GreeN-H2 Namibia

Feasibility Study for Green Hydrogen in Namibia

Report on desalination, brine treatment options, disposal options and its potential impacts on maritime life

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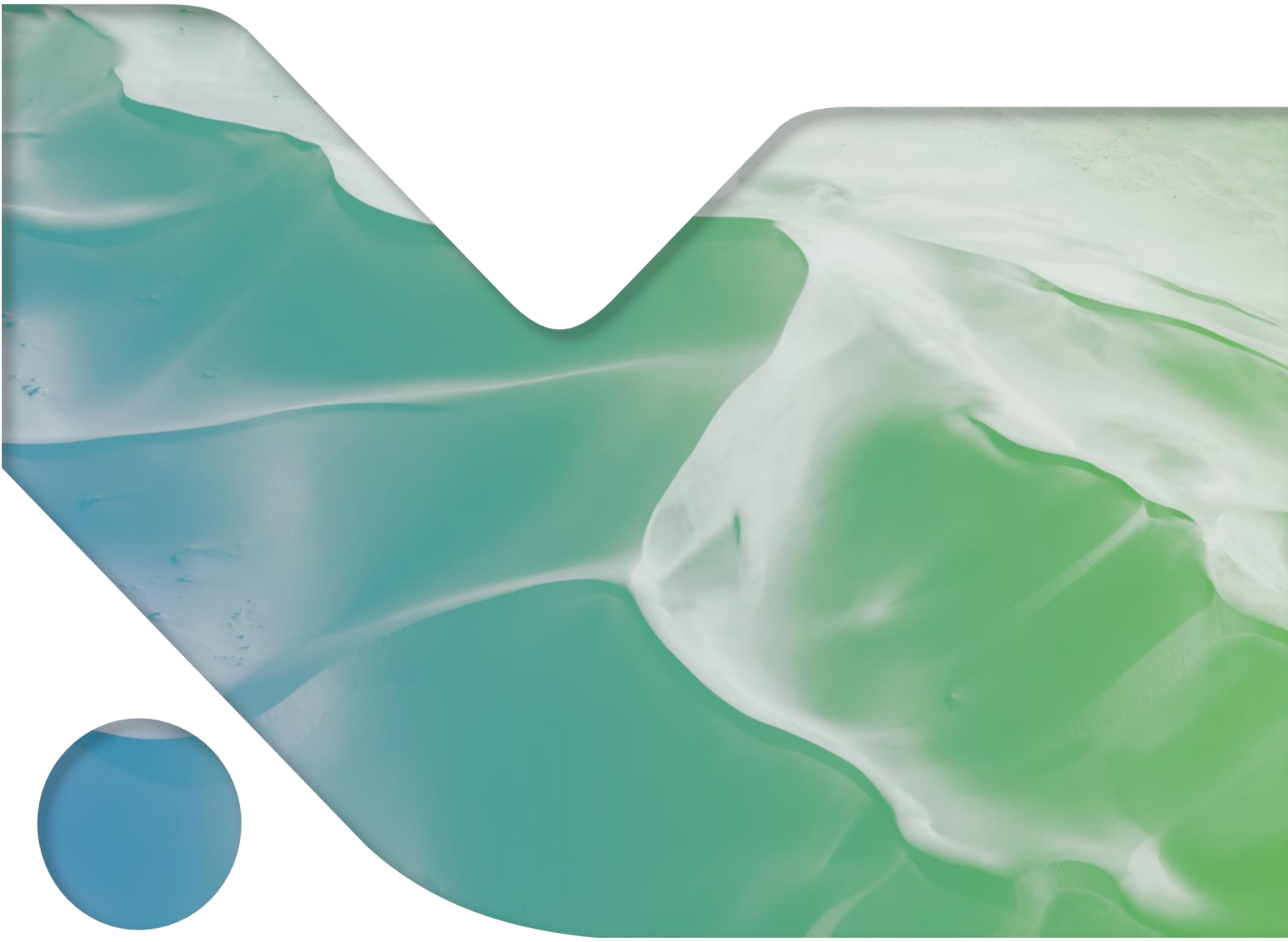

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Scope of the project GreeN-H2-Namibia

The GreeN-H2 Namibia project aims to provide important facts on Green Hydrogen and Power-to-X materials production in Namibia. The results of the project are addressed to all stakeholders operating in and with Namibia and to the government, which can use them to implement its strategy.

The GreeN-H2 project is intended to mediate between the various state-supported and private-sector initiatives, as well as to answer fundamental questions such as: what infrastructure is needed to ramp up the Hydrogen economy, what potential can be exploited at which locations and how can this development be established as a sustainable economic factor for Namibia.

The project addresses the following overall objectives:

- Recommendation and development of a concept for socio-economic, technical and environmental benefits of Green Hydrogen implementation in Namibia
- Identification of desirable and sustainable future target scenarios of Green Hydrogen production, processing and distribution in Namibia
- Identification of transformation pathways to achieve the target scenarios considering transformation barriers as well as social and ecological vulnerabilities
- Assessment of institutional capacities, cooperation structures and enabling environments for PtX applications regarding transformation requirements
- Define markets and financial attractiveness for a successful implementation of a Green Hydrogen production in Namibia

Structure of the consortium

DECHEMA is an interdisciplinary society with more than 5,800 personal and institutional members (including about 500 small and medium sized enterprises (SMEs), whose activities cover wide areas relevant to the process industries. DECHEMA is dedicated to the implementation of innovations in various fields of chemical engineering, environmental protection (esp. water management) and biotechnology. DECHEMA's work is supported by close to 100 working groups and technical committees covering experts from academia, industry and the public sector and including authorities. DECHEMA is co-organiser of the International Exhibition-Congress on Chemical Engineering, Environmental Protection and Biotechnology (ACHEMA – 3,800 exhibitors, 160,000 visitors) and of around 50 conferences with over 10,000 participants per year.

The ISOE - Institute for Social-Ecological Research is one of the leading independent institutes for sustainability research, especially in the water sector. The research unit Water Infrastructure and Risk Analyses (Dr.-Ing. Martin Zimmermann) has already dealt in different national and international projects with questions of the water management and the accompaniment of socio-ecological transformation and innovation processes. The ISOE can draw on many years of experience in the integration of actors from science and practice for the transdisciplinary integration of different bodies of knowledge, especially in an international context.

Key findings of the report on desalination and brine treatment

In order to capture important information from the report, the key information have been compiled below. Strengths, weaknesses, opportunities, and risks should hereby not be understood as positive or negative assessments. In the eyes of the authors, it is important that attempts are and will be made to minimize the weaknesses and risks and to maximize the strengths and opportunities for a successful and sustainable Green Hydrogen Industry in Namibia.

Observations
• The Green Hydrogen Industry, as envisioned in the Namibian Green Hydrogen Strategy, will have an additionally large water demand in comparison to the current water demand of Namibia. • Groundwater as the single water source can be a suitable option for the early stages, yet does not seem to be suitable to supply the planned Green Hydrogen Industry. • Seawater conditions at the coast of Namibia divide from existing, better investigated desalination regions, such as the Mediterranean Sea or the Arabian Gulf, however, the following observations are valid nonetheless: ○ The production of brine is inevitable, if desalination is used. ○ Brine discharge into the ocean seems to be the economically cheapest option for brine treatment. Globally it is the most used treatment option to date. ○ In terms of operational costs and energy consumption of the overall hydrogen production chain, the impact of desalination and brine treatment seems to be low. ○ Infrastructure for seawater desalination and brine treatment needs to be build and maintained properly.

Strength	**Weaknesses**
• Seawater desalination is a stable solution to supply the Green Hydrogen Industry with the water needed. • Natural water resources and current water supply systems will not be additionally stressed by the Green Hydrogen Industry. • No competition for water sources between urban water supply and emerging industry. • Current EIA´s of other desalination projects in Namibia see low to very low environmental impacts of brine discharge.	• Regional impacts at the brine discharge points are to be expected. Direct impacts need a clearer investigation in location-specific EIA´s. • There is currently no EIA overlooking the overall coastal impact of all potential brine discharged at several locations along the coast. A strategic EIA for impacted regions seems to be helpful. • Natural occurring phenomena like H_2S plumes can be hindering and harmful for the environment, as well as the desalination process.
Opportunities	**Risks**
• Supplying the affected regions with water from the seawater desalination plants seems to make sense from a socio-economic perspective, as long as suitable distribution plans can be made for affected stakeholders and responsible entities. • The treatment or usage of brine could start secondary markets, such as recovery of valuable minerals, salt production or aquaculture.	• Local impacts at the brine discharge points are to be expected: Physicochemical effects have the potential to negatively affect the area around the discharge points. Continuous and thorough monitoring is suggested. • Further treatment and usage options of brine are more energy and cost intensive. A more detailed investigation would be needed in order to state the feasibility.

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List of abbreviations

Abbreviation	Meaning
AEM	Alkaline water electrolysis
BW	brackish water
CAPEX	Capital Expenditure, referring to investment costs
Chl-a	Chlorophyll-a
DI water	Deionized water
EAF	Ecosystem Approach to Fisheries
EC	Electrical Conductivity
ED	Electrodialysis
EDR	Electrodialysis reverse
EIA	Environmental Impact Assessment
FO	Forward Osmosis
GW	groundwater
H_2	Hydrogen
H_2S	Hydrogen Sulfide
HTE	High-temperature electrolysis
ISOE	Institute for Social-Ecological Research Ltd.
(LOW)	Low Oxygen water
MD	Membrane Distillation
MED	Multi-Effect Distillation
MLD	Minimal Liquid Discharge
MSF	Multi-Stage Flash Distillation
MSP	Marine Special Planning in Namibia
N	Nitrogen, nutrient for biological growth
NASAP2	Namibia’s Second National Biodiversity Strategy and Action Plan
OPEX	Operational Expenditures, referring to recurring costs for the operation of a plant
P	Phosphorus, nutrient for biological growth
PEM	Polymer electrolyte membrane electrolysis
pH	Potential of Hydrogen, scale used to specify the acidity or basicity of an aqueous solution
PtX	Power-to-X, Concept for the conversion and storage of electricity into energy carriers
RO	Reverse osmosis
SEC	Specific energy consumption
SEOC	Solid Oxide Electrolyser Cell
SW	seawater
SME	Small and Medium-sized Enterprises
TDS	Total Dissolved Solids, also referred to as salinity
WW	wastewater
ZLD	Zero Liquid Discharge

Versions and Contribution History

This report was prepared within the project GreeN-H2-Namibia and is part of work package 2 “technical aspects”. The project is funded by the German Federal Ministry of Education and Research.

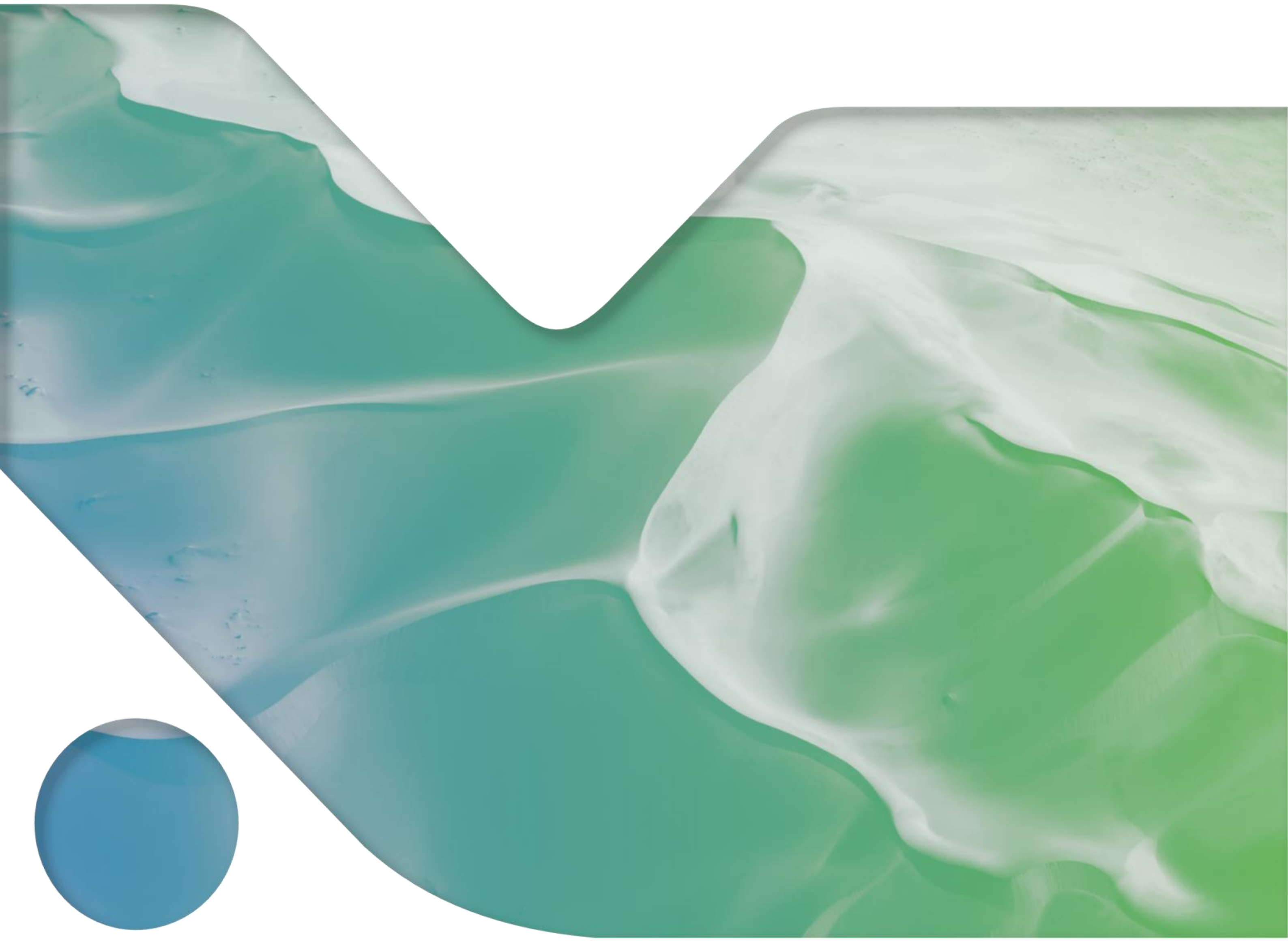
The report has been developed as a desk study and is based on public information, research by DECHEMA e.V. and substantive feedback from stakeholders in the water and Green Hydrogen Industries in Namibia. The report is meant to be publicly available. The authors reserve the right to publish an updated version of the report if there are any significant differences between the information provided and the situation at hand.

An overview of the versions of the document, as well as contributors, can be found below:

Version	Date	Modified by	Reasons for modification
V0	February 2023	Robert Schmidt, Dr. Daniel Frank	1st Draft
	February 2023	Luisa Lopez, Dr. Robin Ruff	Internal Review
Draft Version	March 2023	Robert Schmidt	2nd Draft
	May 2023	Robert Schmidt	Presentation of preliminary results and receiving external feedback (Germany)
	June 2023	Dr. Daniel Frank	Presentation of preliminary results and receiving external feedback (Namibia)
Public Version	September 2023	Robert Schmidt, Dr. Daniel Frank	3rd Draft, Implementing updated results and external feedback

This document is intended as an initial overview on the topic of desalination for the Green Hydrogen industry in Namibia. It is planned that follow-up reports on the regions //Kharas, Erongo and Kunene will follow, which will take a more detailed look at the situation present and potential impacts in the regions. Further reports and factsheets on the topics of energy supply, infrastructure needs, and socio-ecological aspects are planned within the project GreeN-H2-Namibia.

1 Introduction



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Possessing ideal conditions for the generation of wind and solar power, Namibia is well-suited for the production of Green Hydrogen, an important solution in achieving net-zero emissions. In Namibia, less wind, and solar capacity would be required for the same level of output. Further, due to the country's low population density and moderate population growth, Namibia will be able to meet its own demand for renewable energy and Green Hydrogen fast and therefore quickly reach the export threshold. According to Namibian authorities, Namibia intends to export Green Hydrogen as early as 2025.

Namibia is however the most arid country in sub-Saharan Africa and consequently, the production of hydrogen, which requires large amounts of water, will rely on seawater desalination. Previous analyses have shown that desalination only has a minor effect on the price of hydrogen as it accounts for only about 1% of production costs. When implementing the production of hydrogen, economic, social and environmental impacts need to be considered.

