Environmental effects of brine disposal and seawater usage for offshore green hydrogen production and storage in the Dutch North Sea.

Master’s Thesis - Marine Sciences

Author: M.P. van der Linden

Student number: 6292348

e-mail: m.p.vanderlinden@students.uu.nl

Ects: 45

Supervisors: L.H. van der Heijden

J. Koornneef

F. Sangiorgi

Utrecht University

North Sea Energy offshore system integration

Abstract

The Dutch energy transition faces multiple challenges and opportunities with the development of green hydrogen and offshore wind. The intermittency of offshore wind energy and the economic challenges of transporting electricity over long distances require novel solutions. One promising solution is the offshore production and storage of green hydrogen by electrolysis on platforms powered by wind farms. One possibility is the system studied in this thesis, which uses power-to-gas (P2G) technology to convert electricity into hydrogen, which is then transported via existing or new pipelines, with the excess stored in salt caverns under the North Sea. Ongoing technical and economic research highlights the P2G potential. However, it also raises environmental concerns that must be addressed before this offshore energy system can be developed.

The objective of this thesis is to conduct technical-environmental research on the environmental impact of the P2G energy system, with particular emphasis on brine production and its use of seawater. To address this, the following research question was defined:

"What is the projected seawater intake requirement for offshore green hydrogen production and storage by 2050, and what strategies could effectively mitigate the ecological impacts of waste streams like brine and cooling water in the Dutch North Sea?"

To address this question, a literature review was conducted on the environmental impacts of offshore green hydrogen production and storage, focusing on brine disposal, cooling water management, and emissions of hazardous substances. The impact of these processes on the marine ecosystem was investigated. A case study modeled the impact of brine discharges from offshore salt cavern construction, while a scenario analysis projected the future demand for salt caverns and seawater for electrolysis and cooling, with hydrogen production and associated storage projected for a 1 GW, 8 GW, and 20 GW scenario in 2050.

This study concluded that while no negative environmental impacts were identified that would preclude the implementation of a comprehensive green hydrogen production and storage system, a definitive assessment of the environmental impacts is not possible without more in-depth research into the combined effects and as yet unexplored influencing factors. This study predicts that by 2050, hydrogen production and storage will require up to 100 m^3/s of seawater, primarily for electrolyser cooling, with a minimal amount for salt cavern construction. Brine production could reach 2.3 m^3/s during cavern construction, but environmental impacts are expected to be limited to a zone of 900 meters maximum.

Overall, this study demonstrates that brine discharge is likely to have manageable environmental and ecological impacts, but emphasizes the need for additional research to develop detailed plans for a complete P2G system, with a focus on modeling cooling water impacts and monitoring the effects of cooling water use in offshore hydrogen production pilots.

Contents

1. Introduction

1.1. Background

The Netherlands' energy transition to 2050 is a pivotal step in effectively addressing the challenges of climate change, such as extreme weather events and sea level rise. This transition requires a fundamental change in our energy production, distribution and consumption, with a focus on the use of renewable energy sources. This is necessary to meet international commitments such as the Paris Agreement and limit the global warming of the 21st century to a limit of 1,5°C [1]. The urgent need to limit global warming underscores the importance of sustainability. The energy transition is critical to achieving the 2050 goals, especially to avoid irreversible changes to earth's climate. Within this transition, the introduction of green hydrogen and the expansion of offshore wind energy are two key factors [2].

Green hydrogen produced from renewable energy sources promises to be a sustainable alternative to fossil fuels, ideal for sectors such as heavy industry and transport industry, while emitting zero greenhouse gases [3]. In addition, the shallow waters of the North Sea offer unique opportunities for large-scale wind energy production. The Dutch government aims to generate up to 72 GW of offshore wind energy by 2050 [4].

The technical challenges of offshore wind energy generation include intermittent power supplies and the challenge of delivering energy to shore over long distances. It is costly to transmit power from offshore wind farms using conventional electrical cables. There is a significant energy loss associated with cable resistance at distances greater than 100 kilometers from shore, so it may be more economical to look for alternative energy transport methods [5], [6].

One possible solution currently under consideration is energy transport via molecules in the form of hydrogen. Hydrogen is produced from seawater by offshore electrolyser platforms powered by offshore wind farms and transported ashore via (already existing) pipelines. Power-to-gas (P2G) solves both problems by converting electricity into hydrogen, which is then transported to land via existing pipelines. In addition, hydrogen can be stored in salt caverns under the North Sea, providing a solution to the intermittent supply of renewable energy [8]. A schematic representation of this energy system is depicted in figure 1.1. This can solve both problems and the existing and new pipeline structures in the North Sea can act as an (international) hydrogen network [9], [10].

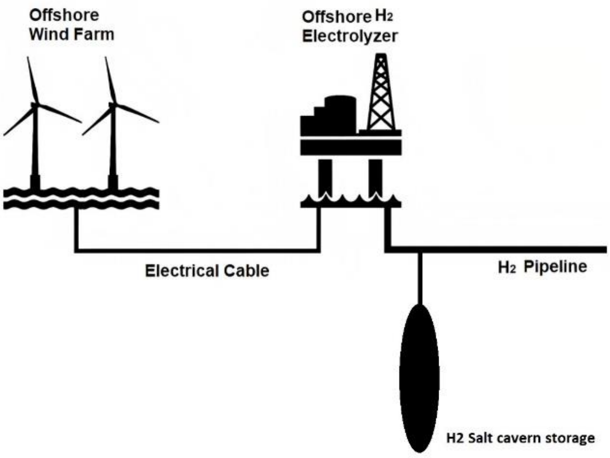


Figure 1.1 | A schematic overview of the P2G energy system studied in this thesis. *Offshore wind farms generate electricity, which is then transferred to an electrolyser platform. Here, electricity is used to split seawater into hydrogen, which is then transported via a pipeline to land or is stored in subsurface offshore salt caverns constructed for hydrogen storage.*

Technical and economic research is ongoing to realize the potential of such an energy system, with studies indicating that offshore green hydrogen production, transportation, and storage can be part of a future energy system aimed at achieving the lowest societal system costs [10]. In addition to technical and economic research, environmental research is also needed [11], [12].

Salt cavern construction and seawater electrolysis are processes that generate large quantities of brine, which requires an efficient disposal method. Although discharging brine into the North Sea is an option, the ecological and environmental consequences of such actions are not fully explored and researched [8]. An important challenge in the emerging energy landscape is the effective management of seawater demand and effluent streams, such as brine and cooling water for electrolysis plants.

1.2. Objective and research question(s)

This thesis aims to conduct techno-environmental research on the environmental impacts of the Power-to-Gas (P2G) energy system, with particular emphasis on its scale. It also examines the waste streams generated during the production and storage of marine green hydrogen and how they can be efficiently managed. Identifying and quantifying the impacts of these waste streams, including any pollutants, is critical in developing strategies to reduce these impacts. Finally, the study serves to provide a picture of the environmental impacts of the entire energy system, so that future targeted research can be conducted to address specific environmental impacts, or this research can serve to inform policy considerations. To investigate this, the following research question was defined:

"What is the projected seawater intake requirement for offshore green hydrogen production and storage by 2050, and what strategies could effectively mitigate the ecological impacts of waste streams like brine and cooling water in the Dutch North Sea?"

To delineate the research aims more clearly, this study is compartmentalized into three distinct sections: a literature review, a case study, and a scenario analysis. Each section is designed to address a specific sub-question:

1. The literature review: *"How does offshore green hydrogen production and storage, including brine disposal, cooling water management, and associated hazardous substances, affect the ecological balance in marine areas, and does it meet current environmental standards?"*
2. The case study: *"How will a brine discharge of 0.3* m^3/s *with a PSU of 280 affect the surrounding seawater over a period of 2.5 years, and what measures could be taken to mitigate the negative environmental impact?"*
3. The scenario analysis: *"What are the projected seawater intake and discharge outputs, including heat water and brine, for offshore electrolysis operations under 1 GW, 8 GW, and 20 GW production scenarios, during the period from 2025 to 2050?"*

Based on the findings of the sub-questions, a comprehensive conclusion can be drawn on the environmental impacts of green offshore hydrogen and production.

1.3. Research approach and methodology

Chapter 2 conducts a literature review to identify potential pollutants and the ecological impact of waste waters from the Power-to-Gas (P2G) system. In Chapter 3, a case study is used to model the brine discharge resulting from the leaching of a salt cavern for hydrogen storage at a specific site. The modeling process uses a near-field model in Excel and a far-field model in Delft3D FM, utilizing the Dutch Continental Shelf Model - Flexible Mesh (DCSM-FM) version with a mesh size of 0.5 nautical mile [13]. Chapter 4 presents a scenario analysis that predicts the size of offshore hydrogen production in 2050. The analysis includes three scenarios: 1 GW, 8 GW, and 20 GW. To calculate the total amount of seawater required for salt cavern leaching, as a source of electrolysis, and as cooling water for the electrolyser platforms, the required storage capacity in salt caverns is modeled in Excel. The chapters' collective findings are discussed in the general discussion, followed by the conclusion and recommendations. Additional information can be found in the appendices.

1.4. Theoretical background

This section explains the scope of the thesis and provides additional information that is necessary for the understanding of the P2G system and the assessment of its environmental impact.

1.4.1. The configuration of offshore hydrogen production

There are several ways to configure offshore electrolysis. The first strategy is wind farm electrolysis, where a central electrolysis unit is installed on an offshore platform within or adjacent to the wind farm. These units are expected to have capacities in the range of 100 to 500 MW. This centralizes hydrogen production, which can lead to cost savings and economies of scale. This process is currently being used in pilot projects of a few MW and could be scaled up if the test results are positive [14]. This thesis assumes that large-scale P2G production will only occur with this technology .

A second approach is direct electrolysis at individual wind turbines. The energy generated by each turbine, typically between 15 and 20 MW, is used directly to produce hydrogen on site. The hydrogen produced is piped to a central collection point, then compressed and transported to the mainland. This method reduces the energy losses associated with transporting electricity over long distances and makes efficient use of the existing turbine infrastructure [14].

A third approach is the development of electrolysis plants on so-called energy islands. Hydrogen is produced on purpose-built artificial islands that serve as hubs for multiple wind farms. These islands are designed for multi-gigawatt hydrogen production and represent a large-scale, integrated approach to hydrogen production, storage, and distribution. The advantage of this project is the large scale, which requires fewer platforms and serves as a large energy hub connected to other countries around the North Sea [14].

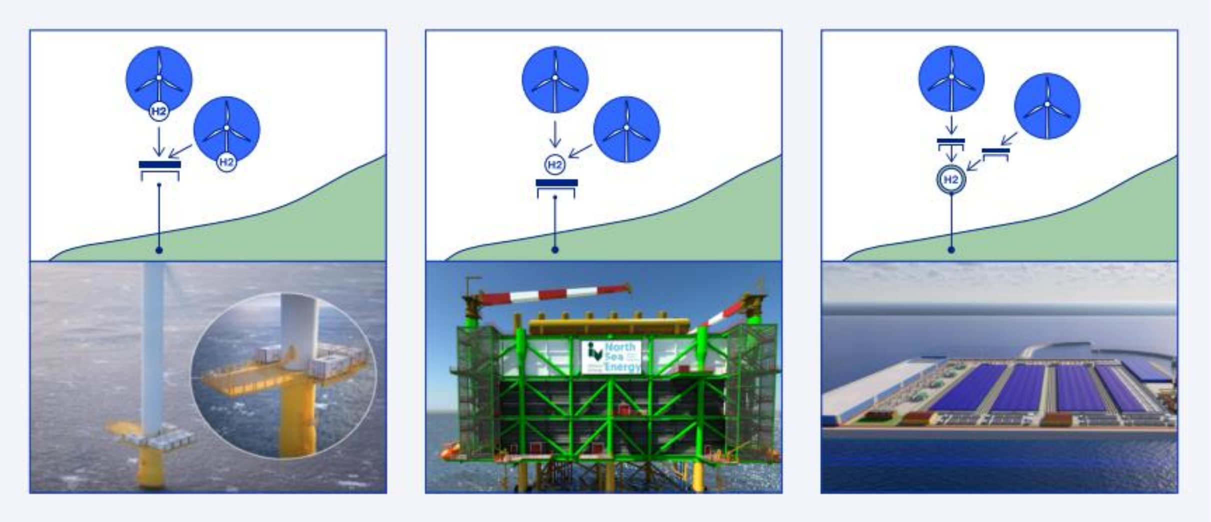


Figure 1.2 | An overview of the offshore hydrogen electrolysis methods.
This figure illustrates three methods for producing hydrogen by electrolysis in offshore environments. (a) Electrolysis at the turbine: shows a single wind turbine with the electrolysis unit directly integrated, with a capacity of 15 to 20 MW. This approach uses direct power generation for on-site hydrogen production. (b) Wind farm level electrolysis: A central electrolysis unit is installed on an offshore platform with a capacity of 100 to 500 MW. This centralizes production for multiple turbines within a wind farm. (c) Electrolysis on an energy island: represents a large-scale solution where a purpose-built island acts as an electrolysis hub with a capacity of several gigawatts. This is an integrated approach that serves multiple wind farms. Derived from [14].

1.4.2. The theoretical potential of offshore hydrogen production in the Netherlands

Given the favorable conditions in the wind-rich areas of the North Sea, the theoretical potential for offshore green hydrogen in the Netherlands could be significant [2]. Several data points are used to determine the theoretical potential for offshore hydrogen in 2050. Offshore hydrogen must use offshore wind as energy source (and possibly offshore solar, but this is not yet well developed compared to offshore wind). The first condition for the wind farms is that they are not built before 2030, as large-scale offshore hydrogen production is not feasible before then [15]. The second requirement for wind farms is that they are located at least 150 kilometers from the point of landfall. This distance may allow wind energy to be converted to hydrogen for onshore transportation more affordable than electricity [5], [6]. The future wind energy search areas 3, 5, 6 and 7 are positioned to meet these requirements and show the significant theoretical potential for offshore wind energy development in the Netherlands until 2050. Beyond 2030, these areas could theoretically provide up to 50 GW of offshore wind capacity combined. However, the most recent concrete plans of the Dutch government assume a total potential of 20 GW of wind energy production for this area, as shown in Figure 1.3, and this is the amount that this study assumes as the potential of the Netherlands for offshore green hydrogen production in 2050 [4].

Figure 1.3 | The theoretic potential for offshore hydrogen production in the Dutch North Sea.

This map illustrates the locations and energy capacities of wind farms suitable for green hydrogen production within the Dutch EEZ. Areas 3, 5, 6 and the additional section within area 6, and area 7 are shown with potentials of 2 GW, 2 GW, 10 GW, and 8 GW, respectively, contributing to a total theoretical potential of 20 GW for 2050.

1.4.3. Electrolyser type

The trend towards widespread use of Proton Exchange Membrane (PEM) electrolysers in offshore hydrogen production is evident from the current emphasis on them in offshore pilots [12]. In this study PEM electrolysers will become the standard for such applications, given their possible suitability for the marine environment. Their compactness, efficiency, and suggested ability to quickly adapt to fluctuating wind energy output are distinguishing characteristics. They can operate at lower temperatures and resist corrosion, ensuring the safety and durability of offshore platforms [3]. PEM electrolysers typically operate at an efficiency of 67%, where the rest is converted to heat that needs to be dissipated [16].

A cooling water system is used to remove this heat. The focus here is on a once-through cooling water system, which is commonly used for industrial or power plants that require seawater cooling [17]. While there are options for closed loop cooling and developments are underway for potential air cooling methods, these alternatives are not considered in this analysis.

In this study, the primary method for determining the amount of seawater required for electrolysis is reverse osmosis (RO), a widely used process that demineralizes water by forcing it through a special membrane under pressure [18]. Despite its widespread use, RO has some drawbacks, including the need for routine maintenance and the use of chemicals [19]. The Sea2H2 study [20] investigated an alternative approach, thermal desalination, which uses the heat generated during the electrolysis process to evaporate seawater. However, this method was not considered for large-scale application in this study due to uncertainties about its feasibility on a larger scale [20]. In the RO process, a brine reject stream is produced from the seawater residue that is not converted in to demineralized water.

1.4.4. The appearance of salt layers in the Dutch North Sea

The main rock salt layers, that can function as a source for salt cavern construction, in the Dutch subsurface are found in the Zechstein Group and the Röt Formation rock layers, which were formed approximately 251-260 and 238-244 million years ago, respectively [21]. These salt layers were formed in shallow, partially sealed salt lakes. The process of salt formation began with the evaporation of seawater, leaving salt at the bottom. A typical evaporite cycle begins with the deposition of limestone, then anhydrite, and finally rock salt (pure halite) and potassium-magnesium salts, depending on the salinity of the water [21]. The arrival of new seawater signals the start of a new cycle. In the Netherlands, several Zechstein cycles have resulted in thick rock salt layers, which is displayed in figure 1.5 [22].

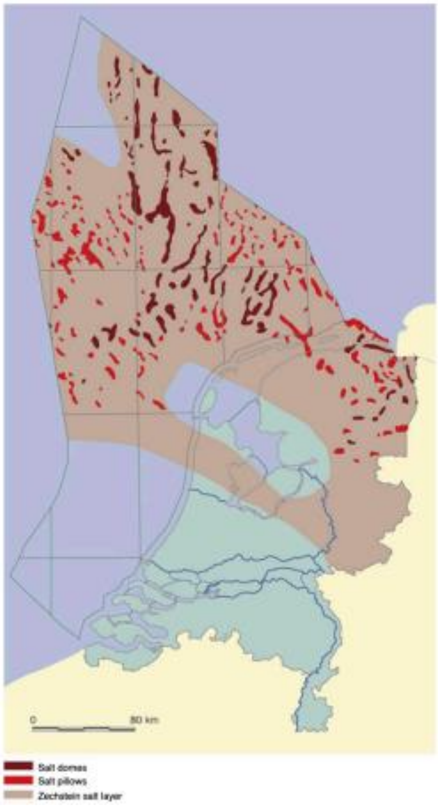


Figure 1.5 | An map of the Zechstein salt deposits in the Netherlands.
In this figure the salt deposits of the Zechstein are displayed in grey for the Netherlands and its exclusive economic zone (EEZ). Here the salt diapirs and salt domes that could possibly used for salt cavern construction are displayed in red and brown. Derived from [22].

These rock salt formations can be divided into three types: layered packages, salt pillows and salt pillars. Salt pillows and pillars develop after the initial salt deposit. The salt becomes plastic as it is successively covered by younger rock layers and exposed to higher temperatures [23]. Depending on subsurface movement and the weight of the overlying layers, the salt may concentrate and form a pillow-shaped body that eventually becomes a salt pillar. Salt pillows are more gradual curves in the salt body, while salt pillars are narrow, steep structures that break through the overlying layers. They can reach heights of over 2.5 kilometers and depths of 1,000 to 1,500 meters. These formations are ideal for the construction of salt caverns [21], [23].

1.4.5. Salt cavern construction

The first step in building a salt cavern for hydrogen storage is to find a suitable site where there is a layer of salt several hundred meters thick at a depth of 1,000 to 1,500 meters [24], typically a salt dome or pillar. To begin leaching a salt cavern, a well must first be drilled into the salt formation to the desired depth.

By injecting water, the salt is dissolved to create a cavern. There are two main methods of this dissolution process: reverse circulation and direct circulation. In direct circulation, when water is pumped through an inner pipe, the salt is dissolved and the brine rises between the inner pipe and the outer casing. This forces the cavern to grow at the bottom. In reverse circulation, the heavier brine is released at the bottom and water is pumped up between the outer casing and a second, smaller tube. This process promotes the expansion of the upper cavern. Insoluble materials, such as tiny rocks or silt, sink to the bottom of the salt cavern and remain there during this process. Nitrogen is also used as a fluid blanket during leaching. This reduces the possibility of unwanted chemical reactions, helps maintain a constant pressure in the cavern, and allows for more constant leaching and more controlled formation of the cavern [25].

Careful monitoring is required to ensure that the cavern is formed to the correct shape and size for the intended storage. Once the target volume is reached, the leaching process is stopped and the brine is extracted by filling the cavern with gas. This will always leave a layer of brine because the pipes do not reach the bottom, making it impossible to completely remove the brine. The brine tunnel is then excavated. The infrastructure required for injecting and extracting the stored materials is then installed in the borehole [25].

The offshore cavern leaching process is expected to take two to three years. During this process, brine is produced at a salt concentration of 260 to 330 grams per liter [8]. Once the leaching process is complete, it takes an additional three to five years for the cavern to become fully operational. This time is necessary to allow the cavern to dry and for the necessary infrastructure to be constructed for operational use. In addition, preliminary research into a suitable spot for an offshore cavern, such as seismic surveys, feasibility studies, and geotechnical validation, can take four to seven years, this brings the total to 9 to 15 years to develop an offshore cavern [8].

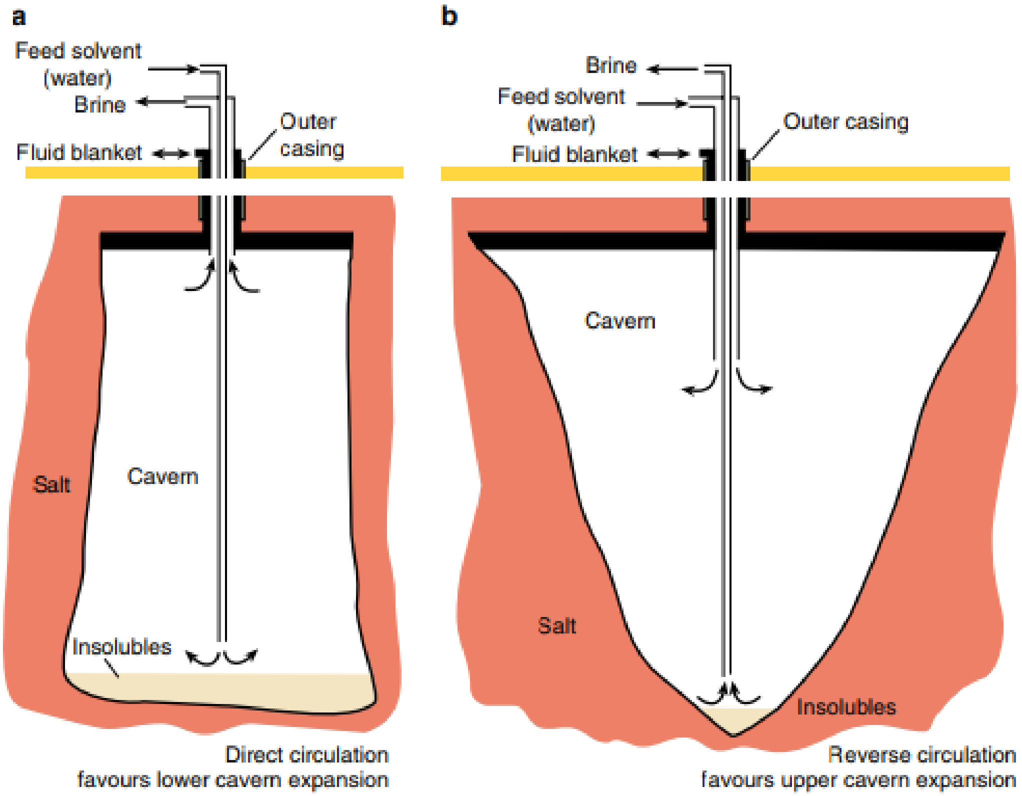


Figure 1.6 | The solution mining process for the construction of salt caverns. *Two schematic representations of the techniques for constructing salt caverns for hydrogen storage are shown in Figure 1.6. The direct circulation process is shown in Figure 1.6a, where dissolved salt as brine rises between the inner tube and the outer casing, while water as solvent is pumped down through an inner tube. This causes the lower cavern to expand. Insoluble residues sink to the bottom of the cavern. A fluid blanket at the top of the cavern stabilizes the pressure and ensure safety. The reverse circulation process is depicted in figure 1.6b, where the heavier brine at the bottom is released by pumping water upward between the outer jacket and a second pipe. This technique promotes the growth of the upper cavern. Figure is depicted from* [25].

1.4.6. Types of brine

Brine is a highly concentrated solution of salt in water that occurs in various industrial processes and natural environments . Two different types of brines are considered in this study. The first type is desalination brine, a by-product of reverse osmosis where seawater is purified to produce fresh water. This type of brine has a salinity range of 44 to 70 PSU (Practical Salinity Units), indicating a significant increase in salt concentration compared to the original seawater[25]. The second type is hypersaline brine, which is produced by leaching of salt caverns. These brines have a much higher salinity, ranging from 260 to 330 PSU [8], reflecting the intense concentration of salts. Both brines have unique characteristics and implications for the environmental impact when disposed of in the North Sea.

1.4.7. Salt cavern leaching with seawater

Freshwater is traditionally leached into salt caverns, which are typically found on land [27]. However, recent research and practical applications have shown that seawater is a useful and potentially more affordable substitute, especially for offshore projects. Because seawater contains minerals, it may not dissolve rock salt as well. This is a potential problem. However, this need not be a barrier, as the desired result can be achieved simply by using more seawater.

The oil and gas industry has experience with seawater leaching through salt formations [28]. In salt cavern construction, unsaturated brine solutions are sometimes used [29], demonstrating the effectiveness of mineral-rich water in leaching rock salt.

Carbon capture and storage (CCS) projects in Brazil are exploring the possibility of leaching salt caverns located far offshore using seawater instead of freshwater [30]. This demonstrates the viability and potential of using seawater in this type of application.

Another notable example is the Islandmagee group in Northern Ireland, where salt caverns were constructed in 2019 using seawater to store methane. In the future, this site could be used to store hydrogen mixed with natural gas or even just pure hydrogen [31]. This demonstrates that caverns, used for storing different gases, can be leached directly with untreated seawater [32].

By avoiding the need for extensive freshwater pipelines, the production of offshore hydrogen stored in salt caverns becomes 15% to 30% more cost-effective [8]. Additionally, employing seawater to leach salt caverns for this purpose has beneficial environmental outcomes. This method significantly reduces freshwater consumption and the carbon emissions associated with the construction of these pipelines.

1.4.8. Current state of the North Sea

The North Sea is a body of water that is home to a wide variety of marine and bird species. Due to its natural wealth and its geography it faces numerous challenges including offshore activities, sand mining, pollution, commercial fishing, and the introduction of invasive species. Climate change is one of the greatest long-term threats to the North Sea, where human activities have impacted the ecosystem over the past century and continue to do so [33]. Marine renewable energy provides long-term benefits by mitigating climate change, but short-term environmental impacts must be thoroughly investigated and addressed. Recent studies have shown that the development of offshore renewable energy infrastructure will have a negative impact on the health (or biodiversity) of the North Sea [34]. The recent OSPAR report on the state of the North Sea showed that the biodiversity of the North Sea is still declining [35]. This underlines the need for a careful approach to the use of the North Sea for sustainable energy, including the P2G system.

2. Literature review

This literature review forms the basis of the thesis, and aims to identify and understand the ecological and environmental impacts of processes involved in hydrogen production and storage. It also aims to explore existing literature on similar ecological and environmental impacts of processes similar to hydrogen storage and production.

The following sections of this thesis model the dispersion and dissolution of brine in seawater using a scenario analysis and a brine disposal case study. It is also determined how much brine, seawater, and heated water are generated during these processes. These studies shed light on the physical elements, such as variations in temperature and salinity and the growth of mixing zones, where effects can be quantified. Unfortunately, these studies do not translate directly into ecological impacts, and instead focus on near-field and far-field effects, especially when it comes to impacts on ecology within mixing zones.

Therefore, in order to move from environmental effects to ecological effects, this literature review is critical. It examines potential pollutants used or released during offshore green hydrogen production and storage, as well as the ecological effects of brine and cooling water discharge. The following research question and its sub-questions should be addressed in the literature review:

"How does offshore green hydrogen production and storage, including brine disposal, hot water management, and associated hazardous substances, affect the ecological balance in marine areas, and does it meet current environmental standards?"

Sub-questions:

- What harmful pollutants are used or released during the production and storage of offshore green hydrogen, and what are the potential environmental impacts?
- What is the ecological impact of brine disposal at potential hydrogen storage sites?
- What is the impact of cooling water discharge and cooling water intake on the marine environment at offshore hydrogen production sites?

2.1. Harmful substances

Certain potentially hazardous substances may be released into the North Sea during the production and storage of offshore green hydrogen. The nature of these substances and their potential effects must be researched for each component of the production and storage system. Specifically, the possibility of contaminants in cooling water, emissions from reverse osmosis, and contaminants in electrolyser membranes were considered. While these membranes are not in direct contact with seawater, it's still important to consider the possibility of environmental damage, including leaks into the marine environment. In addition, the possible generation and release of contaminants during the storage of hydrogen in salt caverns will be evaluated.

2.1.1. Chemicals in cooling water

In offshore and industrial settings, the use of cooling water systems poses a risk of dangerous material leakage into the ocean. Biocides such as chlorine (Cl_2), sulfuric acid (H_2SO_4) and various halogens are of particular concern when released into the marine environment.

Chlorine (Cl_2) is commonly used as a disinfectant in industrial cooling water systems. However, its release into marine ecosystems can have negative consequences for water organisms, despite its effectiveness in regulating biological growth and scale. Additionally, the reaction of chlorine with organic matter in the water can form potentially hazardous byproducts called trihalomethanes. High concentrations of chlorine bleach lye can be highly toxic, therefore, it is recommended to avoid large-scale releases of this chemical into environmental waters.

Sulfuric acid (H_2SO_4) is used for pH regulation in cooling systems and may be a byproduct of industrial processes. The acidification of seawater due to sulfuric acid discharge can negatively impact marine biodiversity, including the corrosion of calcareous elements and disruption of the marine ecosystem [36].

Halogens, such as bromine and iodine, can be used as biocides in cooling water systems as an alternative to chlorine. However, they can react with organic materials in the water, forming potentially harmful compounds. The impact of halogens on the marine environment depends on their concentration and specific properties [37].

Haloforms, such as those produced by the use of hypochlorite in cooling water systems, can be harmful to the marine ecosystem. These chemicals are toxic to many aquatic organisms, can bioaccumulate in the food chain, and can change the chemical composition of water, which can have negative effects on the biodiversity and health of marine ecosystems [38].

Proper management and control of substances in cooling water systems is vital to prevent environmental damage and negative impacts on marine ecosystems. Cooling water systems are widely used in power plants, heavy industry, and offshore oil and gas extraction. However, to avoid potential risks, these substances must be closely monitored.

2.1.2. Harmful substances from reverse osmosis

During the RO desalination process, there is a risk of releasing substances, such as heavy metals, due to corrosion and the use of certain chemicals for maintenance. For example, the use of low-quality stainless steel can result in the release of metals, including iron, chromium, nickel, and molybdenum, into the environment [39]. However, the concentrations of these metals are typically below the threshold that would cause harm to the environment, as detailed in specific studies and in Table 2.1, which compares these values to the concentrations found in seawater [40].

In addition to heavy metals, reverse osmosis can leave behind chemicals from the cleaning membranes that are added to the effluent. These consist of detergents and biocides, as well as cleaning agents with varying pH levels [41]. When released in small amounts and irregularly, these substances typically pose little risk to the environment. Many of these potential pollutants are neutralized by the inherent properties of seawater, leaving the discharged water with a pH comparable to that of the surrounding seawater. Environmental safety is ensured by the presence of antiscalants in the discharged water and by treating biofouling with oxidants such as chlorine that have been neutralized beforehand [19]. However, care must be taken to avoid potential ecological damage and discoloration from untreated backwash water. Experience and research show that prudent risk management can successfully reduce hazards, with salinity fluctuations having a greater environmental impact than chemical exposure [40].

Seawater						**Wastewater**			
constituent	unit	samples	Min	Med	Max	samples	Min	Med	Max
Ammonia-Nitrogen	mg/L	72	0	0,02	0,46	480	153	207	294
Nitrate-Nitrogen	mg/L	57	0	0,09	2	145	0,1	0,7	15
Phosphate	mg/L	65	0	0,07	3,1	124	2	12	44
Sulfate	mg/L	-	-	5480	-	136	1087	1630	1967
Arsenic	mg/L	12	2,46	2,9	3,84	458	0,01	11	45
Bromide	mg/L	-	-	130	-	n/a	n/a	n/a	n/a
Barium	mg/L	-	-	0,1	-	108	147	240	335
Calcium	mg/L	-	-	820	-	n/a	n/a	n/a	n/a
Iron	mg/L	-	-	<0,04	-	148	3	28133	49067
Magnesium	mg/L	-	-	<0,02	-	n/a	n/a	n/a	n/a
Silica	mg/L	72	0	0,29	0,93	n/a	n/a	n/a	n/a
Sodium	mg/L	-	-	21800	0	4	2053	2357	2613

TABLE 2.1 | Comparison of constituents in Seawater and wastewater brine from RO processes.

This table presents a comparison of various chemical constituents found in seawater and wastewater resulting from different RO desalination processes. It includes minimum, median, and maximum concentrations of key elements such as ammonia-nitrogen, nitrate-nitrogen, phosphate, sulfate, arsenic, and others in both seawater and RO wastewater, highlighting the *significant changes in chemical composition due to the desalination process. The data and table are derived from* [40].

2.1.3. Hazardous substances from PEM electrolysis

The presence of perfluorinated compounds (PFCs) in the membranes, such as PFAS (per- and polyfluoroalkyl substances), is a major concern in the study of PEM electrolysers [42]. Due to their potentially hazardous properties, these substances, although not in direct contact with the marine environment, must be closely monitored to ensure that they are never released into the water. PFCs have a long half-life in the environment and are likely to bioaccumulate in aquatic life, making them a cause for concern. PFAS can be found in the anodes and cathodes, gas diffusion layers, core membrane, and other areas of the electrolyser. PFAS are persistent in the environment, non-biodegradable, can leach into drinking water sources and bioaccumulate in fish and wildlife. Nafion or perfluorosulfonic acid (PFSA) polymer membranes are also PFCs. These membranes serve as thin, solid proton-conducting membranes and are essential to the operation of PEM electrolysis cells. They consist of a highly acidic network structure, primarily due to sulfonic acid groups that facilitate proton mobility. The high fluorine content of these membranes is one of their key characteristics. Because fluorine is an extremely stable element, it is difficult for them to degrade in the environment. This makes them potentially harmful, as they can accumulate in muscle and fat tissue and are toxic to humans and animals[43], [44].

One important concern is the risk of PFCs leaking into marine environments due to the persistence and accumulation of these materials in the ecosystem. Further research and development of safer alternatives or mitigation strategies is crucial for the use of PEM electrolysers in offshore environments to prevent or significantly reduce the emission of PFCs and avoid endangering the marine environment and associated ecosystems [45]. If this is not feasible, it may be the reason why large-scale offshore electrolysis will not occur.

