Balancing Water Scarcity and Clean Energy: A Cost-Benefit Analysis for Integrated Minimal Liquid Discharge Systems

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Masters Degree

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COSEM

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Abstract

(S) The global transition to a carbon-neutral economy increasingly relies on alternatives such as hydrogen as a clean energy carrier. However, hydrogen production through electrolysis requires ultrapure water, which places additional stress on freshwater resources that are already under pressure due to population growth, urbanisation, and climate change. Over 2.7 billion people are affected by water scarcity yearly and this poses major challenges to human health, socio-economic development, and environmental stability. Desalination of seawater is a promising solution to produce the required water. However, water desalination also produces a high-salinity byproduct called brine. Consequently, traditional discharge methods threaten marine ecosystems with brine disposal. New desalination approaches such as Zero Liquid Discharge (ZLD) and Minimal Liquid Discharge (MLD) technologies offer a potential to mitigate environmental harms with brine by reducing or even eliminating the liquid waste. However, these systems require a lot of technologies placed in series with energy demand which makes the new approach expensive. This leads to concerns about the economic feasibility of MLD and ZLD technologies.

(**C)** Most studies evaluating MLD and ZLD systems rely on Techno-Economic Analysis (TEA). TEA methods focus on capital expenditures (CAPEX) and operational expenditures (OPEX). The downside of TEA is that it often fails to capture broader societal and environmental externalities such as marine degradation from brine discharge or benefits of freshwater recovery in water-stressed regions. Furthermore, the choice between ZLD and MLD is also very complicated. ZLD achieves higher recovery rates than MLD and single water desalinations but at the same its technological complexity and high energy consumption make it a difficult application. In contrast, MLD systems offer lower recovery rates but may present a more cost-effective and feasible solution. Despite this, the literature lacks a more societal and environmental application such as a Cost-Benefit Analysis (CBA) to assess whether the broader societal value of MLD systems justifies their higher costs. This absence represents a significant knowledge gap in the literature and policy evaluation.

(**Q**) To address this knowledge gap, the following research question is formulated which focuses on Nanofiltration (NF) and Multi-Effect Distillation (MED) as the core technologies for MLD, in order to keep the research feasible within the 21-week timeframe of this study:

"What are the societal costs and benefits of Minimal Liquid Discharge (MLD) technologies, with a focus on Nanofiltration (NF) and Multi-Effect Distillation (MED), for hydrogen production?"

(**A**) This thesis applies a CBA framework to assess the economic and societal viability of two MLD configurations. The first MLD is a stand-alone MED system and the second MLD a hybrid NF-MED system. The research uses a mixed-methods approach by combining a structured literature review with expert interviews to identify and validate cost elements, operational parameters, and environmental impacts. All cost elements of the CBA including CAPEX, OPEX, and environmental externalities were monetised, so the Net Present Value (NPV) of the two MLDs can be calculated. The CBA demonstrates that while both systems carry significant upfront and operational costs, the standalone MED and the hybrid NF-MED result in positive NPVs. The hybrid NF-MED MLD results in higher water recovery at reduced steam cost per unit of ultrapure water because of the opportunity to operate at higher temperatures. The

results show that wider benefits, such as protecting ecosystems and saving freshwater, can make up for the high upfront costs. Especially if certain conditions are met such as access to green electricity or free waste heat. However, this is dependent on which individuals have standing in the CBA and how they value the wider benefits. The study also shows that using only a TEA gives an incomplete picture, because it leaves out these important environmental and social benefits.

(**R**) This research recommends the adoption of CBA as a complementary tool to TEA in evaluating MLD systems, especially in sustainability sectors like hydrogen production. Policymakers should consider regulatory frameworks that internalise the environmental impact of brine discharge, making MLD systems financially more competitive. For project developers and investors, the hybrid NF-MED system represents a promising solution between conventional water desalination brine discharge and the more expensive ZLD. Further research should focus on scaling the pilot project with additional pre- and posttreatment, and exploring the integration of entirely renewable energy sources and alternative waste heat to further reduce OPEX.

Keywords: Desalination, Brine, Zero Liquid Discharge (ZLD), Minimal Liquid Discharge (MLD), techno-economic analysis (TEA), cost-benefit analysis (CBA), cost-effectiveness analysis (CEA), life cycle analysis (LCA)*[1]

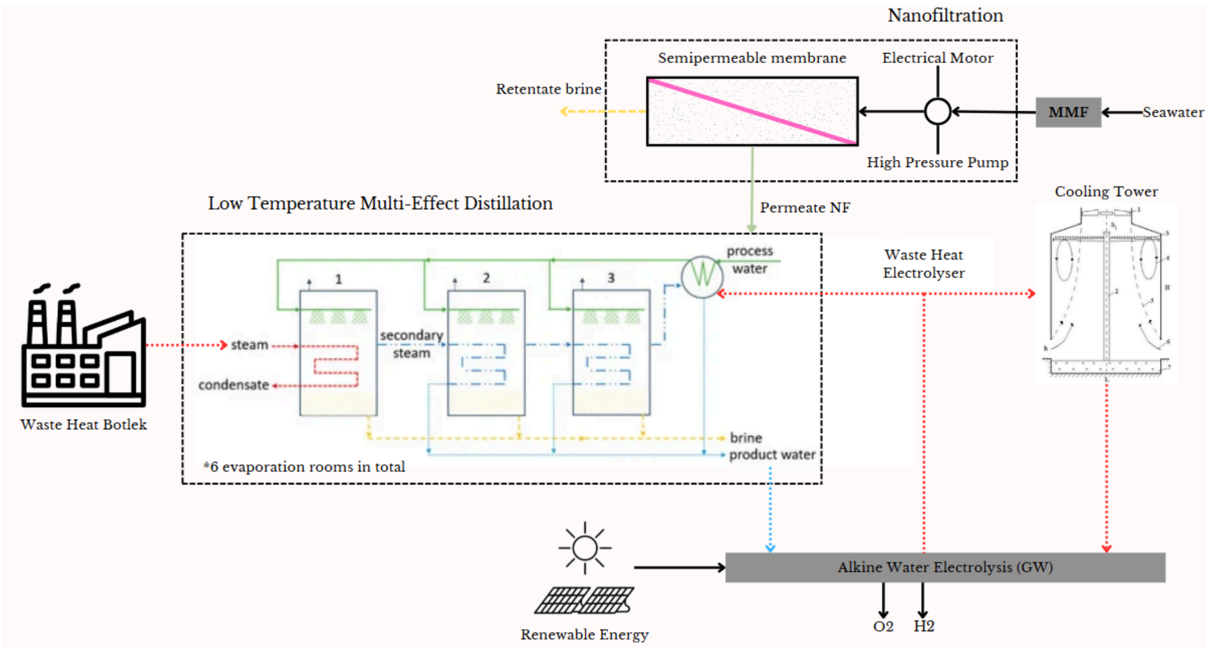


Figure 1 : NF-MED Minimal Liquid Discharge Technology

[1] * An Abbreviation Table is added in Appendix C

1. Introduction

Hydrogen plays a key role in replacing fossil fuels to meet the needs of a carbon-neutral economy, but the transition faces several limitations. One key limitation is the reliance on freshwater to produce the ultrapure water needed for hydrogen generation. In water-scarce regions, this poses sustainability concerns and limits scalability. This thesis explores how MLD technologies can support sustainable hydrogen production by treating seawater while minimising environmental harm from brine disposal. The study will contribute to the societal challenge of water security and sustainable energy transition.

Due to continuous growth of population and rapid urbanisation, freshwater demand keeps increasing (Yaqub et al., 2019). Even though water seems abundant, covering 70% of the planet's surface, it is not evenly distributed and is limited in freshwater which results in 2.7 billion people facing water scarcity for at least one month a year (Alenezi and Alabaiadly, 2025). Water scarcity threatens health and livelihoods but also poses significant challenges to economic development and social stability.

To address this issue, water desalination is a promising technology that aims to obtain freshwater from saline water resources, such as seawater (Elsaid et al., 2020). The produced freshwater can be used as drinking water, but for this research the freshwater is further developed to produce ultrapure water for the electrolysis to generate hydrogen. The ultrapure water production will contribute to economic development and social stability. Various desalination methods exist, which can be categorised into two processes: membrane and thermal-based processes. The leading desalination technologies are Reverse Osmosis (RO), Multi-Stage Flash (MSF), Multi-Effect Distillation (MED), and Nanofiltration (NF).

Although water desalination offers human health and socio-economic welfare by providing a reliable water supply and reducing water stress, environmental negative effects are raised (Elsaid et al., 2020). Desalination impacts the environment in different ways and at different levels, depending on the nature of the utilised feedwater, the desalination technology in use, and the management of waste brine generated. Brine is the byproduct of the desalination process and has a high salinity level (Panagopoulos and Giannika, 2024-a). The high salinity, together with other toxic elements present in the byproduct, poses significant environmental challenges. The global production of water desalination brine is estimated to exceed 129 million cubic meters per day and therefore needs a sustainable solution.

Recent developments in desalination suggest that hybrid approaches such as MLD and ZLD can reduce brine output (Panagopoulos and Giannika, 2024-a).ZLD aims for complete reuse of treated water with no discharge. This can eliminate the risk of water contamination via wastewater discharge and also maximises water usage efficiency (Yaqub et al., 2019). MLD reduces the water discharge but is not able to reuse all the brine because less appropriate treatment is available (Panagopoulos and Giannika, 2024-a). ZLD and MLD can help realise the sixth sustainable development goal (SDG) of the United Nations, which is '*clean water and sanitation*', but indirectly also contributes to the seventh sustainable goal, '*affordable and clean energy*' in regard to the production of hydrogen.

MLD and ZLD technologies are considered promising solutions for seawater desalination technologies (Panagopoulos and Giannika, 2024-a). However, the industrial applications of MLD and ZLD are restricted due to their high cost and intensive energy consumption. The costs are high because multiple water desalination technologies are needed in parallel to treat the seawater and brine. Previous studies have primarily used TEA to assess these systems. While TEA provides valuable insights into technical feasibility and direct economic costs, it often overlooks broader societal benefits and environmental impacts. As a result, TEA may undervalue the potential of MLD and ZLD technologies.

This study aims to fill that gap by applying a CBA approach. The CBA framework allows for a more comprehensive evaluation by including not only costs but also environmental benefits and social impacts. This broader perspective of the CBA may lead to a different valuation of MLD systems and provide new insights into their potential role in sustainable hydrogen production. Although both MLD and ZLD are promising technologies for seawater treatment, this study focuses exclusively on MLD systems for the CBA. This choice is based on the relatively lower technological complexity of MLD systems, which makes them more feasible to analyse within the 21-week timeframe of this research.

Specifically, this research conducts two CBAs to evaluate the economic and environmental performance of MLD systems. The first CBA assesses an MLD configuration that uses a single desalination technology which is the thermal water desalination MED. The second CBA examines a hybrid MLD system that combines a membrane water desalination NF as preconcentration for MED, to investigate whether integrating multiple technologies in series enhances overall efficiency and cost-effectiveness. The MED and NF were selected based on their relatively low energy consumption and operational costs compared to alternatives such as MSF and RO. The synergy between these two technologies is still novel which gives the study a renewed focus within the MLD industry.

The analysis follows a mixed-method approach, combining a literature review with expert interviews. The literature review identifies known cost components and the expert interviews validate these and identify additional ones. The interviews validate costs and add unknown costs. By comparing these two CBAs, the study aims to determine whether combining desalination technologies leads to improved cost-effectiveness and sustainability. The scope of the analysis is limited to commercially available technologies and is constrained by the 21-week research period. The following research question is formulated:

"What are the Societal Costs and Benefits of Minimal Liquid Discharge (MLD) technologies, with a focus on Nanofiltration (NF) and Multi-Effect Distillation (MED), for hydrogen production?"

In the following introductory sections, the discussed academic knowledge gap is identified through a structured literature review. This review will clearly show the current state of research, highlight what is missing, and justify the main research question presented. Understanding this gap is essential to demonstrate the relevance and necessity of this study. After identifying the knowledge gap, the methodology is outlined. This section explains the sub-questions used to answer the research question, including the reason behind the chosen methods and how they are applied. Before diving into these sections, the next part discusses the relevance of this research within the context of the MSc programme in Complex Systems Engineering and Management (COSEM) at TU Delft. This reflection highlights how the study aligns with the programme's interdisciplinary focus on addressing complex societal and technological challenges.

Relevance to COSEM

This section outlines the relevance of the research to the COSEM master's program and demonstrates how it aligns with the required competencies. COSEM encourages students to look beyond the technical design of societal challenges and to consider the broader context for successful implementation in the industry, using an interdisciplinary and systems-oriented approach. The program focuses on tackling complex societal issues through the integration of technology, policy, and management. A relevant societal challenge is the increasing global water scarcity, which is closely linked to the urgent need for sustainable energy solutions. This research addresses both challenges by exploring how desalination technologies can support green hydrogen production and contributes to two important pillars of sustainable development: water security and the sustainable energy transition.

From a technological perspective, the study investigates two water desalination systems that aim to minimise environmental impact while maximising water recovery. These technologies are not only technically complex, but also require system-oriented thinking for the integration into the industry. Additionally, the research aligns directly with the energy track of the COSEM program, as it explores how desalinated water can serve as a sustainable water input for hydrogen production.

From a policy perspective, the study applies a CBA to evaluate and compare the two water desalination technologies. This method monetises both the costs and the benefits, including environmental benefits. The use of a CBA reflects on the focus of COSEM on integrating economic reasoning into the evaluation of technological and policy alternatives.

From a management perspective, the research involves strategic decision-making in defining the cost elements of the CBA and understanding the results to make clear and well-supported conclusions and recommendations. This requires leadership, analytical thinking, and the ability to balance multiple stakeholder interests.

The research adopts a socio-technical systems approach, which is a core principle within COSEM. It acknowledges that technological and social components are interconnected and mutually influential. Rather than isolating technical innovation from the societal context, the study integrates both dimensions into the analysis.

This research is creative in its use of a CBA to evaluate MLD systems. While most studies rely on TEA, this project broadens the analytical scope by incorporating environmental and social benefits. This approach provides a more comprehensive understanding of the value of these technologies, which is essential for decision-making in complex systems. In summary, this research embodies the COSEM core components by combining engineering, economics, and management to address societal challenges in a structured, interdisciplinary, and systems-oriented approach.

2. Academic Knowledge Gap

This chapter aims to identify and define the academic knowledge gap related to the societal challenge discussed in the introduction, that determines the reason for this research. In the introduction, the societal challenge is explained about the growing scarcity of freshwater, which poses a barrier to the large-scale production of green hydrogen. One solution is the use of MLD technologies to alter seawater into ultrapure water suitable for electrolysis. However, the MLD technologies are often considered technically complex and expensive. The high costs pose a challenge for the implementation process and are caused by the many required techniques and high energy consumption.

To better understand the current state of knowledge and to position this research within the academic field, a literature review is conducted. A literature review is a helpful tool for researchers to obtain a structured overview of the literature and assists in making the knowledge gap explicit (Van Wee & Banister, 2015). Therefore, this chapter contributes to the academic foundation of the thesis by clarifying what is already known but most importantly what is still missing.

The review focuses on studies related to MLD and ZLD systems and reveals that most existing research evaluates these systems with TEA. While TEA provides useful insights into technical feasibility and economic performance, it often overlooks broader societal and environmental impacts. Alternative economic evaluation methods such as Cost-Effectiveness Analysis (CEA) and Life Cycle Analysis (LCA) are rarely applied in the studies and the economic evaluation method CBA is not used at all.

This chapter adds value to the research by establishing the academic relevance of the research topic, identifying the dominant methodologies used in the applicable literature, highlighting the lack of CBA applications in the evaluation of MLD and ZLD systems, and determining the knowledge gap which assists in formulating the research question. In summary, this chapter determines the foundation for the research by clearly defining the academic gap and explaining why this study offers a novel and valuable contribution to the field by applying a CBA to MLD systems.

As a guide, the chapter begins by defining the key concepts that were used as search terms to retrieve relevant literature from academic databases. This is followed by a detailed explanation of the search strategy which is used to collect the relevant studies to determine the knowledge gap. The results are presented in an overview table, which highlights the absence of CBA in evaluating the profitability of MLD and ZLD technologies. The limitations of the literature review are also outlined which could impact the interpretation of the results.

2.1. Definition of Concepts from Economic Assessment Literature Review

This section defines the key concepts that form the foundation of the literature review. These concepts are essential for constructing effective search terms used in the chosen academic databases. Clearly defined concepts improve the literature search and lead to more targeted results. Moreover, establishing the definitions provides a consistent framework for comparing and analysing studies, which is crucial for identifying the academic knowledge gaps. An overview of the key concepts desalination, brine, ZLD, MLD, and economic assessment studies is also provided in Appendix B.

2.1.1. Desalination

Desalination is the process of removing excess salt and other dissolved chemicals from seawater to reduce salt concentrations and produce fresh water (Darre and Toor, 2018). Desalination of brackish water and seawater has rapidly expanded to help address water scarcity. There are two main desalination processes as shown in table 1, thermal based and membrane based processes. Thermal desalination requires heat to operate and is generally realised by phase change such as evaporation or crystallisation (Mika et al., 2024). Membrane technologies are separation mechanisms that use membranes to allow certain molecules to cross and others to stop. Thermal based technologies tend to be used in regions where water salinity levels are high and energy costs are low (Darre and Toor, 2018). Membrane based technologies are popular for their lower energy consumption, lower environmental footprint and more flexible capacity.

Table 1 : Desalination methods (Mika et al., 2024)

Desalination method	Desalination Technologies
Thermal methods	• Multiple-effect distillation (MED) • Multi-stage flash (MSF) • Thermal vapour compression (TVC) • Mechanical vapour compression (MVC) • Adsorption desalination (AD) • Solar distillation (SD) • Humidification-dehumidification (HDH) • Freeze crystallisation (FC)
Membrane Methods	• Reverse osmosis (RO) • Electrodialysis (ED) • Nanofiltration (NF) • Forward osmosis (FO)

2.1.2. Brine

Brine is the byproduct of the water desalination process and has a severe impact on the environment due to its high salinity (Panagopoulos et al., 2019). Viable and cost-effective brine management systems are needed to reduce the environmental impact of brine. Currently, there are different brine management methods which can be divided into discharge of brine into the environment, brine reduction, and recovery of metals and minerals (Mika et al., 2024). The most common solution is to discharge brine into the environment through surface water discharge, sewer discharge, deep-well injection, evaporation ponds, and land application (Mika et al., 2024; Panagopoulos et al., 2019; Panagopoulos A. and Giannika V., 2024-b). However, this generates local water pollution and has a negative impact on the environment, such as on marine life. ZLD and MLD technologies are desalination processes that aim to minimise the amount of waste generated.

2.1.3. Zero Liquid Discharge

ZLD technologies extract all the fresh water from the feed water during the desalination without any discharge into the environment (Mika et al., 2024). ZLD and MLD technologies can replace the current disposal methods as shown in figure 2. The difference between desalination and ZLD is that desalination aims to extract freshwater from feed saline water and ZLD also focuses on purifying the byproduct brine when producing fresh water to recover minerals and to reduce the toxicity.

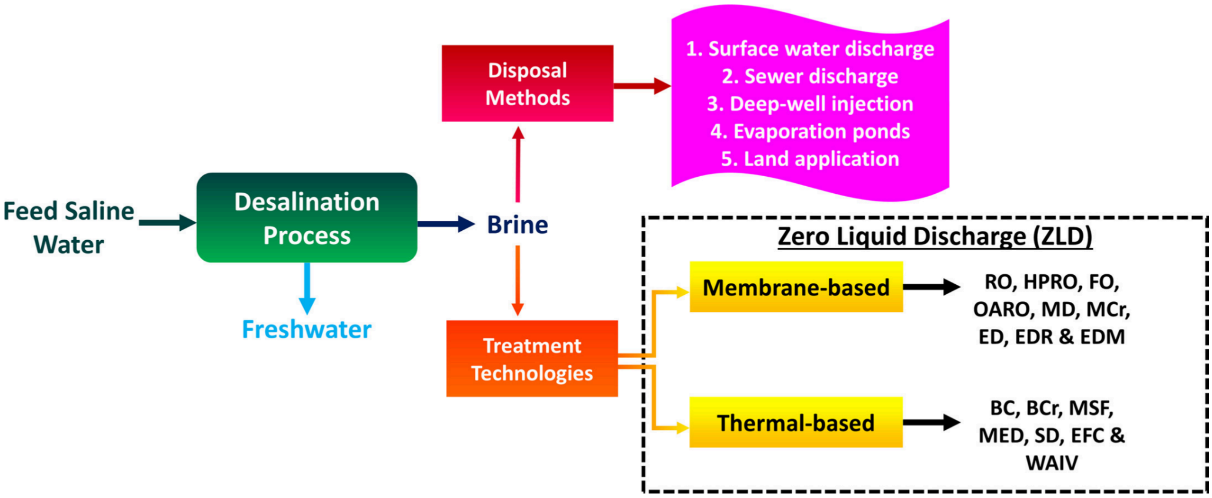


Figure 2 : Graphical abstract of Brine Management (Mika et al., 2024)

Figure 3 shows the general four steps for a typical ZLD treatment process which contains pretreatment, preconcentration, evaporation, and crystallisation (Xiong and Wei, 2017). Pretreatment is used to protect the technologies in the preconcentration by removing potentially problematic particulates from the water. It is necessary to remove precursor ions and potential organic foulants from brine to protect the downstream processes (Semblante et al., 2018). By eliminating these compounds, pretreatment also minimizes downstream treatment requirements. There are several pretreatment options such as chemical precipitation, ion exchange and nanofiltration.

Preconcentration involves thermal or membrane processes to recover water and reduce the volume of the concentrated liquid waste as much as possible (Xiong and Wei, 2017). Evaporation and crystallisation eliminate the final concentrated liquid waste through phase change with the input of energy. It is evident that the technology almost always involves a combination of membrane and thermal-based technologies.

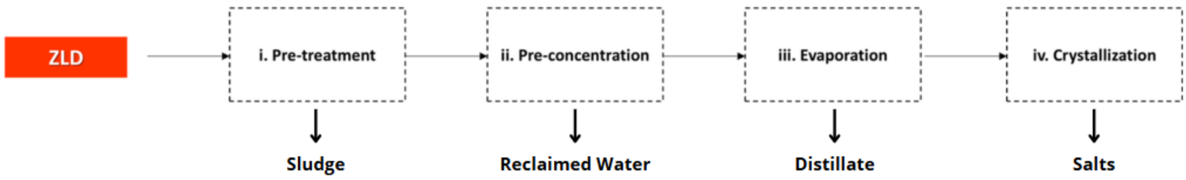


Figure 3 : General steps of a ZLD flow sheet (Panagopoulos and Michailidis, 2025; Xiong and Wei, 2017).

2.1.4. Minimum Liquid Discharge

MLD processes reach a water recovery of 80% in comparison with ZLD processes that reach water recovery up to 95-99% (Morgante et al., 2024-a). This is because MLD does not include evaporation and crystallisation as visualised in figure 4. ZLD is therefore more sustainable but also more complex (Panagopoulos et al., 2019). Pretreatment is a crucial step in water desalination and therefore implemented in both ZLD and MLD technologies because the membranes are sensitive to scaling and fouling (Morgante et al., 2024-a; Mika et al., 2024). Scaling is the formation of salts and minerals on the surface membranes and can lead to reduced membrane permeability, higher operational pressure, and increased energy costs. Fouling refers to the undesired accumulation of solid substances on the surface of membranes and also reduces the efficiency of the membranes, lowers water quality, and can lead to frequent cleaning or even replacement of the membranes.

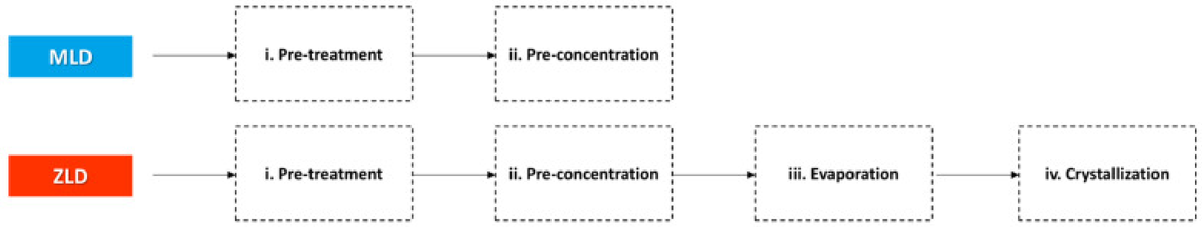


Figure 4 : MLD and ZLD configuration (Panagopoulos and Michailidis, 2025)

2.1.5 Economic Assessment Study

The economic assessment studies address the main criteria on whether to approve a ZLD or MLD project (Li, 2022). There are different methods to undertake an economic assessment such as Techno-Economic Analysis (TEA), Cost-Benefit Analysis (CBA), Cost-effectiveness analysis (CEA) or a Life Cycle Analysis (LCA). Each method has its own elements to determine economic performance.

In contrast, a Multi-Criteria Analysis (MCA) is not primarily intended to assess economic performance. Instead, it evaluates the overall desirability of policy options by incorporating both quantitative and qualitative criteria (Mouter et al., 2020). MCA offers flexibility, but it also introduces subjectivity due to the lack of a strict theoretical framework. Therefore, when defining economic outcomes, it is preferable to rely on structured methodologies such as CBA or TEA. These methods follow standardized procedures and provide clear indicators.

1. *Techno-Economic Analysis (TEA)*

A TEA investigates the economic and technical elements of a system to show how the technology could be competitively delivered in the market (Panagopoulos A. and Giannika V., 2024-b; Langhorst et al., 2022). For MLD and ZLD this means various direct and indirect component costs such as capital expenditures (CAPEX) and operational expenditures (OPEX).

2. *Cost-Benefit Analysis (CBA)*

A CBA is defined as the process used to measure the benefits of a decision minus the costs associated with taking that action (McCord et al., 2021). The aim is to form a social perspective on the project and take all the positive and negative externalities into account in monetary terms (Koopmans and Mouter, 2020). CBA offers a consistent analytical framework for decision-making and is designed to assist decision-makers by determining which option should be selected in order to maximise social welfare (Moran and Sherrington, 2007). When conducting a CBA, it is important to determine a baseline against which to evaluate the costs and benefits of the project. For an MLD or ZLD system, the baseline is discharging brine into the environment.

3. *Cost-Effectiveness Analysis (CEA)*

CEA is a method to combine the net cost of a given invention and its outcomes with its effectiveness, then use the resulting cost-effectiveness ratio to compare that intervention to interventions that are aimed at accomplishing the same goal (Gift and Marrazzo, 2008; McCord et al., 2021). CBA and CEA are similar methods but CBA is a higher-level analysis compared to CEA (Li, 2022).

4. *Life Cycle Analysis (LCA)*

LCA looks at all the energy and material flows involved in a system or process to minimise the negative environmental impacts (Langhorst et al., 2022). It is typically used to compare the environmental impacts of different products that perform the same functions (Schleisner, 2000). When assessing the environmental impacts of systems like ZLD, it is crucial to account for the energy-related emissions throughout the entire life cycle of the materials and technology. In monetary terms all negative impacts from the operation phase to the disposal of the technology at the end of its lifetime is included in such an analysis.

2.2 Search Strategy of Economic Assessment Literature Review

After identifying the key concepts to this literature review, a structured search strategy was developed to systematically collect the relevant academic sources. This strategy ensures that the literature review is both clear and repeatable. Scientific articles were retrieved from two major academic databases called Google Scholar and Scopus. These platforms were selected because they provide broad access to peer-reviewed literature in the fields of environmental technology and economic evaluation. All selected articles are written in English to maintain consistency and accessibility.

The search strategy was built around combinations of the previously defined key concepts. These combinations were used to construct search strings. Given the increasing academic interest and importance in water scarcity, a large number of studies are available on desalination, MLD, and ZLD technologies. It is important to note that desalination is not only applied for hydrogen production but also for freshwater production or extracting salts from seawater. To maintain a clear focus, this research concentrates specifically on seawater desalination for hydrogen production. However, this literature review focuses on all types of MLD and ZLD technologies as the review is conducted to evaluate the economic assessment studies used across the total spectrum.