President Hage Geingob said Namibia wants to be the first African country to achieve carbon neutrality and utilise the African Continental Free Trade Area (AfCFTA) to export clean hydrogen energy to its neighbours and abroad. Namibia aspires to create an at-scale green fuels industry with a production target of 10 – 12 million t/a hydrogen equivalent by 2050. To this end, it will develop three hydrogen valleys: in the southern region of //Kharas, the central region including Walvis Bay port and the capital Windhoek, and the northern region of Kunene [1].

Presidential advisor James Mnyupe said that the project could attract over a billion dollars in potential investments. "Of course, people look at Green Hydrogen as a 'project', but it is simply an initiative to create an avenue for synthetic energy in the future for Namibia. It is a project with huge potential for the country and can create much-needed jobs and economic benefits," he said. He added: "it is an innovative initiative the government has embarked on by researching global trends, engaging in hydrogen diplomacy, and considering what attracts foreign direct investment." [2]

At such a scale (assumingly 120 GW of electrolysers), Namibia's entire energy sector would not only be fully decarbonised but could also support the efficient decarbonisation of other regions with lower renewables potential. The Green Hydrogen economy in Namibia is therefore full of opportunities but also associated with risks, e.g. related to ecological impacts, water scarcity, water-related conflicts, and social vulnerabilities. For this reason, it is relevant that projects include not only technical possibilities, but also address risks, possible red lines and knockout criteria as well as capacity deployment requirements in the whole country.

Hydrogen production and desalination

The production of 1 kg of hydrogen through water electrolysis requires 9-14.5 kg of deionized water (DI water). A 1 GW hydrogen production plant with an estimated efficiency of 55 kWh/kg hydrogen, while producing 18 t of hydrogen per hour, requires 162-261 m^3 of water per hour, depending on the water source and the treatment technology. This hydrogen plant would require between 1.576 and 2.44 million m^3 of DI water per year. This value does not include water treatment losses and water requirements on the production of additional Power-to-X (PtX) processes like methane, methanol and ammonia production. Hydrogen production will therefore be a global competitor for future water demand.

Current available electrolyser technologies on an industrial scale (AEC, PEM, SOEC, AEM) and prototypes (HTE) require highly desalinated water. This also applies for the PtX processes, as for the cooling and heating cycles. The salinity of water can be described either by the number of dissolved salts or by the conductivity. Both parameters increase with increasing salt concentration. The required conductivity for most water electrolysers is very low (<10 µS/cm).

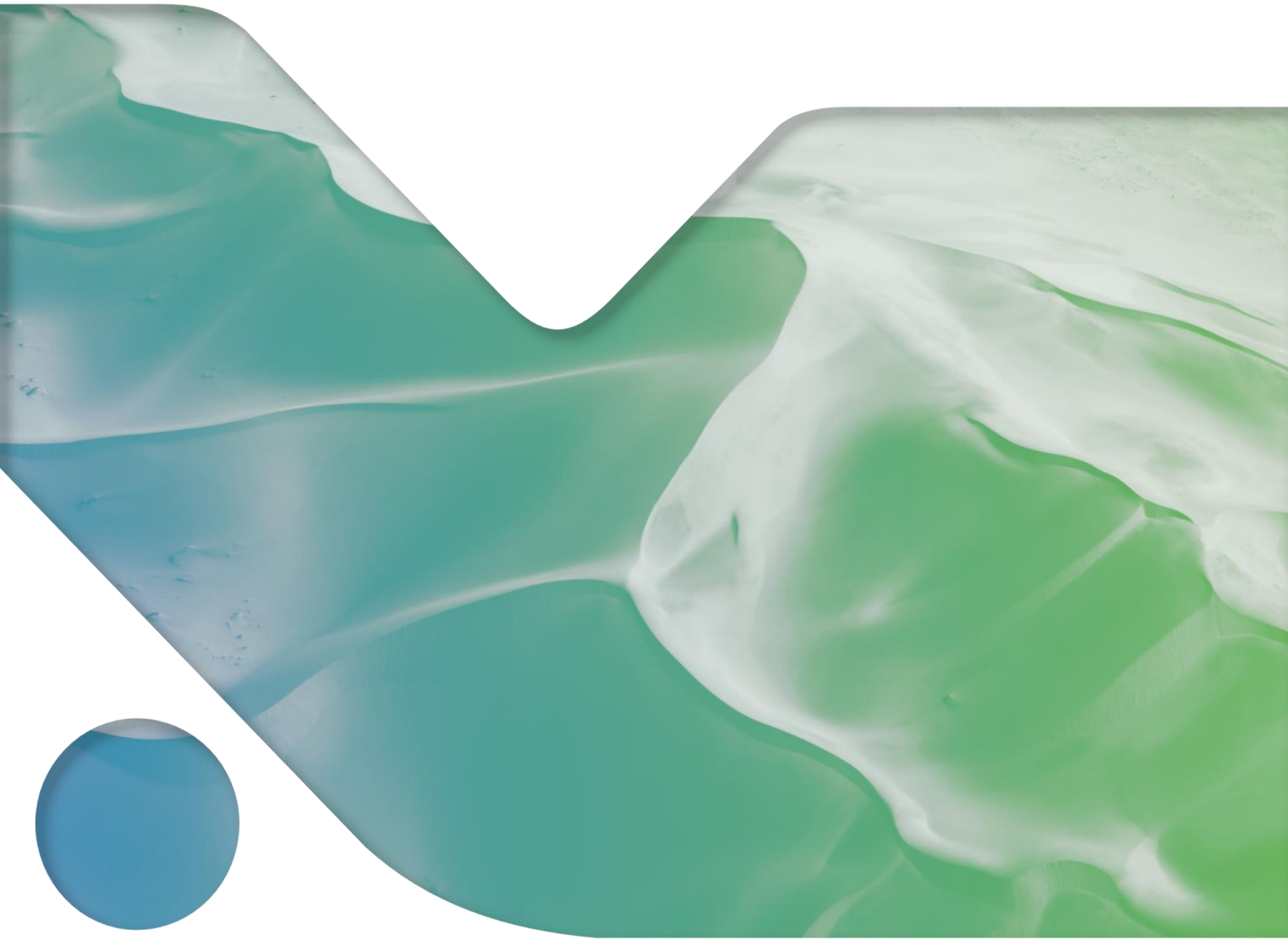
Groundwater, with the lowest conductivity (50-700 µS/cm), is the most favourable water source when it comes to water treatment. Because the concentration of dissolved solids is low, the treatment costs are comparably small. However, groundwater is a limited and a highly vulnerable source, with varying availability around the world. Drinking water is already pre-treated and has a conductivity around 300-800 µS/cm. Sea water instead has the highest salinity with up to 3.4-3.7% (5,000 S/cm) and should only be used when no other sources are accessible – as is the case for Namibia. The big advantage of seawater is the nearly infinite availability. However, the desalination process itself – without any pre- or post-treatment – produces a highly concentrated brine solution, which is oftentimes discharged into the sea.

Objective of this report

This report outlines the potential influence of brine on the maritime life and fishing areas along the coastline of Namibia under the assumption of different stages of Green Hydrogen production development. It will introduce desalination as a well-known technology and highlight the coastal system in Namibia, including its currents and fishing areas. The majority of this report will focus on brine discharge and its potential impact, but brine treatment and recovery strategies for salts and metals from the brine are also addressed.

It is important to note that this report does not claim to be or replace an environmental impact assessment (EIA). For the planning of a production facility where environmental impacts are expected, EIAs must be conducted for the specific facility and site conditions. This report is intended to provide an outlook on potential issues related to desalination and the resulting brine discharge as well as possible alternatives in the context of the Green Hydrogen Industry in Namibia.

2 Overview of seawater desalination



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Desalination offers a solution to meet the increasing demand for deionized (DI) water, which is especially interesting in regions where water resources are scarce. **An increase in the amount of desalination plants can be seen globally, desalination plants can provide a stable water supply for communities and industries.** This chapter will address the issue of seawater desalination and presents the technologies used, the resulting brine and brine characteristics, and the expected impact of desalination on Namibia's water situation.

2.1 Desalination technologies

Seawater desalination was first introduced in the 1960s, with thermal desalination processes dominant in the market until 2000. Starting around that time, membrane-based technologies, especially reverse osmosis (RO) started to take over the market of newly build desalination plants. [3]

Technology options for desalination are classically divided into thermal, mechanical/membrane or electrically driven processes. The distinction refers to the forms of energy required for the process.

In thermally driven processes, water is evaporated via temperature gradients and DI water can be obtained via the resulting condensate. Thermally driven processes for seawater desalination are mostly multi-stage flash (MSF), multi-effect distillation (MED) or membrane distillation (MD).

Mechanical driven processes mostly refer to membrane driven processes, which for seawater desalination mainly include reverse osmosis (RO), and in parts forward osmosis (FO) and nanofiltration (NF). In membrane-driven processes, water is passed over a membrane and removed from the raw water using differences in osmotic pressure. For RO, a pressure is built up on the raw water side that exceeds the osmotic pressure, forcing the water through a membrane, but preventing the passage of impurities. RO processes are traditionally further differentiated according to the raw water sources used, with seawater desalination being referred to as seawater reverse osmosis (SWRO).

Electrically driven processes, such as electrodialysis (ED) and electrodialysis reversed (EDR), use an electric field to pass charged particles through cation or anion exchange membranes and thus removing them from the feedwater stream.

In addition to the individual processes, there are also process combinations, known as hybrid processes. Here, an initial treatment is usually carried out using a membrane-driven process, mostly RO, and in a second step another technology with a higher salinity limit is used. These process combinations can reduce energy and resource costs and produce more DI water.

An overview of important key parameters for the market-leading technologies RO, MSF, MED and ED can be seen in Table 1. The data serve as orientation values and is strongly dependent on the existing framework conditions of a plant, which means that they may vary for each built plant. The table shows values for:

- Recovery rate, which is the percentage of freshwater reclaimed from the raw water source
- Specific energy consumption (SEC), which is the energy needed to treat 1 m^3 of raw water
- OPEX, which is the costs needed for 1 m^3 of treated raw water
- Salinity limit, which gives an approximated value for the salinity to which the raw water can be concentrated

Table 1: Orientation values for key desalination technologies reverse osmosis (RO), multi-stage flash (MSF), multi-effect distillation (MED), electrodialysis (ED) and membrane distillation (MD) [4], [5]

	Recovery rate [%]	**SEC [kWh/m³]**	**OPEX [US$/m³]**	**salinity limits [mg/L]**	**technology readiness**
RO	0.42	2-6	0.75	< 70,000	commercially available and market leading
MSF	0.22	15.5-24	1.4	< 180,000	commercially available
MED	0.25	7.7-21	1.1	< 180,000	commercially available
ED	0.86	7-15	0.85	< 200,000	commercially available
MD	0.9	39-67	1.17	< 350,000	emerging technology

For all desalination processes, pre- and post-treatment of the water is required to achieve conditions in which the raw water can be desalinated well and remains stable in the downstream process. Pre-treatment may include steps such as screening, coagulation & flocculation, filtration by ultrafiltration or nanofiltration, addition of chemicals for antifouling, anti-scaling and dechlorination, as well as heating or cooling of the raw water.[6] The post-treatment processes vary depending on the intended use of the water. Mineralization, hardening by addition of lime, addition of corrosion inhibitors, removal of boron, pH adjustment and disinfection may occur.[7] After desalination, two liquid streams are obtained. The treated water stream is called permeate and is adapted to the intended use by post-treatment. After post-treatment, the permeate can be used as DI water for industrial processes or as freshwater for human consumption. For the use of the permeate in electrolysis, a further desalination step is usually carried out to achieve the required water qualities and is further referred to as DI water in this report. The separated stream with the remaining impurities is called concentrate and subsequently brine. [8]

Figure 1 shows a schematic overview of how much water is required to obtain 1 kg of Green Hydrogen via RO desalination.

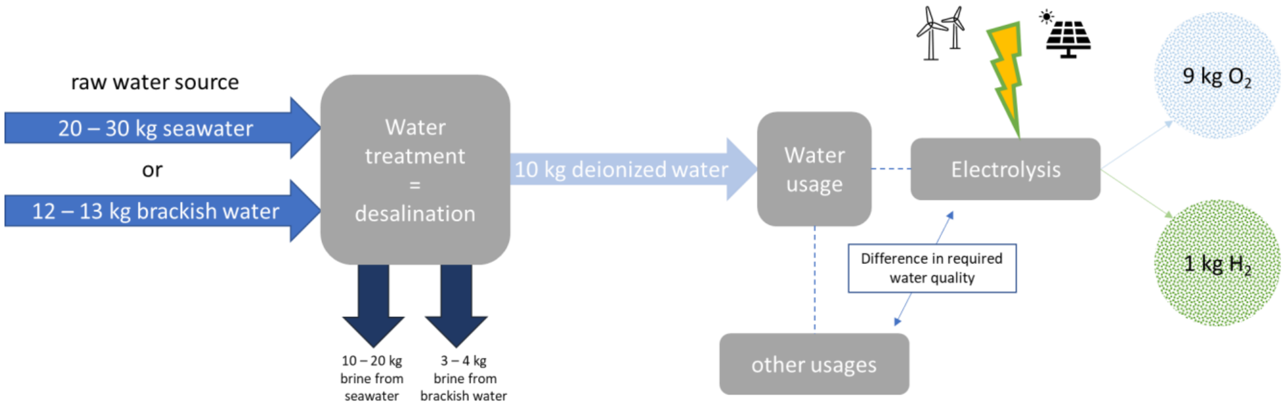


Figure 1: Overview of water consumption for electrolysis, based on DVGW, 2023 [9]

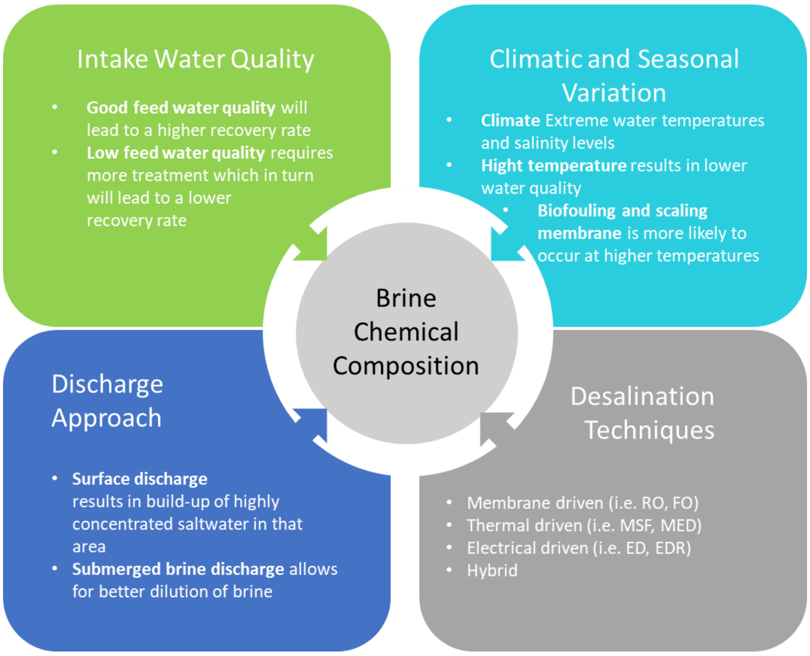
RO is currently the leading technology for newly build desalination plants because it represents a very robust and stable process, requires less cost and energy per volumetric unit of deionized water, as seen in Table 1, and is easy to operate. However, extensive pre- and post-treatment must take place, which includes the removal of particulate matter and the addition of chemicals for pH adjustment and protection against fouling, scaling, corrosion and stabilizing water conditions after desalination. The majority of today´s desalination plants, about 69%, is expected to be operated with RO desalination and also the majority, about 61%, use seawater as a raw water source. [4]

During the desalination of raw water, brine is inevitably produced as a waste stream. A desalination with 100% efficacy via various desalination and crystallization steps is a theoretical approach, as it is very energy and therefore cost-intensive. The amount of brine produced is directly related to the recovery rate. For raw water sources with lower salinity like brackish water or groundwater, for example, a recovery rate of about 90% can be achieved, which means that the amount of brine can be kept very small. For raw waters with a high salinity, such as seawater, about 30 to 50% can be recovered in standard operation, resulting in a large amount of brine with high contents of Total Dissolved Solids (TDS), also called salinity.

Jonas et al. calculated that a volume of 95.37 million m³/d of desalinated water will be produced globally through desalination plants and a brine volume of 141.5 million m³/d will be generated as a by-product. In a global comparison the Sub-Saharan Africa region produced in 2018 the least amount of desalinated water, 1.78 million m³/d (about 1.9%), and brine, 1.5 million m³/d (about 1%) according to the report.

