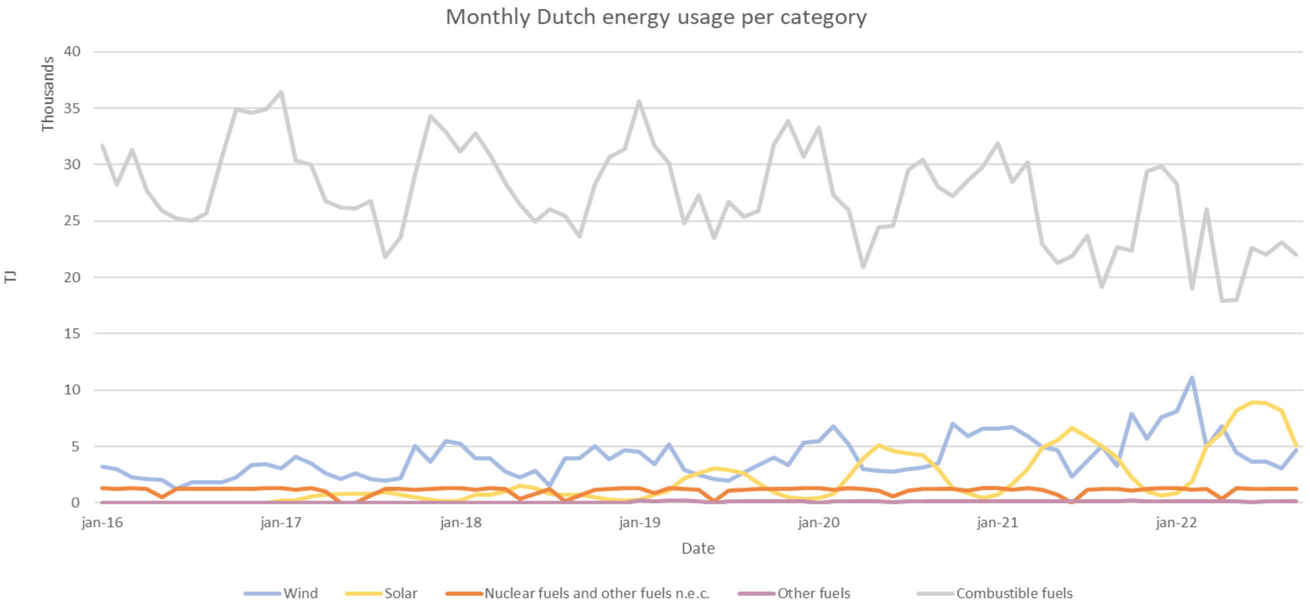


Fig. 11: The Dutch energy usage per source category, based on data from EUROSTAT.

Zooming in on the renewable energy usage per source over the most recent available years, the contributions of sub category energy sources is shown in Fig. 12. The data for most renewable energy usage subcategories appears to be measured from 2017 onwards. The above describe wave-like annual cycle can again be detected in the zoomed in graph, as can the capricious annual cycle of wind energy contribution – both on- and off shore. Other renewable energy sources and thermal solar energy did not play a considerable role in the Dutch renewable energy usage mix, and were therefore left out of the graph. Hydro power, however small, does play a role and is therefore shown at the bottom of the graph. It is interesting to see that the contribution of renewable combustible fuels, which has grown irregularly over the years.

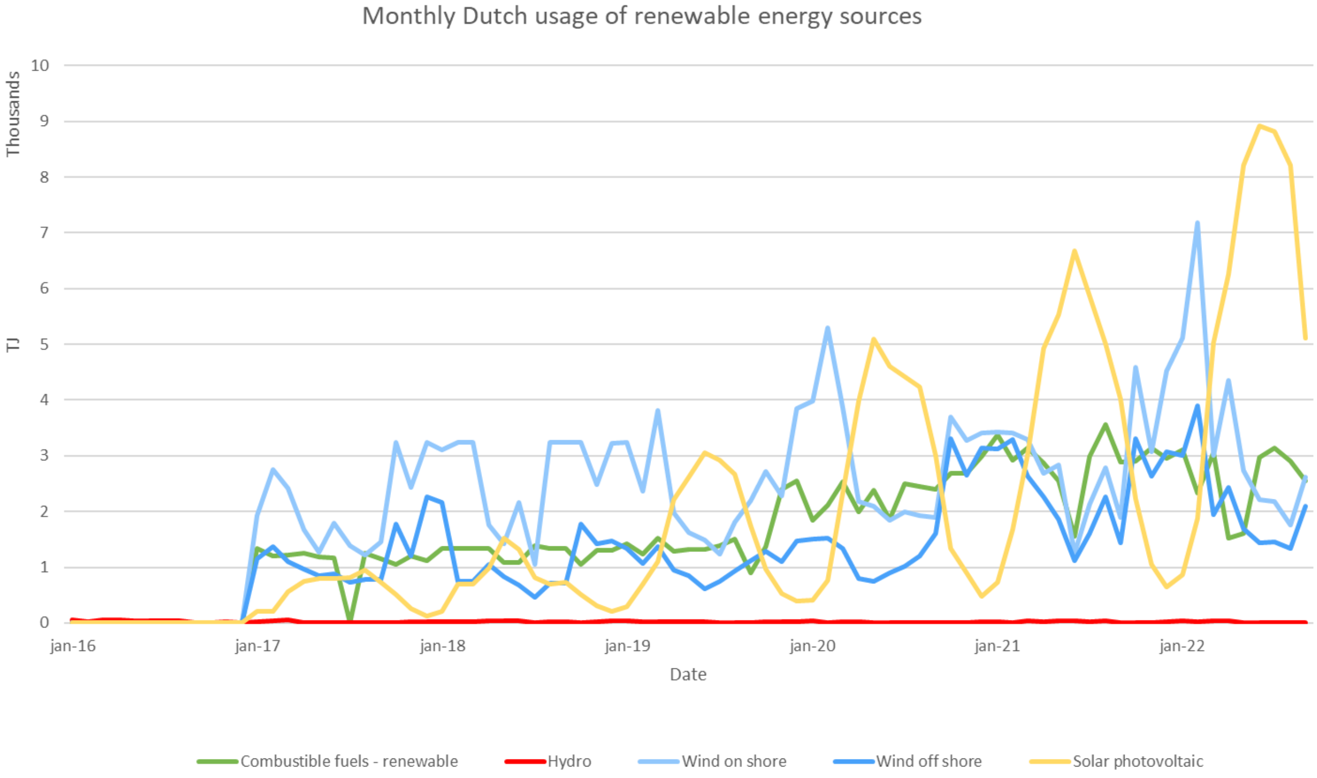


Fig. 12: The Dutch energy usage per category for renewable energy sources, based on EUROSTAT data.

Given the Dutch governmental ambitions to reduce greenhouse gas emissions by 55% in 2030 and becoming emission free in 2050, as discussed in the background literature study, the share of renewable energy can only be expected to increase. The expected electrification of the entire energy system, as described in Scheepers (et al., 2022) and (Scheepers, 2022), leads to an even higher renewably produced electrical energy demand than was quantified based on the 2020 energy gap – up to 500 TWh (or 1.8 million TW) in 2050. All in all, the gap between non-renewable and renewable energy is sufficiently large to conclude that there is a demand for renewable electrical energy, such as from RED. Considering the energy ambitions of the Netherlands, and considering past developments, this gap is likely to remain large within the foreseeable future.

4.2. External limitations

To what extent the energy gap can be closed with renewable RED energy, the maximum production capacity should be examined. The quantification of external physical limitations to RED, together with an analysis on the limitations imposed by societal factors, are used to examine the maximum production capacity.

4.2.1. Results Volume

The importance of the physical limitation of power production proposed by the volume of water is described in the background literature, as is the argumentation to work with REDstack's rule of thumb of 1 m^3/s of fresh and saline feedwaters equalling 1 MW power output. The amount of water that can potentially be used by REDstack, which is the fresh water discharged from the Afsluitdijk, depends on the water balance. Therefore, this chapter will zoom in on- and quantify the water balance of the IJsselmeer area.

Thirty years of data were downloaded from Rijkswaterstaat. The water is discharged at two points: at the Stevin sluices at Den Oever and at the Lorentz sluices at Kornwerderzand. The total amount of water in m^3/s, daily discharged water from the Afsluitdijk, could therefore easily be calculated by adding the values of the two measurement points Den Oever and Kornwerderzand and then calculating the mean monthly discharge. Over thirty years, the mean monthly discharged water was visualized in Fig. 13.
Seasonal variability can be detected in the graph, where summers show less discharge and winters show more. This can be explained by the higher water level set during the summer months, together with more evaporation, which leaves less water to be discharged during the warmer months. During the wintertime, on the other hand, a lower set water level equals more water to be discharged. Using the time periods used for the so called 'flexible' water level management of the IJsselmeer, the year can be divided into the summer period, ranging from April to October, and the winter period, ranging from October to April (Rijkswaterstaat, 2018). The mean discharge during the summer months was calculated to be 337.63 m^3/s,

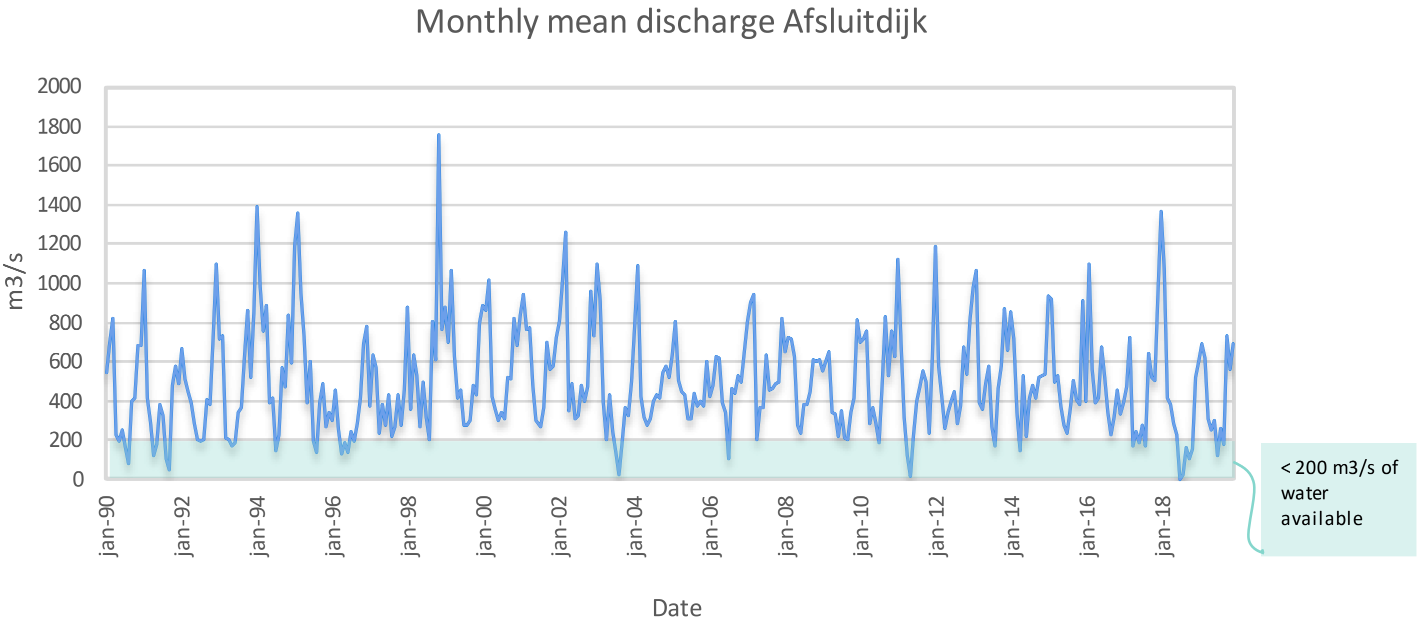


Fig. 13: Mean monthly fresh water discharge from the Afsluitdijk, based on Rijkswaterstaat data.

whereas the mean during the winter months was set at 653.84 m^3/s. The data distribution around these means can be found in the form of an histogram in Appendix 3.

A quick visual scan already tells us that the amount of water needed to scale REDstack up to the production capacity of 200 MW, in other words 200 m^3/s, is discharged most of the time from the Afsluitdijk. So the question arises if REDstack could benefit from scaling the power plant up to an even higher production capacity. That would mean that it could not produce at full capacity all the time, but only for a certain amount of time.

Using the daily discharge data from the Afsluitdijk, it could be calculated that there were 2843 days over the 30 years dataset (10957.5 days) on which there was less water than 200 m^3/s being discharged, about 26% of the time. That means that if the powerplant were to be scaled up to 200 MW, as per REDstacks own ambitions, the powerplant could produce at full capacity for 74.05% of the time. Using this reasoning, the following graph could be developed, where the percentage of time the power plant could produce at full capacity is linked to the amount of water available. If the powerplant were to be built to handle a maximum capacity of 400 m^3/s, it could produce at full capacity for about 48.86% of the time. For 600 m^3/s, it would function at full capacity for 31.04% of time – to highlight a few. This is visualized in Fig. 14. Using this information, a cost benefit analysis could help determine to what extent the powerplant could be enlarged in a later stage. Since there were 748 days in the most recent 30 years of data that no water was discharged from the Afsluitdijk, the graph has an odd start. The corresponding values can be found in Appendix 2.

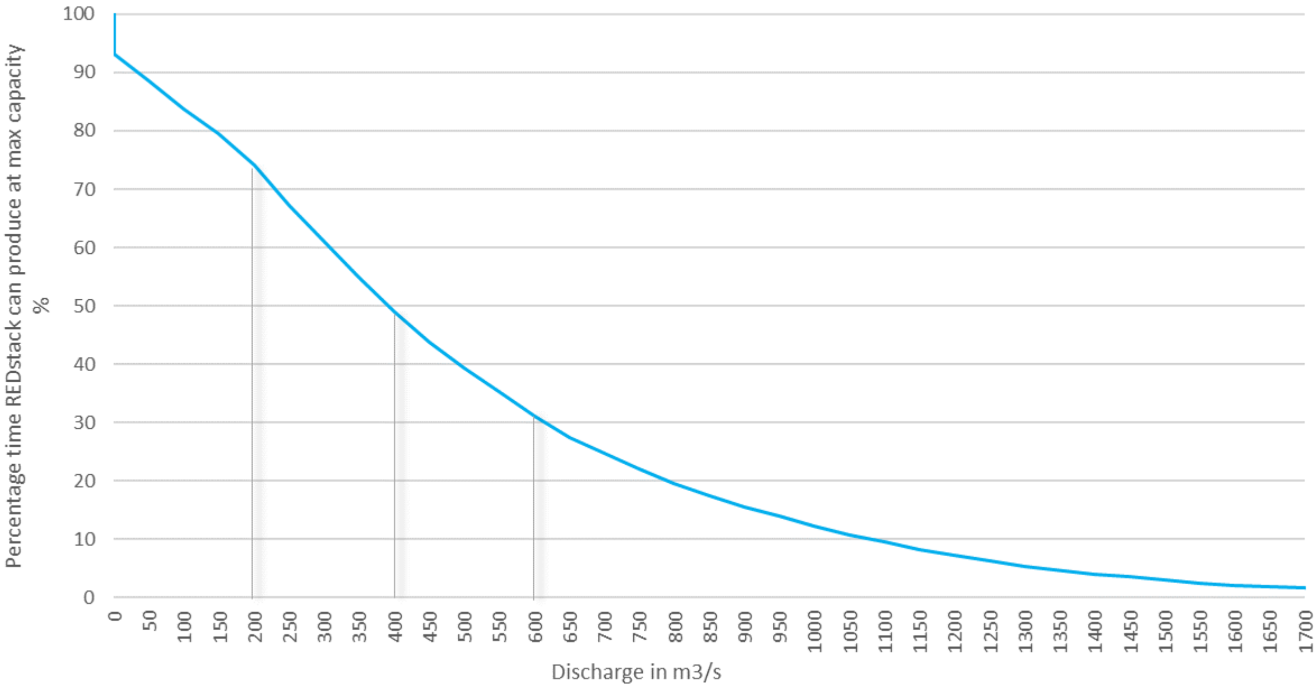
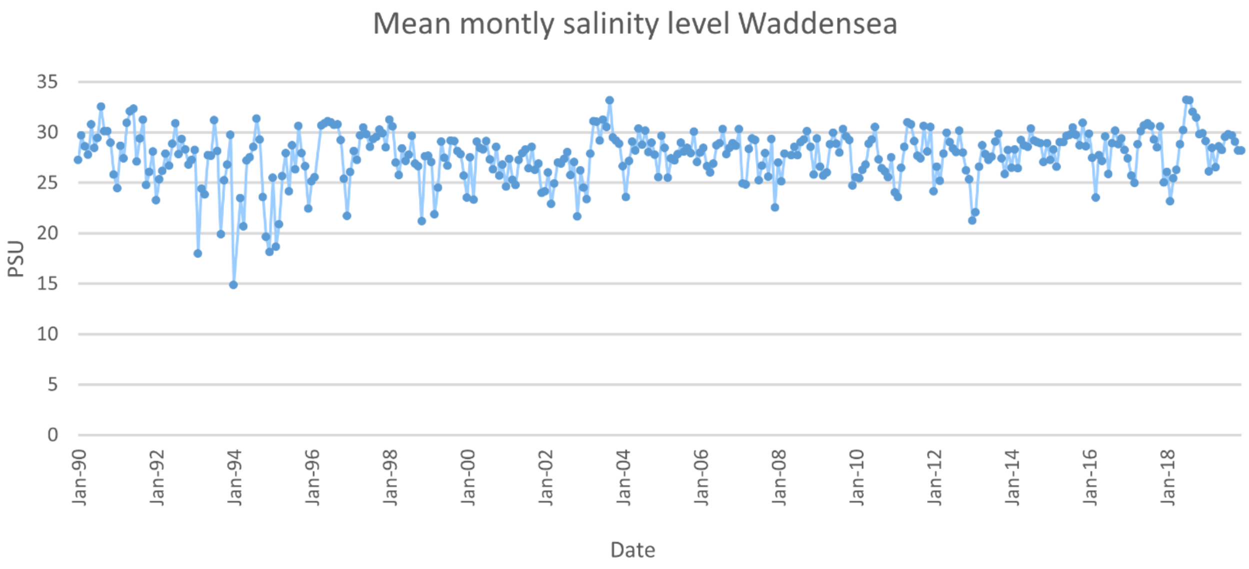


Fig. 14: Percentage of time (based on the last 30 years) a certain amount of water was discharged from the Afsluitdijk, based on Rijkswaterstaat data.

4.2.2. Results Salinity

The relationship between the water salinity gradient and the power output could not be quantified without knowledge on the internal REDstack set up. As described in the background information, we assume that a slight increase in the salinity gradient will increase yield, but since the powerplant is optimized for the current salinity gradient, large deviations may result in a loss of productivity.

Times of measurements being taken differed each month, as did the days the measurements were taken. Without consistent daily measurements, the monthly means are less reliable, that is why the graph shows the markers per month instead of the line that was used in other graphs. Mean monthly values were calculated of the measurement points, resulting in the following graphs in Fig. 15.



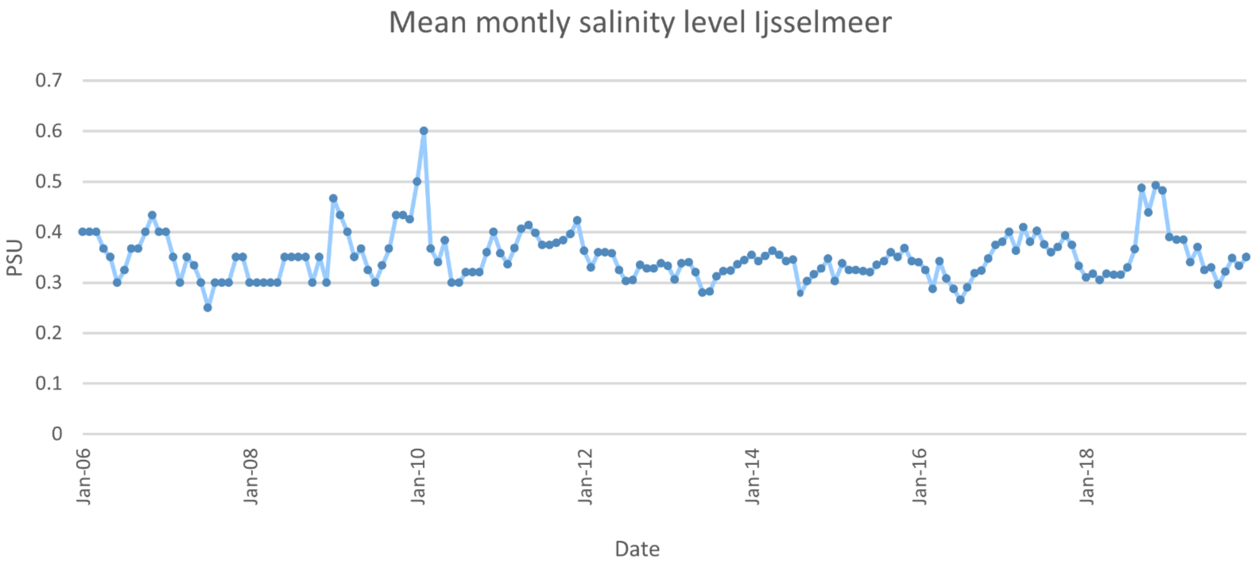


Fig. 15: Mean monthly salinity levels of both feedwaters.