In addition to PFCs, other materials hazardous to the marine environment, such as heavy metals, can be found in electrolyser membranes. Although these materials are not typically in contact with seawater, it's important to identify them because if the water supplied is not completely pure, impurities can form in the hydrogen [43], [44]. Appendix 2 provides a detailed description of these impurities.

Impurities in PEM electrolysers can lead to the synthesis of toxic compounds that can have serious effects on the environment and the performance of the electrolyser. These impurities can come from the materials of the unit, from the water used for electrolysis, or from wear and tear on individual parts [44], [46]. Contaminants such as carbon monoxide (CO) and hydrogen sulfide (H_2S) are produced and are present in the hydrogen stream, which is a serious problem. If residual organic contaminants or sulfur compounds remain in the feedwater, they can break down and release H_2S and CO. These compounds can have detrimental effects on the electrolysers catalysts. For example, CO can bind to the platinum catalyst and reduce the efficiency of hydrogen production. Although this binding is reversible, prolonged exposure to CO can permanently reduce catalytic activity. The effects of H_2S are even more dangerous because it often interacts with the catalyst in an irreversible manner, causing irreversible damage and reduced performance [46]. In addition, it is critical to prevent the release of H_2S into the atmosphere. In fact, hydrogen sulfide is hazardous to the aquatic environment.

Toxic byproducts can also be formed as a result of contaminants in the incoming water, such as organic compounds and chlorine [46]. These materials, which include organochlorides and chlorine gas, have the potential to alter the purity of the hydrogen produced and reduce the efficiency of the electrolyser. In addition, trace amounts of ozone or other reactive gases may be produced during the electrolysis process . These gases have the potential to adversely affect aquatic ecosystems and air quality. To reduce these adverse effects, it is critical to use high-quality materials, carefully treat and purify the feedwater, and perform routine maintenance and monitoring of the electrolyser. This will ensure that fewer pollutants are released into the marine environment and will also extend the life and efficiency of the electrolyser [44], [46].

2.1.4. Hazardous contaminants from hydrogen storage and transport

Hazardous material formation is a risk associated with the storage of hydrogen gas. The potential formation of H_2S, a byproduct that is not only toxic and corrosive, but can also seriously affect the marine environment, the integrity of the storage infrastructure, and the quality of the stored gas, is one of the most concerning aspects [47].

Concentrations of specific elements such as sodium chloride (NaCl), sulfate, potassium, ammonium, nitrate, nitrite, phosphate, and iron have been shown by hydrochemical analysis of brine samples from hydrogen storage caverns to be significant indicators of formations of microbiomes in salt caverns [48], [49]. In addition, the differences in total inorganic carbon (TIC) and dissolved organic carbon (DOC) are important because they indicate the presence of different carbon sources necessary for microbial growth [48]. This implies that there could be microorganism activity in salt caverns where hydrogen is stored and there could be potential metabolic activity of microorganisms in response to hydrogen storage [47], [48], [49]. Although there are no documented cases of sulfide formation in underground gas storage facilities using natural gas, more research is needed to determine whether hydrogen could be the catalyst for microbial processes such as sulfate reduction

Hydrogen is used by microorganisms in their metabolism, which can have undesirable side effects such as hydrogen loss, H_2S formation and methane production, acid formation, fouling and corrosion. These activities are dependent on the unique environmental conditions of individual storage sites, underscoring the need for comprehensive assessments of microbial and geochemical characteristics to determine appropriate storage, monitoring, and remediation tactics [43], [44], [45].

A major concern is the potential for H_2S contamination in salt caverns used for hydrogen storage. Numerous variables such as bacterial growth, reduction rate, brine volume, sulfate concentration, brine pH, ionic strength, cavern pressure and temperature, and ferrous ion concentrations all affect the increase of risk and more research into microbiome activity in salt caverns is required.

2.2. Composition of brines from salt cavern construction

To estimate the potential harmful substances contained in a hypersaline brine originating from solution mining for salt caverns, a composition of a Zechstein sample provided by TNO, Advisory Group Economic Affairs Department was used. This sample is typical of the salt domes in the North Sea in which the salt caverns could potentially be constructed. This was compared with an environmental impact report of the discharge of brine into the North Sea from salt cavern construction in similar salt formations in Ireland and with the European quality standards (EQS) for seawater [50], [51].

To estimate the concentration of solution mining brine in this salt layer, a first-order estimate was made based on the composition of the salt layer. This was compared with values from Ireland and the EQS. From the rough estimate done using the sample from the TNO, it was found that values could possibly be exceeded the EQS for the following metals: Nickel (Ni), Copper (Cu), Zinc (Zn), Lead (Pb), Boron (B). And possibly the following halogens: Fluorine (F), Iodine (I), Bromine (Br).

It is important that this be carefully analyzed and investigated should concrete plans arise to discharge hypersaline brines from underground salt deposits in the North Sea. If brine from offshore salt caverns were to be discharged into the sea, extensive research should be done first, to comply with the EQS.

Moreover, the discharge of brine not only releases harmful metals into the sea. The discharge of this brine from rock salt causes also a change in the composition and salt balance of seawater, making it more saline. Since brine is also oxygen-depleted, it cannot be immediately released into the environment due to the toxic effects of its high salinity, low oxygen content and unique salt composition [40]. Brine discharge is only allowed under strict guidelines and regulations designed to reduce environmental impact.

Geologically, it is extremely unlikely to find a perfectly homogeneous salt layer hundreds of meters thick that could be used to store hydrogen [52]. Sediments and other geological variances are common in naturally occurring salt formations. Therefore, it is reasonable to expect that some sediment and drill cuttings (small pieces of rock released during drilling) will enter the brine during the leaching process used to create salt caverns. Smaller particles may rise with the brine and eventually be released, but larger pieces will remain at the bottom of the cavern. As a result, the seawater near the discharge point experiences an increase in suspended sediment particles [53]. Tidal currents are expected to gradually spread these sediments over a larger area, although they may initially form mounds on the seafloor. This is a normal occurrence in offshore drilling operations and is not expected to have a significant ecological impact within 100 meters or beyond this radius [8], [53].

2.3. Brine regulations

According to Article 81(1) of the Mijnbouwbesluit, regulations govern the discharge of brine from mining operations. While there are currently no specific guidelines for this discharge, paragraph 3 of the same article suggests that they could be created in the future. The Ministries of Infrastructure and Water Management (I&W) and Economic Affairs and Climate (EZK) are responsible for drafting these regulations [8].

There are currently few guidelines or laws governing brine discharges in Northern Europe, mainly due to the lack of brine disposal activities. However, brine discharges have been reported in Germany and the United Kingdom where salt caverns have been developed for gas storage. Existing brine discharge regulations apply primarily to warmer regions where fresh water is scarce and brine is a by-product of seawater desalination plants. Table 2.2 provides an overview of the different regulations worldwide.

Region	Salinitiy limit	unit	compliance points	Source
US EPA	4	ΔPSU	-	[40]
Caelsbad, CA	40	PSU max	305	[40], [54]
Huntington Beach, Ca	40	PSU max	305	[40], [55]
Western Australia guidelines	5	%	-	[40]
Oakajee Port, Western Australia	1	ΔPSU	-	[40], [56]
Perth, Australia/ Western Australia EPA	1.2 & 0,8	ΔPSU	50& 1000	[40], [57]
Sydney, Australia	1	ΔPSU	50-75	[40], [58]
Gold Coast Australia	2	ΔPSU	120	[40]
Okinawa Japan	1	ΔPSU	end of near field	[40]
Abu Dhabi	5%	%	end of near field	[40]
Oman	2	ΔPSU	300 m	[40], [59]
Eastern Irish Sea, VK	7	ΔPSU	500 meter/near field	[53]
Larne Lough, VK	0,5	ΔPSU	100 meters	[51]
Epe, Germany	-	-	-	[8]

Table 2.2 | Overview of regulations and salinity limits for brine disposal worldwide. *This table provides a comprehensive overview of global regulations and salinity limits for brine disposal, highlighting specific requirements across various regions. It details salinity limits in PSU or percentage changes relative to natural seawater, along with compliance points measured from the discharge location in meters. The table is derived from* [40] *and has been modified and supplemented for this thesis.*

The variety of standards and compliance criteria in Table 2.2 illustrates how each region develops its own environmental policies and guidelines for brine discharge. This demonstrates that brine discharge cannot be approached in a one-size-fits-all manner; local conditions such as proximity to shorelines, protected natural areas, and whether the discharge is temporary or permanent are critical in determining acceptable discharge practices.

This means that no concrete value can be found that is directly applicable to specific circumstances, such as brine discharge into the North Sea at or beyond 150 kilometers from the Dutch coast. However, a common approach in the examples is the use of diffusers to reduce the environmental impact.

The recommendation could be to discharge the brine with a salinity difference of no more than 2 PSU at a distance of 100 meters from the discharge point, measured on the seabed, given the distance from the coast, the lack of nearby protected natural areas, and the expected duration of the discharges, which could last up to three years depending on the size of the cavern. This would ensure minimal impact on the marine environment and be in line with international practices.

2.4. Ecological impacts of brine disposal

Marine life is negatively affected by brine discharges. However, the specific effects of these discharges on marine ecosystems are complicated and depend on a number of variables. Osmotic imbalances, changes in habitat quality, effects on food chains, disruption of reproductive cycles, shifts in species diversity, physical effects on sediments, and cumulative and synergistic effects are some of these factors [60].

Brine discharges primarily affect benthic communities due to its heavy weight, which causes it to sink to the seafloor. Studies show that the ecological effects of brine discharges are complex, with the main contributing factors being high salinity, the presence of heavy metals, oxygen depletion and high temperatures (typically between 30 and 50 degrees Celsius) [61]. Within these communities, the toxic effects and decline in biodiversity are caused by this combination of conditions.

Benthic communities in the mixing zone of the discharge showed remarkable effects [62], according to a field study on the effects of brine discharges in Spain [63], [64]. Along three transects, benthic infaunal communities were dominated by polychaetes, nematodes and bivalves prior to discharge. Polychaete diversity and abundance decreased up to 400 m from the discharge site after the desalination plant opened, while nematode dominance and abundance increased. Research conducted in Algeria showed that highly diverse benthic microbial life underwent physical and compositional changes, most likely as a result of brine in combination with biocides and antiscalants. Laboratory studies showed a decrease in microbial community diversity, which may indicate a tipping point in the local food web [65], [66].

The ability of benthic species to tolerate elevated salinities varies. High tolerance is exhibited by polychaetes and some crab species, which can tolerate salinities up to 60 psu. Bivalves and gastropods have moderate tolerance. Shrimps, copepods and amphipods are less tolerant [61]. Certain copepods and nematodes genera/species are particularly sensitive and are used as indicators to measure the effects of hypersaline discharges [67]. Benthic diatom communities show reduced richness and chlorophyll-a content in regions where desalination concentrations are present [40], [68]. As seagrasses are expected to be found further offshore, they are not discussed here.

The effects of North Sea brine discharges on benthic communities have received little scientific attention. One study compared benthic communities inside and outside the port of Rotterdam [69]. The results of this study, which focused on benthic macroinvertebrates, showed that the biodiversity in the port was much lower. This variability was caused by a number of stressors, including chemical and organic discharges, shipping, dredging, and river engineering, as well as salinity fluctuations and elevated levels due to brine discharges. In addition, two invasive species were found in the harbor, indicating poorer environmental quality [69].

The biodiversity of the benthic fauna is limited in the area far from the coast where brine discharge may occur, partly as a result of overfishing [70]. However, the presence of reef-building species could change this. By building a hard substrate on the North Sea floor, these pioneering species have the ability to establish entire ecosystems. This lays the foundation for the growth of reefs and the emergence of a diverse ecosystem. The flat oyster (Ostrea edulis), the sand mason worm (Lanice conchilega), the northern horse mussel (Modiolus modiolus) and the Ross worm (Sabellaria spinulosa) are the species that have the potential to do this [71]. These have the potential to increase biodiversity in the North Sea and it is policy to ensure that they thrive or are released. It is therefore important to estimate the effects of brine discharges on these species. However, as this is unwieldy, this review will primarily consider brine discharges in relation to salinity fluctuations.

The flat oyster is a species that is sensitive to many factors and difficult to reintroduce. It once almost disappeared from the North Sea. The ability of the flat oyster to withstand changes in salinity is not entirely clear. Research suggests that the parasite that threatens the oyster is more resistant to high salinity than the oyster itself [72]. Studies have also shown that higher salinity levels are associated with reduced growth and increased mortality in other flat oyster species [73].

The effects of changes in salinity on the common horse mussel, Modiolus modiolus, have not been the subject of specific research. However, a recent study of members of the family to which this species belongs, the mythilidae, indicates that they appear to be well adapted to general climatic stressors as well as changes in salinity [74]. This research suggests that it is likely that Modiolus modiolus also has some tolerance, although it is not known exactly how this species responds to changes in salinity. This supports the widely held belief that bivalves are comparatively resistant to salinity fluctuations [75].

It is unclear how certain species, such as Lanice conchilega and Sabellaria spinulosa, are affected by changes in salinity or brine discharges. However, studies of the larger group of marine polychaetes, which includes both species, show that they are typically well adapted to high salinity [61], [76]. In a field study at a desalination plant in Spain, a decline was demonstrated for these species groups, however, that may have been caused by other substances in the brine.

In summary, the available literature indicates that several key North Sea species have varying degrees of sensitivity to changes in salinity. While northern horse mussels may be somewhat resilient, flat oysters are particularly susceptible. Less is known about the effect on Sabellaria spinulosa and Lanice conchilega, although polychaetes tend to adapt well to high salinity. This underscores the importance of carefully monitoring salinity changes to protect these species and the ecosystems on which they depend, especially when they result from human activities such as brine discharges.

The mobility and osmoregulatory abilities of pelagic species greatly influence their sensitivity to salinity changes. By moving to areas of more suitable salinity, mobile species can withstand changes in salinity [61]. Benthic organisms, such as reef building species, are more sensitive to increases in salinity. Studies have shown different responses: at low increases, squid face growth and survival problems, but up to a much higher threshold, sea bream and bonefish larvae show no negative effects. These conclusions are corroborated by observations that the reproductive capacity of most marine species is affected by significant increases in salinity, with eggs failing to hatch and larval development being inhibited. This underscores the importance of understanding the salinity tolerance limits unique to each species, as these limits have a direct impact on the ability of marine species to survive and behave in saltwater environments. The limitations for pelagic species are displayed in figure 2.1 [61]. Seabirds and marine mammals are indirectly affected, mostly through reduced food availability. The survival and well-being of these animals can be affected by a reduction in the food supply of benthic populations, which are a vital source of food for them. Pelagic communities are less affected by changes in salinity, although benthic communities are primarily directly affected. This is because pelagic communities can migrate and adapt to new environmental conditions [26]. These indirect effects highlight the complexity of marine ecosystems and the need for an integrated approach to assessing the consequences of brine disposal in the North Sea.

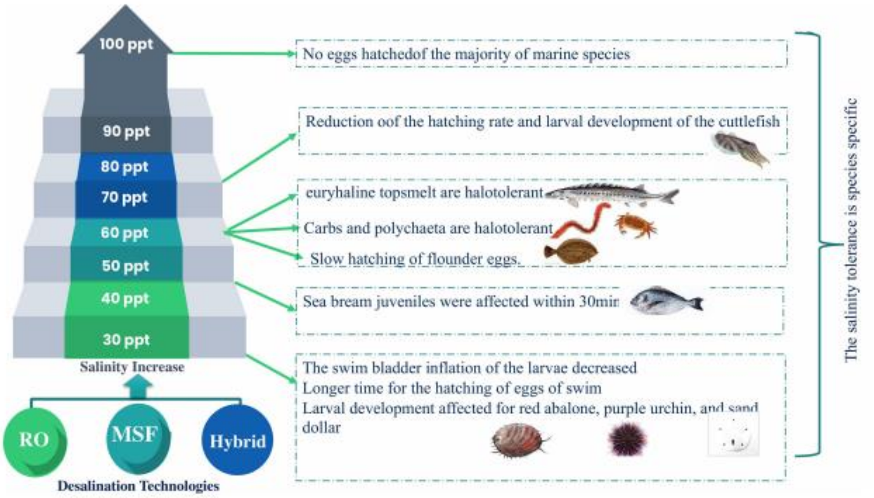


Figure 2.1 | The effect of increasing salinity on pelagic species.
Figure 2.1 illustrates the potential effects on a range of marine animals of increasing salinity levels from laboratory studies as they occur in brine discharges from different desalination technologies. It shows particular salinity thresholds above which adverse effects on a range of marine organisms begin to manifest. Juvenile sea bream show effects at 30 PSU, and larvae show a delay in swim bladder development at 40 PSU. At higher salinities, the effects are even more severe: at 60 PSU, flounder eggs hatch poorly, and at 90 PSU, squid have major

reproductive and developmental problems. At 100 PSU, the eggs of most marine species cease to hatch. Derived from [61].

2.5. Cooling water regulations

In the Netherlands, the use of seawater for cooling purposes and the subsequent release of the cooling water are regulated by strict laws. The purpose of these regulations, which are described in Article 3.6 of the Activiteitenbesluit and Section 4.110 of the Activities in the Besluit activiteiten leefomgeving, is to reduce the impact on surface water [77]. If the cooling water discharge has a heat load of more than 50 megawatts, a special water permit is required . To prevent significant water pollution, additional assessments and special requirements (such as conducting an immission test) are required if chemicals are added to the cooling water. Companies that use cooling water systems and use more than 25,000 cubic meters of water per year are required to report. To avoid overheating the receiving surface water, the heat load of the cooling water (based on flow rate and temperature differential) is carefully calculated. Surface water temperatures in marine environments shouldn't exceed a rise of 3°C. Depending on the characteristics of the receiving water, the law allows for changes in heat loads or the use of chemicals [77]. The goal of these measures is to reduce the negative impact of cooling water discharges on the environment and water quality.

This review found no international consensus on the treatment of cooling water, particularly for offshore operations such as those in the oil and gas industry. The use and discharge of heat and cooling water is not regulated by specific agreements or guidelines established by environmental organizations such as the European Union and the OSPAR Convention. To prevent the discharge of pollutants into the sea, conventions and legal texts focus on the treatment of water to remove hydrocarbons, oil residues and heavy metals. However, global standards for the management of cooling water are still largely absent.

Thus, Dutch regulations primarily govern the feasibility and operational parameters of offshore electrolysis in the Netherlands, including cooling water usage and its impact on surface water temperatures. Offshore electrolysis can take place on a large or small scale if there are no objections from the Dutch authorities.

2.6. Ecological impact of cooling water usage

The use of cooling water and heat release into saltwater environments affects marine life in the North Sea in different ways. Cooling water plants primarily affect surface water life, while brine discharges primarily affect the benthic environment.

The ecological impact of cooling water plants is determined by three primary factors. The first factor is the extraction of cooling water from seawater, which can harm organisms drawn into the cooling water system [78]. It is imperative to avoid removing cooling water from areas that are home to a large number of fish larvae, spawning grounds, and juvenile fish. The second factor is the mixing zone. Additional water quality standards are applicable in the area of the discharge point. There have been suggestions to restrict the area of this zone to a specific portion of the mixing zone. The final term, 'warming', describes the overall warming of surface water throughout the system [79].

Fish have a lower tolerance for warmer water. Benthic species, such as flatfish, are already in danger at temperatures between 25 and 28 ºC. Species that resemble herring are also at risk at 22 ºC. If sensitive species are unable to swim away, they will not survive in areas where discharged water reaches these temperatures. Table 2.3 presents the documented effects of temperature rise on different organisms in the Dutch North Sea. Research indicates that as water temperatures rise, different plankton groups have varying rates of mortality and potential recovery times.

Heat is dispersed by the discharge water as it mixes with the surrounding water, driven by wind, waves, and tides. The cooling water plume often forms a thin layer of heated water on the surface, depending on the exact discharge location. It is crucial to limit heat disposal in sensitive ecosystems like the North Sea, especially during seasons such as spring and fall. This is important for preserving the local fish population and protecting the areas where fish spawn and raise their young.

Activities associated with cooling water plants, such as the withdrawal of cooling water, has a significant adverse effect on aquatic life. The Ems plant in 1992/1993 and 1996/1997 is estimated to have sucked in between 12 and 18 million fish annually at a withdrawal flow rate of 18 m^3/s. It is believed that between 70 and 90 percent of these fish died [79], an estimation is displayed in table 2.5.

Organism	22 °C	25-28 °C	30 °C	34 °C	37 °C	40 °C	Eggs	Larvae	adults
Cladocera (Zooplankton)	n/a	n/a	0% mortality	20-50% survival	0-5% survival	0% survival	n/a	n/a	n/a
Copepoda (Zooplankton)	n/a	n/a	0% mortality	0% mortality	50% survival	5% survival	n/a	n/a	n/a
Rotatoria (Zooplankton)	n/a	n/a	0% mortality	0% mortality	0% mortality	20-50% survival	n/a	n/a	n/a
Diatoms (Phytoplankton).	n/a	n/a	0% mortality	50% mortality	Unkown	Unkown	n/a	n/a	n/a
Flatfish (Benthic)	n/a	Direct threat of mortality	``	``	``	``	n/a	n/a	n/a
Herring species	Direct threat of mortality	``	``	``	``	``	n/a	n/a	n/a
Sole	n/a	n/a	n/a	n/a	n/a	n/a	90%	63%	-
Turbot	n/a	n/a	n/a	n/a	n/a	n/a	93%	27%	-
Seabass	n/a	n/a	n/a	n/a	n/a	n/a	80%	70%	-
Common shrimp	n/a	n/a	n/a	n/a	n/a	n/a	-	73%	-
Lobster	n/a	n/a	n/a	n/a	n/a	n/a	-	85%	-
Acartia tonsa (copepod lobster)	n/a	n/a	n/a	n/a	n/a	n/a	-	-	80%

Tabel 2.3 | The impact of water temperatures on various North sea organisms and their developmental stages.

Table 2.3 provides an overview of the survival and mortality rates of different aquatic organisms in relation to varying water temperatures and developmental stages. The table *illustrates the potential effects of heat disposal on the North Sea ecosystem. Data from* [77], [79] *were used to create the table.*

Species/year	1981/82	1992/93	1996/97
Herring + Sprat	1.360.000	3.040.000	4.320.000
Three-spined stickleback	1.280.000	720.000	1.040.000
Smelt	560.000	240.000	480.000
Gobies	400.000	2.160.000	7.200.000
Eel	7.200	320	4.800
Lesser sand eel	400.000	3.040.000	480.000
Plaice	320.000	80.000	320.000
Flounder	4.000	4.800	64.000
Sole	720.000	800	16.000
Dab	400.000	32.000	64.000
Butterfish	16.000	1.600	4.000
Eelpout	16.000	2.400	8.000
Sea scorpion	8.000	1.600	40.000
Armored sea robin	8.000	8.000	64.000
Searobin	80.000	32.000	80.000
Cod	8.000	160	160.000
Five-bearded rockling	48.000	24.000	16.000
Whiting	80.000	16.000	8.000
River lamprey	24	1.600	-
Twaite shad	2.400	40.000	-
Total number of fish species	**38**	**35**	**34**
Total fish mortality	**4.960.000**	**9.600.000**	**14.300.000**

Table 2.4 | Estimation of marine mortality due to cooling water intake at the Eemscentrale.

This table presents an estimate of fish species mortality resulting from ingestion by the Ems power plant's cooling water system over three different years (1981–1982. 1992–1993, and 1996–1997). The original table only estimated the number of fish ingested, but this table has been adjusted to reflect an estimated mortality rate of 80% due to ingestion. The table demonstrates the significant impact that industrial processes, such as the intake of cooling water. can have on aquatic ecosystems. The data and original table have been derived from [79].

Cooling water plants have complex effects on marine life, which are influenced by variables such as the location of the discharge. seasonal variations, temperature rises, and ingestion mortality. Accurate estimates of fish populations near cooling water intakes and a solid understanding of the ecology and population dynamics of the relevant species are necessary to fully comprehend this influence. Based on a literature review, it is evident that cooling water installations have a significant ecological impact [77], [78], [79]. Large-scale water withdrawals as cooling water for electrolysis and the combined effects of multiple plants have an impact, although it is difficult to precisely determine their effects.

2.7. Conclusion(s)

- **Is it feasible to leach salt caverns using seawater?**

The use of seawater to dissolve salt caverns is not only feasible, but has been used successfully in the past to store gas. Such applications can be found in offshore projects and in the oil and gas industry, where seawater has been used to create salt caverns or to dissolve the salt layer to access oil and gas reservoirs.

- **What harmful pollutants are used or released during the production and storage of offshore green hydrogen, and what are the potential environmental impacts?**

Several pollutants are used or released during the production and storage of offshore green hydrogen, with potentially serious environmental consequences. Major pollutants include biocides such as Cl_2, H_2SO_4 and various halogens found in cooling water that can harm aquatic life when released into the marine environment.

RO membranes are maintained with harmful chemicals such as antiscalants and detergents that are highly acidic or alkaline. In addition, corrosion can cause the release of toxic heavy metals into the environment.

PFCs, including PFAS, are used in PEM electrolysers. These substances can bioaccumulate in the marine ecosystem and are toxic to organisms, with the potential for non-degradation, which is dangerous. In addition, electrolyser membranes and components contain heavy metals that can harm marine life if leaked into the environment.

Finally, the storage of hydrogen can produce H_2S, which is not only toxic to the environment, but also corrosive to the systems involved.

Given these risks, more research on these pollutants is needed before large-scale hydrogen production and storage is implemented.

- **What is the ecological impact of brine disposal at potential hydrogen storage sites?**

The ecological impact of brine disposal at potential hydrogen storage sites is multifaceted and can have profound consequences for marine life. Brine discharges primarily affect benthic communities, as the negatively buoyant brine sinks to the seabed and directly impacts benthic life. Research shows that the main ecological effects of brine discharges stem from high salinity levels, the presence of heavy metals, oxygen depletion and high temperatures. This combination of conditions leads to toxic effects and a decrease in biodiversity within these communities.

Specifically. studies have shown that benthic infaunal communities undergo changes following brine discharge. For example. there has been a noted decrease in the diversity and abundance of polychaetes, while the dominance of nematodes has increased. Additionally, a reduction in the diversity of the microbial community has been observed, indicating a potential shift in the local food chain. The tolerance of benthic species to elevated salinity levels varies. Polychaetes and some crab species exhibit high tolerance, while bivalves and gastropods have moderate tolerance. Meiofauna such as copepods and nematodes are particularly sensitive and are used as indicators of the effects of hypersaline discharges.

Regarding specific North Sea species. such as the flat oyster and the common horse mussel. the impact of salinity changes is less clear. It has been shown that higher salinity levels are associated with reduced growth and increased mortality in other flat oyster species. No specific research has been conducted on the common horse mussel, but related research suggests some tolerance to salinity changes.

The sensitivity of pelagic species to salinity changes is greatly influenced by their mobility and osmoregulatory abilities. Mobile species can survive by moving to areas with more suitable salinity levels. Various studies have shown that significant increases in salinity affect the reproductive capacity of most marine species.

These findings underscore that brine disposal can impact the surrounding ecosystem. particularly the area falling within the mixing zone. This highlights the importance of careful policy regarding brine discharges.

- **What is the impact of cooling water discharge and cooling water intake on the marine environment at offshore hydrogen production sites?**

The impact of cooling water discharge and intake on the marine environment at offshore hydrogen production sites is complex and multifaceted. The ecological impacts are primarily influenced by extraction of cooling water and thermal pollution.

The withdrawal of cooling water from the sea can harm marine organisms, especially in areas rich in fish larvae, spawning grounds and juvenile fish. Withdrawal of large volumes of water can result in significant fish mortality due to entrainment and impingement at intake points. with estimates ranging from 70 to 90 percent of fish entrained dying. For example, the Ems power plant cooling water system is estimated to kill millions of fish annually, highlighting the significant impact of cooling water intakes on local fish populations.

The second factor is thermal pollution: The discharge of heated water back into the marine environment can create a 'warming' effect. This rise in water temperature can have detrimental effects on marine life, particularly fish and benthic species. Fish, for example, have a lower tolerance for warmer water. and species like flatfish and herring are at risk at temperatures between 22 and 28 ºC. Elevated temperatures can lead to increased mortality rates, altered growth and development, and changes in behavior and distribution of marine organisms.

Laboratory studies have shown varying rates of mortality and potential recovery times for different plankton groups as water temperatures rise

These factors have a significant ecological impact. and together they underscore the need for more research into their effects and the need for a strict policy on the use of cooling water at offshore hydrogen production sites. The ecological impacts. particularly in sensitive ecosystems such as the North Sea. can be significant and affect a wide range of marine organisms from plankton to larger fish species. This highlights the importance of considering both the direct and indirect effects of cooling water discharge and intake on the marine environment.

"How does offshore green hydrogen production and storage. including brine disposal, cooling water management and associated hazardous substances affect the ecological balance in marine areas, and does it meet current environmental standards?"

Given current environmental standards, offshore green hydrogen production and storage have significant impacts. particularly in terms of brine disposal and thermal pollution. Therefore, a more cautious and research-oriented approach is necessary. Although it is feasible to use seawater for creating salt caverns, the broader ecological consequences are not yet fully understood. The need for comprehensive investigation and informed policy-making is highlighted by the consequences of brine disposal and thermal pollution. The urgency for extensive research is underscored by the significant impact observed on local fish populations and marine biodiversity. Further study is needed to examine the potential leakage of hazardous substances into marine environments. Effective mitigation strategies and stringent policies must be developed for managing this in the offshore environment. Offshore green hydrogen production and storage practices, including brine disposal, cooling water management and hazardous substance management, require environmental precautions. Before implementing these technologies on a large scale, it is essential to ensure their compliance with environmental standards and their safety for marine ecosystems and that monitoring is used in pilot studies. This is important not only for regulatory purposes but also for the sustainable development of offshore green hydrogen production and storage. It ensures that these innovative technologies can be developed responsibly with minimal ecological impact.

3. Case study for hydrogen storage in offshore salt caverns

3.1. Introduction

A detailed case study is required to fully understand the environmental impact of brine discharges from salt cavern construction in the North Sea. There has been little research into brine discharges far from shore. Most of the known studies concentrate on coastal sites, where brine is mostly produced by land-based or coastal activities [60]. In addition, hypersaline brine discharges are studied less than discharges of desalination brine or brine waste from other sectors [8], [40].

The proposed wind farms for P2G projects are at least 150 kilometers from shore [5], [6]. These farms are planned to be built after 2030, when the technology for large-scale production of hydrogen at sea is planned to become available. From an economic and technological point of view, it is more efficient to transport the generated energy to land in the form of hydrogen rather than electricity [10]. However, these wind farms are located close to important Marine Protected Areas (MPAs) such as Doggerbank, Klaverbank and the Central Oyster Grounds [80]. This highlights the importance of appropriate modelling and assessment of the impact of brine discharges to avoid environmental damage.

The area under consideration for offshore hydrogen production and storage is characterized by its moderate depth, ranging from 30 to 60 meters [81], which plays an important role in current dynamics and ecological processes. The current patterns in this area of the North Sea are complex, influenced by both tidal and wind-driven currents. These currents are critical for the transport of salt water, sediment, nutrients and oxygen [82].

Stratification in the Dutch North Sea, a phenomenon in which layers of water with different temperatures and salinities form, occurs mainly during the summer months, resulting in temperature differences of 5 to 10°C between the surface and deeper water [83], [84]. Given that the average depth of the North Sea exceeds 20 meters, stratification is a regular occurrence [83]. The most important consequence of this stratification is a significant reduction in vertical mixing. This reduced mixing has profound implications for the region's ecological dynamics, affecting everything from nutrient cycling to oxygen processes and the overall productivity of the marine food web. By affecting nutrient distribution, carbon cycling (including fixation, excretion, and storage), oxygen production, and potential anoxia, stratification is fundamental in shaping the composition of the water column and the health and functionality of the surrounding ecosystem [85].

Understanding the ecological impact and influence on stratification in the Dutch North Sea, on locations where future hydrogen storage infrastructure is proposed, requires modeling the consequences of brine discharge. Given the region's complexity and fluctuation, it is impracticable to perform this for all hydrogen-eligible wind parks. As a result, a representative site in the bottom half of wind area 7 was chosen for the case study, which is considered feasible for future offshore hydrogen production and storage. This 45-meter-deep site, which is prone to summer stratification and is close to the Central Oyster Grounds, provides an excellent opportunity to investigate and model the environmental impact of brine discharges from the leaching of salt caverns.

3.1.1. Brine-disposal and diffuser-use

The discharge of brine from salt cavern leaching is a critical factor in the environmental impact assessment of offshore hydrogen storage. This brine needs to be managed effectively, which includes options such as direct discharge to surface water, deep sea discharge, dilution prior to discharge and dispersion through a brine diffuser [26], [40], [60].

Despite its high salinity, the brine produced in this case study is manageable according to existing literature [8]. However, interviews with experts and a prior literature review indicate that such hypersaline brines will require a diffuser and the brine will most likely need to be diluted beforehand [86]. For the specific conditions of the intended study site, this method was identified as the most effective and environmentally friendly approach. The diffuser distributes the brine over a larger contact area, reducing the salt concentration in the ambient water and thus reducing the impact on the marine ecosystem.

The selection of a brine diffuser is based on techno-environmental considerations, as economic considerations are beyond the scope of this thesis. This emphasis on ecological impact assists in reducing the negative environmental impact. The use of a brine diffuser provides a balanced solution by increasing brine dilution efficiency while reducing the impact on the local environments

3.1.2. Dynamics of Brine Plumes

Understanding the dissolution dynamics of brine in the surrounding seawater and the resulting environmental impact is critical in the context of this study. This requires a detailed analysis of brine buoyancy. Consider a hypersaline brine with a temperature of 15°C and a salinity of 280 PSU compared to a desalination brine with the same temperature and a salinity of 68 PSU. Compared to seawater, which has a temperature of 15°C but a salinity of 33 psu, there is a significant difference in density: seawater has a density of 1024.42 kg/m^3, desalination brine has a density of 1051.68 kg/m^3 and hypersaline brine has a density of 1233.42 kg/m^3.

When discharged into the ocean, these brines form descending currents or "brine plumes" due to their higher densities [87]. These negative buoyancy underwater currents sink under the force of gravity, in contrast to the density of the surrounding medium. Several factors influence the dynamics and distribution of these plumes, including the density difference between the brine and the surrounding water, water temperature, discharge depth, and ocean current patterns [40], [88]. Understanding these interactions is critical to assessing the environmental impact of brine discharges in marine environments.