2.2 Characteristics of desalination brine

The properties of brine can be highly dependent on the conditions present. The main influencing variables are the water quality of the raw water source, the selection of the desalination technology, the selection of the discharge variant, as well as seasonal and climatic influences (Figure 2).



Intake Water Quality

- **Good feed water quality** will lead to a higher recovery rate
- **Low feed water quality** requires more treatment which in turn will lead to a lower recovery rate

Climatic and Seasonal Variation

- **Climate** Extreme water temperatures and salinity levels
- **Hight temperature** results in lower water quality
  - **Biofouling and scaling membrane** is more likely to occur at higher temperatures

Brine Chemical Composition

Discharge Approach

- **Surface discharge** results in build-up of highly concentrated saltwater in that area
- **Submerged brine discharge** allows for better dilution of brine

Desalination Techniques

- Membrane driven (i.e. RO, FO)
- Thermal driven (i.e. MSF, MED)
- Electrical driven (i.e. ED, EDR)
- Hybrid

Figure 2: Influences on the physiochemical characteristics of discharged brine, recreated from Omerspahic et al., 2022 [10]

This report focusses on seawater desalination and its produced brine. Water sources with lower salinity would mainly lead to better recovery rate and could avoid problems with scaling and fouling. However, this is only possible if alternative raw water sources are available in sufficient quantities, which is not the case for a fully developed Green Hydrogen production throughout Namibia. In addition to selecting a different raw water source, raw water quality can also be negatively influenced by a poorly planned or operated discharge management system. Care should be taken to ensure that the discharge point of brine does not allow indirect recirculation into the intake point, in case the brine is discharged into the same water body as the raw water source it is taken from. The selection of desalination technology is the largest influencing factor on the physiochemical properties of the brine. Brine from RO processes is defined primarily by higher salinity levels. It can have about 50% higher dissolved solids concentration than feed water, depending on the recovery rate of the desalination plant. Since RO is a separation process operated only by pressure, there is no significant increase in brine temperature during treatment compared to feed water. Membrane operated processes require more extensive pre-treatment steps then thermal or electrical processes to ensure a consistent and long-lasting process of the membranes. These include the addition of acids, chlorines, anti-scalants and anti-fouling agents, which are subsequently released into the environment via the brine. These agents are used, among other things, to adjust the pH of the raw water, limit biological growth in the plant, prevent scaling, and minimize or prevent corrosion damage.

As a result of added chemicals during pre-treatment, for thermal, membrane and electrically driven processes, the brine can have a different pH-value and higher concentrations of chlorides and heavy metals then ambient seawater. In contrast, brines usually have lower concentrations of dissolved oxygen and biodegradable organic matter. In the case of reduced organic matter, it is because screening is used as a pre-treatment, which filters particulate matter and some organic matter, such as plankton, out of the seawater. The concentration of dissolved oxygen decreases during water treatment [7]. If the oxygen depletion is too high and stress for the local aquatic ecosystem is expected at the point of discharge, the brine must be re-aerated as a post-treatment step.

In Table 2, an overview of brine characteristics and contaminations from treatment of seawater by reverse osmosis desalination is given.

Table 2: General characteristics of reverse osmosis brine from seawater desalination plants [11]

Parameters	**Details**
Physical characteristics	Salinity: above 55,000 mg/L of TDS; conductivity: 0.6 W/mK at 25 °C; temperature: ambient seawater; pH: 7–8.
Inorganic salts	Example: sodium chloride ($NaCl$), calcium chloride ($CaCl_2$), and magnesium chloride ($MgCl_2$) are the major constituents.
Metals caused by corrosion	Brine might have high levels of iron, chromium, nickel, and molybdenum if the facility uses low-quality stainless steel.
Nutrients	Ammonia, nitrate, and phosphorus.
Pretreatment chemicals	Antiscale additive (ethylenediaminetetraacetic acid: EDTA, sodium hexameta phosphate). Biofouling control additives such as chlorine (small quantities)—coagulants.
Halogenated organics	Trihalomethanes are common byproducts of chlorine addition (low content).
Cleaning chemicals	-Acidic solutions used to adjust the pH of the seawater. -Detergent such as EDTA, oxidants (sodium perborate) and biocides (formaldehyde) are used to clean the membrane.

The brine from thermal processes, such as MSF, MED or MD, is characterized by an increased salinity and an increased temperature. The temperature of the brine during discharge can be 1.37 to 1.82 times higher in thermal processes than in membrane processes. The salt content of brine from thermal processes is somewhat lower than that from membrane processes, since thermal processes need a lesser intensity of pre-treatment and therefore introduce less chemicals into the water. [10]

Lastly, climatic and seasonal conditions also have an influence on the desalination process and thus on the characteristics of the brine. Seasonal fluctuations in concentrations of various substances, salt content and temperature differences create varying conditions for the desalination process and need be considered on a case-by-case basis.

2.3 Seawater desalination plants operating in Namibia

So far there is a seawater desalination plant in Namibia, about 30 km north of Wlotzkasbaken. The Orano Desalination Plant, also known as the Erongo Desalination Plant, was built in 2010 by Orano Resources Namibia (then Areva Resources Namibia) and has been operated ever since. Potable water produced in this plant is sold to NamWater, which supplies the mines in the coastal region and the surrounding urban region with drinking water. 75% of the drinking water in the city of Swakopmund is obtained from the Orano desalination plant. [12] The plant has a current capacity of about 20 million m^3/a, meaning that approximately 20 million m^3/a freshwater can be produced for human and industrial uses. [12] The desalination plant includes the processes screen filtration, ultrafiltration, reverse osmosis, limestone contact and chlorination for potable water. The Orano Desalination plant has a seawater abstraction permit of up to 60 million m^3/a [13], whereby apparently only around 48 million m^3/a seawater is abstracted and around 31 million m^3/a brine is discharged into the ocean. [14]

In 2020, criticism was raised by mining companies that they were not supplied with enough water and as a result posted losses of around N$ 1.9 billion. This was attributed to elevated sulfur levels on the coast, which meant that the desalination plant had to be shut down in the meantime and could only be put into operation once the sulfur levels had normalized. [15]

This led to the approval for the construction of a second desalination plant at Swakopmund, location at Mile 6, with a capacity around roughly 25 million m^3/a in 2022. The desalination plant is intended to secure the water supply in the central coastal region, Windhoek and the en-route users. The desalination plant includes seawater intake screen filtration and seawater disinfection to protect the screens and the RO, a pre-treatment system with coagulation and dual media filters, a reverse osmosis system with energy recovery, a post-treatment system with mineralization (using carbon dioxide and limestone) and chlorination. The brine is discharged via pipes into the ocean. In the draft scoping report for the desalination plant (April 2021), a recovery rate of 35% was calculated, which leads to a seawater abstraction of about 71 million m^3/a and a brine discharge of about 46 million m^3/a to obtain a potable water volume of about 25 million m^3/a.

The construction of the second desalination plant also responded to the requirement of the Harambee Prosperity Plan II, in which a plant with a capacity of 30 – 50 million m^3/a was planned. This in combination with the increasing water demand of Namibia and neighboring countries, e.g. Botswana, could mean that further desalination plants for the production of water for human consumption have to be planned and built, or – that planned desalination plants for the Green Hydrogen economy need an even larger capacity.

No other desalination plants are currently being built in those dimensions. A small seawater desalination plant with a capacity of 3.5 m^3/h (approx. 30,000 m^3/a) on the Sam Nujoma campus of the University of Namibia (Unam) in Henties Bay was put into operation in May 2019 and supplies water for 400 olive trees. [16]. A desalination plant for the treatment of brackish water with a capacity of 487 m^3/d drinking water (about 178,000 m^3/a) was realized in Bethanie to provide drinking water for the community. [17]

Seawater desalination plants are also planned for Hydrogen production, but so far, very little information is available on their state of planning/realization: one plant is planned in Swakopmund and the DI water will be used directly for a PEM electrolyser. The desalination plant is planned within the HDF Energy Renewable Swakopmund Project. The capacity of the 2-stage RO plant will produce 200 m^3/d potable water (approx. 73,000 m^3/a) and will be supplied with electricity via an 85 MW solar system. Subsequently, the brine generated will be evaporated via the evaporation ponds of the Swakopmund Salt Works or alternatively discharged into the ocean. [14] Few valid information could be found about the desalination plant for the HYPHEN project, so the following estimations were made: the plant is supposed to be built near Lüderitz and the amount of water produced is to be used for the electrolysis of 350,000 t/a of Hydrogen. It is assumed that the HYPHEN project will require 4.375 million m^3/a of DI water, resulting in a seawater abstraction of about 10.9 million m^3/a and a brine discharge into the ocean of about 6.56 million m^3/a. If the HYPHEN project is successfully implemented, it can be assumed that the Green Hydrogen industry in Namibia will expand, which would require even more quantities of DI water.

When considering the use of further desalination plants in Namibia, it is important to bear in mind that a large part of the infrastructure for these plants will have to be newly built and conscientiously maintained.

2.4 Estimations for the impact of increased seawater desalination by the Green Hydrogen industry

It is difficult to predict accurately the exact impact of expanded seawater desalination on Namibia. In addition to the benefits of significantly increased freshwater volumes and the need for desalinated water for Green Hydrogen production, factors such as seawater abstraction, potential brine discharge, energy requirements, and economic factors need to be considered.

To obtain a general idea of the dimension, estimations were made for the potentially necessary desalination capacity for Green Hydrogen production via the HYPHEN project (SCENARIO 1). A second scenario was calculated with a Green Hydrogen production of 3,000,000 t/a, as aimed for the year 2035 by the Namibian Green Hydrogen Strategy (SCENARIO 2) and in order to estimate the impact of the currently planned target production for Green Hydrogen production by 2050, a third scenario was calculated with a Green Hydrogen production of 12,000,000 t/a (SCENARIO 3). Additionally, the necessary desalination capacity of desalination plants to produce water for human use was calculated in all scenarios. For scenario 1 the capacity for the currently planned 25 million m^3/a desalination plant was added and in scenario 2 and 3 the capacity was extended to 50 million m^3/a, as actually planned by the Harambee Prosperity Pan II until 2025. Results of the first estimations can be seen in Table 3.

In the following, the results of the estimates are compared with the figures for water demand, amounts of seawater abstraction and amounts of industrial effluents into the ocean in Namibia. These values were taken from public sources and may show deviations from the data available in the future.

Table 3: Results of the estimates from scenarios 1, 2 and 3

Scenario	Green H_2 production [t/a]	Desalination for hydrogen production			Desalination for human use		
		DI water produced [10^6 t/a]	Brine produced [10^6 t/a]	Seawater abstracted [10^6 t/a]	freshwater produced [10^6 t/a]	Brine produced [10^6 t/a]	Seawater abstracted [10^6 t/a]
1	350,000	4.38	6.56	10.94	25	37.5	62.5
2	3,000,000	37.5	56.25	93.75	50	75	125
3	12,000,000	150	225	375	50	75	125

An estimate of the Namibian water demand, values from the Integrated Water Resources Management plan for Namibia from 2010 [18] were used, which predicts the water demand of Namibia for different sectors for 2030. Additionally, the amount of DI water needed for the Green Hydrogen industry was added to the forecasted water demand, as it was not considered back in 2010.

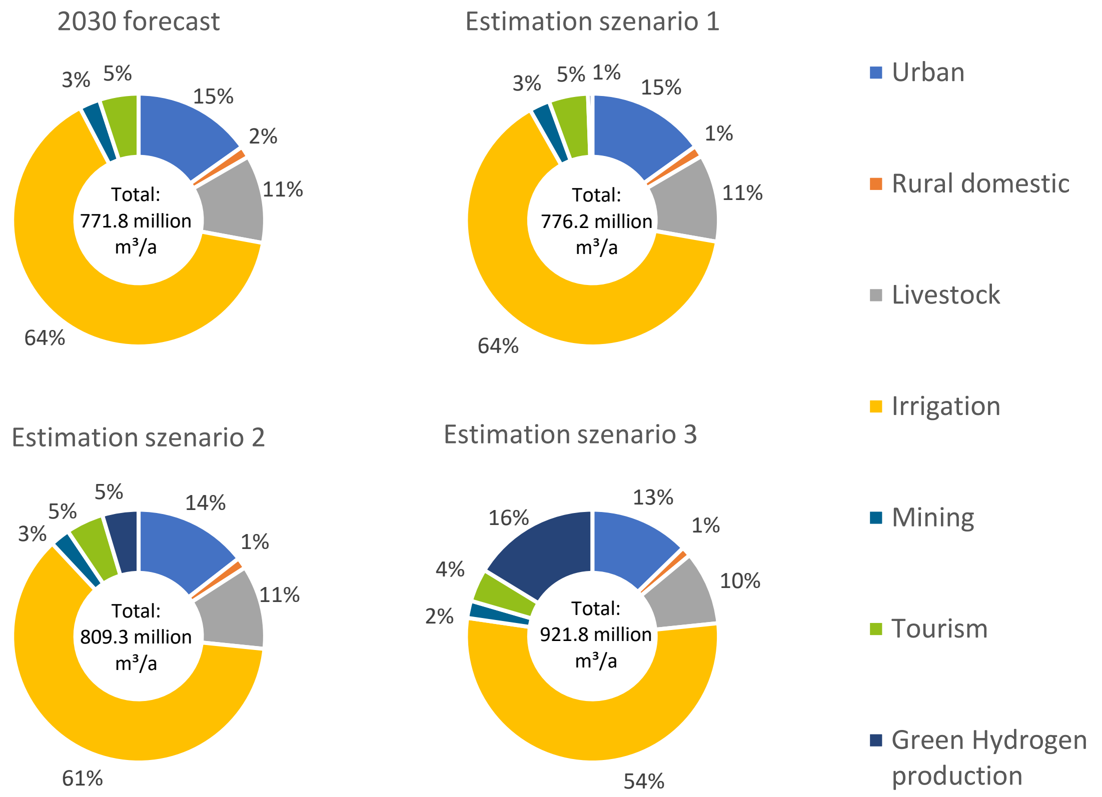


Figure 3: Water demand of Namibia forecast for 2030 in different scenarios. Top left: values forecast for 2030. Top right: Scenario 1; Bottom left: Scenario 2; Bottom right: Scenario 3.

For the year 2030, a total water demand of 771.8 million m³/a was predicted, of which 64% will be used for irrigation [18]. The DI water demand for the HYPHEN project was estimated to be about 4.375 million m³/a., resulting in a total water demand of 776.2 million m³/a. The water demand for the Hydrogen production would represent only 0.6% of Namibia's total water demand in Scenario 1. This leads to the assumption that **the water demand of the Green Hydrogen industry in the initial phase should not place a significant burden**

on the existing infrastructure and water supply, as long as the presented water demand for 2030 is met. However, the data basis is relatively vague and the demand is location-specific, which requires a specific analysis for the region concerned. In Scenario 2 the total water demand of Namibia would add up to 809.3 million m³/a with a demand of DI water for the Hydrogen production of 4.9%. For Scenario 3 the total water demand of Namibia would further increase to 921.8 million m³/a with a demand for the Hydrogen production of 19.4%, which represent 150 million m³/a of DI water. The calculations in Scenario 2 and 3 show that t**he water demand for the later stages of the Green Hydrogen Economy will play a significant role in Namibia's total water demand. It is further assumed that groundwater will not be sufficient for this water demand without creating a conflict of use with other users.**

Seawater abstraction and the discharge of industrial effluents into the sea were taken into consideration. Values for the current conditions were taken from the Marine Spatial Plan (MSP) and from the calculation results mentioned above.