The mean monthly salinity levels of the Wadden Sea scatter between 15 and 35 PSU, which is a broad range. However, most of the measurement points are between 25 and 30 PSU. Seasonal cycles are hard to detect, but the mean PSU level in the summer months shows a slightly higher value of 28.66 PSU, compared to 26.59 PSU during the winter months. The data distribution around these means can again be found in Appendix 3, by means of an histogram.

The mean monthly salinity levels of the IJsselmeer scatter closely between 0.3 and 0.4 PSU, with a few outliers towards 0.6 PSU. The mean values show less seasonal variability than the Wadden Sea, with mean values of 0.36 PSU during the winter months and 0.34 PSU during the summer months. This appears counterintuitive, as salinity levels are expected to increase in the lake during the summer months due to increases in evaporation. But the summers' higher set water level, and therefore a larger volume of retained fresh water, is the probable cause that results in a slightly lower PSU level. The difference in salinity is 28.32 PSU during the summer months and 26.23 PSU during the winter months.

Overall, the measurement values correspond with values mentioned in the literature, with Wadden Sea salinity at about 28 PSU and IJsselmeer salinity at about 0.2 to 0.5 PSU (Jang et al., 2020; Tedesco et al, 2016). Local conditions mentioned in the background information, such as wind and water flux, could have resulted in the slight deviation of salinity in the measurements and the expected values from the literature.

4.2.3. Results Temperature

The relationship between the water temperature and the power output of the RED power plant is blatantly described as "the higher the temperature, the better the power output" in the background literature study. Even if one of the feedwaters temperatures is higher, it should be beneficial for the power output. After cleaning up the datasets, the mean daily data was calculated, which was then used to calculate the monthly mean water temperatures (Fig. 16).

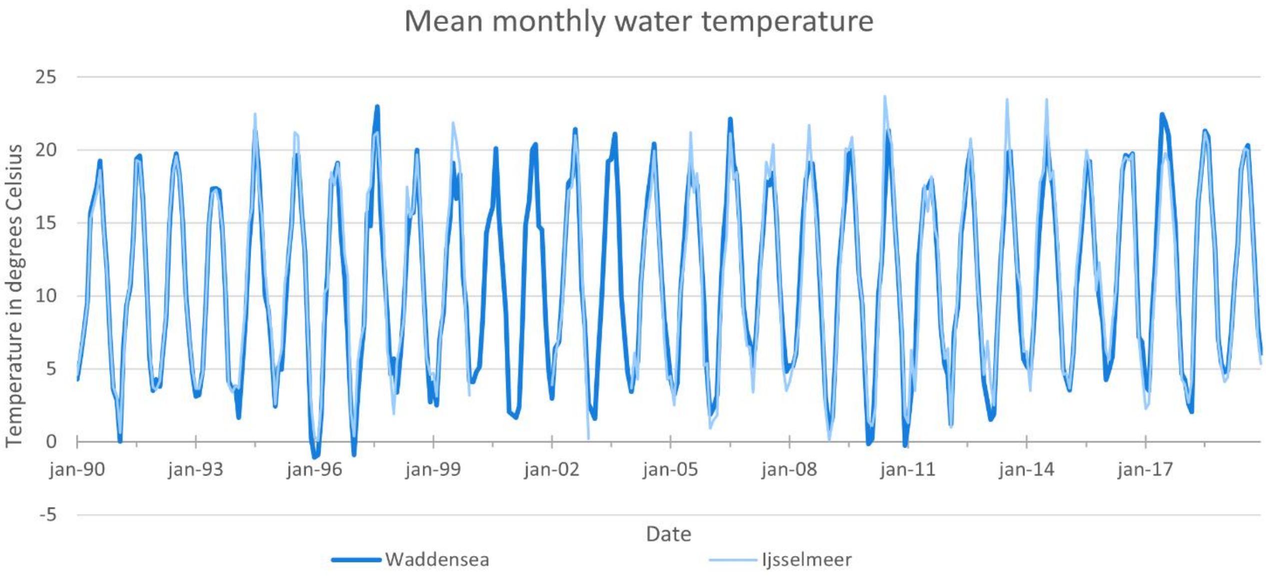


Fig. 16: Mean monthly temperature levels of both feedwaters.

As can be derived from Fig. 16, there is quite a large water temperature variability throughout the seasons for both variables. The temperatures range from 0 to 5 °C in winter times and between 17 to even 25 °C in the summer. That would mean that the production capacity of REDstack should be substantially larger in the summer than during the winter. Interestingly, the water temperature lines of the Wadden Sea and the IJsselmeer overlap greatly. It does get slightly warmer in the IJsselmeer during the summer, and a bit colder in the Wadden Sea during the winter, but both relatively shallow waterbodies follow a similar water temperature oscillation throughout the seasons. Mean seasonal temperature differences also shows similar values for both variables. The mean temperature is 16.0 °C in the Wadden Sea and 16.2 °C in the IJsselmeer during the summer months. During the winter months, the mean water temperature for the Wadden Sea is 6.1°C and that for the IJsselmeer is 6.2 °C. An histogram illustrating the data distribution can be found in Appendix 3. The seasonal differences indicate that the power output of REDstack should be higher during the summer months than during the winter months.

4.3. Societal limitations

As shown by the renewable energy gap in chapter 3.1 Energy Gap, there is a demand for renewable electric energy in the Netherlands. Considering past developments, the gap is likely to remain large within the foreseeable future. Renewable energy, generated using RED, could contribute to a lessening of this gap and create a supply for the renewable energy that is in demand. But, RED energy production will make use of resources that could be in conflicting interest of other parties. In this chapter, the societal limitations to RED power generation will be discussed.

Lake IJsselmeer fulfils multiple purposes for the Dutch society. The freshwater of the lake is used as a fresh water buffer, serving drinking water, agricultural, industrial, nature conservation and recreational purposes, amongst others. This chapter will dive further into these fresh water demands, and aims to quantify the societal limitations on water availability to perform RED on the Afsluitdijk. The anthropogenic influences on the physical factors, as well as how a new renewable power plant would be received by society, form limitations on the maximum power production of the RED powerplant. Similar to the availability of water from lake IJsselmeer, the water from the Wadden Sea serves multiple societal and nature purposes as well. The advantages and disadvantages of implementing a RED powerplant for society, specifically for the area of interest, will be discussed in this chapter.

4.3.1. Stakeholders

The location of REDstack is about 12 kilometres away from the mainland Friesland, and has no permanent inhabitants nearby. The main stakeholders are therefore those involved with the dyke's structure, its planning goals and its ecological surroundings. The Afsluitdijk, the dyke on which REDstack is situated, has evolved from solely a water barrier to a multistakeholder system that aspires to make the dyke and it surroundings future proof by innovative measures (Gorny et al., 2022). The governance system of the Afsluitdijk consists of the Rijkswaterstaat, responsible for implementing policies and projects ordered by the Ministry of Infrastructure and Water management, and the large-scale operation 'DNA', consisting of provinces and municipalities whose aim is to coordinate sustainable innovations, initiatives and projects (Gorny et al., 2022). The stakeholders of the trilateral Wadden Sea area (Dutch, German and Danish) are shared under the multi-stakeholder platform 'Wadden Sea Forum'. This forum consists of representatives from regional and local governments, stakeholders from private economic sectors of energy, fisheries, agriculture, industry, harbour, tourism and non-governmental environmental protection organisations (Gerkensmeier & Ratter, 2018). The sea is a protected nature conservation area, as well as a cultural heritage area, protected by the trilateral Wadden Sea Cooperation (11th Trilateral Governmental Converence, 2010). The stakeholders involved with the IJsselmeer are already described in chapter 'Background information volume' and will be discussed further in the next subchapter 4.3.2.

Multiple stakeholders, both on the Afsluitdijk itself – given the DNA project- and on the Dutch national Government - bounded by the Climate Agreement (2019)- , have ambitions to make the area future proof and have shown interest in renewable energy production processes. Therefore, it is assumed that the idea of an upscaled version of REDstack would fit right into their ambitions. Since there are no permanent inhabitants living closely to the trial site, the 'not in my backyard' effect is avoided, another perk for upscaling a RED plant at this specific location. The stakeholder issue would likely focus on the protection of the ecological services of the surrounded protected areas. Similar to the financial and ecological effects of an upscaled plant, the costs and benefits of the implementation of a larger powerplant for its surroundings is something that should be researched in a next stage. .

4.3.2. Water related societal limitations

The biggest resource that is needed to perform RED power production is considerable quantities of fresh and saline water. The amount of fresh water that REDstack is allowed to demand depends on the availability, physical and societal wise. This chapter will dive into the societal limitations.

As Zandvoort et al. (2019) described, dealing with uncertainty is an inherent part of water management, especially for long time periods. The centuries long history of water management in the Netherlands, together with the precision water level management of the IJsselmeer up to 1 centimetre exactness, has resulted in the reigning idea of technocratic 'make-ability' of water management and planning (Zandvoort et al., 2019). Hydraulic models, weirs, locks and real-time steering of pumps have made the water level at the IJsselmeer reliable and stable, resulting in a diminished dynamic nature of the lake.

Management of lake IJsselmeer is in the hands of the national government, so called 'national waters', while the water management of surrounding terrestrial areas is in hands of the regional water authorities (Deltaprogramma Zoetwater, 2021). This means that the national waters have a double function: on the one hand they supply the buffer of which local water authorities may withdraw water, on the other hand they demand a lot of water to maintain the water level of, in this case, the IJsselmeer. Rijkswaterstaat, the executive force of the Dutch Ministry of Infrastructure and Water Management (Gorny et al., 2022), analysed and calculated the demands for the freshwater of the IJsselmeer in 2021, using the 'Nationwide Hydrological Model' (Deltaprogramma Zoetwater, 2021). Using their conclusions, the societal water demand of the IJsselmeer can be divided into five categories: water level maintenance, irrigation, area flushing, industrial and drinking water. They performed their research as follows. Each terrestrial water district was converted into a subregional water balance calculation unit. All of them have (some of) these demands, but they also have their own water supply in surface and subsurface water. If users' demand is bigger than their supply, the hydrological model will check if surrounding districts may have a surplus, and if not, the district may demand water from the IJsselmeer. The amount of water that is demanded from the IJsselmeer is used to quantify the long-term societal water demand in this research.

The Deltaprogramma (Deltaprogramma Zoetwater, 2021) used the National Hydrological Model to quantify the societal water demand from the IJsselmeer area -- which is not limited to the IJsselmeer alone, but includes the lakes IJsselmeer, Markermeer, surrounding lakes on the edges of the larger lakes, and all surrounding areas that demand water from the national waters during dry periods. They based the calculations on data of all Dutch regional water authorities, meteorological data and added a new model, which translates to the Water Demand Prognosis tool, to determine the water demand of national waters. A short description of water demanders used in this model is as follows. The water demanders were divided into categories; water level maintenance, irrigation, flushing, industry and drinking water. The category water level maintenance calculated the amount of water needed to maintain the national and regional water levels. The regional water levels were based on meteorological influences and subsurface influences, for the national water level maintenance, the subsurface influences were considered negligible. National waters play a dual role, on the one hand they provide the buffer for water subtraction, on the other side they demand water if the national water level is to be maintained. The demand for regional water maintenance consists of three subcategories: maintenance for peatlands, to avoid land subsidence, a demand for flushing of vulnerable wet nature (to avoid salinization), and maintenance for other demands. The next category is irrigation, which is a relative small water demander compared to the water level maintenance categories, and is nearly exclusively demanding water during June, July and August when most crops are in need of irrigation. The category flushing consists of the water that is withdrawn from the system and does not return to the system – as it exits towards the Wadden Sea or the North Sea. Flushing is quite weather and water quality dependent, and is therefore not constant throughout the year. The flushing of the IJsselmeer to prevent salinization is included in this category and consists of 40 m^3/s. The remaining categories; industry, drinking water and other demanders, are not specified further in the report of the Deltaprogramma Zoetwater (2021).

It should be noted that water demand does not necessarily mean that the water is extracted forever, but it can return to the lake in time through several ways – groundwater water flux, returned water after being used as cooling water, etcetera. Instead of absolute extraction, the water demand table can be seen as a system of fluxes in itself and with the outside world, where water may circle back to another demander or exit the system. The model quantified the average water demand for the categories between 1912 - 2012 as follows (Table 2 & Fig. 17):

Table 2: The fresh water demanders of the IJsselmeer and their demand in m^3/s, based on Deltaprogramma Zoetwater (2021).

Water demander	**Demand in m^3 /s**
National water level maintenance	186.5
Regional water level maintenance	58.1
Drinking water	48.5
Flushing to prevent salinization	40
Agricultural irrigation	33
Others	15.8
Temporary irrigation capital-intensive crops	14.1
Grass- and cornland irrigation	10
Processing water	2.1
Cooling water for electrical energy producers	0.6

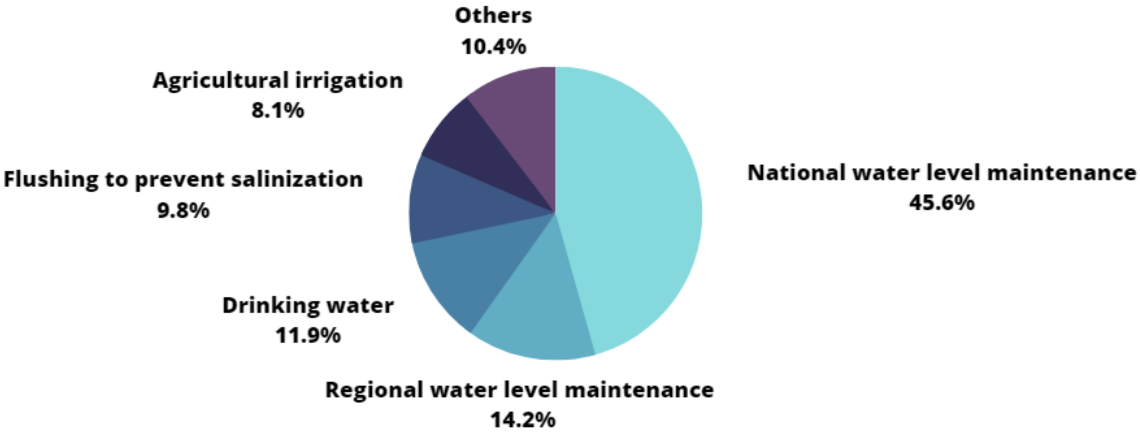


Fig. 17: Pie graph of the proportional share of the total water demand of 408.7 m3/s, based on data from Deltaprogramma Zoetwater (2021).

The total average water demand for the whole IJsselmeer region comes down to 408.7 m^3 /s between 1912 and 2012, as calculated in the model study of Deltaprogramma Zoetwater (2021). The study showed that the demand is biggest during the summer months, which makes sense as the water demand comes down to the amount of water that is needed to compensate precipitation shortage (Deltaprogramma Zoetwater, 2021). A comparison between the winter and summer months could not be quantified based on their information. Other demanding parties on the IJsselmeer do not subtract fresh water, but demand a certain water level and quality of the lake. These parties include fishery, recreational, transport and sand extraction (Van Ginkel et al., 2022).

The low lying Netherlands' water management plans have been focused on flood defence measures for centuries. An extremely dry summer period took place in 2018, which revealed unknown bottlenecks in the IJsselmeer area. Increased salinity levels in the lake up to 100 mg/l over the maximum level of 150 mg, accompanied by a high water demand, showed that fresh water can become a scarcity and new measures must be taken to become more resilient to drought (Nationaal Deltaprogramma, 2020a). The water demands on the IJsselmeer appeared to increase during these dry times, to social-economically deal with the drought and to avert peatland subsidence. During a meteorological drought, the water buffer of 400 million cubic meter, or 20 cm water layer, is depleted by demands and evaporation in about 2 weeks (Van Ginkel et al., 2022). The following emergency 10 cm water buffer layer may only be used by certain demanders, as explained below. If the water level drops below this critical level, the dyke stability is at risk and therefore, no water may be retrieved from the lake (Van Ginkel et al., 2022).

Dry periods take place nearly every year, but, as discussed above, are expected to become increasingly extreme due to climate change. If the dry period leads to a severe water shortage, the Dutch 'Water law' describes the repression sequence of societal and ecological demands that should be taken into account (Waterwet, 2022, article 2.1). Within the four categories, there may be internal repression hierarchies set by provincial governments. The hierarchy is presented in Fig. 18.

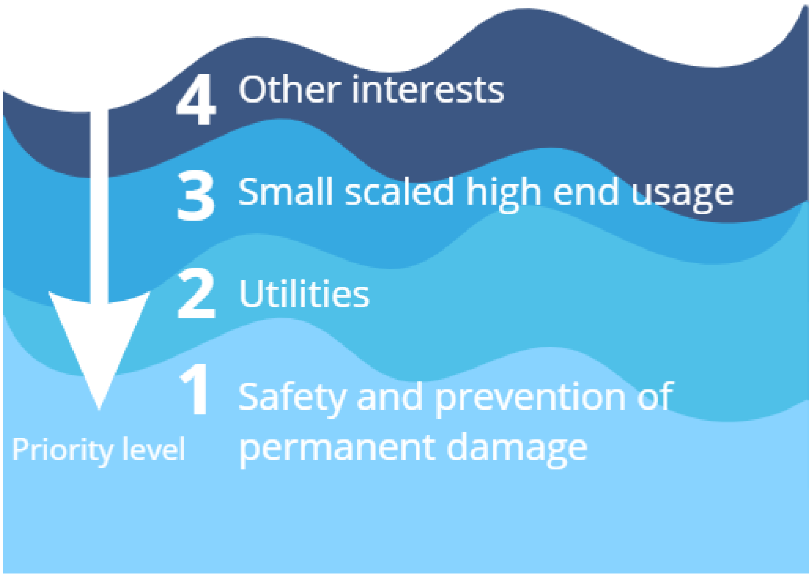


Fig. 18: The water demanders hierarchy during droughts, according to the Waterwet (2022, article 2.1).

The first category that stops getting access to water is 'Other Interests (economic considerations, also for nature)', which consists of shipping, agriculture, nature (that suffers no permanent damage), industry, water recreation and inland fishing. The second category in the sequence is 'Small scaled high-end usage', consisting of temporary irrigation for capital-intensive crops and processing water. The 3rd category are the drinking water- and energy supply under 'Utilities', and the last category that loses access to water is 'Safety and prevention of permanent damage'. The latter consists of the stability of water defence mechanisms, prevention of (peat)land subsidence and nature (linked to soil conditions) (Waterwet article 2.1). At a first glance, REDstack would fall under the second-last category 'Utilities', as it is an energy supplier. However, it might be an exception to this category as the need to maintain the water buffer of the IJsselmeer could be considered more important than the energy supplied by REDstack, especially since there are alternative energy producers that do not require the scarce IJsselmeer water during drought.

Overall, it can be argued that the water demands have been adjusted to the 'made' availability of the water, since the margins for water level change in the IJsselmeer are small. With such a stable water level, adjusted to previously discussed water demands and vice versa, a new demand for fresh water, such as REDstacks, could better make use of rest water than compete with other stakeholders that currently are demanding fresh water from the IJsselmeer. As discussed before, the water that leaves the lake through the Afsluitdijk could be considered 'rest' water, that does not serve any other societal demand, and will therefore be used as the only source of fresh water for RED. Therefore, the implementation of RED is not expected to change the water balance, but is expected to change the ways water is discharged from the Afsluitdijk. As it can continuously pump water through the powerplant, discharge is no longer dependent on the low tide 'discharge windows', nor does the surrounding ecosystems have to deal with bidaily fresh water shocks. The RED pumps can also help mitigate 'multi peak levels' of water (as discussed in chapter

3.2.1), which will increase the stability of the water level in the IJsselmeer. This rest water is usually abundantly available, but during extreme climatic events such as droughts, conflicting water demands put pressure on the water availability for RED purposes.

4.3.3. Non water related societal limitations

The demand for more renewable electric power has been researched in chapter 3.1 Energy Gap, however, that demand that does not necessarily describe a demand for RED electric power if it is extremely expensive and/or environmentally unfriendly. As said before, the economic aspects and predictions are outside the scope of this research. Although economic factors are deemed highly important to determine how realistic an upscaling process of the REDstack powerplant is, it is considered to be a next step in the process. First, it should be determined if it is physically possible and socially desirable to scale the powerplant up and afterwards, it should be determined if it is financially interesting to do so. Therefore, this research will leave a full financial analysis outside of its scope and will hopefully provide knowledge that follow up financial research can build further upon. A first estimate, based on literature, shows that it is financially not unrealistic to build such a powerplant. Budde's research (2021) showed that estimated capital investments to build a 200 MW plant would be around 900 million euro, which would be comparable to the price to build 140-240 wind turbines to generate roughly the same amount of energy, which would end up between 700 – 1400 million euros. If recent membrane prices of 50 €/m^2 could be reduced to 4.3 €/m^2 , which might be possible by scaling up the production and using cheaper materials, electricity can be produced for 0.18 €/kWh (Tufa et al., 2018). With the current risen energy prices, due to the war in Ukraine, RED energy could become economically compatible even sooner.