3.1.3. Dilution and impact points

Understanding the environmental impact of brine plumes requires an understanding of how they are diluted and dispersed in the marine environment. Dilution is necessary to reduce the environmental impact of brine plumes. Dilution of brine plumes ensures that the plume eventually merges and mixes with the surrounding water. The degree of dilution of a plume is determined by measurement or modelling from the point of impact (S_i). The 'point of impact' is where the brine plume first comes into contact with the seabed [88].

Several factors contribute to the dilution of brine plumes from the point of impact. These factors include the density and temperature of the brine, the flow velocity and direction and movement of the surrounding seawater, and the roughness of the seabed [89]. The density and temperature of the brine determine how quickly it sinks and disperses after contact with the seabed. The dynamics of the surrounding seawater, such as currents and tides, influence the dispersion and dilution of the brine plume. The roughness of the seabed is also important as it can help or hinder the spread of the plume over a larger area [88].

3.1.4. The Near- and Far Field

To effectively study the movement, dilution and impact of the brine plume, it is necessary to distinguish between the near field and the far field. Figure 3.1 illustrates this distinction schematically. Under normal conditions, the near field does not extend more than 100 meters from the point of discharge, after which the far field begins. Depending on the conditions, the far field can extend for several kilometers [40].

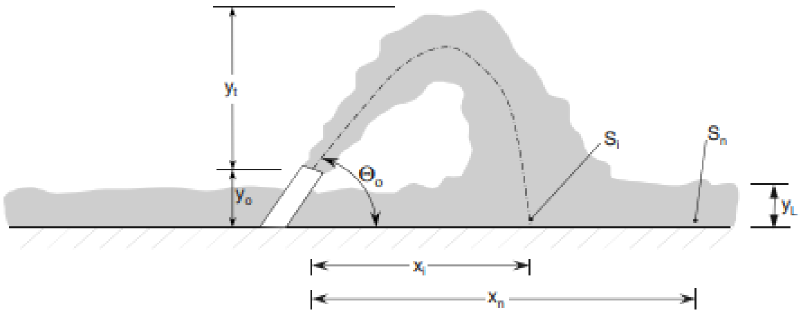


Figure 3.1 | Near- and far-field dispersion of a brine plume in the marine environment with a diffuser.
This figure depicts the the initial descent and subsequent horizontal spread of brine in the near field. Here Y_t *height of the top of the brine jet,* Y_l *is the thickness of the brine plume in the far field,* θ_o *is the angle descent angle of the diffuser,* X_i *is the distance to the point of contact,* X_n *is the distance to the end of Near field,* S_i *is the dilution at the point of impact and the point beyond* X_n *is the far field. Derived from* [90].

The area where brine mixing is impacted by discharge parameters is known as the near field [90]. The near field is a hydrodynamic or physical concept where the brine plume reaches its highest concentration and has the greatest potential for direct ecological impact [40]. Initial discharge conditions such as brine outflow velocity, density and temperature have the greatest influence on the plume. These conditions are primarily determined by the diffuser in this study. The interaction of the plume with its immediate environment, such as the seabed and local currents, is critical in determining the initial dilution rate, and near-field dilution is generally enhanced by strong currents [91]**.** The near field ends where the self-induced turbulence decreases under the influence of the induced density stratification [40], [91].

The long-term dynamics of brine plume dispersion are explained by the far field, which extends well beyond the immediate discharge point. In this extended zone, the brine plume mixes and dilutes over long distances. This is a complicated phase influenced by extensive ocean current patterns, regional temperature variations and seasonal changes [40]. While the far-field effects are less immediate and concentrated than those in the near-field, the long-term effects on extensive marine ecosystems can be significant, especially if the brine remains for long periods in areas with limited mixing or stratified waters [60]. Far-field analysis is therefore essential to assess the overall ecological impact of brine plumes.

For a detailed assessment of the ecological impact of brine discharges, a thorough analysis of both near-field and far-field effects is required. This case study focuses on modelling and calculating the near-field and far-field concentration differences associated with both the ambient seawater and the discharged brine, thus emphasizing the determination of the far-field extent. Such an integrated approach is essential to understand and mitigate the full extent of the environmental impact of brine discharges.

In order to determine the environmental impact of this hypothetical brine discharge into the Dutch North Sea, specific research questions need to be identified. These are necessary to quantify the expected environmental impact of the proposed brine discharge and to develop effective mitigation strategies. The research question and related sub-questions are presented below:

3.2. research question(s):

“How will a brine discharge of 0.3 m^3/s with a PSU of 280 affect the surrounding seawater over a period of 2.5 years, and what measures could be taken to mitigate the negative environmental impact?”

Sub-questions:

- What is the maximum dilution and minimum salinity difference with the ambient seawater that is feasible in the near field?
- What degree of dilution is required before brine discharging to achieve acceptable/optimal values at the end of the near field?
- How should a brine diffuser be designed to achieve levels of maximum dilution?
- What is the environmental impact in the far field on the water column? Without dilution prior to disposal and with optimized diluted brine?
- How do brine discharges affect physical processes in the far field such as currents, temperature distribution and salinity in the North Sea?
- How does brine disposal affect far-field stratification?
- Does the far field stretches to MPAs and if so, to what extent?

3.3. Method

3.3.1 Site details

The area of hypothetical brine disposal is located in the southern part of Wind Area 7, approximately 200 kilometers offshore, as shown in Figure 3.2. Discharge will take place on the seabed at a depth of approximately 45 meters [13]. In accordance with the agreements within the NSE consortium, the exact location of the salt caverns where the brine is discharged is not specified, but is within the orange circle shown in Figure 3.2. The choice of location for the caverns is strategic: proximity to the wind farm, to existing pipelines that can be adapted for hydrogen transport to land, and the presence of a salt structure large enough to create three caverns with a volume of $1*10^6$ m^3 each.

Here a disposal of a brine flow of 0.3 m^3/s and a PSU of 280 will be modelled to assess the impact to the environment. At this location, the extracted salt from the halite deposits is discharged to the bottom of the sea through a diffuser.

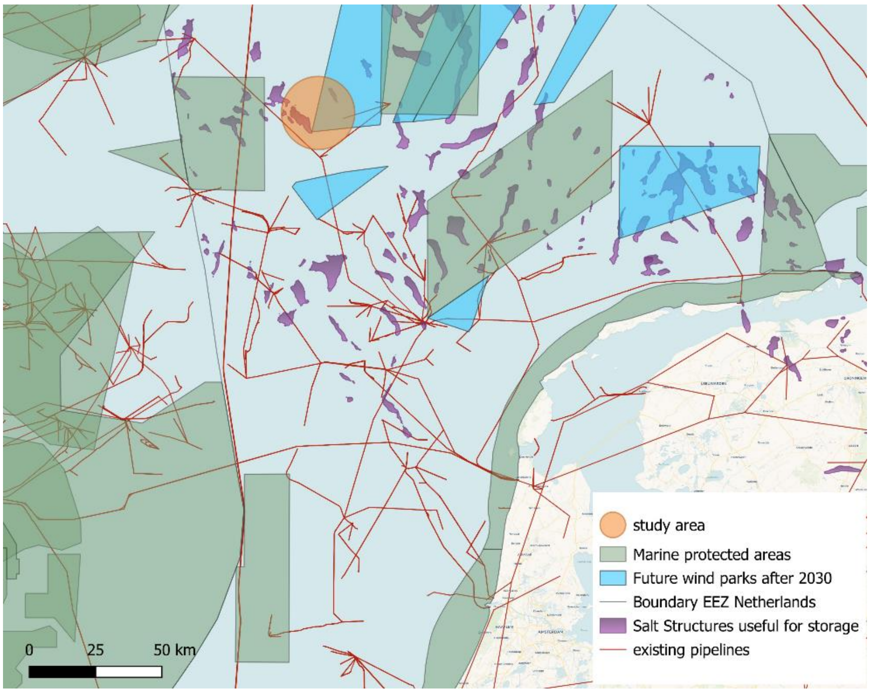


Figure 3.2 | A geographic overview of the brine disposal site and nearby MPAs and planned future wind farms.

This map outlines the brine disposal site, shows nearby Marine Protected Areas, future wind farm sites after 2030, existing pipelines that could be used for hydrogen transport, and potential salt structures for storage, providing a concise spatial analysis of environmental and industrial elements.

3.3.2. Near Field modeling

Various modelling techniques can be used to assess the environmental impact of brine discharges. Commonly used software such as CORMIX, UM3, Visual Plumes, VisJet and NRFIELD are effective for modelling positive buoyancy from a diffuser, but less effective for substances with negative buoyancy such as brine [40], [90]. Physical modelling in a laboratory environment is an alternative, but is complex, time consuming and costly. A practical approach is therefore semi-empirical near-field impact modelling. This involves applying existing knowledge and formulas for dilution and diffuser design to achieve the optimum diffuser size and desired dilution. This method, which has been validated in several studies, is widely used for designer diffusers and provides a realistic picture of near-field dilution. For more complex scenarios involving factors such as bottom roughness, currents, bottom slope and merging rays, numerical modelling is required, although it is generally reserved for complex cases [40], [91].

To determine the impact of the hypothetical brine discharge a semi-empirical model in excel has been established, which makes calculations using the following parameters and assumptions and formulas:

3.3.3. Density of Water as a Function of Temperature and Salinity

The density of ambient water and brine is calculated in this study using the McCutcheon et al. 1993 formula [92]. Unlike the more complex UNESCO formulae, the density of the solution in this formula is determined solely by temperature and salinity. As the study is limited to a relatively narrow range of variables, this choice reduces unnecessary complexity. The formula meets the accuracy requirements for modelling the density of both ambient water and discharged brine, which is consistent with the methodological approach that excludes more complex factors such as seabed roughness and flow patterns.

First the density of as a function of only temperature needs to be calculated:

$$\rho = 1000(1 - \frac{T+288{,}9414}{508929.2 * (T+68{,}12963)} * (T - 3{,}9863)^2 \qquad (1)$$

In this formula ρ is the density in kg/m³ and T is the temperature in degrees Celsius (°C).

After the density is calculated as a function of temperature, the density can be calculated as a function of temperature and salinity with the following formula:

$$\rho_S = \rho + AS + BS^{3/2} + CS^2 \qquad (2)$$

In this formula:
- ρ_s *is the density in kg/m³.*

- *S is the salinity in g/kg.*

- ρ *is the density calculated from the temperature-only formula in kg/m³.*

- *A, B & C are coefficients, that are calculated as followed:*

$$A = 0{,}824493 - 4{,}0899 * 10^{-3} * T + 7{,}6438 * 10^{-5} * T^2 - 8{,}2467 * 10^{-7} * T^3 + 5{,}3675 * 10^{-9} * T^4 \qquad (3)$$

$$B = -5{,}724 * 10^{-3} + 1{,}0227 * 10^{-4} * T - 1{,}6546 * 10^{-6} * T^2 \qquad (4)$$

$$C = 4{,}8314 * 10^{-4} \tag{5}$$

The salinity and temperature values that are required to calculate the density of the ambient water are derived from the reference run from the far field modelling.

How much the brine needs to be dissolved is determined using the following formula:

$$D_f = (S_{amb} - S_{eff}) / \Delta S_{max} \tag{6}$$

Here:

- *D_f is the dilution factor, how much the effluent needs to be diluted in order to meet requirements.*
- *S_{amb} is the salinity of the ambient water in g/kg.*
- *S_{eff} is the salinity of the effluent water in g/kg.*
- *ΔS_{max} is the maximum allowed salinity increase in g/kg.*

To calculate the volume flux of brine out of each port of the brine diffuser the jet volume flux needs to be calculated:

$$Q_0 = Q_t / n \tag{7}$$

Q_0 is the jet volume flux in m^3/s, Q_t the total brine flux through the diffuser in m^3/s and n is the number of ports.

The velocity at which the brine is discharged from the jets could now be determined. This is derived from the jet volume flux per port and the port diameter. This formula quantifies the rate at which brine is being expelled from each individual port.

$$U_0 = Q_0 / ((D_0 / 2)^2 * \pi) \tag{8}$$

In this formula:

- *U_0 is the outflow velocity in m/s, this cannot be larger than 6 m/s, due to stress on the diffuser and is kept below 4 m/s preferably.*
- *Q_0 is the jet volume flux in m^3/s.*
- *D_0 is the port diameter in m.*

Subsequently, the factor of density difference between the effluent and ambient water needs to be factored, as well as the standard acceleration due to gravity. This is done by calculating the Modified Acceleration Due to Gravity, this is essential for understanding how density affects the brine’s buoyancy:

$$g_0' = g(\rho_{amb} - \rho_{eff})/\rho_{eff} \tag{9}$$

Here:

- *g_0' is the modified acceleration attributable to gravity in m/s^2.*
- *g is the gravity, which is 9,81 m/s^2.*
- *ρ_{amb} is the density of the ambient water in kg/m^3.*
- *ρ_{eff} is the density of the effluent water in kg/m^3.*

Moreover, the Jet Densimetric froud number needs to be calculated. This a dimensionless number, which is used to characterize the flow regime of the effluent:

$$Fr = U_0 / \sqrt{g' * D0} \tag{10}$$

- *Fr is the jet Densimetric froud number*
- *U_0 is the outflow velocity in m/s.*
- *g_0' is the modified acceleration attributable to gravity in m/s^2.*
- *D_0 is the port diameter in m.*

The distance between the ports of the diffuser could be calculated by:

$$s = 2 * D0 * Fr \tag{11}$$

With s being the distance between the ports in meters, D0 is the port diameter in meters and Fr is ‘’.

The total length of the diffuser could be described as:

$$L = (n - 1) * s \tag{12}$$

Here L is the total length in meters, n is the number of ports and s is the distance between the ports in meters.

The dilution in the near field can be calculated. Near field dilution is described with the following formulas:

$$Sn_{\text{single jet}} = 2{,}6 * Fr \tag{13}$$

$$Sn_{\text{multiple jets single direction}} = 1{,}1 * Fr * (s / (D_0 * Fr) \tag{14}$$

$$Sn_{\text{multiple jets opposing ports}} = 0{,}8 * Sn_{\text{multiple jets single direction}} \tag{15}$$

Lastly, the dilution in the end of near field can now be derived (16)

$$Sn_{\text{final}} = (S_{\text{effluent}} – S_{\text{ambient}}) / Sn \tag{17}$$

To ensure adequate dilution of the effluent, the calculated final near-field dilution (Sn_{final}) must exceed the dilution factor (Df). This requirement confirms that the effluent has been sufficiently diluted to meet the environmental standards.

Furthermore, the design specifications of the diffuser nozzles, which play a critical role in optimizing brine dilution, should be highlighted. The diffuser nozzles are set at a 60-degree angle for this study, a configuration that has been empirically validated to be the most effective for brine dilution [88].

The formulas were derived from the following literature: [88], [89], [92], [93], [94].

3.3.4. The Far field model

A detailed hydrodynamic model is required to quantify the far-field effects of brine discharge. Given the complexity of coastal discharge and diffusion in the far field, taking into account a variety of environmental conditions and their temporal variations, the diffusion and dilution of the brine plume must be modelled in three dimensions [40]. As the far field in this situation involves deeper waters where stratification plays a role [84], and complex currents and bottom roughness play a much greater role for the far field [40], a three dimensional model is required.

In the case study, the Dutch Continental Shelf Model - Flexible Mesh (DCSM-FM) version 0.5 nm was used to model the far field. This is a Delft3D-FM model that runs on the D-HYDRO Suite software and covers the entire North Sea, including the Dutch Continental Shelf. It is part of the sixth generation of model schematics. This model has been developed primarily for operational water level forecasting and studies of dust dispersion, salt intrusion and temperature [13]. This makes it ideal for simulating far-field brine dispersion.

The DCSM-FM 0.5 nm model features a relatively coarse grid, with a maximum resolution of approximately 0.5 nautical miles (around 900 meters) at the study site, and incorporates 20 vertically flexible layers adapted to depth variations. Covering the majority of the Northwest European Continental Shelf—spanning from 15°W to 13°E and 43°N to 64°N—it encompasses the full North Sea and Wadden Sea. Figure 3.3 illustrates the North Sea basin of the Netherlands, showing the model's varying grid sizes.

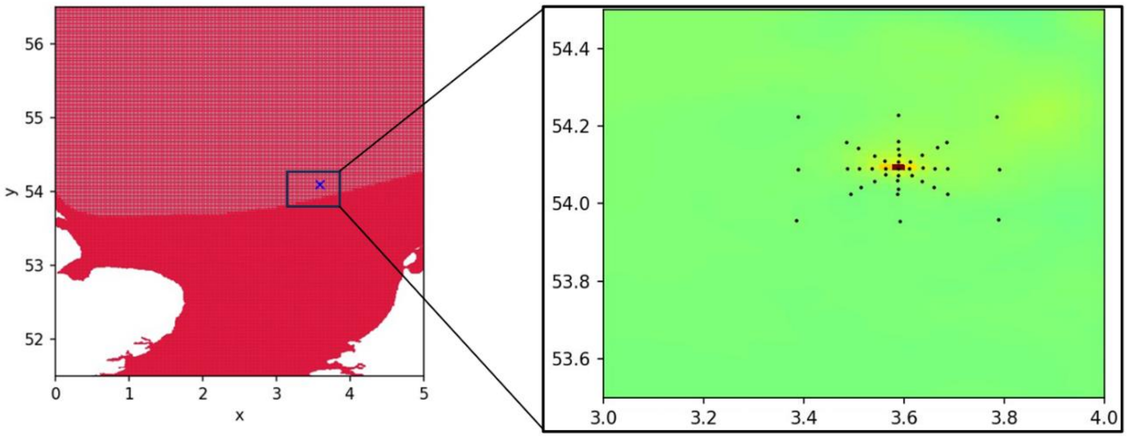


Figure 3.3 | An overview of the DCSM-FM 0.5 nm model and the brine disposal site. *Figure 3.3 illustrates the brine disposal site in the North Sea in the DCSM-FM model, showcasing the transition from a coarser 0.5 nautical mile grid in the brine disposal area to a finer 0.25 nautical mile resolution near the Dutch coast. The left side of the figure highlights the broader model coverage, while the right side provides a detailed close-up of the disposal site, surrounded by an array of monitoring points established to measure the impact of brine discharge on the water column.*

The geographical data on which the model is based are provided by the Baseline-NL databases, a special ArcGIS database at Rijkswaterstaat for the development of hydrodynamic models. For areas outside Dutch waters, data from the international European Marine Observation and Data Network (EMODnet, October 2016 version) are used. Bathymetry in Dutch waters is referenced to Normal Amsterdam's Peil (NAP), and beyond that to mean sea level.

The computational grid of the model is configured as a uniform quadrangular mesh that is progressively refined in three steps along contours of constant depth. The DCSM-FM 0.5 nm model has approximately 630,000 nodes.

The vertical grid of the model consists of 20 uniformly distributed layers, so that each computational chamber has a fixed number of layers with varying thicknesses depending on the local water depth. The depth data for the parts outside the Dutch North Sea are taken from EMODnet, while the data for the Dutch part are based on detailed bottom information from the Dutch Baseline database.

The soil roughness in the model is expressed by a Manning roughness coefficient, which is divided into 60 different zones. Bilinear interpolation is used between these zones to ensure a smooth transition of roughness values from 0.012 $s/m^{1/3}$ to 0.050 $s/m^{1/3}$.

A comparison of model data with observations from 2006 to 2012 shows that the model simulates salinity and temperature accurately. The average temperature deviation from weather station measurements was -0.34°C, with a maximum deviation of -0.53°C. The model underestimated salinity by -0.3 psu on average, with the largest measured difference being -0.7 psu. These values indicate that the model can accurately model differences in brine plume density.

3.3.5. Modeling of the Far Field

Two simulations were conducted using the DCSM-FM 0.5nm model to assess the effects of brine discharge in the far field. For both simulations a pre-run was conducted for the calibration of the model spanning from 1 January 2013 to 31 December 2013. After that the model was split in two runs spanning from 1 January 2014 to 1 January 2015. The first run was a base run with no discharge and the second simulation modelled the effects of continuous brine discharge at a salinity of 280 psu and a flow rate of 0.3 m^3/s,.

To ensure the accuracy of the model, 2013 served as a 'tuning-in' period, establishing a reliable baseline for the subsequent years. However, the simulations did not extend beyond 1 January 2015 due to time constraints. Therefore, while the preparatory run in 2013 was used to adjust the model, only the results up to the start of 2015 are included in this study. The period following the active discharge phase was not modeled, and the potential long-term impacts beyond this date remain unexplored.

The model assumed that the temperature of the brine was equal to the ambient temperature. In order to avoid scatter that could not be accounted for in the model, the bottom water temperatures (BWTs) of the three closest monitoring stations were averaged and a prediction function in R was applied to them, resulting in a brine water temperature equal to the ambient temperature.

Brine flow was inserted into the model as a flow rate at 45 meters depth to simulate brine discharge conditions, similar to how rivers are represented in the model. Although the near-field data could not be directly integrated into the far-field model, nor could the diffuser be directly incorporated into the model, this approach provides the best simulated representation of brine dispersion in the far-field.

Additional monitoring points were added additional to the existing monitoring points around the discharge site and all relevant parameters in the water column were continuously recorded.

Figure 3.4 displays locations and distribution of the measured values based on the data collected.

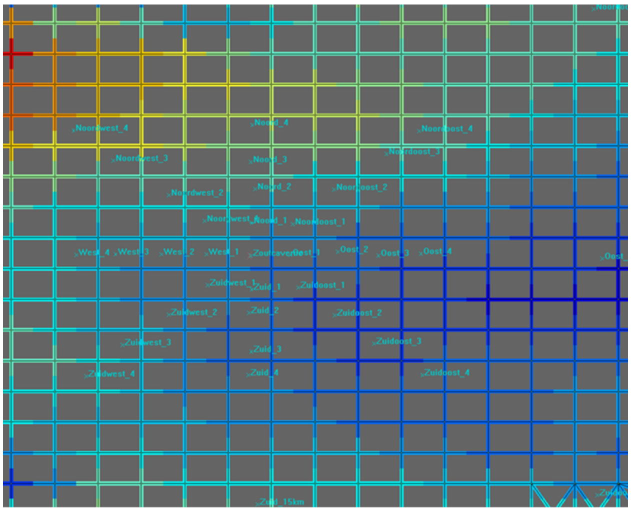


Figure 3.4 | The enhanced monitoring framework in the DCSM-FM 0.5nm Model near the brine disposal site.
This figure provides an overview of the additional monitoring points added into the DCSM-FM 0.5 NM model.

3.4. Results

3.4.1. Results in the Near Field

The following near field end of dilution values were derived from the Excel near field analysis model for undiluted discharge with a PSU of 280 and a flow of 0.3 $m^{3/}$s. Even with the most advanced diffuser designs and an allowable discharge velocity of up to 6 m/s, but preferably no greater than 4 m/s, it was not possible to find values that would result in acceptable dilution and that would result in a realistic diffuser design with discharge velocities that would not be too stressful on the equipment. Table 3.1 shows the range of most acceptable values found for a salinity of 280 PSU.

Next, each liter of brine was diluted with one liter of seawater, with a PSU of 33 (average value of the 3D model). As a result, the brine flow had a PSU of 157 and a flow of 0.6 m^3/s. While these values have less ecological impact, they are still below the standards discussed in Chapter 2. Table 3.1 also shows the optimum range of values. Dilution with two liters of seawater per liter of brine resulted in a flux of 0.9 m^3/s and a salinity of 115 PSU. As shown in the table 3.1, these values are approaching acceptable limits. Finally, a dilution of three liters per liter of brine was used, resulting in a PSU of 92.5 and a flux of 1.2 m^3/s. These values are very similar to those of desalination plants and the resulting brine discharges. These values can meet international standards with an appropriately selected diffuser and are unlikely to be visible in the far field [91].

PSU brine (in g/L)	dilution factor	Flux (in m^3/s)	number of ports	port diameter	Fr	Sn	ΔPSU(in g/L)	U0 (m/s)	distance between ports (in m)	total length diffuser (in m)
280	123,5	0,3	1	0,30	11,6	30,2	8,2	4,2	7,0	0,0
280	123,5	0,3	5	0,14	15,6	40,6	6,1	3,9	4,4	17,5
280	123,5	0,3	10	0,10	18,1	47,1	5,2	3,8	3,6	32,6
280	123,5	0,3	20	0,07	22,1	57,4	4,3	3,9	3,1	58,7
280	123,5	0,3	40	0,05	25,6	66,6	3,7	3,8	2,6	99,8
280	123,5	0,3	60	0,04	29,8	77,5	3,2	4,0	2,4	140,7
280	123,5	0,3	100	0,03	36,7	95,5	2,6	4,2	2,2	218,1
280	123,5	0,3	200	0,02	50,6	131,6	1,9	4,8	2,0	402,8
280	123,5	0,3	300	0,02	33,7	87,7	2,8	3,2	1,3	403,5
280	123,5	0,3	1000	0,01	57,25	148,8	1,7	3,8	1,1	1143,8
157,0	61,8	0,6	1	0,44	8,9	23,2	5,3	3,9	7,8	0,0
157,0	61,8	0,6	5	0,20	12,8	33,3	3,7	3,8	5,1	20,5
157,0	61,8	0,6	10	0,14	15,6	40,6	3,1	3,9	4,4	39,3
157,0	61,8	0,6	20,0	0,10	18,1	47,1	2,6	3,8	3,6	68,8
157,0	61,8	0,6	40,0	0,07	22,1	57,4	2,2	3,9	3,1	120,6
157,0	61,8	0,6	60,0	0,06	21,6	56,3	2,2	3,5	2,6	153,2
157,0	61,8	0,6	100,0	0,05	20,5	53,3	2,3	3,1	2,0	202,8
157,0	61,8	0,6	200,0	0,03	36,72	95,5	1,3	4,2	2,2	438,5
157,0	61,8	0,6	300,0	0,03	24,48	63,7	1,9	2,8	1,5	439,2
157,0	61,8	0,6	400,0	0,03	18,36	47,7	2,6	2,1	1,1	439,6
157,0	61,8	1,6	1000,0	0,03	19,59	50,9	2,5	2,3	1,2	1174,0
115	41,2	0,9	1	0,6	6,2	16,0	5,1	3,2	7,4	0,0
115	41,2	0,9	5	0,24	12,2	31,6	2,6	4,0	5,8	23,4
115	41,2	0,9	10	0,17	14,4	37,5	2,2	4,0	4,9	44,1

115	41,2	0,9	20	0,12	17,2	44,8	1,8	4,0	4,1	78,5
115	41,2	0,9	40	0,09	17,7	45,9	1,8	3,5	3,2	124,0
115	41,2	0,9	60	0,07	22,1	57,4	1,4	3,9	3,1	182,4
115	41,2	0,9	100	0,06	19,5	50,6	1,6	3,2	2,3	231,4
115	41,2	0,9	200	0,04	26,8	69,8	1,2	3,6	2,1	427,2
115	41,2	0,9	300	0,03	36,7	95,5	0,9	4,2	2,2	658,8
115	41,2	0,9	400	0,03	27,5	71,6	1,1	3,2	1,7	659,4
94,8	30,9	1,2	1	0,6	8,2	21,4	2,9	4,2	9,9	0,0
94,8	30,9	1,2	5	0,27	12,1	31,4	2,0	4,2	6,5	26,1
94,8	30,9	1,2	10	0,18	16,7	43,3	1,4	4,7	6,0	54,0
94,8	**30,9**	**1,2**	**20**	**0,14**	**15,6**	**40,6**	**1,5**	**3,9**	**4,4**	**83,1**
94,8	**30,9**	**1,2**	**40**	**0,1**	**18,1**	**47,1**	**1,3**	**3,8**	**3,6**	**141,2**
94,8	**30,9**	**1,2**	**60**	**0,08**	**21,1**	**54,8**	**1,1**	**4,0**	**3,4**	**199,0**
94,8	30,9	1,2	100	0,06	26,0	67,5	0,9	4,2	3,1	308,5
94,8	30,9	1,2	200	0,05	20,5	53,3	1,2	3,1	2,0	407,6
94,8	30,9	1,2	300	0,04	23,9	62,0	1,0	3,2	1,9	570,6
94,8	30,9	1,2	400	0,03	36,7	95,5	0,6	4,2	2,2	879,2

Table 3.1 | The effects of ports configuration and dilution on the near field mixing of brine. *This table presents a detailed analysis of how different dilution factors and port configurations affect the flow dynamics of brine diffusers. Data include the brine concentration (PSU brine) in g/L, dilution factor, flux measured in cubic meters per second* (m^3/s)*, number of ports, diameter of each port in m, Froude number (Fr), the near field dilution (Sn), the difference in salinity end of near field (ΔPSU) in g/L, the initial velocity* (U_0) *in meters per second (m/s), the distance between the ports in meters (m), and the total length of the diffuser in meters (m).*

Table 3.1 provides a good overview of dilution and a possible diffuser. However, to achieve good and realistic dilution in the near field, the following conditions must be met:

Dilution factor > Sn: The degree of mixing or dilution is indicated by the Sn value. If it is greater than the dilution factor, it indicates that mixing is effective enough to dilute the brine concentration. The table shows that for each dilution there is a diffuser setting that meets this requirement.

U0 ≤ 4 m/s: If this value is 4 m/s or less, the scenario meets an important operational requirement to avoid excessive disturbance of the marine environment and to avoid excessive pressure on the material. If no values appear to meet this requirement, diffusers with discharge rates up to 6 m/s can be considered, but this is not ideal.

Δ PSU ≤ 2 g/L, The Δ PSU value indicates the difference in salinity between the brine and the surrounding seawater. A Δ PSU of up to 2 g/L is preferred to avoid large changes in water salinity, thereby minimizing the ecological impact and the impact on the water column.

Based on these criteria, the scenarios in the table that meet all three criteria can be selected as the best. These scenarios consider the configurations of diffusers and prediluted brine that have the least impact on the marine environment while still providing adequate brine dilution. The results for all of these scenarios are shown in the 3.6 table below:

PSU brine	**dilution factor**	**flux**	**number of jets**	**port diameter**	**Fr**	**Sn**	**ΔPSU**	**U_0**	**distance between ports**	**total length**
280	123,5	0,3	1000	0,01	57,25	148,8	1,7	3,8	1,1	1143,8
157,0	61,8	0,6	300,0	0,03	24,48	63,7	1,9	2,8	1,5	439,2
115	41,2	0,9	20	0,12	17,2	44,8	1,8	4,0	4,1	78,5
115	41,2	0,9	40	0,09	17,7	45,9	1,8	3,5	3,2	124,0
115	41,2	0,9	60	0,07	22,1	57,4	1,4	3,9	3,1	182,4
115	41,2	0,9	100	0,06	19,5	50,6	1,6	3,2	2,3	231,4
115	41,2	0,9	200	0,04	26,8	69,8	1,2	3,6	2,1	427,2
115	41,2	0,9	400	0,03	27,5	71,6	1,1	3,2	1,7	659,4
94,8	**30,9**	**1,2**	**20**	**0,14**	**15,6**	**40,6**	**1,5**	**3,9**	**4,4**	**83,1**
94,8	**30,9**	**1,2**	**40**	**0,1**	**18,1**	**47,1**	**1,3**	**3,8**	**3,6**	**141,2**
94,8	**30,9**	**1,2**	**60**	**0,08**	**21,1**	**54,8**	**1,1**	**4,0**	**3,4**	**199,0**
94,8	30,9	1,2	200	0,05	20,5	53,3	1,2	3,1	2,0	407,6
94,8	30,9	1,2	300	0,04	23,9	62,0	1,0	3,2	1,9	570,6

TABLE 3.2 | The optimum configurations of brine diffusers and their values near field values.

This table presents a the optimum values of the excel model. Data include brine solution concentration (PSU brine) in g/L, dilution factor, flux measured in m^3/s*, number of ports, diameter of each port in m, Froude number (Fr), the end of near field dilution (Sn), the difference salinity end of near field (ΔPSU), the initial velocity (*U_0*) in meters per second (m/s), the distance between the ports in meters (m), and the total length of the diffuser in meters (m).*

These results show that a brine with a salinity of 280 PSU would require very small diffuser ports and a significant length, which does not seem feasible in practice due to the high viscosity of the brine. In addition, the near-field mixing zone would be extended to 1200 meters by 200/100 meters. The same is true for brine with a PSU of 157, resulting in a mixing zone/safety zone of 600 by 200 meters. We find more viable options for dilutions with 2/3 seawater and ¾ seawater.

3.4.2. Far field results

Data from the reference simulation and the 2014 model run were used to represent the results in the far field. To assess the impact of brine discharge in the far field, these data sets were compared based on various parameters and distances from the discharge location. The year 2013 was not considered in detail because there was no brine discharge in that year, and it was used only as a run-in year to ensure the accuracy of the model for the period when discharge occurred. The entire 2.5 year period was not modeled due to time and cost constraints, as well as the fact that it would provide far too much data to manage within the scope of this thesis. Salinity plots from the two simulation runs were compared over the entire vertical profile for different monitoring sites throughout the year. Temperature and salinity plots were also examined, resulting in the following figures:

Deltares' DFM Matlab tools were used to generate the results [95]. These tools were specifically chosen for their ability to process data from a Delft3D model and present it in a clear and structured manner. The most insightful and relevant figures are shown and explained below, with the full set available in Appendix 3.

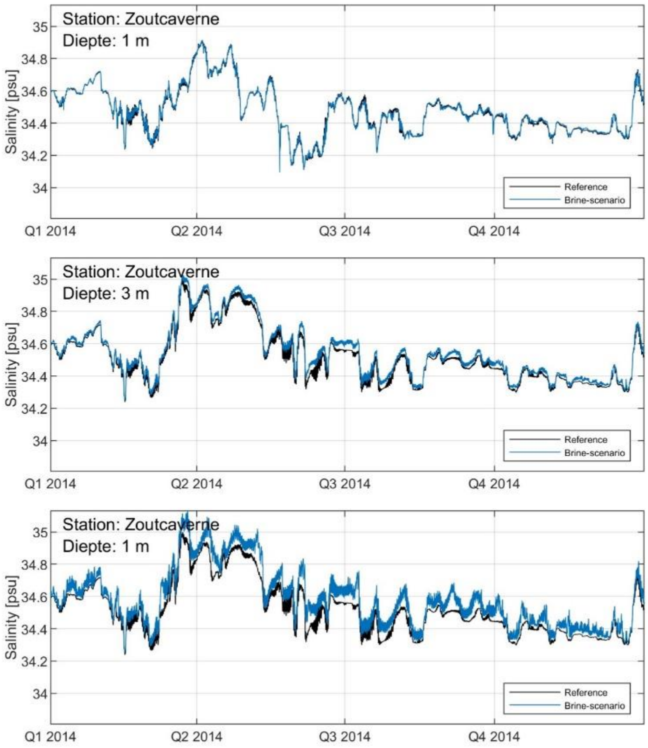


Figure 3.5 | Comparison of salinities between reference and brine run at the disposal site. *This was done for the year 2014 at three different depths: one meter below the water surface (top), three meters above the seafloor (middle), and one meter above the seafloor (bottom). The black line represents salinity in the absence of brine discharge, while the blue line represents salinity in the presence of brine discharge.*

The variability in salinity values for the reference scenario and the brine discharge scenario, is illustrated in Figure 4.5, which displays the results of the time series analysis of the salinity data for 2014. In the brine discharge scenario, an increase in salinity was observed at one meter above the seafloor, which appears to be a direct result of the brine discharge. Throughout the year, the brine discharge run has a consistently higher salinity, averaging about 0.1 PSU higher than the reference run. These differences are amplified during the summer, with more pronounced salinity peaks in the brine discharge scenario. In addition, the brine discharge run has a more variable salinity pattern than the reference run, which has a relatively stable trend compared to the erratic pattern of the brine discharge run.