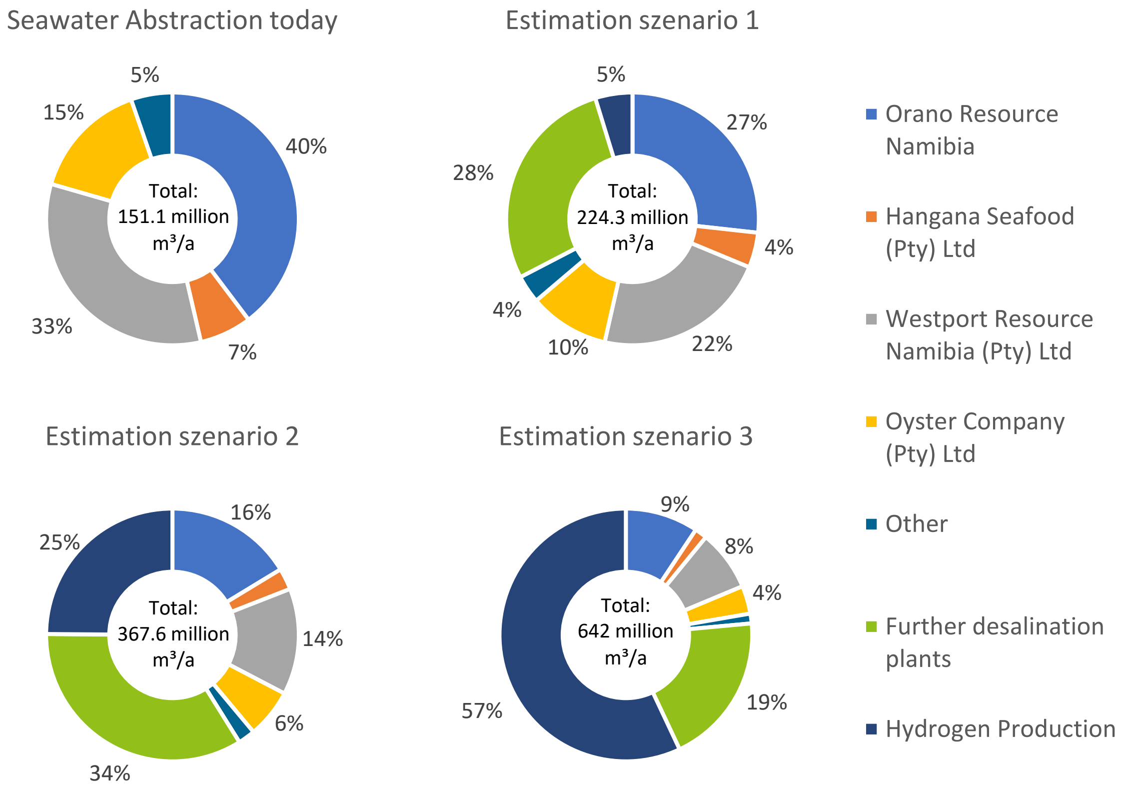


Figure 4: Seawater abstraction in different scenarios. Top left: values today; Top right: Scenario 1; Bottom left: Scenario 2; Bottom right: Scenario 3

Figure 4 shows the seawater abstraction along the entire coast of Namibia. An abstraction quantity of 151.1 million m³/a is currently permitted, with the largest amount, approximately 40% of the total being withdrawn by Orano Resource Namibia, and the second largest amount, approximately 33% by Westport Resource Namibia (Pty) Ltd, also operating a seawater desalination plant. [13] Companies with a seawater abstraction permit of less than 10 million m³/a were included in Figure 4 as others. The estimations in Scenario 1 show a required increase in seawater abstraction of around 73.2 million m³/a to 224.3 million m³/a, whereby the abstraction for Green Hydrogen production would then account for 5% and the seawater abstraction for further desalination plants would account for 28% of the total amount. The currently permitted amounts of seawater abstraction would account for 67% of the total abstraction quantity in scenario 1. In scenario 2, these values increase significantly.

The estimations in scenario 2 show an increase in seawater abstraction of around 216.5 million m³/a to a total amount of 367.6 million m³/a was calculated, whereby the abstraction for Green Hydrogen production would then account for 34% and the seawater abstraction for further desalination plants would account for 25% of the total amount. The currently permitted amounts of seawater abstraction would account for 41% of the total abstraction quantity in scenario 2. The seawater abstracted form the ocean increases about 143% to the present situation.

In scenario 3, a further increased expansion of seawater abstraction can be observed, which would increase by 490.9 million m³/a, or 324.8% compared to today's values and would amount to a total of about 642 million m³/a.

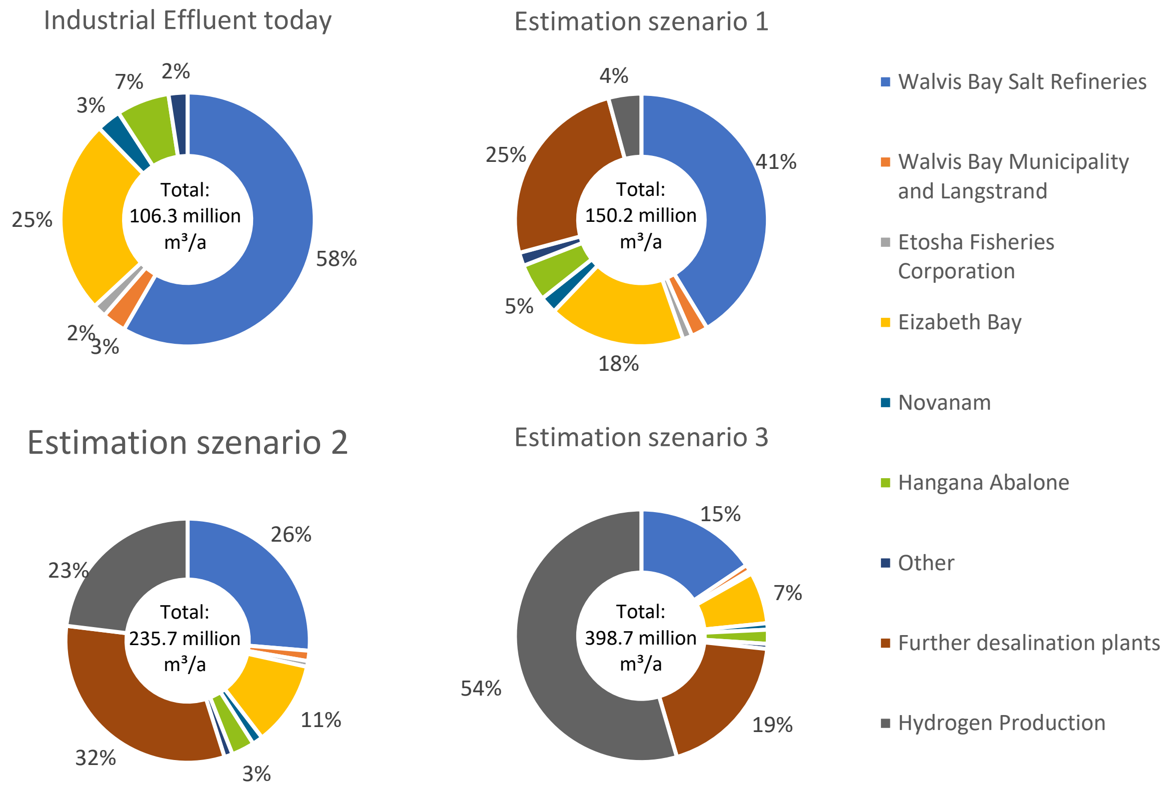


Figure 5: Industrial effluent into the ocean in different scenarios. Top left: values today. Top right: Scenario 1; Bottom left: Scenario 2; Bottom right: Scenario 3.

Figure 5 shows the volumes of industrial wastewater discharged into the ocean along the entire coast of Namibia. Currently, a wastewater discharge of 106.3 million m³/a is authorized, with the largest volume, approximately 58% of the total, discharged by Walvis Bay Salt Refineries. Companies with a permitted wastewater volume of less than 4,000 m³/d were included as Other in Figure 5. The estimates in Scenario 1 show an increase in discharge of about 43.8 million m³/a to 150.2 million m³/a, in which case the discharge of desalination brine from Hydrogen production would account for 4% of the total discharge and the discharge of desalination brine for other desalination plants would account for 25% of the total discharge. The currently permitted discharge volumes to the ocean would represent 71% of total discharge in Scenario 1.

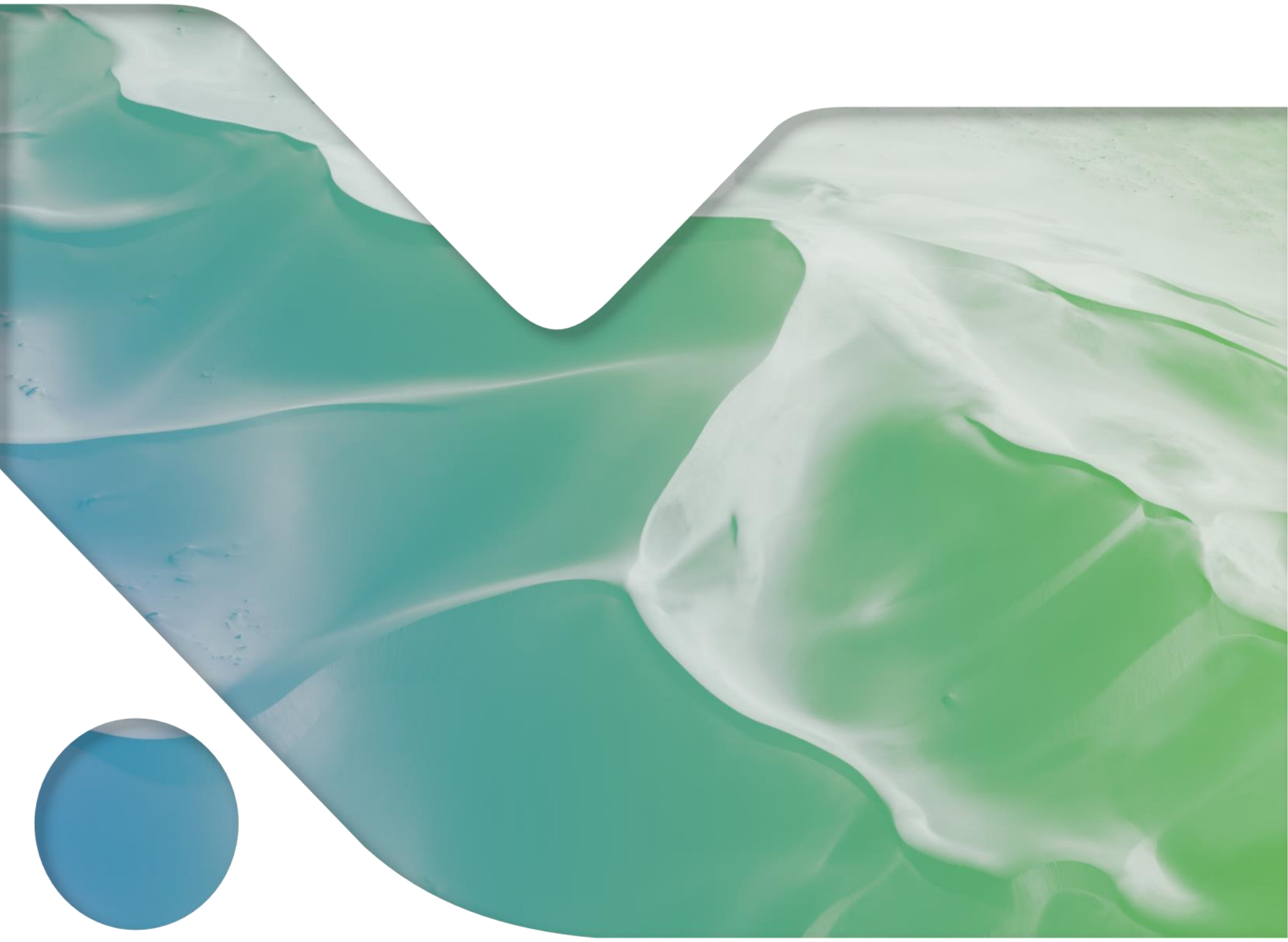
The estimates in Scenario 2 show an increase in discharge volumes by about 129.4 million m³/a to the current values, leading to a total of 235.7 million m³/a. This would mean an increase in discharge volumes of about 121.6%. The discharge of desalination brine from Hydrogen production would then account for 23% of the total discharge to the ocean and the discharge for additional desalination plants would account for 32% of the total discharge to the ocean. The currently permitted discharge volumes to the ocean would represent 45% of the total discharge volume in Scenario 2.

In Scenario 3, the estimates show an increase in discharge volumes of about 292.4 million m³/a to the current values, leading to a total of 398.7 million m³/a. This represents an increase in discharge volumes of about 275%. Discharges of desalination brine from hydrogen production would then account for 54% of the total discharge to the sea, and discharges for additional desalination plants would account for 19% of the total discharge to the sea. Currently permitted discharges to the sea would account for 27% of the total discharge in Scenario 3.

It should be mentioned that the calculation of discharge volumes is highly dependent on the actual conditions of the desalination plants.

It can be stated that the estimated impact of Green Hydrogen production on the water demand of the country is significantly lower than the estimated impact of Green Hydrogen production on seawater abstraction and wastewater disposal. This is partly because Namibia currently uses other water sources more intensively and that seawater desalination is a relatively new water source for the country. However, it is also due to the fact that the production of 1 liter of DI water requires about 2.5 times the amount of seawater. The estimations for the seawater abstraction and the industrial wastewater discharge show that **an increase in desalination could lead to a significant increase in the impact on the marine ecosystem**, as both parameters would be significantly increased by the desalination for the Green Hydrogen Industry. From this, **it can be concluded that increasing Green Hydrogen production should necessarily be accompanied by good management of (sea-)water resources**. Especially when several projects are locally close to each other and so are the abstraction of large amounts of seawater, as well as the associated brine discharge. If larger quantities of desalination plants are concentrated in one region, as may be the case for the regions around Walvis Bay and Lüderitz, **attention should be paid to a more regionally specific impact assessment of the plants and their combined seawater abstraction and brine discharge**.

3 Information about the marine and coastal system in Namibia



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From a global point of view, regions where desalination is quite common are situated at the Mediterranean Sea or the Arabian Gulf, both are so-called inland seas. The influence of brine on maritime life in these regions is part of ongoing research. However, assumptions can be drawn from that to the Namibian context, due to the totally different water and current situation. In order to understand and estimate the impact of brine, the marine and coastal system have to be looked into first.

3.1 Currents

Namibia’s coast is strongly influenced by the Benguela Current. This is a current in the South Atlantic that is formed where the cold South Atlantic Current meets the warm Agulhas Current. The cold Benguela Current flows northward along the coast of South Africa and Namibia and meets the warm Angola Current flowing southward. This creates the South Equator Current, which flows westward.

Currents at the coastal sea surface are mainly influenced by upwelling cells. In upwelling, wind masses hit the ocean, heating and pushing away the upper ocean layer. Due to the movement of the upper warm sea volume, a cold sea water volume is transported upwards and produces a current.

The most important upwelling zones are found at Lüderitz and at Cape Fria. Due to the upwelling zone near Lüderitz, a southern current develops on the coast below Lüderitz and a northern current on the coast above Lüderitz in the period from August to November. The upwelling zone off Cape Fria provides a southern flow, especially in the months of January to May. The coastal current is also influenced by a southward Kelvin current (Yellow arrow), originating from extensions of the Angola Current (Figure 6). [19]

Based on this information, a southern near-shore current and a northern far-off shore current along Namibia can be assumed. In addition, near the coast it is assumed that a flow towards the open sea takes place. Figure 6 shows the main physical and chemical features, including insolation, prevailing southern wind-driven upwelling, deep countercurrent (purple arrows), coastal countercurrent (deep-blue arrows), Kelvin waves (yellow arrows, upper part of the picture) and potential environmental hotspots for low oxygen water (LOW) and H_2S occurrences in the area. The wind rose shows predominantly southern winds for the period 2009-2015. [19]

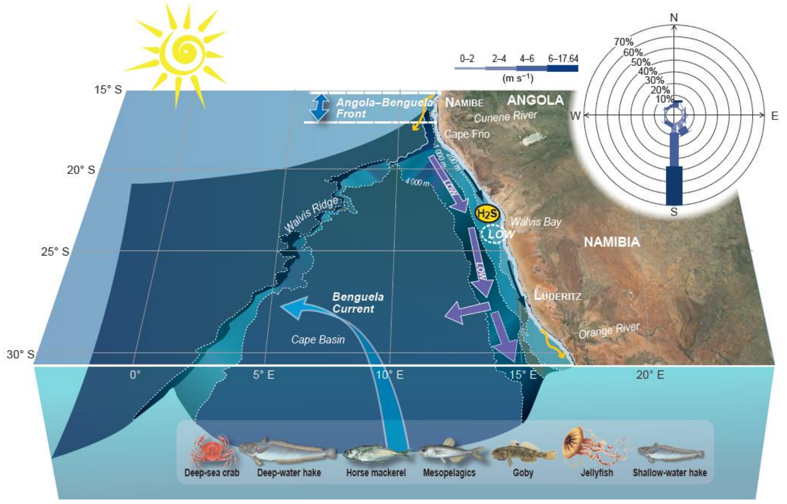


Figure 6: Map of the oceanography of Namibia showing important current systems, as well as prominent marine fish [19]

3.2 Seawater quality parameters

To make statements on desalination and the consequences of the discharge of highly concentrated brine, the water quality on the coast of Namibia must also be looked at. An estimate of the water quality on the coast of Namibia can be seen in Table 4.