The ecological impact of a RED powerplant on the Afsluitdijk is also outside the scope of this research, but a short mention of relevant research might shed some light on whether it is ecologically devastating or not. Research by Deltares (Herman et al., 2020), showed that the power plant of REDstack could be scaled up to at least 100 MW, without major implications for the environmental surroundings. The salinity of the Wadden Sea would not be impacted significantly by upscaling the powerplant - even to 600 MW – since only a small percentage of the fresh water discharge to the sea is going through the REDstack, whilst most of it is discharged through the sluices. A cumulated effect of a return stream of brackish water was not detected in simulations by Deltares, nor was a large effect on surrounding environment and direct mortality effects of zooplankton and other organisms detected (Herman et al., 2020). Therefore, the environmental impact a scaled up version of REDstack would have is considered to be minimal and will not be researched further in this report.

4.3.4. Energy market

A upscaled renewable powerplant should, of course, be well connected to its customers. The connection should exist of proper energy transportation and the produced power should be economically competitive with other renewable energy sources. The Dutch energy landscape will shortly be discussed, to determine if there is space for REDstack to participate in the energy market.

Energy transitions, like the one proposed in the Climate Agreement (2019), are not a new phenomenon (de Jong & Stremke, 2020). The Dutch energy landscape has gone through major changes throughout history, including the transition from renewable energy (mostly wood and wind energy) sources to a fossil fuelled society. The transition "back" to a low-carbon society as a climate change mitigation measure started at the end of the 20th century and involves the reduction of energy usage and the increase of the share of renewable energy in the total energy mix. This energy landscape transition also transforms the physical landscape in the Netherlands – including wind turbine parks, photovoltaic parks and energy crops along with an improved electricity network (de Jong & Stremke, 2020). These renewable energy sources require a relatively large share of land, compared to fossil fuels. The Climate Agreement (2019) states the needed transition towards a CO2 emission free electricity system as a society-wide undertaking. The involvement of citizens, companies, governmental institutions, scientists, societal organisations and neighbouring countries is deemed crucial for the success of the transition. The objective is to reduce the CO2 emissions from the electricity system with at least 20.2 Mton in 2030 – meaning an upscaling of the renewable electricity production to 84 TWh or 302,400 TJ in 2030.

The energy value chain involves various actors, from the producers to end-users, which are guided by institutions and economic governance systems (De Bakker et al., 2020). Traditionally, the electric energy chain consisted of the generation and trading done by commercial production companies. The transmission – which is the electricity transport through the high voltage grids -- operated by the Transmission System Operator Tennet, the local medium to low voltage distribution by Distribution System Operators and the final delivery to the end-users (De Bakker et al., 2020). This value chain used to be dominated by the Dutch national government and energy companies, with little to no role for society besides consuming, until the 1980's. The neo-liberalisation wave led to the unbundling of the distribution network (state owned) and the other parts of the value chain (liberalised), which resulted in the rise of many competing, independent, profit-led energy companies and suppliers (De Bakker et al., 2020; Kwakkel & Yücel, 2014).

The new, open energy market has invited citizens to be stakeholders in the energy landscape as well, dividable along two axes: individual actors versus collective actors and producing exclusively renewable energy versus producing non-renewable or mixed energy sources (Horstink et al., 2021). This pluralization of the energy market complicates the system on the one hand, since actors can now take on many forms, e.g. prosumers, but on the other hand has also led to room for citizen innovations and initiatives, such as local prosuming cooperatives. In the Netherlands, these ambitious local cooperatives often find themselves driven into the hands of commercial partners because of internal deficits and external legal constraints (De Bakker et al., 2020).

The Dutch Climate Agreement ("*Klimaatakkoord*") of 2019 discusses the transition towards 2050, which considers a large-scale wind energy production in the North Sea, a transition to other energy carriers such as hydrogen and a flexible supply and demand energy system -- as most renewable energy producers are weather dependent (Rijksoverheid, 2019). On the other side, the small-scaled citizen and cooperative energy contributions are expected to work together with larger energy actors in a well knitted decentralized energy web. As a result of the Climate Agreement, the electricity demand will increase to 300 – 500 TWh (or $1.08 \cdot 10^6$ to $1.8 \cdot 10^6$ TJ) in 2050, according to TNO's model studies (Scheepers, 2022). The idea is that anyone can participate in the system. The expectation in the Climate Agreement is that the renewable energy prices will drop through, amongst others, technological advancements and the expansion and optimalization of the distribution networks, to a competing point with non-renewable energy in 2025 (Rijksoverheid, 2019).

Combining these factors, REDstack has the ability to scale up considerably, given the growing societal demand for electricity, the governmental structures and the increasingly supported opportunity to take part in the Dutch energy system.

5. FUTURE DEVELOPMENT OF LIMITATIONS

Trends of the previously described external factors will be used to describe a future prognosis until 2050, to examine if Reverse Electrodialysis will be increasingly or decreasingly interesting for the Netherlands to invest time and resources in. To execute this prognosis, data linked to the external limiting factors will be derived from KNMI and Delta scenarios. First, the methodology and background information on these scenarios will be discussed. Next, linear forecasts of the physical factors, based on the Rijkswaterstaat data, are extrapolated to 2050. Afterwards, the Delta scenarios are applied to the external limitations and their results are analysed. Lastly, literature on expected trends will be discussed.

5.1. Scenarios

The natural temporal and spatial variability of the climate, defined as the average weather including the statistical distribution, together with the anthropological forcing, makes it difficult to predict the climate very precisely and accurately multiple decades ahead. Nonetheless, a description of probable future states of the regional climate are helpful foresights for society. Basing these images on historic and current observed climatic drivers and applied (model) projections, the conditional 'scenarios' can be considered the best estimates of the future (van den Hurk et al., 2014). A climate projection is defined as a simulated climatic response to imposed forcing, or a potential future situation based on a forced scenario, by IPCC in 2013(b) (derived from van den Hurk et al., 2014). A climate scenario is described, in the same report, as a simplified but plausible representation of the future climate, often based on climate projections and additional information on the current system. A climate scenario is often used as input for impact models (van den Hurk et al., 2014).

A climate model is used as a forecasting tool for decisionmakers and to improve the understanding of the current climate system. Historically, adaptation measures were taken after a natural event had taken place, but in recent years the Dutch authorities have shifted to shape the landscape in anticipation for probable future conditions. The – at this moment most recent - 2014 KNMI Climate Scenarios were for example used in the Dutch Delta Program to strengthen the delta infrastructure and hydraulic landscape (van den Hurk, 2014).

5.1.1. KNMI scenarios

The Royal Dutch Meteorological Institute "KNMI" is the national data and knowledge institute on climate sciences, which advices the ministry of Infrastructure and Climate. Using climate models, they translated the - then most recent- 2013 IPCC report into probable climate scenarios for the Netherlands (van den Hurk et al., 2014). This resulted in the following five scenarios: GL (global temperature increase of 1^{o} Celsius in 2050 and 1.5 in 2085, with little airflow change), WL (global temperature increase of 2^{o} Celsius in 2050 and 3.5 in 2085, with little airflow change), GH (same temperature increase as in GL, with changes in airflow), WH (same temperature increase as in WL, with changes in airflow) and the extra scenario WHdry, a scenario that includes severe droughts in the summertime over the whole continent (Klijn et al., 2015). Mens et al. (2020), used the relative changes for the Dutch summer and winter in 2050 compared to the reference date 2017, based on the 2014 climate scenarios by KNMI, into a graph. They left out WHdry. It is adapted into the following table 3:

Table 3: The meteorological changes per KNMI scenario for 2050, in reference to 2017. Based on Mens et al. (2020).

Scenario		**GL**	**GH**	**WL**	**WH**
Summer	Mean precipitation	+ 1.2%	- 8%	+ 1.4%	- 13%
	Potential evaporation	+ 4%	+ 7%	+ 4%	+ 11%
	Mean temperature	+ 1° C	+ 1.4 ° C	+ 1.7 ° C	+ 2.3 °C
Winter	Mean precipitation	+ 3%	+ 8%	+ 8%	+ 17%
	Mean temperature	+1.1° C	+ 1.6 ° C	+ 2.1 ° C	+ 2.7 ° C

5.1.2. Delta scenarios

In 2017, the KNMI climate scenarios were combined with WLO’15 socio-economic development scenarios (translated to ‘Prosperity and Living-environment’) by the national institutes for Planning (CPB and PBL). This resulted in the so called ‘Delta scenarios’, which are primarily meant to be used within the Delta programme (Wolters et al., 2018). Later on, these Delta scenarios were also translated into model input for the National Water Model, to perform a freshwater bottleneck analysis (Hunink et al, 2018).

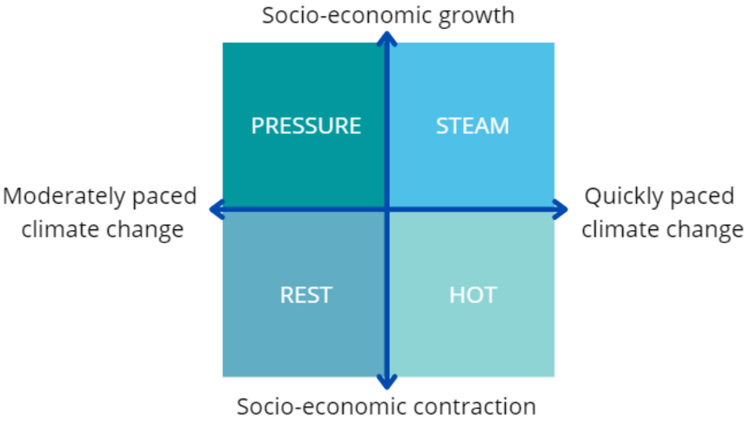


Fig. 19: The uncertainty axes system of the Delta scenarios, which combine the KNMI scenarios (2014) and socio-economic scenarios by PBL and CPB.

The Dutch Delta Programme, created by the government as a policy analysis programme, based the scenarios on the uncertainties involved with climate change and socio-economic development (Wolters et al., 2018). Climate change might lead to more droughts and to more extreme rainfall, to sea level rise and to periodically higher river discharges. Socio-economic developments might result in an economic growth and/or in an increased population – which both would affect the determined flood risk levels and fresh water supply. Therefore, four scenarios have been created, based on two uncertainty axes of socio-economic development and climate change: “*Druk*” (pressure), *“Stoom”* (steam), “*Rust”* (Rest) and “*Warm*” (hot), as shown in Fig. 19 (Wolters et al., 2018).

The details and storylines of each scenario are well described in literature (Wolters et al., 2018; Nationaal Deltaprogramma, 2022; van den Hurk et al., 2014), therefore only a brief description will be presented in this thesis. In scenario Pressure, a global transition to low carbon energy production takes place before 2050, as a result of growing fossil fuel scarcity and high energy prices. In line with the Paris Agreement, the maximum temperature increase to 1.5 à 2° Celsius will be achieved. In scenario Steam, the quick population and economic growth towards 19 million inhabitants in the Netherlands in 2050 is accompanied by a fast-changing climate. In Rest, a contraction in population and economy leads to less greenhouse gasses being emitted. Energy- and climate-innovations thrive, as well as sustainable regional economies. International climate agreements are therefore relatively easy to achieve. In scenario Hot, no climate agreements will be achieved, and the energy sector will continue to produce fossil fuel-based energy. Globally, there are few investments in climate innovations and technologies, therefore the earth heats up quickly (Wolters et al., 2018).

The physical and societal changes, most relevant for this study, in the Delta scenarios are described in the following Table 4, which is based on Wolters et al. (2018). The scenarios' names were changed in most results from the Delta scenarios, into: S2050 (Delta scenario Steam (*Steam* in Dutch)), W2050 (Delta scenario Hot (*Warm* in Dutch)), D2050 (Delta scenario Pressure (*Druk* in Dutch)) and R2050 (Delta scenario Rest (*Rust* in Dutch)).

Table 4: Societal and physical changes per scenario for 2050, compared to reference year 2017. Adapted from Wolters et al. (2018).

Variable	Unit	Reference 2017	Scenario Pressure 2050 (D2050)	Scenario Steam 2050 (S2050)	Scenario Rest 2050 (R2050)	Scenario Hot 2050 (W2050)
Temperature increase	˚C	0	1	2	1	2
Sea level rise	cm	0	15	40	15	40
Yearly precipitation sum	mm	851	+ 4%	+ 5%	+ 4%	+ 5%
Yearly potential evaporation sum	mm	559	+ 3%	+ 7%	+ 3%	+ 7%
Repetition time high discharge Rhine (> 14400 m^3/s)	years	1250	200	200	200	200
Relative change Rhine discharge during 7 lowest discharge days	%	0	+ 5%	- 20%	+ 5%	- 20%
Dutch population	million people	17	19	19	16	16
Economic growth	%/year		+ 2%	+ 2%	+ 1%	+ 1%

As mentioned before, the Delta scenarios were put to use in the Dutch Delta Programme's National Water Model, which is a set of integrated models used to analyse decisions related to the water management, for example to quantify severe water problems and to identify tipping points and their timing. Part of the input data consisted of modelled responses of the rivers Rhine and Meuse to these climatic changes. The river Rhine, which is the main source of the river IJssel, retrieves its water from an extensive catchment area, consisting of multiple sub-catchment areas (Klijn et al., 2015). Snowfall in the Alps, lakes in the mountains of Switzerland and the Bodensee in Germany all have a dampening effect on the oscillating discharge regime of the river (Klijn et al., 2015). Therefore, there are currently not large differences between the summer and winter discharge. However, the Delta scenarios of 2014 showed that in all scenarios, extreme precipitation, especially during the winter will lead to a more erratic river discharge of the Rhine, with on average higher discharges during the winter months and lower discharges during the summer.

5.2. Forecasts in literature

The results of the KNMI and the Delta scenarios are described in literature (Buitelaar et al., 2015; Klijn et al., 2015) and integrated in national Delta programmes (Wolters et al., 2018; Nationaal Deltaprogramma, 2022). The results that describe or may influence the future of the physical factors that limit RED are discussed below.

5.2.1. Physical factors

Climate change prognoses for the IJsselmeer area include an increase in winter precipitation over the catchment area of the river Rhine -- and therefore an increase in (peak)discharge of the river IJssel (Van Ginkel et al., 2022). On the other side of the Afsluitdijk, the sea water level of the Wadden Sea is also expected to rise. KNMI expects a sea level rise of 30 - 121 cm in the year 2100 under different scenarios for the Dutch coastal area (KNMI, 2021). These changes will affect the IJsselmeer area in multiple ways, which include a smaller discharge window from the Afsluitdijk, resulting in higher water levels in the IJsselmeer and therefore an increase in flood risks.

Climate change will most likely change the incoming and outgoing flow of water in the IJsselmeer water balance. In all climate scenarios, the mean precipitation increases, especially in the winter, while the summers get slightly drier – except for KNMI scenario WHdry, where it becomes much drier in the summer (Klijn et al., 2015). It is expected that high discharges will become extremely higher and low discharges will become lower (Buitelaar et al., 2015). All Delta scenarios show that the increased precipitation will result in higher discharges of 10-20% of the Rhine River in 2050. In 2085, it might even increase up to 40% during winter months. As a result, the flood risks also increase by means of frequency and water levels. All scenarios show a discharge of 12.000 m^3s^{-1} water every 30 years in 2050, while it is currently once every 100 years (Klijn et al., 2015). On the other hand, most scenarios show merely a small decline in low discharge levels at the end of the summers, except for the driest scenario (WHdry), which shows 20 – 30% lower water levels in the Rhine in 2050 during this period (Klijn et al., 2015). On top of that, the river IJssel will receive proportionally less Rhine water due to erosion in the Rhine, which disrupts the water distribution. A stress test showed that if we continue with business-as-usual policies and have severe climate change (KNMI scenario Steam 2050), the IJsselmeer water buffer layer will be depleted every 5 years (Buitelaar et al., 2015).

The governmental strategy on how to deal with climate change in regards to the IJsselmeer, is as follows. The winter water level should remain the same until 2050, to ensure water safety and drinking water supply. To make sure that the rising sea level and the predicted higher IJssel discharge do not lead to a rising water level in the IJsselmeer, pumps will be installed at Den Oever. If it is deemed necessary to increase the water level during the winter, the change will only take place 25 years after the decision making moment. This ensures the predictability and stability for the involved stakeholders and the environment, as well as the time to make socio-environmental just decisions (Nationaal Deltaprogramma, 2020).

The sea level will rise in all KNMI scenarios, which will influence the water level of the Wadden Sea (Wolters et al., 2018). Pumps are therefore being installed on the Afsluitdijk, to ensure that water can be discharged, even if the discharge window gets smaller. In 2050, the overall sea level is expected to rise 11 centimetres in scenario Gl, compared to the water level in 2017 (which was 7 cm above NAP), and 36 centimetres in Wh, compared to 2017 (Mens et al., 2020). A lack of precipitation, also described as a meteorological drought, will happen more frequently in the KNMI scenarios with rapid climate change, just as the discharge shortage for the river Rhine.

Salinity levels in the IJsselmeer are expected to increase with a warmer climate and rising sea level, as a result of more evaporation and saltwater intrusion, which threatens the drinking water security of the Netherlands, as well as other societal demands. Therefore, several measurements have been proposed to counteract the process as described by Rijkswaterstaat (2021). With these potential interventions ready to be installed, it may be assumed that salinity levels in the IJsselmeer will remain similar to current levels until 2050. Changes in salinity levels of the Wadden Sea are not discussed in the Deltascenarios, nor in the KNMI scenarios. Therefore, it is assumed that they do not change substantially.

Water temperatures of the Wadden Sea and lake IJsselmeer are not discussed in the scenario studies of KNMI and the Delta scenarios, nor could they be found in relevant academic literature. So, the best estimation of the development of the surface water temperature over time is linking it to the most recent IPCC report (IPCC report 6) and to the expected changes in local air temperature. The average ocean surface temperature has been increasing for a while, as reported in the 6th IPCC report by Fox-Kemper et al (2021), and is projected to increase by 0.86 °C towards 2100 under their scenario SSP1-2.6, and by 2.89 °C under scenario SSP5-8.5. This is a global average, but it confirms that warming water trends are observed globally and are very likely to continue into the future. As Morrill et al. (2001) described, air and water temperature do not often show a linear 1:1 temperature trend, but the majority of their measurements in streams show a 0.6 to 0.8 degrees water temperature increase for every 1 degree increase in air temperature. As with all future predictions, we can only describe our ‘best guess’, and without any other model quantifications, it is our current best guess that the water temperatures will follow the air temperature increase in the scenarios. Since the air temperature changes are known, the water temperature changes can be assumed too. Following the Delta scenarios, the water temperatures will increase with 1°C in scenarios Pressure and Rest, and with 2°C in scenarios Steam and Hot (Wolters et al.., 2018).

5.2.2. Forecasts societal factors

The extremely dry summer of 2018 has shown that the drinking water demand will probably increase with the predicted more extreme dry periods (Nationaal Deltaprogramma, 2020b). The water demand of the IJsselmeer is also expected to increase to fight peat land subsidence and oxidation and as a result of socio-economic developments (Nationaal Deltaprogramma, 2020b). Expected changes in water demands from the whole IJsselmeer region, under the Delta scenarios, were described by Wolters et al. (2018) in percentages. With these percentages, the absolute numbers could be calculated using the reference data from Rijkswaterstaat, as described in chapter 4.3 Societal Limitations. Unfortunately, not all water demanders were described in the Delta scenarios, so only a few show changes.

Table 5: Quantified water demands according to the changes under the Delta scenarios for 2050, based on Rijkswaterstaat (2021) and Wolters et al. (2018).

Water demanders	Reference from Rijkswaterstaat (2021)	Relative changes in 2050 (Delta scenarios)	Absolute changes in 2050 (Delta scenarios)	Relative changes in 2050 (Delta scenarios)	Absolute changes in 2050 (Delta scenarios	Relative changes in 2050 (Delta scenarios)	Absolute changes in 2050 (Delta scenarios)	Relative changes in 2050 (Delta scenarios)	Absolute changes in 2050 (Delta scenarios)
Scenario		Pressure	Pressure	Steam	Steam	Rest	Rest	Hot	Hot
National water level maintenance	186.5								
Regional water level maintenance	58.1								
Drinking water	48.5	+10%	53.35	+35%	65.475	-10%	43.65	0	48.5
Flushing to prevent salinization	40	-25%	30	+100%	80	-10%	36	+20%	60
Agricultural irrigation	33	(Land use) +4%	34.32	(Land use) +55%	51.15	(Land use) +8%	35.64	(Land use) +60%	52.8
Others	15.8								
Temporary irrigation capital-intensive crops	14.1								
Grass- and cornland irrigation	10								
Processing water	2.1								
Cooling water for electrical energy producers	0.6	-80%	0.12	-80%	0.12	-80%	0.12	-80%	0.12

The mean societal water demand came down to 408.7 m^3/s between 1912 and 2012, as described in chapter 4.3 Societal Limitations. The mean societal demands under the scenarios, taking the changes provided by the Delta scenarios (Wolters et al., 2018) into account, were calculated based on the following table 5.