Although hydrogen is important to the research scope, it was not included as a key concept in the search strings. This decision was made to keep the literature review focused on the economic assessment methods applied to MLD and ZLD technologies, rather than on hydrogen production processes. Table 2 shows the determined search strings from the key concepts. However, only the final two search strings, indicated in blue, were actually used to reduce the article hits as much as possible. Two search strings were used because search string 3 retrieved relevant articles that were not captured by search string 4. This ensures a more comprehensive coverage of the existing literature.

Table 2 : Search Terms Used for the Academic Knowledge Gap Literature Review

#	Search Strings	# Google Scholar	# Scopus
1	Seawater Desalination	352.000	14.210
2	Seawater Desalination AND [ZLD OR MLD]	3.650	71
3	Seawater Desalination AND [ZLD OR MLD] AND Economic Assessment Studies	2270	6
4	Seawater Desalination AND [ZLD OR MLD] AND [TEA OR CBA OR CEA OR LCA]	446	1

The blue search strings still have too many hits to all be evaluated. To manage the wide variety of search results in Google Scholar, an initial delimitation was conducted on the first 30 articles retrieved using search strings 3 and 4. The 30 articles were chosen because the first 10 articles were all from the researcher Panagopoulos. It is essential for identifying the academic knowledge gap to gain insight into how different researchers approach the assessment of water desalination technologies.
The initial screening involved analysis of the most recent articles after 2021, removal of duplicates from the search strings, and if the articles were peer reviewed. Further screening involved assessing the title, publication year, and number of citations. Next, the abstract and keywords of the remaining articles were reviewed. Finally, the introduction, discussion, and conclusion were examined to select the 21 most relevant articles. Notably, all selected articles from Scopus were duplicates of those found in Google Scholar. The entire literature review process is illustrated in Figure 5.

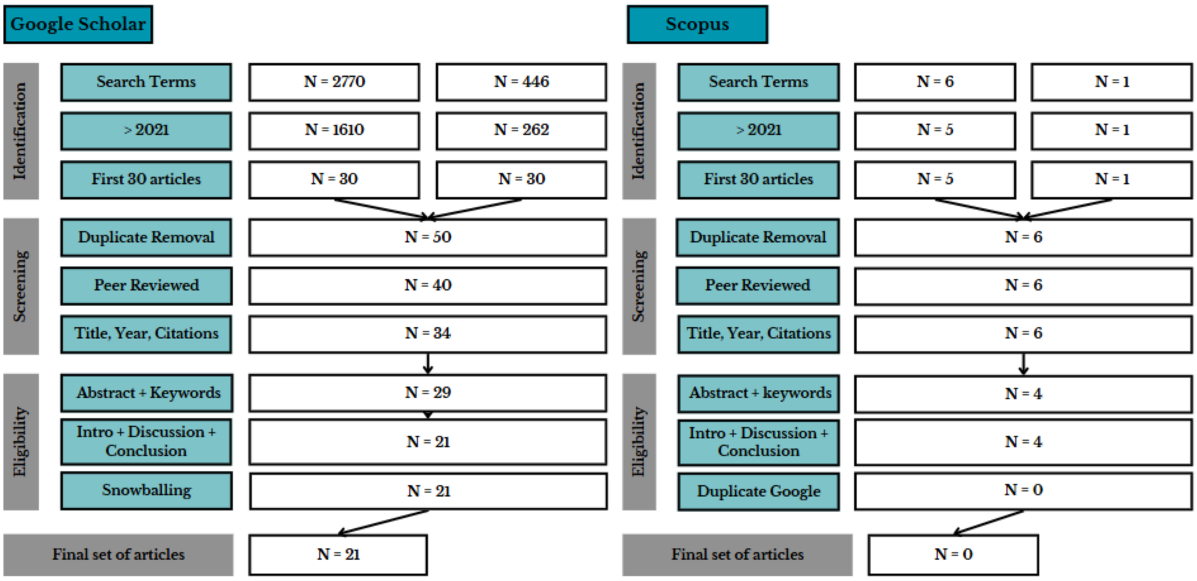


Figure 5 : Academic Knowledge Gap Literature Review Process

2.3 Results of Economic Assessment Literature Review

Table 3 presents an overview of the selected studies on ZLD and MLD systems with the corresponding economic assessment methods applied. Most articles focused primarily on TEA to evaluate the systems. This is partly because 8 articles were authored by Panagopoulos. However, 18 out of the 21 reviewed articles used TEA as the primary evaluation method. Only one study applied CEA to assess a ZLD system and 4 studies incorporated LCA. Notably, none of the reviewed articles applied CBA to evaluate ZLD or MLD systems. This absence highlights a clear gap in the literature and underscores the relevance of this research, which aims to explore the potential of CBA as an alternative and complementary evaluation method.

Table 3 : Overview of Economic Assessment Literature Review

#	Article/concept	Seawater Desalination	Brine	ZLD	MLD	CBA	TEA	CEA	LCA	Envir. assessment
1	(Panagopoulos and Giannika., 2024-a)	X	X	X	X		X			
2	(Panagopoulos and Giannika., 2024-b)	X	X	X	X		X			
3	(Cipolletta et al., 2021)	X	X	X	X		X			
4	(Panagopoulos., 2021-a)	X	X	X	X		X			
5	(Panagopoulos, 2021-b)	X	X	X	X		X			
6	(Li, C., 2022)	X	X	X				X		
7	(Panagopoulos, 2022-a)	X	X	X	X		X			
8	(Panagopoulos, 2022-b)	X	X	X			X			
9	(Panagopoulos and Giannika., 2022)	X	X	X	X		X			

10	(Panagopoulos, 2021-c)	X	X	X	X					X
11	(Morgante et al., 2024-a)	X	X	X	X		X			
12	(Shokri and Fard, 2023)	X	X				X			
13	(Micari et al., 2019)	X	X				X			
14	(Von Eiff et al., 2021)	X	X	X			X			
15	(Figueira et al., 2023)	X	X	X	X		X			
16	(Felix and Hickenbottom, 2025)	X	X	X	X				X	
17	(Alrashidi et al., 2024)	X	X	X	X				X	
18	(O’Connell et al., 2024-b)	X	X	X	X		X		X	
19	(Julian et al, 2021)	X	X	X	X		X			
20	(Grauberger et al., 2025)		X	X			X		X	
21	(Poirier et al., 2022)	X	X	X			X			

2.4 Limitations of the Economic Assessment Literature Review

The limitations of this literature review are discussed because it is essential to ensure transparency regarding the results and potential biases. By acknowledging these constraints, the reliability and interpretability of the findings can be better understood, and subjects for future research can be identified.

Firstly, the literature review was conducted within a timeframe of 21 weeks. The large number of search results from Google Scholar made it impossible to screen all available articles within this timeframe. As a result, not all potentially relevant articles could be included and that could affect the completeness of the review. Secondly, only English written articles were considered. While this decision ensured consistency and accessibility for the readers, it may have excluded valuable insights from non-English sources, thereby limiting the global perspective of the review.

A more concerning limitation is the dominance of a single author in the initial search results. 8 out of the 21 reviewed articles were authored by Panagopoulos and he only uses TEA. This concentration may have an impact on the representation of methodologies in the literature. To mitigate this, a broader selection of 21 articles was selected to include enough studies from other researchers, 13 out of 21 articles.

Another limitation lies in the diversity of ZLD and MLD technologies discussed across the selected studies. These technologies vary significantly regarding the design and cost items. Consequently, the TEA outcomes differ widely and that makes direct comparisons between systems challenging. This variation complicates the decision on a preferred MLD system for hydrogen production. Therefore, an overview is given of the ZLD and MLD technologies per selected article in table 4.

In summary, this literature review provides valuable insights into the current state of research on economic assessments of ZLD and MLD systems, but the findings should be evaluated in light of the mentioned limitations. Future studies could expand the scope by including non-English literature, screening a broader range of sources, and including an even wider variety of researchers.

Table 4 : ZLD and MLD technologies discussed in the literature review

#	Article	ZLD/MLD	Technologies
1	(Panagopoulos and Giannika., 2024-a)	ZLD	BC, HPRO, MPC
2	(Panagopoulos and Giannika., 2024-b)	ZLD	scenario 1 : MPC scenario 2 : WAIV
3	(Cipolletta et al., 2021)	ZLD/MLD	no specifics
4	(Panagopoulos., 2021-a)	ZLD	scenario 1 : RO, BC and BCr scenario 2 : NF, RO, BC1, BCr1, BC2, BCr2
5	(Panagopoulos., 2021-b)	MLD	RO, high-pressure RO, FO, OARO, MD
6	(Li, C., 2022)	ZLD	NF, MED, BCR, Multiple Feed-Plug Flow Reactor, Eutectic Freeze Crystalliser, Bi-Polar Membrane Electro-Dialysis
7	(Panagopoulos, 2022-a)	ZLD	scenario 1 : BCr scenario 2 : WAIV
8	(Panagopoulos et al., 2022-b)	ZLD	HPRO, BC, BCr
9	(Panagopoulos and Giannika., 2022)	MLD	RO and RO
10	(Panagopoulos, 2021-c)	ZLD	RO, BC, BCr
11	(Morgante et al., 2024-a)	MLD	NF, MED, MF-PFR, EP, EDBM
12	(Shokri and Fard, 2023)	single technology	RO
13	(Micari et al., 2019)	single technology	MED
14	(Von Eiff et al., 2021)	MLD	MD, MSF-Cr
15	(Figueira et al., 2023)	MLD	NF-SWRO
16	(Felix and Hickenbottom, 2025)	MLD	MD
17	(Alrashidi et al., 2024)	ZLD/MLD	ZLD/MLD trains shown in Appendix F
18	(O'Connell et al., 2024)	ZLD/MLD	7 overarching treatment train with 75 different configurations shown in Appendix F
19	(Julian et al, 2021)	ZLD	RO, SWDM
20	(Grauberger et al., 2025)	ZLD	EDC
21	(Poirier et al., 2022)	ZLD	Multi-crystallisation

2.5 Current Knowledge Gap and Research Questions

This research is driven by the clear knowledge gap identified in the literature review. The review indicated that TEAs are mostly used to evaluate the competitiveness of ZLD and MLD technologies in the water desalination sector. However, there is limited research on the broader societal and environmental impacts of these technologies. Despite the potential of ZLD and MLD for brine treatment, the literature reveals a lack of studies that integrate both economic and environmental evaluations. Several authors that were selected for the literature review emphasize the need for future research to apply different economic assessment methods, such as CBA and LCA, to better understand the full value of these technologies (Panagopoulos and Giannika, 2024-b; Panagopoulos et al., 2019).

To address this gap, it is important to first consider the available assessment methods and their respective strengths and limitations. As discussed in Section 2.1.5 Economic Assessment Study, each method offers a different perspective.

1. LCA focuses on the environmental impact of a technology throughout its entire life cycle, from cradle to grave (Langhorst et al., 2022). However, it does not include the economic performance from the TEA.
2. CEA evaluates the cost-effectiveness of a technology by comparing costs to the outcomes (Gift and Marrazzo, 2008). It includes both economic and environmental aspects in comparison with LCA. However, it is less suitable for comparing technologies with different types of outcomes.
3. CBA expresses all costs and economic, environmental, and societal benefits in monetary terms. This makes it particularly useful for comparing different technologies and understanding their overall value.

CBA is considered the most appropriate method for this study, as it enables the assessment of both the economic and societal value of MLD technologies for hydrogen production. A CBA goes beyond the scope of a traditional TEA, which typically focuses on the costs. As a result, TEA often concludes in the literature review that MLD is too expensive. In contrast, CBA incorporates the same cost categories but places them within a broader societal context, potentially revealing that the investment is economically profitable. CBA also facilitates a clear monetary comparison between different desalination technologies, making it more suitable than CEA.

Due to the limited scope and timeframe of this research, it is not feasible to analyse all ZLD and MLD configurations identified in the literature. Therefore, a selection was made initially based on two key criteria. The first criteria is the ability of the combined technologies to produce ultrapure water suitable as feedwater for electrolysis in hydrogen production. The second criteria is a high Technology Readiness Level (TRL) to ensure that all relevant cost components can be identified and assessed in the CBA. Based on these criteria, NF and MED were selected as the focus of this study. More considerations were used for the justification for this selection and is explained in Chapter 4. The research question will be:

"What are the Societal Costs and Benefits of Minimal Liquid Discharge (MLD) technologies, with a focus on Nanofiltration (NF) and Multi-Effect Distillation (MED), for hydrogen production?"

To answer the research question, the research approach and 7 sub-questions need to be determined. To effectively address the main research question, it is essential to break it down into sub-questions. Each sub-question targets a specific aspect of the research and is associated with its own methodology and data requirements. This structured approach clarifies the research process and ensures that all necessary components are systematically explored. The following chapter, called methodology, will give a comprehensive overview of how this study will answer the main research question through explaining and determining the research approach and the sub-questions.

3. Methodology

A structured methodology is needed to answer the research question; *What are the societal costs and benefits of Minimal Liquid Discharge (MLD) technologies, with a focus on Nanofiltration (NF) and Multi-Effect Distillation (MED), for hydrogen production?* This chapter presents the methodological framework of the study and explains how the research is structured to answer the main research question. A clear methodology is essential to ensure that the research is reliable, transparent, and reproducible.

First, the research approach is outlined which adopts a mixed methods design combining both quantitative and qualitative methods. This approach allows for a comprehensive analysis by integrating academic knowledge with insights from the industry through expert interviews. Secondly, the 7 sub-questions are discussed that break down the main research question into manageable parts. Each sub-question uses its own method to collect the needed information to contribute to the overall research in a logical order.

Finally, the 6 normative value judgements are explained and answered which are needed to conduct a CBA. The judgements include decisions about whose preferences count in the CBA, how impacts are valued, and which discount rate is applied. The study ensures transparency and allows readers to interpret the results within the defined ethical context by making these assumptions explicit.

3.1 Research Approach

The research approach is needed to form the basis for further developing the research design and needs to fit the main research question. The research approach will break down the research question into sub-questions. This research is a mixed method approach because the CBAs will be conducted through quantitative and qualitative research (Creswell et al., 2011). Quantitative research test theories by examining relationships between measurable variables. Qualitative research focuses more on individual experiences and meanings in the real-life industry. The mixed method approach combines the strengths of both qualitative and quantitative research.

The cost items of the CBA are collected with quantitative research through a literature review. A literature review is a helpful tool for researchers to obtain a well-structured overview of the literature and assists in making knowledge gaps explicit (Van Wee and Bannister, 2015). The literature review will assist in determining how the cost items are valued in other studies and how that is applicable for this research. The cost items will be checked with interviews and the knowledge gaps will also be filled by these interviews. The interviews are qualitative research, making this research a mixed method approach.

The quality of the results in quantitative research relies on the reliability and validity of the instruments used and can be a limitation as important insights might be missed (Creswell et al, 11). However, by conducting interviews with experts who work in the field, the static data can be analysed within real-life contexts to ensure that the CBA includes all relevant insights. This mixed method process merges research results to form a complete analysis.

As mentioned in the introduction, to effectively address the main research question, it is essential to break it down into sub-questions. Each sub-question targets a specific aspect of the research mentioned above and is associated with its own methodology and data requirements. The sub-questions guide a logical order of the research and lead to a comprehensive answer of the main research question. The following section presents the sub-questions and explains how each contributes to addressing the overall research.

3.2 Research Sub-Questions

As mentioned, this study adopts a mixed methods approach by combining both quantitative and qualitative research methods. However, to address the main research question in a structured and manageable way, the main research question has been divided into 7 sub-questions. These sub-questions serve as building blocks that guide the research process step by step. The order of the questions is so that each sub-question builds upon the findings of the previous one, but also provides essential input for the questions that follow.

In this section, each sub-question is determined and explained in detail. Every sub-question explains the included relevant technologies, used research methods, types of collected data from each research method, and their contribution to the overall research. Table 5 presents a structured overview of the sub-questions, including the methods used, the content gathered, their connections, and the chapters in which the questions are answered.

1. *What are the technical and economic characteristics of implementing NF and MED technologies for hydrogen production?*

The first sub-question aims to define the composition of the MLD system, as the academic literature review revealed that no MLD system has been identified as the most suitable for producing ultrapure water for hydrogen electrolysis. Addressing this sub-question is essential, as it lays the technical and economic foundation for the subsequent CBA. So to conduct a good CBA, it is necessary to first determine the key characteristics of the MLD system, including the type of desalination technologies used, the order in which these technologies are applied, the operational scale of the system, the input and output flows, and the resources required for the operation. These elements are critical for identifying the relevant cost items and performance indicators that will be used in the economic evaluation.

This sub-question will be addressed through desk research. Desk research is collecting and analysing existing information that has been published by other researchers. As existing data could be outdated from the industry or have some lack of specificity for this research, the findings will be discussed in the mentioned expert interviews to improve the composition of the MLD system. This mixed-method approach ensures both theoretical grounding and industry applicability.

By answering this sub-question, the research establishes a clear reasoning for selecting NF and MED as the technologies for the MLD system. It also provides the technical and economic context needed to define the cost items for the CBAs. In doing so, it directly contributes to answering the main research question by clarifying what is being assessed and why these technologies are relevant for hydrogen production.

2. *What are the environmental costs associated with not implementing NF and MED in seawater desalination for green hydrogen production?*

This second sub-question follows the first sub-question that focused on identifying the technical and economic characteristics of NF and MED technologies. This second sub-question shifts the focus to a broader economic perspective. It aims to assess whether implementing an MLD system using NF and MED for ultrapure water production is beneficial by including social and environmental benefits.
To answer this sub-question, the structure of the CBA must be determined including the type of CBA, the relevant cost and benefit categories, and the steps required to execute the CBA systematically. A specific focus lies on identifying and monetizing the environmental effects, such as brine reuse. These elements are essential for capturing the societal impact of the MLD system which makes the difference between a CBA and a TEA.

The method used to formulate the CBA is desk research, which involves collecting and analysing existing data from academic literature. The findings from the literature will be validated and adjusted through expert interviews since secondary data may be outdated or not fully aligned with the specific context of this study. These interviews help ensure that the chosen cost and benefit items include all relevant items to form a comprehensive CBA.

Together, the first and second sub-questions provide a complete foundation for evaluating the societal value of the chosen MLD technologies. The first sub-question defines the technical operation and the second sub-question assesses whether it is beneficial from a societal perspective. This includes evaluating the potential environmental gains, which are important to evaluating the MLD system differently from a technical analysis. This sub-question contributes directly to the main research question by providing a structured, evidence-based evaluation of the societal impact of NF and MED technologies.

3. *What are the technical and economic costs of implementing MED technologies?*

This third sub-question builds directly on the outcomes of the first two sub-questions. After defining the technical operation of the MLD system and establishing the structure and scope of the CBA, this sub-question focuses on identifying and quantifying the technical and economic cost components associated with implementing the MED technology.

To answer this sub-question, a literature review will be conducted. The key concepts for this literature review are the determined categories of the CBA framework defined in sub-question 2. This method is appropriate because it allows for a comprehensive overview of existing academic knowledge regarding the cost structure of MED systems. However, not all cost data may be available in the literature and expert interviews will be used to validate the findings and fill in any knowledge gaps.

This sub-question contributes directly to the execution of the first CBA with the standalone MED determined in sub-question 6. By identifying the full range of technical and economic costs of the MED, it ensures that the CBA for the MED system is based on accurate and complete input data.

Moreover, this sub-question assists sub-question 6 and 7 to compare the determined CBAs with TEA findings, which characterize MLD systems as costly.

4. *What are the technical and economic costs of implementing NF technologies?*

This fourth sub-question also builds directly on the outcomes of the first two sub-questions. After defining the technical operation of the MLD system and establishing the structure and scope of the CBA, this sub-question focuses on identifying and quantifying the technical and economic cost components associated with implementing the NF technology.

To answer this sub-question, a literature review will be conducted. The key concepts for this literature are the determined categories for the CBA from the second sub-question without the benefits. This is because the NF technology is not able to directly produce ultrapure water for the electrolyser. Only the CAPEX and OPEX of the NF can be determined and the output needs an additional technology to produce the ultrapure water for making hydrogen. This sub-question solely is researched to assist sub-question 5.

The literature review is an appropriate method because it allows for a comprehensive overview of existing academic knowledge regarding the cost structure of NF systems. However, not all cost data may be available in the literature and expert interviews will be used to validate the findings and fill in any knowledge gaps.

This sub-question contributes to the execution of the second CBA with the NF-MED combination determined in sub-question 7. By identifying the full range of technical and economic costs of the NF, it ensures that the CBA for the NF-MED system is based on accurate and complete input data. This sub-question is needed to determine sub-question 5.

5. *What are the technical and economic costs of implementing the combined NF-MED technologies?*

This fifth sub-question builds on the outcomes of sub-questions 3 and 4 and uses the characteristics determined in sub-question 1 and 2 to determine the effects of the MLD in synergy. After defining the technical operation of the MLD system and establishing the structure and scope of the CBA, this sub-question focuses on identifying and quantifying the technical and economic cost components associated with implementing the NF-MED technology.

To answer this sub-question, the literature reviews of sub-questions 3 and 4 are used. The parameters for this literature are the determined categories for the CBA from sub-question 2. This method is appropriate because it allows for a comprehensive overview of existing academic knowledge regarding the cost structure of the NF-MED system. However, not all cost data is available from the desk research and the conducted literature reviews, because the technology combination is quite new. Therefore, expert interviews will be used to validate the combined literature reviews and fill in any knowledge gaps.

This sub-question uses sub-question 3 and 4 to directly contribute to the execution of the second CBA determined in sub-question 7. By identifying the full range of technical and economic costs, it ensures that the CBA for the NF-MED system is based on accurate and complete input data. Additionally, it enables a comparison between TEA results and the broader CBA, now that societal and environmental costs are also considered in the literature review.

6. *What is the cost-benefit analysis of the Minimal Liquid Discharge technology implementing only MED?*

This sixth sub-question builds directly on the outcomes of sub-questions 1, 2, and 3. After defining the technical operation of the MLD system in sub-question 1, establishing the structure and scope of the CBA in sub-question 2, and identifying the specific technical and economic cost items for MED in sub-question 3, this sub-question focuses on applying that knowledge to make the CBA. A singular CBA for an MLD system that uses only MED is determined.

The purpose of this sub-question is twofold. In the first place to determine whether implementing MED as a standalone MLD technology is beneficial, by calculating the NPV based on the identified costs and benefits from the literature review in sub-question 3. In the second place to provide a baseline for comparison with the hybrid NF-MED system, which will be analysed in the following sub-question.

This sub-question contributes directly to the main research question by providing a complete CBA of one specific MLD operation. It also allows for a comparison with existing academic findings from TEAs, which often suggest that MLD systems are too costly. In summary, this sub-question helps determine whether MED alone can be a solution for ultrapure water production in green hydrogen systems, and sets the stage for evaluating the added value of integrating NF in the next step.

7. *What is the cost-benefit analysis of the Minimal Liquid Discharge technology NF-MED?*

This seventh sub-question builds directly on the findings of sub-questions 1, 2, 3, and 4. Sub-question 1 explained the technical functioning of the MLD system. Sub-question 2 defined the structure and scope of the CBA. Sub-questions 3 and 4 identified the specific technical and economic cost components for MED and NF. Building on this foundation, the seventh sub-question focuses on applying that knowledge to carry out the CBA.

The purpose of this sub-question is also twofold. In the first place to determine whether implementing NF and MED as an MLD technology is beneficial, by calculating the NPV based on the identified costs and benefits from the literature reviews in sub-question 3 and 4. In the second place to compare the hybrid NF-MED system with the baseline of only MED from sub-question 5.

This sub-question contributes directly to the main research question by providing a complete CBA of one specific MLD operation. It also allows for a comparison with existing academic findings from TEAs, which often suggest that MLD systems are too costly. In summary, this sub-question helps determine whether NF-MED can be a solution for ultrapure water production in green hydrogen systems and be less expensive than the standalone MED MLD technology.

In summary, the sub-questions divide the main research question into 7 manageable research parts. By dividing the research question into parts it is easier to address the overall societal challenge. The order is structured so that each sub-question builds upon the previous one. Table 5 provides an overview of the sub-questions, the relevant technologies, the methods used to answer each sub-question, the type of content collected with each method, the contribution each sub-question has to the following sub-questions, and the chapter in which each question is discussed.

Table 5 : Sub-Questions and contribution to the Research Question

#	Sub-question	Technology	Method	Content	Contribution	Chapter
1	What are the technical and economic characteristics of implementing NF and MED technologies for hydrogen production?	NF & MED	Desk Research & Interviews	MLD operation	Sub-question 2, 3, 4, 5, 6 & 7 Research question	4
2	What are the environmental costs associated with not implementing NF and MED in seawater desalination for green hydrogen production?	NF & MED	Desk Research & Interviews	General CBA framework with Social & Environmental Impact	Sub-question 3, 4, 5, 6 & 7 Research question	5
3	What are the technical and economic costs of implementing MED technologies?	MED	Literature Review & Interviews	MED CAPEX, OPEX & Benefits	Sub-question 5, 6 & 7 Research question	6
4	What are the technical and economic costs of implementing NF technologies?	NF	Literature Review & Interviews	NF CAPEX & OPEX	Sub-question 5, 6 & 7 Research question	7
5	What are the technical and economic costs of implementing the combined NF-MED technologies?	NF-MED	Sub-question 1,2, 3 & 4	NF-MED CAPEX, OPEX & Benefits	Sub-question 6 & 7 Research question	8
6	What is the cost-benefit analysis of the Minimal Liquid Discharge technology implementing only MED?	MED	Sub-question 1, 2, 3 & 5	CBA of MLD with standalone MED	Research question	9
7	What is the cost-benefit analysis of the Minimal Liquid Discharge technology NF-MED?	NF-MED	Sub-question 1, 2, 3, 4 & 5	CBA of MLD with NF and MED	Research question	10

The initial kick-off is included in Appendix E. It outlines the original research approach, sub-questions, and planned interviews. The sub-questions and interview strategy were adjusted as more information was known about the MLD system, especially regarding the water production of a standalone NF technology. Not all initially planned interviews could be conducted due to difficulties in reaching certain experts. However, alternative interviews were arranged to ensure that the knowledge gaps were filled. Appendix Q represents the anonymous summaries of the conducted interviews to protect the privacy of the interviewees.

3.3 The Six Normative Value Judgements of the CBA

After the framework of the CBA is chosen in sub-question 2, 6 normative value judgements need to be made (Mouter, 2019). Normative judgements are statements that cannot be proven or rejected by using empirical evidence. In a perfect situation, no normative statements are made to indicate whether situations are desirable or undesirable. Only positive statements are made which are value-free and do not contain any indication of how a situation should be. However, there are 6 normative questions that can only be answered through normative judgement. This is a limitation of the CBA. To reduce the limitation, the 6 judgments are important to determine before conducting the research. The assumptions will reflect certain principles that align with personal beliefs, which may not be shared by all stakeholders involved in the CBA. By presenting the values beforehand, the reader can take this into account.

1. <u>Which individuals have standing in a CBA?</u>

A CBA generally adopts an approach to social evaluation which implies that consequences for animals in this project only count when humans value them (Mouter, 2019). This approach also counts for foreigners or non-citizens. It is usually defined that a CBA only accounts for persons within a country's national boundaries. However, this approach is questioned by experts as animals and foreigners can be impacted by certain choices.

The CBAs for this study are done to determine the costs and the benefits of MLD processes and the impact of synergy for hydrogen production. The analyst does not include individuals such as animals or outsiders. For example, animals, such as marine life, must find it very important that brine is not disposed of into the sea. In a utilitarian approach both individuals then must be compensated regarding the CBA valuation of the environmental impact. However, the analyst does not value the CBA for all marine life but for the investments companies are willing to make. So, marine life is only considered based on the value that companies assign to them.

2. <u>Which preferences have standing in a CBA?</u>

After deciding which individuals have standing in the CBA, the preferences must be determined that are included in the analysis (Mouter, 2019). The companies own preference is the economic benefits of investing in seawater desalination to produce ultrapure water when water is a scarce resource. On the other hand, the companies also have altruistic preferences to positively impact their surroundings by improving the water resources and reducing the environmental impact of brine disposal.