The increase in salinity caused by the brine discharge is less noticeable three meters above the seafloor, and this trend is further minimized one meter below the water surface. The detected salinity peaks in the source discharge scenario indicate a clear, although locally limited, effect of source discharge on water properties near the discharge site. These results seem to indicate that the differential vertical influence of brine within the far field is not very strong, but it is critical to consider nearby monitoring sites and other parameters before drawing such conclusions.

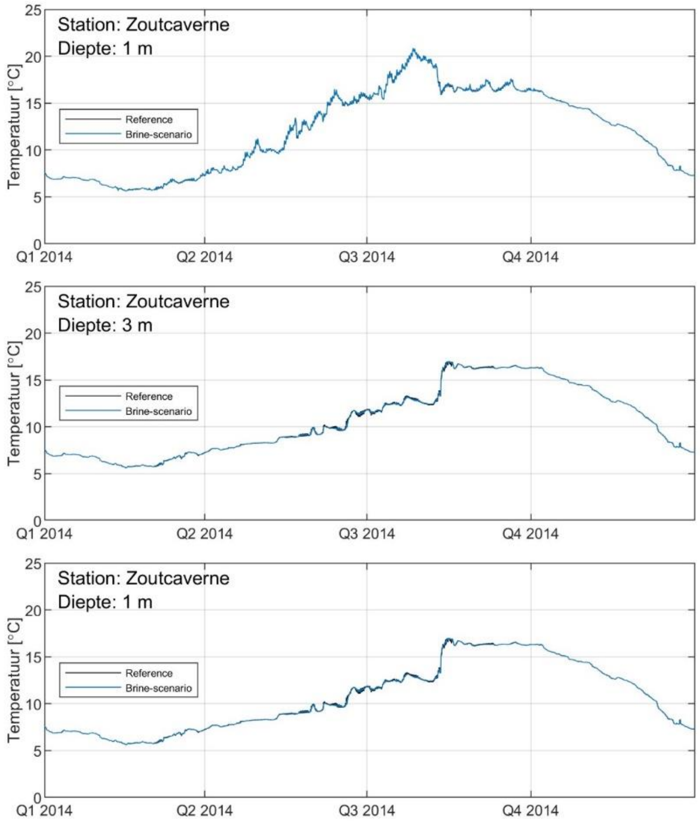


Figure 3.7 | Comparison of temperature profiles at different depths at the disposal site. *This figure illustrates temperature profiles for the year 2014 at three different depths at the disposal site. The top graph shows the temperature one meter above the seafloor, the middle graph three meters above the seafloor, and the bottom graph one meter below the water surface. The black line represents the temperature in the reference scenario without brine discharge, while the blue line represents the temperature in the brine scenario.*

Figure 3.7 shows the temperature profiles in the brine disposal grid cell, measured at three strategically chosen depths within the water column. The data sets for the year 2014 follow the expected seasonal variations in temperature, with no significant differences observed between the scenarios with and without brine discharge. This observation suggests that the brine discharge does not have a significant impact on the thermal dynamics of the water column. This is consistent with the initial assumption, as the temperature of the discharged brine is tuned in the model to be as close to the ambient temperature as possible. The consistency of the temperature profiles confirms that the temperature of the brine has been implemented in such a way that it is equal to the temperature of the ambient water. This depicts that temperature variations between brine and ambient water are not an explanatory factor for changes in the water column caused by brine discharge into the far field, and that salinity differences are the driving factor.

Analysis of salinity differences throughout the water column throughout the year suggests that these differences are minimal. No significant deviations are observed between the two runs because the model's error for salinity exceeds the observed differences; the observed differences, with a maximum of 0.2 PSU, are smaller than the model's average deviation of 0.3 PSU. Figure 3.8 shows these salinity differences between the two simulations throughout the water column and throughout the year.

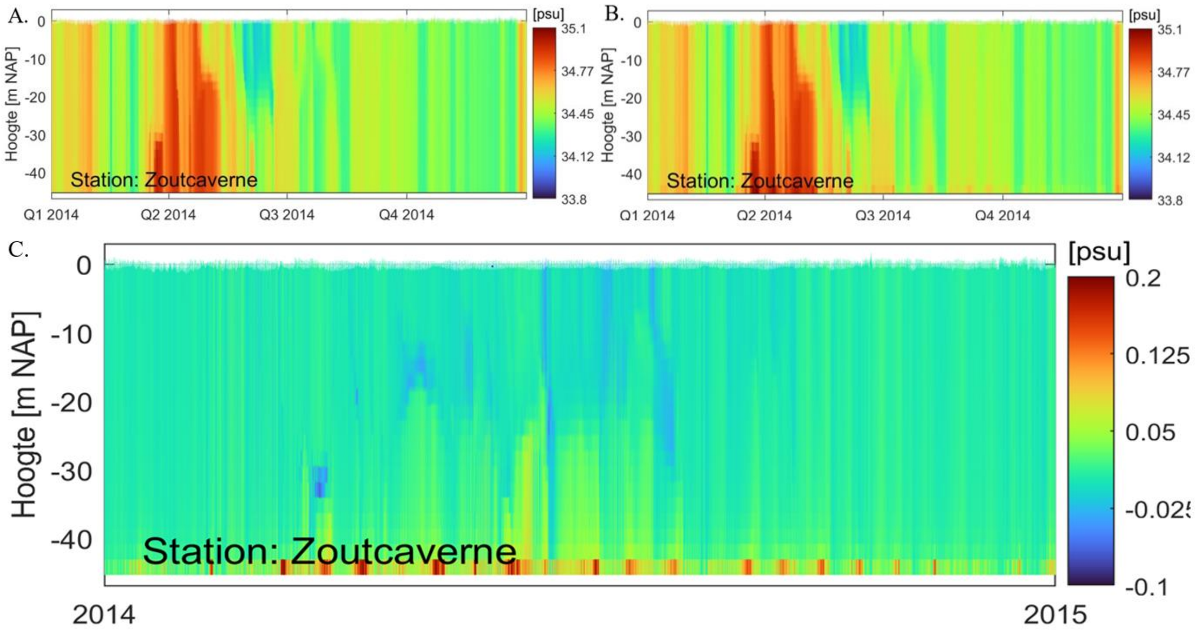


Figure 3.8 | Salinity profiles of the water column at the disposal site during 2014.
Figure 3.8 shows the changes in salinity at different depths of the water column directly at the salt caverns discharge site over the course of the year 2014. Panel A represents the reference run and panel B represents the source run. Panel C represents the difference in salinity between the two runs. Shades of color indicate salinity levels, with warmer colors representing higher salinity.

The salinity distribution in the reference run is fairly uniform, indicating an undisturbed environment with no brine discharge. The brine run, on the other hand, shows increased salinity in the lower layers of the water column as a direct result of the brine discharge. This increase in salinity is most noticeable on the seafloor and varies throughout the year.

Analysis of the data reveals a subtle difference in the deeper layers where the brine disposal occurs, with a peak during the summer months. This could be due to reduced vertical mixing resulting in a higher concentration of brine at the bottom. The most significant differences between runs are found near the seafloor, right at the discharge zone, reflecting the effects of brine discharge on water quality in benthic areas and confirming the hypothesis that benthic life is most vulnerable to brine discharges.

However, the upper water layers of both scenarios show no noticeable difference, indicating that brine discharge has little effect on surface water conditions. This could be due to the effective dispersion and dilution of brine in the North Sea.

To determine if any effects were noticeable beyond the grid cell of the brine discharge, a series of northern monitoring points were analyzed for salinity differences in the water column for both model runs over an entire year. The results, presented in Figure 3.9, show no significant differences between the runs during this period.

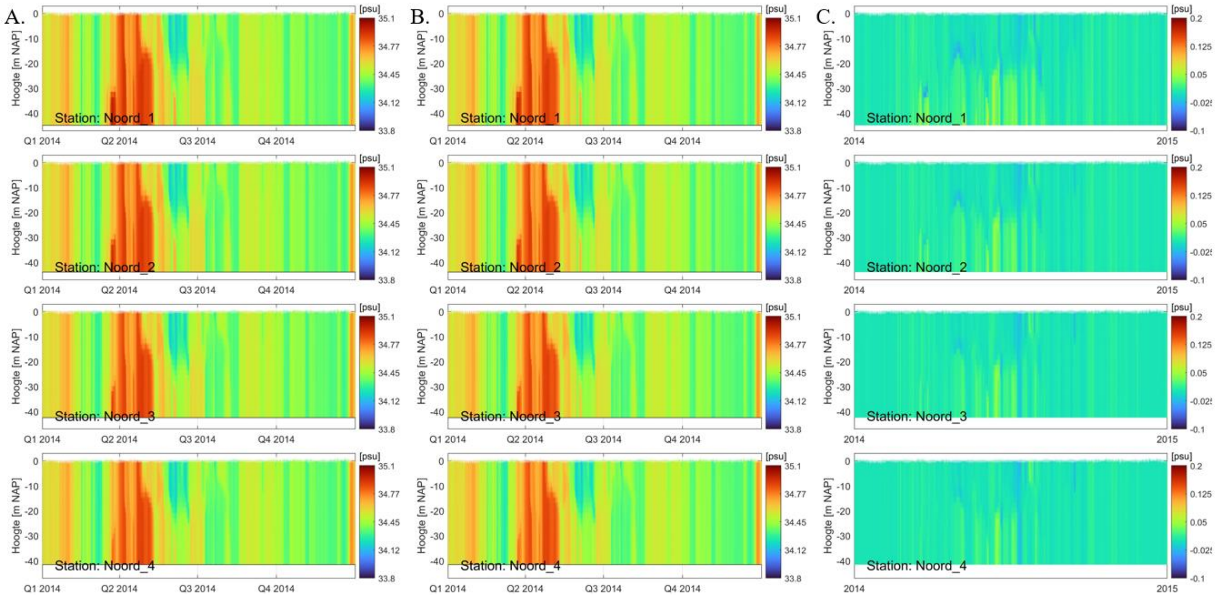


Figure 3.9 | Comparison of Vertical Salinity Profiles at Northern Stations over 2014. *This set of figures illustrates the distribution of salinity at different depths within the water column for four stations north of the source discharge site during the year 2014. Panel A shows the salinity profiles for the brine run, and the middle panel (B) shows the profiles for the reference run. Panel C on the right displays the difference in salinity between the two runs for the water column during the year. The varying colors show salinity levels from the water surface to the seafloor, with the gradations visualizing changes through the year. Station North 1 is located 900 meters north of the discharge site, followed by Station North 2 at 1800 meters, Station North 3 at 2700 meters, and Station North 4 at 3600 meters away from the brine discharge site.*

The difference in salinity between the two scenarios disappears at 900 meters from the discharge point. This indicates that the brine has been completely dissolved and dispersed into the water column, with no detectable residual concentration in the water column. Figure 3.10 confirms this observation and shows in more detail that the average salinity differences are 0.5 meters above the seafloor for the entire model run.

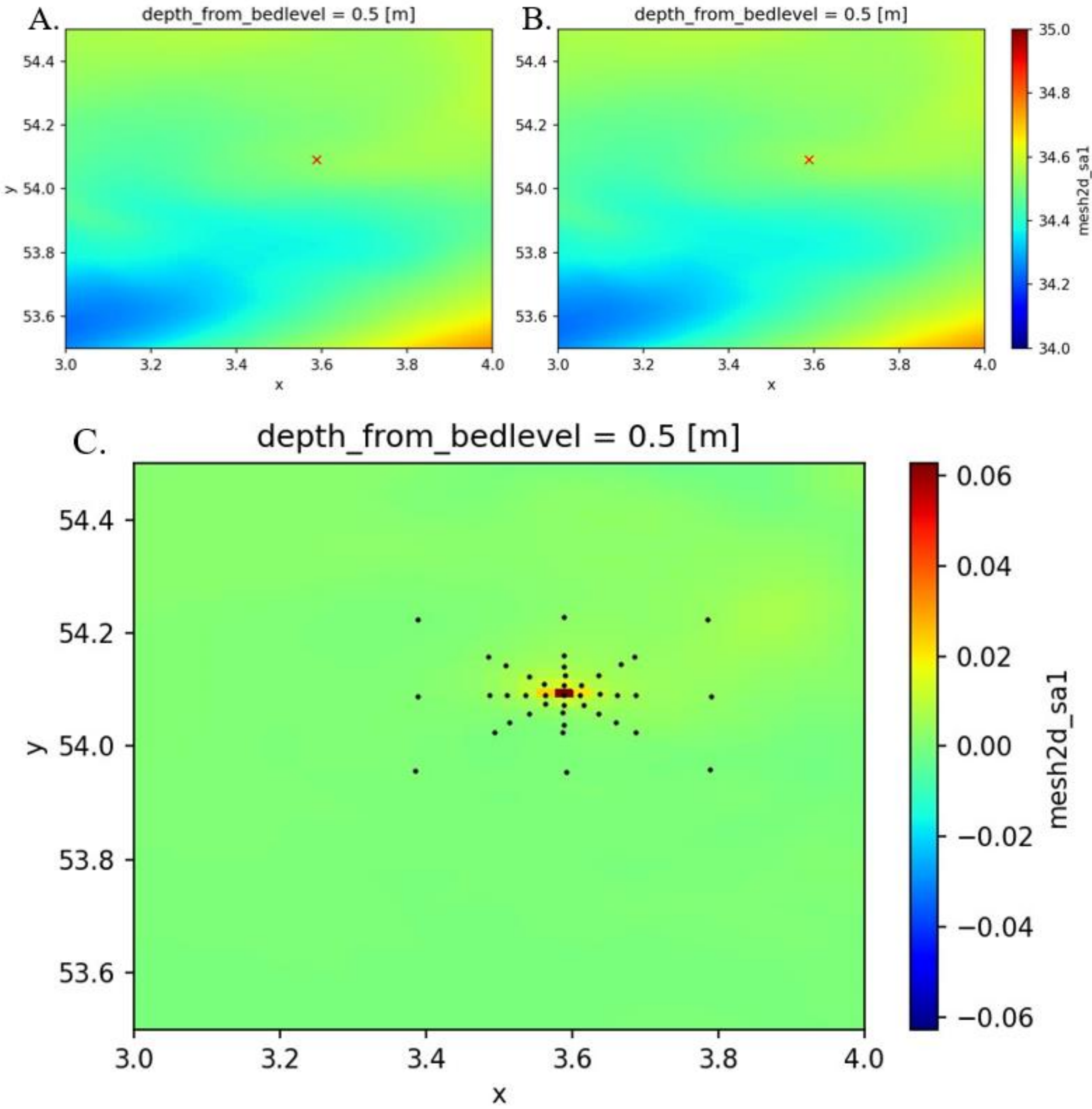


Figure 3.10 | The annual salinities and differences near the seafloor for the brine and reference run.

Figure 3.10 illustrates the comparison of average salinities half a meter above the seafloor throughout 2014. Panel A shows the salinity for the brine discharge run, while Panel B represents the reference run without brine discharge. Panel C highlights the average salinity differences between the two runs, indicating the impact of brine discharge on the near-bottom water salinity over the year.

Finally, the seafloor currents around the brine discharge site were evaluated because of their importance for dispersion and mixing. The model data show that bottom currents are low, with velocities not exceeding 0.5 m/s, and that the direction of flow varies throughout the year. Figure 3.11 illustrates this by showing the bottom flow from the brine discharge at three random times during the year.

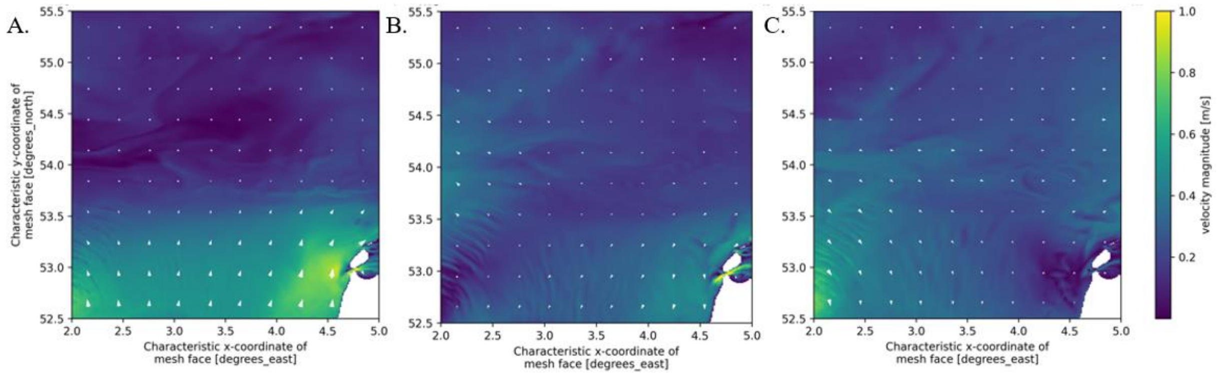


Figure 3.11 | Variability of seafloor currents around the brine disposal site.
Figure 3.11 shows three snapshots capturing the variability of seafloor currents near the brine disposal site. Each panel represents a different moment in time, reflecting the low velocity, which does not exceed 0.5 m/s, and the changing directions of the currents over the course of the year. The visualization emphasizes the dynamic nature of seafloor currents at the disposal site. The color gradient from blue to yellow represents the magnitude of the flow velocity, with blue indicating lower velocities and yellow indicating higher velocities up to 1.0 meters per second. The arrows indicate the direction of flow, with the length and orientation of each arrow reflecting the velocity and direction of flow, respectively.

3.5. Discussion

3.5.1 Near field

The Excel near field model has been simplified to focus solely on the influence of temperature and salinity on water density. However, this exclusion of complex hydrodynamic factors, such as seabed roughness and currents, raises questions about the precision of the simulation of brine plume dynamics. The choice of a semi-empirical method to calculate brine dilution and discharge, which balances computational speed and precision, invites a discussion of the limitations in prediction accuracy and practicality. Furthermore, the formulas used to construct the model and calculate dilution were based on literature that assumes desalination brine, rather than hypersaline brine from solution mining. However, it was found that when the brine was first diluted with at least two or three liters of seawater, the values became similar to those of desalination brine. This resulted in realistic and effective values, consistent with the literature used. To account for this, the near-field values were presented as a range rather than a single optimal value. If a similar situation to the case study were to be implemented, it should be modeled accurately.

In this case study, the near and far fields were separated, which presents a challenge for integrating their effects in a coherent manner. This separation may affect the understanding of ecosystem and water column impacts. Therefore, a more nuanced modeling approach is needed to account for complex environmental interactions and provide a more accurate representation of brine spreading and its ecological impacts.

3.5.2. Far field

The small differences in salinity observed between the reference and scenario simulations can be attributed to several factors. First, the grid cells used to calculate salinity, density, and temperature have a relatively low resolution of 900 meters. As a result, the brine should be significantly diluted within each grid cell, resulting in small salinity differences throughout the water column, except at the bottom where a difference of about 0.1 PSU is observed. Given the size of the grid cell (vertical layers of roughly 2,5 meters at the study site and 0.81 km2), which represents a volume of about 2.0 * 106 cubic meters of seawater, it is possible that the brine is already well mixed with the surrounding seawater.

The current study had some limitations in modeling far-field effects, particularly in the choice of grid size. To capture more detailed information on brine dispersion, the far-field model should have used a finer grid size, especially within a few kilometers radius of the discharge point. However, due to practical constraints, the model used a 900-meter grid size, resulting in a significant scale transition from the near-field analysis, which was calculated within a 100-meter radius. Near the near-field environment, a finer grid size of the model would have provided a more accurate representation of the brine's initial dispersion and subsequent dilution patterns. With a smaller grid size, it would have been possible to more accurately determine the distance where the brine is diluted to environmentally acceptable concentrations.

This case study excluded potentially valuable ecological parameters that would have been critical in determining the ecological impact of source discharges. Incorporating primary production, oxygen levels, and pH into the model would have provided a more comprehensive picture of the environmental impacts. The relationship between primary production, oxygen concentrations, pH, and salinity levels would provide a comprehensive understanding of potential disruptions to the local marine ecosystem. Although the current study shows that there is an impact, there is insufficient data to accurately quantify the magnitude of this impact.

However, incorporating these parameters into the model would require a significant increase in computational intensity. As the model files become significantly larger and more complex, the time, cost, and computing power required will increase. The decision to limit this study to the current parameters was motivated by the small size of the study and its practicality within the context of a master's thesis. Future studies that wish to model the ecological effects of source discharges should consider these parameters, as they have the potential to provide a more detailed representation of the effects on the marine ecosystem.

When evaluating model results, it is important to consider the inherent uncertainties and margins of error associated with comparing model data from both runs. The model has an average bias of -0.3 PSU and the maximum observed bias is 0.7 PSU. Given this margin of error, the observed difference in salinity is within the margin of error of the model. Therefore, a difference in salinity between the reference run and the scenario run cannot be conclusively stated. These slight differences in salinity, such as 0.1 and 0.2 PSU, cannot be attributed to the effects of brine discharge, but could also be the result of limitations and inaccuracies in the model. The results indicate that no significant effects are observed when undiluted brine is discharged within a 900 m radius of the brine discharge site. Based on the central location of the brine discharge site in the model's grid cell, it could be that the brine is fully dissipated and diluted within a 500-meter radius of the discharge site, without any detectable environmental impact. To refine and possibly reduce this observation zone, a smaller grid size would be necessary. However, with the current model resolution and data, this cannot be confirmed.

The flow patterns observed on the North Sea floor, as shown in Figure 3.11, demonstrate fluctuating currents around the discharge point. These currents are likely to assist in the long-term dilution of brine, especially in the far field. The dynamic currents play a crucial role in the efficient mixing of the brine with the surrounding seawater, contributing to the observed dilution and the minimal salinity differences at greater distances from the discharge location. Furthermore, further investigation is warranted to assess the impact of tides on the dilution process at this depth. Tidal movements are known for inducing significant water mass movements, which could enhance the dispersion and mixing of brine, acting as a natural diluting agent [96], [97]. Additionally, in-depth study is required to understand the role of turbulence in promoting the dilution of brine.

3.5.3. Comparison with other studies

The results of this case study are consistent with the results of two previous studies of hypersaline brine discharge (from salt deposits where solution mining occurs) into the sea, indicating consistency in research findings. In the first study, the "Gateway Gas Storage Project" in the eastern Irish Sea in the United Kingdom, brine was discharged from salt deposits 24 kilometers from shore [53]. The brine sank to the seabed after being injected directly into the sea, where it was dispersed and diluted by ocean currents. Within a 500 meter radius, a maximum salinity increase of 7 PSU was observed above the ambient level of 35 PSU, which was completely diluted. The impact was deemed insignificant by the relevant authorities, CEFAS (Centre for Environment, Fisheries and Aquaculture Science) and Defra (Department for Environment, Food and Rural Affairs).

A second study describes the discharge of brine from a Permian salt layer in Northern Ireland (Larne Lough), which is similar to the Zechstein salt [51]. The brine, which had a salinity of up to 260 PSU and a temperature of about 2°C above ambient, was disposed of 450 meters offshore in water 27 meters deep. By the time it reached the seafloor, the concentration had been diluted to between 37.6 and 50.5 PSU. Medium- to far-field dispersion models predicted that discharges of up to 1000 m3/h through two diffusers would have little impact at any distance from the diffuser, with no expected salinity increase of more than 0.5 PSU above background at distances greater than 100 meters from the diffuser.

These previous studies support the results of the current case study, which found no significant differences in the far-field between the reference and scenario simulations. Although peaks of up to 10 PSU increase were detected in the near-field, these results are consistent with the findings of the other studies. If the far-field model had a finer resolution, the values could have been similar to those observed in Northern Ireland.

3.6. Conclusion(s)

- **What is the maximum dilution and minimum salinity difference with the ambient seawater that is feasible in the near field?**

The maximum dilution of an undiluted brine with a concentration of 280 PSU is achieved at a flux of 0.3 m3/s and an outflow velocity of 3.8 m/s over 1000 jets, resulting in a Δ PSU of 3.2. This indicates significant near-field dilution and limits the salinity increase to 3.2 Δ PSU above ambient. However, the practical feasibility of this approach is questionable, as the small nozzle diameter of one centimeter and the high viscosity of the brine pose significant technical challenges. In addition, the diffuser would be nearly 600 meters long, which is inefficient and does not meet the requirement to keep the Δ PSU below 2.

A more practical configuration for a diffuser with the same PSU and flux but only 60 jets, each four centimeters in diameter, and an outflow of 4.0 m/s would result in a Δ PSU of 6.2. Although the diffuser in this scenario is only 72.8 meters long, the Sn is less than the dilution factor (40.1 < 123.5), indicating that the dilution is insufficient.

Given these results, it is clear that brine must be diluted prior to discharge to meet international environmental standards.

- **What degree of dilution is required before brine discharging to achieve acceptable/optimal values at the end of the near field?**

Dilution of brine with seawater at a ratio of 1:2 results in practically achievable dilution values. A brine concentration of 115 PSU, combined with a dilution factor of 41.2 and a flux of 0.9 m^3/s, can be achieved with a configuration of 60 jets with a diameter of 7 centimeters and an outlet velocity of 3.9 m/s. This arrangement results in a minimum Δ PSU of 1.4, indicating effective dilution and a small increase in salinity in the nearshore environment.

At a mixing ratio of one part brine to three parts seawater, several suitable configurations become possible. For brine with a PSU of 94.8, a dilution factor of 30.9 and a flux of 1.2 m^3/s with 40 jets of 10 centimeters diameter and an outlet velocity of 3.8 m/s yields a maximum Δ PSU of 1.3. These data suggest that such a diffuser configuration facilitates significant dilution and provides the lowest relative increase in salinity.

In conclusion, brine should be diluted with at least two to three parts seawater per part brine to achieve acceptable salinity levels at the near field end.

- **How should a brine diffuser be designed to achieve levels of maximum dilution?**

For a brine concentration of 94.8 PSU, the diffuser should be equipped with nozzles with a 60-degree discharge angle. The number of nozzles should range from 20 to 60, with diameters ranging from 14 cm to 8 cm, depending on the specific requirements of the outlet location and the desired dilution efficiency.

To ensure uniform brine diffusion and to optimize interactions between individual jets, the distance between individual jets should be between 2.3 and 1.7 meters. The total length of the diffuser should be between 43 and 103 meters, depending on the number of ports outside the diffuser.

Due to the inherent uncertainties and approximate nature of the model calculations, it is important to emphasize that these specifications represent a range rather than absolute values. The actual design may vary within this range to achieve the desired dilution results, starting with a difference of less than 2 PSU within one hundred meters of the discharge point.

- **What is the environmental impact in the far field on the water column? Without dilution prior to disposal and with optimized diluted brine?**

According to the current far-field model, there are no observable environmental effects on the water column beyond 900 meters from the discharge site. The far field model shows no significant differences in the physical properties of the water column at this distance, indicating that the effects of undiluted brine discharges are limited. Impacts on the water column for optimized diluted brine are also not measurable at distances greater than 900 meters from the discharge site, using the current model resolution and design.

- **How do brine discharges affect physical processes in the far field such as currents, temperature distribution and salinity in the North Sea?**

The available data and model analyses show that brine discharges do not cause significant changes in currents, temperature distribution, or salinity in the far field of the North Sea. Due to model resolution limitations, any influence on these physical processes remains undetected, especially in the area between the far field and the near in, which is still in the first grid cell of the model.

- **How does brine disposal affect far-field stratification?**

The modeling shows that brine discharges have a limited effect on stratification, which appears to be confined to the brine discharge grid cell, where there is a slight increase in seafloor stratification, especially during the summer months. There are no significant changes in stratification outside of this grid cell in the far field.

- **Does the far field stretches to MPAs and if so, to what extent?**

According to current model predictions and data analysis, the impact of source discharges does not extend to MPAs. The impact is limited to the immediate area surrounding the discharge site, and there is no evidence that it extends to ecologically sensitive areas further away.

“How will a brine discharge of 0.3 m^3/s with a PSU of 280 affect the surrounding seawater over a period of 2.5 years, and what measures could be taken to mitigate the negative environmental impact?”

A brine discharge of 0.3 m^3/s into the surrounding seawater with a PSU of 280 for 2.5 years is likely to significantly increase local salinities, especially in the near field. This concentrated discharge has the potential to disrupt marine ecosystems by altering salinity gradients and affecting marine life and flora.

Several measures have been proposed to mitigate the negative environmental impacts of such a discharge. First and foremost, the brine must be diluted with seawater prior to discharge. A brine/seawater dilution ratio of at least 1:2, preferably 1:3, would significantly reduce the impact of salinity at the point of discharge. This dilution helps to reduce the increase in salinity to acceptable levels by the time it reaches the end of the near field, thereby minimizing damage to the marine environment.

Second, the use of an effective brine diffuser is critical. The diffuser must be configured to maximize brine spreading and mixing with seawater. This implies optimizing the number of nozzles, nozzle diameter, and the angles and spacing between nozzles to ensure effective dispersion, to increase the contact area and flow along the ambient water. Such a design will promote rapid mixing and dilution of the brine, further reducing its impact.

Model predictions indicate that the effects of far-field discharge are minimal. However, it is critical to validate these model predictions with actual field data and adjust mitigation strategies as needed before such brines are discharged, and more detailed modeling is required before such hypersaline brines are discharged.

4. Scenario Analysis

4.1. Introduction

Current research on energy transition emphasizes the indispensable role of green hydrogen as a sustainable and promising energy carrier. Although the emphasis is usually on the technical and economic facets of producing and storing green hydrogen, it is essential to have a thorough understanding of the environmental impact of large-scale offshore projects in the Dutch North Sea. With offshore green hydrogen production and storage emerging as a promising energy system, anticipating environmental impact is crucial for efficient planning of future offshore green energy projects without the need for revisions.

This chapter investigates and analyzes potential future scenarios for offshore green hydrogen production in the Netherlands. The aim of the study is to understand the scale of these systems, which will lead to a more comprehensive picture of the environmental impacts of green hydrogen production and storage in the Dutch North Sea. The main focus is on the inflow and outflow of the seawater and waste water. Seawater flows are required for various purposes, including cooling water, solution mining of salt caverns for storage and electrolysis, and it is necessary to map the magnitude of these flows.

Another critical aspect of this research is the quantification of the by-products of offshore green hydrogen production and storage, such as brine and heat. A detailed picture of the quantities of seawater required and the expected waste streams discharged into the sea is presented through three carefully constructed scenarios, each reflecting different growth ambitions for offshore green hydrogen. In addition, this analysis calculates the number of salt caverns required for storage to ensure a consistent energy supply throughout the year

This chapter reviews the available literature on offshore hydrogen production in the North Sea from today to 2050 and uses it to develop a scenario study for 1 GW, 8 GW, and 20 GW of offshore hydrogen. These scenarios are based on studies and programs that will serve as guidelines for the expansion of the Dutch hydrogen sector [16],[98]. These scenarios are essential for understanding the operational requirements and environmental impact of offshore hydrogen production systems, which are key to the Netherlands' pursuit of a sustainable energy future.

4.1.1. Assumptions for timeline construction and scenario development

This research focuses the quantification of the by-products of offshore green hydrogen production and storage, such as brine and heat. A detailed picture of the quantities of seawater required and the expected waste streams discharged into the sea is presented through three carefully constructed scenarios, each reflecting different growth ambitions for offshore green hydrogen. These scenarios are based on studies and programs that serve as guidelines for the expansion of the Dutch hydrogen sector.

The scenarios are based on current forecasts and national hydrogen targets for offshore hydrogen production and offshore generated hydrogen production in the Netherlands. It is important to emphasize that these scenarios, although heavily influenced by the results of these studies, are not exact replicas. In order to create practical scenarios suitable for further analysis, room for interpretation and adaptation has been left open. The primary objective of these scenarios is to map seawater and wastewater flows rather than to ensure sufficient energy supply for the Netherlands. This method allows to investigate these specific aspects of hydrogen production and management with an emphasis on environmental impact.

The scenarios outlined in this research draw from an array of foundational insights, integrating the anticipated progression of offshore green hydrogen production technology and pilot programs. They reflect the incremental advances from small-scale initiatives to larger, more ambitious projects that are critical for understanding the evolution of the sector. The progression, from the initial 1 MW pilot near Scheveningen to the proposed 500 MW installations, informs the projected growth rates applied within the scenarios. That pilots will not exceed a total capacity of 1 GW offshore, supports the prediction that green hydrogen production in the Netherlands will be limited until 2035 [15]. These results are important for establishing the annual growth rates in the scenarios. This takes into account the duration and learning curve of the pilots, which is critical for determining the potential for scale-up and commercial viability of offshore P2G.

Given the current limited operational pilots and large-scale projects yet to be launched, significant offshore P2G developments in the Netherlands are not expected before 2030 [11]. As a result, the scenarios developed in this study start in 2030, in line with the national targets for offshore hydrogen production: 4 GW by 2030, 8 GW by 2032 and 20 GW by 2040, including blue hydrogen [15]. In line with these targets and broader ambitions for 2050, the study assumes a maximum achievable annual growth of 0.5 GW for offshore green hydrogen production from 2030 to 2040, followed by an increase of maximum 1.5 GW per year from 2040 to 2050. This reflects the Dutch government's commitment to significantly increase offshore hydrogen production, thereby contributing to the energy transition and meeting climate targets.

The scenario analysis assumes that electrolysis for offshore wind farms becomes economically interesting compared to onshore electricity when they are located at least 150 kilometers from the coast [6], [10]. Such distant offshore farms are not expected to be built until after 2030. This is consistent with the expectation that the technology required for P2G will not be sufficiently advanced until at least 2030.