Based on this quantification, the total water demands from the whole IJsselmeer area change from 408.7 m^3/s in the reference data to 404.39 m^3/s in scenario Pressure, 402.01 m^3/s in scenario Rest, 483.35 m^3/s in scenario Steam and 448.02 m^3/s in scenario Hot.

The reasoning behind these societal water demand changes is described by Van Ginkel et al. (2022), and can be summarized as follows. The Dutch Climate Agreement (*Klimaatakkoord* 2019), states that the emissions from peatland oxidation should be reduced by one megaton CO_2 equivalent, which means that the water demand for irrigation of these peatlands will increase. Calculations show that in the current climate, $200 \cdot 10^6$ m^3 of fresh water are needed to irrigate these areas, which will increase up to $400 \cdot 10^6$ m^3 in 2050 under the most severe climate scenarios (Van Ginkel et al., 2022). Technological advancements may also result in an increased water demand, such as data centres and hydrogen production facilities. Because of droughts, the agricultural land that needs irrigation will likely expand, up to 60% surface increase. That also increases the water demand for irrigation purposes (Wolters et al., 2018). Water demand for electrical energy production cooling purposes decreases in all scenarios with 80% since the scenarios integrated a transition towards renewable energy sources – resulting in a decreased demand for cooling water. Not included in the table, but noteworthy is that the regional water demand, consisting of the polder flushing, irrigation and regional water level maintenance, is expected to rise from 1750 million m^3 to 2600 million m^3 during extremely dry years in 2050 (Van Ginkel et al., 2022).

Van Ginkel et al. (2022) also describe the fresh water demands complications, that are expected to result from climate change and societal developments. Under the most extreme KNMI climate scenarios, the freshwater availability declines severely during the summer months due to an increased societal demand, resulting from demographic growth and an industrial response to climate change. Under current circumstances, the primary water buffer will only be depleted once every 50 or 100 years. Model studies by the KNMI show that the freshwater buffer of the IJsselmeer is no longer sufficient under the most extreme scenario's in 2050, showing a water shortage every 6 out of 100 years. Human interventions could deviate this scenario to 2 times every 100 years, by redirecting the discharge of the Rhine into the IJssel or redirecting water from the Amsterdam Rhine channel into the IJsselmeer (Nationaal Deltaprogramma, 2020).

The National Delta programme for 2023 (Nationaal Deltaprogramma, 2023) states that the safety goals for 2050 seem achievable. They do note that new water demanders and land use changes should be critically evaluated if they do not endanger the goal. Stress tests done in the same year, show that the freshwater buffer may not suffice for the coming years, which is why they advise that this buffer should increase, and new water demanders should be denied (Nationaal Deltaprogramma, 2022). The current flexible water level, which ensures the water buffer, will therefore be evaluated in 2028.

Quantification of scenarios may give the false idea that the numbers are set in stone, as is of course not the intention of forecasting and scenarios. As stated before, only time can tell what the future holds. But, the Delta scenarios applied to the influx of lake IJsselmeer and to the societal demands might reveal future bottlenecks in water shortages – which might be interesting to look at before implementing an upscaled RED powerplant.

5.3. Applied Delta scenarios

To test the consistency of the data provided by the Delta scenarios, the mean monthly values of the discharge from the Afsluitdijk of the reference scenario of the Delta scenarios were compared to those previously used from Rijkswaterstaat (2021) (see chapter 4.2.1). The datasets could be compared on the overlapping years, which ranged from 1990 – 2012. The resulting graph, Fig. 20, can be seen below.

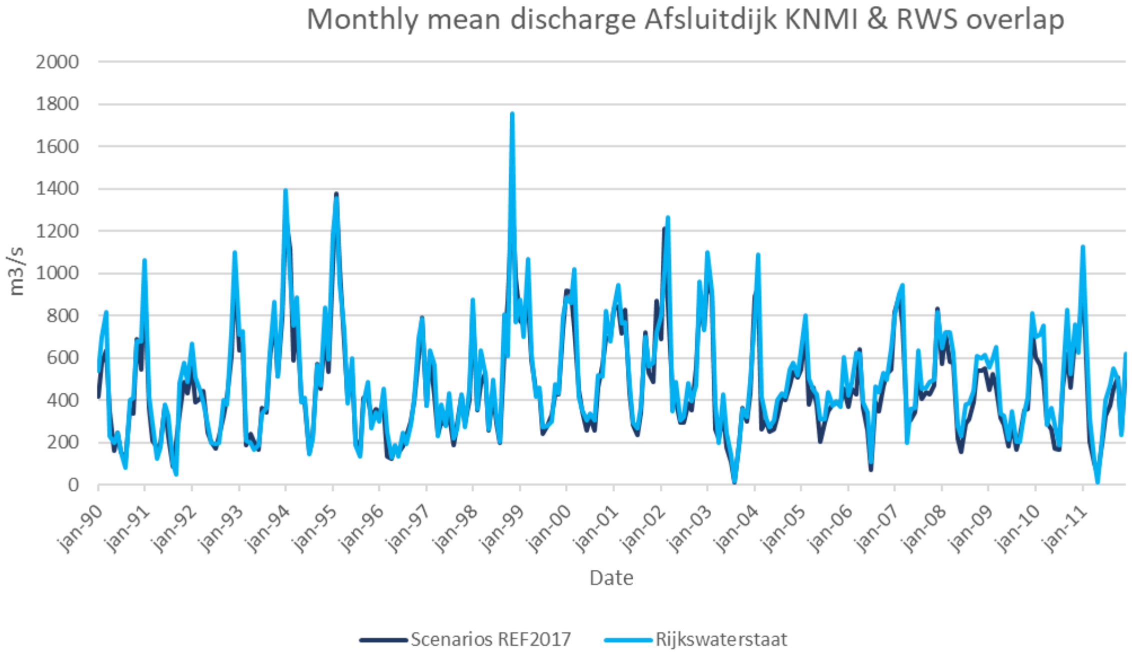


Fig. 20: Comparison between REF2017 (Delta scenarios) and Rijkswaterstaat data.

Visually, it appears to be quite a good match. As expected, the reference scenario is strongly driven by the observations. After calculations, the Nash-Sutcliffe (which used to assess the predictive skill of an hydrological model) shows a value of 0.89, which is bigger than 0.6 and therefore acceptable. The Relative Volumatic Error, on the other hand, shows a value of -8.1 %, which is not acceptable as it does not fall within the +- 5% range. That means that there is a volumetric discrepancy between the two datasets, and it cannot be accepted as a fair representation of the reference model, which is Rijkswaterstaat in this case. However, this is a cut out of a small period, and it could be that the values of the Nash Sutcliffe and Relative Volumatic Error would both show acceptable results if taken over the whole 100 year time period. Most likely, it could be that the Delta scenarios were based on the Rijkswaterstaat data but assimilated to close the model's water balance.

Since the volumetric error is rather large, there ought to be a separation between the Delta scenarios and the observed Rijkswaterstaat data. That is why they will not be combined in this study. As mentioned before, the scenarios are visualized over a 100 year period, to show variability and take extreme climatic events into account. Therefore, one result value in 2050 cannot be presented (and does not mean that much) but the result consists of a different climatic pattern, from which conclusions can be drawn. For example, the number of meteorological droughts per 10 years, or the in- or decrease of flood risk for regions. To visualize the data, the results from all scenarios were plotted on top of each other for a thirty year period, to show to what extent they differ from the REF2017 data, as shown in Fig. 22. Differences were hard to detect over the 100 year period, therefore it was zoomed into a 30 year period. To clarify the differences even better, the reference data were subtracted from the prediction data. This shows the difference between the monthly values of the scenarios compared to the reference data, as shown in Fig. 21.

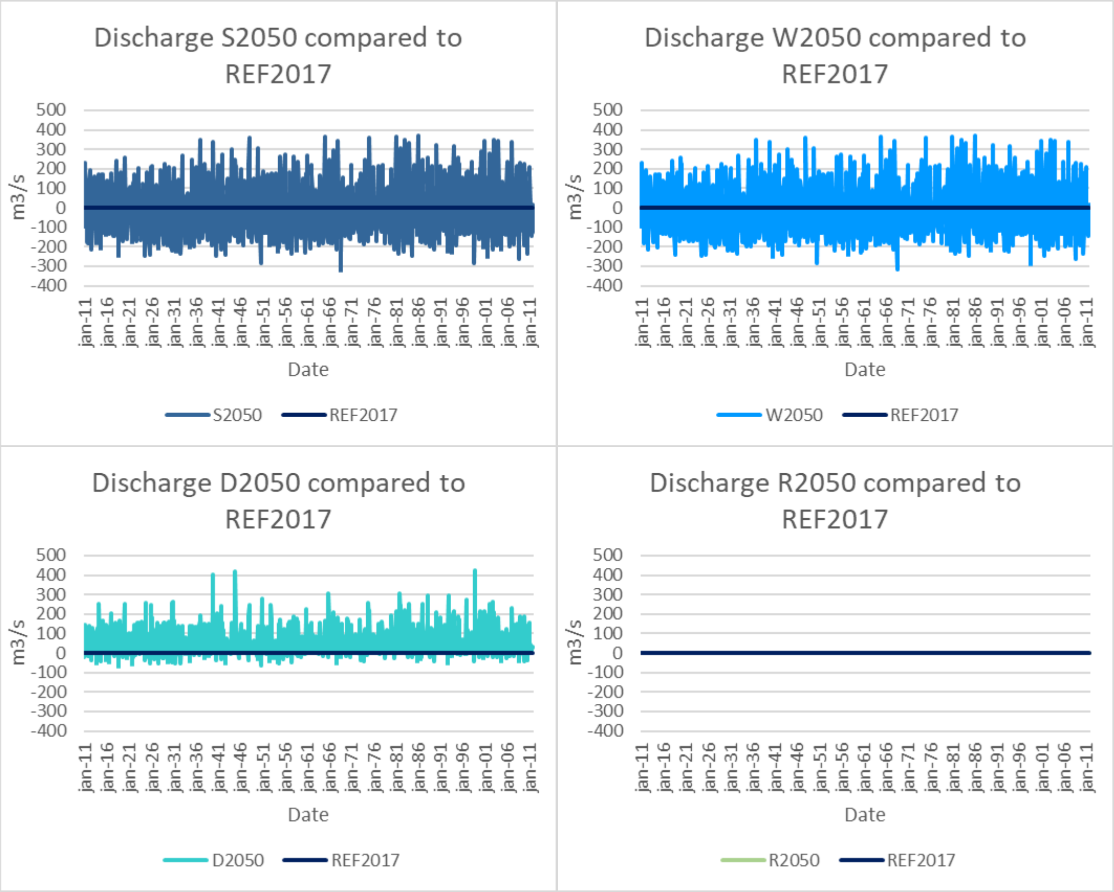


Fig. 22: Difference between results from scenarios compared to the REF2017 data.

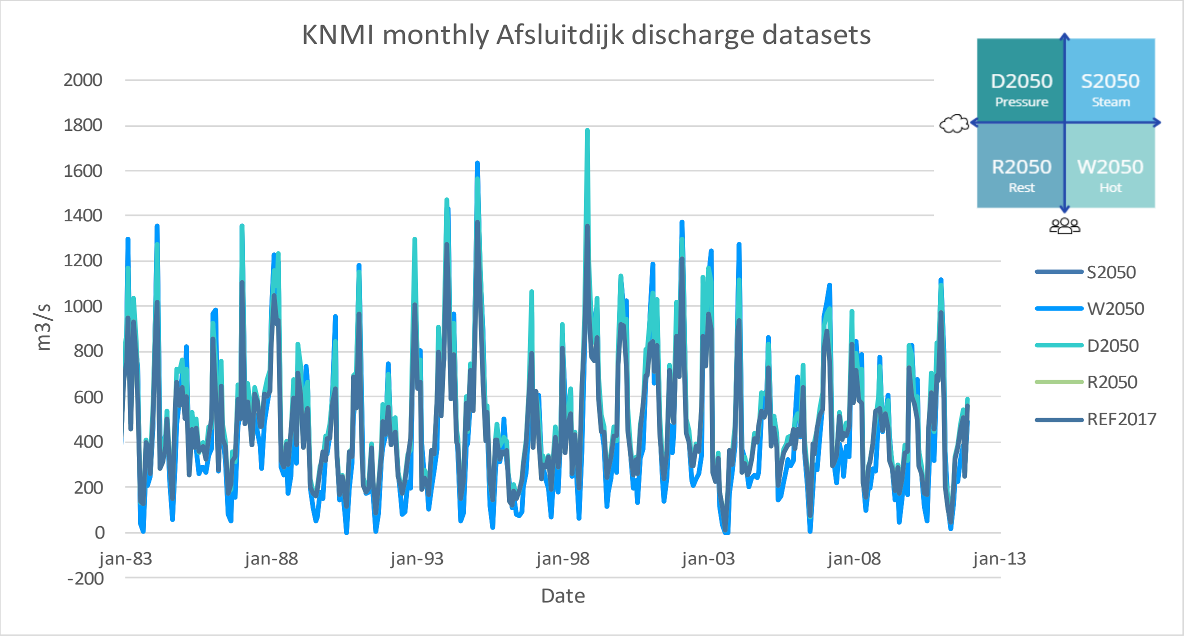


Fig. 21: All Delta scenarios results for the discharge from the Afsluitdijk, shown between 1983 - 2013.

It can be derived from the visualizations that scenarios Steam (S2050) and Hot (W2050) show more extreme discharges, with higher as well as lower discharges during the whole 100 year periods, and appear to follow a similar oscillation. Scenario Pressure (D2050) shows mostly higher discharges over the Afsluitdijk. Interesting to see is that scenario Rest (R2050) shows no differentiation from REF2017. It could be that discharge changes do appear in other measurement points, and for some reason do not at this specific point. The reason why there is no difference is not known at this point, and should be researched for further reference.

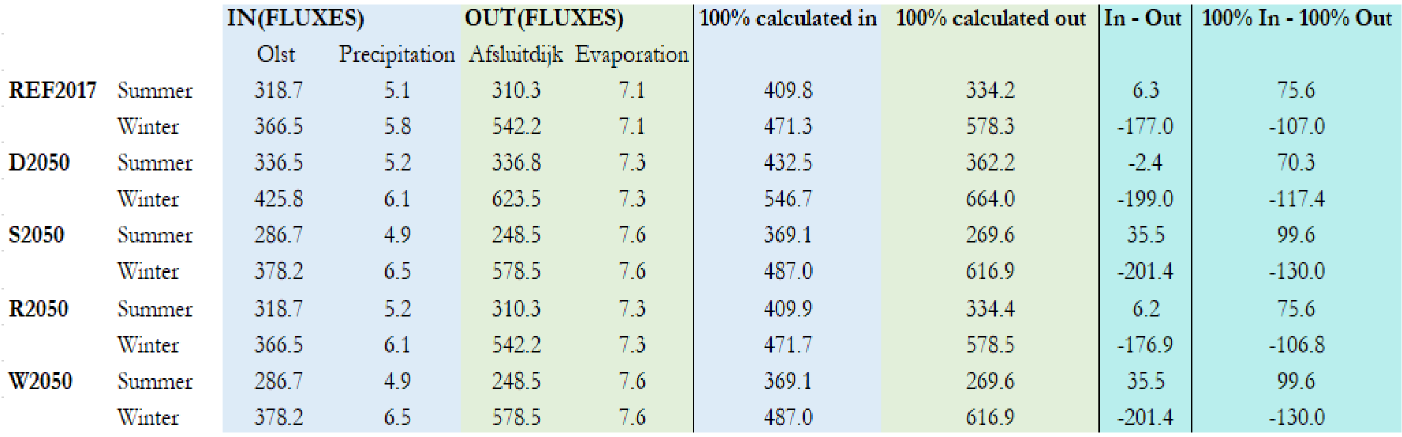
After visualizing the data, the scenarios were used to show expected volumetric values of discharge over the Afsluitdijk -- which are useful to estimate what the volumetric limitation could be in the future. In line with the conclusions based on the visualization of the data above, the scenarios Steam and Hot show higher values in the winter time and lower values in the summer time. In addition to that, the values of both scenarios are the same, explaining why the graphs in Fig. 21 looked so similar. The means per season for scenario Pressure show higher values, as expected based on the graphs before, and the means per season of scenario Rest are the same as those of REF2017. The data distributions can be found in Appendix 4, in the form of histograms per season. The mean values are presented in the following table 6:

Table 6: Scenario's discharge means Afsluitdijk per season.

Scenario	**Winter mean in m³/s**	**Summer mean in m³/s**
REF2017	542.23	310.33
S2050	578.46	248.47
W2050	578.46	248.47
D2050	623.51	336.76
R2050	542.23	310.33

Similarly to the mean discharge of the Afsluitdijk per season per scenario, the mean discharge of Olst could also be retrieved from the Delta scenarios. The precipitation and evaporation variation could be derived from the Delta scenarios as well, as shown in Table 5. Using these datasets, simplified water balances could be calculated, as presented in Table 7. Using the relative contributions the fluxes have to the total water balance of the IJsselmeer, as shown in Fig. 7 (chapter 3.2.1), the values of the in- and outfluxes could be recalculated to 100% inflow and 100% outflow. Do note that none of these water balances close, not even the ones that were calculated to the in and outflow of 100%, strongly visualizing the uncertainty that is involved in these datasets. These balances are presented to indicate seasonal

Table 7: Simple water balances of the Delta scenarios in m3/s.



		IN(FLUXES)		**OUT(FLUXES)**		**100% calculated in**	**100% calculated out**	**In - Out**	**100% In - 100% Out**
		Olst	Precipitation	Afsluitdijk	Evaporation				
REF2017	Summer	318.7	5.1	310.3	7.1	409.8	334.2	6.3	75.6
	Winter	366.5	5.8	542.2	7.1	471.3	578.3	-177.0	-107.0
D2050	Summer	336.5	5.2	336.8	7.3	432.5	362.2	-2.4	70.3
	Winter	425.8	6.1	623.5	7.3	546.7	664.0	-199.0	-117.4
S2050	Summer	286.7	4.9	248.5	7.6	369.1	269.6	35.5	99.6
	Winter	378.2	6.5	578.5	7.6	487.0	616.9	-201.4	-130.0
R2050	Summer	318.7	5.2	310.3	7.3	409.9	334.4	6.2	75.6
	Winter	366.5	6.1	542.2	7.3	471.7	578.5	-176.9	-106.8
W2050	Summer	286.7	4.9	248.5	7.6	369.1	269.6	35.5	99.6
	Winter	378.2	6.5	578.5	7.6	487.0	616.9	-201.4	-130.0

differences in the fluxes per scenario. Noticeable are the differences between the reference scenario REF2017 and R2050, which did not show differences so far. In all scenarios, the calculated 100% influxes are greater than the 100% outfluxes in the summer months, while in the winter months, the 100% outfluxes are substantially larger than the calculated influxes. The yearly difference between 100% in and out comes down to about -30 m³/s for all scenarios, while the yearly water balances of the influxes (In – Out) show a greater variety in the scenarios (REF2017 -170.7; D2050 -201.4; S2050 -165.9; R2050 -170.7; W2050 -165.9). The main message from this table is that in all scenarios, there is more water leaving the water balance than is flowing in.

Using the Afsluitdijk discharge values of the scenarios, a similar graph to Fig. 14 could be created, showing the percentage of time REDstack could produce at maximum capacity, given the available volume of water. The same approach was applied as discussed in chapter 4.2.1, resulting in the following Fig. 23. As explained above, the lines of scenarios Steam and Hot overlap, as do those of REF2017 and Rest.