3. <u>Which procedure is used to value impacts?</u>

Most cost items can be determined by literature reviews and expert interviews. However, not all impacts are easy to monetize, such as valuing a technology's ability to reduce environmental impact. The monetary value can be determined through the willingness of individuals to pay (WTP) for technologies that reduce environmental impact (Mouter, 2019). There are different approaches to assess individuals WTP. Private WTP represents the amount of money an individual is willing to pay for certain advantages or to reduce risks. Collective WTP involves a more joint approach and transcends the perspective of being a negligible individual when conducting a referendum-style experiment. For this study a collective WTP is involved to determine the benefits in the Netherlands of implementing an MLD system.

4. On which dimensions are standing numbers differentiated?

People can value impacts differently (Mouter, 2019). Start-ups might indicate different monetary values in comparison with multinationals. An analyst can decide to differentiate standing numbers or to comply with uniform values. Uniform values can result in serious welfare losses because a general perspective could cause opposites to not value the seawater desalination technologies. For this CBA uniform values will be used to stay consistent and not value elements differently depending on the size and morals of an individual. This is because the cost items in this CBA will not differ for individuals. Subsidies could differentiate costs but these are not within the scope of the CBA.

5. Which weight is assigned to preferences of individuals in the social welfare function?

The common approach is to use a utilitarian social welfare function to put an equal amount of weight to everybody's utility changes regardless of their current situation (Mouter, 2019). However, in theory the CBA is only conducted to have a clear cost and benefit overview of the technologies for companies. So, it is recognized that only weight is attached to companies' utility changes and animal utility changes depending on how much value the company indicates for animals.

6. Which approach is adopted to select the social discount rate?

Analysts also need to make a decision about the rate at which future cash flows should be discounted (Mouter, 2019). This is because the technology will have long-term impacts. This percentage determines the extent to which future well-being counts to current well-being. An investment is only socially profitable if it generates additional welfare and the present value of future benefits exceeds the costs (Rijkswaterstaat, n.d.). The discount rate can also be understood as the return requirement to be placed on a public investment or project from a societal point of view. The discount rate is a percentage by which expected future costs and benefits are discounted back to the base year of the project. In the Netherlands, the discount rates are predetermined depending on the sector, which was last changed and applicable from January 1 of 2021. The type of discount rate is accommodated in three different sectors; standard discount, discount rate for fixed, sunk costs and discount rate for highly non-linear income. The standard discount rate applies to all types of costs and benefits and has two exceptions; the sunk costs and the benefits that are highly non-linear with use. This is not applicable for the water desalination technologies, so for the CBAs the standard discount rate of 2,25% is used (Rijkswaterstaat, n.d.).

4. Minimal Liquid Water Desalination Technologies

The literature review on economic assessments did not explicitly identify which MLD technology is most suitable for producing ultrapure water for hydrogen production. Given the limited 21 week timeframe of this study, it is not feasible to analyse all available technologies from the literature review. Therefore, one MLD technology must be selected and defined in detail before conducting the CBAs.

Based on the review, NF and MED desalination technologies have been selected for the MLD system because this system is capable of producing ultrapure water and both technologies also have a high TRL to make them suitable for evaluating whether a CBA leads to a different conclusion than a TEA. Furthermore, NF and MED can be applied in series, so the potential synergy effects can also be assessed. This chapter elaborates on the selection process and explains all the relevant characteristics of the MLD to answer the first sub-question: '*What are the technical and economic characteristics of implementing NF and MED technologies for hydrogen production?'*

The aim of this chapter is to build a comprehensive understanding of how an MLD system can be effectively designed and optimised for hydrogen production. The structure of the chapter follows the key decisions and technical considerations involved in designing such a system. It begins by explaining the reason for selecting an MLD approach over a ZLD system. This comparison is essential to understand the trade-offs between water recovery efficiency, system complexity, and costs.

Next, the individual process steps that make up the MLD system are defined. Identifying these steps is crucial, as they form the foundation for the technical design and influence the selection of appropriate technologies. Once the process steps are established, the operational scale of the system is determined. This step ensures that the chosen technologies are dimensioned correctly and can meet the required water output and purity levels.

Following this, the specific desalination technologies are selected based on the defined process and operational parameters. These technologies are evaluated for their suitability in achieving the desired performance within the MLD framework. Finally, the chapter addresses key design choices related to the plant's operational characteristics, such as the type of fuel and electricity source. These factors influence both the environmental impact and the economic feasibility of the system.

4.1 Minimum Liquid Discharge (MLD)

This section outlines the differences between MLD and ZLD systems and explains the reason for selecting an MLD approach over ZLD. A ZLD system is more complex and includes additional treatment steps that are not only unnecessary for producing ultrapure water for hydrogen production, but also fall outside the scope of this research. To come to this conclusion, the MLD and ZLD steps must be determined compared to the needed steps for making ultrapure water.

The water desalinations steps are dependent on your feedwater and the results desired from the technology (Panagopoulos and Michailidis, 2025). For this study the water desalination technology must produce ultrapure water to serve feedwater for the electrolyser, enabling the production of hydrogen. This is done with seawater as inlet fuel. The Total Dissolved Solids (TDS) in seawater are

35.000 mg/L, whereas the TDS in ultrapure water are less than 0,5 mg/L (Ellersdorfer et al., 2023). To get this result, a water desalination technology must be used. At best, an MLD technology or a ZLD technology can be implemented to reduce environmental impacts. This section outlines the differences between selecting an MLD technology versus a ZLD technology and discusses the impact these choices will have.

A ZLD system usually has four main steps as shown in figure 4 (Panagopoulos and Michailidis, 2025). The first step is the pretreatment, followed by the preconditioner, evaporation and crystallisation. The pretreatment can have various approaches such as a membrane-based or biological-chemical technology. The purpose of the pretreatment is to get rid of impurities and extract valuable salts. The preconcentration is a membrane-based technology to recover the water and cut down on the wastewater. The purpose of the preconcentration step is to reduce some of the performance pressure on the following step. Although this step involves an additional technique, it is expected to reduce overall costs. This study will investigate this cost-saving potential. The evaporation and crystallisation steps are included to maximise the water recovery and reduce the brine production to zero. The ZLD process recovers 99% of the water (Morgante et al., 2024-a).

The MLD technology only has two steps, the pretreatment and the preconditioner, which are also shown in figure 4 (Panagopoulos and Michailidis, 2025). The MLD process therefore is not able to maximise the water recovery and still produces brine. The MLD process recovers around 80% of the water (Morgante et al., 2024; Panagopoulos and Giannika, 2022). However, this is dependent on the chosen technologies within the MLD system.

This study wants to determine the costs and benefits of using multiple water desalination techniques for producing hydrogen. To complete this study within the 21 week timeframe, it is not possible to analyse every step regarding costs and benefits. Therefore, the final crystallisation step has been omitted, as it is unnecessary for reducing brine production to zero in order to produce ultrapure water for the electrolyser. Only the costs and benefits are determined regarding the preconcentration step. Therefore, executing an MLD process is sufficient for this study. Figure 6 illustrates two MLD systems, one without and one with the preconcentration. These two systems can be compared through CBAs to determine the effect of the preconcentration.

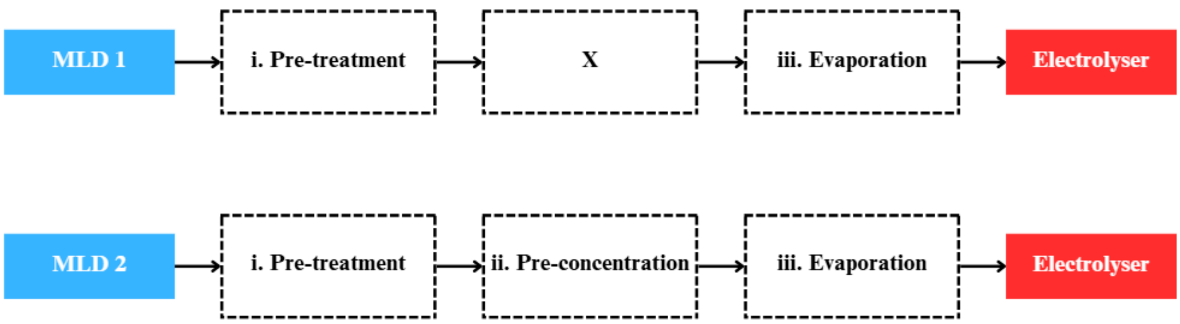


Figure 6 : MLD configuration 1 and 2 for this study

4.2 Water Desalination Technologies for the MLD System

This section presents the selected technologies for each step of the MLD system and explains the reason behind these choices. The selection is primarily based on cost-effectiveness and technical suitability for producing ultrapure water for hydrogen production. The selection process begins at the end of the MLD system, with the evaporation step, as this defines the required water quality and helps determine which upstream technologies are necessary to meet that standard.

Besides, it is important to mention that for both MLD systems the pretreatment and evaporation step have the same desalination technology. This is to be able to compare the MLD systems on the synergy effect.

4.2.1 MED as Evaporation Step

At the end of the MLD system is an electrolyser that will produce hydrogen. The electrolyser requires feedwater with a TDS quality of less than 5 mg/L (Ellersdorfer et al., 2023). The evaporation step must meet this water quality requirement. However, additional factors also determine the appropriate technology for this MLD process.

Currently, three desalination technologies are commercially available for seawater treatment in the context of hydrogen production by water electrolysis: RO, MED, and MSF (Mika et al., 2024). MSF and MED are the leading thermal-based desalination technologies, while RO is dominant among membrane technologies (Panagopoulos et al., 2019). Many studies prefer RO due to its economic performance and lower energy consumption (Mohammadi et al., 2020). However, Ellersdorfer et al. conducted a study on the operation of electrolysers using desalinated seawater produced by either RO or low-temperature MED, and found that LT-MED is 85% cheaper than RO.

This analysis, combined with MED's ability to handle high salinity feed and harsh water conditions such as seawater, makes MED the optimal technology for the initial MLD system without preconcentration (Ortega-Delgado et al., 2022; Prajapati et al., 2022). Although both MSF and MED produce high-quality freshwater through steam and require minimal pretreatment, MED is preferred over MSF due to its lower energy requirements for producing a cubic meter (m^2) of desalinated water (Panagopoulos et al., 2019).

On average, MSF requires 30 kWh/m^3, whereas MED requires only 13.5 kWh/m^3 (Mohammadi et al., 2020). The significant difference in energy consumption is because the MED reuses steam in the evaporation rooms and operates at a lower temperature around 70°C, while MSF does not reuse steam and operates around 100°C. The key advantage of MED is its operation below atmospheric pressure, which lowers the boiling point of water. As a result, less steam is needed to achieve evaporation, making MED more energy efficient (Manesh et al., 2021). These characteristics enable MED to produce the same volume of freshwater as MSF, but with lower energy input.

For the first MLD system, MED has been chosen as the water desalination technology. Consequently, the evaporation step in the second MLD system must also utilise MED to accurately analyse the costs and benefits of a preconcentration step.

4.3.2 NF as Preconcentration Step

In the second MLD system, the preconcentration step is included to lighten the burdens of the evaporation step (Panagopoulos and Michailidis, 2025). Namely, the MED suffers from scaling and fouling and could use the preconcentration step to reduce this (Mika L. et al., 2024). Scale formation in the thermal desalination unit is caused by high operating temperatures, which reduce the solubility of salts such as Ca^{2+}, Mg^{2+}, and SO_4^{2-} in the seawater feed stream (Ortega-Delgado et al., 2022). The reduction of the divalent ions gives the MED the ability to operate at higher temperatures which increases the performance of the thermal desalination. The prevention of scale formation is the main purpose of the preconditioner for the second MLD system.

NF is a membrane based water desalination and effectively removes the bivalent ions Ca^{2+} and Mg^{2+} while being less effective at removing monovalent ions like Cl^- (Sztekler et al., 2024).Due to this selective ion separation, NF is not only suitable as preconcentration but is also increasingly used as a pretreatment step in desalination processes (Elsaid, 2020). This makes NF particularly valuable in MLD systems aimed at freshwater production and mineral recovery. NF membranes can separate divalent ions into the retentate stream and monovalent ions into the permeate stream, enabling the extraction of different salts (Morgante et al., 2024-a).

RO membranes are also able to effectively remove the bivalent ions Ca^{2+} and Mg^{2+} (Curto et al., 2021). However, RO membranes do not only withhold bivalent ions but withhold all ions, including monovalent ions as one stream. Depending on the purpose of the preconcentration, RO or NF is more effective.

For the second MLD system of this study, the preconcentration must reduce the bivalent ions to ease the burden on the MED, and remain cost-efficient. Therefore, NF is chosen as preconcentration. It has the appropriate characteristics, is less costly because of the low energy requirements compared to RO, and can support the MLD system in future developments towards recovering salts (Abushawish et al., 2023; Morgante et al., 2022). However, a downside of NF is membrane fouling, which also occurs with RO membranes.

4.3.3 MMF as Pretreatment Step

Both MLD systems start with a pretreatment. A pretreatment must be implemented to filter the sand and sludge from the seawater and reduce the maintenance on fouling of the preconcentration. UF is a very popular membrane technology for this step (Abushawish et al., 2023). They are cost-effective and have a good removal capability of silt, suspended organics and microbes from the seawater. However, UF also suffers from membrane fouling which affects the performance of the technology. Therefore, MMF is added as a pretreatment to filter the big particles of the sea, reduce the fouling of the NF, and extend the lifetime of the MLD system.

Based on the identified process steps of the MLD and the selection of the most cost-effective technologies, figure 6 can now be filled as illustrated in figure 7.

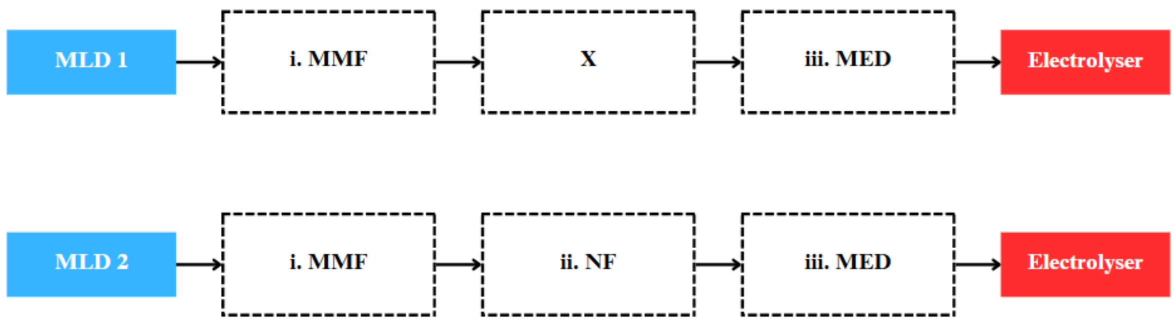


Figure 7 : Filled MLD configuration 1 and 2

4.4 Operation Scale of MLD System

After establishing the reason for selecting an MLD system and outlining the steps to produce ultrapure water for the electrolyser, it is crucial to determine the operational scale of the plant before defining the parameters of the techniques. This makes it easier to understand the decisions of the operation. To determine the scale at which the plant should operate, it's important to start from the end of the system and work backwards through each stage of the process. So, the scale of the electrolyser to produce hydrogen must be determined first. This reverse approach helps ensure that every step is properly sized and aligns with the final requirements.

The European Green Deal states the ambition to install at least 40 gigawatt (GW) of renewable hydrogen in 2030 (ISPT, 2020). To comply with the Green Deal, the Netherlands has started several projects. The largest project in the Netherlands is NortH2, which was launched in 2020 to investigate the feasibility of large-scale production of green hydrogen in the Northern Netherlands (RWE, n.d.). The current plan is to produce 1 GW of electrolyse capacity for the year 2027 and 4 GW in 2030. In addition to the NortH2 electrolyser, several other projects are planned in the Netherlands;

1. The HyNetherlands Project in Eemshaven which aims for an electrolyser capacity of 100 MW in 2028 and the capacity to grow to 1.85 GW in 2035 (HyNetherlands, n.d.).
2. Air Liquide's ELYgator project in Maasvlakte which aims for an electrolyser capacity of 200 MW in 2027 (Air Liquide, 2025-a).
3. Air Liquide's CurtHyl project in Maasvlakte 2 which aims for an electrolyser capacity of 200 MW in 2028 (Air Liquide, 2025-b).

All projects are designed for the electrolyser capacities to grow, so the 100 and 200 MW electrolysers are not the ultimate goal of the project but an intermediate step towards achieving greater capacity. The Maasvlakte 2, in the Port of Rotterdam, is a designated location for electrolyser projects that intend to expand. The Maasvlakte and the Botlek are also strategic locations due to their access to renewable energy, waste heat, and the distribution channels for hydrogen. The Conversion Park will house large-scale hydrogen production units, such as CurtHyl, leading to synergies and economies of scale (Van Wijk et al., 2019).

For this study, an electrolyser capacity of 100 MW is considered, in comparison to the capacities of existing projects. The MED, NF, and MMF technologies need to be analysed to ensure they can adequately supply this size electrolyser. Rough indications are calculated in the following sections below to determine the plant size. To determine the scale, parameters are set by considering the 'worst-case scenario' or an average when multiple values are provided.

4.4.1 Operation Scale MED

The MED is placed before the electrolyser and therefore the next step in determining the operational scale of the MLD systems. As shown in figure 7, the MED receives feedwater from different sources in MLD 1 and MLD 2, which affects the overall system configuration. The first MLD receives seawater from the MMF and the second MLD receives seawater from the NF. This could have an effect on the characteristics and operational scale which will also be discussed in this section.

The operational scale of the MED is determined by the amount of water required by the electrolyser to fully utilize its 100 MW power input for hydrogen production. To produce 1 kg of hydrogen, approximately 50 kWh of energy is required (Folmer et al., 2024). Converted, the 100 MW electrolyser can generate 100.000 kWh as shown in the equation 1 below.

$$Electrolyser\ Energy\ [kWh] = 100\ [MWh] * 1000 = 100.000\ [kWh] \quad [1]$$

Therefore, the 100 MW electrolyser can produce 48.000 kg hydrogen a day as calculated in equation 2. However, the electrolyser has an efficiency of around 80%, so the actual hydrogen production is probably around 38.400 kg of hydrogen per day (Ellersdorfer et al., 2023).

$$H2\ Production\ [kg/day] = (100.000\ [kWh]\ /\ 50\ [kWh/kg\ H2]) * 24\ [h/day] = 48.000\ [kg\ H2/day] \quad [2]$$

To produce 1 kg of hydrogen, the electrolyser requires not only 50 kWh of energy but also 10 litres of water (Folmer et al., 2024; Mika et al., 2024). Therefore, producing 48.000 kg of hydrogen would require 480 m³ of water. However, due to the 80% efficiency of the electrolyser, the actual hydrogen output is 38.400 kg and means that only 384 m³ of water is required in practice. Since efficiency can vary between electrolysers and is not always directly proportional, the full water capacity is still considered in the system design to ensure operational reliability. Equation 3 presents the total water requirement, while a detailed breakdown of the calculations is provided in Appendix G.

$$MED\ Water\ Capacity\ [m^3/day] = 48.000\ [kg\ H2/day] * 0,001m^3/kg\ H2] = 480\ [m^3/day] \quad [3]$$

The Botlek houses two MED units from the company Afvalverwerking Rijnmond (AVR), each with a water capacity of 12.000 m³ per day (AVR-Rotterdam, n.d.). An MED technology of this size could produce water for an electrolyser capacity of 5 GW. This proves that an MED of 480 m³ could be implemented in the Port of Rotterdam. However, an MED system producing 1.000 m³ of water per day is considered. This parameter is chosen because it meets the needs of the electrolyser and can expand with a growing electrolyser capacity, while remaining feasible and not being overly extensive.

After determining the needed output from the MED, the needed input must be determined. The standalone MED has a recovery rate of around 30%, so the MED system needs to process at least 3.333 m³ of seawater per day to produce 1000 m³ pure water (Ellersdorfer et al., 2023). This is the case for the first MLD system, which uses untreated seawater as feed.

In contrast, the second MLD receives demineralised seawater from the NF. This pretreatment step removes a significant portion of the salts before the water enters the MED unit and results in a more concentrated brine after distillation. This increase in salt concentration is quantified by the Concentration Factor (CF). Equation 4 represents the calculation of CF.

$$CF = \frac{Cbrine}{Cfeed} \quad [4]$$

A higher CF indicates that more water has been recovered as distillate and logically leaves behind a more concentrated brine. The Recovery Rate (RR) of the MED system can be calculated from the CF using the following equation 5.

$$RR = (1 - \frac{1}{CF}) * 100\% \quad [5]$$

In the second MLD system, the CF ranges between 4 and 8, which corresponds to a recovery rate between 75% and 87.5% (Morgante et al., 2024). This demonstrates that the NF pretreatment significantly improves the performance of the MED unit. At a recovery rate of 75%, only 1,333 m³ of seawater is needed to produce 1,000 m³ of pure water and even less when the recovery rate is 87,5%.

This difference between the two MLD configurations can be addressed in two ways:

1. Adjusting the MED scale of the desalination technologies for each MLD process.
2. Maintaining the same MED scales and benefit from higher water recovery and increased output.

For this study, the MED unit scale remains unchanged. Instead, the focus is on the increased water production and economic benefit resulting from the NF pretreatment. This approach allows for a better analysis of the synergy effects and the potential advantages of integrating NF, despite its additional cost.

4.4.2 Operation Scale NF

By maintaining the same scale and benefit from higher water recovery rate, the NF must produce 3.333 m³ of demineralised water for the MED operation. To determine the operation scale, the recovery rate must be calculated first. A membrane scientist determined the recovery rate of the NF membranes to be between 80% and 90% (Membrane scientist, 2025). However, literature suggests lower recovery rates for the NF membranes (Morgante et al., 2024-a; López et al., 2025; Figueira et al., 2023). Therefore, a recovery rate of 70% is used.

Consequently, if the MED system requires an inlet water volume of at least 3.333 m³ per day, the NF permeate must also be at least 3.333 m³ per day. The permeate is 70% of the total inlet of the NF, so the seawater inlet of NF must be at least 4761,43 m³ a day. This is calculated in equation 6.

$$NF\ Water\ Capacity\ [m^3/day] = 3333\ [m^3/day]\ /\ 0,7 = 4761,43\ [m^3/day] \quad [6]$$

4.4.3 Operation Scale MMF

The inclusion of the NF impacts the operation scale of the MMF between MLD 1 and MLD 2. Again, the recovery rate must be determined to calculate the operation scale of both MMFs. The MMF recovery rate is between 90% and 98% depending on the media selection and the feed water quality (Mak Water, n.d.). A recovery rate is taken of 90%, as the feedwater has a high salinity level of 35.000 mg/L (Ellersdorfer et al., 2023). For the first MLD process, the MMF needs to filter 3333 m³ of seawater per day. For the second MLD process, it needs to filter 4761,43 m³ of seawater per day. The water input is calculated in equation 7 and equation 8.

$$MMF\ Water\ Capacity\ [m^3/day] = 3333\ [m^3/day]\ /\ 0,9 = 3.703,33\ [m^3/day] \quad [7]$$

$$MMF\ Water\ Capacity\ [m^3/day] = 4761,43\ [m^3/day]\ /\ 0,9 = 5.290,27\ [m^3/day] \quad [8]$$

Based on the calculated operation scale of the two MLDs, figure 7 can now be further filled in.

With the operational scales of both MLD systems defined, figure 7 can be further completed. The figure 8 below shows the improved flow processes. A third process is added, to show the difference between a recovery rate of 75% and 87,5% for MLD 2 (Morgante et al., 2024). In a future study, a sensitivity analysis could indicate whether a higher concentration factor and recovery rate is more profitable. For this study, the recovery rate of 75% is used.

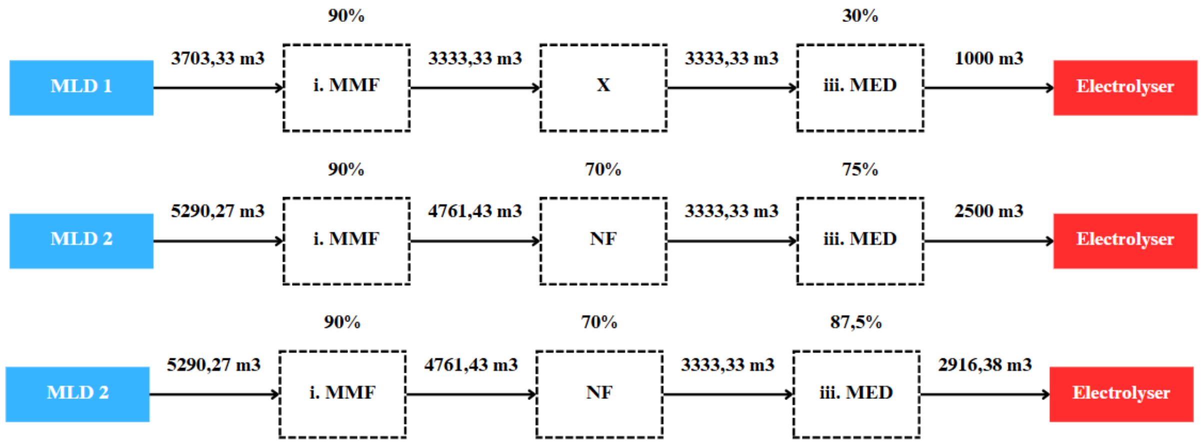


Figure 8 : Operational Scale Filled MLD configuration 1 and 2

4.4 MLD Technology Explanation

After identifying the scale of technologies for the two MLD processes, it is essential to explain each technology in detail so the characteristics are well determined. The technologies will be presented in the same chronological order by starting at the back of the MLD system with the electrolyser and followed by the MED, NF and MMF.

4.4.1 Electrolyser

Hydrogen can be produced in several ways, as shown in figure 9. One of the cleanest methods is water splitting powered by renewable energy, since it produces no carbon emissions (Nikolaidis and Poullikkas, 2017). This can be done using three main technologies, but electrolysis is the most efficient.

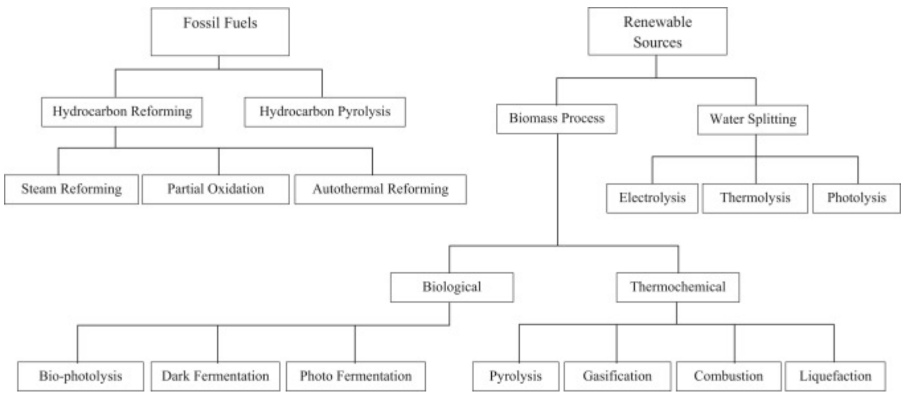


Figure 9 : Hydrogen production processes (Nikolaidis and Poullikkas, 2017)

Besides the wide variety of production methods, several technologies are also available for electrolysers. The most common technologies are alkaline (AWE), proton exchange membrane (PEM), anion exchange membrane electrolyser (AEM), and solid oxide electrolysis cells (SOEC) (Nikolaidis and Poullikkas, 2017).

The required purity of the feedwater produced in the MED depends on the electrolysis technology (Folmer et al., 2024). Table 6 shows the required water quality for each type of electrolyser. Micro-Siemens per centimetre (µS/cm) measures the electrical conductivity of a substance, indicating the amount of ions present and the water quality. AWE and PEM are commercially available (TRL 9) and are therefore most suitable for an economic assessment study (Folmer et al., 2024).