The maximum annual growth rate of 1.5 GW for offshore hydrogen production is based on the fact that the technology is still in its early stages and there is uncertainty about the scalability of offshore electrolysers. In addition, there is a known limit to the growth of associated wind farms, which according to TenneT can only grow by a maximum of 2 GW per year due to logistical challenges [99]. These limitations appear to apply to the development of offshore electrolysers, with the rate of scale-up yet to be determined. Therefore, the most extreme scenario assumes a maximum growth of 1.5 GW.

This study used findings from the II3050 study by Netbeheer Nederland [98], the National Hydrogen Program [100], the WOZEP program on offshore wind energy, the TNO-EBN study on offshore underground hydrogen storage [8], and the North Sea Energy 4 program [15] to construct scenarios for green hydrogen production in the Netherlands. These studies are guiding the development strategy, focusing on hydrogen integration, advanced storage solutions and the strategic use of the North Sea for hydrogen production and storage.

4.1.2. Scenarios

1 GW Baseline scenario: Minimal efforts and agreements

This scenario represents a conservative approach, with green hydrogen playing a limited role in the North Sea region by 2050. The focus is on maintaining the current status quo, without taking significant steps forward in the production and use of offshore green hydrogen.

By 2030, the existing pilot projects will have established around 500 MW of offshore electrolysis capacity in the North Sea. This capacity is expected to increase incrementally, reaching 0.7 GW by 2035 and achieving 1 GW by 2040. Beyond this point, no further expansion is anticipated, with the existing electrolysers continuing to operate and maintain the 1 GW capacity through to 2050.

8 GW Ambitious growth scenario: Growth and political ambition.

This scenario represents an optimistic vision in which green hydrogen plays a prominent role in the North Sea as a result of ambitious policies and investments. The result is 8 GW of capacity by 2050. P2G is promising for transporting energy from remote wind farms to the mainland, but other methods of energy transport are also used.

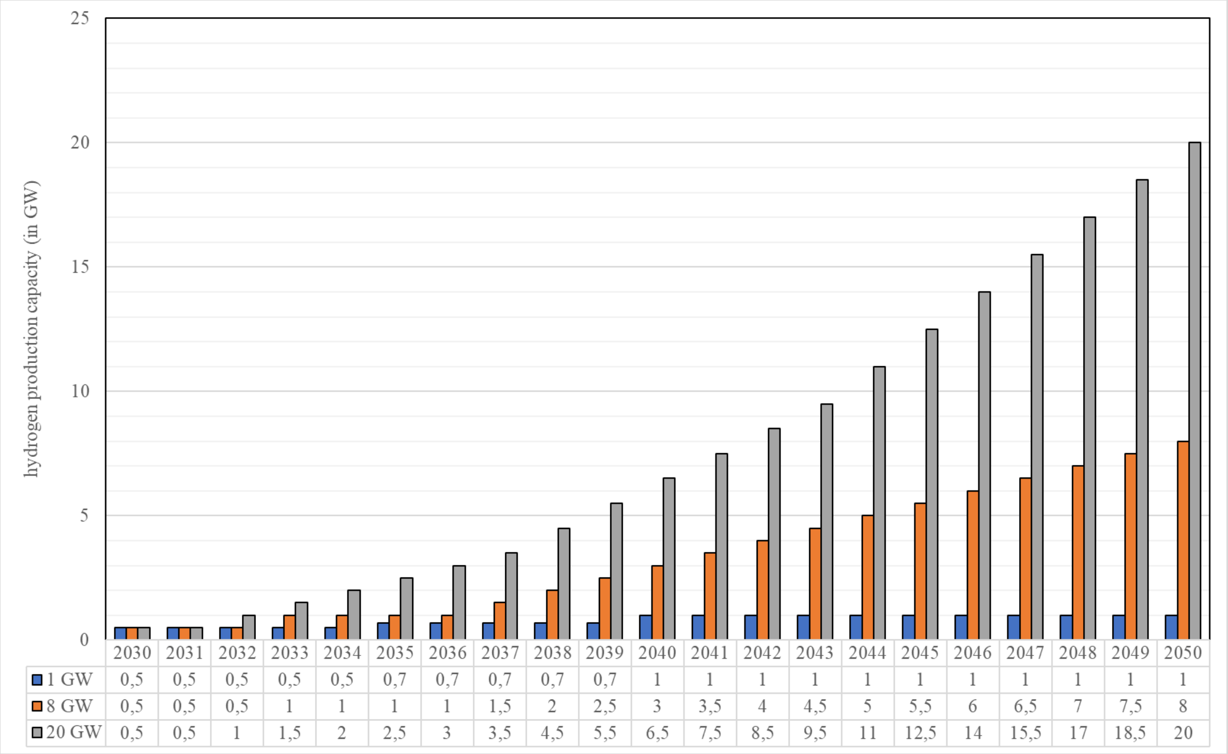
In this scenario, offshore hydrogen production starts in 2030 with a capacity of 0.5 GW, gradually increasing to 3 GW by 2040. From 2040, there is a steady annual growth of 0.5 GW, culminating in a total capacity of 8 GW by the end of 2050.

20 GW Technology breakthrough scenario: Technological Breakthrough

In this scenario, technological advances promote a transition to green hydrogen production, facilitating large-scale operations in the North Sea. This development makes it possible to achieve 20 GW of offshore green hydrogen capacity by 2050.

The development of offshore hydrogen is projected to start in 2030 with an annual increase of 0.5 GW. This consistent growth is expected until 2040, after which the rate of expansion will intensify, reaching 1 GW per year between 2040 and 2043. From 2044 onwards, the growth rate will further escalate to 1.5 GW annually, culminating in a total offshore electrolysis capacity of 20 GW by the year 2050.

The development and progression of the three scenarios are shown in Figure 4.1.



	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
■ 1 GW	0,5	0,5	0,5	0,5	0,5	0,7	0,7	0,7	0,7	0,7	1	1	1	1	1	1	1	1	1	1	1
■ 8 GW	0,5	0,5	0,5	1	1	1	1	1,5	2	2,5	3	3,5	4	4,5	5	5,5	6	6,5	7	7,5	8
■ 20 GW	0,5	0,5	1	1,5	2	2,5	3	3,5	4,5	5,5	6,5	7,5	8,5	9,5	11	12,5	14	15,5	17	18,5	20

Figure 4.1 | The offshore green hydrogen production capacity storyline the three different scenarios.

Figure 4.1 outlines the projected trajectory of offshore green hydrogen production capacity, comparing three prospective scenarios over two decades, from 2030 to 2050. The bar chart differentiates each scenario with a different color: blue bars indicate the 1 GW scenario, orange for the 8 GW scenario, and gray for the 20 GW scenario. These scenarios reflect different levels of investment and technological advancement aimed at developing green hydrogen production facilities in the Dutch North Sea.

4.1.3. Research question(s)

"What are the projected seawater intake and discharge outputs, including heat water and brine, for offshore electrolysis operations under 1 GW, 8 GW, and 20 GW production scenarios, during the period from 2025 to 2050?"

Sub-questions:

- What are the estimated volumes of seawater intake needed for offshore electrolysis in 2050, across the scenarios (1 GW, 8 GW & 20 GW), considering the requirements for both cooling processes and reverse osmosis?
- For each scenario, how many salt caverns are necessary for consistent hydrogen supply, and what are the associated total and annual maximum seawater usage and brine production rates?
- What is the total seawater requirement for hydrogen storage and production in each scenario, and which key factors most significantly influence these seawater needs?
- What are the detailed annual, monthly, and peak hourly rates of seawater intake and discharge for a 500 MW electrolyser?

- In the projected timeframe of 2025 to 2050, which years are expected to have the greatest environmental impact, and which factor among brine disposal from cavern construction, brine disposal from reverse osmosis, or the intake and discharge of heated water from cooling electrolysers is expected to contribute most to this impact?

4.2. Method

An Excel calculation model was created to address the research questions. This model combines data from a modeled wind year using a TNO study, using their hourly profiles with other relevant parameters. These variables are needed to calculate the annual hydrogen production and the associated seawater requirements. Furthermore, the model allows to calculate the required storage capacity and thus to estimate the number of salt caverns needed to represent the total water usage and brine production. This is combined to calculate the total annual brine production and water withdrawal.

4.2.1. calculating hydrogen production, seawater intake and discharge

The annual hydrogen production in gigawatt hours for different scenarios is calculated using the TNO model for the wind year 2030. The calculation starts by calculating the total operating hours for the electrolysers, taking into account a maintenance period in April, which has been identified in the model as the least windy month, reducing the operating hours to 4420 out of a total of 8760 hours in a year. The gigawatt-hour production is then calculated by multiplying these operating hours by the average efficiency range of the electrolysers, which is 67% but can range from 62% to 78% [15], and the power output in GW specified in the scenario and year.

$$\text{GWh } H_2 = \textit{full load hours} * \textit{efficiency} * \textit{capacity of the electrolyser}$$

The quantification of hydrogen production in each scenario, expressed in gigawatt hours (GWh), includes an accurate energy value per kilogram of hydrogen. In this study, the lower heating value (LHV) of hydrogen is used as the measurement standard, as opposed to the higher heating value (HHV). The main difference between LHV and HHV is how they treat the energy associated with water vapor condensation; HHV includes this energy while LHV does not. Given that the LHV of hydrogen is 33.33 kWh/kg, 1 GWh is approximately 30,003 kilograms of hydrogen [101].

To determine the amount of seawater required for electrolysis, the amount of demineralized water must first be calculated. This determination can be made using the electrolysis specific water to hydrogen ratio, which is consistent with the stoichiometric balances in the water splitting reaction [102]. The chemical reaction for electrolysis consists of two half reactions:

$$2\,H_2O_{(l)} \rightarrow O_{2\,(g)} + 4\,H^+ + 4\,e^-$$

$$4\,H^+ + 4\,e^- \rightarrow 2\,H_{2\,(g)}$$

In the electrolysis process, each mole of H_2 requires one-half mole of H_2O. The molar mass of the reactants is critical in determining the water-to-hydrogen mass ratio. Given that water has a molar mass of about 18 g/mol and hydrogen has a mass of about 2 g/mol, the mass ratio is about 9:1. As a result, it typically takes about nine kilograms of water to produce one kilogram of hydrogen, assuming the electrolysis process is free of significant losses or inefficiencies [102].

In the RO process for the desalination of seawater, one liter of demineralized water requires approximately 3.5 liters of seawater. Seawater has a density of 1024.46 kg/m³ at 15 °C and a salinity of 33 g/l on average at typical offshore production sites according to datapoint TERSLG135 [103]. During RO, approximately 2.5 liters of the seawater input is converted to reject water or brine. This brine has an elevated salinity of 44.8 grams per liter. The required volume of seawater for the osmosis process can be calculated by multiplying the density of the seawater by 3.5 liters. Similarly, the volume of brine produced is computed as the product of the seawater's density and 2.5 liters [35], [37].

The amount of cooling water needed to cool the electrolysis plants was calculated using a simplified method. As suggested by Rijkswaterstaat, an accurate calculation would require the creation of a model that calculates the amount of heat that surface water can absorb before warming by 3°C [77]. Because this calculation is complex and because cooling water is not the focus of this thesis, some simplified assumptions are made to provide a rough estimate. These assumptions are based on guidelines from Rijkswaterstaat [77].

To estimate the cooling water requirements, the calculation assumed that 33% of the total energy input (100% minus the electrolyser efficiency) was transformed into heat. It was further hypothesized that 8% of this heat would be dissipated through air and other means, leaving 92% to be mitigated by cooling water [104].

To translate this into a measurable quantity, 1 GWh is equivalent to $3.6 * 10^{12}$ joules. The total heat load that must be addressed by the cooling water is determined by multiplying this energy value by the number of hours the system operates at full capacity, the capacity of the electrolyser itself, the proportion of energy that becomes heat, and finally, the 92% that is managed via cooling water. This approach provides a framework for calculating the cooling water needed for efficient operation of the electrolyser system.

The cooling water is assumed to be discharged at a maximum temperature of 28°C after being heated by a maximum increase of 5°C. Under this assumption, the requirement for realistic cooling water volumes is met, but the thermal tolerance increase of the surface water is kept to a maximum of 3°C. The specific heat capacity of seawater (4190 kJ/kg [105]) is multiplied by the temperature (in this case, 5°C) to determine how much heat it can absorb in one liter of seawater. By dividing the total heat produced by the maximum absorption value of one liter of seawater, the amount of cooling water required can be determined.

4.2.2. Calculating storage and brine production from caverns

To manage the variability in energy output, it's necessary to have an energy storage strategy. This paper simplifies the calculation by assuming a steady energy supply based on average production levels. Using a capacity of 20 GW with an efficiency of 67% and the annual full load hours of the wind profiles, the average energy production is estimated to be about 7.1 GWh per hour. The calculation then assesses the energy surplus or deficit for each hour throughout the year compared to the previous hour. This approach results in a cumulative surplus or deficit, as shown in Figure 4.2.

From this analysis, the maximum cumulative surplus reaches 1524.5 GWh and the maximum deficit falls to -3880 GWh. Th minimum storage volume required to manage these fluctuations is the absolute difference between these two values, which is approximately 5404.55 GWh out of a total of 62503 GWh produced. This analysis indicates that about 9% of the total energy production needs to be stored.

To be conservative, this study assumes a storage percentage of 10%, with a conservative estimate of 5% and an upper estimate of 15%. These percentages are consistent with typical parameters used in energy studies of this type.

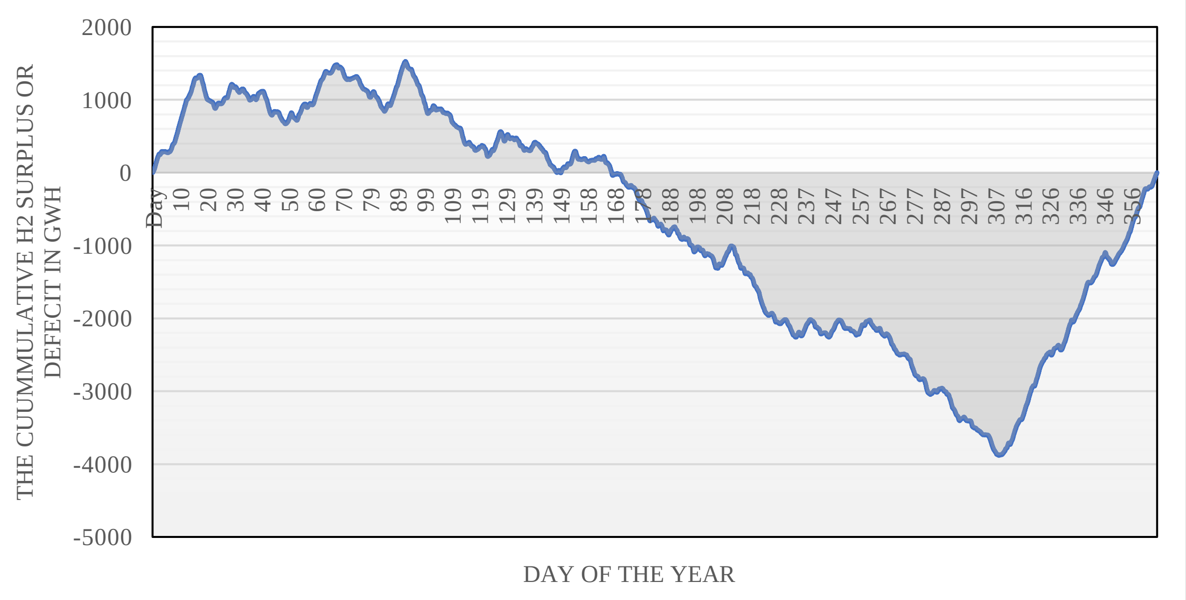


Figure 4.2 | Annual net hydrogen production variance.

Figure 4.2 depicts the net variance in offshore hydrogen production throughout the year. The y-axis represents the hydrogen surplus or deficit in gigawatt-hours (GWh), while the x-axis corresponds to the days of the year. The line plot showcases the fluctuations in hydrogen production, highlighting periods of surplus (above the horizontal zero line) and deficit (below the zero line). The graph reaches a peak surplus of 1525 GWh and a peak deficit nearing -3880 GWh. The absolute difference in GWh hours between the surplus and deficit peak, reflects the total storage requirement of hydrogen.

In this context, it is clear how much hydrogen needs to be stored. This thesis assumes that the produced hydrogen is stored in salt caverns near the production site. Hydrogen storage is assumed to be limited to salt caverns offshore, assuming that aquifers, depleted gas fields, and other storage options will be used for various purposes. It is assumed that these salt caverns will be as large as possible due to the complexity and higher cost of constructing them offshore (estimated at 1.5 to 3 times the cost of onshore) [106]. Each of the salt caverns can hold an estimated 250 GWh of hydrogen, as the design of the caverns assumes a capacity of $1*10^{6}$ m^{3} [27].

Two sources from the North Sea Energy consortium report that the density of rock salt layers in the North Sea ranges from X (known within TNO) to 2168 kg. For the purposes of this study, a density of 1700 kg/m^{3} was assumed for the salt domes.

This study examines the solubility of rock salt in water. The results indicate that one liter of water at 20°C can theoretically dissolve up to 350 grams of rock salt. However, practical observations suggest a slightly lower capacity. According to reports from NLOG, the concentration of brine from solution mining at the Zechstein salt mine in Zuidwending is measured at 304 PSU. This finding is consistent with other studies, which typically report brine concentrations from salt mining ranging between 250 and 300 PSU. Therefore, this study assumes a concentration of 280 PSU for its calculations.

Given the average salinity of the North Sea at 33 PSU, it is calculated that one liter of seawater can dissolve an additional 247 grams of rock salt, considering the difference between the assumed brine concentration and the sea's salinity (280 - 33 = 247 grams per liter). To create a cavern of 1 million cubic meters within the salt layer, approximately 6.8 million liters of water are required, calculated as $1{,}7 * 10^9 / (247 / 1000) * 1000$ liters. Taking into account environmental considerations that prevent direct discharge of this highly saline solution into the sea, it is determined that the solution must be diluted with three times its volume in seawater to mitigate potential harm to the surrounding ecosystem, as one could conclude from chapter 3. Consequently, the construction of each cavern would necessitate a total of approximately 27 million cubic meters of brine. This approach ensures the resulting outflowing diluted brine has a PSU of 94, optimizing environmental safety while achieving the desired cavity size.

Subsequently, the number of salt caverns that need to be constructed each year must be calculated. This is achieved by determining the storage requirements for the year and dividing this figure by 250 GWh, which represents the storage capacity of one cavern. The number of salt caverns required is then adjusted by subtracting the count from the previous year, thus determining the total of salt caverns that must be delivered within the current year.

This study assumed a two-year period for leaching a salt cavern, followed by an additional three-year phase for operational readiness, including drying and constructing essential infrastructure like compressors and pipelines [8]. Thus, the total time from the start of construction to operational readiness of a salt cavern is estimated to be around five years. This timeframe is integral for planning the construction schedule of each cavern. The model used in this study is flexible, allowing for adjustments in these time estimates to accommodate varying project needs and scenarios.

Finally, the Excel model calculates the annual seawater requirements and associated brine production for hydrogen production and storage. This contributes to a detailed estimate of the environmental impacts related to how many caverns are needed on an annual basis. This information can then be used to determine activities.

4.3. Results

The results of the scenario analysis shed light on the annual production of hydrogen in GWh and kg. Figure 4.3 graphically shows the annual hydrogen production for each scenario. The amount of seawater required for production and storage, as well as the annual brine production, were calculated from these baseline data. These data are further broken down monthly based on the maximum hourly load for a typical model wind year.

The more detailed data are provided in the appendix in order to maintain the clarity and conciseness of the results. This is especially true for the annual seawater intake and heat dissipation data for the different hydrogen production scenarios. The production load data is directly visible in the data presented for the 500 MW electrolyser, as well as the total annual seawater intakes and brine production. However, the results related to the salt caverns are discussed in more detail in the main text due to the numerous intermediate steps and assumptions involved.

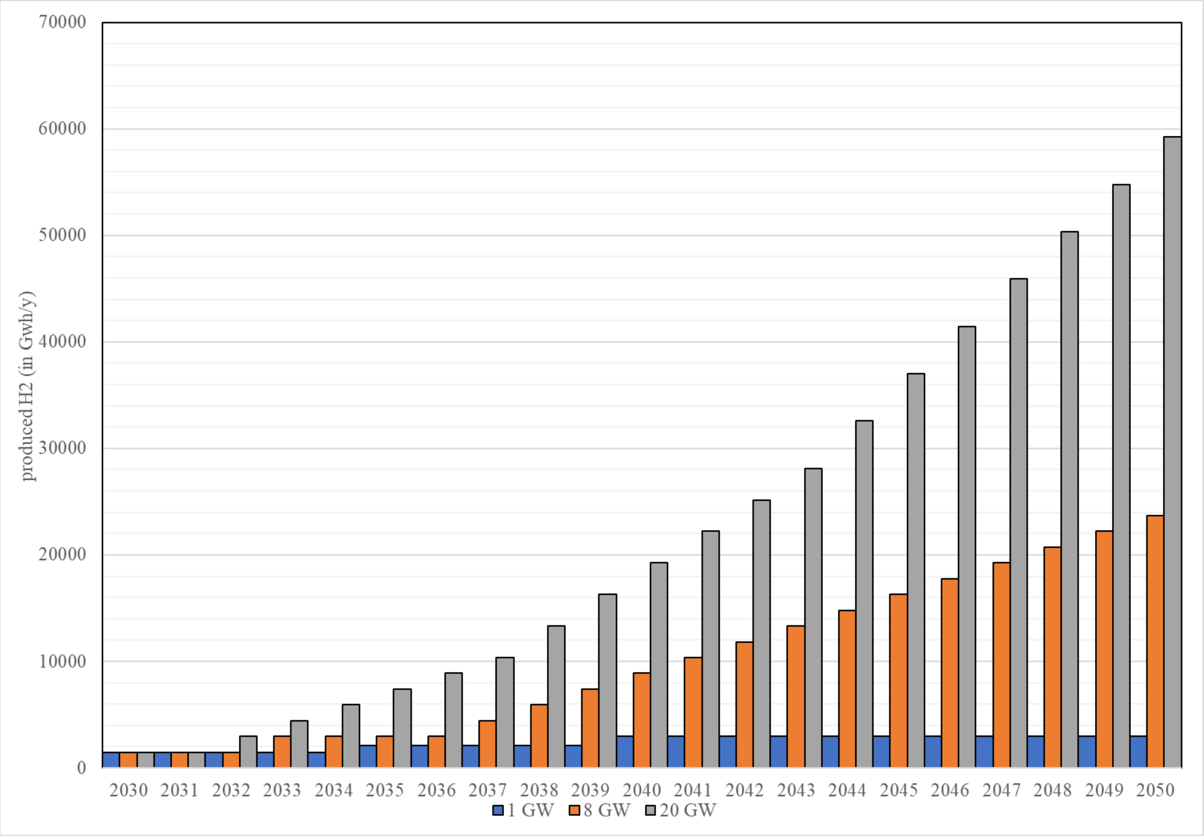


Figure 4.3 | The projected annual green hydrogen production in GWh for the period 2030-2050.

This figure presents the projected production of green hydrogen in the Netherlands from 2030 to 2050, measured in GWh. Three production scenarios are depicted: 1 GW (blue bars), 8 GW (orange bars), and 20 GW (grey bars), each showing an increasing trend over the 20-year period. The y-axis quantifies the produced hydrogen, revealing a significant rise, especially in the 20 GW scenario, which suggests a substantial increase in green hydrogen production towards the latter years. The x-axis marks the years of the projected period.

4.3.1. Heat disposal

Significant heat is generated during the hydrogen production process, and this heat must be removed using cooling water. Figure 4.4 graphically depicts the annual heat dissipation to the ocean through cooling water. This information was used to calculate the annual cooling water demand, which is shown graphically in Figure 4.4 and included in Appendix 4.

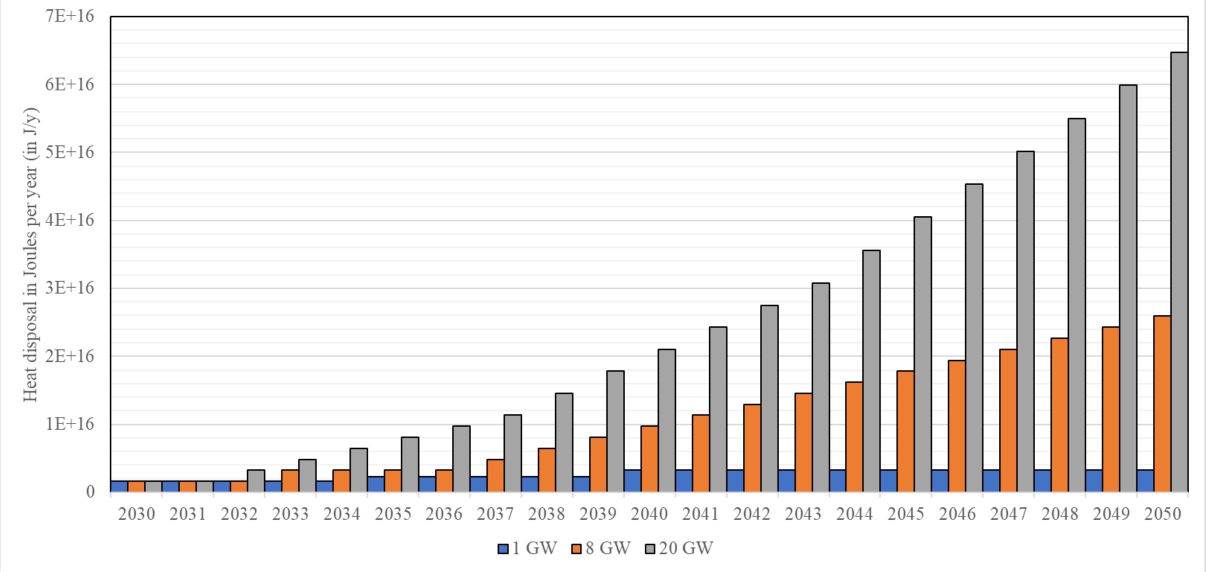


Figure 4.4 | The projected annual heat disposal into the North sea from electrolysis operations.

This figure displays the projected annual heat disposal into the sea from electrolysis operations in the Netherlands over the period from 2030 to 2050. The y-axis measures the heat disposal in Petajoules per year, indicating the total thermal output disposed into the marine environment. The x-axis enumerates the years within the forecast period. The data is segmented into three scenarios based on the capacity of the electrolysis facilities: 1 GW (depicted in blue), 8 GW (depicted in orange), and 20 GW (depicted in grey). Each bar represents the estimated amount of heat disposed of in a given year, with the overall trend showing an increase in thermal disposal.

4.3.2. Offshore hydrogen storage results

The scenario analysis demonstrates that the number of salt caverns to be built between 2025 and 2050 varies depending on the production capacity. Ten salt caverns are required for the 8 GW scenario, compared to two for the 1 GW scenario. Twenty-four salt caverns will need to be built in the most extensive 20 GW scenario. These calculations are based on the assumption that 10% of the total energy produced needs to be stored. The growing infrastructure required to facilitate the expansion of hydrogen energy storage is shown in Figure 4.5.

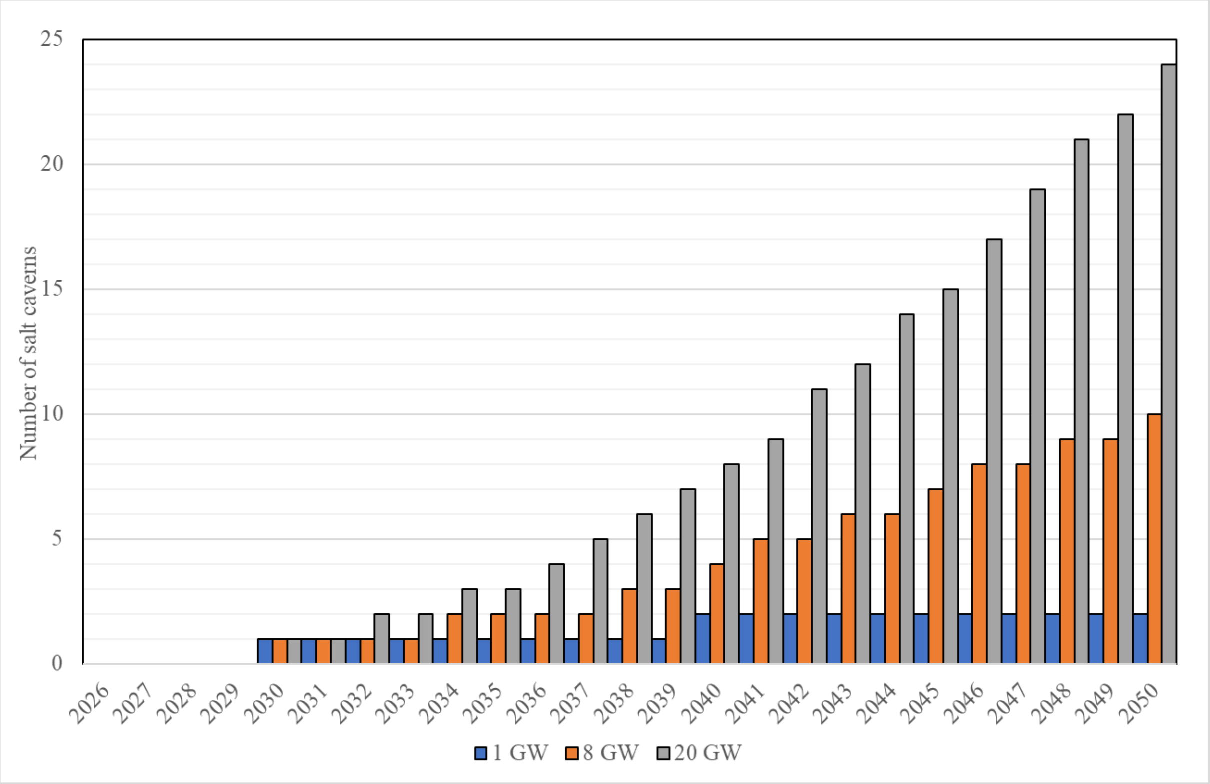


Figure 4.5 | The projected number of salt caverns that is required for hydrogen storage. *This Figure presents the number of offshore salt caverns required for hydrogen storage from the year 2026 through 2050. The y-axis quantifies the number of salt caverns, while the x-axis represents the timeline of years under consideration. The chart categorizes the data into three different production scenarios, each with a corresponding color: 1 GW (blue), 8 GW (orange), and 20 GW (grey).*

From there, it was determined how many caverns would need to be built each year and how much brine would be produced. The number of caverns planned for construction each year is shown in Figure 4.6. It is noteworthy that all three scenarios in this scenario study call for cavern mining to begin as early as 2025. This is due to the assumption that the initial 500 MW of offshore electrolysis will require a cavern to immediately store the hydrogen produced. This allowed the calculation of the annual water intake required for cavern leaching and related brine production, as shown in Figure 4.7.

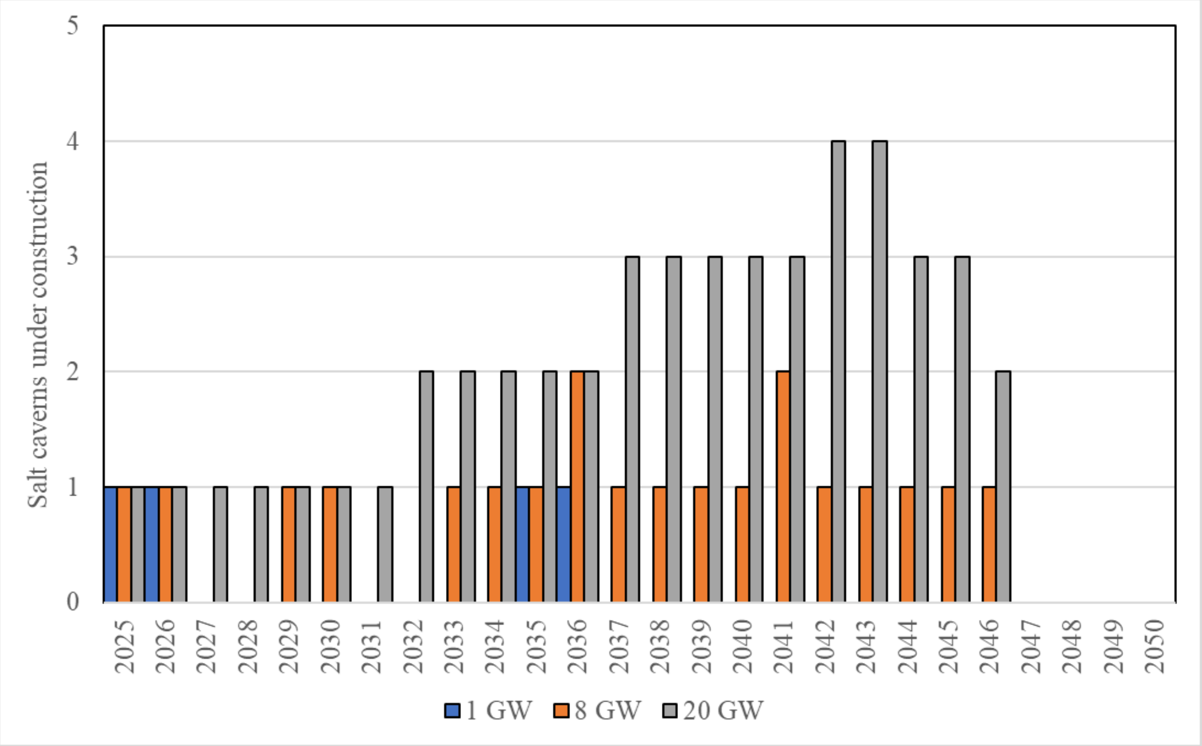


Figure 4.6 | The projected number of offshore salt caverns under construction for hydrogen storage during the period 2025 to 2050.

Figure 4.6 displays the projected number of salt caverns under construction each year, which are intended for hydrogen storage, spanning from 2025 to 2050. The y-axis indicates the count of salt caverns being constructed, and the x-axis lists the years across the forecasted timeframe. The data is broken down into three capacity-based scenarios for hydrogen storage construction: 1 GW (blue), 8 GW (orange), and 20 GW (grey). Each bar on the chart represents the number of caverns that are expected to be in the construction phase in a given year for the corresponding scenario. A clear pattern emerges from the data, showing fluctuating yet increasing construction activity over the years, with the 20 GW scenario frequently having the highest number of caverns under construction.