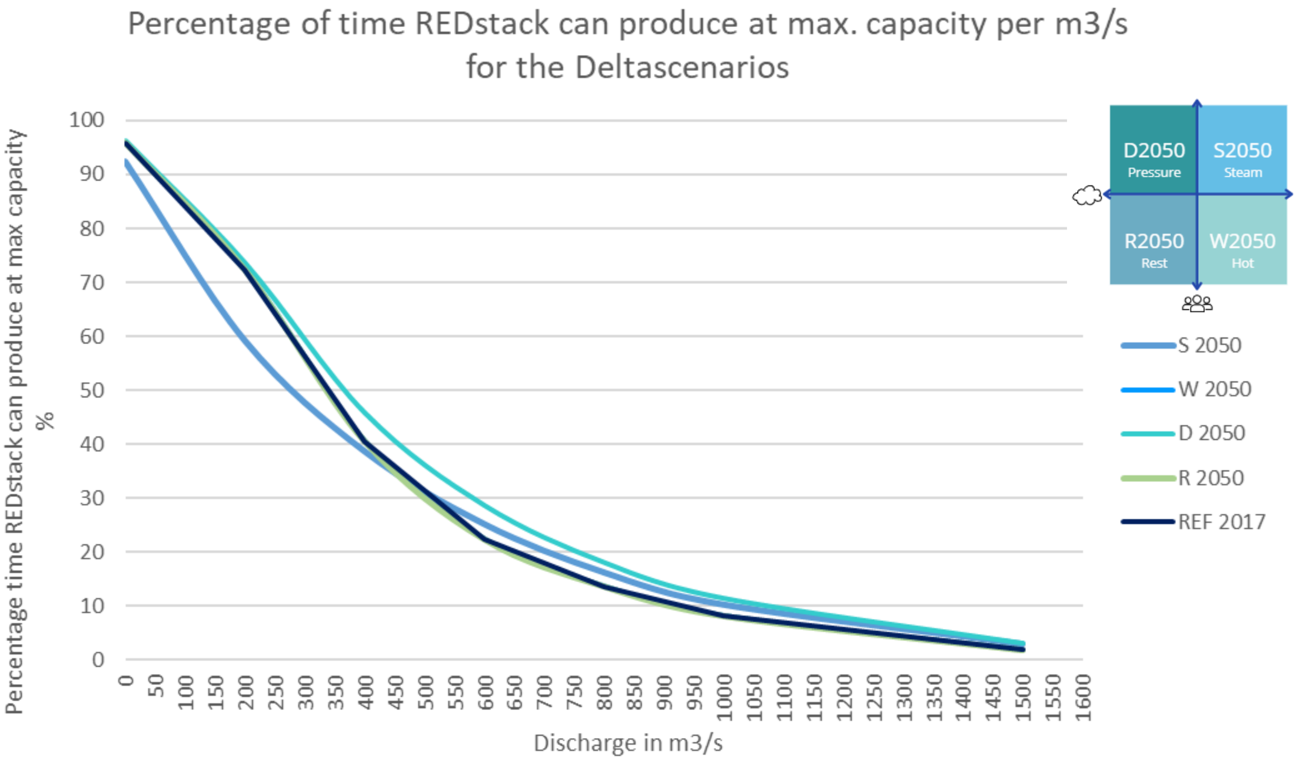


Fig. 23: Percentage of time a certain amount of water was discharged from the Afsluitdijk, based on the Delta scenarios.

It appears that the scenarios follow different trajectories than that of REF2017. The trajectory of available volume of water per percentage of time for scenarios Steam and Hot drops substantially quicker at the lowest discharge values than the line of the REF2017 and scenario Rest. Interestingly, the lines do cross each other later on, around 500 m³/s or 30% of the time, after which REF2017 and scenario Rest shows lower values than that of the S2050 and W2050 lines. Scenario Pressure, on the other hand, appears to follow a trajectory along higher discharges and higher percentages of time, compared to REF2017 and scenario Rest.

From the Figure 23 and table 6, it can be concluded that there will be as much or more water discharged from the Afsluitdijk during the winter months for all scenarios, with scenario Pressure showing the highest impact on discharge and the RED powerplant. During the summer months, less water will be discharged under scenario Steam and Hot, the same amount of water will be discharged under scenario Rest, and more water will be discharged under scenario Pressure – the latter again showing the most promising results for REDstack. Fig. 23 showed that up until 500 m³/s, REF2017, Rest and scenario Pressure present the highest percentages of time that the amounts of water are available for RED purposes. After 500 m³/s, REF2017 and scenario Rest show the lowest percentages per volume of water, followed by scenarios Steam and Hot, and scenario Pressure showing – again – the most promising results for available volume of water.

6. DISCUSSION

This research aimed to clarify the impacts of external limiting factors on the reverse electrodialysis process, specifically for the study area where the trial site REDstack is based. The main findings will be discussed first, after which assumptions, limitations and conclusions of this research are defined. In the following Fig. 24, the main findings of external limitations on the RED plant at the Afsluitdijk are visualized.

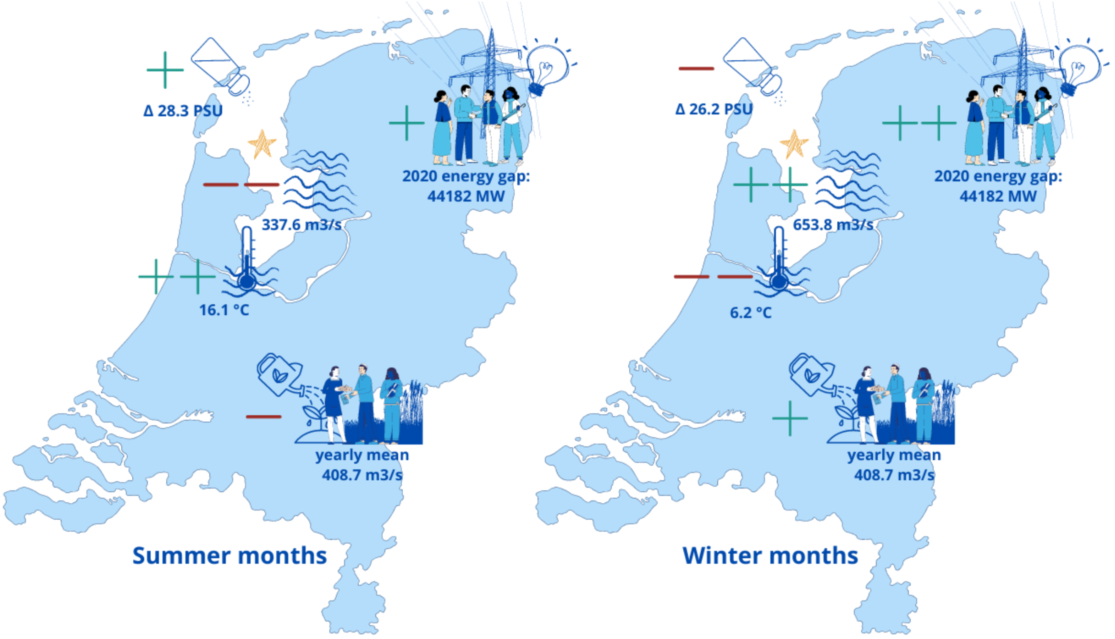


Fig. 24: Current quantified external limitations of RED at the Afsluitdijk.

6.1. Determining the renewable energy gap

By analysing energy usage in the Netherlands, the demand for renewable energy was illustrated as the ‘energy gap’ – the difference between non-renewable and renewable energy usage. Although the share of renewable energy is growing in the total energy mix, the gap is substantially large and expected to remain large in the foreseeable future (Figs. 10 & 11). In 2020, the difference between non-renewable and renewable energy consisted of more than 44 GW for the Dutch total energy usage, and nearly 6.5 GW for electrical energy usage.

It was assumed that the energy demand could be derived from domestic energy usage instead of looking at energy generation, which might have resulted in substantially different demand as energy could be transported to and from other countries. The Dutch energy system is not a closed system within its borders, and it is therefore interesting to see how the energy demand would be determined when looking at a broader spatial scale. It was also assumed that the trends seen in Figs. 5 & 6 would continue into the future.

It should be noted that the summed total energy demand values are not the same for the two used datasets (EUROSTAT and CBS data), which introduces uncertainty into the analysis. Nonetheless, the renewable energy gap is much larger than a realistic maximum power output from REDstack, even taken those uncertainties into account.

The Netherlands aim to reduce their greenhouse gas emissions by 55% in 2030 and become greenhouse gas emission neutral in 2050, as set out in the Paris Agreement. Since most emissions are connected to energy consumption, this reduction is inherently linked to the energy transition. The production of greenhouse gas emission free and renewable electrical energy with the RED process could contribute to these developments. Given the ambitions and the current large energy gap, it is concluded that there is a Dutch demand for more renewable electrical energy production. An analysis of the current developments of the Dutch energy market showed that the designed structure allows for new parties to take part, which is beneficial if REDstack desires to scale up.

6.2. External limitations

To what extent this gap can be ‘filled’ with RED produced energy, depends on the internal and external limitations. This research focuses on the external socio-physical limitations and aimed to decrease the wickedness arising from the various stakeholders and a changing climate by casting light on the interaction and limitations posed by external factors. An important finding is that the external limitations are highly interconnected.

The volumetric availability of fresh water was measured at the discharge sluices on the Afsluitdijk, as this water leaving the water balance of the lake was argued to be ‘rest’ water and could therefore be used in its totality for RED purposes. Based on the analysed data, the mean available amount of water was 337.6 m^3/s during the summer period and 653.8 m^3/s during the winter period. Quantification of the dependence of output power on temperature and salinity was not possible, as a literature study produced relationships that depended strongly on setup parameters such as membrane characteristics and flow velocity - parameters that could not be obtained from REDstack. Therefore, it was assumed that the REDstack powerplant is optimized for the current salinity difference between the feedwaters, and that great changes in this gradients are therefore not preferable. The salinity gradient was 28.3 PSU during the summer months and 26.2 PSU during the winter months. Since REDstack does not artificially alter the water temperatures, the naturally occurring seasonal temperature oscillations impact the power output. The analysed data showed that the water temperatures of the IJsselmeer and the Wadden Sea are fairly identical throughout the year, and both show an increasing trend over time. This means that over time, the power output is expected to increase. Besides that, it can also be concluded that the power output should be higher during the summer months, with a mean value of 16.1 °C, than during the winter months, with a mean value of 6.2 °C.

Both feedwater sources fulfil more purposes than merely a feedwater supply. The biggest freshwater buffer of the Netherlands, lake IJsselmeer, is used for flood defence, as a freshwater buffer and distributer and as an ecological network. The fresh water from the lake is needed for many societal demands, hierarchically listed as follows: demands for national water level maintenance, regional water level maintenance, drinking water, flushing, agricultural irrigation and others. An upscaled version of a sustainable powerplant seems to lie in line with the ambitions of the stakeholders at the Afsluitdijk, and would not necessarily alter or compete with the current fresh water demands if it uses the rest water that is being discharged from the Afsluitdijk. Wickedness arises when there is too little water available for all fresh water demands, which prompts the question if REDstack would still be allowed to operate during drier periods.

A fair amount of assumptions had to be made to execute this research, which posed limitations on this report. One of these assumptions that forms the base for many results, is the assumption that the water being discharged from the Afsluitdijk could be used in its volumetric entirety for RED purposes, as it had already served all other societal demands. It should be researched if this is, in fact, the case. In addition, it is also assumed that the water demand assigned to desalinization measures (the "flushing" water, which is discharged through the sluices on the Afsluitdijk) could also be discharged through REDstack. It might lead to complications for the IJsselmeer water management, or might not be beneficial for REDstack as it affects the salinity gradient. Following up on salinity linked limitations, it would be beneficial for the research to know if the assumption that the REDstack powerplant was optimized for the current salinity gradient is correct or not. The lack of knowledge on internal settings led to limitations on the relationship between the salinity gradient and the power output, and the relationship between the water temperatures and the power output. Likewise, it was also assumed that the temperature of the feedwaters does not change within the powerplant, again resulting from a lack of knowledge on the internal set up of the plant. To determine the monthly mean for the salinity gradient and the water temperatures, the daily mean was taken from multiple measurement points in the Wadden Sea and the IJsselmeer, as discussed in the chapters, which leads to inaccuracies as the calculated value presented in this report may not have been actually measured at any of the points. On top of that, it can be considered an assumption that these monthly means say anything about the feedwaters in the RED power plant, as there were no measurements taken at the location of the plant itself. Locally taken measurements of the water temperatures, the salinity gradient and the availability of saline water – which was assumed to be infinite in this research – would increase the reliability of the results presented in this research. The discussed societal limitations were also limited by assumptions. It was assumed that the plan for an upscaled renewable powerplant would fit right into the plans of local stakeholders and would not compete with other societal demands. It would be most interesting to see if these assumptions were correct.

6.3. Forecasted limitations

Climate projections show that climate change will likely impact the state of the physical and societal factors limiting the RED capacity. The Wadden Sea water level is expected to rise, but the IJsselmeer water level will be managed to stay the same to current levels – which might become increasingly difficult to do. The salinity level of the IJsselmeer is expected to increase, but with intervention measures in place to prevent salinization, we can expect it to be controlled until 2050 and thus remain similar levels to the current situation. No information on changes in salinity levels for the Wadden Sea could be found in literature. The temperature levels of both feedwater sources were also not discussed in literature, but could be assumed to be similar to air temperature changes. They will therefore probably warm up between 1 to 2°C, depending on the scenarios. Societal challenges lie in sustaining the current water levels in the IJsselmeer, under extreme climatic events. The freshwater buffer is expected to be depleted increasingly often under the most extreme scenarios – endangering the water demands such as the drinking water supply.

The used data was published by research institutes of good reputation, but data uncertainties were not documented. This introduces uncertainty into the research, as it was not possible to quantify the reliability of the data. Uncertainties involve measurement uncertainties and inaccuracies, model uncertainties, inaccuracies involved with rounding up numbers, typing errors, etcetera. For the scenarios, uncertainties are expected in every step of the process, from forcing uncertainties involved with crude precipitation and evaporation projections to technical uncertainties involved in the modelling processes. An example of uncertainty given is the difference between the data retrieved from Rijkswaterstaat and that of REF2017 in the Delta scenarios, which showed a relative volumetric error of -8.1%. No hard facts may therefore be derived from these scenario studies, as they are mere simulations of simplified but plausible scenarios. The discussed quantified effects on the external limiting factors come with the same uncertainty warning.

This research was focused on the study area of the REDstack powerplant and its surroundings, but was written with the intent that the methodology could be applied elsewhere too. Researching the proposed physical and societal limitations with a similar methodology, could provide knowledge in other areas as well. After spending time on this research, it appears that in-depth knowledge on the (fresh) water balance and all its influences is the most crucial knowledge needed to describe external limiting factors for RED production.

7. CONCLUSIONS AND RECOMMENDATIONS

The following could be concluded from this research. The gap between non-renewable and renewable energy is substantially large, and is expected to remain large for the foreseeable future. As it is the Dutch ambition to become greenhouse gas emission free in 2050, it can be concluded that there is a large demand for renewable energy – and therefore interesting to research the limitations of the renewable RED technology. The structure of the Dutch energy market also seems to allow for an upscaled RED powerplant. Over the last years, the energy system became more open and easy for non-traditional energy suppliers to take part.

The mean available water was calculated to be 337.6 m^3/s during the summer months (April to October), and 653.84 m^3/s during the winter months (October to April). Seasonal differences could be detected for the salinity gradient between the IJsselmeer and the Waddensea, showing the PSU levels during the summer months at 28.66 PSU for the Wadden Sea and 0.34 PSU for the IJsselmeer. For the winter months, the mean salinity level lied at 26.59 PSU for the Wadden Sea and 0.36 for lake IJsselmeer. The mean water temperatures of the IJsselmeer and the Wadden Sea did not differ substantially. Noticeable was the seasonal variance in water temperatures, ranging from means 6.1°C (Wadden Sea) and 6.2°C (IJsselmeer) during the winter months, to the mean values of 16.0°C (Wadden Sea) and 16.2°C (IJsselmeer) during the summer months. Summarized, the highest power output can be expected during the winter months for the volume of fresh water, and during the summer months for the highest salinity gradient and water temperatures.

There are several societal forces in play that promote the implementation of more renewable energy sources. Under normal conditions, the water demand of REDstack would not alter the water balance. The wickedness of the situation was specified to be applicable to the fresh water demand when there is too little water available. Analysis showed that over the last 100 years, the societal demand for water from lake IJsselmeer was on average 408.7 m^3/s. These demands are intertwined with the management of the water levels in the lake. During droughts, which are expected to become more frequent due to climate change, the situation may arise that there is not enough water to supply the demanders. In that case, the hierarchical repression sequence is applied, showing who is allowed to retrieve water from the lake during droughts. The RED powerplant is likely to be the second last to still be allowed fresh water, as it would probably fall under the category 'Utilities' as an energy supplier.

By making use of KNMI scenarios and Delta scenarios, the 'best guesses' of what the future holds were discussed. For the physical factors, it is expected that the water balance of the IJsselmeer will likely change. The influx of water is expected to change under most scenarios, with the high discharges expected to become higher and the low discharges to become – under most scenarios - lower. Until 2050, the water level management will not change its current set water levels, to ensure the stability and predictability for all users. The Wadden Sea water level is expected to rise in all KNMI scenarios. Salinity levels are expected to increase in the IJsselmeer, but human interventions are in place to reduce this effect. Water temperatures were not described in the scenarios, but are expected to follow the trends of air temperature increase. The expected societal demand changes were quantified, based on the Delta scenarios and reference data from Rijkswaterstaat, and showed to increase substantially in scenarios Steam and Hot (to 483.3 m^3/s and 448.02 m^3/s, respectively) and to decrease slightly in scenarios Pressure and Rest (404.39 m^3/s and 402.01 m^3/s, respectively).

Further research is highly encouraged. Particularly the quantification of the relationship between internal powerplant settings and external limitation is deemed crucial for further reference, as is an more in depth study on the societal response to the proposed intervention. The quantification of the societal demands, now based on model output for a larger area than the IJsselmeer, would be highly recommended to investigate further. The made assumptions in this research would all benefit from further research. It would be also be highly interesting to see if the used methodology would be useful for studies elsewhere.

All in all, the answer to the research question "How much energy can be generated using RED presently and in the foreseeable future, given the societal and physical circumstances?" is that inherently intertwined socio-physical limitations showed an upscaling potential under all investigated circumstances. Season wise, most water would be available for RED purposes during the winter months, but the optimal conductivity and resistance circumstances are more likely to occur during the summer months. Given the scenario studies, this antithesis may tilt in the near future. With more water expected to enter the lake during the winter months, less water during the summer months, more water evaporating during the summer months - decreasing the salinity gradient -, and overall warmer water temperatures, the winter months may become preferable overall. The societal water demands are expected to change over time, depending on the scenario becoming substantially more or slightly less than the current demand. What can be concluded is that RED is a source of renewable energy that can be substantially upscaled, when societal and physical limitations are taken into account. It is therefore fascinating to continue the research on reverse electrodialysis.

LIST OF REFERENCES

11th trilateral Governmental Conference. (2010). 2010 Joint Declaration on the Protection of the Wadden Sea. Retrieved on 29-3-2023 from https://www.waddensea-worldheritage.org/sites/default/files/2010_joint_declaration.pdf

Acheampong, A. O. (2018). Economic growth, CO2 emissions and energy consumption: What causes what and where? *Energy Economics*, *74*, 677–692. doi:10.1016/J.ENECO.2018.07.022

Ahmad, T., & Zhang, D. (2020). A critical review of comparative global historical energy consumption and future demand: The story told so far. *Energy Reports*, *6*, 1973–1991. doi:10.1016/J.EGYR.2020.07.020

Altıok, E., Kaya, T. Z., Güler, E., Kabay, N., & Bryjak, M. (2021). Performance of Reverse Electrodialysis System for Salinity Gradient Energy Generation by Using a Commercial Ion Exchange Membrane Pair with Homogeneous Bulk Structure. *Water 2021, Vol. 13, Page 814*, Vol. 13, p. 814. doi:10.3390/W13060814

Arcadis. (2022). Saliniteitseffecten gebruik nieuwe spuimiddelen Afsluitdijk; achtergrondrapport bij de natuuranalyse Levvel & Rijkswaterstaat. *Arcadis.*

Avci, A. H., Tufa, R. A., Fontananova, E., Profio, G. D., & Curcio, E. (2018). Reverse Electrodialysis for energy production from natural river water and seawater. *Energy*, *165*, 512–521. doi:10.1016/J.ENERGY.2018.09.111

Benneker, A. M., Rijnaarts, T., Lammertink, R. G. H., & Wood, J. A. (2018). Effect of temperature gradients in (reverse) electrodialysis in the Ohmic regime. *Journal of Membrane Science*, *548*, 421–428. doi:10.1016/J.MEMSCI.2017.11.029

Bestuurlijk Platform IJsselmeergebied. (2020). Joint Fact-finding Studie Robuustheid IJsselmeergebied bij droogte. *Nationaal Deltaprogramma.*

Budde, J. (2021). A comparison of reverse electrodialysis and pressure retarded osmosis as technologies for salinity gradient power. *EGU Master Journal of Renewable Energy Short Reviews* (2021_14), 72-78. https://doi.org/10.25974/REN_REV_2021_14

Buitelaar, R., Kollen, J., & Leerlooijer, C. (2015). Operationeel waterbeheer IJsselmeergebied Inventarisatie huidige waterbeheer IJsselmeergebied door Rijkswaterstaat en Waterschappen. Grontmij, Sweco.

Central Bureau of Statistics (CBS). (2022). *S*tatLine—Energiebalans; aanbod, omzetting en verbruik. *StatLine*. https://opendata.cbs.nl/#/CBS/nl/dataset/83140NED/table

Central Bureau of Statistics (CBS). (2023). *Klimaatmonitor*. Retrieved from Grontmij, Sweco website: http://www.klimaatmonitor.nl/

Daniilidis, A., Herber, R., & Vermaas, D. A. (2014). Upscale potential and financial feasibility of a reverse electrodialysis power plant. *Applied Energy*, *119*, 257–265. https://doi.org/10.1016/j.apenergy.2013.12.066

De Bakker, M., Lagendijk, A., & Wiering, M. (2020). Cooperatives, incumbency, or market hybridity: New alliances in the Dutch energy provision. *Energy Research & Social Science*, *61*, 101345.