Table 6 : Water Quality per Water Electrolysis Technology (Folmer et al., 2024)

Electrolysis Technology	TRL	Energy Consumption	Water Quality	Cooling Capacity	Temperature [°C]
AWE	9	55 kWh/kgH2	< 5 µS/cm	20 kWth/kgH2	65-100
PEM	9	50 kWh/kgH2	< 0,2 µS/cm	15 kWth/kgH2	70-90
AEM	6	53 kWh/kgH2	< 0,2 µS/cm	17 kWth/kgH2	45-60
SOEC	7-8	40 kWh/kgH2	steam	<5 kWth/kgH2	650-800

The AWE is the most mature technology and uses two electrodes through which electrical conduction takes place (Folmer et al., 2024). In figure 10 it is illustrated how the cathode is the hydrogen production side and the anode produces oxygen. The AWE costs between 0,5 to 1,3 million euros per MW. The PEM also represents an advanced technology and is gaining popularity because of its efficiency and flexibility. The PEM does not use a circulating liquid through which electrical conduction takes place but rather of a proton exchange membrane to split the hydrogen and oxygen, also shown in figure 10. The PEM is more compact but costs 1 to 1,5 million euros per MW.

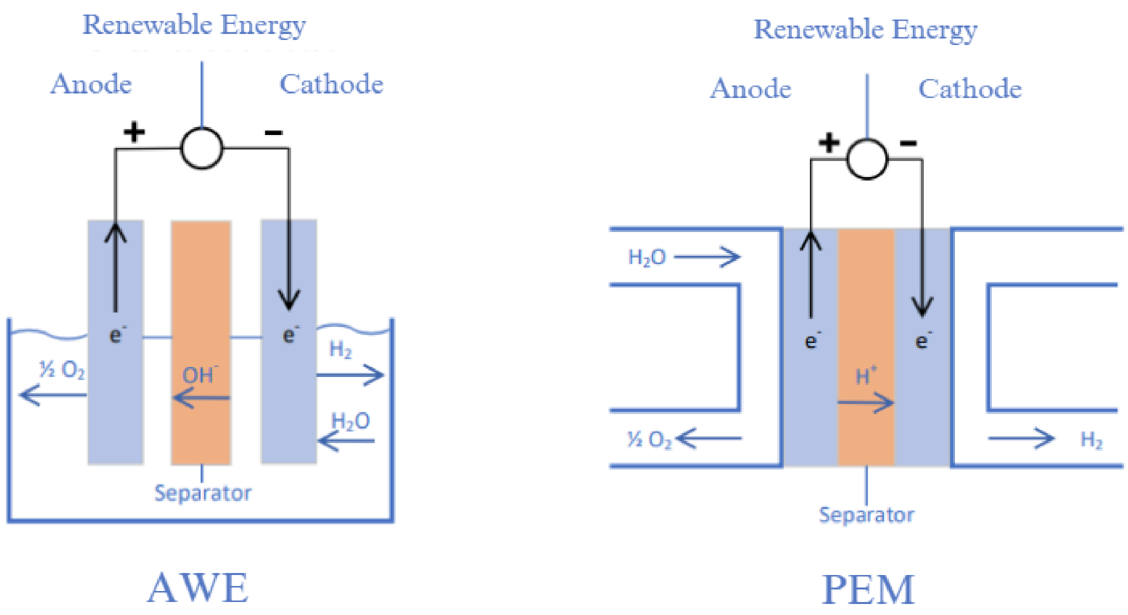


Figure 10 : PEM Electrolyser and AWE Electrolyser

For this study, the type of electrolyser does not impact the synergy effects of the water desalination technologies. However, the electrolyser must be compatible with the MLD system. The type of electrolyser could heavily impact the total CAPEX and OPEX costs of the hydrogen production. Specifically, AWE electrolysers have lower capital costs and a longer operational lifetime of up to 80.000 hours, compared to PEM electrolysers, which typically operate for 60,000 hours and have higher capital costs (Husaini et al., 2025). Assuming an annual operation of 4,000 hours for an electrolyser, PEM systems have a shorter lifespan and require more frequent replacement, increasing long-term capital costs.

In terms of operational costs, electricity accounts for approximately 64% of the Levelized Cost of Hydrogen (LCOH) (Husaini et al., 2025). While PEM electrolysers are more expensive to install, they are more energy-efficient, requiring 5 kWh less per kilogram of hydrogen than AWE systems. This makes PEM more favourable from an OPEX perspective, especially in regions with high electricity prices.

However, the most critical factor in this study is the compatibility of the electrolyser with the water quality produced by the MLD system. The MED unit delivers water with a TDS of 2–3 mg/L (Ellersdorfer et al., 2023). This is difficult to directly compare with the <5 µS/cm required for AWE and <0.2 µS/cm for PEM, due to the lack of a universal conversion between mg/L and µS/cm (Folmer et al., 2024). However, a common approximation is that 1 µS/cm is 0.55 mg/L. Based on this, the MED output is not pure enough for direct use in a PEM electrolyser without additional post-treatment. Therefore, the AWE electrolyser is chosen.

For sizing the plant, a rule of thumb of 50 kWh/kg H_2 was used, which aligns with PEM performance. Consequently, the AWE system requires 55 kWh/kg H_2 and will produce 1.818,18 kg of hydrogen per hour, instead of 2.000 kg/h. Detailed calculations are provided in Appendix G. Although the actual hydrogen production is 1818.18 kg/h, a value of 2000 kg/h is chosen for sizing purposes to align with standard industrial scales, and simplify system design. The land footprint of the AWE system is estimated at 187 by 219 m² (Business Developer, 2025).

4.4.2 Evaporation: Low Temperature Multi-effect Distillation

A standalone LT-MED is a thermal desalination process that operates at approximately 70 °C, where freshwater is extracted by condensing vapour generated from boiling seawater across a series of interconnected vessels (Mika et al., 2024; Malik et al., 2023). For the first MLD process without NF membranes, the MED process is illustrated in simplified form in figure 11. The feedwater is the seawater, the grey pretreatment box is the MMF, and the process water is the seawater after separation with sludge and sand.

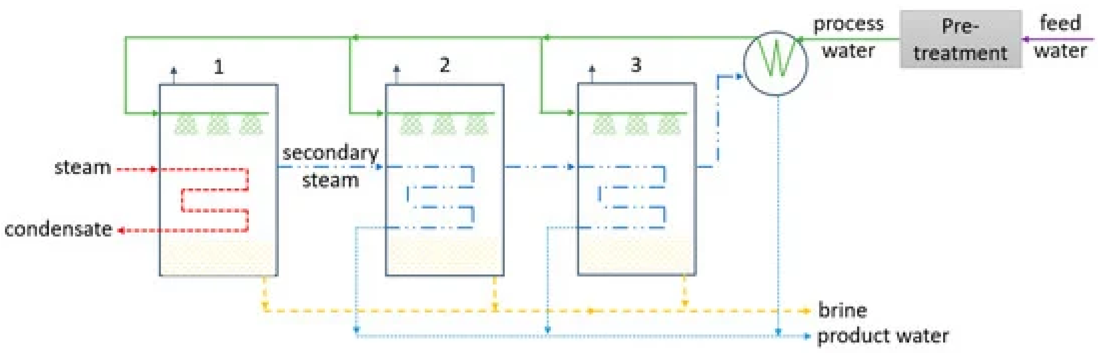


Figure 11 : Multi-effect Distillation Process (Mika et al., 2024; Dastgerdi and Chua, 2018)

The MED consists of multiple evaporation rooms which are also called effects (Scelfo et al., 2025). The vapours produced in one effect, indicated in blue in figure 11, can be used to heat the next with the exception of the first effect, which needs to be heated by an external source (Malik et al., 2022). In most industries, this energy source is the waste steam from a steam-operated power plant. However, this heat can also be provided by renewable energy. The choice for waste steam over renewable energy is further explained in section steam production.

The steam is compressed to a certain pressure in comparison with the needed temperature and in the first effect, the process water is heated by this steam which passes in the tubes (Malik et al., 2022). The seawater is sprayed on the tubes, indicated in green in figure 11, which results in water evaporating and leaving behind the salt rich water known as brine, indicated in yellow in figure 11. The evaporated water, then flows into the next effect as secondary steam to heat and evaporate more seawater by condensing itself to become the wanted fresh water. So, each effect basically recycles the energy from the earlier effects to reduce energy consumption. However, the temperature and pressure drops subsequently with each effect. In the final effect, known as the condenser, steam is cooled using seawater, causing the product water to condense. At the same time, the seawater is heated and then used as feedwater for evaporation in the first effect. This is shown in figure 12 (Dastgerdi and Chua, 2018).

The first MLD system operates with a steam temperature of 70°C as represented in figure 12 below (Dastgerdi and Chua, 2018). To operate at a saturation state at 70°C, the pressure has to be around 0,3 bar (Kretzschmar and Wagner, 2024). The inlet of the feedwater is heated by the condenser before entering the first evaporation room. In the first evaporation room, the seawater will evaporate by the heat of the waste heat.temperature. In every following evaporation room the temperature drops around 3°C to 5°C (Dastgerdi and Chua, 2018; Kosmadakis et al., 2018; Tendering Manager, 2025). This will also affect the pressure in each room to be lower (Kretzschmar and Wagner, 2024; Christ et al., 2015). The MLD operates at 70°C to present scaling with the MED system (Ortega-Delgado et al., 2022). The second MLD system can operate at temperatures of 125°C, as the bivalent ions are separated by the NF membranes which cause scaling (Ortega-Delgado et al., 2022).

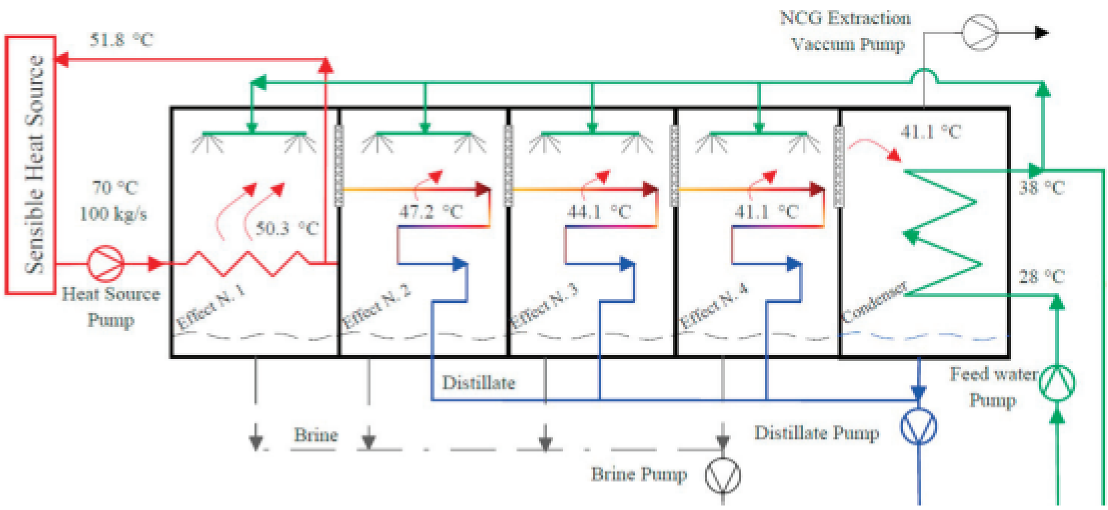


Figure 12 : Multi-effect Distillation Temperatures (Dastgerdi and Chua, 2018).

A vacuum pump is used after the final condensation stage to keep the pressure low inside the system. The pressure maintains low by removing any remaining water vapour and gases that do not condense (Malik et al., 2022). The pressure in the different stages of the MED system is mainly controlled by the pressure of the incoming steam and the steam that condenses in the last stage. The pressure difference between the stages is usually no more than 5 kPa, which helps the evaporation process work more efficiently.

The Gain Output Ratio (GOR) is the measure of how well the MED system performs (Malik et al., 2022; Omar et al., 2021). It shows how much fresh water is produced compared to the amount of heating steam used. A higher GOR means the system is more efficient at turning steam into clean water. The number of effects in an MED system plays a key role in balancing the cost of the system with the amount of fresh water it can produce. More effects can increase efficiency as shown in figure 13 below (Malik et al., 2022; Mistry et al., 2013).

$$GOR = \frac{M_{distillate}}{M_{steam}} \quad [9]$$

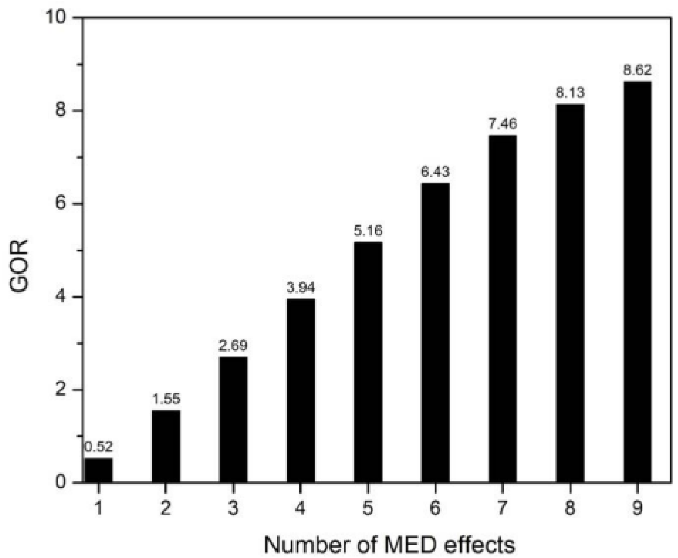


Figure 13 : Impact of number of MED effects on GOR (Malik et al., 2022)

The number of effects can range from 3 to 30, depending on the feed-in temperature (Kosmadakis et al., 2018). The lowest heat input temperature of 60°C can achieve eight effects. A heat input of 80°C already rises to 15 effects. The number of effects generally are considered to be one of the strongest determinants of an MED system's performance. Guo et al. (2020) calculated the characteristics of each effect when more effects are placed in series in an MED system. They observed that the vapour mass flow rate increases as more effects are added. This is because each additional effect utilises the heat from the previous effect, leading to more efficient evaporation and higher overall vapour production. They also noted that the brine mass flow rate decreases in the evaporation rooms. This is due to the increased removal of water as vapour, which results in a more concentrated brine.

Despite these advantages, there are some downsides. One significant issue is the degradation of vapour quality in each subsequent effect (Guo et al., 2020). As the vapour passes through multiple effects, its temperature and pressure decrease, which can reduce the efficiency of the system and the quality of the produced water. Figure 14 shows the progress of adding more effects to the MED installation by the calculation results of Guo et al. (2020) from their pilot plant. In short, increasing the number of effects results in more distillate production and more concentrated brine but will increase the capital costs.

The MED plant is considered for the purpose of producing ultrapure water for hydrogen production and researching synergy effects between water desalination technologies. Therefore, the main specifications of the MED plant are selected based on the most common design options: heat source temperature of 70 °C, 8 MED effects, and a recovery rate of 30% for a standalone MED (Kosmadakis et al., 2018; Ortega-Delgado et al., 2022; Manesh et al., 2021). The selection of 8 effects is based on the average number of effects from the reviewed papers relevant to MED plants. The second MED plant is selected based on heat source temperature of 125°C (Ortega-Delgado et al., 2022; Kosmadakis et al., 2018). The impact of a higher heat source temperature will be researched for this study. Both MLD systems have a lifespan of 25 years (Ellersdorfer et al., 2023; Christ et al., 2015; Moharram et al., 2021).

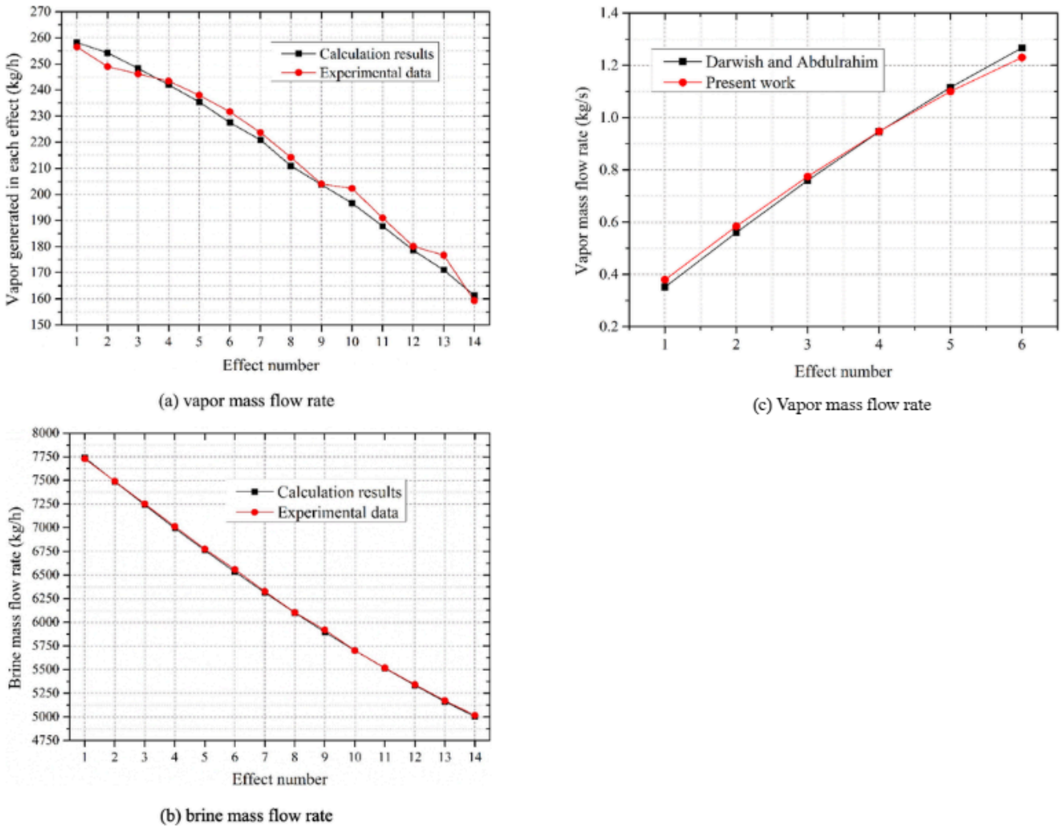


Figure 14 : Impact of number of MED effects on vapour generated, mass flow rate, and brine flow rate (Guo et al., 2020)

4.4.2 Preconcentration: Nanofiltration

NF is a pressure-driven membrane technology that consumes less energy and selectively allows certain ions to pass through compared to the membrane water desalination technology RO (Shen et al., 2024). NF can be applied not only for water purification but also with a focus on resource recovery (Figueira et al., 2023). It is particularly effective as a pretreatment for seawater and as a post-treatment for seawater brine, where it isolates multivalent ions to enable the recovery of valuable salts (Shen et al., 2024).

In the second MLD configuration, NF serves as a preconcentration step to purify the seawater before entering the MED unit. Figure 15 illustrates the role of NF as a pretreatment step. In this setup, the NF retentate stream contains ions such as Mg^{2+} and SO_4^{2-}, which can be used to form useful salts. However, the MLD system in this study lacks the necessary equipment to utilise these resource recovery capabilities. In the NF-MED configuration, NF is primarily implemented to reduce water hardness and protect the MED system from scale formation, rather than to produce ultrapure water. For future studies, salt recovery could have an impact on the NPV of the MLD system.

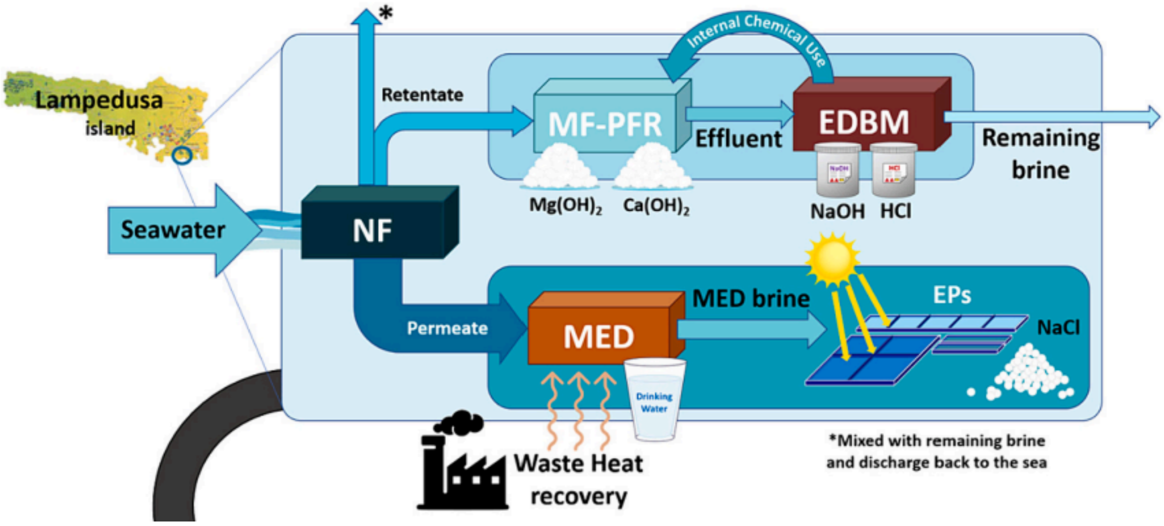


Figure 15 : Seawater desalination scheme using NF retentate (Pioneering minimum liquid discharge desalination: A pilot study in Lampedusa Island - ScienceDirect)

Figure 16 illustrates how a pressure pump pushes water through the semipermeable membrane to remove the red bivalent ions, but not all green monovalent ions are separated (Curto et al., 2021; Van Der Bruggen, 2013). This technology produces soft water, the permeate, and a byproduct of brine. The NF permeate will be the feedwater for the MED technology (Morgante et al., 2024-a).

The elements in the NF permeate are dependent on the characteristics of charge and pore size of the membrane (Van der Bruggen, 2013). The composition of the seawater also influences the rejection of ions. Typical NF membranes have a negative surface charge at neutral pH, which results in higher rejections of the multivalent negative charged ions. A realistic expectation for ion rejections is 90% to 99% for multivalent ions and 10% to 90% for monovalent ions. The rejection characteristics of the membrane for the NF-MED system is to soften the water, so therefore the NF membrane is suitable.

Besides the membrane charges, the pore size is also important. Two types of membranes are distinguished, tight and loose NFs. Tight NFs will reject 99% all multivalent ions and between 60% to 90% of the monovalent salts and resemble RO membranes (Van der Bruggen, 2013). Loose NF membranes, similar to ultrafiltration membranes, will reject 90% to 99% multivalent ions and between 10% to 60% of monovalent salts. As a preconditioner, both the loose and tight NF membrane seem acceptable.

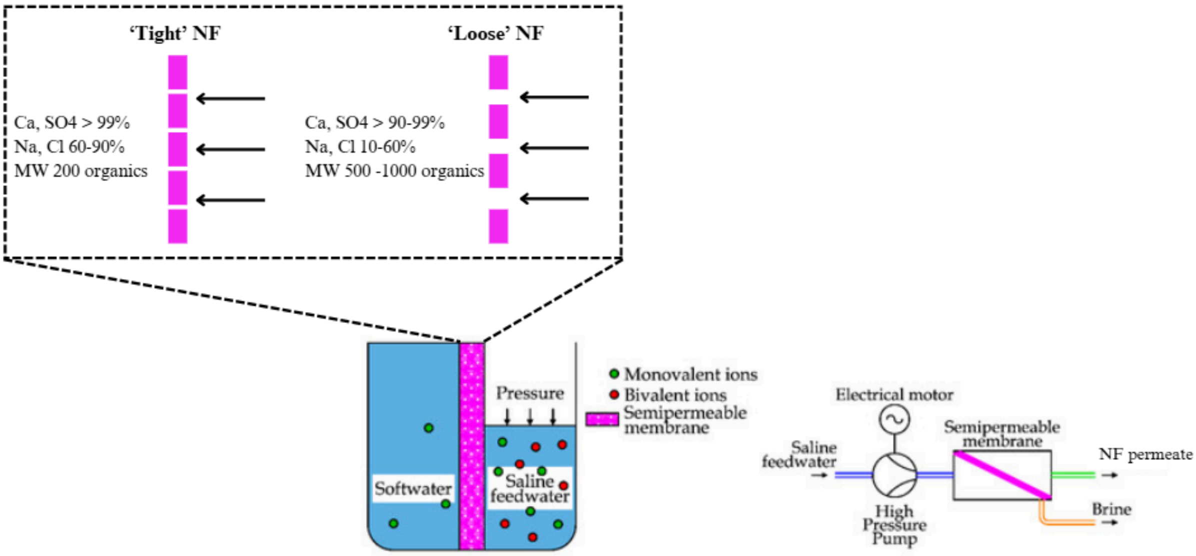


Figure 16 : Nanofiltration Process (Curto et al., 2021; Van der Bruggen, 2013).

The NF model is structured across multiple scales, all of which are illustrated in figure 17 (Micari et al., 2019). At the smallest scale, the model describes the transport mechanisms within a single membrane. The intermediate scale focuses on the behavior of an individual NF element. The largest scale represents the configuration of the entire NF plant. The NF plant contains a certain amount of vessel arranged in parallel, as indicated in the blue box, and each vessel contains NF elements in series.

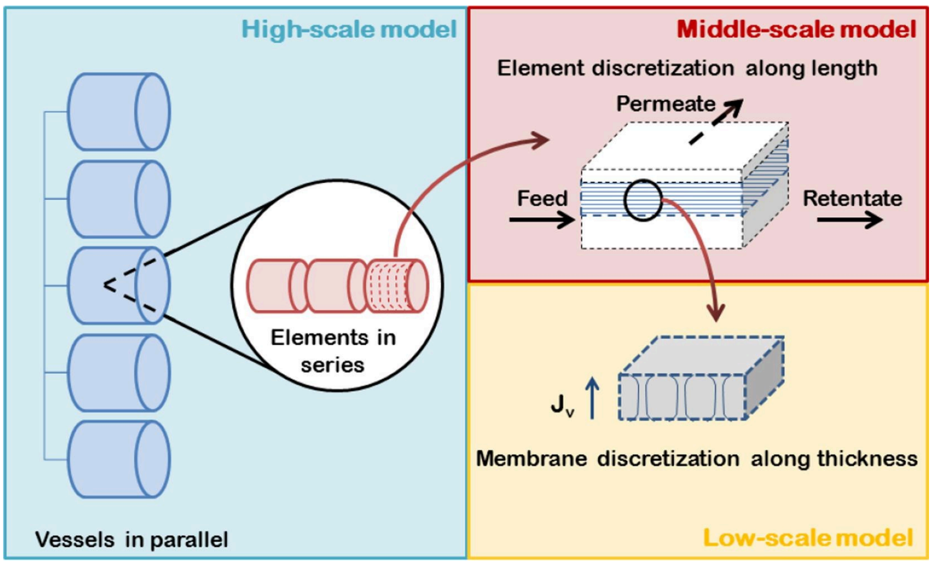


Figure 17 : Different Scales of the Nanofiltration Unit (Micari et al., 2019)

High scale NF plants are determined by each pressure vessel having 6 elements and each element is composed of 5 membrane leaves. The total membrane area exposed by each pressure vessel is $30m^2$, which is in line with the indication from the membrane scientist. The vessels are arranged in parallel in order to increase the available membrane area. For the CBA of this study, it is important to know how much membranes are needed to filter the seawater, so the CAPEX costs can be indicated for the NF.