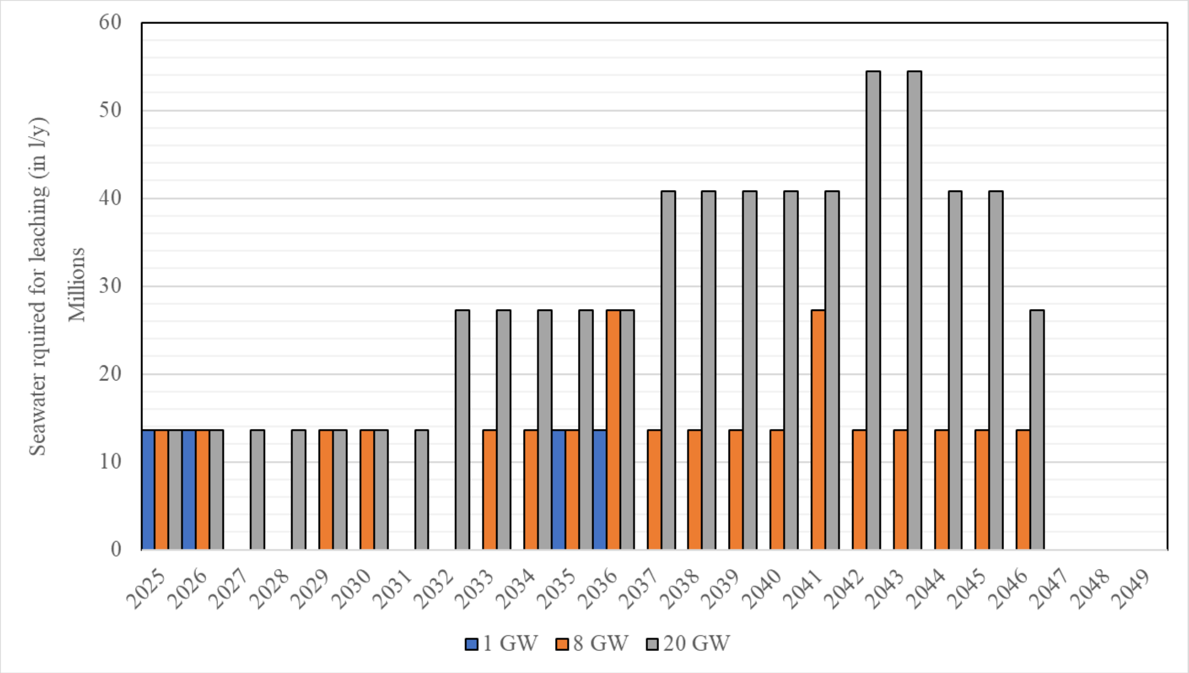


Figure 4.7 | The projected annual seawater intake for salt cavern construction and corresponding brine output (2025-2050).

Illustrated here is the estimated annual intake of seawater required for the leaching processes involved in building salt caverns, which is equal to the annual brine production over the period from 2025 to 2050. Each bar represents a year, with the color coding - blue for the 1 GW scenario, orange for the 8 GW scenario and gray for the 20 GW scenario - indicating the scale of operations. The y-axis quantifies seawater volume in liters per year, the x-axis represents the year and scenario.

4.3.3. Total annual water intake

This section of the analysis focuses on the total seawater intakes required for hydrogen production and storage in salt caverns. Seawater intake projections were calculated for three scenarios spanning the period 2025-2050. The results indicate that seawater demand increases in direct proportion to the capacity of hydrogen production facilities. Figure 4.8 depicts the total water consumption.

Cooling water plays a disproportionately large role in the total seawater intake. Over 95% of the seawater intake is used for cooling, which is far more than the amount of water required for salt cavern leaching or electrolysis feedstock. This suggests that cooling requirements have a significant impact on seawater intake and are therefore an important consideration for offshore hydrogen production and storage. The data also show that despite the various uses of seawater, the total of withdrawals increase dramatically as production capacity increases.

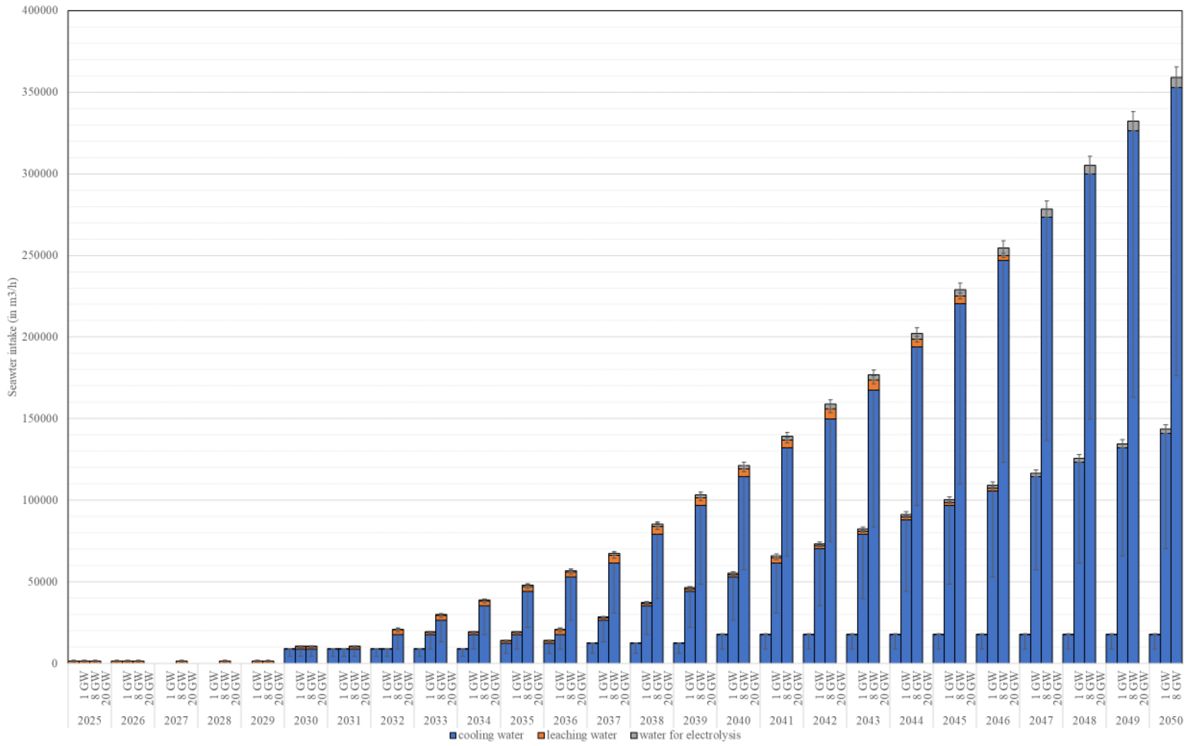


Figure 4.8 | The projected seawater intake for offshore hydrogen production and storage. *Figure 4.8 illustrates the anticipated seawater intake for offshore hydrogen production and storage from 2025 through 2050. The vertical axis quantifies the volume of seawater intake in cubic meters per hour. This volume is expected to increase significantly over the span of 25 years, indicative of the expanding scale of hydrogen production operations. The horizontal axis delineates the years for the projected data. The chart delineates the anticipated seawater intake for three capacity scenarios: 1 GW, 8 GW, and 20 GW. The color blue represents the annual seawater intake, while orange illustrates the leaching water necessary for constructing salt caverns, and grey indicates the seawater utilized in the electrolysis process. Each bar provides an estimate of the seawater intake for that particular year, corresponding to the specified capacity scenario. The data reveals an increase in seawater consumption over time, suggesting an uptick in the operational scale of hydrogen production, as well as the associated increase in water demand for both electrolysis and storage operations.*

4.3.4. Annual brine production

Brine production is critical to the environmental impact of offshore hydrogen production and storage. Figure Y shows the projected annual brine production from 2025 to 2050 under three capacity scenarios: 1 GW, 8 GW, and 20 GW. These estimates are based on the assumption that 10% of total hydrogen production is stored in salt caverns and that each liter of hypersaline brine is diluted with three liters of seawater to reduce environmental impact, the results are depicted in figure 4.9.

The results show that by 2043, salt cavern construction will account for at least three-quarters of total brine production. After that year, electrolysis waste streams will serve as the primary source of brine production. Between 2025 and 2030, brine production will be entirely from leaching during salt cavern construction, as water electrolysis will not yet be operational during this period.

It is interesting to note that there is no linear relationship between the scenario sizes and the amount of brine produced. This non-linear relationship exists because the construction of salt caverns has a mayor influence on the annual brine production. As a result, in some years, especially when cavern is under construction, the amount of brine produced in the 1 GW and 8 GW scenarios is nearly identical.

It is also worth noting that the peaks in brine production shown in the graph correspond to the planned expansion of salt cavern storage capacity. These peaks indicate when environmental pressures will be greatest.

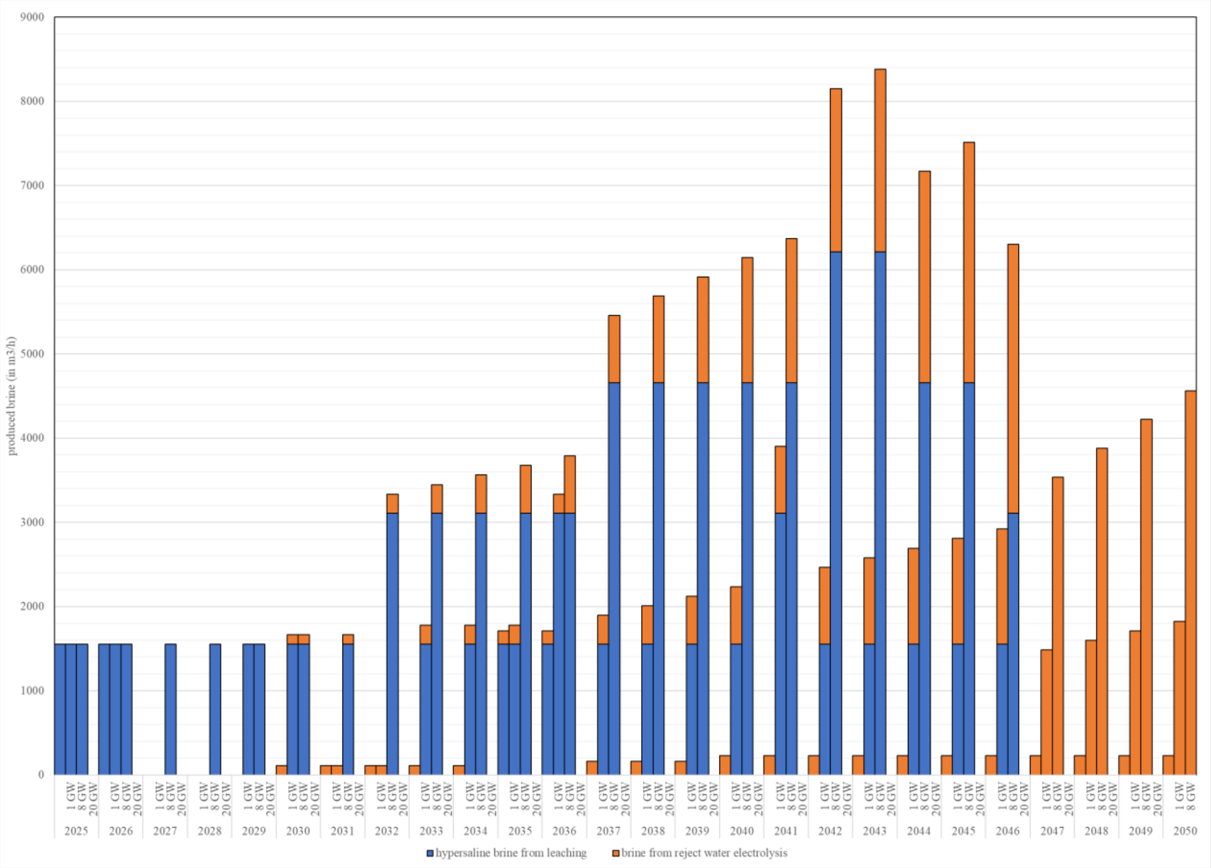


Figure 4.9 | The projected annual brine production for offshore hydrogen production and storage.

This figure compares the projected volumes of brine produced from two different sources in the process of offshore hydrogen production and storage over the period from 2025 to 2050 for the 1, 8 &20 GW scenarios. The y-axis quantifies the volume of produced brine in cubic meters per hour, while the x-axis represents the timeline in years. Two types of brine production are illustrated: hypersaline brine resulting from the leaching process (shown in blue) and brine generated from reject water in electrolysis (depicted in orange). Each set of dual bars for a given year indicates the respective volumes of brine production, with the overall trend showing an increase in brine production over time, particularly from the leaching process.

4.3.5. Operational seawater intake and discharge of a 500 MW electrolyser

To understand the annual seawater consumption of a 500 MW electrolyser and the resulting environmental impact, the operation of the electrolyser was simulated. Hourly peak loads and monthly demand were included in the analysis. The monthly inflow and outflow of seawater is displayed in figure 4.10. According to the data, almost 99% of the total input and output of the plant is cooling water. The remaining portion, or about 1%, is used in reverse osmosis processes, depicted in figure 4.11.. Approximately 0.83% of this fraction, with a PSU of 44.8, enters the cooling water as effluent and is subsequently returned to the sea. Of this fraction, 0.33% is converted to hydrogen (displayed in figure 4.10).

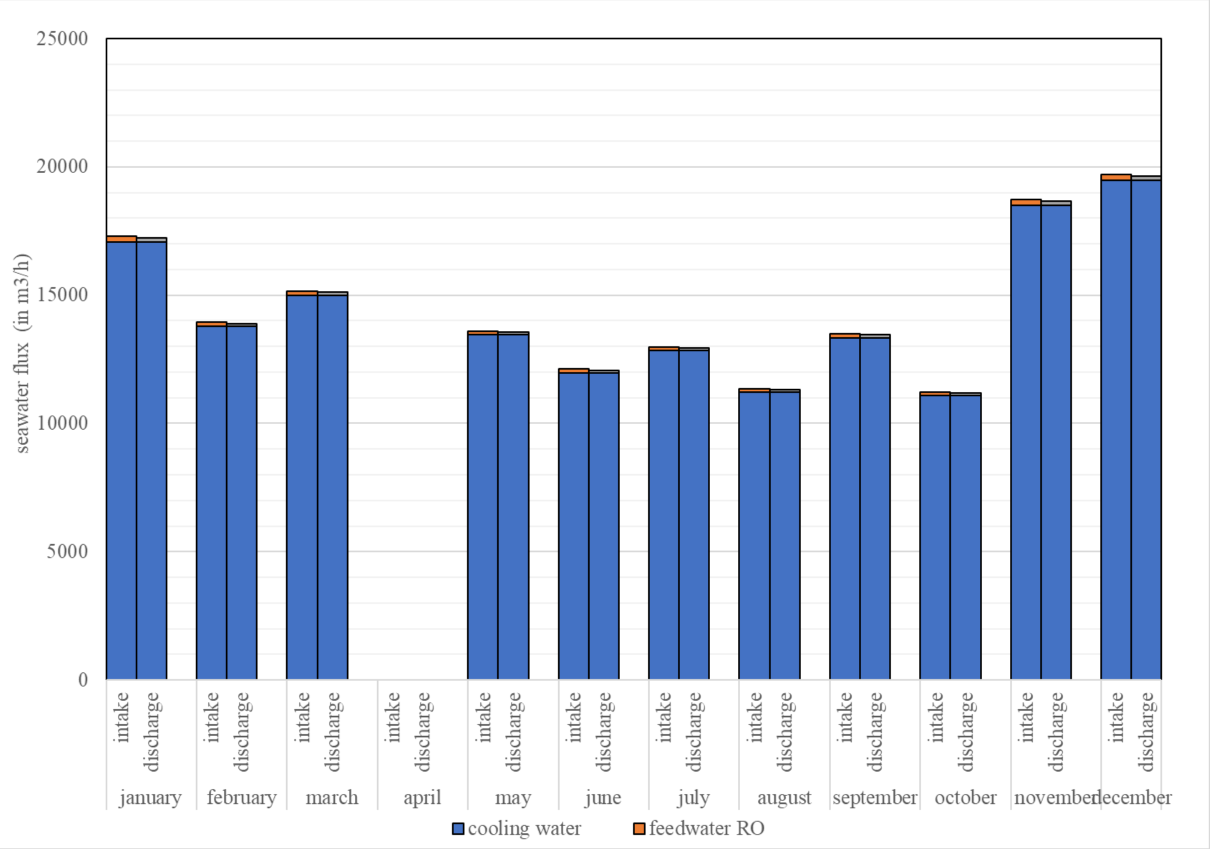


Figure 4.10 | The comparative monthly intake and discharge of seawater from a 500 MW electrolyser.

Figure 4.10 details the monthly intake and discharge of seawater for a 500 MW electrolyser over the course of a year. Each pair of bars represents a month, with the left bar indicating seawater intake and the right bar showing seawater discharge. The y-axis measures the volume of water in cubic meters per hour. Three components of seawater handling are color-coded: cooling water in blue, feedwater RO (reverse osmosis) in orange, and reject feedwater in grey.

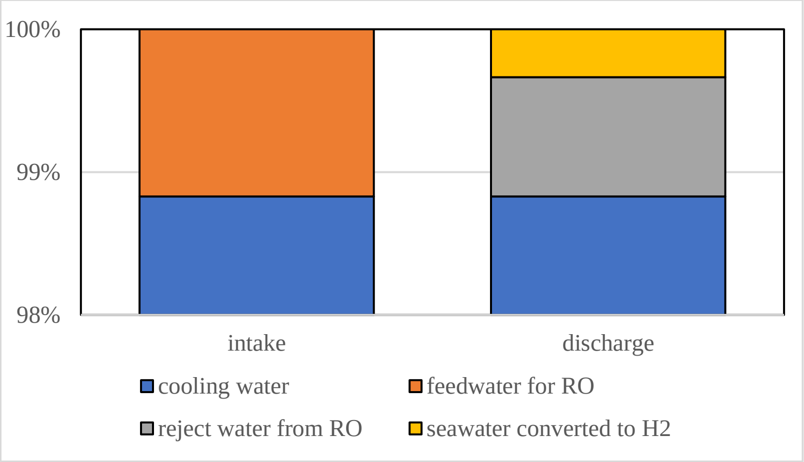


Figure 4.11 | Proportional analysis of seawater usage of a 500 MW electrolyser.
In this figure the intake and discharge processes is broken down into percentages, For both intake and discharge, the chart categorizes the seawater usage into four parts: cooling water depicted in blue, feedwater for RO shown in orange, in grey is depicted the brine reject water from RO and in yellow the seawater that is converted to hydrogen. The left bar represents the distribution of the two types of seawater intake, while the right bar shows the proportions of seawater discharge. The chart indicates that 99% of the intake is used for cooling, whereas the rest is required for feedwater. On the discharge side, 0,33% of the seawater is converted to hydrogen and 0,83% was brine as it was reject water from RO. The percentages shown reflect the relative volumes of water used in each stage of the operation.

The performance metrics for a 500 MW electrolyser are summarized in Table 4.1, which is derived from the Excel model. It shows the average and peak operating statistics based on annual data, excluding April due to maintenance. After maintenance, the electrolyser runs an average of 4419.7 full load hours per year with an efficiency of 67%, resulting in an average operating capacity of 252.3 MW for hydrogen production, with a peak capacity of 500 MW. This is based on wind profile data.

In terms of water consumption, the electrolyser uses an average of 13,720 cubic meters of seawater per hour, resulting in an annual intake of approximately 120.19 million cubic meters. The electrolysis process requires a certain amount of feed water, which is approximately 4.50 million cubic meters per year, or an average of 559 cubic meters per hour. The annual consumption of cooling water is 115.29 million cubic meters, or an average of 13,161 cubic meters per hour.

In terms of production, the plant produces an average of 5,071 kilograms of hydrogen per hour, or 44.4 kilotons per year. RO reject water is 36 percent more saline, and total water discharge (which includes cooling water and brine) is 1.05 percent more saline. It is reported that the average brine discharge rate is 399 cubic meters per hour, or 3.5 million cubic meters per year. The process raises the temperature of the hot water discharge by 5°C above the surrounding sea level. The amount of heat released into the marine environment is measured at 0.28 GJ/hour, or 2.4 petajoules annually.

December has the most full-load hours for the electrolysers according to the reference year of the 2030 wind profiles, and the peak hourly load is based on the assumption of a sustained full-load hour, as shown in Table 4.1.

	unit	average	maximum
Capacity	MWe	500	500
full load hours	h/month	368,3	555,3
	h/year	4419,7	4419,7
efficiency	%	67%	67%
Flows in			
electricity	MW	252,3	500
Total sea water	m3/h	13720	27193
	m3/month	10009971	15099016
	m3/y	120185506	120185506
Feed water	m3/h	559	1108
	m3/month	407908	615288
	m3/y	4495041	4495041
Cooling water	m3/h	13161	26085
	m3/month	9602063	19467
	m3/y	115287925	115287925
Flows out			
Hydrogen	kg/h	5071	10051
	kt/month	3,70	5,58
	kt/year	44,4	44,4
	GWh/h	0,169	0,335
	GWh/month	123,4	186,0
	GWh/y	1480,6	1480,6
Brine, the Feed water reject of RO	m3/h	399	792
	m3/month	291363	439491
	m3/y	3498272	3498272
Cooling water	m3/h	13161	26085
	m3/month	9602063	19467
	m3/y	115287925	115287925
Salinity of brine	g/l	44,8	44,8
salinity increase of reject water		36%	-
salinity increase of outflow total water		1,05%	-
temperature increase	°C	5	5
heat disposal in to sea	GJ/h	0,28	0,55
	TJ/month	201	303
	PJ/y	2,4	2,4E+00

Table 4.1 Analysis of an operational 500 MW PEM Offshore Electrolyser.

The table summarizes the operational performance of a 500 MW electrolyser producing hydrogen by electrolysis. The average values represent continuous operation throughout the *year, including maintenance periods, and the maximum values represent peak performance under optimal operating conditions. The system capacity, electricity and hydrogen production, seawater consumption, and environmental impact in terms of salinity and temperature increase are shown in the table, which projects the energy output and environmental impact of offshore hydrogen production based on predicted wind profiles for 2030 according to the TNO wind profiles.*

4.6. Discussion

4.4.1. The exploratory nature of this scenario analysis

This study examined the use of cooling water in electrolysis processes and emphasized that a number of factors can have a large impact on the outcome. Significant uncertainties and margins of error are introduced by the decision to choose between air and water cooling, the effect of wind profiles on cooling water requirements, and the assumptions made regarding the density of the salt layer and the amount of seawater required for leaching salt caverns. These features highlight the exploratory nature of the investigation and the influence of these margins of error on the results, suggesting that additional work and investigation is required.

4.4.2. Assessing seawater intake and discharge and ecological impacts of offshore hydrogen production and storage.

According to the data from the Excel model, cooling water uses the most water overall and is likely to have the greatest environmental impact. In fact, cooling water accounts for more than 90% of total water use. However, the brine flow from the electrolyser appears insignificant because it can be discharged with the cooling water, increasing the salinity of the effluent by only 1%.

The amount of water needed to build salt caverns and release brine seems to be within reasonable limits. The maximum brine discharge in the 20 GW scenario with a salinity of 94 g/l could be as high as 6120 m^3/h. This peaks at 3096 m^3/h for the 8 GW scenario, but is typically around 1548 m^3/h. The conclusions of the case study suggest that this shouldn't have a major environmental impact. It is possible that there will be a noticeable increase in salinity in the lower water column in the immediate area of the discharge points, up to a radius of 500 meters (more likely around 100 meters). However, this increase will not exceed 1 g/l in addition to the existing salinity of the surrounding water, as shown in the case study. In the 20GW scenario, a maximum of four salt caverns could be built simultaneously in the North Sea; in the 8GW scenario, a maximum of two caverns could be built for a maximum of two years, with the exception of other years when there may be only one cavern or none at all. This means that significant environmental problems from brine discharge are unlikely.

The cooling water is a complicated issue. In his study, the limits of Rijkswaterstaat were used and the exact environmental impact is still unknown, there is still the question of whether the inflow and outflow rates could have an impact on the local environment. The inflow is 4.9 m^3/s for 1 GW, 39.2 m^3/s for 8 GW and up to 98.0 m^3/s for 20 GW. These are significant volumes that, depending on local conditions, can affect nearby water flows and ecology. Therefore, it is critical that more research be conducted on these issues to determine the potential local impact of such inflow and outflow rate.

4.4.3. Cooling water modelling

For simplicity, this study followed a guideline that allows the cooling water to warm up to 5°C before discharge. This appeared to have the least impact on the environment. If a temperature increase of up to 10°C before discharge were chosen, it would become more difficult to meet the requirements: the cooling water should not exceed 28°C and the surface water should not heat up by more than 3°C [77].

One approach to regulating cooling water discharge at electrolysis plants could have been to implement a different discharge schedule based on the time of year. During the three hottest months, cooling water was discharged at a temperature differential of only 5°C, which could be increased to 10°C during the rest of the year. Another option would be to maintain a temperature differential of 7.5°C throughout the year. These methods could reduce the amount of cooling water required, but may have a greater impact on surface water warming.

The proposed method of using temperature differences in different seasons to discharge cooling water has not been implemented. This is primarily because the current implementation, which does not require in-depth modeling knowledge, is considered the most practical and likely option for implementation. Adherence to a standard procedure simplifies and makes the process more manageable, which is important given the inherent complexity and environmental impact of offshore electrolysis.

Finally, the main problem with the cooling water is uncertainty because the heat release to the ocean has not been modeled. As a result, it is unclear how much the surface water heats up. This was not the main focus of this study; an explanatory study was conducted that was primarily concerned with the brine produced during storage and hydrogen production. Nevertheless, modeling these heat discharges in the future is critical to better understand the environmental impact and cumulative impact of multiple electrolysers in the North Sea or within a single wind farm. This is an important follow-up study that will provide a more accurate estimate of the amount of seawater required.

4.4.4. Comparison cooling water discharge in other industries

An interesting comparison of offshore hydrogen production can be found in an analysis of the use of cooling water by industrial plants in the Wadden Sea region, which includes the Dutch, the German and Danish Wadden Seas. According to a survey, the 16 operating plants in the area, with a total capacity of 9511 MW plus planned expansions of 11730 MW, mainly use flow cooling systems. These systems remove large volumes of water from the Wadden Sea or its estuaries, resulting in an estimated flow rate of 416 m^3/s, or more than 13.1 billion m^3 per year, which is about 2.4 times the total volume of the Wadden Sea [78].

On the other hand, much less cooling water is needed for offshore hydrogen production, especially for green hydrogen. According to the analysis, the amount of cooling water needed for a 1 GW production facility is about 4.9 m^3/s; this increases to 39.2 m^3/s for 8 GW and 97.97 m^3/s for 20 GW.

4.4.5. Densities of rock salt, brine concentrations and dilution

In this study, the density of rock salt was evaluated using an average value between the known density of pure rock salt (approximately 2168 kg/m³ [107]) and a lower value specific to salt caverns. Pure rock salt most likely has a density near this higher value. However, in salt domes, where rock salt is more plastic and rises to the surface, the density may be lower (the exact value has been measured and is known, but is confidential). To account for this difference, this study used an average density that falls between these two values. This explains why the density in this study may be lower than other studies that use the standard density of rock salt.

Brine concentrations were calculated assuming a PSU of 280. This is consistent with the results of previous studies and practices in salt mining or salt cavern construction. For example, the salinity of the brine from Zuidwending was measured to be 304 grams per liter [108], while the brine used to build salt caverns in Ireland had a salinity of 260 grams per liter [51]. The value of 280 grams per liter therefore seems to be a good average.

Data from other studies also supports the study's assumptions regarding the water requirements for these processes. The Zuidwending facility had a water flow rate of 0.15 m³/s, comparable to the 0.12 m³/s used in the scenario analysis [108]. This similarity in water requirements is supported by studies such as Leith 2001 [109] and Evans 2007 [110], which examine gas storage practices in salt caverns. These studies confirm the assumed leach rates, salinity, and water requirements, which help to validate the scenario analysis.

It is also important to note that the plastic properties of rock salt in salt domes influence the final density and structure of the salt. Uplift and deformation can change the composition and porosity of rock salt, resulting in physical properties that differ from those of pure rock salt. These factors are essential in determining how much brine will be released and how much water will be required for leaching, as they are proportional to the density of the rock salt.

The scenario analysis was based on the idea that for every liter of brine produced during the construction of salt caverns, three liters of seawater should be added. This approach is based on the results of the case study discussed in Chapter 2, which indicated that this was necessary to achieve acceptable environmental levels. A quarter of the calculated value of the brine component in the study would be the result of discharging the brine undiluted as hypersaline. However, it is important to consider both the practicality of diluting the brine and the feasibility of releasing it in an undiluted state without impacting the environment.

4.4.6. Offshore salt caverns development

The development of offshore salt caverns for hydrogen storage is an important topic of discussion. According to this scenario analysis, construction of these caverns should begin as early as 2025, with the goal of being operational by 2030. This appears to be an ambitious timeline given the current emphasis on launching pilot projects for offshore hydrogen production. These pilots have yet to begin, and it is critical that the lessons learned from them be incorporated before large-scale hydrogen production begins. Successful completion of these pilots is a prerequisite for investment in expensive offshore salt caverns. Before 2030, alternative storage methods such as ammonia tanks are more likely to be considered than direct investment in salt caverns for hydrogen storage.

The high cost of building offshore salt caverns is an important factor that could influence the scenario analysis. These costs are approximately 1.5 to 3 times higher than the costs of building onshore salt caverns . Before developing offshore storage, other less expensive options such as onshore salt cavern storage may be considered. This could mean that the total number of offshore salt caverns will be lower than predicted in the study [106].

However, there is an important caution: the discharge of brine into the sea during the construction of salt caverns is a common practice in countries such as Ireland and Germany [8]. This happens when the amount of brine produced is so large that it is not economically viable to use it for salt or chemical extraction. So even if the salt caverns are built on land, the brine can still be discharged into the sea via a pipeline, as has been done in other countries. This may also be an option in the Netherlands, where caverns can be built in the northeast and the brine discharged into the sea.

There are concerns about hydrogen storage near housing because of the safety risks involved and the public's lack of familiarity with hydrogen as an energy carrier. These concerns may contribute to the "not in my backyard" effect, where people are reluctant to have hydrogen storage near their homes [111]. This may lead to a preference for offshore storage, particularly in areas where land is scarce. Concerns include the greater explosive range of hydrogen compared to natural gas, the difficulty of detecting leaks, and the need for changes in infrastructure and regulations to ensure safe use in residential areas. As a result, despite higher costs, hydrogen storage may eventually take place offshore.

Another factor to consider is ongoing research into the feasibility of storing hydrogen in depleted gas fields. Modeling studies are currently underway to assess the potential for such storage, and one depleted gas field is being considered as a pilot study [112]. These underground storage studies consider the possibility of hydrogen storage in gas fields, which is not covered in the current study. This may result in a reduction in the expected brine production, as the total number of salt caverns required may be less than originally estimated. This is because the availability of empty gas fields as storage sites may reduce the need to build new salt caverns.

4.4.7. Annual salt production from cavern construction

The annual production of salt from the construction of salt caverns could be impressive, as a comparison with salt mining in the Netherlands shows. According to the scenario analysis, the construction of a single salt cavern can produce an estimated 1.687 billion kilograms of rock salt per year over a period of two years, as shown in appendix 4. In comparison, the total salt production of Zuidwending in 2022 was approximately 1.522 billion kilograms [113].

Comparing these figures to the total salt production in the Netherlands, which is approximately 5.893 billion kilograms in 2022, salt production from a single cavern represents approximately 28.6% of national salt production. This comparison highlights the potential of salt caverns as a significant source of salt production, with the 20 GW scenario capable of meeting almost all of the Netherlands' salt demand during the projected peak years of 2037 to 2045. It implies that, despite the complexity and costs associated with the construction and management of mined brine, they have the potential to make a significant contribution to the salt industry if brought to shore.

4.5. Conclusion(s)

- **What are the estimated volumes of seawater intake needed for offshore electrolysis in 2050, across the scenarios (1 GW, 8 GW & 20 GW), considering the requirements for both cooling processes and reverse osmosis?**

If the discharge temperature difference is 5 degrees Celsius, then in all three cases, 99% of the seawater intake is utilized for cooling. Nonetheless, the percentage is 98% if a temperature differential of 10 degrees is taken for granted. For the 1 GW scenario, this means an average intake of 4.9 m³/s, or 1.1 x 10^8 m³/year, at a temperature difference of 5 degrees. This translates to an average of 39.2 m³/s for the 8 GW scenario, or 9.0 x 10^8 m³/yr. This translates to an average intake of 98.0 m³/s for the 20 GW scenario, or 2.2 x 10^9 m³/year in 2050.

- **For each scenario, how many salt caverns are necessary for consistent hydrogen supply, and what are the associated total and annual maximum seawater usage and brine production rates?**

The study calculated the number of salt caverns required to provide a continuous supply of hydrogen: Two caverns at 10% storage, one at 5% and three at 15% are required for 1 GW. For 8 GW, 10, 5, and 15 caverns are required, and for 20 GW, 24, 12, and 36 caverns are required. 10% storage is assumed, with lower and upper bounds of 5% and 15%.

The total volume of seawater consumed and the total volume of brine released are equal. The PSU of the released brine is 94. With 10% storage, the total discharges for the years 2025-2050 are 5.4 * 10^7 m³ for the 1 GW scenario, 2.7 * 10^8 m³ for the 8 GW scenario, and 6.5 * 10^8 m³ for the 20 GW scenario. For 1 GW, 8 GW, and 20 GW, the maximum discharge rates are 0.43 m³/s, 0.86 m³/s, and 1.7 m³/s, respectively.

- **What is the total seawater requirement for hydrogen storage and production in each scenario, and which key factors most significantly influence these seawater needs?**

In the 1 GW scenario, 2.7 * 10^9 m³ of seawater was required, 8 GW required 1.1 * 10^{10} m³, and 20 GW required 2.6 * 10^{10} m³. The amount of seawater required for RO for electrolysis was minimal in all three cases at 0.06%. Among the scenarios, the percentage of seawater required for salt cavern leaching ranged from 2.0% to 2.5%. Between 97.5% and 97.9% of the seawater was used as cooling water. Cooling water accounts for 98% of the variance in seawater intake. Even if the cooling water output is reduced by half to allow for a 10 degree temperature differential, cooling still accounts for approximately 95% of the seawater intake.

- **What are the detailed annual, monthly, and peak hourly rates of seawater intake and discharge for a 500 MW electrolyser?**

Variations in specific intake and discharge values are common for a 500 MW electrolyser. It is important to note that there can be notable variations in monthly and peak hour loads, which can have an impact on the nearby ecosystem. For detailed numbers please refer to table 4.1.