De Jong, J., & Stremke, S. (2020). Evolution of energy landscapes: a regional case study in the Western Netherlands. *Sustainability, 12(11),* 4554.

Deltaprogramma Zoetwater. (2021). Actualisatie Waterverdeling IJsselmeergebied.

Donatelli, C., Duran-Matute, M., Gräwe, U., & Gerkema, T. (2022). Statistical Detection of Spatio-Temporal Patterns in the Salinity Field Within an Inter-Tidal Basin. *Estuaries and Coasts*, *45*, 2345–2361. doi:10.1007/S12237-022-01089-3/FIG.S/17

Eurostat. (2022). Net electricity generation by type of fuel - monthly data. *Estuaries and Coasts*, *45*, 2345–2361. doi:10.1007/S12237-022-01089-3/FIG.S/17

Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu. (2021). Ocean, Cryosphere and Sea Level Change. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. *Cambridge University Press, Cambridge*, United Kingdom and New York, NY, USA, pp. 1211–1362, doi: 10.1017/9781009157896.011.

Gerkensmeier, B., & Ratter, B. M. W. (2018). Multi-risk, multi-scale and multi-stakeholder – the contribution of a bow-tie analysis for risk management in the trilateral Wadden Sea Region. *Journal of Coastal Conservation*, *22*, 145–156. doi:10.1007/s11852-016-0454-8

Gorny, J., Lijzenga, H., & Van Geest, W. (2022). Re-examining the impact of megaproject governance on project performance: A case study of the Afsluitdijk, The Netherlands.

Head, B. W. (2014). Evidence, Uncertainty, and Wicked Problems in Climate Change Decision Making in Australia. *Environment and Planning C: Government and Policy*, *32*(4), 663–679. https://doi.org/10.1068/c1240

Hekkenberg, M., Benders, R. M. J., Moll, H. C., & Uiterkamp, A. J. M. S. (2009). Indications for a changing electricity demand pattern: The temperature dependence of electricity demand in the Netherlands. *Energy Policy*, *37*, 1542–1551. doi:10.1016/J.ENPOL.2008.12.030

Herman, P., Jager, Z., van Walraven, L., Grasman, S., Wijsman, J., van Duren, L., & Siebers, R. (2020). Onderzoek Omgevingseffecten Blue Energy. *Deltares. Delta Life; Onderzoek Omgevingseffecten Blue Energy.*

Horstink, L., Wittmayer, J. M., & Ng, K. (2021). Pluralising the European energy landscape: Collective renewable energy prosumers and the EU's clean energy vision. *Energy Policy*, *153*, 112262. https://doi.org/10.1016/J.ENPOL.2021.112262

Hunink, J., J. Deisman, G. Prinsen, L. Bos - Burgering, N. Mulder, M. Visser (2018) Vertaling van Deltascenario's 2017 naar modelinvoer voor het Nationaal Water Model. Deltares rapport 11202240-009-ZWS. Utrecht, oktober 2018.

Informatiepunt Leefomgeving (2018). *Uitvoer Basisprognoses 2018 - Zoetwater - Informatiepunt Leefomgeving.* Retrieved from Deltares website: https://iplo.nl/thema/water/applicaties-modellen/watermanagementmodellen/nationaal-water-model/basisprognoses/basisprognoses-2018-zoetwater/uitvoer-bp-2018-zw/

Jang, J., Kang, Y., Han, J. H., Jang, K., Kim, C. M., & Kim, I. S. (2020). Developments and future prospects of reverse electrodialysis for salinity gradient power generation: Influence of ion exchange membranes and electrodes. *Desalination*, *491*, 114540. doi:10.1016/J.DESAL.2020.114540

Kadoshin, S., Nishiyama, T., & Ito, T. (2000). The trend in current and near future energy consumption from a statistical perspective. *Applied Energy*, *67*, 407–417. doi:10.1016/S0306-2619(00)00033-7

Kang, S., Li, J., Wang, Z., Zhang, C., & Kong, X. (2022). Salinity gradient energy capture for power production by reverse electrodialysis experiment in thermal desalination plants. *Journal of Power Sources*, *519*, 230806. doi:10.1016/j.jpowsour.2021.230806

Kleiterp, R. (2012). The feasibility of a commercial osmotic power plant. MSc thesis for Hydraulic Engineering at *TU Delft.*

Klimaatmonitor Rijksoverheid. (n.d.). Klimaatmonitor—Bekende hernieuwbare energie. Retrieved 6 November 2022, from https://klimaatmonitor.databank.nl/Jive/

Koninklijk Nederlands Meteorologisch Instituut (KNMI) (2016). Historisch verloop en statistiek van neerslag en verdamping in Nederland. *Ministerie van Infrastructuur en Waterstaat.* Retrieved 1 januari 2023, from: https://www.meteobase.nl/index.php?tb=basisgegevens&dp=basisgegevens

Koninklijk Nederlands Meteorologisch Instituut (KNMI). (2021). *KNMI klimaatsignaal '21. Hoe het klimaat in Nederland snel verandert.* https://cdn.knmi.nl/knmi/asc/klimaatsignaal21/KNMI_Klimaatsignaal21.pdf

Kwakkel, J.H., Yücel, G. An Exploratory Analysis of the Dutch Electricity System in Transition. *J Knowl Econ* 5, 670–685 (2014). https://doi.org/10.1007/s13132-012-0128-1

Lammens, E., van Luijn, F., Wessels, Y., Bouwhuis, H., Noordhuis, R., Portielje, R., & van der Molen, D. (2008). Towards ecological goals for the heavily modified lakes in the IJsselmeer area, The Netherlands. In T. Nõges, R. Eckmann, K. Kangur, P. Nõges, A. Reinart, G. Roll, H. Simola, & M. Viljanen (Eds.), *European Large Lakes Ecosystem changes and their ecological and socioeconomic impacts* (pp. 239–247). Springer Netherlands. https://doi.org/10.1007/978-1-4020-8379-2_28

Martinez-Soto, A., & Jentsch, M. F. (2019). A transferable energy model for determining the future energy demand and its uncertainty in a country's residential sector. *Https://Doi.Org/10.1080/09613218.2019.1692188*, *48*(6), 587–612.

Mehdizadeh, S., Yasukawa, M., Abo, T., Kuno, M., Noguchi, Y., & Higa, M. (2019). The Effect of Feed Solution Temperature on the Power Output Performance of a Pilot-Scale Reverse Electrodialysis (RED) System with Different Intermediate Distance. *Membranes 2019, Vol. 9, Page 73*, *9*, 73. doi:10.3390/MEMBRANES9060073

Mei, Y., & Tang, C. Y. (2018). Recent developments and future perspectives of reverse electrodialysis technology: A review. *Desalination*, *425*, 156–174. https://doi.org/10.1016/j.desal.2017.10.021

Mens, M., Hunink, J., Delsman, J., Pouwels, J., & Schasfoort, F. (2020). Geactualiseerde knelpuntenanalyse voor het Deltaprogramma Zoetwater fase I*I (No. 11203734-003-ZWS-0002; p. 100). Deltares Zoetwater.*

Mens, M., Pouwels, J., & Kielen, N. (2021). Stresstest van de IJsselmeerbuffer toont noodzaak voor adaptief beleid. *Deltares & Rijkswaterstaat.*

World Meteorological Organization (WMO). (2018). Guide to Climatological Practices. *WMO*, *100.* http://public.wmo.int/en/

Ministerie van Infrastructuur en Waterstaat. (2018). Agenda IJsselmeergebied 2050. Krachten bundelen voor het Blauwe Hart. https://www.hetblauwehart.org/wp-content/uploads/2018/06/AgendaIJsselmeergebied2050_LR.pdf

Moomaw, W., F. Yamba, M. Kamimoto, L. Maurice, J. Nyboer, K. Urama, T. Weir. (2011): Introduction. In *IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C.von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Moreno, J., Grasman, S., van Engelen, R., & Nijmeijer, K. (2018). Upscaling Reverse Electrodialysis. *Environmental Science & Technology*, *52*(18), 10856–10863. https://doi.org/10.1021/acs.est.8b01886

Morrill, J. C., Bales, R. C., Conklin, M. H., Morrill, J. C., Bales, R. C., & Conklin, M. H. (2001). The Relationship Between Air Temperature and Stream Temperature. *AGUSM*, *2001*, H42A-09. Retrieved from https://ui.adsabs.harvard.edu/abs/2001AGUSM...H42A09M/abstract

Nationaal Deltaprogramma. (2020a). *Synthesedocument deltaprogramma IJsselmeergebied; Achtergronddocument H4 bij Deltaprogramma 2021.*

Nationaal Deltaprogramma. (2020b). *Achtergronddocument H4 bij Deltaprogramma 2021; Synthesedocument deltaprogramma IJsselmeergebied.*

Nationaal Deltaprogramma. (2022). *Deltaprogramma Zoetwater: Voortgang 2021 en terugblik eerste fase 2015-2021.*

Nationaal Deltaprogramma. (2023). *Nationaal Deltaprogramma 2023 hoofdlijnen*. www.deltaprogramma.nl

Nazif, A., Karkhanechi, H., Saljoughi, E., Mousavi, S. M., & Matsuyama, H. (2022). Recent progress in membrane development, affecting parameters, and applications of reverse electrodialysis: A review. *Journal of Water Process Engineering*, *47*, 102706. https://doi.org/10.1016/j.jwpe.2022.102706

Ortiz-Imedio, R., Gomez-Coma, L., Fallanza, M., Ortiz, A., Ibañez, R., & Ortiz, I. (2019). Comparative performance of Salinity Gradient Power-Reverse Electrodialysis under different operating conditions. *Desalination*, *457*, 8–21. https://doi.org/10.1016/J.DESAL.2019.01.005

Ortiz-Martínez, V. M., Gómez-Coma, L., Tristán, C., Pérez, G., Fallanza, M., Ortiz, A., Ibañez, R., & Ortiz, I. (2020). A comprehensive study on the effects of operation variables on reverse electrodialysis performance. *Desalination*, *482*, 114389. https://doi.org/10.1016/J.DESAL.2020.114389

Pawlowski, S., Huertas, R. M., Galinha, C. F., Crespo, J. G., & Velizarov, S. (2020). On operation of reverse electrodialysis (RED) and membrane capacitive deionisation (MCDI) with natural saline streams: A critical review. *Desalination*, *476*, 114183. doi:10.1016/J.DESAL.2019.114183

Pintossi, D. (2021). *Fouling in reverse electrodialysis: monitoring, modeling, and control*. Retrieved from Chemical Engineering and Chemistry. Technische Universiteit Eindhoven website: https://pure.tue.nl/ws/portalfiles/portal/173364803/20210611_Pintossi.pdf

Prinsen, G., Sperna Weiland, F., & Ruijgh, E. (2015). The Delta model for fresh water policy analysis in the Netherlands. *Water Resources Management*, *29*, 645-661.

REAPower. (n.d.). *Reverse Electrodialysis Alternative Power Production*. Retrieved June 29, 2022, from www.reapower.eu

Klijn, F., Hegnauer, M, Beersma, J.J., Sperna Weiland, F. (2015). Wat betekenen de nieuwe klimaatscenario's voor de rivierafvoeren van Rijn en Maas? Samenvatting van onderzoek met GRADE naar implicaties van nieuwe klimaatprojecties voor rivierafvoeren. *Deltares*. Delft. Deltares-rapport 1220042. doi: 10.13140/RG.2.1.4399.5601

Rijksoverheid. (2012). Reverse Electro Dialysis: REDstack-membranen. *RVO.nl. Rijksdienst.* https://data.rvo.nl/subsidies-regelingen/projecten/reverse-electro-dialysis-redstack-membranen

Rijksoverheid. (2019). Klimaatakkoord. *Klimaatakkoord*, 250. Retrieved from https://www.klimaatakkoord.nl/binaries/klimaatakkoord/documenten/publicaties/2019/06/28/klimaatakkoord/klimaatakkoord.pdf

Rijkswaterstaat. (2018). Peilbesluit IJsselmeergebied. *Ministerie van Infrastructuur en Waterstaat.*

Rijkswaterstaat. (2021). Infographic Verzilting IJsselmeer en Markermeer. *Ministerie van Infrastructuur en Waterstaat.*

Rijkswaterstaat. (2021). Rijkswaterstaat Waterinfo. *Ministerie van Infrastructuur en Waterstaat.* Retrieved on 21-12-2022 from: https://waterinfo.rws.nl/#!/nav/bulkdownload/huidige-selectie/

Rittel, H. W. J., & Webber, M. M. (1973). Dilemmas in a General Theory of Planning. *Policy Sciences*, *4*(2), 155–169.

Roldan-Carvajal, M., Vallejo-Castaño, S., Álvarez-Silva, O., Bernal-García, S., Arango-Aramburo, S., Sánchez-Sáenz, C. I., & Osorio, A. F. (2021). Salinity gradient power by reverse electrodialysis: A multidisciplinary assessment in the Colombian context. *Desalination*, *503*, 114933. https://doi.org/10.1016/j.desal.2021.114933

Ros, J., Koelemeijer, R., Peters, J., & Hekkenberg, M. (2011). Naar een schone economie in 2050: routes verkend Hoe Nederland klimaatneutraal kan worden. *Planbureau van de Leefomgeving & Energieonderzoek Centrum Nederland.*

Scheepers, M. (2022). Een klimaatneutraal energiesysteem voor Nederland; nieuwe verkenning toont grenzen mogelijkheden. *TNO.*

Scheepers, M., Palacios, S. G., Janssen, G., Botero, J. M., Van Stralen, J., Oliveira, C., Santos, M. Dos, Uslu, A., & West, K. (2022). Towards a sustainable energy system for the Netherlands in 2050-Scenario update and analysis of heat supply and chemical and fuel production from sustainable feedstocks. *TNO.*

Sharma, M., Das, P. P., Chakraborty, A., & Purkait, M. K. (2022). Clean energy from salinity gradients using pressure retarded osmosis and reverse electrodialysis: A review. *Sustainable Energy Technologies and Assessments*, *49*, 101687. https://doi.org/10.1016/j.seta.2021.101687

Simões, C., Vital, B., Sleutels, T., Saakes, M., & Brilman, W. (2022). Scaled-up multistage reverse electrodialysis pilot study with natural waters. *Chemical Engineering Journal*, *450*, 138412. https://doi.org/10.1016/J.CEJ.2022.138412

Sun, H., Edziah, B. K., Kporsu, A. K., Sarkodie, S. A., & Taghizadeh-Hesary, F. (2021). Energy efficiency: The role of technological innovation and knowledge spillover. *Technological Forecasting and Social Change*, *167*, 120659. doi:10.1016/J.TECHFORE.2021.120659

Tamburini, A., Cipollina, A., Tedesco, M., Gurreri, L., Ciofalo, M., & Micale, G. (2019). Chapter 17 - The REAPower Project: Power Production From Saline Waters and Concentrated Brines. In A. Basile, E. Curcio, & Inamuddin (Eds.), *Current Trends and Future Developments on (Bio-) Membranes* (pp. 407–448). Elsevier. https://doi.org/10.1016/B978-0-12-813551-8.00017-6

Tedesco, M., Cipollina, A., Tamburini, A., Micale, G., Helsen, J., & Papapetrou, M. (2015). REAPower: Use of desalination brine for power production through reverse electrodialysis. *Desalination and Water Treatment*, *53*(12), 3161–3169. https://doi.org/10.1080/19443994.2014.934102

Tedesco, Michele, Scalici, C., Vaccari, D., Cipollina, A., Tamburini, A., & Micale, G. (2016). Performance of the first reverse electrodialysis pilot plant for power production from saline waters and concentrated brines. *Journal of Membrane Science*, *500*, 33–45. doi:10.1016/J.MEMSCI.2015.10.057

Tristán, C., Fallanza, M., Ibáñez, R., & Ortiz, I. (2020). Reverse Electrodialysis: Potential Reduction in Energy and Emissions of Desalination. *Applied Sciences*, *10*(20), Article 20. https://doi.org/10.3390/app10207317

Tufa, R. A., Pawlowski, S., Veerman, J., Bouzek, K., Fontananova, E., di Profio, G., … Curcio, E. (2018). Progress and prospects in reverse electrodialysis for salinity gradient energy conversion and storage. *Applied Energy*, *225*, 290–331. doi:10.1016/J.APENERGY.2018.04.111

UN General Assembly (2015). Transforming our world : the 2030 Agenda for Sustainable Development. , A/RES/70/1,. https://sdgs.un.org/goals

United Nations. (n.d.). What is renewable energy? *United Nations; United Nations*. Retrieved 9 November 2022, from https://www.un.org/en/climatechange/what-is-renewable-energy

United States Agency for International Development (USAID) & Tetra Tech ARD. (2014). A REVIEW OF DOWNSCALING METHODS FOR CLIMATE CHANGE PROJECTIONS. *ARCC African and Latin American Resilience to Climate Change Project.*

Van Aken, H. M. (2008). Variability of the salinity in the western Wadden Sea on tidal to centennial time scales. *Journal of Sea Research*, *59*(3), 121–132. https://doi.org/10.1016/J.SEARES.2007.11.001

Van Den Hurk, B., Siegmund, P., Klein Tank, A., Attema, J., Bakker, A., Beersma, J., Bessembinder, J., Boers, R., Brandsma, T., van den Brink, H., Drijfhout, S., Eskes, H., Haarsma, R., Hazeleger, W., Jilderda, R., Katsman, C., Lenderink, G., Loriaux, J., van Meijgaard, E., … van Zadelhoff, G.-J.

(2014). *KNMI'14: Climate Change scenarios for the 21st Century-A Netherlands perspective.* www.climatescenarios.nl

Van Der Ham, W. (2007). Verover mij dat land. Lely en de Zuiderzeewerken. Amsterdam, Boom.

Van Ginkel, K., Klijn, F., Mens, M., & Ter Maat, J. (2022). Verkennende systeemanalyse IJsselmeergebied. *Deltares.*

Van Riel, M., Verdonschot, R., & Verdonschot, P. (2021). Systeemanalyse van het IJsselmeergebied: Verkenning van de water- en stoffenstromen in het IJsselmeergebied voor de toepassing in een systeemanalyse. *Zoetwaterecosystemen, Wageningen Environmental Research.* https://doi.org/10.18174/555265

Veerman, J., Saakes, M., Metz, S. J., & Harmsen, G. J. (2009). Reverse electrodialysis: Performance of a stack with 50 cells on the mixing of sea and river water. *Journal of Membrane Science*, *327*, 136–144. doi:10.1016/J.MEMSCI.2008.11.015

Vermaas, D. A., Guler, E., Saakes, M., & Nijmeijer, K. (2012). Theoretical power density from salinity gradients using reverse electrodialysis. *Energy Procedia*, *20*, 170–184. doi:10.1016/J.EGYPRO.2012.03.018

Waterbesluit, artikel 2.1, Pub. L. No. BWBR0026872 (2022). Retrieved from: https://wetten.overheid.nl/BWBR0026872/2022-12-23.