Each membrane provides a permeate flow rate of approximately 1.0 m^3/h (Process Advisor, 2025; Membrane Specialist, 2025). The second MLD system must treat 4.761,43 m^3 of seawater per day to supply sufficient feedwater to the MED unit. This corresponds to a flow rate of 198.39 m^3/h, requiring at least 199 membranes to meet the demand. Due to the high salinity of the seawater, the operating pressure must be maintained between 30 and 40 bar. Provided that the feedwater is properly conditioned, the membranes are expected to have a lifespan of up to five years (Membrane Specialist, 2025).

$$NF\ Water\ Capacity\ [m^3/h] = \frac{4761,43\ [m^3/day]}{24\ [h/day]} = 198,39\ [m^3/h] \quad [10]$$

In López et al. the water recovery rate of SWRO brine treatment is 60% with 8000 operating hours (López et al., 2025). In Figueira et al. the recovery rate is only 40%. The higher the recovery rate, the lower the average rejection of the different ions (López et al., 2025). As more water is going through, more ions get through as well. This is represented in figure 18A below. In figure 18B it is illustrated what the recovery rate does to the permeate flux according to different pressures (Figueira et al., 2023). The pressure is needed to counter osmosis, which is called reverse osmosis. The permeate flux is illustrated in LMH which stands for $L/m^2 * h$. With a higher recovery rate, it is harder to maintain the same permeate flux and reduces a little bit. Since the NF membranes are designed for treating seawater rather than brine in this study, and taking into account the impact of high permeate recovery rates as well as insights from expert interviews, a recovery rate of 70% has been selected.

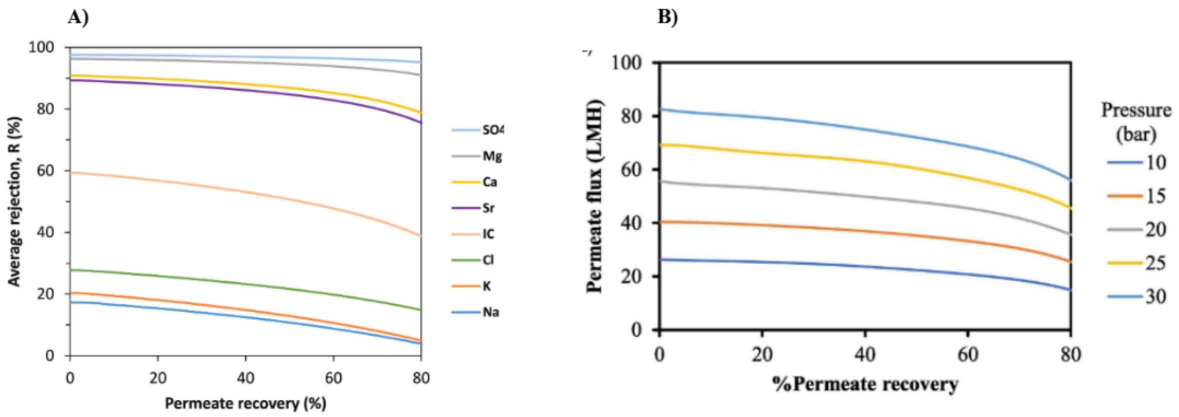


Figure 18 : A) Average Ion Rejection with Permeate Recovery Rate (López et al., 2025) B) Permeate Flux with Permeate Recovery Rate (Figueira et al., 2023)

The NF can use a 1-pass or a 2-pass membrane system (López et al., 2025). As illustrated in figure 19 on the left, a 2-pass NF system operating at a fixed pressure results in lower concentrations of $CaCO_3$ and hardness when treating SWRO brine compared to a 1-pass NF system. The 2-pass NF does not really have much impact on the NaCl, this could be explained because NaCl are monovalent ions. However, it is important to note that the cost of using a 2-pass NF system also is higher. As shown in figure 19 on the right, almost double treatment costs. Therefore, only a 1-pass membrane is chosen for the second MLD system.

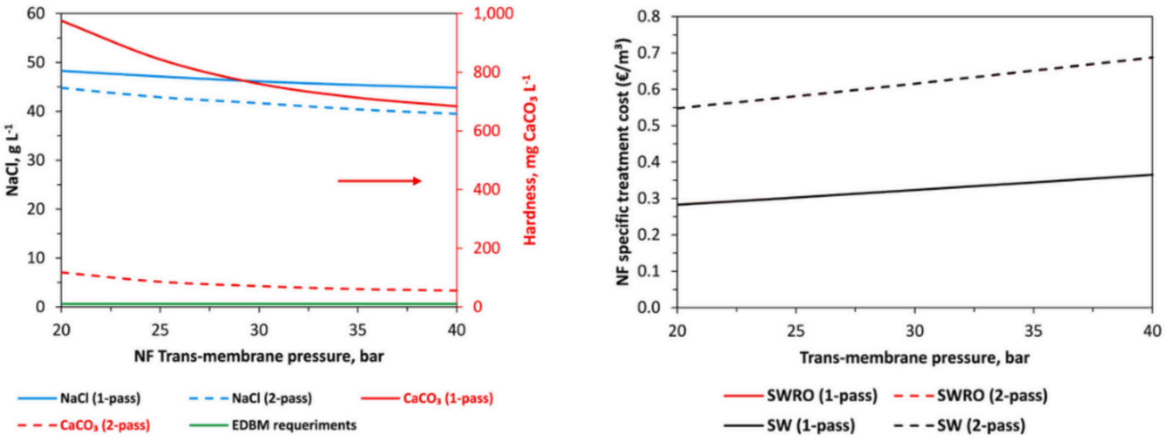


Figure 19 : 1-pass vs. 2-pass NF membranes (López et al., 2025)

4.4.1 Pretreatment: Multi-Media Filter (MMF)

A pretreatment is needed to protect the NF and MED technologies from particles in the seawater. The pretreatment is not in scope, but very relevant to indicate as an important element of the MLD system. For example, The MMF impacts the maintenance needs of the water desalination technologies. The MMF impacts the characteristics of the NF and MED.

An MMF is an intake channel which filters large objects such as plastics, clay, micro-organisms and sludge (Morgante et al., 2024-a; Folmer et al., 2024). The seawater is taken from a beach well for the removal of these residual suspended solids. These harmful particles are filtered out to protect the membrane of the NF and the MED components. Figure 20 is an image of the MMF with all the optional compartments and layers. However for this study, the MMF is only important to specify the different needs the two MLDs have.

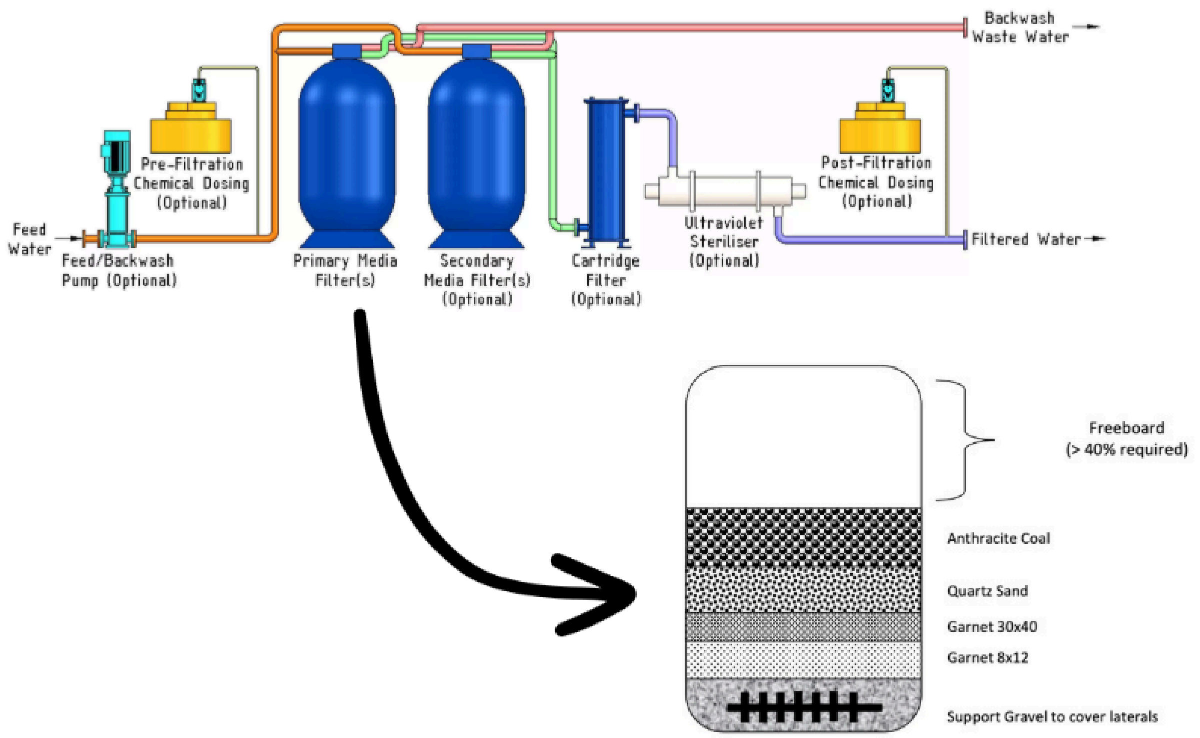


Figure 20 : Multi-Media Filter (MAK water, n.d; Puretec, n.d.)

The MMF needs to have a certain size and energy capacity to pump and filter enough seawater to produce 3333 m^3 of demineralised water for the MED. For the first and second MLD system, the MMF operation scale has been determined. The first MLD system needs an MMF that filters 3.7033,33 m^3/day and the second MLD system with the NF membrane needs to filter 5.290, 27 m^3/day. In table 7 below an overview is given of standard specifications of two standard capacity MMF technologies. The power consumption is determined for the energy needed to pump the seawater through the filters.

Table 7 : MMF Parameters (MAK Water, n.d.)

MMF\Parameters	Flow rate m3/day]	Flow rate [m3/h]	Recovery Rate [%]	Power Cons. [kWh]
MMF-2.500	2.500	106,4	90	30
MMF-5.000	5.000	212,8	90	55

4.5 MLD Technology OPEX Demarcations

The second MLD system, including all integrated desalination technologies, is illustrated in figure 21. While the previous sections have defined the core technologies, an additional set of operational parameters must be identified to fully evaluate the performance of the MLD systems. The choices regarding the fuels, cooling, chemicals, and electricity is discussed in this section.

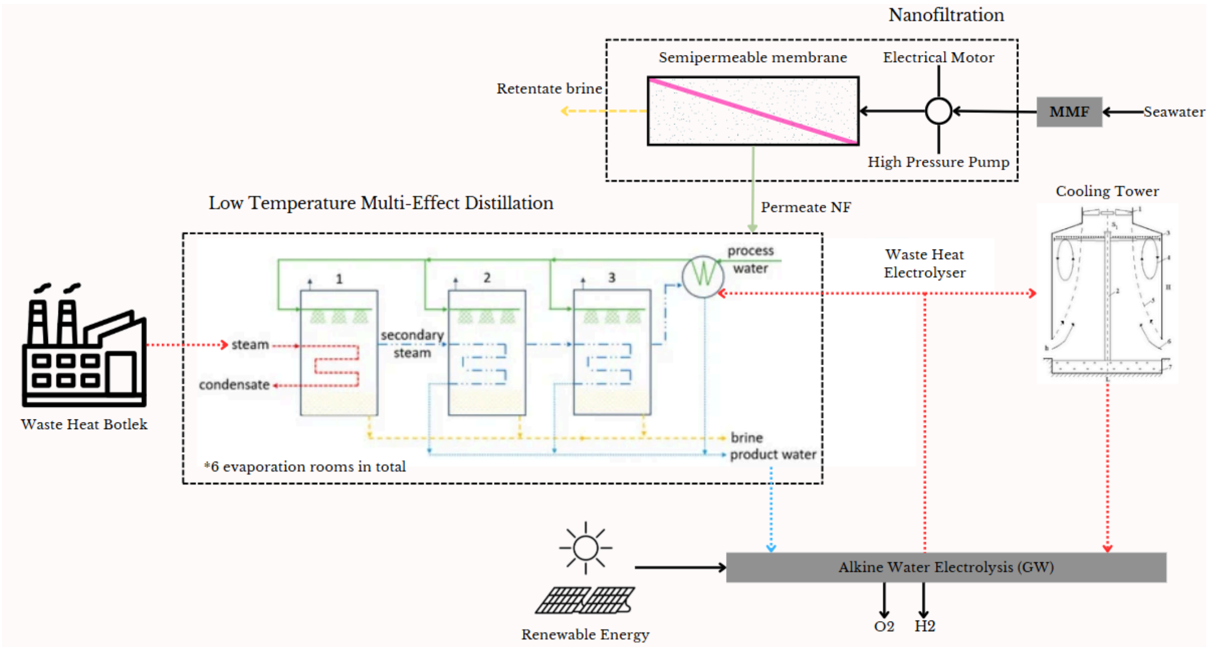


Figure 21 : NF-MED Minimal Liquid Discharge Technology

4.5.1 Seawater as Feedwater

The feedwater for the MLD technologies is seawater. There are four reasons for using seawater as a feedstock for desalination in this research. Firstly, most potential hydrogen production sites are located near saltwater areas according to the Dutch Ministry of Economic Affairs and Climate Policy and the Ministry of Infrastructure and Water Management, shown in figure 22 (Folmer et al., 2024). Therefore, seawater is an easily accessible feedwater source. Secondly, the energy supply in the Netherlands primarily relies on surface saltwater and freshwater, with only a small amount of groundwater and drinking water being used as feedstock, also shown in figure 22.

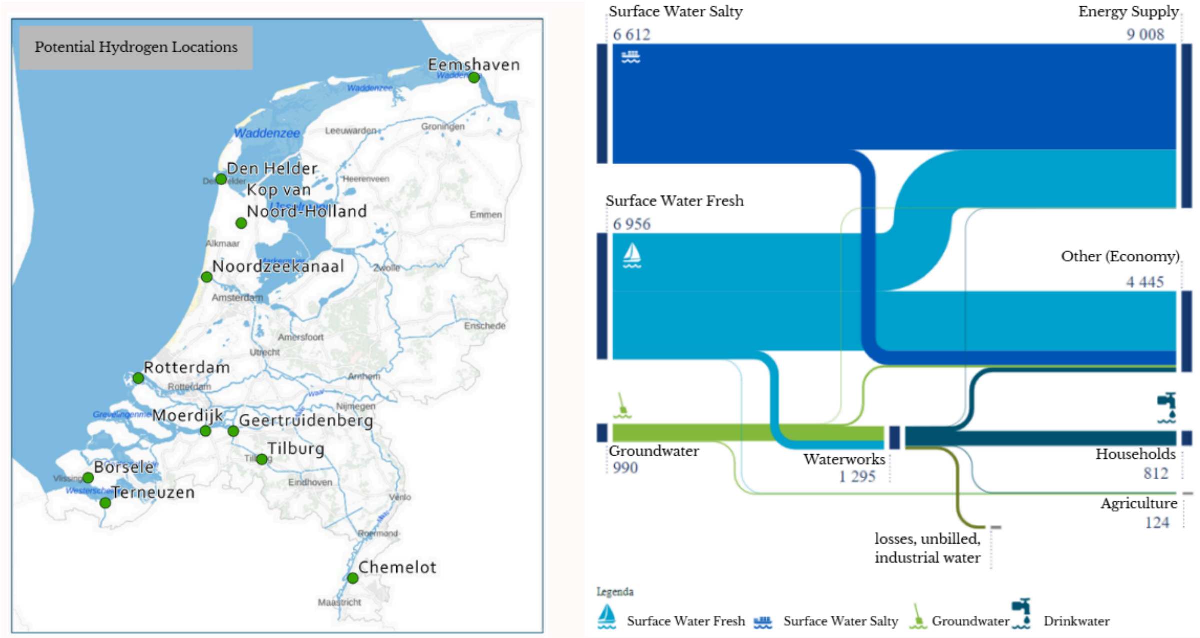
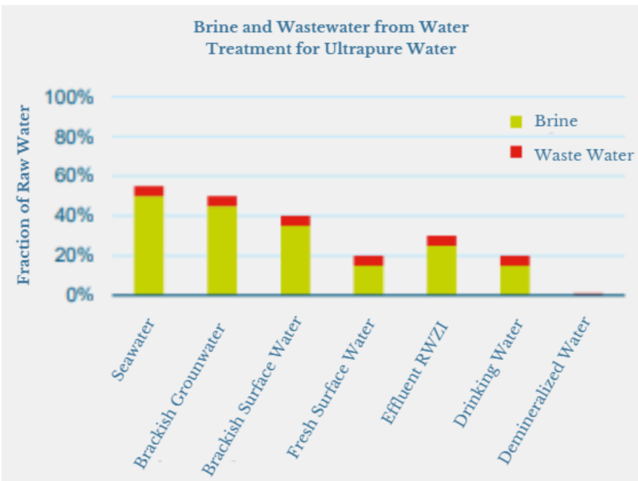


Figure 22 : Hydrogen production locations and Water Usage in the Netherlands (Folmer et al., 2024)

Thirdly, most brine is produced by the desalination of seawater as shown in figure 23 (Folmer et al., 2024). Seawater produces around 50% brine disposal when using an NF-RO-EDI ZLD technology and is the most polluting for hydrogen production, also shown in figure 23 (Folmer et al., 2024; Ministerie van Infrastructuur en Waterstaat, 2024). Fourthly, looking into future expansions of the MLD technology, ZLD technologies not only produce fresh water but can also serve as a more sustainable alternative to terrestrial mining. Seawater contains several valuable elements, such as sodium, magnesium, calcium, and potassium (Morgante et al., 2024-a). This way, seawater desalination can be used to produce hydrogen and to mine other valuable elements when the MLD technology expands. The locations of hydrogen production, Dutch water distribution, brine production and the valuable extraction of elements determine that seawater is the most interesting and impactful feedstock to research.



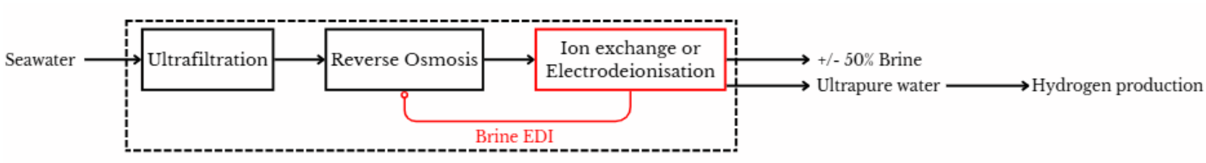


Figure 23 : Brine from Hydrogen Water Treatment (Folmer et al., 2024)

4.5.2 Heating and Cooling System

The MLD system uses multiple technologies and therefore needs both heating and cooling depending on the type of technology. The MED system needs to be heated, but the AWE needs to be cooled down. A combination could be made to passively cool the AWE and use the waste heat for the MED. This section will discuss the feasibility of active and passive cooling.

4.5.2.1 Heating System of the MED

Active heating can be used to make the steam for the MED system, such as waste heat from the Port of Rotterdam or an E-boiler. The waste heat needs to have a temperature of 70°C, as shown in figure 24. The Botlek houses around sixty oil processing and chemical plants of Shell which produce waste heat that is currently used for district heating (ANWB, n.d.; Vattenfall, n.d.). Waste heat from a company as Shell can also be used as a heat source for the MED technology.

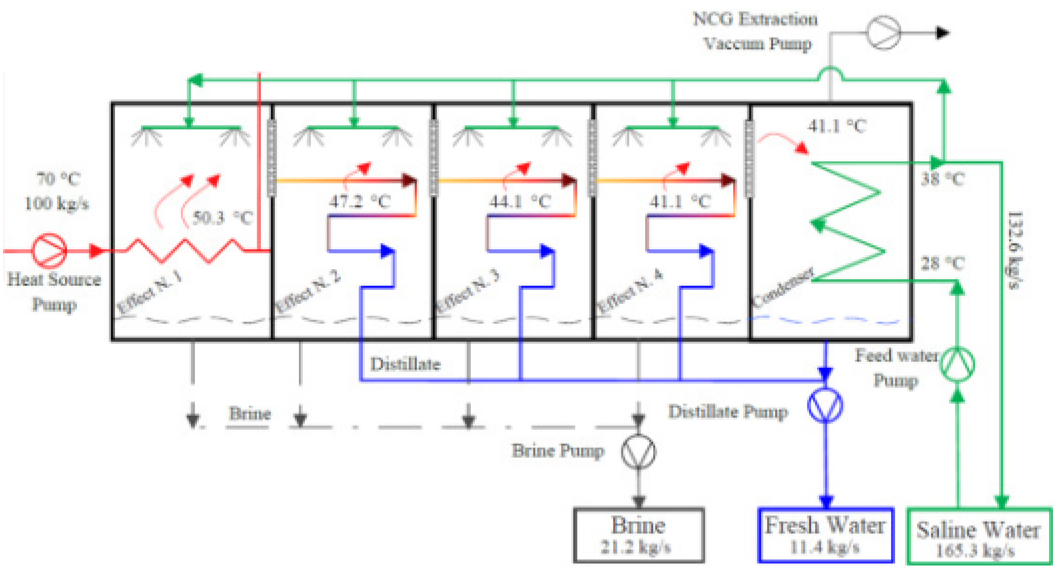


Figure 24 : Multi-effect Distillation Temperatures (Dastgerdi and Chua, 2018)

The evaporated pure water is condensed in the final evaporation chamber, known as the condenser. At the same time, the incoming seawater must be preheated before entering the first effect. These two processes can be efficiently combined. As shown in figure 24, the feedwater pump circulates seawater through the condenser, where it comes into contact with the vapour from the purified water. The vapour condenses in contact with the seawater. which in return absorbs the heat. This process preheats the seawater before it enters the first effect.

In an MED system with 8 effects, the condenser operates at around 40°C (Dastgerdi and Chua, 2018; Tendering Manager, 2025). However, as discussed with the tendering manager (2025), operating at a GOR of 8,13 requires 9 effects and the condenser will function at a temperature of 35 °C. The condenser will then operate at a temperature of Seawater temperatures in the Netherlands range from 3°C to 25°C, as shown in figure 25. The cooling water temperature should be 3°C to 10°C lower than the operating temperature of the final effect (Ellersdorfer et al., 2023),. This means that Dutch seawater is always cold enough to absorb heat in the condenser and be heated up to approximately 38°C (Dastgerdi and Chua, 2018). This heat exchange improves the energy efficiency of the system by making optimal use of the available thermal energy.

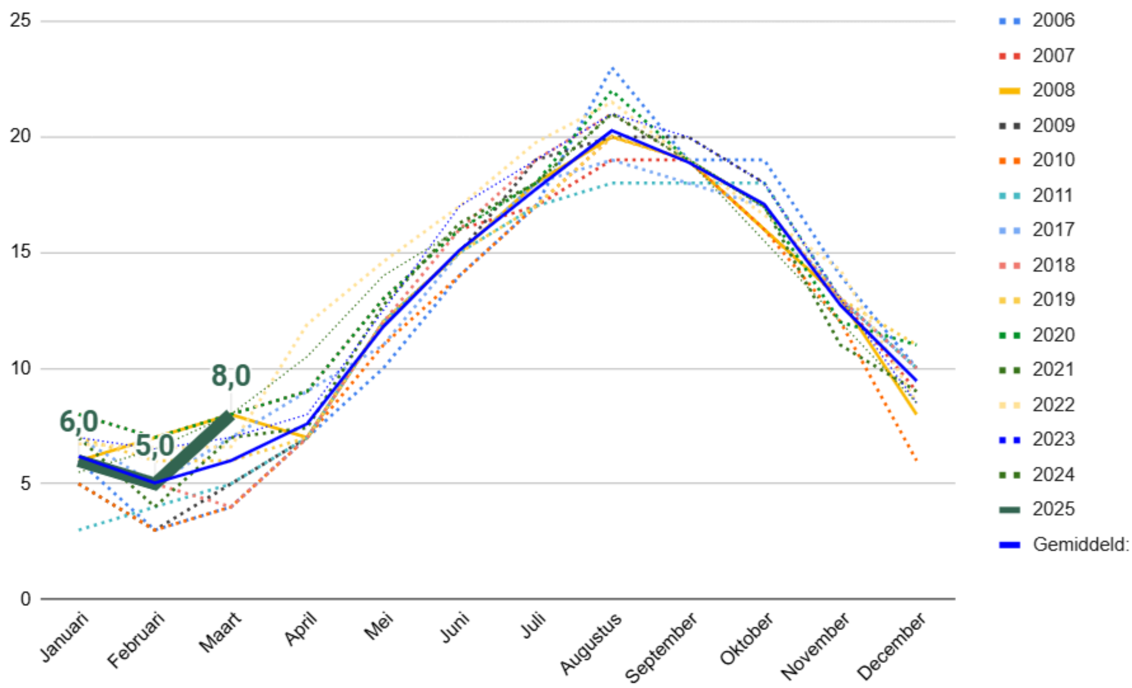


Figure 25 : Temperatures of the North Sea (Boardshortz, n.d.).

Passive heat exchange could also be used between the waste heat of the AWE and the steam needed for the MED (Ellersdorfer et al., 2023). Currently, 60 to 80% of the total energy is directly used for the production of hydrogen from the electrolysis. The rest of the energy is inefficient and will result in the generation of heat during the electrolysis process. This is the heat that normally will be cooled with a cooling system. Now, the MED can function as a heat sink.

The AWE has an operation temperature between 65°C and 100°C (Folmer et al., 2024). However, from the expert interview with a business developer these temperatures are corrected to 40 °C to 50°C. This would not be enough to function as steam for the LT-MED. In contrast, a PEM operates at higher temperatures that are suitable for steam generation (Business Developer, 2025). This could reduce the MED costs immensely.

On the other hand, an interview with a tendering manager indicated that 80% of the waste heat from the electrolyser would be sufficient to produce the full volume of ultrapure water required to feed the electrolyser. In fact, the available waste heat is often more than sufficient, meaning that even a single MED unit can produce more water that the electrolyser consumes. In such cases, an additional cooling system is needed for the electrolyser to manage the heat.

4.5.2.2 Cooling System of the Electrolyser

Although the cooling system of the electrolyser falls outside the scope of this research, it is important to highlight this for future studies. For passive cooling of the electrolyser, the MED system itself serves as the cooling mechanism. However, if waste heat from the Botlek is used to generate steam, a separate cooling tower is required to manage the excess heat.

The cooling system of an electrolyser has four different options; flow-through cooling system, closed cooling system, air cooling, and hybrid cooling system (Folmer et al., 2024). The types of cooling are represented in figure 26. The first option is a closed cooling system and exchanges heat from an industrial process without exposing it to the atmosphere. In this system, the liquid circulates continuously through tubes in a closed loop. The refrigerant absorbs heat from the electrolyser and then transfers that heat off to another water system to cool down through evaporation.

The second option is a flow-through cooling system and pumps water from a nearby source to pass it through the network of heat exchangers only once to absorb the electrolyser heat. This water is then returned to the original source. The third option is air cooling and only uses air instead of water. Heat can be dissipated by creating a large surface or by increasing airflow over the electrolyser to be cooled. The last option is a combination of dry and evaporative heat removal technologies. The option uses air when the outside temperature is moderate and uses water when the outside temperature rises.

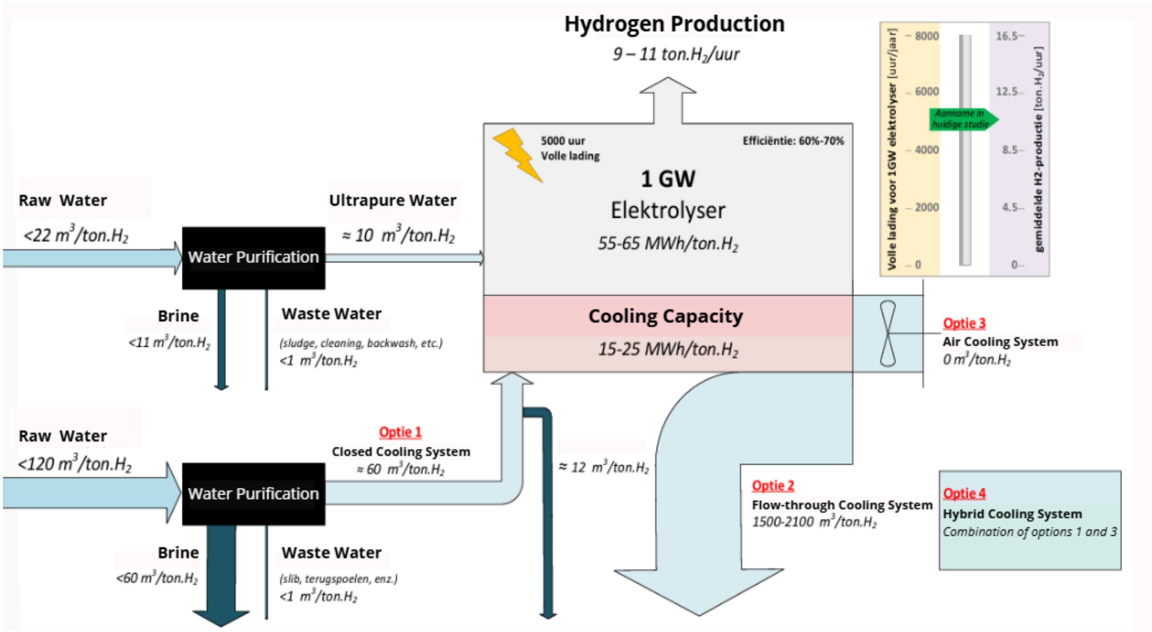


Figure 26 : Water need and hydrogen production with 1GW electrolyser (Folmer et al., 2024)

For the passive cooling, a closed cooling system is used to transfer the heat from the electrolyser to the MED as a passive cooling system. The closed system is chosen because it is able to exchange the heat from the industrial process without exposing it to the atmosphere (Folmer et al., 2024). The refrigerant absorbs the heat from the electrolyser and then releases that heat to the MED as heat exchanger.