Table 4: Water quality parameters reported for seawater along the coast of Namibia [20]–[24]

Parameter	Unit	range of reported values
salinity	g/L	34.2 - 36.6
conductivity	S/cm	4.75 - 5.5
average temperature	°C	14 - 18
pH	-	~8.01
dissolved oxygen	mg/L	0 - 6

A lower salinity level can ensure that more water can be recovered during desalination. The Benguela Current and upwelling cells result in coastal waters with high levels of plankton, which is one of the main reasons for the good productivity off the coast of Namibia.

Another special feature of Namibia are naturally occurring Sulfide plumes on the Namibian coast. These are associated with good conditions for Oxygen depletion of the water due to the combination of abundant plankton, light and nutrients. These conditions can lead to an overproduction of phytoplankton in the water, reducing the concentration of dissolved oxygen and creating zones where almost no dissolved oxygen is present. As a consequence, dead biomass is decomposed and Hydrogen Sulfide (H_2S) is formed. The H_2S deposits often remain for days before they are reduced by the water system itself. The H_2S deposits on the one hand consume further Oxygen from other zones to reduce the H_2S and on the other hand, cause fish mortality, which can have severe consequences for fishing in affected regions. Potentially endangered regions are mainly found in the area off Walvis Bay, as well as north of Lüderitz, but Sulfide plumes can occur on the entire coast of Namibia. [25] As this natural phenomenon can have negative consequences for the marine environment as well as for the potential desalination plants, **further investigations are recommended, to determine whether a potential discharge of brine supports the phenomenon or whether countermeasures, such as artificial aeration of the brine, need to be taken.**

3.3 Comparison of water quality on Namibia’s coast with other water bodies

As mentioned before, the maritime conditions at the coast of Namibia differ from the maritime conditions of other regions with a high amount of desalination plants. In Figure 7 it can be seen that the majority of desalination plants are located in the Middle East and North Africa.

The seawater sources in this area are mainly the Arabian Gulf and the Mediterranean Sea, both of which are inland seas and thus have less current influence than is the case on the Namibian coast. As a result, there is less exchange with the water masses of oceans in both seas and a slightly different water quality can be observed between the waters.

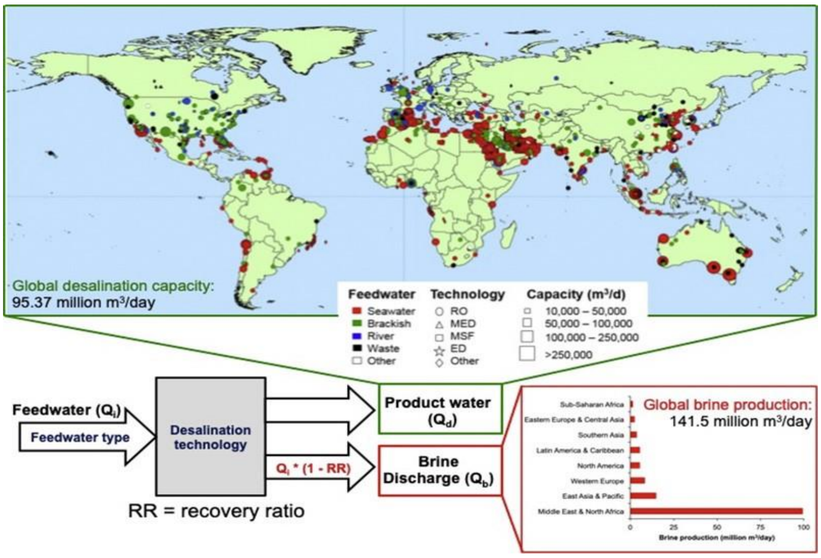


Figure 7: Graphical Abstract of `The state of desalination and brine production: A global outlook` by Jones et al., 2019 [4]

A short overview of the different published water qualities can be seen in Table 5. While these values are not site specific, it can be seen that most of the world's experience in seawater desalination and its associated environmental impacts comes from waters that have a significantly higher salinity than the sea off the coast of Namibia.

For seawater desalination in Namibia, various conclusions can be drawn for this when it is compared to desalination in the Mediterranean and Arabian Gulf regions. First, a lower salinity in the raw water ensures that a better water recovery per m³ of desalinated water can be created. However, much more attention must be paid to site-specific conditions when brine is discharged. Due to the generally lower salinity and dissolved oxygen concentrations at the coast of Namibia, brine can have a stronger influence in local zones. However, compared to the two inland seas, a stronger current is observed on the coast of Namibia and as a result, a stronger dilution of the brine over the entire water body can be assumed.

Table 5: Comparison of water quality parameters between Namibian Coast, Mediterranean Sea and Arabian Gulf

Parameter	Unit	Namibian coast	Mediterranean Sea	Arabian Gulf
salinity	g/L	34.2 - 36.6	36.5 - 39.71	38.54 - 45.88
conductivity	S/cm	4.75 - 5.5	-	7.24 - 12.25
average temperature	°C	14 - 18	17 - 27	21.7 - 34.9
pH	-	~8.01	7.23 - 8.54	7.64 - 8,34
dissolved oxygen	mg/L	0 - 6	4.16 - 8	1.35 - 8
sources		[20]–[24]	[26], [27] [28]	[29], [30] [31]

For seawater desalination in Namibia, various conclusions can be drawn for this when it is compared to desalination in the Mediterranean and Arabian Gulf regions. First, a lower salinity in the raw water ensures that a better water recovery per m³ of desalinated water can be created. However, much more attention must be paid to site-specific conditions when brine is discharged. Due to the generally lower salinity and dissolved oxygen concentrations at the coast of Namibia, brine can have a stronger influence in local zones. It should also be mentioned that compared to the two inland seas, a stronger current is observed on the coast of Namibia and as a result, a stronger dilution of the brine over the local water body can be assumed.

3.4 Fishing

Fishing is the third largest industry in Namibia, accounting for around 4.5% of GDP. Around 14,000 people are directly employed in the fisheries sector. About 550,000 tons of fish are sold annually in Namibia for about N$ 7 – 10 billion. Fishing has been identified as one of the key industries in the National Development Plan 5 (NDP5). However, the Marine Resources Act and Namibia's Second National Biodiversity Strategy and Action Plan (NASAP2) also stipulated that the maritime ecosystem should remain in its current state and be used sustainably based on ecosystem approach to fisheries (EAF) principles.

Nineteen species of fish are caught commercially in Namibia's waters. The main fish species are hake, kob, monkfish, orange roughy and pelagic fish such as swordfish and albacore tuna as an example. However, fishing has to adapt to seasonal periods and regional ranges of fish species. For example, for seasonal periods, the fishing season for rock lobsters is between November and April and sardine fishing is most active from March to July. The catch areas of the main fish species can be seen in Figure 8 and the activity of different fishing vessels can be seen in Figure 9. Fishing areas are located at the entire coast of Namibia. However, it can be seen from the figures that most of the fishing areas are in the northern and central parts of the Namibian ocean basin. Above all, hake and monkfish are caught off the coast of Lüderitz.

The rich productivity of fish growth off the coast of Namibia stems from the good living conditions created by the Benguela Current and Walvis Ridge. The Benguela Current is rich in Oxygen and nutrients and also has a high concentration of plankton. This water condition in combination with the cold temperatures of the Benguela Current and a natural catchment basin created by the Walvis Ridge attracts large schools of fish and makes Namibia and South Africa among the coveted fishing grounds on earth. [32]

Based on the information found for fisheries, it is assumed that especially regions in the north of Namibia are economically important for the fishing industry in the country. It could be assumed that a discharge of larger quantities of brine in the region below Lüderitz, in combination with expected southwesterly currents along the coast, would have a lower risk potential for the fishing industry in Namibia. However, in the region around Lüderitz there is also a high dependence on fishing and a possible influence of brine discharged close to fishing grounds should not be taken too lightly. For example, a new offshore aquaculture with a production of about 35,000 t/a by Benguela Blue Aqua Farming, that might be directly affected, is currently planned and approved.

In the interest of the fishing industry, care should be taken to ensure that the brine discharge does not lead to a reduction of the commercially exploited fish stock. As discussed in Chapter 3.2, low concentrations of dissolved oxygen in the water column can lead to sulfide plumes, which can have detrimental effects on fish stocks. Although the expected impact of brine is limited to a local region around discharge points (Chapter 4.4), measures should be taken to protect waterbodies in the event of an increased discharge of brine. These measures could mean, for example, **increased monitoring systems in the affected regions of discharge or reducing the impact of the discharged brine by further treatment**. In addition to the influence of excessively elevated salinity and pollutant concentrations in the area around the discharge point, the reduction of oxygen concentration is considered the greatest potential risk.

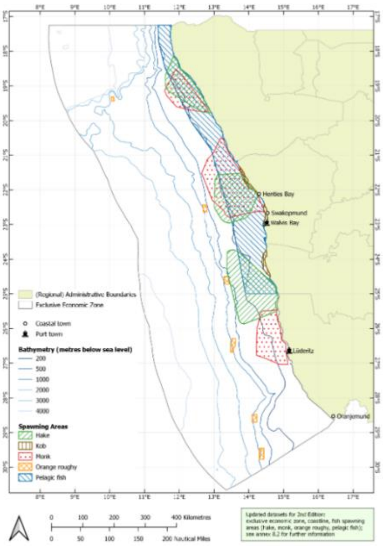
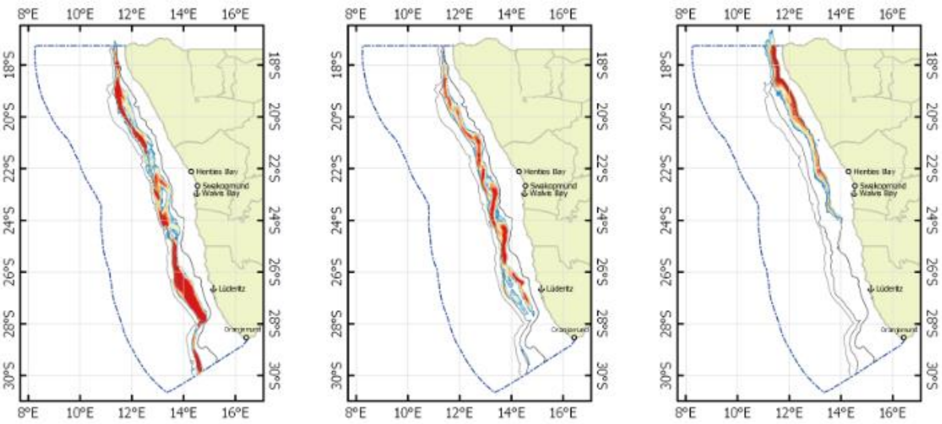


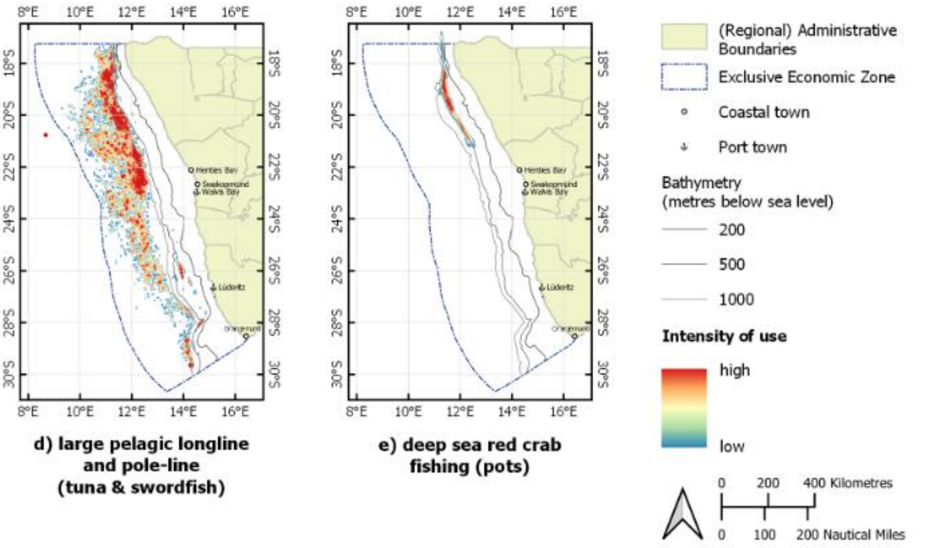
Figure 8: Approximate locations of known main spawning areas of important fish species off the coast of Namibia [13]



a) bottom trawling for hake

b) bottom trawling for monk and sole

c) midwater trawling for horse mackerel

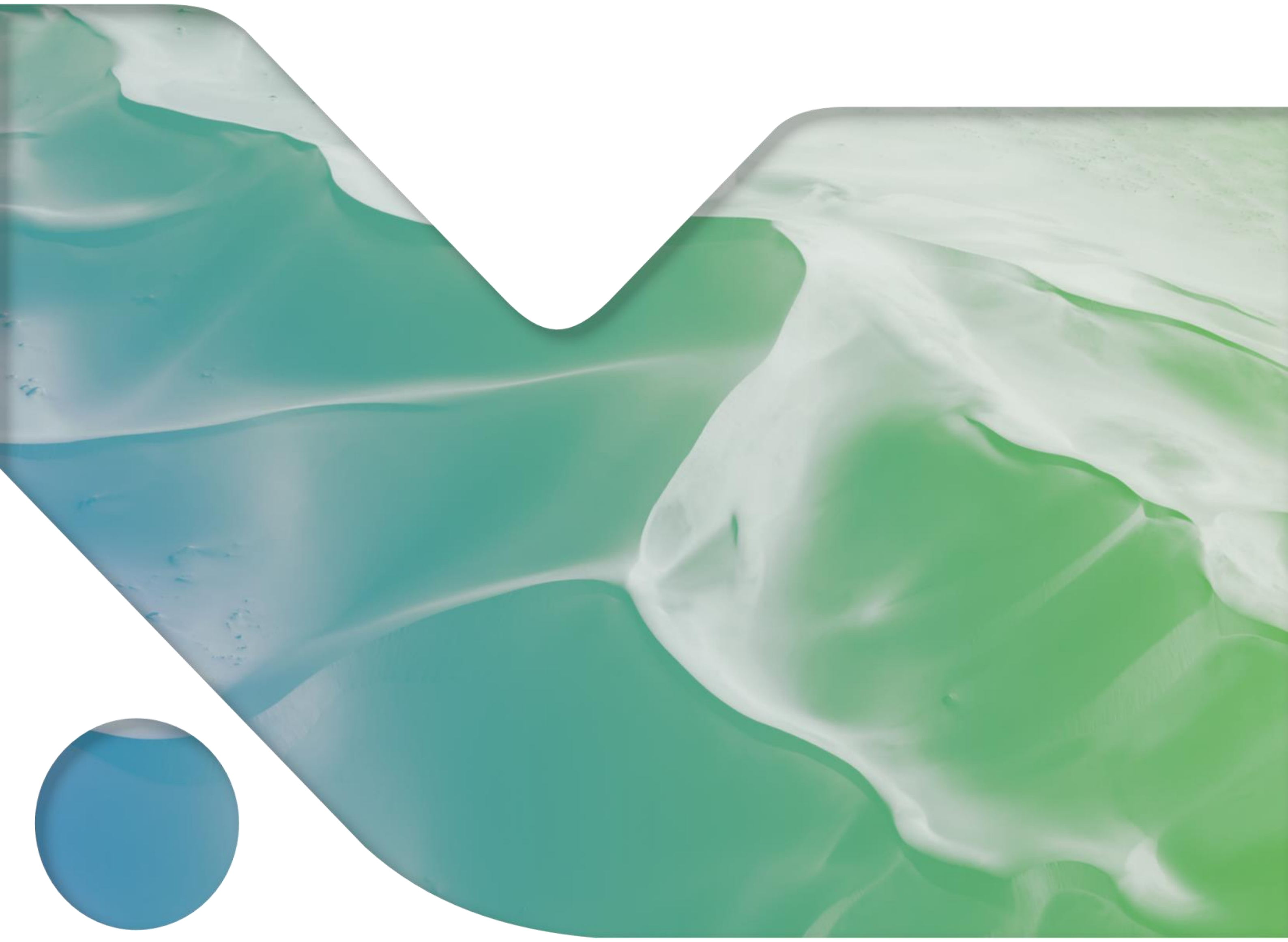


d) large pelagic longline and pole-line (tuna & swordfish)

e) deep sea red crab fishing (pots)

Figure 9: Fishing intensity of different fishing vessels derived from vessel monitoring system (VMS) data [32]

4 Brine disposal options



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The options for brine disposal, the resulting influence on physiochemical properties and the marine ecosystem on the Namibian coast will be considered. As there are already desalination plants in Namibia and another larger desalination plant is currently planned, this chapter also reviews conclusions of feasibility studies that have already been carried out and which address brine discharge in Namibia.