Wolters, H. A., van den Born, G. J., Dammers, E., & Reinhard, S. (2018). Deltascenario's voor de 21e eeuw, actualisering 2017. *Deltares.*

Yao, Y., Ivanovski, K., Inekwe, J., & Smyth, R. (2019). Human capital and energy consumption: Evidence from OECD countries. *Energy Economics*, *84*, 104534. doi:10.1016/J.ENECO.2019.104534

Zandvoort, M., van der Brugge, R., van der Vlist, M. J., & van den Brink, A. (2019). Dealing with uncertainty in collaborative planning: Developing adaptive strategies for the IJsselmeer. *Journal of Environmental Planning and Management*, *62*(2), 248–265. https://doi.org/10.1080/09640568.2017.1409196

Zhang, B., Gao, H., Tong, X., Liu, S., Gan, L., & Chen, Y. (2019). Chapter 6—Pressure Retarded Osmosis and Reverse Electrodialysis as Power Generation Membrane Systems. In A. Basile, A. Cassano, & A. Figoli (Eds.), *Current Trends and Future Developments on (Bio-) Membranes* (pp. 133–152). Elsevier. https://doi.org/10.1016/B978-0-12-813545-7.00006-4

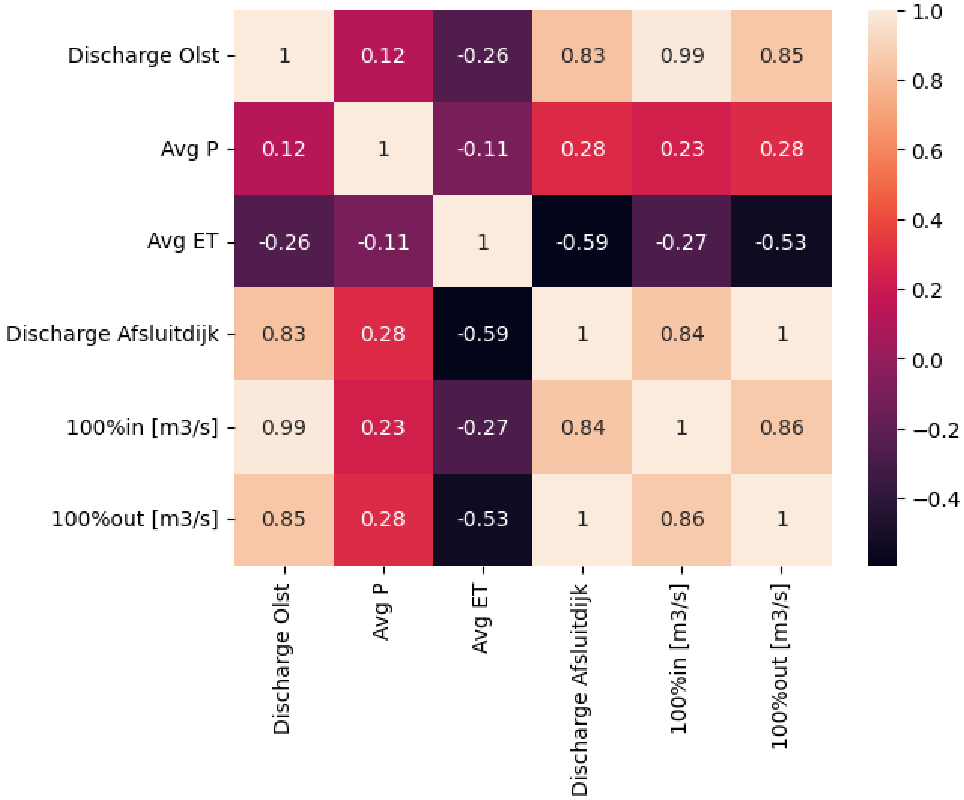
Zoungrana, A., & Çakmakci, M. (2021). Optimization of the reverse electrodialysis power output through the ratio of the feed solutions salinity. *IET Renewable Power Generation*, *15*, 769–777. doi:10.1049/RPG2.12066

8. APPENDIX

8.1. Appendix 1

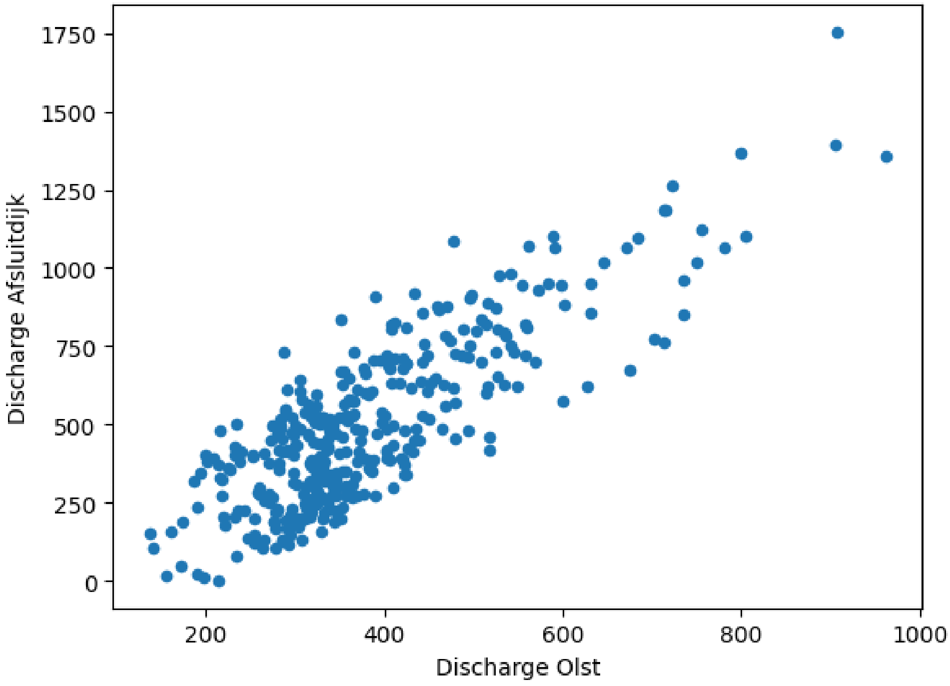
a) Showing the heatmap of Pearson's R correlations between all tested variables.
b) Showing a scatterplot of the discharge from the Afsluitdijk and the discharge from the river Ijssel, measured at Olst.

a)



	Discharge Olst	Avg P	Avg ET	Discharge Afsluitdijk	100%in [m3/s]	100%out [m3/s]
Discharge Olst	1	0.12	-0.26	0.83	0.99	0.85
Avg P	0.12	1	-0.11	0.28	0.23	0.28
Avg ET	-0.26	-0.11	1	-0.59	-0.27	-0.53
Discharge Afsluitdijk	0.83	0.28	-0.59	1	0.84	1
100%in [m3/s]	0.99	0.23	-0.27	0.84	1	0.86
100%out [m3/s]	0.85	0.28	-0.53	1	0.86	1

b)



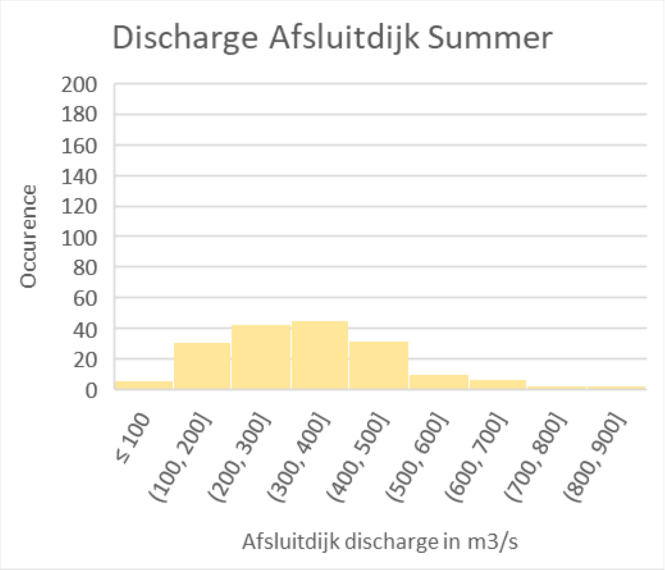
8.2. Appendix 2

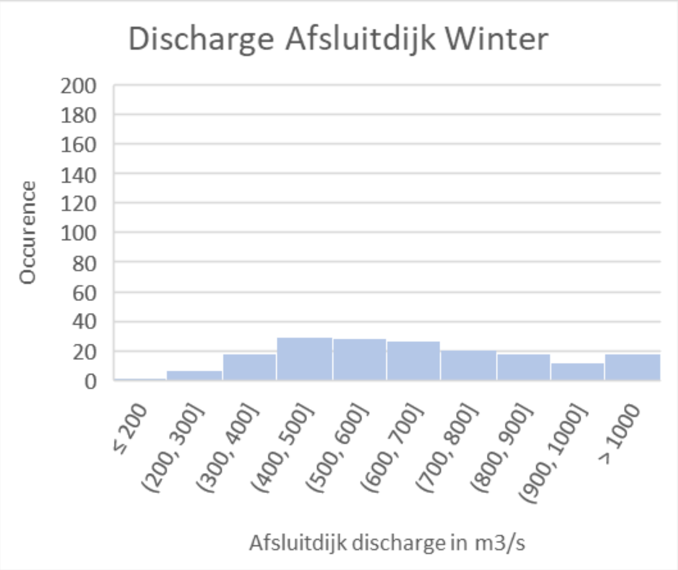
Graph that was used to create Fig. 14 on REDstack volume of water available in percentage of time. Total 30 years = 10957.5 days, which was used to calculate the percentages.

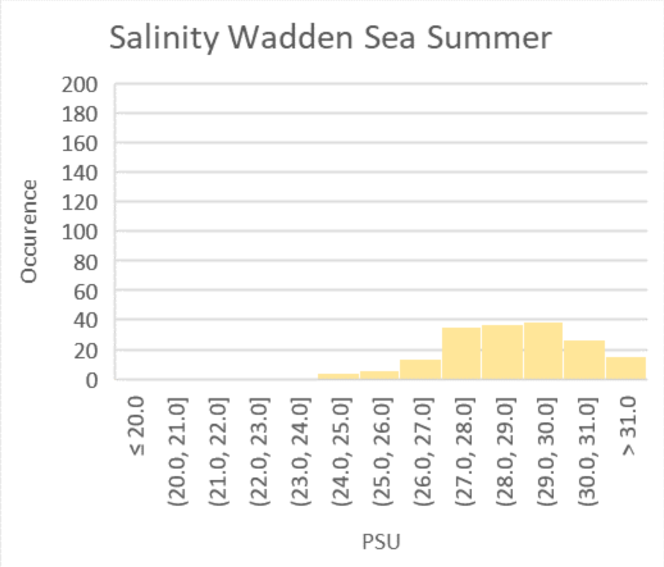
Volume Water		Days less OR equal amount of water was discharged	Percentage of time REDstack can produce at max capacity	
-0.1	m3/s	0	100.00	%
1	m3/s	748	93.17	%
50	m3/s	1252	88.57	%
100	m3/s	1779	83.76	%
150	m3/s	2252	79.45	%
200	m3/s	2843	74.05	%
250	m3/s	3589	67.25	%
300	m3/s	4259	61.13	%
350	m3/s	4950	54.83	%
400	m3/s	5604	48.86	%
450	m3/s	6156	43.82	%
500	m3/s	6643	39.37	%
550	m3/s	7082	35.37	%
600	m3/s	7556	31.04	%
650	m3/s	7955	27.40	%
700	m3/s	8253	24.68	%
750	m3/s	8549	21.98	%
800	m3/s	8817	19.53	%
850	m3/s	9055	17.36	%
900	m3/s	9251	15.57	%
950	m3/s	9436	13.89	%
1000	m3/s	9618	12.22	%
1050	m3/s	9775	10.79	%
1100	m3/s	9921	9.46	%
1150	m3/s	10053	8.25	%
1200	m3/s	10159	7.29	%
1250	m3/s	10271	6.27	%
1300	m3/s	10373	5.33	%
1400	m3/s	10522	3.97	%
1450	m3/s	10574	3.50	%
1500	m3/s	10636	2.93	%
1550	m3/s	10688	2.46	%
1600	m3/s	10722	2.15	%
1650	m3/s	10754	1.86	%
1700	m3/s	10781	1.61	%

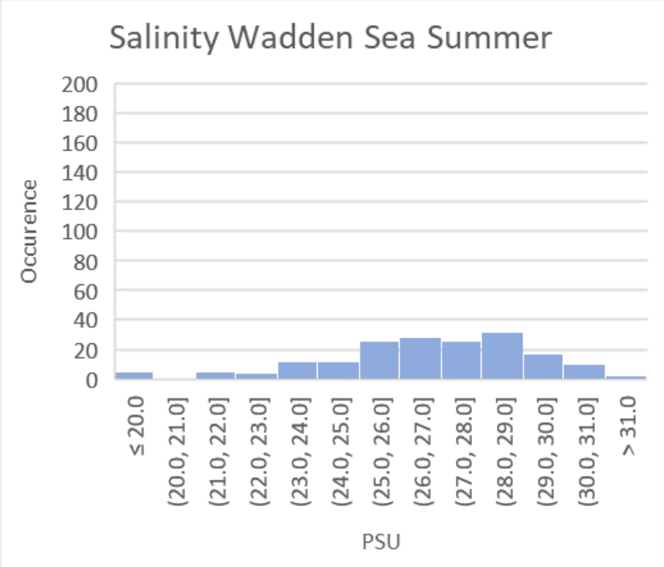
8.3. Appendix 3

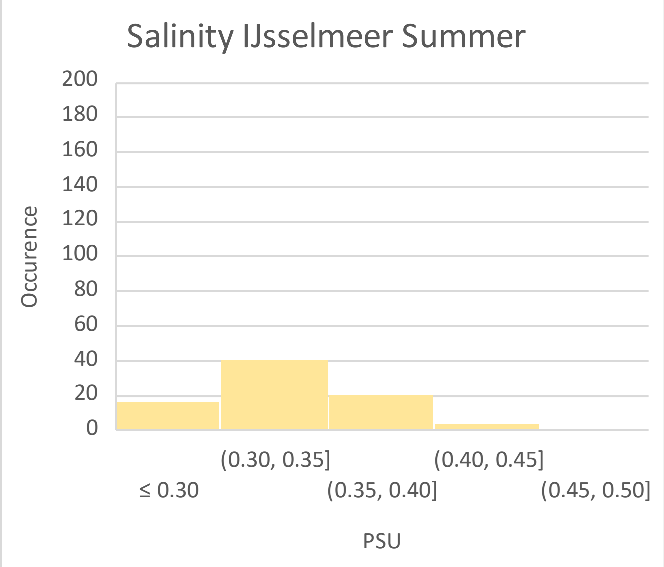
Data distribution per season for the physical factors.

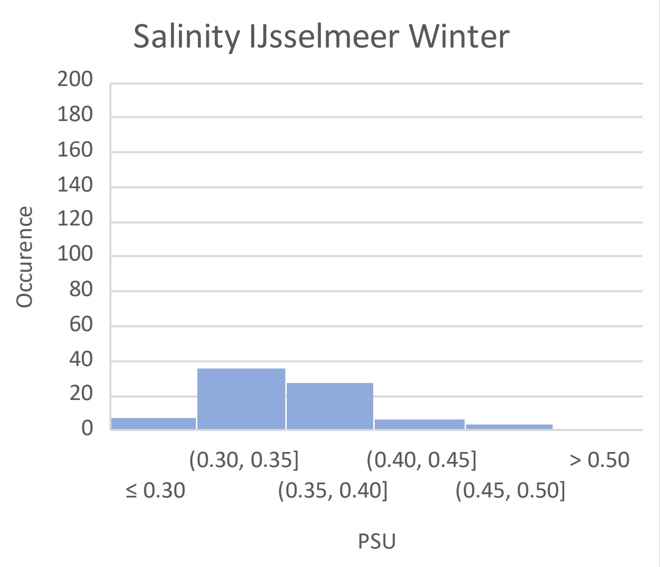


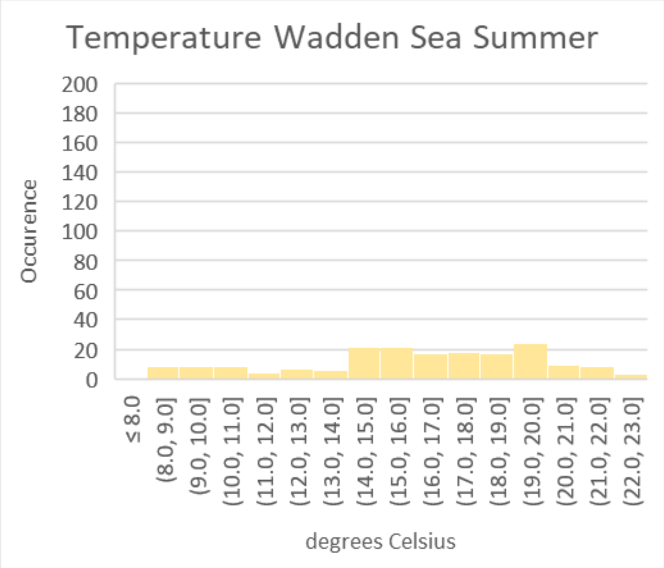


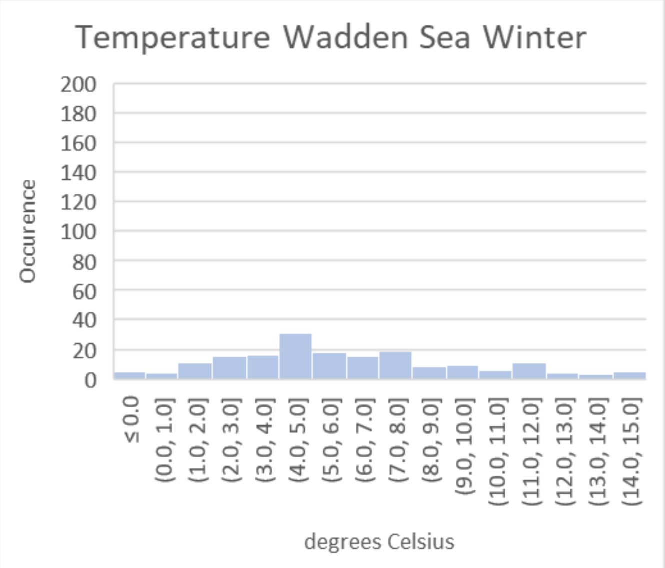


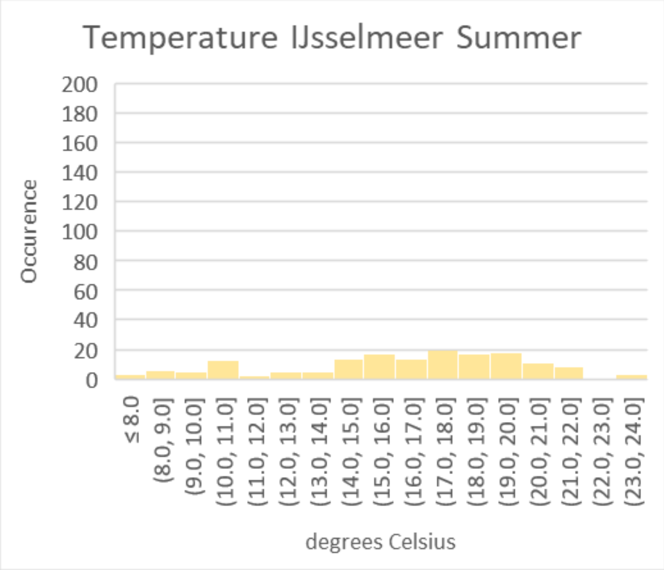


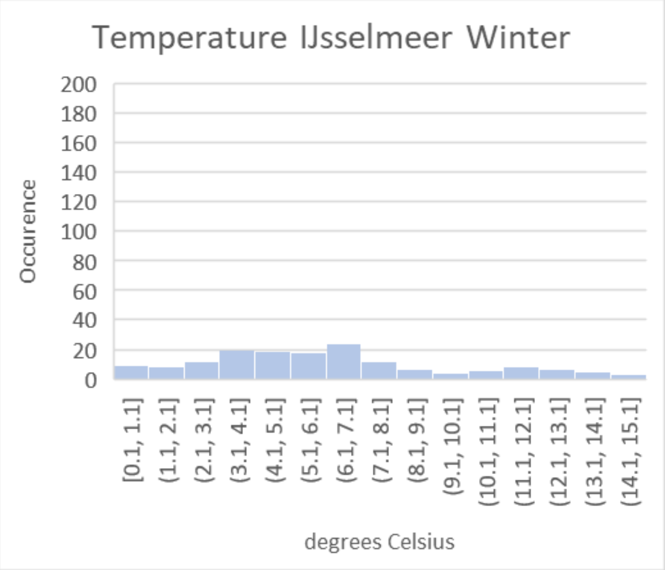





Temperature Wadden Sea Summer
Occurence
200
180
160
140
120
100
80
60
40
20
0
≤ 8.0
(8.0, 9.0]
(9.0, 10.0]
(10.0, 11.0]
(11.0, 12.0]
(12.0, 13.0]
(13.0, 14.0]
(14.0, 15.0]
(15.0, 16.0]
(16.0, 17.0]
(17.0, 18.0]
(18.0, 19.0]
(19.0, 20.0]
(20.0, 21.0]
(21.0, 22.0]
(22.0, 23.0]
degrees Celsius

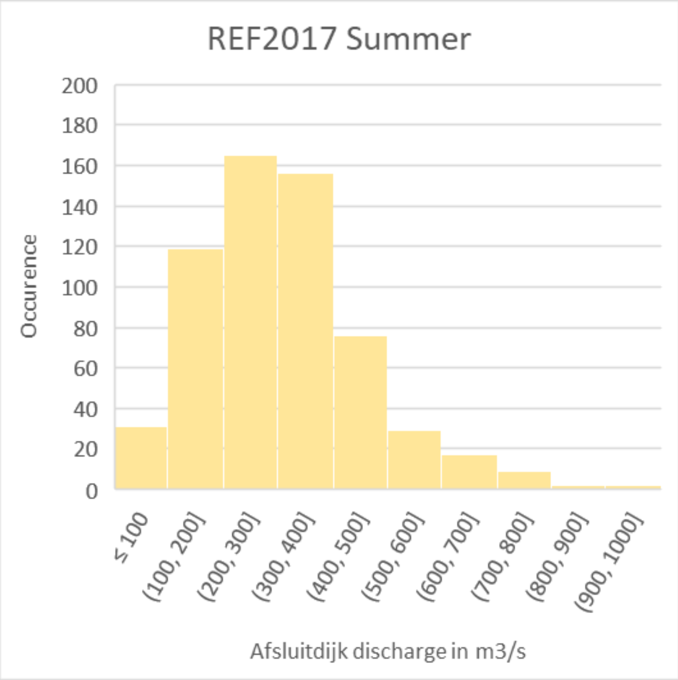

Temperature Wadden Sea Winter
Occurence
200
180
160
140
120
100
80
60
40
20
0
≤ 0.0
(0.0, 1.0]
(1.0, 2.0]
(2.0, 3.0]
(3.0, 4.0]
(4.0, 5.0]
(5.0, 6.0]
(6.0, 7.0]
(7.0, 8.0]
(8.0, 9.0]
(9.0, 10.0]
(10.0, 11.0]
(11.0, 12.0]
(12.0, 13.0]
(13.0, 14.0]
(14.0, 15.0]
degrees Celsius