The benefit of a closed system is that the water requirement is less extensive than for a flow-through cooling system (Folmer et al., 2024). However, the water requirement is still five times higher than the water needed for the electrolyser itself, and it requires desalination. Water purification is needed to achieve a conductivity of less than 600 µS/cm. This means that partial desalination, demineralised water, is sufficient (Folmer et al., 2024; Ellersdorfer et al., 2023). This can be achieved with an ultrafiltration (UF) followed by a high-pressure RO. Figure 27 below shows the flowchart of the closed cooling system which is the lower water purification black box in figure 26.

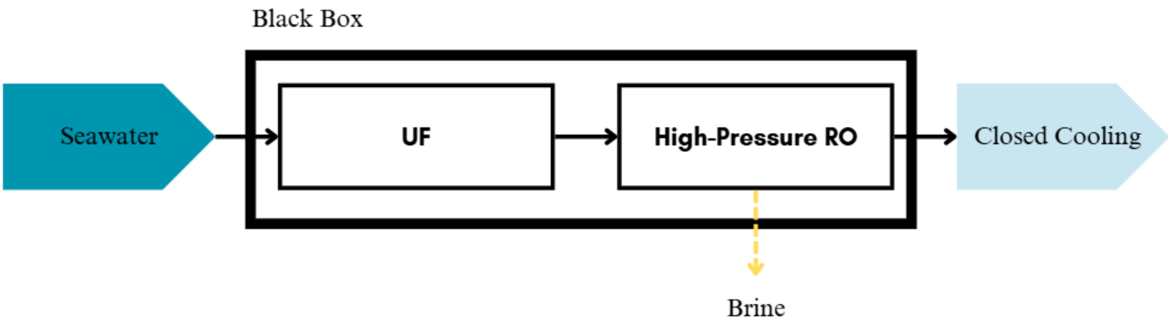
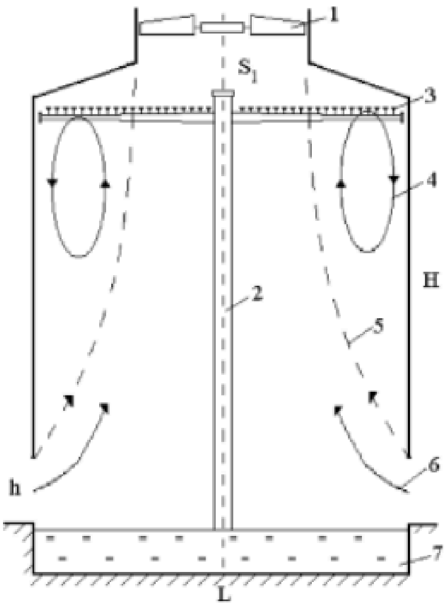


Figure 27 : Flowchart Closed Cooling System

The costs and benefits of a cooling system depends on the size of the electrolyser. The current-scale electrolysers, with a capacity between 5 and 15 MW, can use the mentioned form of passive-cooling alone. However, the passive cooling may no longer be viable at a larger scale and needs additional cooling towers to dispose of the waste heat. This accounts for electrolysers reaching capacities of GW. The current hydrogen projects are all designed to accommodate an increasing electrolyser capacity and therefore this technology could need an additional cooling system for future electrolyser enhancements.

The cooling tower will function as a heat exchanger for active cooling of the electrolyser. The cooling tower effectively dissipates this excess heat to ensure the system operates efficiently. Figure 28 shows that the heat from the electrolysis is pumped into the cooling tower, where it is distributed over fill material (Fisenko et al., 2004). The fill material is closely spaced plastic sheets which efficiently exchanges the heat from the water with the surrounding air. This process arises because a portion of the water evaporates which removes the heat from the water and fans at the top of the cooling tower draw air through the tower. The cooled water could be collected in storage tanks and recirculated back into the electrolysis.



1) Fan
2) Pipeline
3)Water distribution system with spraying nozzles
4) Stagnant zone
5) Edge of stagnant zone
6) Entering air
7) Water-collecting pond

Figure 28 : Flowchart Cooling Tower (Fisenko et al., 2004)

In short, passive cooling uses a closed-loop system where the heat from the electrolyser is transferred to the MED unit, which acts as a heat sink. This method is efficient and reduces water use, but may not be sufficient for large-scale GW electrolysers. On the other hand, active cooling uses a cooling tower to dissipate excess heat. This system is necessary for larger electrolyser capacities and ensures stable operation but requires more infrastructure and water.

4.5.4. Steam Production

As mentioned, there are three ways to produce steam; waste steam heat from the Botlek, waste heat from the AWE, or from the E-boiler. To determine the most suited type of steam production, first the needed amount of steam must be calculated. The GOR represents the amount of distillate water produced per unit of steam consumed (Malik et al., 2022). For an MED system with 8 effects, the GOR is determined to be 8.13 as shown in figure 13. This implies that 1 kg of steam can generate approximately 8.13 kg of distillate water. This is because the heat can be reused in the following effects. From an expert interview, it was explained that this GOR actually required 9 effects compared to the academic determined 8 effects (Tendering Manager, 2025). The production of the MED in this study is 1000 m³ of distillate water. When using equation 11, this corresponds to a steam requirement of approximately 123.000 kg per day. The calculations supporting this estimate are provided in Appendix H.

$$GOR = \frac{M_{distillate}}{M_{steam}} \quad [11]$$

When using waste heat from the Botlek to desalinate seawater the following occurs. The waste heat is available in the form of steam at approximately 70°C (Mika et al, 2024). This steam transfers its thermal energy through a heat exchanger to indirectly evaporate the seawater. Within the heat exchanger, the steam heats the incoming seawater to its boiling point under reduced pressure around 70°C, causing it to evaporate. The low evaporation temperature reduces scaling and fouling of the

MED. This evaporated seawater becomes the new steam used in the following effects of the MED process, which is then condensed and collected as ultrapure water.

To convert 1 kilogram of seawater into steam at 70°C, approximately 2333.1 kJ of latent heat is required (Wakeham, 2011). The total thermal energy needed for this phase change can be calculated using the equation 12. Q is the total thermal energy required (in kJ), m is the mass of seawater to be evaporated (in kg), and L_v is the latent heat of vaporization (2333.1 kJ/kg). It is important to remember that, thanks to the GOR of 8.13, you only need to add about 1/8th of the total evaporation energy externally. Based on this calculation, the daily energy requirement for the process is approximately 286.971.170 kJ per day. The calculations are represented in Appendix H.

$$Q\,[kJ] = m\,[kg] * L_v\,[kJ/kg] \qquad [12]$$

When using an E-boiler, the water in the E-boiler must first be heated using sensible heat to reach a temperature of 70°C. The heated water in the E-boiler then goes into the MED to convert the seawater into steam with latent heat. This is a costly alternative because the E-boiler must be installed, the water must be demineralised to prevent scaling in the E-boiler, and sensible heat is required (Product Specialist, 2025). The sensible heat required can be calculated using equation 13. In this equation, m represents the mass of the water, c is the specific heat capacity of water, which is 4,2 kJ/kg°C, and ΔT is the change of temperature.

$$Q\,[J] = m\,[kg] * c\,[kJ/kg°C] * \Delta T[°C] \qquad [13]$$

This determines that the E-boiler is a very costly process, even if green energy is being used (Product Specialist, 2025). In addition to the financial cost, the high electricity demand of the E-boiler places a significant burden on the regional power grid. As illustrated in figure 29 below, the Port of Rotterdam is marked in red and references a shortage in transport capacity with a waiting list (Stedin, 2025). The Maasvlakte is shown in yellow, meaning transport capacity is limited but still available without a waiting list. Given the high energy demand of E-boilers and the growing congestion in the Dutch electricity grid, it would be more efficient to utilise available waste heat, which does not require additional energy input to be used for steam generation in MED systems.

Another reason for choosing waste heat is its extreme purity (Product Specialist, 2025). The water used in an E-boiler requires extensive treatment before it can enter the MED effects. When using very saline water such as seawater, a lot of maintenance is needed to keep the boiler operational. Steam from waste heat is already clean and immediately ready for use. This significantly reduces operational costs and makes steam the more efficient and cost-effective option.

Figure 29 : Energy Transport Shortage Decrease in South Holland (Stedin, 2025)

4.5.5. Cleaning of Materials

Substances in the seawater may cause scaling and fouling (Mika et al., 2024). Scaling denotes the formation of salts and minerals on the surface of the MED evaporation champers or NF membranes and fouling is the undesired accumulation of solid substances. Some substances can also cause foam formation. Therefore, the seawater must be pretreated and preconditioned so the substances are filtered. However, maintenance is still needed. The dosing rate of all the chemicals in the pretreatment process depends on the amount of seawater intake, chemical composition of seawater, pH of seawater, makeup water requirements, and Top Brine Temperature (TBT).

4.5.5.1 Cleaning of NF

Membranes are vulnerable for scaling and fouling (Mika et al., 2024). The chemicals antiscalants and disinfectants are usually added to the seawater to prevent this. The purpose of antiscalants is to limit salts and minerals formation on the membranes, which would lead to clogging of the NF membrane. Clogging causes reduction in the membrane flux and shortens the membrane lifespan. The scaling is caused by formation and deposition of inorganic crystals such as insoluble calcium carbonate ($CaCO3$) and calcium sulphate ($CaSo4$). Antiscalents aim at reducing the deposition of calcium carbonates and sulfates through phosphate-based or polymer-based agents. If the pH of the feedwater is high, an addition of acids is also recommended which is the case for seawater. Disinfectants such as bacteria, viruses and other living organisms can also lead to membrane fouling and therefore the membrane is also treated with chlorine.

4.5.5.2 Cleaning of MED

Scaling and fouling also impact the operation of the MED and (Mika et al., 2024). Additionally, some substances may cause undesired foam formation in the MED. Like NF, MED requires filtration, disinfection, and antiscalants but this technology also needs additional cleaning with antifoam agents, which are usually poly(ethylene oxide)-based and added in small amounts. A corrosion inhibitor can also be added, but it is not obligatory.

4.5.6 Green electricity

The desalination processes require energy for the pumps in the MLD process. For example, the high pressure pump of the NF to counter the natural flow of osmose. In the Netherlands the variable electricity price is dependent on the need and available electricity (De Vries, 2023). If more electricity is required than sustainable energy such as wind or solar energy is available, grey energy needs to fill up the gaps. The most expensive type of energy needed to supply the market, determines the variable costs of all the electricity, as indicated as the black dotted line in figure 30.

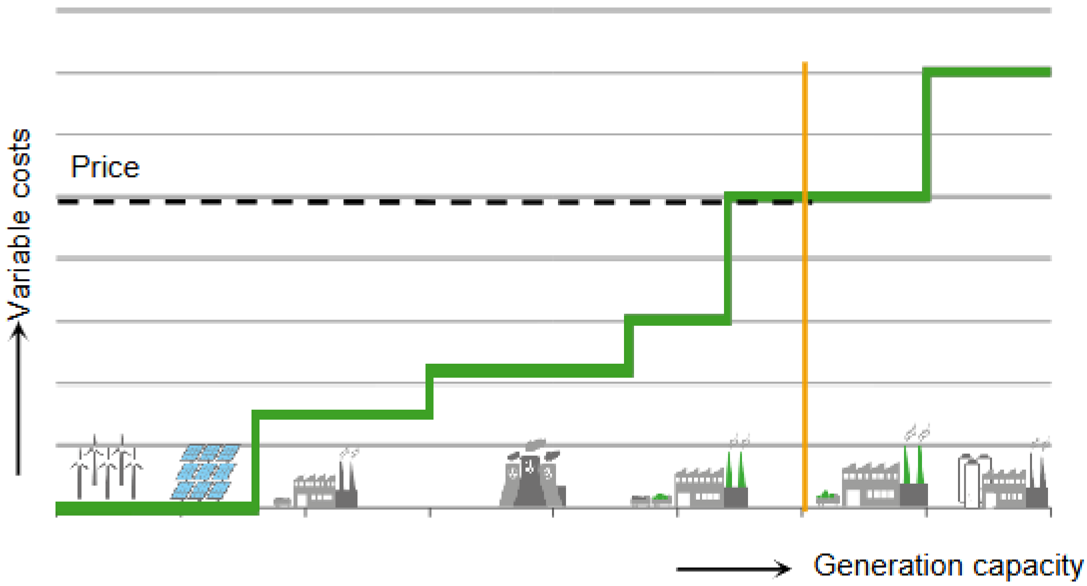


Figure 30 : Variable Electricity costs (De Vries, 2023)

As mentioned, one of the cleanest energy carriers available is water splitting that uses renewable energy sources (Nikolaidis and Poullikkas, 2017). As illustrated in figure 30, it is also possible for hydrogen to be produced with grey energy sources. Three alternatives can be employed to produce purely green energy. Alternative number one is to install a battery to save energy for periods when renewable energy sources such as solar energy and wind energy are not available. Alternative number two is to only operate the MLD technology when renewable energy is available. Alternative number three is to use geothermal energy. The following section explains that operating with wind energy for intermittent operation is the best option. As the NF-MED technology already has a reduced amount of operating hours because of scaling maintenance, wind energy is used in continuous operation with grey energy for this study.

4.5.6.1 Geothermal Energy

Geothermal, solar and wind are all clean and renewable energy sources with a great potential of electricity generation (Li et al., 2015). Geothermal energy has dominated the renewable energy market in terms of installed electricity thirty years ago. However, solar and wind energy are growing and overtaking the renewable energy industry. Geothermal energy does have many advantages over solar and wind systems such as being unaffected to seasonal changes, it is economical and efficient regarding the traditional sources, it is a stable energy source with a high capacity factor of 90%, requires less land and has less ecological effects, and it has high thermal efficiency (Li et al., 2015; Prajapati, 2022). The disadvantage is that the total installed capacity of geothermal electricity is much less than those of solar and wind energies in the Netherlands.

4.5.6.2 Solar Energy

The choice between wind and solar energy largely depends on the renewable energy resources available at the desalination location. This can significantly impact the CAPEX costs and the construction timeline. Solar energy is easy to install, easy to scale up and has a short construction period (Li et al., 2015). The disadvantage is that solar energy is not weather proof and costs need to be made for energy storage.

To reduce the costs, a distinction can be made between continuous mode of operation and intermittent mode of operation (Arunachalam et al., 2024). Intermittent operation focuses on optimising the use of renewable energy by operating at full capacity during peak production periods and at reduced capacity in off-peak hours. Arunachalam et al. did a study on this regarding an MED technology with a seawater capacity of 10.000 m3/d which could make 24000 kg H2 per day. Table 8 shows the difference is CAPEX costs and determines that an intermittent installation is less costly. During the six hours that the installation runs on solar energy, it is more than three times as productive per hour. However, it produces 3140 kg less hydrogen per day.

Table 8 : continuous vs. intermittent Solar CAPEX (Arunachalam et al., 2024)

Mode of Operation	MED CAPEX [M$]	H2 Production [kg/h]	H2 Production [kg/day]
Continuous	727,096	1000	24.000
Intermittent	439,0773	3478	20870 (6 hours)

4.5.6.3 Wind Energy

Wind energy, like solar energy, is not weather proof and therefore requires energy storage solutions or intermittent operation. However, as shown in table 9, operating under intermittent conditions can actually reduce overall costs (Arunachalam et al., 2024). When comparing solar and wind energy, wind has a lower CAPEX and results in only 1.670.4 kg less hydrogen production per day. According to the Dutch government, the cost of offshore wind energy has significantly decreased over the years and makes it the most cost-effective large-scale source of renewable energy.

For the desalination technologies considered in this study, wind energy is selected as the primary electricity source. This choice is not based on CAPEX, since both wind and solar energy are already available at the Maasvlakte 2 site, and thus the CAPEX of electricity is excluded from the CBAs. Wind energy is chosen for two main reasons:

1. Higher reliability in the Dutch climate compared to solar energy,
2. Alignment with current hydrogen projects, such as NortH2, which also prioritize wind energy.

When choosing wind energy, it is important to note that wind power is only reliably available for approximately 9.6 hours per day (Arunachalam et al., 2024). During the remaining hours, grey electricity is required to ensure a continuous operation of the MLD process. Battery storage is not considered in this study due to the high cost per kWh for large-scale applications.

Table 9 : Continuous vs. intermittent Wind CAPEX (Arunachalam et al., 2024)

Mode of Operation	**MED CAPEX [M$]**	**H2 Production [kg/h]**	**H2 Production [kg/day]**
Continuous	613,017	1000	24.000
Intermittent	329,242	2326	22.329,6 (9.6 hours)

The CAPEX are included in this section to form a well-considered decision when wind and solar energy is not readily available at the sight of a new MLD technology. The mode of operation is included to make operators aware that without help of a battery or grey energy, wind is the most suited option.

Selecting the energy source based on its specific characteristics is a suitable approach for all MLD technologies More specifically, it is also important to consider the surroundings of the MLD technology. In the Netherlands, wind energy is generally the better choice as it is more consistently available than solar energy and offshore wind energy is the cheapest large-scale source of sustainable energy.

5. Cost Benefit Analysis

Policy measures often have a range of effects and so decisions on these measures involve weighing up various advantages and disadvantages (Romijn and Renes, 2013). A CBA is a tool which provides a systematic overview of these advantages and disadvantages of possible measures. For this study, two CBAs will be conducted to evaluate the characteristics of an MED technology, NF technology, and an integration of both technologies to produce pure water for hydrogen electrolyse. The measures are all quantified in euros and presented as the sum of the benefits minus the costs. If the total benefits to society are greater than the total costs, the result is that society will benefit from the measurement. If the total benefits are lower than the total costs, the measurement should not be taken. It is important to mention that the conducted CBAs in this study reveal the welfare economics consequences of a change, but it does not evaluate a situation in itself.

In this chapter an overall framework is carried out for the CBA which consists of eight steps. The first three steps, also called the preliminary phase of the CBA, analyse the situation; the problem analysis, the baseline alternative and the policy alternatives. From these first three steps, the type of CBA can be determined. Once the situation and the type of CBA are determined, the fourth step is to define the effects and benefits included in the CBA. It is important to establish how the costs and benefits are distributed within the involved society. Step 5 determines the costs of the chosen effects and benefits from step four. If the distributional effects are not included, the analysis will be less meaningful. The Six Ideological Value Judgements are used to overcome this.

Step 6 analyses variants and risks because the CBA is partly based on assumptions such as step two, the baseline alternative. This is done through a sensitivity analysis. Step 7 uses calculations to let all the costs and benefits occur at the same time. For a meaningful comparison, all values need to be calculated back to one common base year. Step 8 is to represent the results in a clear, user-friendly, and reproducible way. To carry out a CBA, several rules and guidelines need to be followed. However, the steps also offer flexible guidance to suit various sectors. The two CBAs for this study are all analysed for the same sector and therefore adhere to the same rules and guidelines.

Together, this chapter will explain the effects and monterey values of the CBAs for this research. Most importantly, chapter 5.5.3 assists in answering the second sub-question; *What are the environmental costs associated with not implementing NF and MED in seawater desalination for green hydrogen production?*.

5.1 Step 1: The Problem Analysis

The problem analysis reveals the nature of the problem and how it is expected to develop (Romijn and Renes, 2013). The problem analysis should also contain a description of the objectives of the measures to be developed in response to the problem. The nature of the problem involves the costs and the production of brine associated with water desalination technologies needed to produce ultrapure water for green hydrogen production to comply with the European Green Deal and avoid exacerbating global drinking water scarcity.

The European Green Deal is a set of policy initiatives by the European Commission aimed to make the European Union climate-neutral by 2050 (Hydrohub Innovation Program, 2020). Part of this deal is the ambition to install at least 40 GW of renewable hydrogen electrolysers by 2030. The Netherlands wants to contribute 3 to 5 GW in 2030. The ambition to install 40 GW of electrolysers is a technical challenge itself but the global water scarcity touches upon this problem as well.

Around the world, 2.7 billion people face water scarcity for at least one month a year and this clashes with the need of ultrapure water for sustainable water electrolysis (Alenezi and Alabaiadly, 2025). The growing need of water for the growing hydrogen production will cause even more severe water scarcity if measurements are not taken. The use of seawater reduces the need for scarce drink- and groundwater. A water desalination technology could be installed before the electrolysis to produce ultrapure water. However, the water desalination technology has its sustainable flaws.

Brine is a wastewater byproduct of the technology with a very high salinity level which affects the environment when disposed back into the sea (Panagopoulos and Giannika, 2024-a). ZLD and MLD technologies are water desalination technologies that tackle the disposal brine by concentrating the salts and getting the most water out of the seawater feed in (Morgante et al., 2024-a). However, the MLD technologies are expensive because a lot of technical parts and energy are required to produce pure water and reduce the environmental footprint. This study will analyse two different types of MLD technologies and the possible need of synergy through CBAs to address the statement that MLD technologies are too expensive to replace current hydrogen production.

5.2 Step 2: The Baseline Alternative

The baseline alternative describes the most likely scenario without the introduction of any new initiatives and serves as a reference against which to measure the effects of new policy (Romijn and Renes, 2013). The most likely scenario without the introduction of an MLD or ZLD technology is impairment of the ocean by brine disposal if no proper brine management is in place and the loss of water recovery during the desalination process. Desalination emerges as a promising solution because it offers a potentially infinite source of useful water (Panagopoulos and Gianniaka, 2024-a). The desalination process with brackish and seawater has been extensively employed to produce drinking water. Presently, there are more than 21.000 operational desalination facilities who together produce approximately 140 million cubic of drinking water per day. The downside of the technology is the generation of saline wastewater, also known as brine. The technologies already globally produce 129 million cubic meters of brine every day and will grow if no alternatives are implemented.

Depending on the feedwater, there are different disposal routes for brine such as surface water discharge, sewer discharge, deep-well injection, evaporation ponds and land application (Mika et al., 2024). The feedwater is seawater, so according to Dutch policy the brine must be disposed back into the sea which falls under brine disposal as surface water discharge. Brine harms marine life because it increases seawater salinity, changes the temperature, and contaminates the environment with chemicals, such as antiscalants, heavy metals, and microbial loads from pre- or post-treatments (Panagopoulos and Giannika (2022). Several studies have shown that this disposal negatively impacts the ecosystem. The environmental impacts are expected to reach a zone of 900 meters (Linden, 2024).

Besides impairment of the ocean, the desalination technology also has a lower water recovery. A standalone membrane desalination such as reverse osmosis will recover 40.8% of water and a standalone thermal desalination will recover around 50% of water (Mohammed et al., 2023; Feria-Díaz et al., 2021). MLD processes reach a water recovery of 80% and ZLD processes reach a water recovery up to 95-99% (Morgante et al., 2024-a). So, the most likely scenario without an MLD or ZLD technology also misses out on a lot of potable water production. Ofcourse, the trade-off explored in this study is the cost associated with implementing MLD.

5.3 Step 3: The Policy Alternative

The policy alternative is a description of a measure which is expected to help solve the problem and which will be analysed in the CBA (Romijn and Renes, 2013). There are two policy alternatives to consider which help solve the problem; ZLD or MLD technologies. The difference between the technologies is already mentioned but the policy alternatives will be briefly summarized again. ZLD technologies extract all the fresh water from the feed water during the desalination without any discharge into the environment and replace the current disposal methods as shown in figure 31 (Mika et al., 2024). The difference between a standalone desalination technology and a ZLD technology is the water recovery percentage and the purification of the byproduct which recovers all salts from the waste stream and reduces the toxicity to zero. The disadvantage of a ZLD is the high costs and complex technology process.

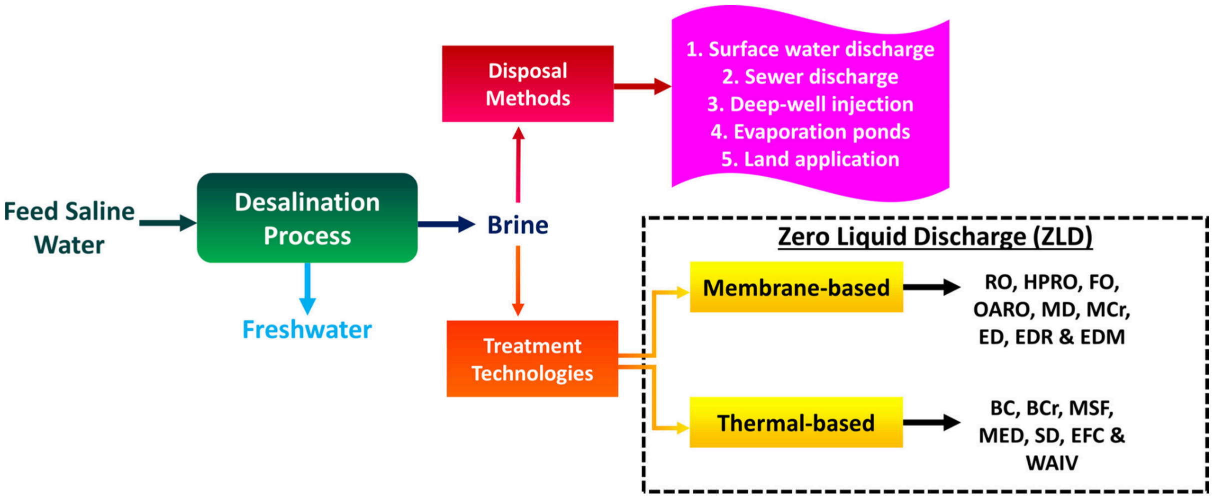


Figure 31: Graphical abstract of Brine Management (Mika et al., 2024)

The MLD process has a lower water recovery percentage and is not able to recover all salts from the brine stream. However, the MLD technology is therefore less expensive and complex. For the CBAs the policy alternative of an MLD technology is chosen because of the 21 week length of the study.

5.4 The Type of CBA

There are two types of CBAs; comprehensive CBAs and indicative CBAs (Romijn and Renes, 2013). In a comprehensive CBA all the research steps are carried out and all effects are identified as accurately as possible (Romijn and Renes, 2013). The best information is available and this offers the decision-makers the most detailed insight into the advantages and disadvantages of a measure. The CBA is therefore very lengthy and costly to carry out. An indicative CBA is less precise and is based on rules of thumb and index numbers. This type of CBA is quicker and cheaper to make but is less detailed and of poorer quality. An indicative CBA can increasingly become more like a comprehensive CBA when more time and information is available.

The principle of sensible analysis describes only conducting the necessary level of analysis to avoid delaying the decision-making process (Romijn and Renes, 2013). The type of CBA is chosen depending on the stage of the decision-making process, application to the field in which it is used, time available, and the information available. An overview is made in the following table 10. The comprehensive CBA is for companies preferred to be fully aware of all costs, but the reality of this research is satisfied with the most elaborate verse of an indicative CBA.