- **In the projected timeframe of 2025 to 2050, which years are expected to have the greatest environmental impact, and which factor among brine disposal from cavern construction, brine disposal from reverse osmosis, or the intake and discharge of heated water from cooling electrolysers is expected to contribute most to this impact?**

Although this conclusion is presented with caution, the analysis indicates that the environmental impact of discharging cooling water may be greater than that of building salt caverns. Under the scenarios, the environmental impact will increase in direct proportion to the increase in offshore green hydrogen production. Considering the temperature variations at discharge and the fact that cooling water accounts for 98% of seawater intake and discharge, this particular factor will have the greatest impact. Also taking into account that the disposal of brine, does dilute well when measures are taken and does not have to lead to a salinity increment. The years approaching 2050 are likely to have the greatest environmental impact. The construction of offshore green hydrogen production and storage systems also has an effect, especially between 2040 and 2050, when construction activity will increase to meet the projections.

"What are the projected seawater intake and discharge outputs, including heat water and brine, for offshore electrolysis operations under 1 GW, 8 GW, and 20 GW production scenarios, during the period from 2025 to 2050?"

In conclusion, for the period 2025-2050, the projected seawater intake for offshore hydrogen production and storage in the scenarios are as follows: 1 GW requires 2.7 * 10^9 m³, 8 GW requires 1.1 * 10^{10} m³, and 20 GW requires 2.6 * 10^{10} m³. In 2030, the seawater intake for 1 GW is about 4.0 * 10^7 m3/y, for 8 GW 5.4 * 10^7 m³/y, and for 20 GW also 5.4 * 10^7 m³/y. By 2050, this has increased to 8.0 *10^9 m³/y for 1 GW, 6.4 *10^9 m³/y for 8 GW, and 1.6 * 10^9 m³/y for 20 GW. Averaged over the period 2025 to 2050, this is 5.7 * 10^7 m³/y for 1 GW, 2.4 * 10^8 m³/y for 8 GW, and 5.5 * 10^8 m³/y for 20 GW. Of the seawater required, 98% is used as cooling water and 2% for the construction of salt caverns. Only 0.02% is converted to hydrogen and oxygen, so the inflow and outflow are practically equal and the difference is negligible. The salinity of the combined discharge stream of cooling water and reject water increases by 1% compared to the intake. The salinity of the brine from the salt cavern construction is 94 g/l. The amount of brine discharged varies annually and does not increase consistently like the other water streams.

5. Discussion

5.1. Combining the results of the three chapters

The findings from each of the three chapters are interesting and relevant, but when combined they provide new insights. This discussion section brings together the findings from the literature review, the case study, and the scenario study, which helps to understand the findings in a larger context. Each section produced unique findings, and combining them provides new perspectives and insights.

When the results of the literature review are combined with the case study results, it is clear that brine discharge has a limited impact on the local ecology. According to the near-field model, brine can be effectively diluted and dispersed using a brine diffuser, resulting in a salinity difference of less than 2 PSU at a distance of 100 meters from the discharge point. The far-field model shows that brine is not detectable outside of a grid cell in the North Sea model, suggesting that impacts are limited to a radius of 500 to 900 meters.

These results suggest that ecological impacts are primarily concentrated within a 100 meter radius of the discharge point. In this area, a reduction in benthic biodiversity is expected, according to a comparative literature review. Beyond this radius, there appears to be no significant environmental or ecological effects.

If brine is diluted to a salinity of 94 PSU and then discharged through a diffuser at 1.2 m^3/s, it is unlikely to have ecological effects beyond a radius of 100 meters. An undiluted discharge with a salinity of 280 PSU and a flow rate of 0.3 m^3/s is unlikely to have ecological effects beyond a radius of 900 meters. However, benthic biodiversity may be reduced in this nearshore zone, particularly in the immediate vicinity of the outfall. Outside these mixing zones, no significant ecological effects are expected.

According to the scenario analysis, it is unlikely that more than three or four of such source discharges will occur simultaneously in the North Sea, limiting the total ecological impact to 2.5 km^2. Due to the coarse resolution of the model, the actual impact area is likely to be smaller than predicted. In addition, it is questionable whether it is realistic to expect four offshore caverns to be built simultaneously to achieve a production and storage capacity of 20 GW. It is also important to note that the environmental impact of brine discharge ends once the cavern is completely filled. Thus, based on the data in this thesis, it appears unlikely that brine injection for hydrogen storage will have an environmental and ecological impact beyond a few square kilometers.

Moreover, the scenario analysis showed that the cooling electrolysers consume more than 95% of the total seawater intake for the offshore hydrogen storage and production system, which is substantial. As a result, the expected environmental and ecological impacts are high. The 8 and 20 gigawatt systems produce approximately 25,000 and 65,000 TJ/y of heat, which is released into the North Sea surface waters. This requires $8.9 * 10^8$ m^3/y (39 m^3/s on average) and 2.2 * 109 m^3/y (100 m^3/s on average) of cooling water. Given these quantities, it is apparent that this will have an impact on the surrounding water.

It is important to accurately model the effects of this heat release, especially because the area where cooling water is discharged is prone to seasonal stratification [84]. Discharging cooling water can increase stratification and reduce mixing of water layers, which can affect nutrient distribution, oxygen levels, and overall water quality [83]. Add to this the fact that this is happening next to or in yet to be built wind farms, which themselves depending on the location might also increase stratification and reduce mixing of water layers [83].

Cooling water releases heat, which affects both the water column and its ecosystem. Increased surface temperatures can have a significant negative impact on marine life, which is often dependent on specific temperature ranges and nutrient availability [114]. Increased temperatures can cause higher mortality rates, altered growth and development, and changes in the behavior and distribution of marine organisms, particularly fish and pelagic species [114]. Studies have shown that different groups of plankton respond differently to rising water temperatures, with different mortality rates and recovery times [115]. In addition, higher surface temperatures can promote harmful algal blooms [116]. These changes can affect plankton growth, fish migration patterns, and the overall health of marine life.

Another important aspect of electrolyser impacts is the potential for fish mortality from cooling water intakes. The literature review found that fish mortality from cooling water intakes at power plants is high, with mortality rates ranging from 70% to 90% for fish entering the cooling system. This resulted in an annual fish mortality of approximately 9.6 to 14.4 million at an intake of 18 m^3/s. However, this was in an estuarine environment and not in the open ocean, so the figures are not directly applicable to situations around electrolysers.

The cooling water intake of a 500 MW electrolyser averages 3.7 m^3/s (the total intake of offshore electrolysers can reach 100 m^3/s), suggesting that fish mortality due to ingestion may be a prominent issue. It is therefore necessary to investigate the mortality of plankton, algae and fish as a result of the use of cooling water by a 500 MW electrolyser. This research is critical for an accurate assessment of the environmental impact, particularly in terms of food web effects. A thorough analysis will contribute to a better understanding of the impact of these systems on the marine ecosystem, allowing appropriate measures to be taken to protect marine biodiversity.

A study of the ecosystems in which electrolysers potentially will be installed is necessary to better identify and mitigate their environmental impacts. This investigation should focus on determining whether the proposed sites serve as habitat for rare or endangered species, as well as evaluating the effects of heat dissipation and cooling water intake on these organisms. It is critical to determine whether these activities will affect the mating behavior of affected species, whether the areas serve as breeding grounds, and whether there are eggs, larvae, or juveniles that may be particularly sensitive to cooling water intakes or elevated water temperatures caused by cooling water discharges. These factors must be evaluated to understand the potential impacts on these sensitive species and their habitats, and to help establish the baselines needed to measure the ecological impacts of offshore green hydrogen production and storage.

5.2. Unaddressed environmental impacts

In addition to the impacts of seawater intake and discharge of brine and cooling water inherent in the green hydrogen storage and production system, there are other environmental effects that have not been studied in this thesis. However, these impacts also have a significant effect on life in the North Sea. The most important of these impacts are noise pollution, light pollution, soil disturbance, electromagnetic radiation, and the physical presence of offshore platforms . These factors have been briefly highlighted in this discussion because of their potential impact on the marine ecosystem.

Underwater noise has a significant environmental impact on offshore hydrogen production and storage, particularly during the various phases of development and maintenance. During the exploration phase, seismic surveys generate large amounts of underwater noise that can disturb marine life. This noise, which is necessary to map the seafloor, can disrupt the natural behaviors and habitats of marine animals.

Pile driving/installation of the foundations for the electrolysis platforms generates additional underwater noise. Driving heavy piles into the seafloor causes sound waves to propagate underwater, potentially disturbing the ecosystem.

In addition, there is a high level of noise pollution during the operational phase. For example, the operation of electrolysers, an essential component of the hydrogen production process, contributes to underwater noise levels. These units, which are required to split water into hydrogen and oxygen, can generate noise during operation that can disturb nearby marine life. Compressors used to store hydrogen in salt caverns generate underwater noise. The equipment needed to transport and store hydrogen under high pressure produces vibrations and noise that can disturb marine life.

Finally, transportation for maintenance and inspection of offshore facilities contributes to underwater noise levels. Ship movements, both for routine maintenance and inspections, produce continuous noise that can be a persistent source of disturbance to the marine ecosystem and is expected to affect large marine mammals, fish and seabirds.

Light pollution is a significant environmental impact associated with offshore hydrogen production and storage, particularly during maintenance and inspection activities. Transportation for maintenance and inspection, including the movement of ships and helicopters, adds significant light to the otherwise dark marine environment. While these light sources are necessary for safe navigation and operations, they have the potential to affect the behavior and life cycles of marine organisms.

For example, nighttime light from ships and helicopters can influence the behavior of fish and seabirds, affecting feeding patterns, migration, and reproduction. Light pollution can also disrupt the biorhythms of marine species, making them vulnerable to predators. In addition, routine maintenance of offshore installations contributes to light pollution. Work performed at night or in the early hours of the morning often requires powerful lighting. This artificial light can be harmful to the nocturnal marine ecosystem, especially in areas where such light sources were previously absent.

Seabed disturbance is a major environmental concern in the development of offshore hydrogen production and storage. The construction of cables and pipelines that alter and disturb the seabed structure is an important part of this process. These activities, which involve uprooting or covering the seabed, can result in habitat loss and disruption to the benthic ecosystem.

Construction activities such as the foundation of offshore structures and the installation of erosion protection have a direct impact on the seabed. These interventions alter the physical properties of the seabed, potentially affecting the organisms that live there. Changes in seabed texture and composition can result in the disappearance of specific habitats, leading to a cascade of ecological consequences. The reef-like effect of subsea structures can promote the establishment of new species not previously present in the area, resulting in an ecosystem shift.

The installation of electrolysers also causes seabed disturbance. These installations require a stable seabed, but can alter the structure of the seabed during installation. This often involves moving sediments and creating new physical barriers on the seabed.

The development of infrastructure around salt caverns used for hydrogen storage introduces further disturbance. The activities required to access and manage these caverns, such as drilling and building underwater infrastructure, can damage the seabed and cause changes in the local marine ecosystem.

Bottom disturbance has the greatest impact on benthic organisms, which include shellfish, worms, and other small bottom dwellers. Their habitats can be destroyed, resulting in loss of biodiversity and ecological imbalances. Bottom disturbance can also affect the food chains on which many fish and other marine animals depend, resulting in fewer food sources and altered migration patterns.

The presence of cables and pipelines at offshore hydrogen production and storage projects creates electromagnetic fields in the marine environment. Electromagnetic fields are generated by the electric currents flowing through these submarine cables and can radiate into the surrounding waters. Although the exact impact of electromagnetic fields on marine organisms is still under investigation, there is growing concern about their potential effects.

Elasmobranchs, such as sharks, rays and certain species of fish, are sensitive to electromagnetic signals. They use natural electromagnetic fields for navigation, foraging and detecting predators. Changes in the electromagnetic landscape due to the presence of cables can disrupt these natural patterns of behavior. This could lead to disorientation, changes in migration routes, and even avoidance of certain areas. In addition, continuous exposure to artificial electromagnetic fields would potentially affect the reproduction and development of some marine species.

The physical presence and spatial use of offshore hydrogen production and storage platforms have a direct impact on the marine environment. Not only do these platforms take up valuable space on the seafloor, but they also cause physical disturbances to the marine ecosystem. These disturbances range from the direct impact of the structure itself on the seabed to changes in local water currents and sedimentation patterns.

In addition, the permanent presence of these structures can affect the migration patterns of various marine species. Large structures can act as physical barriers to the natural movement of fish and other marine life. This can alter migration routes and feeding areas, potentially having a significant impact on the local ecosystem.

It is important to consider these physical impacts when planning and implementing offshore hydrogen projects. To reduce the impact on the marine ecosystem, the footprint of these platforms must be minimized and construction processes must be carefully managed. Ongoing research and monitoring is needed to better understand the long-term effects of these structures on marine life and to ensure sustainable interaction with the marine environment.

5.3. Accumulative environmental impacts

The overall impact of the hydrogen system on the marine environment of the North Sea is a major cause for concern. This sea is already under great pressure from human activities that affect biodiversity and the environment. Current activities include intensive fishing, military exercises, oil and gas extraction, large-scale sand mining, shipping lanes and the (future planned) construction of 72 gigawatt wind farms [33]. These wind farms have a negative impact on ocean stratification and sedimentation patterns, as well as the food web, particularly by the reducing of plankton biomass [85].

The addition of a hydrogen production and storage network adds to the existing pressures. This network introduces new stressors, including seawater withdrawal, heat and brine discharge, noise and light pollution, and the physical presence of infrastructure. These additional factors are expected to have a cumulative negative impact on marine life in the North Sea.

Moreover, the Netherlands is not alone in wanting to make the most of its EEZ. Neighboring countries such as Germany, Belgium, France, England and Denmark also use their EEZs for purposes such as fishing, sand mining and the production of green energy through wind farms [117]. These activities lead to increased activity in the North Sea and the pressure on the area does not seem to be decreasing. This aspect becomes even more important when looking beyond 2030, when the integration of a hydrogen production and storage system will have to be considered in this already congested environment.

Offshore green hydrogen projects require both detailed Environmental Impact Assessments (EIAs) and Strategic Environmental Assessments (SEAs). SEAs provide a systematic and decision-support approach to ensure that environmental and other sustainability issues are effectively addressed in the development of policies, plans and programs [118]. This is essential to prevent further degradation of the North Sea due to cumulative impacts. More research is needed to fully understand and manage these complex interactions and their effects on the marine environment, and agreements should be reached at both national and regional/international levels to protect the ecological well-being of the North Sea.

5.4. Potential future technological developments not addressed

Since pressure can cause salt caverns to shrink and change shape, the storage of hydrogen in offshore salt caverns requires permanent leaching facilities. The volume must be adjusted periodically as it shrinks over time due to subsurface pressure and the plasticity of the rock salt

[119]. However, due to the lack of information on the technologies involved and the frequency of such activities, this issue was not thoroughly addressed in the thesis.

In addition, the development of electrolysers that use air cooling instead of cooling water, or a combination of the two, offers the possibility of drastically reducing the amount of cooling water used. Future technological advances may significantly change this ratio if air cooling is used more than seawater cooling [120], which is an important consideration for reducing environmental impact, although this study assumed 8% air cooling and 92% water cooling.

5.5. Alternative brine disposal method

A recent study of carbon capture and storage (CCS) in the North Sea suggests that undiluted hypersaline brine could be released into the region as a result of pressure management. The results showed that in hydrodynamically active areas such as the North Sea, brine disperses rapidly, limiting environmental impact. The study found that the method of discharge is important: mid-depth and surface discharges result in faster dispersion and smaller footprints on the North Sea seafloor due to vertical dilution [96].

Interestingly, this approach was also suggested in another publication that proposed surface injection of hypersaline brines [53]. It was assumed that the brine would dissolve within 500 meters and be diluted before reaching the seafloor. This discharge method may benefit benthic communities, which are particularly sensitive to environmental changes such as increased salinity or contaminants. By discharging brine at the surface, the direct impact on these species can be greatly reduced. Interaction with surface currents and wave action endorses faster brine dispersion and dilution in the water column [121].

The use of brine diffusers in coastal areas, which often lack the deep vertical spreading layers investigated in these two studies, provides interesting insights. For example, surface discharge may result in less environmentally damaging dispersion than discharge to the bottom through a brine diffuser. The study area for this thesis is typically between thirty and sixty meters deep [81], so brine discharged from the surface here has the potential to mix and dissolve thoroughly before reaching the bottom. This method of discharge may therefore have potential ecological benefits for marine life in the mixing zone and should be researched fully. In addition, it may be cost effective as it eliminates the need to install pipes and a diffusion or irrigation system at depth. This makes this method particularly interesting and warrants further investigation. This approach is not only ecologically beneficial to marine life in the mixing zone, but it also has economic advantages.

5.6. Alternatives to brine disposal

This study assumed that brine disposal was the only viable option for the brine produced. However, exploring alternatives to brine disposal represents an important opportunity to reduce the environmental impact of offshore hydrogen production. These alternatives span multiple sectors, from power generation to industrial processes, and provide new opportunities for brine reuse in the context of sustainability and the circular economy.

One of the most innovative uses of brine would be the production of blue energy that takes advantage of the unique properties of brine. Pressure Retarded Osmosis (PRO) and Reverse

Electrodialysis (RED) are two important technologies in this regard. PRO uses the pressure difference between fresh water and hypersaline brine to generate energy, while RED creates a potential difference by transporting charged ions between fresh water and brine, resulting in energy generation. Because hypersaline brine has a higher pressure or potential difference, it can generate more energy per surface area than the conventional seawater method [122].

In addition, the chemical industry offers opportunities to process brine to extract salt and other valuable chemicals. These processes, which have long been used to extract salt from underground strata, can be applied to the processing of brine from offshore hydrogen production facilities. Using steam, electricity, evaporation and crystallization processes, brine can be converted into products such as table salt, industrial salt and road salt. In addition, some of the brine can be converted into chemicals such as sodium hydroxide (caustic soda) and chlorine, which are used in a variety of industrial processes [123].

Brine can also be used as a coagulant in water treatment processes, helping to aggregate suspended particles and facilitate their removal. In addition, brine is useful as a refrigerant or heat transfer medium, particularly in processes that require extremely low temperatures, such as freezing food in the food industry[124].

In the area of energy storage, brine has potential as a thermal energy storage medium, where excess electricity is used to heat brine and store energy in the form of heat. This stored energy can then be used to generate electricity. Similar principles are used in geothermal power plants where brine is used as a heat transfer fluid [125].

Finally, brine can be used as a feedstock in electrolysis processes to produce more water where brine is used as the electrolyte. The use of brine in this context provides a long-term method for water production, despite technological challenges due to the corrosive effects of chloride ions. The possibilities are still under development/research [126].

The versatile use of brine demonstrates how it can reduce the environmental impact of offshore hydrogen production, while also providing economic value by converting waste into usable resources. Further research into these opportunities could lead to lower green energy costs and more efficient resource use, as well as reduced impact on marine ecosystems. To gain a full perspective, economic analysis is needed to balance the cost of resource processing revenues against infrastructure investments, such as building pipelines to the mainland.

6. Conclusion

The study aimed to determine how much seawater is potentially required to produce and store green hydrogen on a large scale offshore. The study assessed the potential environmental impacts of the offshore green hydrogen production and storage and possible mitigation strategies. The research question was formulated as follows:

"What is the projected seawater intake requirement for offshore green hydrogen production and storage by 2050, and what strategies could effectively mitigate the ecological impacts of waste streams like brine and cooling water in the Dutch North Sea?"

This thesis assessed the implications of using seawater to produce and store green hydrogen at sea, focusing on the quantities required and the environmental impact of waste streams such as brine and cooling water. It is estimated that up to 100 m³/s of seawater will be required for these purposes by 2050, with over 95% used for electrolyser cooling and the remainder for salt cavern development. The proportion used for electrolysis feed is negligible.

Brine production during salt cavern construction can peak at up to 2.3 m³/s diluted and 0.6 m³/s undiluted. However, the environmental impact appears to be limited to the mixing zone, which is up to 900 meters. This possibly even smaller, but was not measurable due to model limitations. Dilution of the brine with seawater and discharge through a diffuser limits the impact on the immediate environment to a radius of 100 meters, resulting in salinity differences of less than 2 grams per liter at the end of the mixing zone. Within this zone, the biodiversity of the benthic community is possibly reduced.

Cooling water can affect seawater stratification and surface temperature, which can have a negative impact on biodiversity. The intake of seawater for cooling purposes may result in the death of pelagic organisms, especially those at the sea surface. The combined results of the scenario analysis and literature review indicate that the cooling water has a negative impact on the surrounding ecosystem, although this could not be quantified.

Although this study did not indicate any overarching negative environmental impact that would prevent the implementation of a comprehensive green hydrogen production and storage system, a definitive judgment on the environmental impacts of a P2G system in the Dutch North Sea cannot be made without a thorough investigation of the combined effects of green hydrogen production and storage and its surrounding infrastructure. Nevertheless, the study found that brine disposal is feasible with manageable environmental and ecological consequences. However, more research is needed to develop detailed plans for a complete P2G system.

7. Recommendations

Based on the study's findings and discussions, the following recommendations are proposed for future research and policy development:

- Further research on pollutants: Investigate the potentially harmful substances released during offshore green hydrogen production, including biocides, antiscalants, toxic metals, H_2S, and PFCs (such as PFAS). It is essential to assess the likelihood and quantities of these substances entering the marine environment, and to explore alternatives for PFCs due to their bioaccumulation.
- Habitat Study: Conduct studies in areas proposed for hydrogen production to understand the local ecology and potential impact on the receiving environment. Establish clear baselines for environmental monitoring if such systems are implemented.
- Cumulative Ecological Impact Research: Research on the cumulative ecological impact of multiple stressors of hydrogen production and storage.
- Cooling Water Heat Dissipation Modeling: Model the effects of heat dissipation on the water column to determine the precise effects of 3 °C surface water warming and the feasibility of staying below that with the heat dissipated from electrolysers. In addition, model the cumulative effects of multiple electrolysers and associated wind farms in the North Sea.
- Planning for salt caverns: Begin early screening of salt cavern sites and geological surveys, taking into account the lengthy process to bring them into service, which could take up to 12 years. This is critical for policy makers looking to scale up hydrogen storage.
- Alternatives for electrolyser cooling: Investigate the possibility of cooling electrolysers with air instead of seawater or a mixture to reduce the impact of seawater use.
- Brine discharge alternatives: Investigate the environmental impact of brine discharge on the sea surface, as its impact may be reduced due to effective mixing and dissolution in the water layer.

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9. Appendix

Appendix 2 literature review

Toxic metals

Heavy metals are required to produce hydrogen in PEM electrolysis. Platinum and iridium. for example. are essential as catalysts. These metals increase the efficiency of the electrochemical reactions. but the sustainability and viability of offshore electrolysis is seriously threatened by their negative environmental impact [46].

For instance. the oxygen evolution reaction (OER) uses iridium oxide (IrO_2) as a catalyst. which is a critical component in this reaction. Other materials can also be used as catalysts. such as ruthenium oxide (RuO_2). which is slightly less active but has greater corrosion resistance. In addition. a mixture of mixed metal oxides is being investigated. These could be materials such as nickel-iron oxides or cobalt-iron oxides that combine several metals. These could provide more affordable and accessible options to the rare and expensive IrO_2 and RuO_2. although they corrode faster and have shorter lifetimes and efficiencies than IrO_2 [43].

Titanium is also critical in PEM electrolysis. particularly in bipolar plates (BPPs). This particular material was chosen for its low hydrogen permeability. high thermal conductivity and low initial resistance. However. titanium is susceptible to corrosion. especially on the anode side. which can lead to the formation of a passive oxide layer and negatively affect the performance of the electrolyser. Expensive coatings such as platinum are often used to overcome this problem. While less expensive. substitutes such as stainless steel can cause the release of metal ions and are not impervious to the corrosive PEM environment [43].

Titanium is often used in the construction of PEM electrolyser collectors. especially on the anode side. to avoid oxidation of other materials. As with BPPs. surface oxidation can occur and affect conductivity. Platinum. gold. or iridium coatings are applied to maintain functionality. Instead of heavy metals. carbon-based materials are often used on the cathode side [43].

The efficiency and partial reactions of PEM electrolysers depend on the use of heavy metals. but this is associated with significant health and environmental risks. The metals mentioned above. ruthenium. iridium. platinum. nickel. cobalt. titanium. gold. and iron (in high concentrations). are all toxic and can significantly harm aquatic ecosystems and accumulate in the food chain. are . Research on these metals is critical. as is ensuring that there is no release of these metals into the environment. Electrolysers should be tested for these metals. especially if they are used frequently and the metals may corrode [46].

Appendix 3 cases study

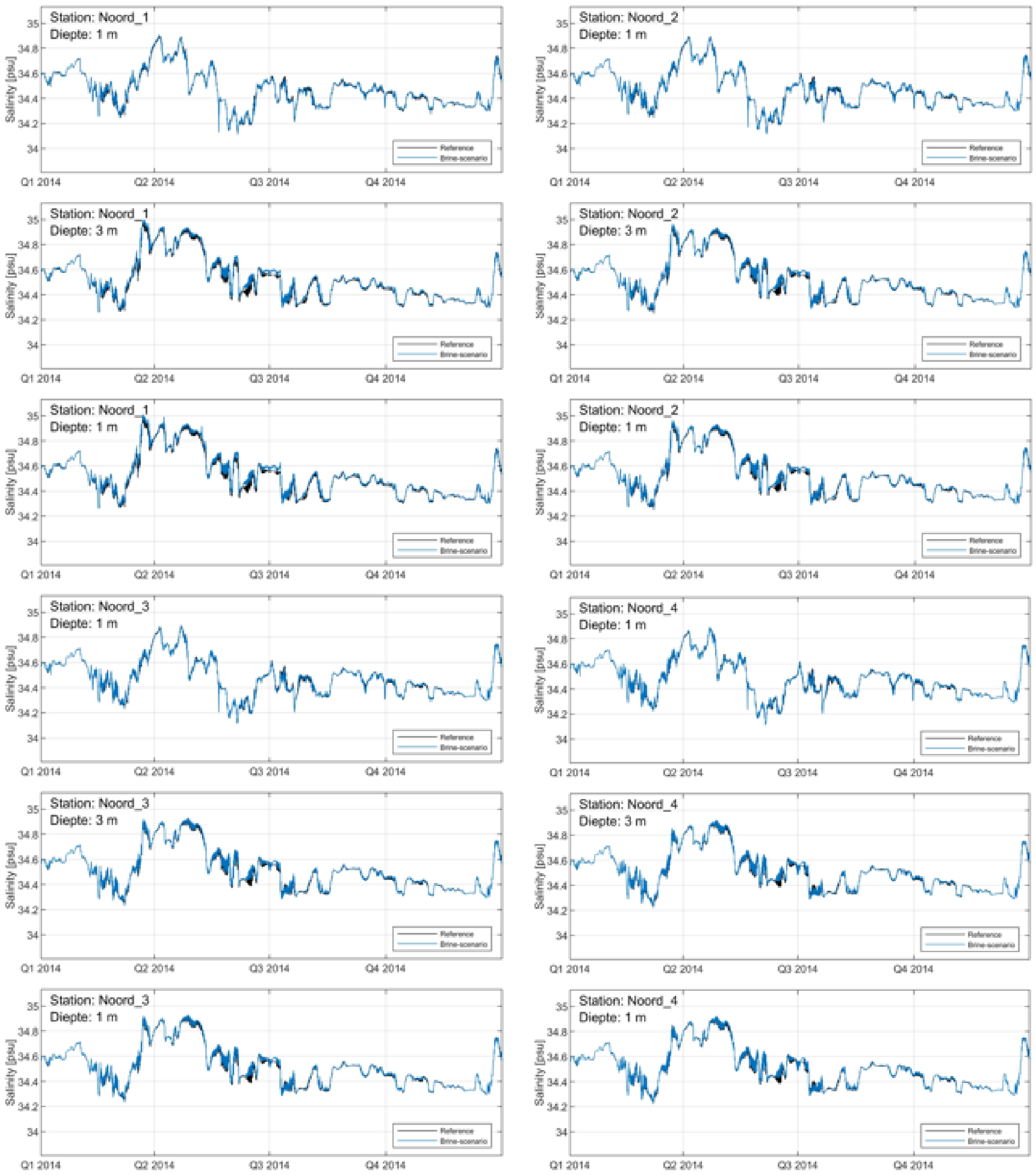

Figure 3A | the seasonal salinity variations at four Northward monitoring points

This figure displays a comparative analysis of salinity measurements taken from four distinct monitoring points, each located 900 meters apart, progressing northward from the disposal site. The data is segmented into three depth categories: 1 meter below the surface, 1 meter above the seafloor, and 3 meters above the seafloor. The monitoring captures seasonal fluctuations in salinity levels throughout the year 2014, with each point showing variations that provide insights into the spatial distribution of the brine in the marine environment. The blue line is the brine run, where the black line is the reference run.

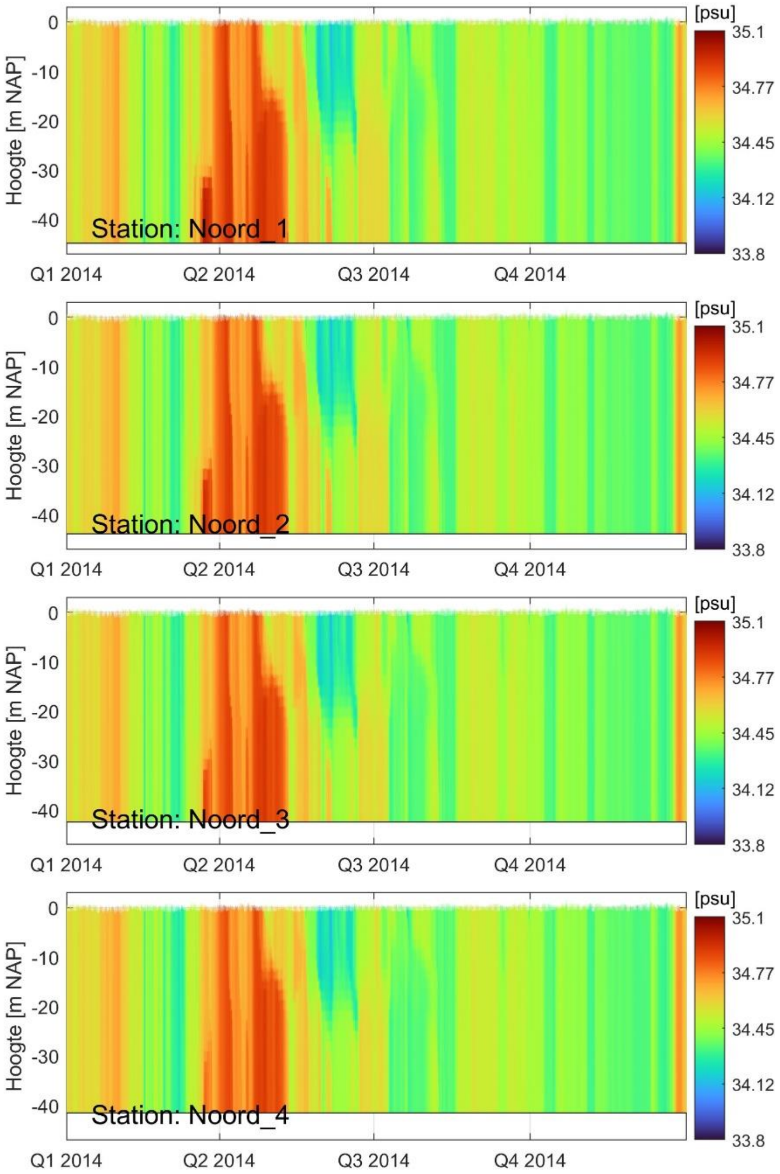

Figure 3B | an enlarged version of figure 3.9A.

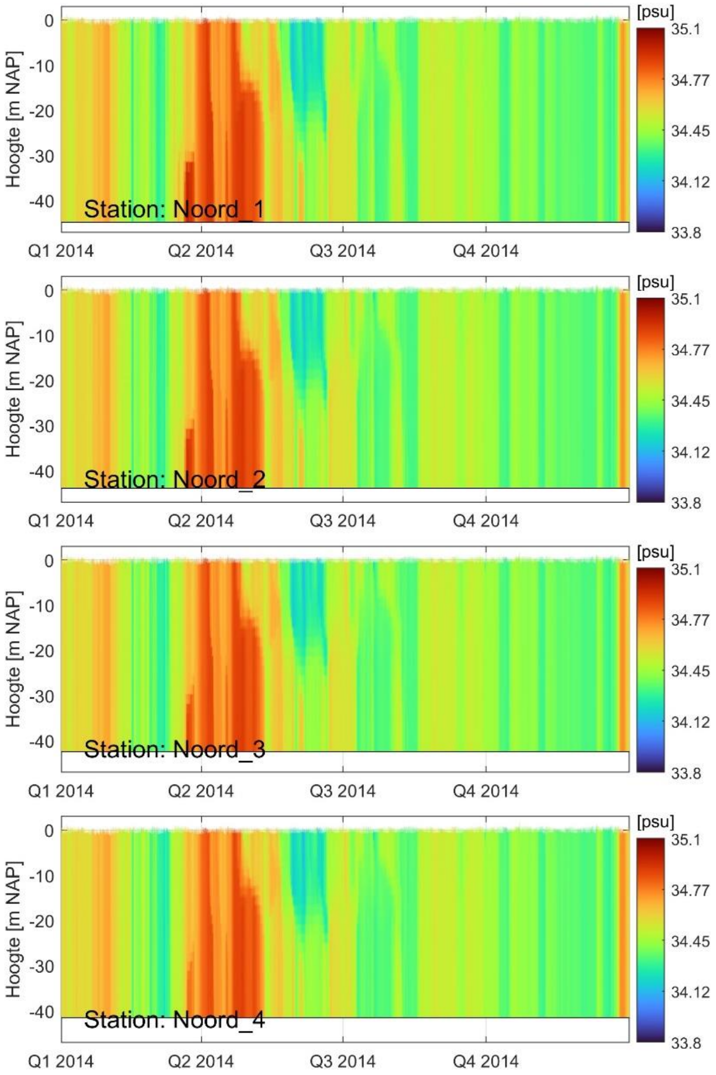

Figure 3C | an enlarged version of figure 3.9B.