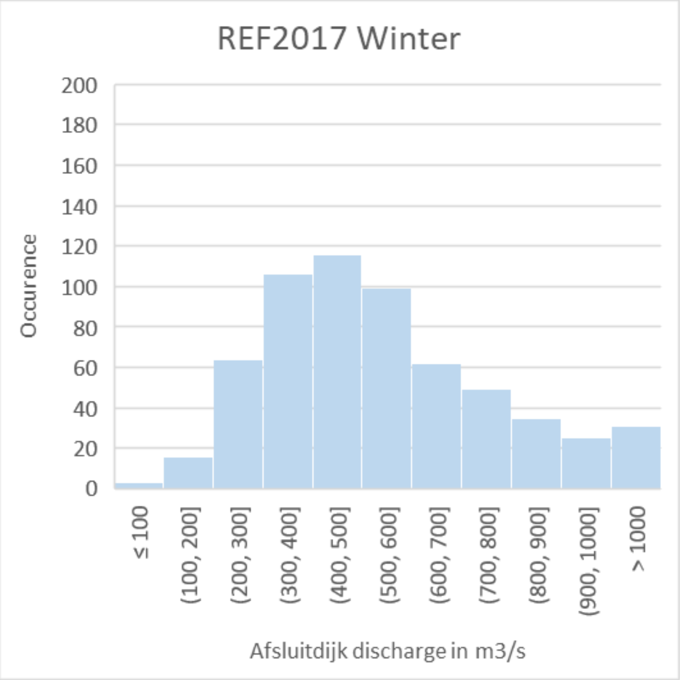

Temperature IJsselmeer Summer
Occurence
200
180
160
140
120
100
80
60
40
20
0
≤ 8.0
(8.0, 9.0]
(9.0, 10.0]
(10.0, 11.0]
(11.0, 12.0]
(12.0, 13.0]
(13.0, 14.0]
(14.0, 15.0]
(15.0, 16.0]
(16.0, 17.0]
(17.0, 18.0]
(18.0, 19.0]
(19.0, 20.0]
(20.0, 21.0]
(21.0, 22.0]
(22.0, 23.0]
(23.0, 24.0]
degrees Celsius

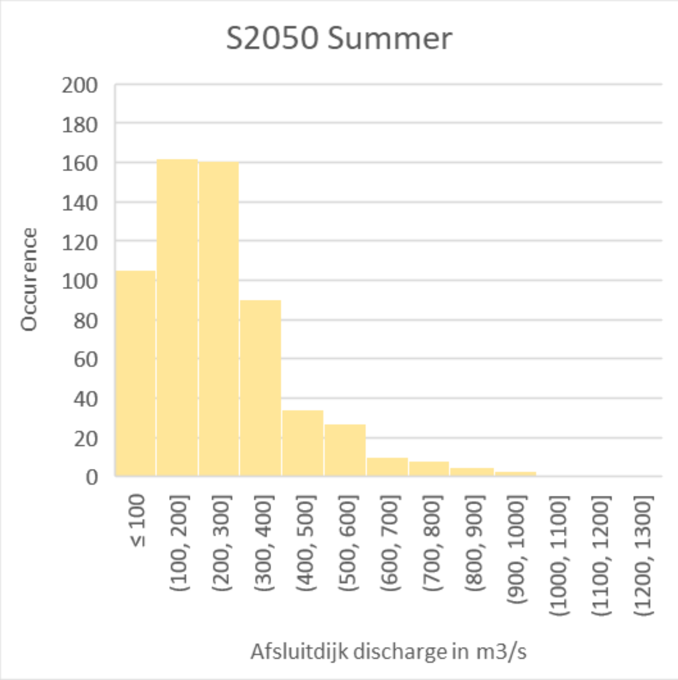

Temperature IJsselmeer Winter
Occurence
200
180
160
140
120
100
80
60
40
20
0
[0.1, 1.1]
(1.1, 2.1]
(2.1, 3.1]
(3.1, 4.1]
(4.1, 5.1]
(5.1, 6.1]
(6.1, 7.1]
(7.1, 8.1]
(8.1, 9.1]
(9.1, 10.1]
(10.1, 11.1]
(11.1, 12.1]
(12.1, 13.1]
(13.1, 14.1]
(14.1, 15.1]
degrees Celsius

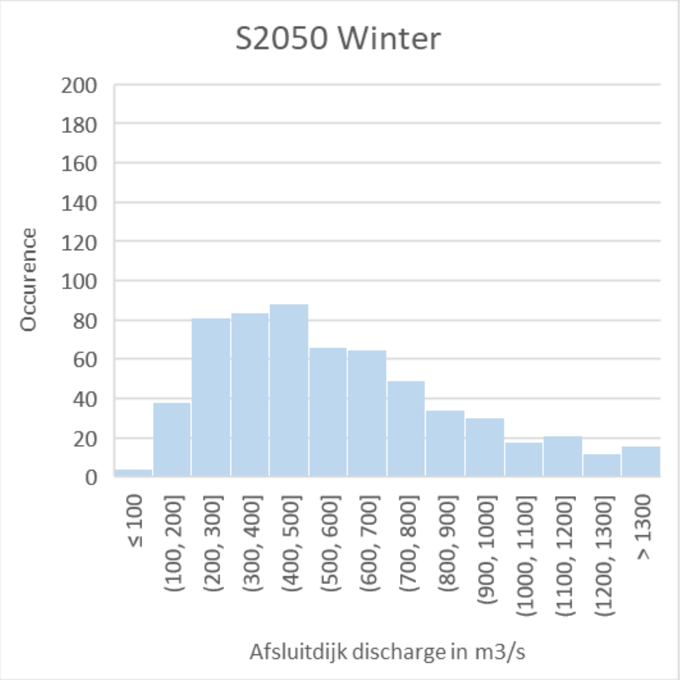
8.4. Appendix 4

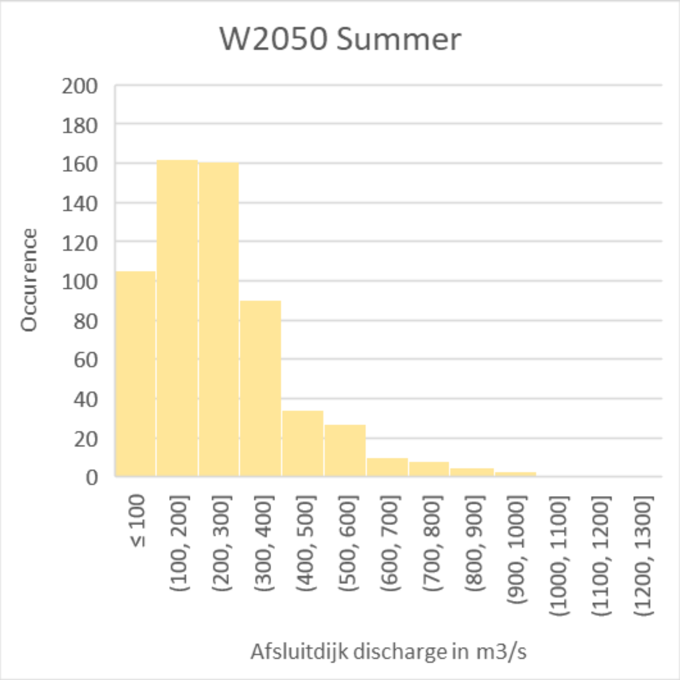
Data distributions per season for the discharge from the Afsluitdijk, per Delta scenario:



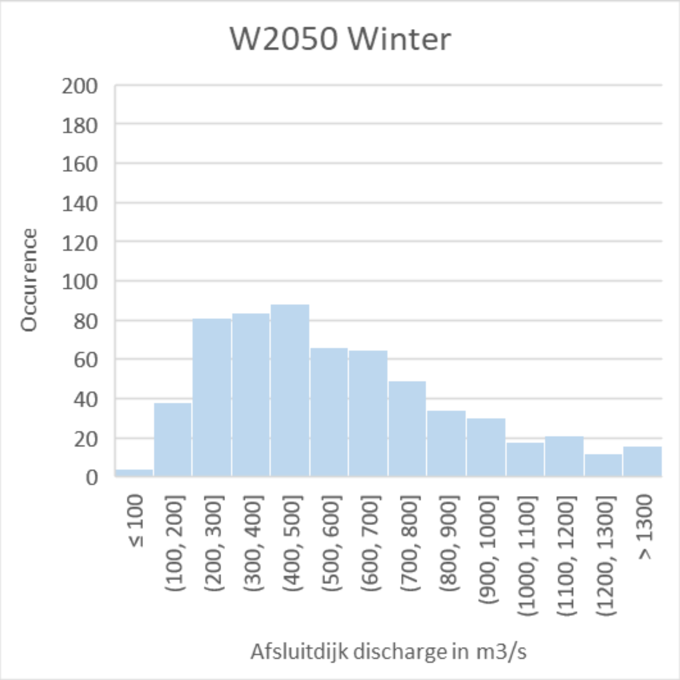




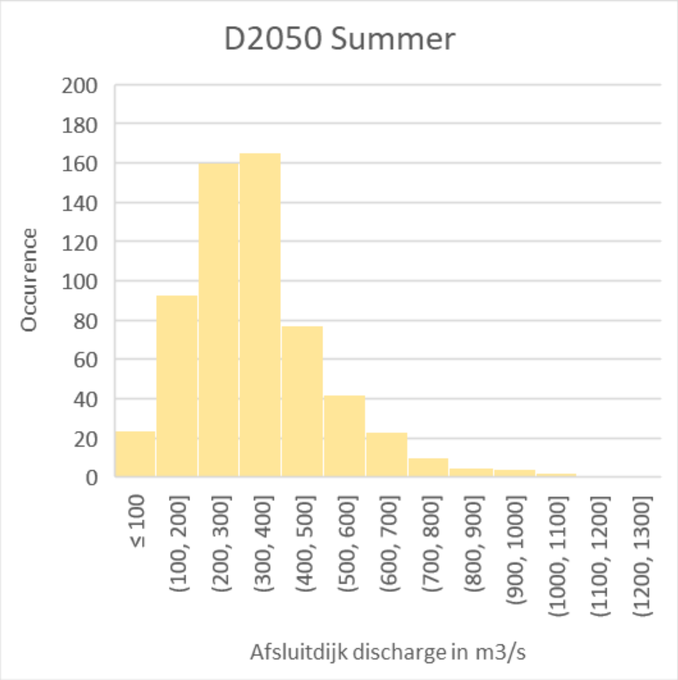




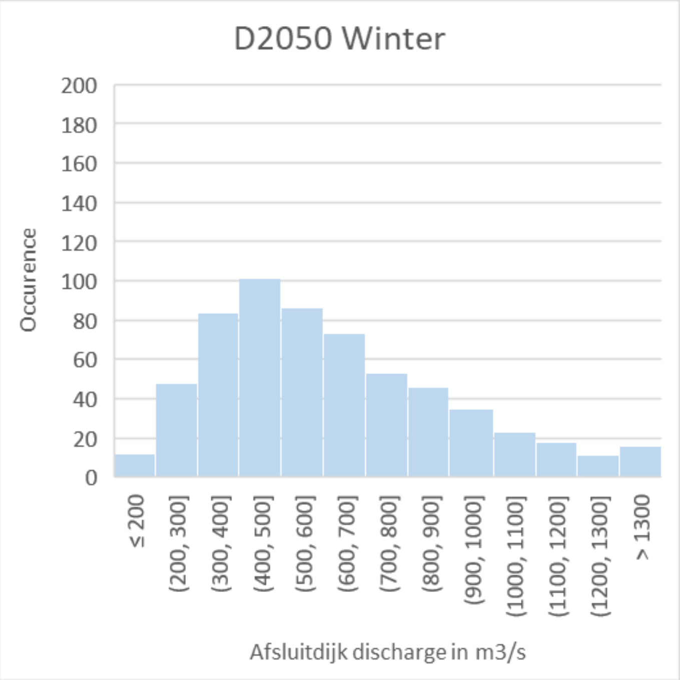
W2050 Summer



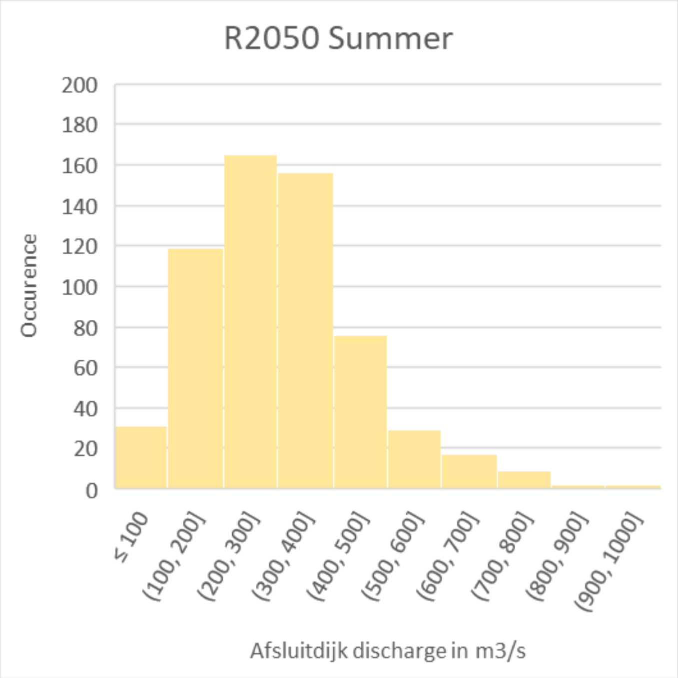
W2050 Winter



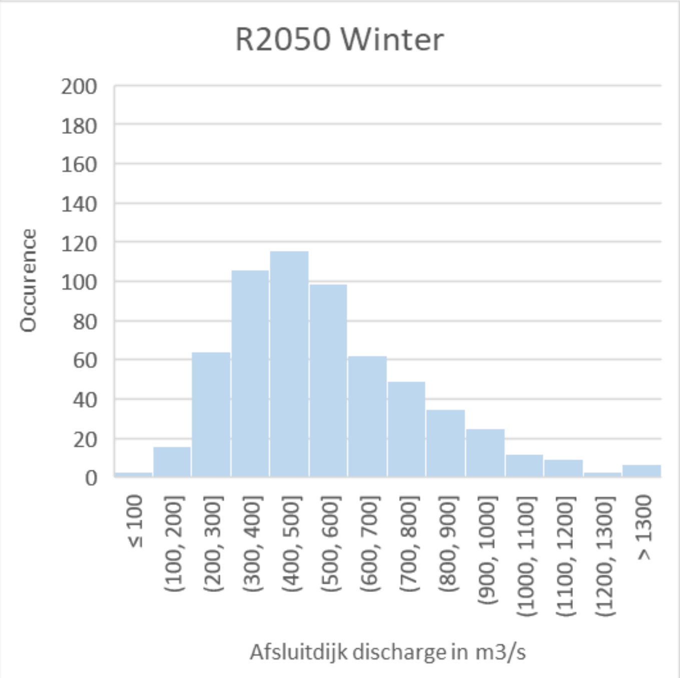
D2050 Summer



D2050 Winter



R2050 Summer



R2050 Winter

8.5. Appendix 5

Data management plan:

Origin of Data: 1 What kind of data will be used during this project 2 What is the source of the data? 3 Are various data sources integrated in the datasets you are going to use? 4 If yes could you identify the individual datasets that are combined?	Data derived from Dutch National or European Union institutes Rijkswaterstaat, CBS, EUROSTAT, KNMI and IPLO. The source is open source data, that can be downloaded from the websites. They will be kept seperated unless it is for comparison reasons, which will be discussed in the text. These are the (reference) data from the Delta scenarios and Rijkswaterstaat.
Data owner(s) 1 Which organization owns the data you are going to use? 2 Can you easily find out what you are allowed to do with the data you are going to use?	Rijkswaterstaat, CBS, EUROSTAT, KNMI and IPLO. Background information on what is to be allowed with the data was not found, unless discussed. This is discussed as a limitation in the discussion.
Data organization: 1 How will you organize your data during the project? E.g. folder structure and names 2 What can you tell about the quality of the data?	Data was organised using name codes (see text on next page) and saved locally, in Overleaf (Python) and uploaded to Teams. The quality seemed reliable and complete.
Metadata: 1 What metadata comes with the data? 2 Is there any metadata missing?	Much of the metadata was missing or limitations were not discussed. This is discussed in the discussion.
Versioning: 1 What would be your strategy concerning versioning your data files during the project 2 How can different versions of a datafile be distinguished?	Data for the analysis steps was isolated into maps, according to the objective of the data (e.g. volume of water = 1 map). These maps were uploaded to teams, so they could be saved in the cloud. Different versions were distinguished by name.
Ethical review: Do you think your project requires ethical approval by ITC Ethics Committee? Why?	No, all data used came from open sources and did not include personal or sensistive information.

1.NAME OF DATA FILE	2. SOURCE (PRIMARY OR SECONDARY DATA)	3. IF SECONDARY, WHO IS THE OWNER?	4. RESTRICTIONS AND LICENSE	5. DATA FORM	6. DATA FORMAT	7. CONTAINS PERSONAL DATA (Y/N)	8. LINK TO WEBSITE AT TIME OF WRITING
Energy gap data Klimaatmonitor	Secondary	Central Bureau of Statistics, open data	-	Text	.csv	N	http://www.klimaatmonitor.nl/
Energy gap data EUROSTAT	Secondary	EUROSTAT, open data	-	Text	.csv	N	https://appsso.eurostat.ec.europa.eu/nui/show.do
Discharge data (Discharge points: Olst, Kornwerderzand, Den Oever)	Secondary	Rijkswaterstaat, open data	-	Text	.csv	N	https://waterinfo.rws.nl/#!/nav/bulkdownload/periode-selectie/
Precipitation data (Measurement points: Swifterbant, Tollebeek, Lemmer (Gemaal Buma), Oudemirdum, Makkum, Kornwerderzand, Den Oever, Krileroord, Medemblik, Hoogkarspel Enkhuizen)	Secondary	Koninklijke Nederlands Meteorologisch Instituut, open data	-	Text	.csv	N	https://www.meteobase.nl/index.php?tb=basisgegevens&dp=basisgegevens
Evaporation data (Measurement points: Stavoren, Marknesse, Lelystad, Berkhout.)	Secondary	Koninklijke Nederlands Meteorologisch Instituut, open data	-	Text	.csv	N	https://www.meteobase.nl/index.php?tb=basisgegevens&dp=basisgegevens
Salinity Surface Water data (Measurement points: Doove Balg West, Marsdiep Noord, Vliestroom, Andijk, Houtribhoek, Ketelmeer West, Steile Bank, Vrouwezand)	Secondary	Rijkswaterstaat, open data	-	Text	.csv	N	https://waterinfo.rws.nl/#!/nav/bulkdownload/periode-selectie/
Water temperature data (Measurement points: Breesem boei 1, Doove Balg Oost, Doove Balg west, Doovebalg midden, -Harlingen, Harlingen havenmond west, Harlingen voorhaven, Kornwerderzand buiten, Westkom / Scheurrak, Andijk, Breezanddijk binnen, Den Oever, Kornwerd Kornwerderzand)	Secondary	Rijkswaterstaat, open data	-	Text	.csv	N	https://waterinfo.rws.nl/#!/nav/bulkdownload/periode-selectie/

Deltascenario's (Measurement points: Lorentzsluizen, Stevinssluizen)	Secondary	Informatie Punt Leefomgeving, open data	-	NetCDF	.nc	N	https://iplo.nl/thema/water/applicaties-modellen/watermanagementmodellen/nationaal-water-model/basisprognoses/basisprognoses-2018-zoetwater/uitvoer-bp-2018-zw/

Organizing and documentation of data was conducted as follows. Data was downloaded from the links described in the table above. It was saved in one of the maps "Energy gap", "Volume of water" [submap "Correlations" or "Discharge"], "Water temperature", "Water salinity" or "Deltascenarios", under the name [DATE]_[SUBJECT MATTER]_[LOCATION IF APPLICABLE]_[RAW/MODIFIED/OTHER STEP PERFORMED]. These files were save locally, in Overleaf and periodically in Teams. Text files were saved as [DATE]_[SUBJECT MATTER]_[VERSION] in teams. A logbook was kept describing the steps taken, which were later on discussed in the thesis. The data is freely available from the websites provided, but the author is willing to share the former versions of the datasets upon request.