4.1 Brine disposal options

For the discharge of brine from desalination, 5 options are classically considered and are addressed in this chapter in relation to the proposed Green Hydrogen industry in Namibia (Table 6). The options are surface water discharge, sewer discharge, deep-well injection, evaporation ponds and land application. In recent years, in addition to the classical methods, the method of further treatment of brine in the concepts of minimal or zero liquid discharge has been investigated (see chapter 5.1).

A column has been added by the authors of this study and shows an estimate of typically used raw water sources that are associated with the disposal options presented.

Brine discharge to a surface water body is by far the most common method. Jonas et al, 2019, showed that about 80% of desalination facilities globally are less than 10 km away from a shoreline and about 49% are even less than 1 km [4]. Panagopoulos et al., 2019, writes that globally, more than 90% of desalination plants use surface water discharge, including oceans and rivers, and also bays, lakes and other open water bodies [5].

Surface discharge creates an area around the discharge point, where the brine becomes diluted and elevates nutrient and salinity levels, as well as decreased dissolved oxygen levels have to be expected. Alternatively, a sub-surface discharge can occur, which transports the brine out toward the ocean and then discharges it. The advantage of this is that (a) a larger volume of water is available for dilution and (b) no direct harm to human health is suspected. The disadvantages of the method are high investment costs and possibly greater damage to the marine ecosystem, as the brine arrives in the marine ecosystem faster and possibly more undiluted.

Due to differences in the density of the brine compared to the average surrounding water, a sinking of the brine can also be expected, which can also affect a depth of several 100 meters depending on the circumstances. This effect can be supported by the fact that a longer introduction of brine creates a dense current, which transports the brine even further.

A variant for minimizing the environmental impact of brine is to mix it with low-concentration wastewater to minimize the specific impact of high salinity and nutrient levels. The combination with cooling water streams from power plants has been used successfully. Dilution of brine with treated wastewater or seawater already before direct discharge can be other options to reduce the local influence of brine at the discharge point. [33]

For the direct discharge of brine into the Atlantic Ocean, an Environmental Impact Assessment (EIA) for specific plants has to be available before the implementation of the desalination plant, since framework conditions of the plants on site have to be considered case-specifically. Besides the salinity, the dissolved oxygen concentration has to be considered. Namibia is one of the few regions in the world where problems with the natural reduction of dissolved oxygen occur, as explained in chapter 3.2 [25]. In addition, it is known that the discharge of brine can lead to the reduction of dissolved oxygen [10]. The direct discharge of brine should therefore be well monitored, controlled and, if possible, avoided. **A good monitoring network in the area of a discharge point is therefore recommended**. Discharge management could reduce the constant influence on a local marine region if there are different discharge points that can be approached periodically.

Table 6: Conventional brine disposal strategies, its environmental impacts [11]

Disposal Methods	Requirements Prior Disposal	Cost in US\$/m^3	Environmental Impact
Surface water discharge	Compatibility with the receiving water body, i.e., dilution to maintain salinity.	0.05–0.30	Pollution of the marine ecosystem by altering the salinity and pH.
Sewer discharge	Basic pretreatment is essential like pH neutralization to maintain the TDS concentration lower than 3,000 mg/L.	0.32–0.66	Potential environmental hazards due to brine's high TDS content.
Deep-well injection	Wells of depth 500–1,500 m is a requisite and should be able to receive brine for 25–30 years. Other parameters are pond size, lining material and monitoring of the injection site.	0.54–2.65	Pollution of nearby water aquifers and ground water contamination. Unsuitable for countries with high seismic activity.
Evaporation ponds	Availability of solar energy, land and favorable climatic conditions affect the evaporation rate.	3.28–10.04	Improper lining or damage can cause percolation into the water aquifer underneath the pond and deteriorate the water quality.
Land application	The concentration of nutrients in the brine needs to be well within the limits when used for irrigation purposes. Other factors include dilution of concentrated discharge, availability of irrigation land, salinity tolerance interval and follow the groundwater quality regulations. There should not be any pathogenic organisms in the stream.	0.74–1.95	High-salinity tolerant plants can only be irrigated with a TDS higher than 2,000 g/L. Ground percolation and surface water runoff can increase the aquifer salinity thereby causing a negative impact on ground water aquifer.
Conventional crystallizers	A process used at the last stage of brine disposal. It can be a combination of RO, electrodialysis or evaporation process to obtain zero liquid discharge.	3–27	Recovery and reuse of waste metal is the objective so that it can reduce environmental impact and generate revenue from brine.

<u>Evaporation ponds</u> can be another option for discharging seawater brine: The water content of the brine is evaporated via an open pond and the resulting salts and particulate matter have to be disposed or sold. This method requires suitable environmental conditions with a lot of solar influence and available space, making Namibia an ideal spot. In addition, there is already experience in the field of salt mining, which is also operated by evaporation ponds.

The above-mentioned options of deep well discharge, sewer discharge and land applications are not considered further in this chapter, since these are traditional options that are used for low brine concentrations of brackish water desalination or for relatively low brine volume flows. These conditions are not expected in the context of desalination for the Green Hydrogen industry in Namibia.

4.2 Potential impact of brine disposal on the physiochemical properties of Namibia's marine waterbody

The influence of brine on the physicochemical properties of a body of water is mainly caused by differences in density, temperature, pH value, salinity and composition. Higher concentrated liquids have a higher density and therefore sink below liquids with a lower density. In the case of a longer time period of discharge, these density-related differences can also cause horizontal currents in the water body. At the same time, water with a higher temperature has a lower density than water with a lower temperature. This could lead to better mixing of warmer brine, which instead of sinking towards the bottom, can rise to the sea surface.

In addition to the differences in density due to salinity and temperature, contamination and nutrient concentrations also play an important role. High nutrient concentrations (primarily N and P) can lead to strong growth of phytoplankton in water bodies, so called eutrophication. As a result, there is increased Oxygen consumption, which can lead to fish deaths and the formation of Oxygen-poor conditions, leading to the formation of H_2S as a by-product of the decomposition of dead biomass, which in turn can lead to further Oxygen consumption.

Contaminations can also be present in the brine, as they enable safe operation of the desalination plant, but can have toxic effects on the environment. This mainly affects the ingredients of the anti-scalant and antifouling agents and heavy metals. It depends on the water quality to be treated, but also the desalination technology itself, if these substances can be avoided. However, avoiding this addition of chemicals in water treatment is recommended whenever possible.

4.3 Potential impact of brine disposal on the marine ecosystem of Namibia

The influence of brine on the living maritime ecosystem could be indicated by three parameters: (i) increased salinity, (ii) contamination with substances foreign to the ecosystem and (iii) Oxygen consumption of the water. An influence of temperature and pH values on specific species can also be observed, but fish species are slightly more resistant to these parameters than to the first three mentioned. When considering the marine ecosystem, a distinction must be made between the pelagic and the benthic ecosystem.

The ecosystem within the water column is called the pelagic ecosystem. Affected creatures are mainly fishes and crabs, and further species that swim in the water column. Most marine fish are osmotic regulators and can regulate the salinity in their cells when the salinity changes.

Most fishes have the ability to adapt to changing conditions in a local zone or to exit that local zone. The vulnerability to a certain salinity is primarily species-specific. Studies in the Arabian Gulf showed that most fish species can tolerate salinity up to 45 g/L but avoid salinity above 50 g/L. Crabs proved to be a very tolerant species and were able to survive concentrations of 60 g/L for several hours. If fish species are exposed to conditions over a longer period of time that do not optimally match their living conditions, they react by laying or hatching fewer eggs and the fish that hatch show less growth overall. Several fish species show greatly increased mortality rates at a salinity of over 70 g/l, which are concentration ranges that can only occur in small local areas around a discharge point and are not reached within the scope of this report.

Ecosystem-foreign substances, such as biocides for cleaning the membrane systems and heavy metals in elevated concentrations can also cause damage. However, the influence of salinity on the ecosystem is considered to be much stronger.

Seaweeds and green algae showed resistance to salinity up to 37.5 g/L. However, in various fauna species, a deviation in salinity of 1-2 g/L outside the tolerance range of the species over a period of a few weeks resulted in a mortality rate of up to 50%. In addition to mortality, effects on sea plants such as reduced root growth or a reduced ability to bind important ions and increased morbidity can also be identified.

Microorganism communities are also affected by an increase in salt concentration and, depending on the species, the first changes already occur within the first 72 hours. Studies showed that increasing the salt concentration to 41 – 45 g/L results in a significant reduction in the production of Chl-a, algal biomass and photosynthetic pigment. It could be observed that salt stress can result from this increased salinity and the reactive centers for photosynthesis in the microorganisms can be deactivated.

The benthic ecosystem is the ecosystem close to the ground, which includes many species that do not have high mobility and cannot easily escape changing living conditions. This ecosystem is most affected when the brine and seawater are not well mixed at the discharge point. [34] Due to the conditions close to the ground of the seafloor, conditions quickly arise in these regions in which there is no or too little dissolved oxygen in the water and damage to the ecosystem can occur. Since species from the benthic ecosystem are often the first link in the marine food chain, protecting the whole ecosystem is essential.

4.4 Results of other feasibility studies

As a further assessment of the impact of desalination brine on the marine environment could not be given within the scope of this report, investigations from feasibility studies already carried out for existing desalination plants were researched. The results of four publicly available reports that addressed the impact of desalination brine on marine ecosystems in Namibia were found and used to gather information.

For the HDF Energy Renewable Swakopmund Project an Environmental Impact Assessment was published by Theo Wricks, SLR Environmental Consulting (Namibia) (Pty) Ldt, in November 2022. The plant plans to desalinate 200 m^3/d, with only about 74 m^3/d needed for Green Hydrogen electrolysis and to make available the remaining amount for human use. The resulting brine from desalination will either be evaporated via evaporation ponds from Swakopmund Salt Works or alternatively discharged directly into the ocean. In the impact assessment for the “Changes in water quality from brine discharge”, the impact is considered insignificant due to the small quantities of brine. [14], [35]

The Marine Spatial Plan (MSP) from the Ministry of Fisheries and Marine Resources is a method to maintain good water quality on the coast of Namibia. The MSP does not assume a negative impact from seawater abstraction. A specific consideration of brine discharge from desalination plants has not been undertaken, but the potential negative impacts from industrial effluent discharge have been noted. The MSP called for

continuous monitoring and increased remedial action in areas of discharge to ensure the health of the marine ecosystem.

The MSP also addresses various impacts on marine ecosystems, including the influence of brine from seawater desalination, with the objectives:

- Improved sustainable management and utilization of existing water resources;
- Ensure water security for human consumption, livestock and industrial development; and
- Ensure access to adequate and improved sanitation facilities.

The MSP stakeholder engagement report discussed a report that examined the impact of brine from the Erongo Desalination Plant and found almost no impact within "tens of meters from the outlet". It was added by the authors of the MSP that further research is needed in this area as the report had not investigated the impact on benthic organisms and had suggested further studies to assess salinity around the discharge points. [13]

In the Draft Scoping Report by Stuart Heather-Clark from April 2021 for the "Desalination Plant and Water Carriage System to Secure Water Supply to the Central Coast, Windhoek and En-route Users" possible influences on the maritime environment were mentioned. In connection with the large amounts of brine disposed, it was recognized that potential key issues related to desalination are related to altered coastal processes and dynamics, which can lead to knock-on effects on marine and coastal biodiversity and ecology. These knock-on effects were initially identified as disturbance, alteration and loss of marine and coastal habitats, as well as direct disturbance and extinction of marine biota. As part of the required EIA, two specialist studies are carried out. One study will deal with the influence of the brine on "Coastal Physical Processes and Dynamics" and the second study will deal with "Marine and Coastal Biodiversity and Ecology". [24]

In 2014, preliminary planning for a desalination plant at Swakopmund was already undertaken for Rio Tinto Rössing Uranium Limited. [36] As part of these preparatory investigations, specialist studies were also undertaken which deal with the discharge of brine into the sea. The Brine Discharge Specialist Study used model considerations to investigate how large the mixed zone around the discharge point would be. A brine flow rate of around 15,000 m^3/d, a salt content in the brine of 66 g/L, a salt content in the ambient seawater of 34.2 g/L and a required salt concentration outside the mixing zone of 36 g/L were used for the modelling. The discharge of the brine into the ocean was considered as a sub-surface discharge into the surf zone off the coast via a discharge line with a diffuser pipe. A visualization of the resulting mixed zone, in which a concentration above the required 36 g/L occurs, can be seen in Figure 10. It can be seen that the radius of the mixing zone is about 20 – 40 meters large and the influence of brine discharge to be expected can be assumed to be locally limited. [37] Following the Brine Discharge Specialist Study, a Marine Ecology Specialist Study was carried out by Dr. Andrea Pulfrich. Within the Specialist Study influences of different parameters of the desalination plant, such as the influence of deviations in temperature, the concentration of dissolved oxygen, the concentration of heavy metals, the influence of the pre-treatment of intake water and others were examined. The impact on the maritime ecosystem was always classified as low or very low. [35]

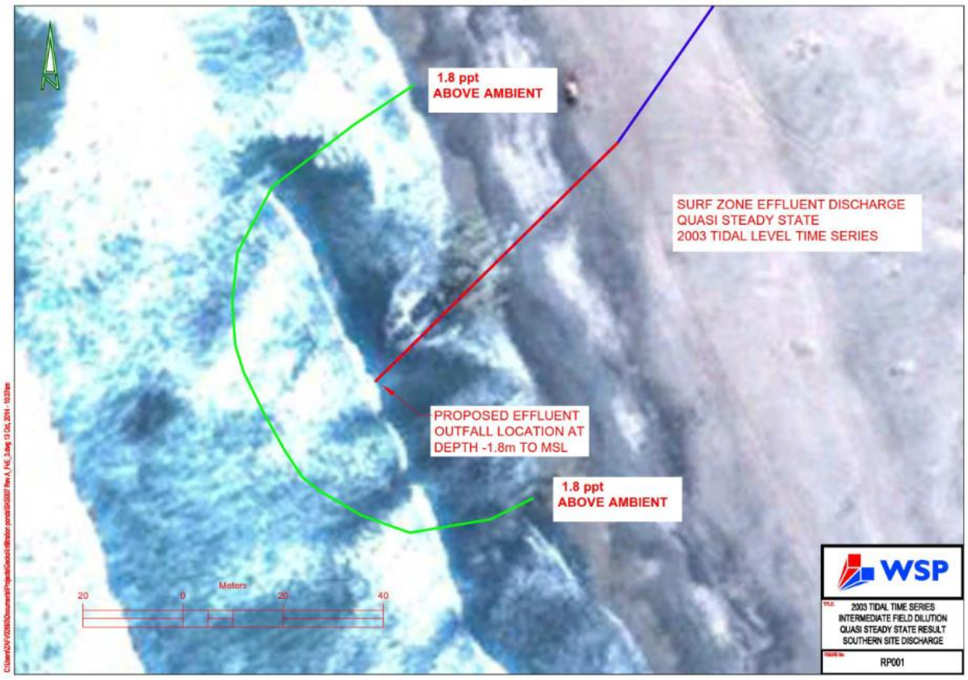


Figure 10: Contour plot of the diluted intermediate field brine influence area (given in parts per thousand above ambient salinity) for the southern [37]

The impact of brine on the marine environment is thus classified as low to very low by various EIAs. From the reports shown, it can be concluded that a **regional impacts of the brine on an area around the discharge points is to be expected, but that no area-wide negative consequences are currently to be expected from the brine discharge into the ocean**. However, there is no strategic environmental impact assessment on this topic for larger regions, like Erongo or //Kharas. This would be recommended, as individual plants may not cause any major effects, but several plants in close proximity can lead to cumulative effects.

4.5 Potential financial and energetic impacts on Green Hydrogen

With the information from Table 1 and Table 6, as well as additional information for the specific energy consumption (SEC), estimates regarding the operational costs, as well as the energy demands for water production, brine disposal or brine treatment in relation to hydrogen production can be considered.

Table 7: OPEX and SEC in comparison to the Hydrogen production [5], [11], [38], [39]

	OPEX [US\$/kg H_2][1]	*OPEX [US\$/m^3]*	*SEC [kWh/kg H_2]*[1]	SEC [kWh/m^3]
Hydrogen production	1 - 3	-	~ 55	-
Desalination (RO)	0.0071	0.75	0.018 - 0.054	2 - 6
Surface water discharge	0.00051 - 0.00271	0.05 - 0.3	Low [2]	Low [2]
Evaporation pond	0.031 - 0.091	3.28 - 10.04	Low [2]	Low [2]
Further brine treatment	0.0271 - 0.2431	3 - 27	0.054 - 0.405	6 - 45[3]

[1] conversion with 1 kg H2 ≈ 9 kg H_2O (stoichiometric amount)

[2] Energy demand results from the required pumps. Value strongly dependent on specific locations.