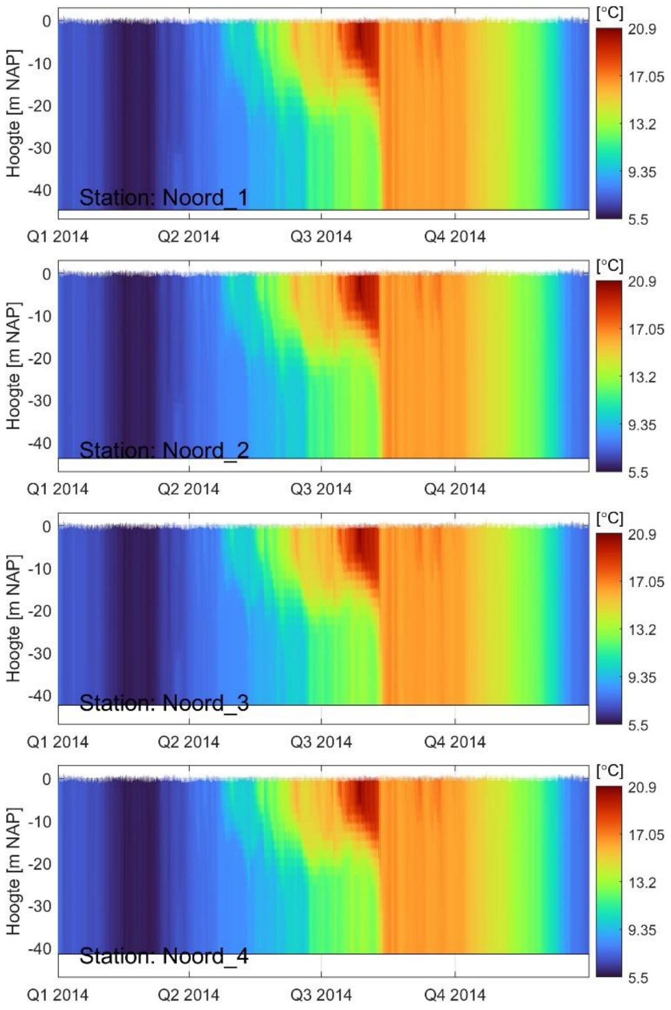

Figure 3D | Annual temperature profiles from the brine disposal run at four Northward monitoring stations.

The figure presents a visual representation of the temperature gradients at four monitoring stations, identified as Noord 1 to Noord 4, over the course of 2014. Each station's data is depicted as a color-coded temperature-depth profile, with variations shown from the surface to a depth of 40 meters. The color spectrum reflects the range of temperatures encountered, with cooler temperatures in blue and warmer temperatures in red.

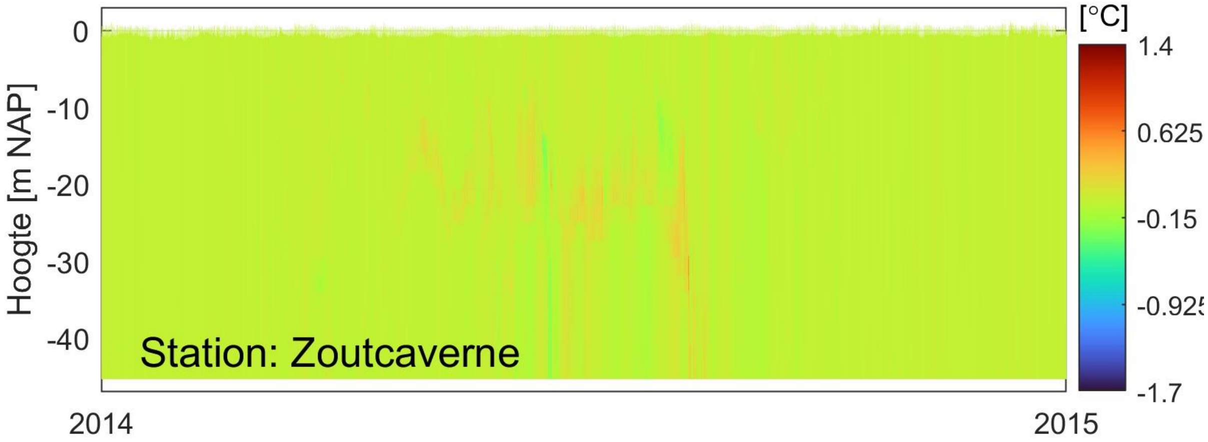

Figure 3E | The difference in temperature between the two runs in the gridcell of the brine disposal

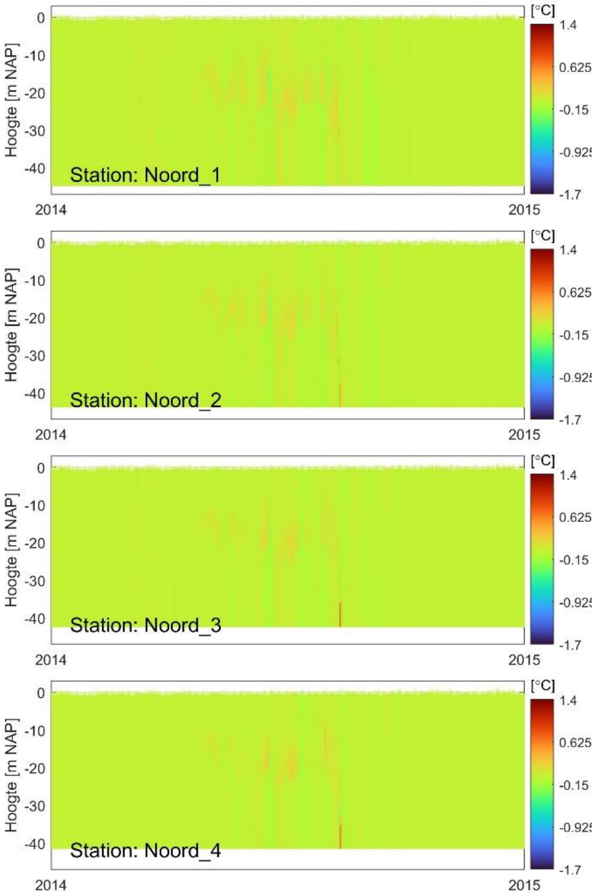

Figure 3F | The difference in temperatures observed at four Northward monitoring stations.

Appendix 4 Scenario analysis

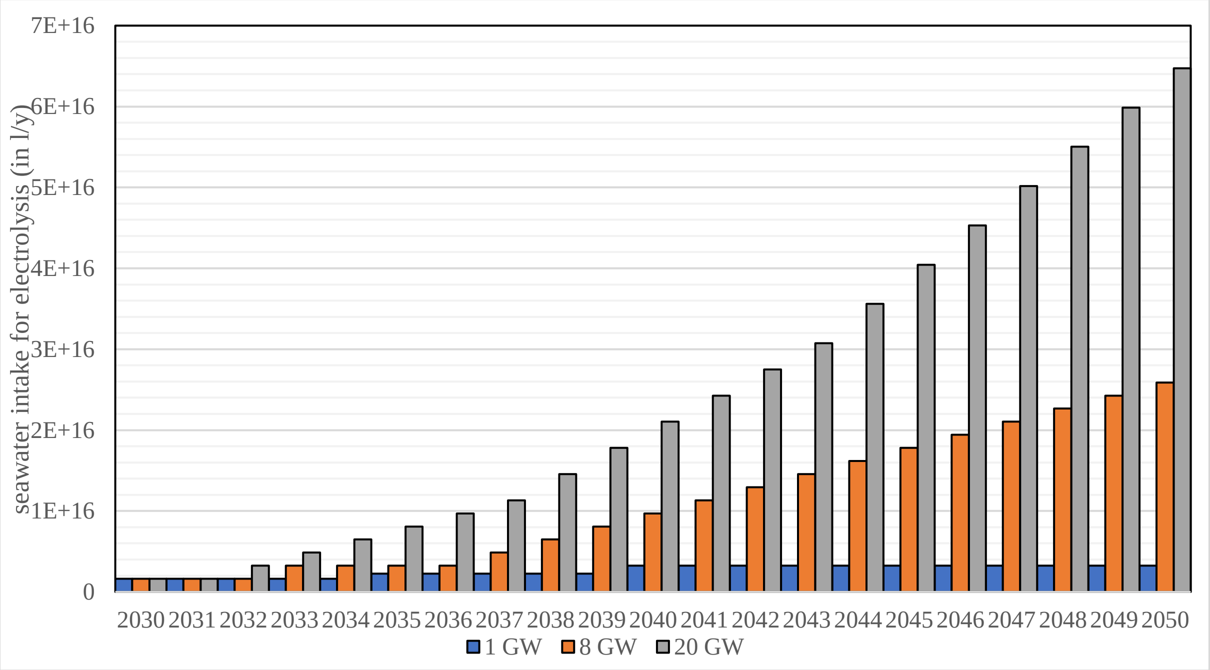

Figure 4A | The projected annual seawater intake for hydrogen production.
This figure depicts the projected seawater intake for electrolysis in the Netherlands from 2030 to 2050. The data is presented in three scenarios. differentiated by bar color: 1 GW (blue). 8 GW (orange). and 20 GW (grey). The y-axis indicates the volume of seawater intake in liters per year (l/y). suggesting large volumes suitable for the production process. Each bar represents the annual projected intake. showing an increasing trend over the years. The x-axis enumerates the years in the projection range. The chart shows a significant rise in seawater intake correlating with the capacity of electrolysis. especially in the 20 GW scenario. implying a substantial increase in seawater usage for hydrogen production as the years progress.

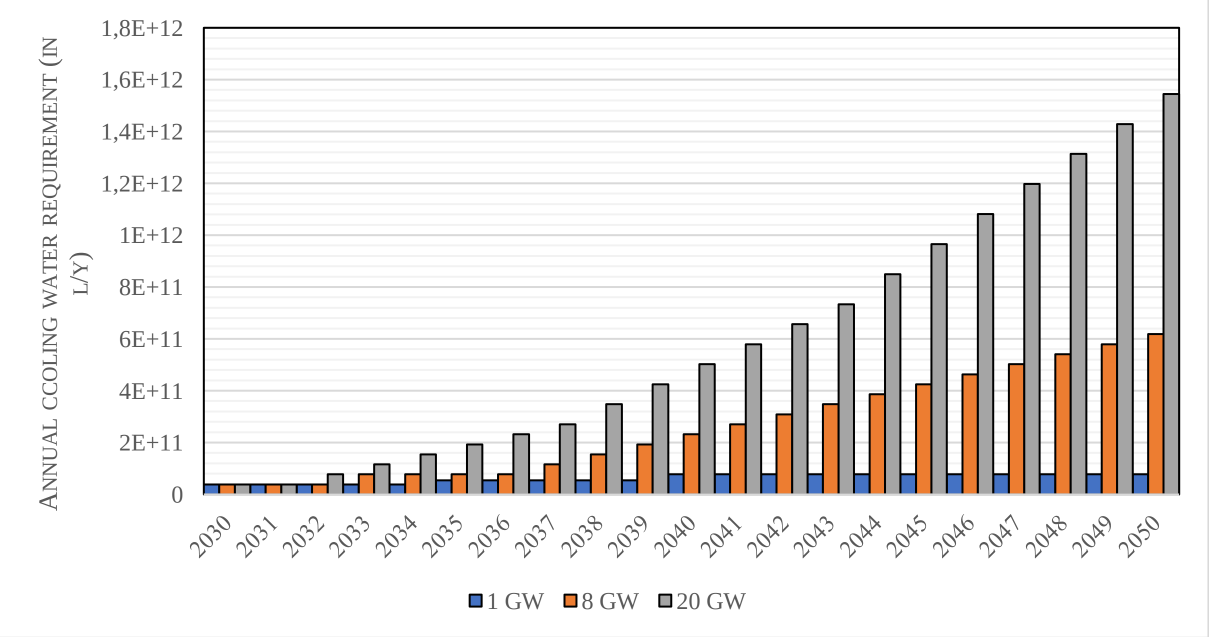

Figure 4B | The Annual cooling water requirements of offshore electrolysis.

This bar chart illustrates the annual requirements for cooling water used in electrolysis operations projected from the year 2030 to 2050. The y-axis indicates the volume of cooling water needed. measured in liters per year. with the scale reaching over three trillion liters annually by 2050. The x-axis displays the years across the forecast period. Three scenarios are depicted with different color-coded bars representing various levels of operation based on their capacity: 1 GW (blue). 8 GW (orange). and 20 GW (grey). Each bar shows the predicted cooling water requirement for the corresponding year and scenario. There is a noticeable increase in water usage over the years. with the most significant volumes associated with the 20 GW capacity scenario. This trend highlights the escalating demand for cooling water as electrolysis operations expand. underscoring the importance of water resource management in future green hydrogen production strategies.

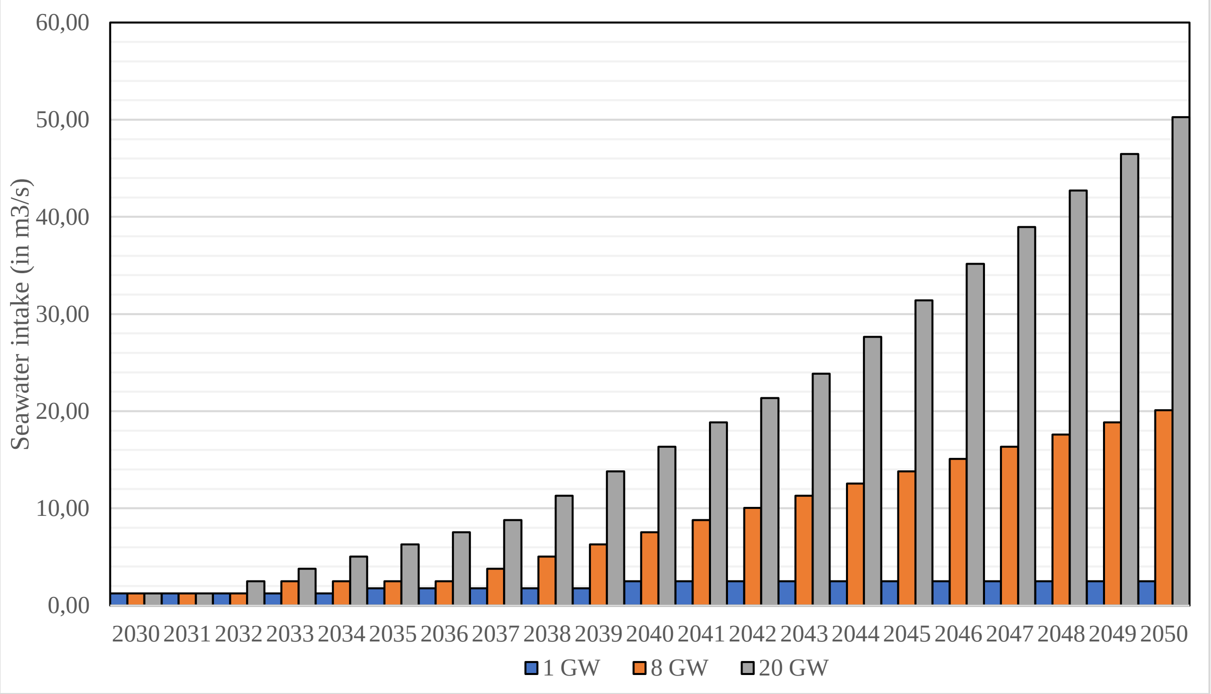

Figure 4C | The projected total seawater intake for offshore hydrogen production.
Figure 4C visualizes the projected total seawater intake required for electrolysis processes from 2030 to 2050. Seawater intake is measured in cubic meters per second and is displayed across three different electrolysis capacity scenarios: 1 GW (blue). 8 GW (orange). and 20 GW (grey). Each bar represents the volume of seawater intake per second for each year. with the bars progressively increasing in height. reflecting an upward trend in the demand for seawater as electrolysis capacity grows.

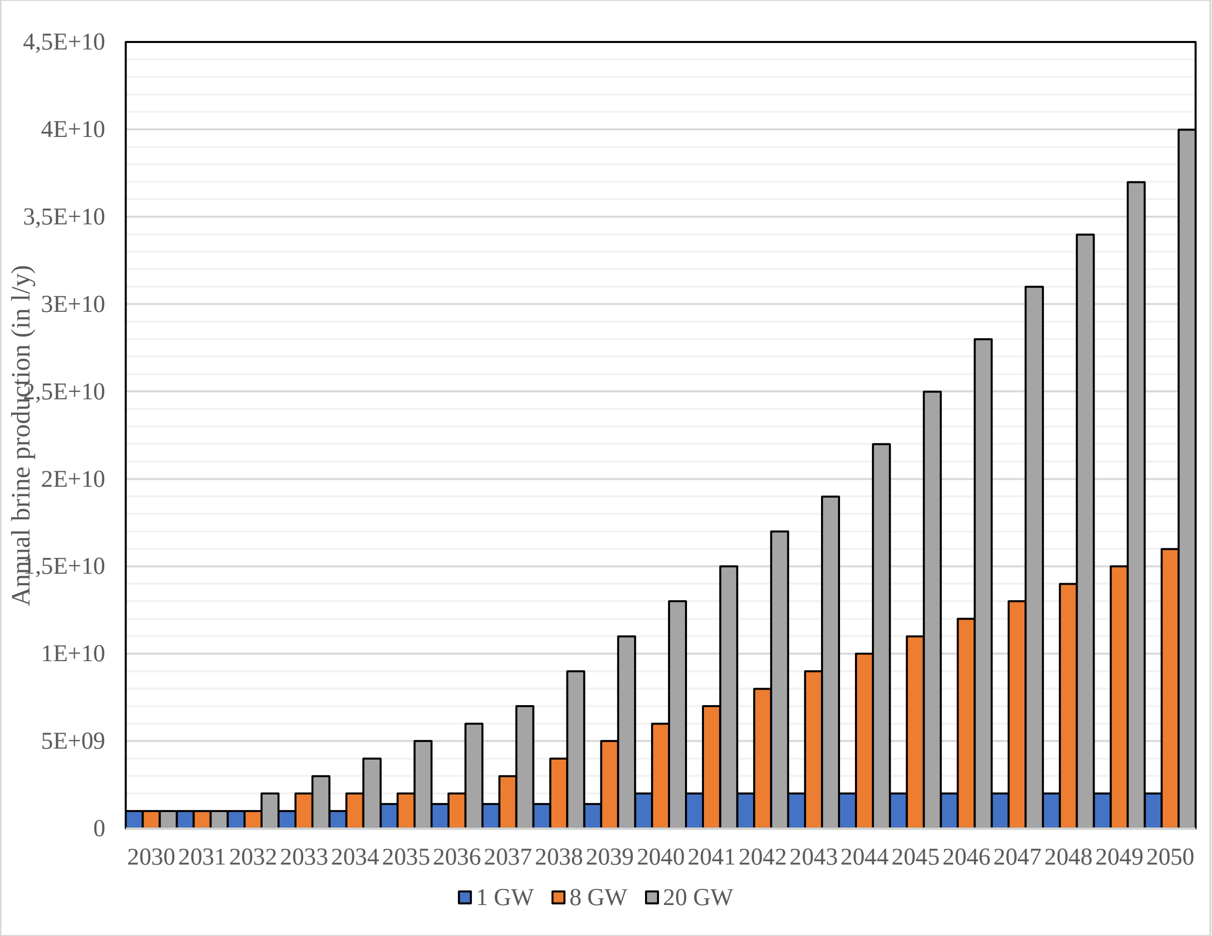

Figure 4D | The annual brine production of offshore green hydrogen operations.

The projected annual brine production from electrolysis operations over a period spanning from 2030 to 2050. Brine production is quantified in liters per year and is categorized into three scenarios based on electrolysis capacity. which are visually distinguished by color: 1 GW (blue). 8 GW (orange). and 20 GW (grey). Each bar represents the expected volume of brine produced per year.

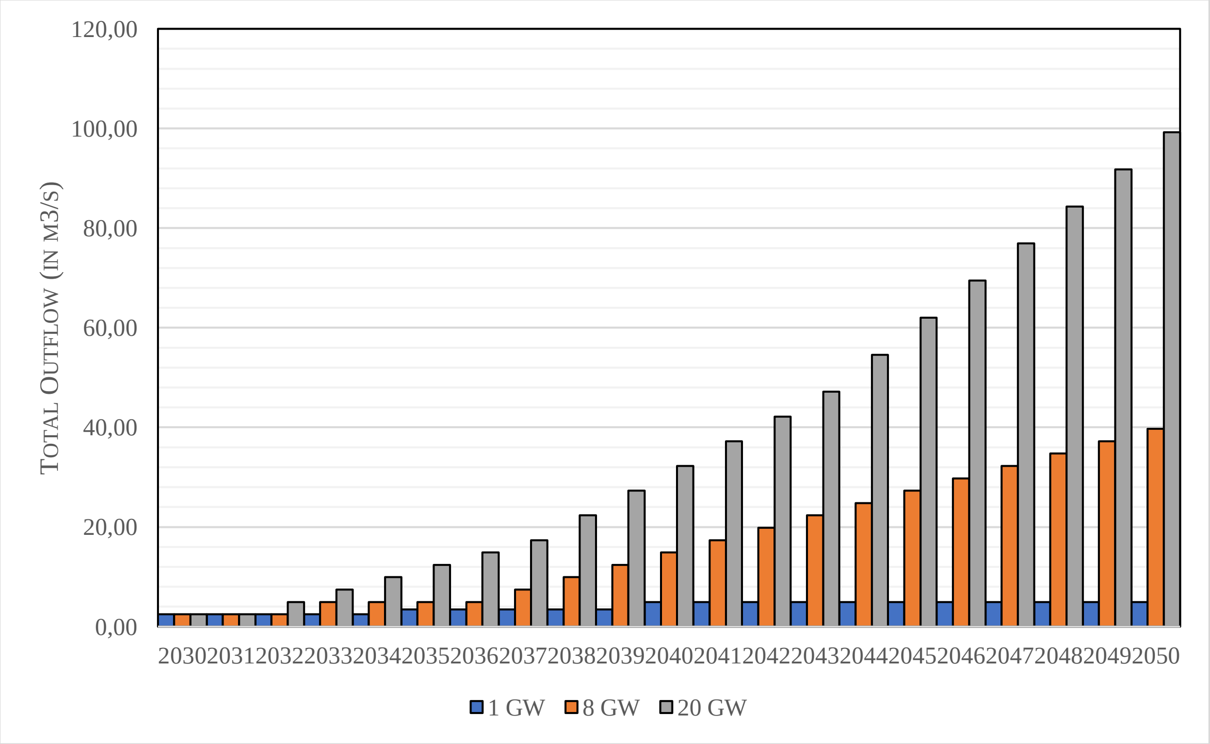

Figure 4E | The Projected total seawater intake for electrolysis capacity.

Figure 4E illustrates the projected total outflow rates of seawater after electrolysis. into the sea from 2030 to 2050. The y-axis measures the outflow in cubic meters per second. highlighting the volume of seawater that is discharged back into the marine environment. The x-axis is marked with the years across the forecasted period. The chart is segmented into three scenarios indicated by the colors: 1 GW (blue). 8 GW (orange). and 20 GW (grey).

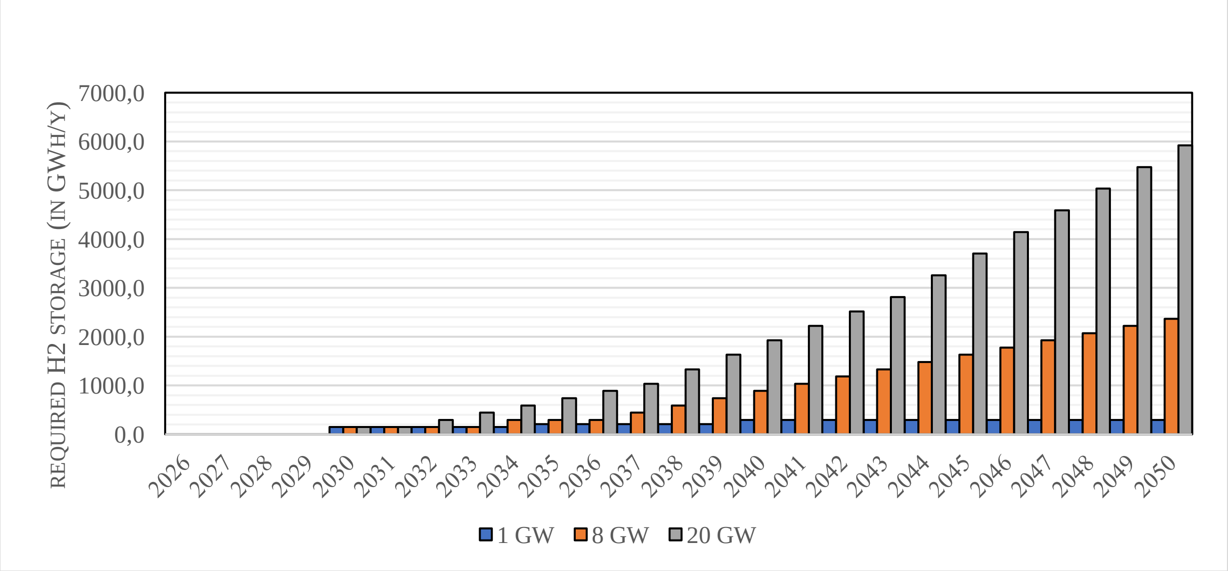

Figure 4F | Projected hydrogen storage requirements offshore (2026-2050).

Here the forecasted annual storage requirements for hydrogen in offshore salt caverns is presented for the projected period 2026 to 2050. Measured in gigawatt-hours per year (GWh/year). the y-axis tracks the volume of hydrogen that would need to be stored to meet the *demand. The x-axis denotes the consecutive years in the assessment period. The storage requirements are stratified by the potential capacity of hydrogen production: 1 GW (blue bars). 8 GW (orange bars). and 20 GW (grey bars).*

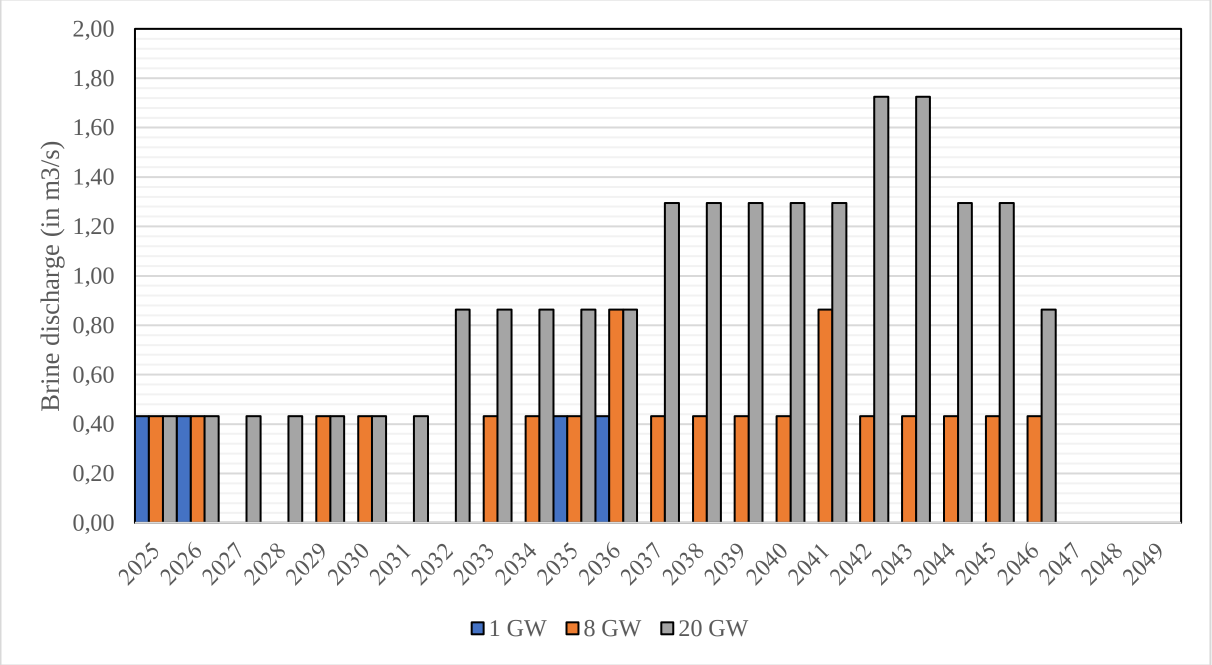

Figure 4G | The annual brine discharge from salt leaching for hydrogen storage facilities.

This figure depicts the projected brine discharge rates into the sea from hydrogen storage facilities over the years 2025 to 2049. The y-axis is scaled to measure the brine discharge rate in cubic meters per second. reflecting the continuous outflow of brine as a byproduct of the storage process. The x-axis categorizes the years during which the brine discharge is expected to occur. The discharge rates are presented for three different scenarios. each represented by distinct colors: 1 GW (blue). 8 GW (orange). and 20 GW (grey) capacities of hydrogen storage.

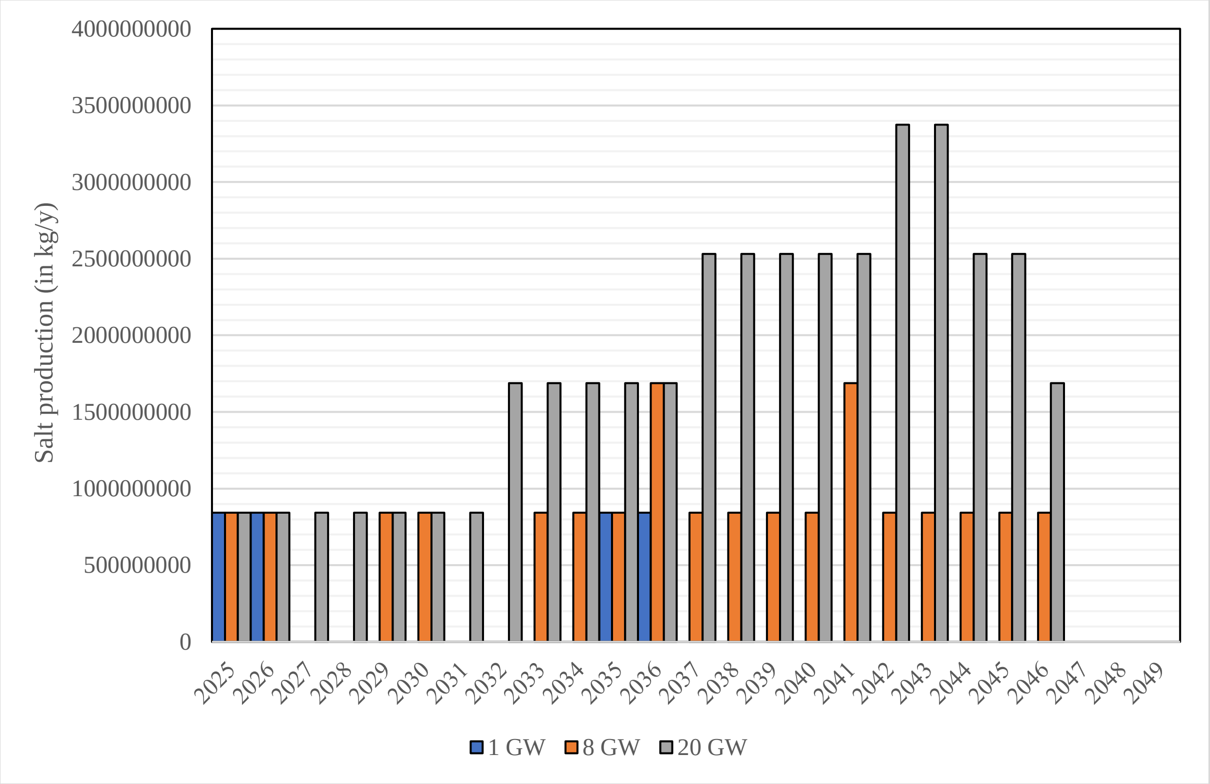

Figure 4H | The projected annual salt production from solution mining for salt caverns for offshore hydrogen storage. during 2025 to 2049.

This figure outlines the annual volume of salt produced through solution mining intended for the creation of offshore hydrogen storage caverns. from 2025 to 2049. The y-axis measures the total production of salt in cubic meters. demonstrating the scale of mining operations required to support hydrogen storage. The x-axis chronologically lists the years covered by the projection. Three scenarios are indicated by different colors. representing varying capacities of hydrogen storage facilities: 1 GW (blue). 8 GW (orange). and 20 GW (grey). Each bar corresponds to the amount of salt that is expected to be mined in each year for each scenario. The trend displayed by the bars shows an increasing volume of salt production over the years. particularly under the 20 GW scenario. which indicates the highest volumes of salt output.

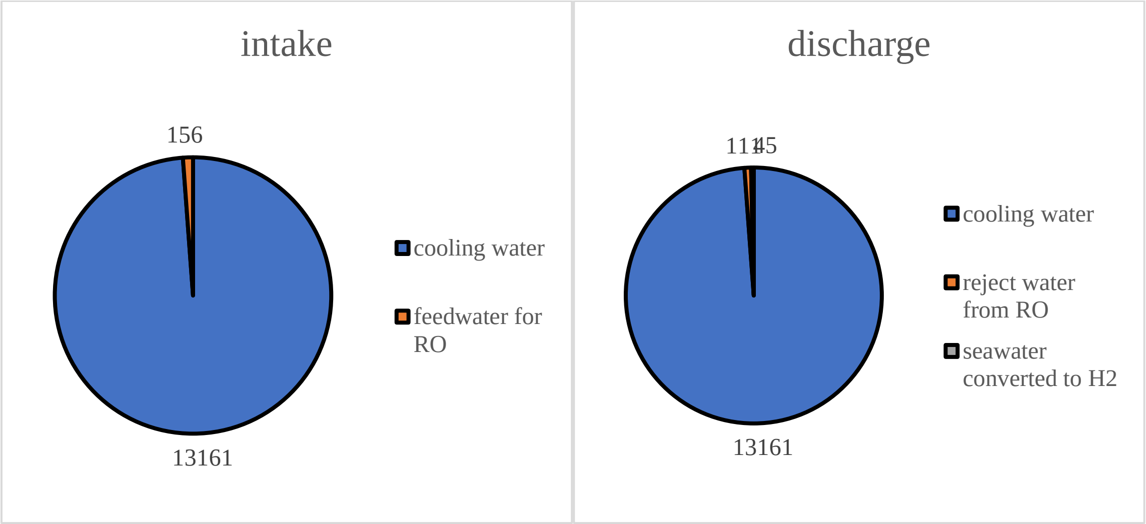

Figure 4I | The intake and discharge of seawater from a 500 MW electrolyser.
The left pie chart represents the distribution of seawater intake for a 500 MW electrolyser. The majority of the intake. denoted by the large blue segment. is used as cooling water. totaling 13.161 m3/h. The smaller orange segment represents feedwater for RO. with 559 m3/h.

The right pie chart illustrates the proportions of seawater discharge from a 500 MW electrolyser. The dominant blue segment shows the volume of cooling water discharged. marked as 13.161 m3/h. The orange slice represents reject water from RO. totaling 111 m3/h. The grey part is the seawater that is converted to hydrogen. which occurs at an average rate of 45 m3/h.