Table 10 : Comprehensive or Indicative CBA

Criteria	Compr.	Indicative	Underpinning
Decision-making stage	X	X	To formulate a deliberate conclusion on the application costs and benefits of an MLD for hydrogen production a comprehensive CBA is preferred but not all costs will be correctly included or overlooked, making an indicative CBA sufficient.
Application to the field	X	X	The application of a CBA in the field of water desalination can use both types of CBAs.
Time available		X	During this study, not enough time is available to include all elements of the technology. Therefore, the CBA analyses in depth the MED and NF technology, but also includes more rough indications of certain characteristics.
Information available		X	The MLD technologies for drinking water are in operational phase but are not yet extensively researched regarding brine treatment (Panagopoulos and Gianniaka, 2024-a). This is not the case for hydrogen production. This will cause some gaps in the available information.

5.5 Step 4: Effects included in the CBA

This chapter is to determine the effects of the desalination technology and delineate the market. The determination of effects and benefits takes place in three steps; identifying the effects, quantifying the effects and valuing the effects (Romijn and Renes, 2013).

5.5.1 Identification of Effects

The identification of effects involves the establishment of what effects a measure has and determining if the effects are also important for the CBA. The effects can be priced or non-priced, which is also called externalities. The first step is to identify the direct effects and the second step is to identify the indirect effects. The direct effects are higher technology costs and higher water recovery rate. The indirect effect is the reduction of environmental impacts. Table 11 shows an overview of the identification of the direct and indirect effects. The production of hydrogen is not included as an identified effect because the CBA is about the changed measure of an MLD technology and the AWE in the technology process has not changed by this measure. Therefore, the amount of hydrogen produced has no different effect.

Table 11 : Identification of Effects

Effects\Costs	Positive Direct	Negative Direct	Positive Indirect	Negative Indirect
High technology costs		X		
High purified water recovery	X			
Environmental Impact			X	

5.5.2 Quantification of Effects

The effects are quantified by comparing the changes in the identified markets caused by the new measure. All effects should be quantified, but this is not always possible because of lack of information or the effect does not lend itself to a quantitative expression. In this case, all effects are quantified and an overview of the CBA is shown in figure 32 below. The effects of table 11 are processed in this CBA and will be further explained in this section.

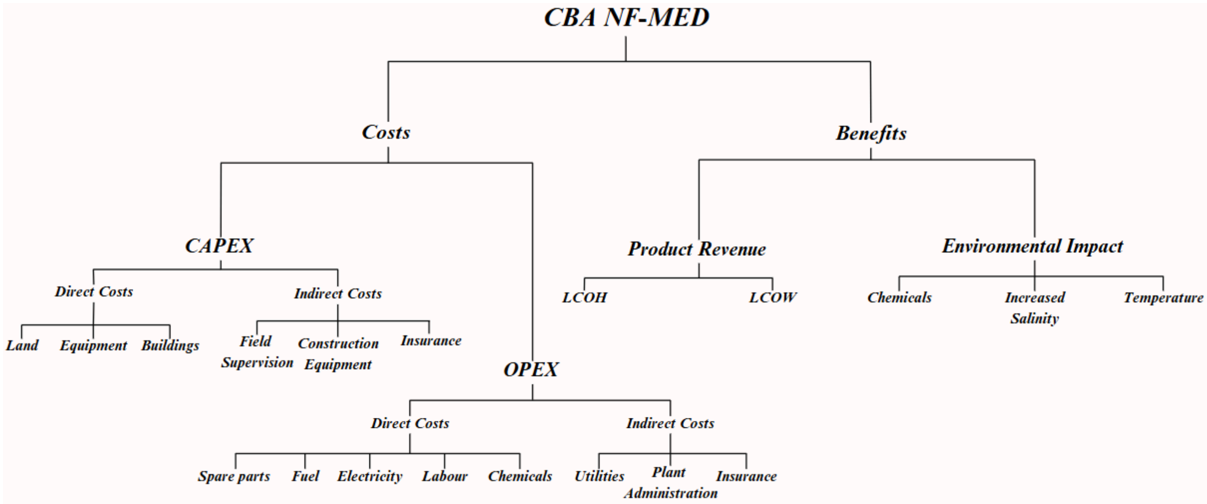


Figure 32 : Overview Quantification Effects

The high technology costs are represented as CAPEX and OPEX of the desalination technology. The CAPEX and OPEX are split in direct and indirect costs to make the costs explicit. The direct CAPEX costs are land, equipment and buildings and the indirect CAPEX costs are field supervision, construction equipment and insurance, The direct OPEX costs are spare parts, fuel, electricity, labour and chemicals and the indirect OPEX costs are utilities, plant administration and insurance. The effects are quantified, based on the cost and benefit determinations from other business cases of water desalination technologies analysed in the literature reviews in chapter 6, 7 and 8.

The significant recovery of purified water is reflected in the product revenue of the desalination technology. Under product revenue the abbreviations LCOH and LCOW stand for Levelized Cost of Hydrogen and Levelized Cost of Water. As the MLD technology does not directly produce hydrogen, only LCOW is taken as product revenue.

The environmental impact is also accounted for within the benefits of the CBA divided into chemicals, increased salinity and temperature. In the MLD system applied to this study, brine production is not reduced compared to normal water desalination processes. This is because no technologies are implemented to extract or isolate the salts. As a result, a discharge permit is required, which depends on the plant's capacity and the environmental impact of the brine (BAL, n.d.). The associated costs are categorized as indirect CAPEX insurance, as this permit must be paid once, if the brine stays the same.

As mentioned, an indicative CBA was chosen to avoid the need for in-depth research on all elements, thereby reducing both the costs and time required for the analysis. The CAPEX represents over 80% of the costs for the desalination technology, while less than 20% is attributed to OPEX according to other studies (Mohammadi et al., 2020). Besides, the direct costs are more influential for the stakeholder decisions than indirect costs. Therefore, the decision was made to explain the elements within the indirect costs of CAPEX and OPEX, but to simplify the indirect costs into a single price indication.

5.5.3 Monetisation of Effects

The valuation of effects are represented by the willingness to pay for the effects of the measure. The effects are represented in monetary terms and if monterey terms are not available, alternative techniques can be used to establish the value of effects. For the CAPEX, OPEX and product revenue monetary terms are available. However, no direct monetary values are available regarding the environmental impact. This section will contribute to how environmental costs are included in the CBAs for sub-question 2.

The environmental impact is hard to monetise because the effect is not so easily expressed in figures. There are several economic estimation methods to overcome this hurdle. For this study, shadow pricing is chosen as an economic estimation method with a damage cost approach. This approach calculates the costs that will be made to recover environmental impacts of brine and will be determined as the monetary value.

In the Netherlands, permits are required from Rijkswaterstaat to be allowed to discharge the brine at sea (Ministerie van Infrastructuur en Waterstaat, 2024). The money collected from the permits will be used for the damage costs (Ghafourian et al. 2022). The willingness-to-pay for an MLD technology from companies is reflected in the costs associated with obtaining the necessary permits. For sustainability purposes, companies might be willing to pay more than the permit costs which could be researched through a survey. However, because of the length of this study, a survey for additional WTP is relevant for a future study. A visual representation is shown in figure 33 about the WTP and additional WTP from companies.

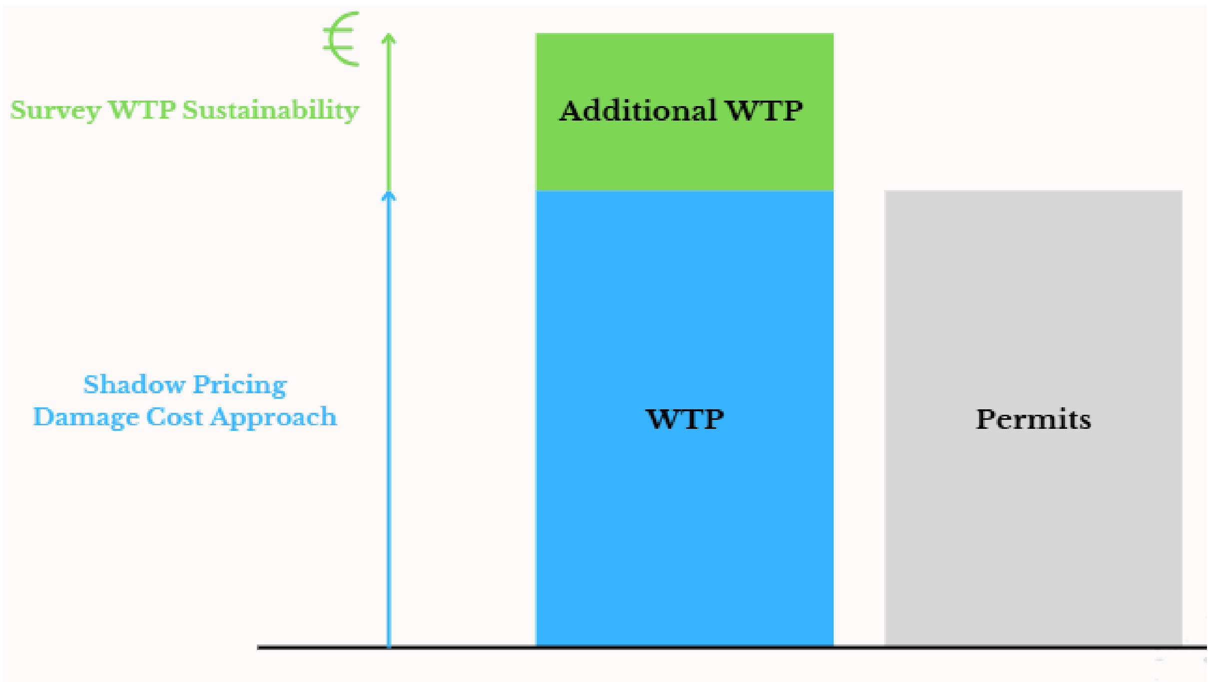


Figure 33 : WTP for companies regarding MLD technologies

5.6 Step 5, Step 6, Step 7, and Step 8

The final four steps of the CBA are each addressed in its own chapter and guided by the specific sub-questions that contribute to answering the main research question. This section outlines the sequence of these steps and explains how each contributes to the overall analysis.

Step 5 focuses on identifying the actual costs associated with the effects selected in step 4. These costs are determined through a combination of literature review and interviews, which help to verify findings and fill knowledge gaps. The sub-questions addressed in this step and the corresponding chapters are listed in table 12. Step 6 involves a sensitivity analysis to explore different scenarios and assess risks. This step builds on the limitations identified in the literature review and is therefore discussed within the same chapters as step 5.

In step 7, all costs and benefits are aligned in time through financial calculations. The results of these calculations are presented in chapters 9 and 10. With step 7, the NPV can also be calculated and provides the input needed for step 8. Step 8 will present the results in a clear table. An overview of all steps and their related sub-questions can be found in table 12. Chapter 13 summaries the steps with a policy letter.

Table 12 : CBA Steps and corresponding Sub-Question

CBA Step	Sub-Question	Chapter
5	*What are the technical and economic costs of implementing MED technologies?*	6
	What are the technical and economic costs of implementing NF technologies?	7
	What are the technical and economic costs of implementing the combined NF-MED technologies?	8
6	*What are the technical and economic costs of implementing MED technologies?*	6
	What are the technical and economic costs of implementing NF technologies?	7
	What are the technical and economic costs of implementing the combined NF-MED technologies?	8
7	*What is the cost-benefit analysis of the Minimal Liquid Discharge technology implementing only MED?*	9
	What is the cost-benefit analysis of the Minimal Liquid Discharge technology NF-MED?	10
8	*What is the cost-benefit analysis of the Minimal Liquid Discharge technology implementing only MED?*	9
	What is the cost-benefit analysis of the Minimal Liquid Discharge technology NF-MED?	10

6. Literature Review MED

This chapter presents a literature review to determine the technical and economic costs of the MED technology, in order to answer the third sub-question; *What are the technical and economic costs of implementing MED technologies?*

The scope of this review is limited to the MED technology within the first MLD system, as this aligns with the scope of the study on determining desalination technology costs through a CBA and potential synergy effects. The first MLD is illustrated in figure 34. A literature review is a helpful tool for researchers to obtain a well-structured overview of the literature and assists in making the knowledge gap explicit (Van Wee and Bannister, 2015). In this context, the review serves three main purposes:

1. To examine how similar cost elements have been calculated in previous studies, providing a methodological foundation for this research.
2. To identify the key parameters and assumptions used in those calculations, which are essential for building a reliable cost model.
3. Determine which cost items are a knowledge gap in the literature, which need to be filled with expert interviews.

This review offers a structured overview of how each cost item in the standalone MED CBA can be identified and quantified. It also highlights which data points are missing or uncertain, and specifies the types of expert input required to address these gaps.

The structure of this chapter is as follows. First, a section is included to define the relevant cost concepts to ensure clarity and consistency. Next, the methodology section outlines the approach used to conduct the literature review, followed by a presentation of the key findings. Lastly, any limitations of the review are also discussed. To enhance the reliability of the results, the findings from the literature review are validated through semi-structured expert interviews. These interviews not only confirm the assumptions made but also help fill in data gaps where the literature lacks sufficient detail.

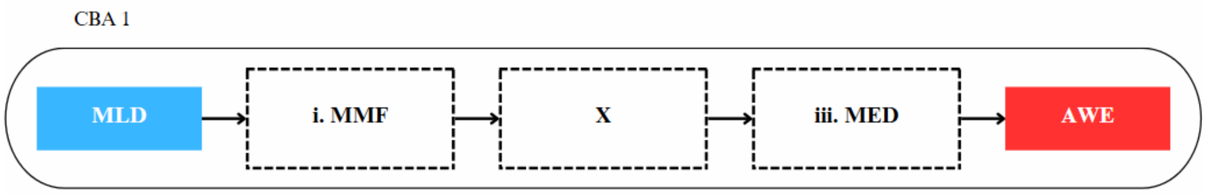


Figure 34 : CBA 1 with MMF, MED and AWE.

6.1 Definition of Concepts

This section defines the key concepts that form the foundation of the literature review for the MED process. The definition of concepts is also relevant for the NF literature review, as this literature review is conducted in the same way. The key concepts taken into account are those variables that affect the operating and capital costs of the MED water desalination. The CAPEX are land, buildings and indirect costs. The OPEX are spare parts, fuel, electricity, labor, chemicals, and indirect costs. The benefits are product revenue and environmental impact. Product revenue is only the water production, because the hydrogen production falls out of the scope. Environmental impact includes the chemicals, rising salinity and rising temperatures of the seawater when disposing brine.

6.1.1 CAPEX

The CAPEX are costs related to the construction period and before the commercial use of the plant (Kehrein et al., 2021). The costs can be direct or indirect. Direct costs are costs that also will be used later in the plant's commercial operation period such as land acquisition, equipment and buildings. Indirect costs are only costs made during the construction period which indicates field supervision, insurance, and construction equipment.

6.1.1.1 Land

Land acquisition refers to the cost of purchasing land for the installation of the MLD plant. The location of the plant can influence overall project costs (Shorki and Fard, 2023). Land is therefore included as part of the CAPEX required for the full deployment of the MLD system. Land costs vary significantly depending on the country and even within regions of the same country.

While globalisation has increased the relevance of land considerations in construction planning, several studies have shown that plant location has only a minor impact on the total cost of water production (Wittholz et al., 2007; Al-Sahali and Ettouney, 2006). However, to indicate the synergy effects it must be determined if the land acquisition has a significant impact on the MLD system.

6.1.1.2 Equipment

Equipment involves the costs of installing each technology of the MLD system. The equipment is highly specific per MLD system and is therefore not commonly determined in the literature. In the literature the following equation 14 is given to determine the price of each MED particle (Micari et al., 2019). C_{BM} is the fully installed costs which is determined by Cp^0 and F_{BM}. Cp^0 is the purchase price of each equipment particle and the F_{BM} is the bare module factor which is a multiplier used to go from the purchase price of a device to the full installed cost.

$$C_{BM} = Cp^0 * F_{BM} \qquad [14]$$

It is hard to determine the Cp^0 for every equipment particle on its own, as equipment costs range a lot in price (DACE, n.d.). Therefore, a combined cost needs to be determined regarding existing MEDs.

6.1.1.3 Buildings

The building is the housing of the MLD plant. The building costs are complicated because of the uncertainties in real-world systems with different limitations (Shokri and Fard, 2023). Therefore, the considerable costs must come from related buildings that already exist and defined through the semi-structured interviews of the experts.

6.1.1.4 Indirect Capital Costs

The indirect costs are determined in this study by field supervision, insurance, and construction equipment. The indirect costs are combined to one price index of maintenance to reduce the time of the analysis. The indirect costs are chosen to simplify because they have a very small effect on the CAPEX costs according to studies from this literature review. This approach aligns with the characteristics of an indicative CBA.

6.1.2 OPEX

OPEX are the costs expended after the construction period and are relevant for the entire lifespan of the water desalination technology (Kehrein et al., 2021). The operational costs are also divided in direct and indirect costs. Direct cost is money spent on the operational process and indirect cost, which is also called overhead costs, is money spent on the desalination plant which is not directly related to the operation process. The direct costs are spare parts, fuel, electricity, labour, chemicals. The indirect operational costs are utilities such as security, plant administration, general expenses such as transportation, and insurance.

6.1.2.1 Spare Parts

Spare parts are the components required throughout the lifespan of the MLD system to repair and replace any elements of the plant that may fail. The costs for spare parts are necessary for replacing components in desalination technology when they break down (Mohammadi et al., 2020). The lifespan of equipment can be partially determined and partially estimated. For example, the MED technology has a lifespan of 25 years, while AWE has a lifespan of 15 to 20 years (Ellersdorfer P. et al., 2023; Husaini et al., 2025; Varras and Chalaris, 2024). However, it is much harder to predict which equipment will need unexpected replacement. Semi-structured interviews with experts help indicate the costs for replacing spare parts.

6.1.2.2 Fuel

For the water desalination process two types of fuels are needed, feed water and waste heat. Electricity might also be seen as a fuel for the process, but has its own definition of concept in the next section. The feed water is needed to filter the pure water from the salts, cool the evaporated pure water in the condenser, and cool the electrolyser. As mentioned, this technology uses seawater as feedwater and extracts from the North Sea.

The waste heat is needed to produce steam to split the salts from the feedwater. The desalination location is at the Port of Rotterdam, so for this situation the industrial waste heat from the Botlek or the Maasvlakte can be used. A very promising solution could also be the waste heat from the electrolyser.

6.1.2.3 Electricity

The electrical expenses are the costs of electricity consumed by all process pumps (Malik et al., 2023; Rahimi et al., 2015). The pumps constitute the main contribution to the total electrical energy consumption of a desalination plant. Other electrical expenses are not included.

6.1.1.4 Labour

The labour costs cover all the workers who maintain the desalination system while it is operational. The labour costs are based on actual cost data of the country where the plant is located (Malik et al., 2023; Rahimi et al., 2015). It is usually defined through the average costs of a water service sector employee.

6.1.1.5 Chemicals

Chemical additives are necessary for ensuring the effectiveness and maintainability of the desalination process and results in an annual expense (Malik et al., 2023). The feed water of the desalination technologies have specific chemical dosing requirements and represents a considerable fraction of yearly expenses. A combined chemical price will be determined.

6.1.1.6 Indirect Operational Costs

The overhead costs encompass a wide range of expenses, including utilities and general expenses. Utilities cover services such as security and fire departments and general expenses include transportation. Similar to CAPEX, these costs constitute only a small portion of OPEX and are therefore combined into a single price of maintenance. This approach aligns with the characteristics of an indicative CBA. It is important to mention that the indirect costs are not always described the same in every article. Indirect operational costs are therefore combined as maintenance activities.

6.1.3 Product Revenue

The revenue of this seawater desalination technology is in the first place the LCOW. Water is a scarce resource and will lead to rising prices in the Netherlands, making water for hydrogen production a lower priority when drinking water is already scarce. The MED technology is built to grow with the energy capacity of the electrolyser. The full capacity of the MED can be used to produce 480 m3 of ultrapure water for the electrolyse and the remaining purified water for other functionalities in the industry. However, LCOH is not a second source of revenue because the hydrogen production is not a direct result from the MLD system. This will lead to incorrect NPVs.

There are revenues that are not included in the CBA because the technology is an MLD technology that is unable to isolate salts due to the lack of a post-treatment crystallisation as shown in figure 4 (Panagopoulos and Michailidis, 2025). The MLD technology of this study does not include these technologies and are therefore not able to sell salts from the brine. Possible further developments of the MLD technology might add costs but will also add benefits in regard to collecting useful solid salts.

6.1.4 Environmental Impact

The environmental impact are external costs (Ghafourian et al. 2022). An externality occurs when producing or consuming a good or service and it causes a positive or negative impact on the third parties that are not directly linked to its creation. The environmental impact of brine on marine life is an externality. The MLD and ZLD systems reduce the environmental impact. However, in the MLD system developed for this study, the brine is more concentrated but not completely eliminated and is therefore still discharged into the sea.

6.2 Methodology

After identifying the key concepts to this literature review, a structured search strategy was developed to systematically collect the relevant academic sources. The literature review aims to gather information on comparable MED technologies, recognizing that no single scientific article will be directly comparable to the developed technology of this research.

Scientific articles were retrieved from two major academic databases called Google Scholar and Scopus. These platforms were selected because they provide broad access to peer-reviewed literature in the fields of MED technologies. All selected articles are written in English to maintain consistency and accessibility. However, the literature review will also identify some knowledge gaps which will have to be filled through semi-structured interviews. The semi-structured interviews are also helpful in verifying the parameters determined through the literature review.

The search strategy was built around combinations of the previously defined key concepts. These combinations were used to construct search strings. Given the popularity of the topic of water scarcity, a lot of articles can be found on MED technologies. However, desalination is not developed for hydrogen production but mainly used for freshwater extraction or as a replacement for land mining raw materials.

Hydrogen is included as a key concept which alters the scientific articles more towards the process of the electrolyser instead of the MED process. To gather comprehensive information on water desalination, it is important to note that some articles do not cover the combination of MED and AWE. This approach aims to collect better data, especially since there are limited articles discussing their synergy even though a lot of hits are given. Table 13 shows the used search terms and the final search strings used, highlighted in blue.

Table 13 : Search Terms Used for the Literature Review MED

#	Search Strings	# Google Scholar	# Scopus
1	Multi-Effect Distillation	18.400	1.241
2	Multi-Effect Distillation AND Water Desalination	16.500	802
3	Multi-Effect Distillation AND Water Desalination AND TEA	3.480	30
4	Multi-Effect Distillation AND Water Desalination AND TEA AND Hydrogen Production	3100	1
5	Multi-Effect Distillation desalination AND CAPEX and OPEX AND Hydrogen Production	686	1

To manage the wide variety of search results, the same guidelines are used as the literature review to find the knowledge gap of this study regarding economic assessment studies. An initial delimitation was conducted on the first 20 articles retrieved using search strings 4 and 5, as both strings produced different relevant articles. The articles need to be published after 2021 to include the most recent findings. This does not count for articles found through snowballing.

The first 20 articles were reviewed because no single researcher or research group stood out. Only Morgante et al. had two relevant articles for this study. The article scope of the literature review on the knowledge gap about economic assessment studies was expanded to include 30 articles because one researcher, Panagopoulos, did stand out with 8 out of 21 articles.

The initial screening involved analysis of the most recent articles after 2021, removal of duplicates and if the articles were peer reviewed. Further screening involved assessing the title, publication year, and number of citations. Next, the abstract and keywords of the remaining articles were reviewed.

Finally, the introduction, discussion, and conclusion were examined to select the 12 most relevant articles. Ellerdorfer et al. had three relevant articles that increased the number of articles to 15 through snowballing. Scopus only resulted in two articles from both strings. From string 4, the article was not relevant and from string 5 it was a duplicate from Google Scholar. Figure 35 illustrates the literature review progress.

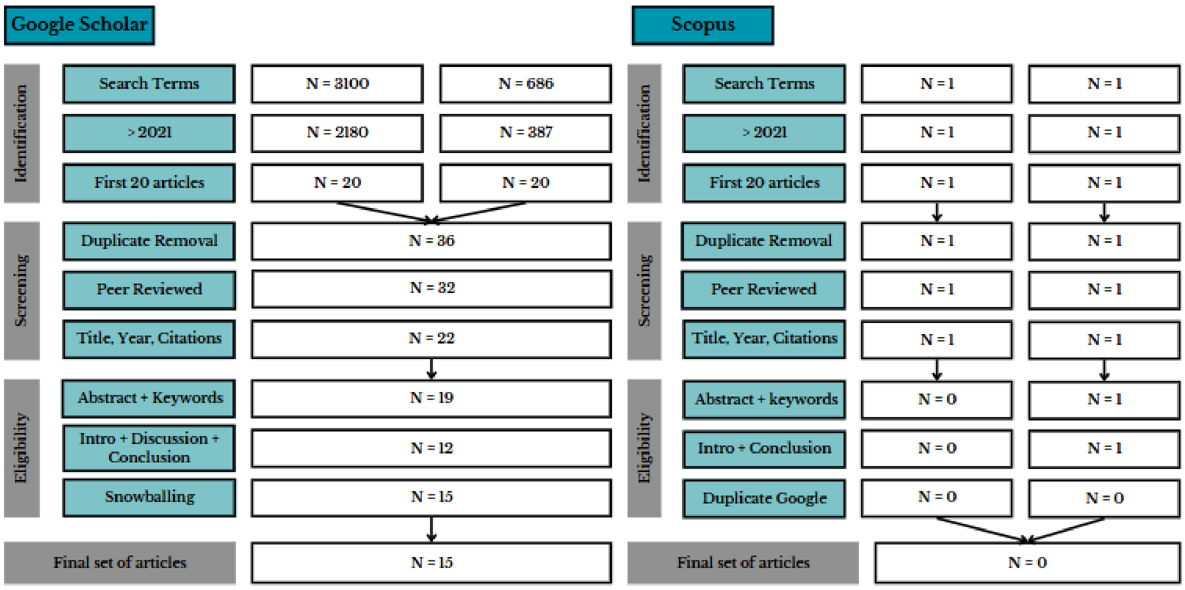


Figure 35 : MED Literature Review Process

6.3 Results MED

The results of the literature review highlight the diverse applications and characteristics of a MED technology. It becomes clear that MED can operate very independently in producing demineralised water for an AWE system. Table 14 provides an overview of the specific applications of the MED technology in the literature review, including its role in generating demineralised water for an electrolyser. This table 14 clarifies the various implementations of MED and these differences may explain variations in reported parameters. When selecting the MED parameters for this study, these contextual differences were taken into consideration.

Table 14 : Overview of MED Applications

#	Article/concept	Seawater Treatment for Electrolyser	Electricity and Water Use of MED	Hybridization MED-AD	Low-Grade Heat Use for MED	Seawater Treatment with reference MED	Seawater Treatment with FO-MED	Seawater Treatment with NF-MED	Seawater Treatment with MLD including NF-MED for Salt Mining
1	(Arunachalam et al., 2024)	X							
2	(Morgante et al., 2022)								X
3	(Moharram et al., 2021)		X						
4	(Manesh et al., 2021)					X			
5	(Ellersdorfer P. et al., 2023)	X							
6	(Son et al., 2020)			X					
7	(Christ et al., 2015)				X				
8	(Kosmadakis G. et al., 2018)					X			
9	(Varras and Chalaris, 2024)	X							
10	(Ortega-Delgado et al., 2022)						X	X	

11	(Malik M. S. et al., 2023)		X						
12	(Dastgerdi and Chua , 2018)					X			
13	(Mika et al., 2024)					X			
14	(Morgante et al., 2024-a)								X
15	(Scelfo et al., 2025)								X

The table 15 below, shows the found information on MED technologies from the literature review illustrated in table 13. The parameters differ from each other depending on plant size, equipment and costs because of the different processes and plant use. It is notable that not a lot of information is given about the land costs, building costs, CAPEX indirect costs, spare parts costs, and the environmental impacts. In the following sections of this chapter, the choices for the calculations and parameters are discussed and explained. The knowledge gaps are filled with expert interviews.