[3] For feed with an initial concentration of 70 g/L TDS [38]. Values are massively dependent on concepts (MLD/ZLD), on selected technologies, on operation and maintenance of the plants.

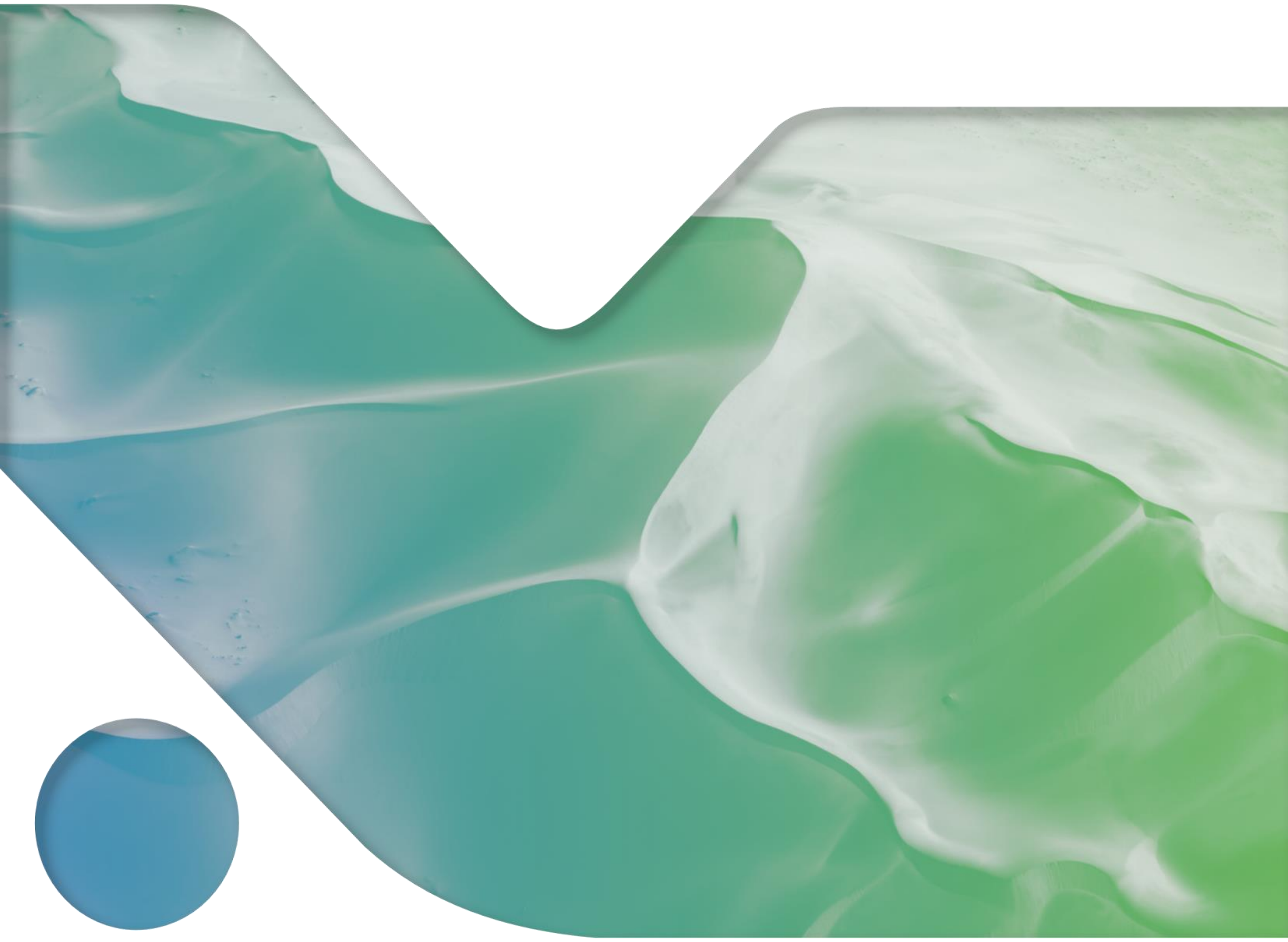
It should be mentioned that the values listed in Table 7 result from literature values and are highly dependent on the available technologies, modes of operation and framework conditions. **In comparison to the process of water electrolysis itself, it can be stated that the operational costs as well as the energy demand for water treatment and discharge steps have a minor influence.**

For brine treatment, surface water discharge is the most cost- and energy-efficient variant, whereby only the operation and not the plant is considered. Values for the discharge are strongly dependent on the location, however as a direct example, the study by Navarro et al., 2023, can be mentioned: an improved brine discharge using diffusers to reduce the negative impact of brine on marine biology at the San Pedro del Pinatar SWRO plant in Spain was investigated. The study showed for a discharge system with a 4790 m outfall an energy demand of 10 – 30 W/m³ and a share of the discharge system of 0.1% to 1% relative to the total economic and energy consumption of the plant [40]. This is the reason why surface water discharge into the sea is the most widely used brine discharge method globally.

Evaporation ponds have higher costs than surface discharge, which is mainly due to the operation and maintenance of the ponds. Evaporation ponds are also assumed to have a very low energy demand in this study, as they consist almost exclusively of transporting and distributing the brine to the ponds, which should be as close as possible to the desalination plant.

Further brine treatment concepts, such as zero liquid discharge (ZLD) or minimum liquid discharge (MLD) have, as they consist of a more complex and energy intensive treatment step, higher costs and energy requirements compared to the alternative brine treatment methods. As these two concepts are still under development and not widely used, CAPEX and OPEX should be evaluated on a case-by-case basis.

5 Brine treatment and usage



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As mentioned in Chapter 4.1, the most important variants for brine discharge are surface water discharge, deep well injections, wastewater discharge, evaporation ponds and land applications, with surface water discharge being the most commonly used variant, especially into the oceans. This chapter is intended to deal roughly with the alternatives to the direct discharge of brine into the ocean. Since direct measures depend heavily on the framework conditions of a specific system, the topics addressed here are to be seen as orientation for further options.

When considering brine management, it must also be considered that the framework conditions for Namibia are different from those of other typical desalination regions:

- the amount of desalinated water and thus the amount of brine produced is and will remain significantly lower than that of regions in the Middle East or the Mediterranean.
- the Atlantic Ocean as a body of water has a greater potential for diluting the desalination brine than the Mediterranean Sea or the Arabian Gulf.

5.1 Further brine treatment / zero liquid discharge

One method of brine disposal would be a further treatment (Figure 11).

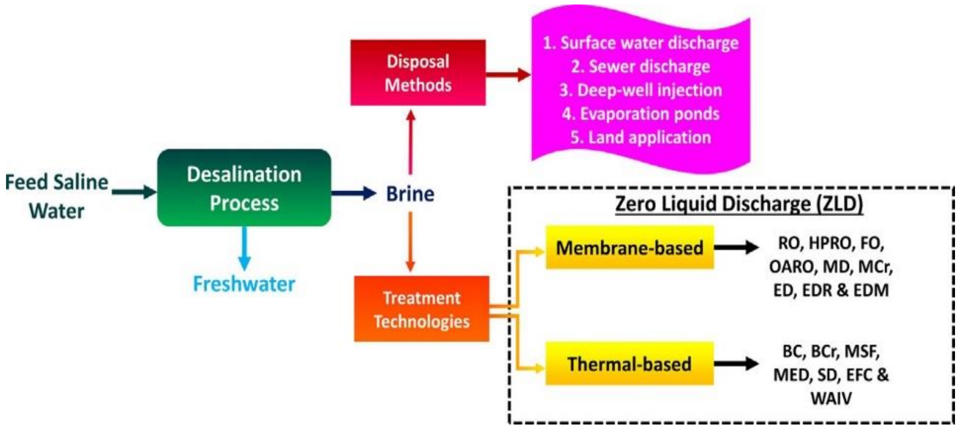


Figure 11: Overview of zero-liquid-discharge approaches as alternatives to brine disposal, with possible technologies indicated as abbreviations. [5]

A concept that is currently the subject of research is the “Zero Liquid Discharge” (ZLD) concept: the brine from desalination is first pretreated, if necessary, then further concentrated and finally crystallized to achieve a DI water stream and a solid waste or by-product stream. First pilot and demonstration plants around the world have been built and operated. The further concentration of the brine is mostly done by thermal or membrane-based processes, which can tolerate a higher limit of salinity in comparison to a classical RO. This aims to combine the advantages of different desalination technologies, like the low energy consumption of a RO process and the higher salinity limit of i.e. thermal processes. The final step in Zero Liquid Discharge is crystallization, where the highly concentrated brine is completely separated into deionized (DI) water and emerging salt. If crystallization is not performed and the salinity limit of the concentration steps are not pushed to a maximum, the concept is referred to as Minimal Liquid Discharge (MLD) (Figure 12).

The main disadvantages of MLD and ZLD are the significantly higher energy consumption (Figure 12) and the greater demands on pre-treatment, for instance higher usage of antiscalants, anti-fouling, corrosion and de-ionization agents, in comparison to other options for brine management.

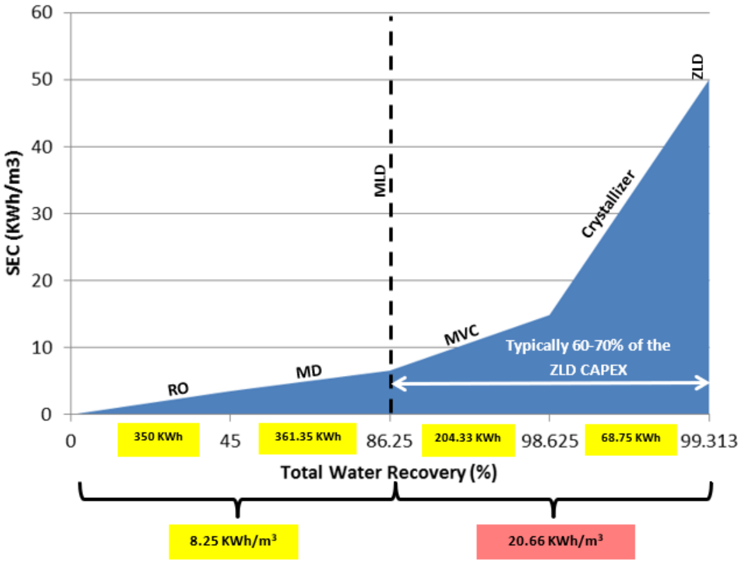


Figure 12: Example figure of energy consumption for MLD and ZLD [41]

MLD and ZLD processes are currently being studied extensively and it is expected that the processes will become a potentially feasible alternative in the coming years. The main factors for feasibility are the high energy consumption is offset by the availability of DI water and the production of salts or other valuable substances. [42] Zuo et al., 2022, showed that operating a membrane distillation with integrated crystallization of RO brine led to a water recovery >95%. [43] Chen et al., 2021, showed that a ZLD method works with MED and evaporation crystallization. The specific costs, CAPEX and OPEX, of the system for a period of 30 years were US$ 4.17/m³. [44]

With the assumption that there are no harmful substances in the RO brine, it can be argued that the brine does not have to be treated completely. A brine could be treated partially with a MLD/ZLD approach, the reclaimed water be used for dilution of the original brine and the concentrate be discharged on land. The diluted brine could cause less potential environmental damage than the concentrated brine would. In this case, however, the ZLD process would not lead to an additional production of DI water beside the amount already produced by the primary desalination plant.

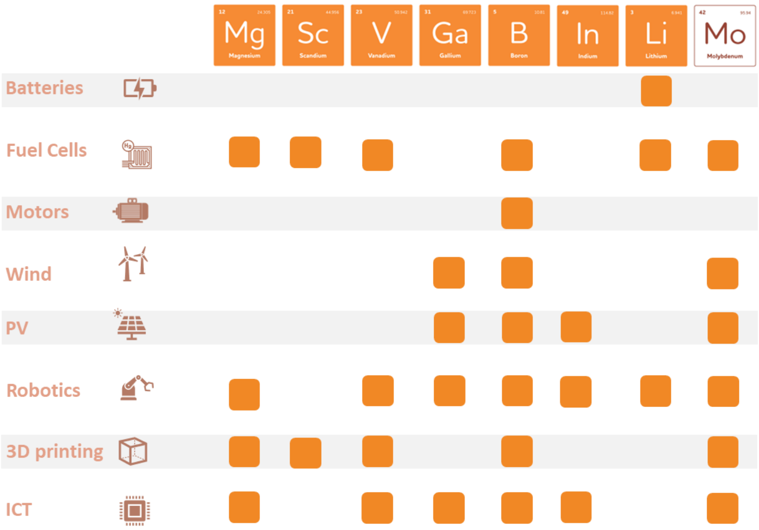
5.2 Further Brine Usage

5.2.1. Brine Mining

Brine mining is a method of extracting valuable minerals and resources from brine, which is a highly concentrated saltwater solution, deriving from seawater desalination as a waste. Within the field of brine treatment especially in ZLD research, this process has gained prominence in recent years due to its potential to yield various essential minerals and chemicals, but it also raises environmental and ethical concerns.

An alternative resource of raw materials, instead of mining, is recycling, which accounted for about 8% of overall material inputs to the economy of the European Union in 2017 [45]. However, recovery might not always be technically or economically feasible and, there are dissipation losses during or after use, also due to improper disposal. Hence, moving toward reuse and recycling will complement currents supply, current and new primary resource extraction will be still needed to meet the EU's and other economies materials demand such as shifting towards circular economy and promotion of local supply. The recovery of valuable minor and trace metals and minerals for commercial purposes from seawater desalination brines, is a potential source of resources which has been raising interest over the past few years [46]. Focusing on the use of brines has the competitive advantage of using an already pre-concentrated stream compared to extraction of raw materials directly from seawater. Taking into consideration that, according to the International Water Association, there were 19,744 desalination plants worldwide in 2017, with a total installed production capacity of 104,7 million m^3/day, thus the business and geopolitical implications are massive.

Among the elements, that are potentially of interest to recover, due to their higher concentration in comparison to seawater are of course sodium, magnesium & calcium, but also lithium, boron and some others. Although the usage of these elements is given (see Figure 13), the overall economic feasibility remains unclear at this stage of development for recovery technologies, since concentration is as stated energy intensive and ion-selective recovery technically challenging.



	Mg	Sc	V	Ga	B	In	Li	Mo
Batteries							■	
Fuel Cells	■	■	■		■		■	■
Motors					■			
Wind				■	■			■
PV				■	■	■		■
Robotics	■		■	■	■	■	■	■
3D printing	■	■	■		■			■
ICT	■		■	■	■	■		■

Figure 13: Potential valuable minerals in seawater brines and potential industrial uses for them [47]

The challenge with extracting low concentration elements from brine lies in:

a) the large amounts of water that need to be processed and removed, which requires catchment and discharge infrastructure and energy,
b) the preparation of commodity grade metals and minerals from complex matrices, such as seawater brines, requires a variety of separation technologies able to selectively recover target elements, which has proven technically and cost-effectively unfeasible with current separation technologies,
c) the need of developing flexible processes and technologies able to work synergistically to recover different elements in the same integrated process increasing the economic and environmental feasibility.

Current research on economic assessment of recovered minerals and metals from seawater

The use of seawater and brines from desalination plants for resource recovery gained much attention and encouraged the interest in nonconventional resources [48]. Besides the benefits of brine mining such us supply of critical and valuable metals the economic feasibility and comparability is another aspect, which supports the market potentials of the recovered minerals and metals. However, the minerals and metals are distributed in seawater not evenly and in different concentration levels. Especially compounds with lower economic value such as chloride, sodium, magnesium and calcium occur in higher concentrations than the "minor" compounds [49]. In Figure 14, the relation between the concentration of the seawater components and the prices of the most commercially relevant salts is shown.

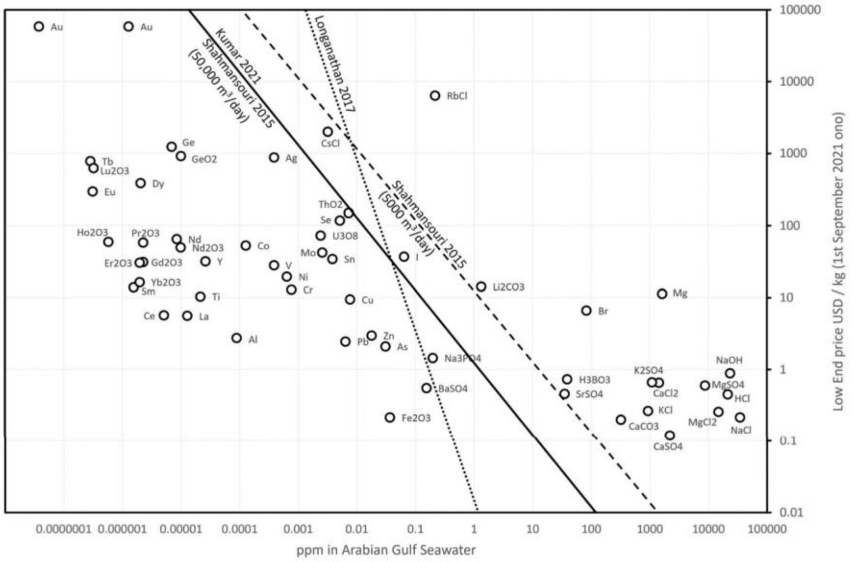


Figure 14: Overview of "Element concentration and price. Concentration of chemical species in seawater and their commercial value, as estimated in September 2021." graph generated by Sharkh et al, 2022 [50]

The inserted lines are intended to indicate the division of the metals into economic feasible and economic challenging by different authors. As can be seen from the graph, the dividing line varies from one author to another. Shahmansouri et al. (2015) have inserted two lines depending on the amount of material processed. They demonstrate that the treated volume has an impact on the assessment of feasibility. It can be concluded that further factors need to be investigated in the feasibility analysis.

As previously mentioned, there is ongoing research which elements might be economically feasible to recover from brine, also the European Union strategically investigates critical raw materials and the potential to reduce import streams[45]. Which potential lies in Namibia remains unclear at the moment and depends on the worldwide measures to make brine mining economically feasible. From a ionic-concentration point of view, a recovery of sodium chloride might be interesting.

5.2.2. Salt production via Evaporation Ponds

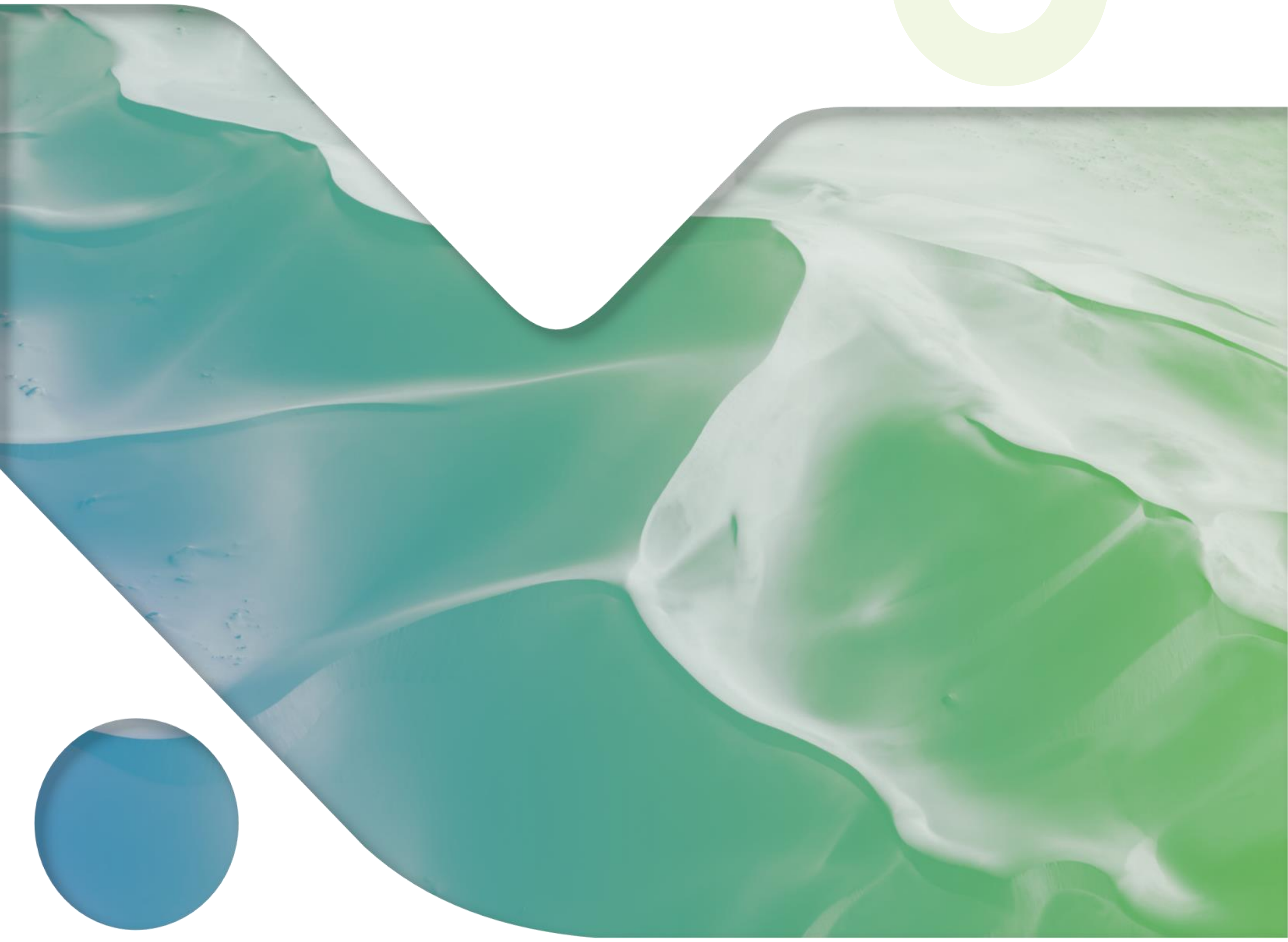
Other options in addition to the targeted brine treatment is its use. It is conceivable that brine from desalination can be used to produce seawater salt if it is possible to avoid contamination of the brine with antiscalants, antifouling agents or other potentially harmful substances. This recycling was also suggested when planning the desalination plant for the Hydrogen project in Swakopmund, where the amount of brine produced daily is quite small. In comparison, the brine produced from the calculated scenario 2 (production of 3 million t/a Green Hydrogen and expanded desalination for freshwater production for human consumption by another 50 million m^3/a), for a brine quantity of about 14.9 million m^3 and an assumed evaporation of 2,600 mm/a [51] an area of about 5.5 km^2 would be required for the evaporation ponds. This is in the order of magnitude of the Salt Works Swakopmund, although it should be noted that these are rough estimates and that additional space should be planned for rainfalls. With a salinity of around 65 g/L the evaporation would lead to a potential salt production of about 945 t/a. One advantage of using evaporation ponds is that expertise in the use of evaporation ponds is already available in Namibia and therefore a lower level of capacity building would be necessary.

5.2.3. Aquaculture

A second possible use for the brine could be aquaculture systems. A pilot project recently investigated the use of brine in the case of Tilapia farming and found a significant increase in productivity. The biomass production per m^3 was increased by 300% and at the same time the amount of feed required per kg of biomass produced was reduced by around 45%. [52] However, a wastewater is generated which needs additional treatment as well. The question remains, which of these potential methods could be of economic interest in comparison to the direct discharge into the Atlantic Ocean.

Similar to the advantage of evaporation ponds, domestic expertise in Namibia can also be drawn upon when considering aquaculture. In Namibia, priority is given to oysters, clams, abalone, mussel species and seaweed. Designated areas are mainly found in Lüderitz and Walvis Bay. [13] Experience with inland aquacultures could also be used, as these are already being operated in northern Namibia. Experience with inland aquacultures could also be used, as these are already being operated in northern Namibia. These focus primarily on commercial freshwater aquaculture of tilapia and catfish. [53]

6 Conclusion and Recommendations



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The development of the Namibian hydrogen economy will require large quantities of deionized water. Although processed groundwater might be an option for the first pilot projects, seawater desalination will inevitably be needed to supply the required amounts of water. As Namibia is one of the most arid countries in Sub-Saharan Africa, groundwater or rainwater are not sufficient for a constant supply for green hydrogen production.

No matter which technology is used, seawater desalination process chains, including pre- and post-treatment, not only produce deionized water, but also brine. General assumptions suggest that 2-3 litres of seawater are required for 1 litre of deionized water produced, if the most common desalination technology of reverse osmosis is applied. This results in 1-2 litres of brine that must be either further treated or discharged.

Impact of brine

The currently prepared EIAs for Namibia's existing and near-term planned desalination plants give the impression that brine discharge has little or no impact on marine life and thus on fishing. However, they obviously consider smaller quantities of brine than would be generated by the Green Hydrogen Industry. Since the hydrogen economy in Namibia will expand over the coming years, the amount of brine produced and therefore the potential impact of brine on maritime life will grow in comparison to the current situation. Additionally, existing feasibility studies from Namibia focus on fish and not on bottom-dwelling creatures. It is known that brine from RO can contaminate life on the seabed, depending on the discharge method (above or below the surface) as it has a higher density due to its salt load. Further, the impact of brine could be influenced by local current flows, as dilution in areas of high flows happens almost immediately.

On a global perspective though, it needs to be evaluated how the future implementation of seawater desalination will affect maritime life, since more and more seawater is and will be needed as a water source for both municipal and industrial use, resulting in a larger brine discharge. In this evaluation, one must differentiate between inland seas and oceans, since the smaller the receiving water body, the higher its increase in salt load and the higher the impact of the brine onto the receiving water ecosystem.

Compared to total production costs of 1-3 US$ per kg hydrogen in the future, the financial costs of desalination are little in comparison to the costs of hydrogen production itself. If one assumes OPEX costs of 0.75 US$/m³ water for Seawater Reverse Osmosis, the costs per kg of produced hydrogen will increase only by 0.007 US$/kg H_2.

Recommendations

Most of the known and available work about the impact of brine on maritime life focuses on inland waters, where the salt level is already higher than in oceans on average. Further investigations into how the continuous discharge of brine is currently affecting maritime life are needed. One suggestion is to monitor the salt concentration and other physical-chemical parameters in the area of discharge points from any new desalination plant. Additionally, it should be evaluated whether the occurrence of negative phenomena can be observed, such as H_2S plumes for example, which are prohibiting the continuous operation of the currently operating Orano desalination plant: brine discharge decreases dissolved oxygen and ultimately result in the formation of H_2S plumes. It needs to be investigated in EIAs if these plumes can occur in other regions along the coastline.

Further brine treatment

To avoid potential impacts from brine discharge, there are four options: 1) implement a system that ensures enough dilution at the discharge points in the ocean, 2) treat the brine onshore, 3) use solar power to evaporate the water and recover the salt for further use or 4) use the elevated Total-Dissolved-Solids concentration of the brine as feed-stream for new aquacultures.

Brine treatment could be a second desalination step by a so-called zero- or minimal-liquid-discharge (ZLD/MLD) module (composed mostly of evaporation technology). The reclaimed water from such a module could be used directly (for hydrogen production for instance) or mixed with a partial flow of the original brine, lowering the salt concentration to that similar to seawater, reducing the associated impacts. If the post-treatment of the brine results in a waste stream with a further increased TDS concentration, discharge into the sea may become impossible. It must be stated that the installation of a ZLD module results in a higher OPEX in the initial stages, but with more reclaimed water and the potential recovery of by-products, brine treatment could actually be beneficial for the overall OPEX of water treatment for the hydrogen economy. Assuming maximum OPEX of 27 US$/m³ for the brine, additional costs of 0.243 US$/kg H_2 would occur. However, additional brine treatment like ZLD/MLD is likely to reduce the environmental impacts and could be installed, if sufficient energy sources are available.

The recovery of ions from brine such as magnesium or lithium is the topic of ongoing research and therefore, an update on the economic feasibility of material recovery can be provided in the future. The potential recovery needs a careful investigation of local and regional markets, as well as OPEX analysis on the ion selective recovery steps.

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Appendix

A.1. Methodology and calculated values for the estimations of water demand, seawater abstraction, brine production

Rough calculations were made for the estimations of the required quantities of deionized water and produced brine, which were presented in the scenarios (see chapter 2.4). These values should serve as an orientation for the potential dimension that can be generated by the green hydrogen industry.

The amount of needed deionized water is calculated as:

$$DI\ water\ [t/a] = DI\ water_{production}\ [t/a] + DI\ water_{Cooling}\ [t/a] \tag{1}$$

$$DI\ water_{production}\ [t/a] = H_{2,produced}\ [t/a] \cdot Di\ water\ needed\ for\ 1\ kg\ H_2 [kg/kg] \tag{2}$$

$$DI\ water_{Cooling}\ [t/a] = DI\ water_{production}\ [t/a] + DI\ water_{production}\ [t/a] \cdot Ratio \tag{3}$$

The amount of needed seawater and brine are calculated as:

$$Seawater_{abstracted}\ [t/a] = DI\ water\ [t/a] \cdot \frac{1}{Recovery\ Ratio} \tag{4}$$

$$brine_{produced}\ [t/a] = \ Seawater\ [t/a] - DI\ water\ [t/a] \tag{5}$$

Values for various parameters within the calculations for DI-water needed, Seawater abstracted and brine produced can be viewed in Table 8.

Table 8: Parameters values used for the calculations of DI-water needed, Seawater abstracted and brine produced

Parameter	Unit	Value range	value in calculation
DI water for 1 kg of H_2	kg / kg	9 – 14.5	10
Ratio between cooling water and production water	m³/m³	-	0.25
Operating hour per year	h	-	8,760
Recovery ratio of desalination with RO plant	%	30 – 50	40
Density DI water	kg/m³	-	1,000
Density seawater	kg/m³	-	1,025
Density brine	kg/m³	-	1,035
Density H_2	kg/m³	-	24,000
H_2 production in Scenario 1	t/a		350,000
H_2 production of Green Hydrogen Industry till 2035	t/a		3,000,000
x-fold growth of Green Hydrogen Industry till 2035	-	-	8.57
H_2 production of Green Hydrogen Industry till 2050	t/a		12,000,000
x-fold growth of Green Hydrogen Industry till 2050	-	-	34.29
x-fold growth of desalination for human use	-	-	2

For the production of Hydrogen in Namibia, the quantities for water demand, seawater abstraction and brine production were calculated. For this purpose, two scenarios were considered in chapter 2.4. Scenario 1 considered the quantities estimated for the HYPHEN project. The results of the calculations for Scenario 1 are shown in Table 9. Scenario 2 considered a production of 3,000,000 t/a hydrogen, which is the production capacity aimed for 2035, as mentioned in the Namibian Green Hydrogen and Derivates Strategy. Scenario 3 considered a production of 12,000,000 t/a hydrogen, which is the production capacity aimed for 2050, as mentioned in the Namibian Green Hydrogen and Derivates Strategy. A X-fold increase in Hydrogen production results in a X-fold increase in the values shown in Table 9.

Table 9: Mass and Volume flows calculated for Scenario 1

	Mass flow		Volume flow	
H2 produced	350,000	t/a	14,583	m³/a
DI water needed for H2 production	3,500,000	t/a	3,500,000	m³/a
DI water needed for cooling	875,000	t/a	875,000	m³/a
DI water needed total	4,375,000	t/a	4,375,000	m³/a
seawater needed for H2 production	8,250,000	t/a	8,536,585	m³/a
seawater needed for cooling	2,187,000	t/a	2,134,146	m³/a
seawater needed total	10,937,000	t/a	10,670,732	m³/a
Brine produced	6,562,500	t/a	6,340,580	m³/a

Analogous to the calculations for Hydrogen production, calculations were made for the production of water for other uses via the already approved desalination plant in Swakopmund (Scenario 1) and a doubling of desalination volumes through possibly additional desalination plants independent of Hydrogen production (Scenario 2 and 3). The results of these calculations can be viewed in Table 10.

The calculation results were compared with published values from the Marine Spatial Plan for Namibia [13] and the Integrated Water Resources Management Plan for Namibia [18]were compared. It should be noted that no regional conditions were considered in the calculations and comparisons, and only overall values for Namibia were calculated and considered.

Table 10: Volume flows calculated for further desalination plants in Scenario 1, Scenario 2 and Scenario 3

	Scenario 1		Scenario 2 and 3	
Produced water for other uses	25,000,000	m³/a	50,000,000	m³/a
Seawater abstracted	62,500,000	m³/a	125,000,000	m³/a
Brine produced	37,500,000	m³/a	75,000,000	m³/a