Table 15 : Results Literature Review MED

#	Article/concept	Land	Equipment	Buildings	CAPEX Indirect Costs	Spare Parts	Fuel	Electricity	Labour	Chemicals	OPEX Indirect Costs	LCOH	LCOW	Chemical Impact	Salinity Impact	Temperature Impact
1	(Arunachalam et al., 2024)		X				X	X				X				
2	(Morgante et al., 2022)		X				X	X		X						
3	(Moharram et al., 2021)	X					X	X	X	X	X					
4	(Manesh et al., 2021)						X	X								
5	(Ellersdorfer P. et al., 2023)		X				X	X	X	X		X	X			
6	(Son et al., 2020)							X								
7	(Christ et al., 2015)							X	X	X	X					
8	(Kosmadakis G. et al., 2018)		X				X									
9	(Varras and Chalaris, 2024)						X									
10	(Ortega-Delgado et al., 2022)		X										X			
11	(Malik M. S. et al., 2023)		X					X	X	X	X		X			

12	(Dastgerdi and Chua, 2018)		X			X		X	X	X	X	X				
13	(Mika et al., 2024)		X				X	X	X	X					X	
14	(Morgante et al., 2024-a)		X					X								
15	(Scelfo et al., 2025)							X	X							

6.4 Determination of the MED parameters

After identifying the key concepts, explaining the methodology of the literature review, conducting the review on MED technologies, and creating an overview of the missing parameters, the MED parameters can be determined. The literature review encompasses various MED technologies and are not always used for producing demineralized water for an AWE. Therefore, it is crucial to explain the sources of information and how they are interpreted for this study. When parameter information is missing, data from expert interviews will be used. This will also be explicitly mentioned in the relevant sections.

The first section outlines the total CAPEX cost equations identified in the literature review on MED installations, prior to introducing the actual cost components used in the CBA. These CAPEX equations are not applied in this study because they do not provide sufficient detail to determine the individual cost items that define a CBA. Besides, they result in unrealistically high costs that are not representative of actual industry costs. Nevertheless, it is important to acknowledge the existence of these equations and to explain why they were ultimately excluded from the analysis.

6.4.1 MED : CAPEX Costs

The most common approach to estimating the capital cost of an MED plant is by correlating the specific cost with the plant capacity (Kosmadakis et al., 2018). This relationship is expressed in equation 15, which applies to MED plants with capacities up to 10.000 m³/day. The D in the question represents the distillate flow rate. For the MED plant with an ultra pure water output of 1000 m³/day, this equation yields a specific capital cost of €2.571,40 per m³/day. As plant capacity increases, the correlation indicates a decrease in specific capital costs. However, these costs typically do not fall below €2.400 per m³/day.

$$Cmed\ [€/m^3/day] = 3054D^{-0.0249} \qquad [15]$$

However, this equation is simplified, as the MED CAPEX differs regarding number of effects, application of water inlet, and the temperature of the heat supply (Kosmadakis et al., 2018). The most important design parameters are the number of effects and the heat exchanger (HEX) area. To increase the accuracy of the CAPEX of the MED plant these design parameters should be included. The equation 16 is refined to be more precise with the inclusion of the HEX area. The coefficient is adjusted to expand to a higher capacity inclusion of 800.000 m³/day and approach the average values instead of the conservative ones.

$$Cmed\ [€/m^3/day] = 6291D^{-0.135}[(1 - fHEX) + fHEX\,(\frac{HEX\ area}{HEX\ area,ref})^{0.8}] \qquad [16]$$

To determine the HEX area, the number of effects in the MED system must first be established (Kosmadakis et al., 2018). For this study, a configuration with 8 effects was selected for the MLD system. As shown in Figure 36, an MED system operating at 70 °C with 8 effects results in a HEX area that is the same as the HEX reference area.

The reference MED has the same parameters as the MED of this study, which is normal as for this study a reference MED is also taken. However, not all CAPEX is driven by the HEX area. Therefore, only a portion of the total capital cost is influenced by the size of the heat exchanger. This is accounted for by the parameter $fHEX$ which ranges between 0 and 1 and represents the fraction of the capital cost attributed to the HEX. Based on this, a modified cost correlation can be derived. The calculations are represented in Appendix I and is €2.475,82 per m³/day.

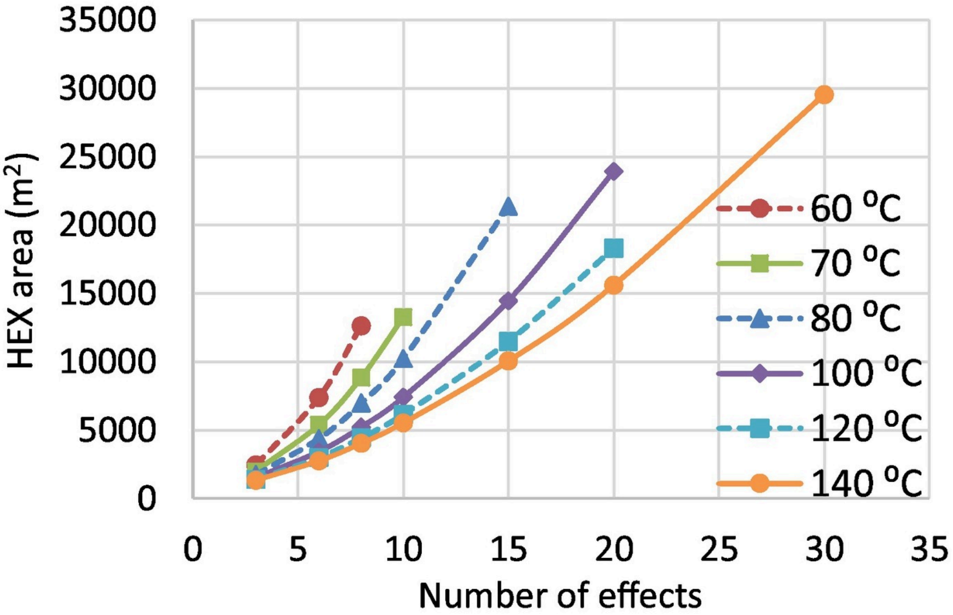


Figure 36 : The Total HEX Area regarding the Number of Effects and Heat Source Temperatures (Kosmadakis et al., 2018).

Equation 17 is a simplified equation by replacing the HEX area with the number of effects and the temperature (Kosmadakis et al., 2018; Ortega-Delgado et al., 2022). The first MED system has 8 effects and operates at 70°C. The $fHEX$ stays the same. Again, the reference MED has the same parameters as the taken MED of this study. The calculation is given in Appendix I and will give the result of 1.485,49 m³/day.

$$Cmed\ [€/m^3/day] = 6291D^{-0.135}[(1 - fHEX(\frac{N}{Nref})^{1.277}(\frac{Ts,ref}{Ts})^{1.048}] \quad [17]$$

These equations provide a useful first estimate of the CAPEX for implementing MED technology within an MLD system. However, they are based on simplified assumptions and do not distinguish between the various components that make up total CAPEX. Moreover, the equations express CAPEX on a daily basis, which can lead to unrealistically high investment cost estimates. The calculations below show the high and unrealistic investment costs.

$$Cmed\ [€/yr] = 2.571,40\ [€/m^3/day] * 1000\ [m^3/day] * 365\ [days/yr] = 939.561.000\ [€/yr] \quad [18]$$

$$Cmed\ [€] = 939.561.000\ [€/yr] * 25\ [yr] = €23.489.025.000 \quad [19]$$

$$Cmed\ [€/yr] = 2.475,82\ [€/m^3/day] * 1000\ [m^3/day] * 365\ [days/yr] = 903.658.300\ [€/yr] \quad [20]$$

$$Cmed\ [€] = 903.658.300\ [€/yr] * 25\ [yr] = €22.591.457.500 \quad [21]$$

$$Cmed\ [€/yr] = 1.485,49\ [€/m^3/day] * 1000\ [m^3/day] * 365\ [days/yr] = 541.226.850\ [€/yr]$$ [22]

$$Cmed\ [€] = 541.226.850\ [€/yr] * 25\ [yr] = €13.530.671.250$$ [23]

To improve accuracy, a more detailed approach is adopted. In this approach, the total CAPEX is broken down into individual cost elements, which allows for a more transparent and reliable cost assessment. These results are then verified through expert interviews.

6.4.2 MED : Land Costs

The literature review did not give any information on land costs as it is highly specific for the location chosen. However, a few things can be done to monetise this CBA element. First, determine the surface area of the MLD technique and then the costs per m^2 of the chosen area. The equation 24 is given below.

$$LC\ MED\ [€] = (MMF\ [m^2] + MED\ [m^2] + AWE\ [m^2]) * Land\ Price\ [€/m^2]$$ [24]

The scope of the literature review is only the MED technology. However, this equation includes the MMF, the MED and the AWE. This broader inclusion is necessary because the plant owner must allocate sufficient space not only for the MED equipment but also for essential infrastructure such as a control room, warehouse, and other storage facilities (Business Developer, 2025)

This cost item also assists in identifying the synergy effects. because the MMF footprint for MLD 1 and MLD 2 differ. According to a process engineer (2025), both systems require three filters to treat the seawater but the diameters for the filters are bigger for the second MMF for MLD 2. The MMF is included in the footprint calculation, even though it falls outside the cost scope of this study. This is to include sufficient space for MLD 1 and MLD 2 and to address the synergy effects.

The AWE is included for similar reasons. This footprint includes the control room, the warehouse, and other important storages. By including this footprint enough space is calculated for all needed equipment to operate the factory. The AWE is determined to be 187 by 219 m^2, according to a business developer (2025). This is a standard indication made in the industry for an 100 MW electrolyser (Business Developer, 2025). For the other cost items, AWE is also not included.

Since footprint data is highly specific and not readily available in the literature, all values were obtained through expert interviews. The MED is determined by a tendering manager to be 330 m^2 (Tendering Manager, 2025). The MED system consists of 9 effects. According to the tendering manager, this number was chosen because achieving a GOR of 8,13 requires 9 effects instead of the standard reference of 8, as determined in academic literature (Malik et al., 2022). An overview of the total footprint is shown in table 16.

Table 16 : MLD 1 Land Area

MLD	Technology	Area $[m^2]$	Resource
MED	MMF	14 * 12 = 168	(Process Engineer, 2025)

MED	MED	11 * 30 = 330	(Tendering Manager, 2025)
MED	AWE	187 * 219 = 40.953	(Business Developer, 2025)
MED	MMF, MED & AWE	41.451	(Process Engineer, 2025; Tendering Manager, 2025; Business Developer, 2025)

Once all the materials are determined, the land price per square meter needs to be determined. As mentioned in figure 22, there are multiple places in the Netherlands that function as hydrogen locations. Every location has different land prices $€/m^2$.

When trying to keep costs as low as possible, locations such as Eemshaven or Den Helder are better suited (Project Manager, 2025). However, when looking at the current electrolyser projects, the focus is on Maasvlakte 2. Therefore, the Port of Rotterdam is chosen as the location for the MLD plant. A medium land price is taken of 79 $€/m^2$ for undeveloped land in Rotterdam (Gemeente Rotterdam, 2024).

6.4.3 MED : Equipment Costs

The initial equipment cost estimate for the MED system was calculated using the DACE cost estimation booklet. This is shown in appendix P. However, this approach appears to underestimate the actual investment, because it does not account for additional mechanical and electrical components that are essential to the system. These components were also not explicitly mentioned in the literature review.

To address this limitation, a more comprehensive cost estimate was obtained through an expert interview with a tendering manager (2025). This expert provided a combined total cost figure that includes the missing elements. The equipment cost estimate for the MED system is presented in Table 17.

Table 17 : MED Equipment Costs

MLD	Technology	Valuation [M€]	Resource
MED	1 unit with 9 effects	5,5	(Tendering Manager, 2025)

6.4.4 MED : Building Costs

The literature review did not include the costs associated with constructing buildings to house the equipment. This omission is due to the fact that building costs are not always necessary and often depend on the preferences of the project owner (Project Manager, 2025). In general, the MMF, MED, and AWE systems do not require buildings because the MED consists of large tanks with evaporators, and the AWE is typically containerized.

A small building may be needed only if a control room is required. However, with current technological advancements, remote monitoring and operation are now feasible. However, in this specific case, the AWE system has a capacity of 100 MW and that exceeds the limits of containerized housing (Business Developer, 2025). As a result, a building is required. Nevertheless, this aspect falls outside the scope of this study. Besides, the building will not change between the first and the second MLD because the size of the AWE will not differ. An overview is given in table 18.

Table 18 : MED Building

MLD	Technology	Building	Resource
MLD	MMF	No	(Project Manager, 2025)
MLD	MED	No	(Project Manager, 2025)
MLD	AWE	Yes	(Business Developer, 2025)

6.4.5 MED : Indirect Capital Costs

As mentioned, the indirect cost is a combined value to make the indicative CBA fit within the timeframe of this study. The indirect capital costs include the field supervision, construction equipment and insurance. The literature review did not give any intel on the indirect capital costs except for the following equation 25 (Ortega-Delgado et al., 2022). No distribution was given on the direct and indirect costs. Therefore, 10% of the equipment and building costs is taken as indirect capital costs which is taken for other techno-economic analyses on water desalination technologies (López et al., 2025; Micari et al., 2019; Figueira et al., 2023). It is important to mention that in the literature review this percentage was determined without the land costs, as these were not included in the analyses. So, only 10% is taken from the equipment and building costs and represented in table 19.

$$Ccapex = Ccapex, d + Ccapex, ind \quad [25]$$

Table 19 : MED Indirect Capital Costs

MLD	Equation	Resource
NF	$Cindirect\ costs\ [€] = 10\%\ (Equipment\ and\ Building)$	(López et al., 2025; Micari et al., 2019; Figueira et al., 2023)

6.4.6 MED : Spare Parts Costs

The spare costs is the first element of the OPEX, from now on the costs are determined in $€/yr$ or need to be altered to be able to compare the different costs. Not a lot was mentioned on spare parts except for the lifetime of the equipment. The MED has a lifetime of 25 years and the AWE has a lifetime of between 11 and 20 years (Ellersdorfer P. et al., 2023; Husaini et al., 2025; Varras and Chalaris, 2024). This means that in the operational time of the MED, the AWE needs to be replaced at least once.

The cost per unit of the electrolyser is based on the price per kW, so an average cost of €1816/kW is taken (Husaini et al., 2025). The following equation 26 is applied to calculate the CAPEX for any capacity AWE. An AWE with a capacity of 100 MW will cost approximately €181.6 million. The 100 MW electrolyser project in Eemshaven is estimated to cost between €50 million and €100 million. This is around €80 million euros less. As the project in Eemshaven is in the Netherlands and representative for this study, an assumption is made with a CAPEX of €100 million for the AWE.

$$CAPEX\ AWE\ [€] = Power\ [kW]\ *\ Cost\ [€/kW] \quad [26]$$

While it is important to consider these types of costs, they do not align with the specific cost category being addressed here. This particular cost item typically represents only 2.5% to 6% of the total CAPEX. Therefore, the focus should be limited to the spare parts associated with the equipment of MED. Articles from the literature review mentioned the OPEX spare parts costs, but did not give any additional information on the cost item besides a combined cost of annual maintenance, spare parts and insurance to be 1,5% of the CAPEX costs (Dastgerdi and Chua, 2018). So, an interview with a Consultancy Manager was needed to indicate the spare parts costs.

The spare parts consist of three categories; commissioning, operational spares, and critical spares (Consultancy Manager, 2025). The categories can be ranked high or low in costs. The commissioning is also called the start-up which is the consumables and wear items needed for initial commissioning and early-life failures. The technology is one of the oldest water desalinations, so the commissioning is ranked low.

The operational spares include parts expected to wear out or require replacement during the first 2 to 5 years. The parts in the MED do not need early replacement, so again the costs can be ranked low. The critical spares are high-cost or long-lead-time components that are essential to avoid extended downtime in the event of failure. For example, failure of the feedwater pump would halt the entire operation. Therefore, it is common practice to ensure that such critical spares are readily available on-site (Project Manager, 2025). So, the total spare costs is 3% of the total CAPEX of the MED as shown in table 20 below.

Table 20 : MED Spare Parts

Spare Part Category	Low [%]	High [%]
Commissioning	1	2
Operational Spares	1	3
Critical Spares	0,5	1

6.4.7 MED : Fuel Costs

There are two types of resources needed for the process of water desalination for hydrogen production: feedwater and waste heat. The feedwater is seawater in this study. The waste heat requirement depends on whether active or passive cooling is used (Ellersdorfer P., 2023).

6.4.7.1 Seawater Extraction

Passive cooling with the waste heat from an electrolyser is effective for the 100 MW current electrolyser capacity, but will need active cooling once the electrolysers reach GW capacity. The passive cooling needs 50 litres of seawater per kilogram of hydrogen to cool the AWE (Folmer et al., 2024). The AWE itself needs 10 litres of seawater to produce a kilogram of hydrogen.. An overview of the needed feedwater is shown in table 21. To monetise the water fuel extraction, the Dutch legislation has some guidelines on extracting water.

In the Netherlands the following is said about extracting seawater from the North Sea according to the Living Environment Activities Decree, Besluit Activiteiten Leefomgeving (BAL) in Dutch (BAL, n.d.). A permit to withdraw water from surface waters managed by the State is required if cited as followed by BAL article 6.36 :

- " The intake flow is more than 1.800 m³/h, the inflow velocity is more than 0.15 m/s and it concerns a specifically designated water. Which waters these are is listed in Article 6.36 first paragraph, under a, of the Ball.
- The flow rate of the abstraction is more than 100 m3/h and it concerns a water other than mentioned in Article 6.36 first paragraph under a of the Ball.
- The inflow velocity is more than 0.30 m/s.
- The abstraction is related to a discharge activity on a surface water body that requires a permit.
- A permit is not required when extracting water from the North Sea. A permit is also not required for the withdrawal of water during dredging activities. The abstraction of water from regional waters is not regulated by state rules, but it may be subject to decentralized rules."

The intake flow from the MMF is 3.7033,33 m³/day and is 2.400 m³/day extra when including the cooling needs. This is 777,53 m³/h which is way below the allowed 1800 m³/h and is extracted from the North Sea. So, the CBA does not need to include costs regarding a seawater extraction permit (BAL, n.d.).

Table 21 : MED Water Fuel

MLD	Water Fuel	Parameters	Resource
AWE	Seawater	10 [L/kg H2]	(Ellersdorfer P., 2023)
		0,01 [m3/ kg H2]	
AWE	Seawater	10 - 22,5 [L/kg H2]	(Mika et al. 2024)
		0,01 - 0,0225 [m3/kg H2]	
AWE	Cooling Water	50 [L/kg H2]	(Ellersdorfer P., 2023)
		0,05 [m3/kg H2]	

6.4.7.2 Heat Fuel

Besides feedwater, the MED needs heat to evaporate the seawater to split the salts from the seawater to make ultrapure water. This heat could come from three different sources; waste heat from the Botlek, waste heat from the electrolyser, or heat from an E-boiler. Waste heat from the Botlek and heat from the E-boiler is active heat exchange and is therefore a cost item. Waste from the electrolyser is passive heat exchange, as the electrolyser is part of the process and does not require additional costs. This is the preferred heat fuel but has its implications. The literature indicated that AWE operates between 65°C and 100°C (Folmer et al., 2024). However, from the expert interview with a business developer (2025) these temperatures are corrected to 40 °C to 50°C. In this case, the AWE does not produce the right temperature of heat making this passive heat exchange not applicable. The remaining choices are waste heat from the Botlek or an E-boiler.

Using waste heat from the Botlek reduces the energy costs because only latent heat is required. However, this decision makes the process dependent on another plant's operation and a company must be found that produces waste water at accurately 70°C. The seawater will need to be converted into steam but remain 70°C, resulting in a daily energy requirement of approximately 286.971.300 kJ as explained in section steam production. This is around 79 kWh/m³.

An alternative would be to install an E-boiler, but this option is costly because the installation and operational setup is already around €500.000, and additional sensible energy is required to raise the temperature of the water in the boiler to 70°C. The steam price for this study can be benchmarked against the cost of natural gas used to power an E-boiler (Product Specialist, 2025). Therefore, the actual steam price is expected to fall somewhere between zero and the equivalent gas price. To ensure an inclusive estimate in this study, the highest possible steam price within that range has been used. The calculation to determine the gas price is shown in Appendix I and discussed in the interview summary with the Product Specialist (2025).

The heat required for the MED production of 1 m³ of water varies in the literature. Varras and Chalaris (2024) estimate a need of 20,6 to 35 kWh/m³, without specifying the MED capacity, suggesting these values are a guideline. Arunachalam et al. (2024) estimate a requirement of 12,4 to 24,1 kWh/m³ for an MED capacity exceeding 5000 m³. The MED capacity of this technology is also in the thousands, but it is five times smaller. An overview is given in table 22.

The heat requirements reported in the literature review are lower than those calculated in this study. Several factors may explain this difference. Varras and Chalaris (2024) do not specify the number of effects used in their MED system. It is possible that their study assumes a higher number of effects, which would allow for greater internal heat recovery and thus lower external energy demand. Additionally, their system operates at higher temperatures, between 90°C and 120°C, which reduces the latent heat required to vaporize each kilogram of water.

Other studies, such as Arunachalam et al. (2024) and Ellersdorfer et al. (2023) do operate temperatures between 60°C and 70°C for their MED systems, similar to this study. However, they also do not specify the number of effects, which may suggest that their systems are optimized for enhanced heat reuse. Interestingly, Moharram et al. (2021) reports specific thermal energy values that align with those calculated in this study. Their system also operates at 70°C but does not specify the number of effects.

Table 22 : MED Heat Fuel

MLD	Heat Fuel	Energy Parameters	Resource
MED	Heat for Steam	20,6 - 35 [kWh/m³]	(Varras and Chalaris, 2024)
MED	Heat for Steam	12,4 - 24,1 [kWh/m³]	(Arunachalam et al., 2024)
MED	Heat for Steam	41.67–108.33 [kWh/m³]	(Moharram et al., 2021)
MED	Heat for Steam	12.2 - 19.1 [kWh/m³]	(Manesh et al., 2021)
AWE	Waste Heat for Seawater	9,3 - 16,7 [kWh/kg H2]	(Ellersdorfer et al., 2023)
AWE	Waste Heat for Seawater	20 [kWh/kg H2]	(Folmer et al., 2024)

The seawater also needs to be heated before entering the evaporation room. The seawater can be heated by the condenser of the MED (Dastgerdi and Chua, 2018; Ellersdorfer et al., 2023). The condenser uses the leftover heat from the evaporation rooms to heat the seawater.

6.4.8 MED : Electricity Costs

For the electricity costs, equation 27 and equation 28 are found to be the most suited to determine the monetary value. Both formulas need the same inputs but are formulated slightly differently.

$$EC\,[€/yr] = 365\,[day/yr] * f * Dt,Design\,[m^3/day] * NPPC\,[kWh/m^3] * EUP\,[€/kWh] \qquad [27]$$

$$Annual\ Electrical\ cost\,[€/yr] = EUP\,[€/kWh] * p\,[kWh/m^3] * Dt\,[m^3/day] * f * 365\,[day/yr] \qquad [28]$$

To calculate the electric costs, all inputs need to be determined. The inputs and their meaning are shown in the table 23 below. The 365 stands for days per year, the f is plant availability, Dt,design is total production rate, NPPC and p stand for power consumption, and EUP stands for electricity unit price.

Table 23 : Electrical Equation Parameters (Dastgerdi and Chua, 2018; Malik et al., 2023).

Input	Meaning	Parameter	Unit	Resource
365	Days	365	Days/Year	(Dastgerdi and Chua, 2018; Malik et al., 2023).
f	Plant Availability	95	%	(Dastgerdi and Chua, 2018; Malik et al., 2023).
Dt,design	Total Production Rate	1000	m3/day	Calculated
NPPC	Normalised Pumping Power Consumption	2	[€/m3]	Table 24
p	Power Consumption	2	[€/m3]	Table 24
EUP	Electricity Unit Price	0,383	[€/kWh]	(CBS, 2025)
EUP	Electricity Unit Price (Wind)	0,06	[€/kWh]	(De Vries, 2023)

Table 23 also shows the chosen parameters and the resource. The days per year is a uniform parameter. The plant availability is 95% (Dastgerdi and Chua, 2018; Malik et al., 2023). The total production rate is calculated for producing hydrogen with a 100 MW AWE. The NPPC was differently valued in the literature review, so a medium of 2 kWh/m^3 is taken. The parameters are shown in table 24.

The electricity price is dependent on the type of electricity inlet. As mentioned in figure 30, in the Netherlands the price is determined by the highest source of energy needed. According to the Central Bureau of Statistics (CBS), the electricity price in the Netherlands for 2024 was around 0,383 euro per kWh. When deciding solely on wind energy, such as with the NorthH2 project, the energy production costs are zero. This does not take away that wind energy is cost-free (Project Manager, 2025). A small amount is still exploited and taken for 0,06 cents.

In this study, wind energy is assumed to be available for 9.6 hours per day, while the remaining 14.4 hours rely on grey electricity to ensure continuous operation of the MED system. This approach maximises the production of ultrapure water throughout the day.

Table 24 : MED Electricity

MLD	Electricity	Parameters	Resource
MED	pumps	1,5 - 2,5 [kWh/m3]	(Ellersdorfer et al., 2023)
MED	pumps	1,5 - 2 [kWh/m3]	(Arunachalam et al., 2024)
MED	pumps	1 - 4 [kWh/m3]	(Mika L. et al., 2024)
MED	pumps	2 - 4 [kWh/m3]	(Moharram et al., 2021)
MED	pumps	2 - 2,5 [kWh/m3]	(Manesh et al., 2021)

6.4.9 MED : Labour Costs

Four different approaches are taken for labour costs. One, the labour costs are 2% of the CAPEX costs (Ellersdorfer et al., 2023). Equation 29 belongs with the first approach and TCC stands for Total Capital Costs. Two, the labour costs are 16 to 23 % of the OPEX costs (Mika et al., 2024). Equation 30 belongs with the second approach and TOC stands for the Total Operational Costs.

$$Labour\ Costs\ [€/yr]\ =\ 2\%\ *\ TCC\ \ [€/yr] \qquad [29]$$

$$Labour\ Costs\ [€/yr]\ =\ 16\%\ *\ TOC\ \ [€/m^3] \qquad [30]$$

Three, an MED plant requires one qualified full-time employee and equation 31 can be used for this approach (Malik et al., 2023). Four, the water capacity is multiplied by 0,1 $€/m^3$ as indicated in equation 32 (Moharram et al., 2021). This is not a good equation, because the size of the plant does not determine the labour costs. The prize of an engineer for maintenance and checks will not differ because of size. The most suited equation is equation three (Project Manager, 2025). In the Netherlands, employer expenses are taken to be the annual wage of €100.000. An overview of the equations is given in table 25.

$$Labour\ Costs\ [€/yr]\ =\ Annual\ Wage\ [€/yr] \qquad [31]$$

$$Labour\ Costs\ [€/yr]\ =\ 0,1\ [€/m^3]\ *\ Water\ Capacity\ [m^3] \qquad [32]$$

Table 25 : MLD 1 : Labour

MLD	OPEX	Valuation	Resource
MED	Labour	2% CAPEX	(Ellersdorfer et al., 2023)
MED	Labour	16%-23% OPEX	(Mika et al., 2024)
MED	Labour	One full-time employee	(Malik et al., 2023)
MED	Labour	120.000	(Christ et al., 2015)

MED	Labour	0,1 [$€/m^3$]	(Moharram et al., 2021)

6.4.10 MED : Chemical Costs

The chemical costs can be determined by the following two equations 33 and equation 34 below. Ellersdorfer et al. (2023) determines the chemical costs by estimating the chemical costs by 0,031 $€/m^3$, However, Malik et al. (2023) determined the coefficient to be 0,0223 $€/m^3$. Both articles indicate that these numbers stem from earlier work from other techno-economic analyses about MED technologies.

These other studies have formed lists on needed chemicals for MED, the unit costs and the dosing rates (Nafey et al., 2006). As Ellersdorfer et al. (2023) determined the costs for an MED to produce feedwater for the electrolyser, the coefficient 0,031 $€/m^3$ is chosen. This is also in agreement with the tendering manager expert interview. All the chemical valuations are determined in table 26.

$$Chemical\ Costs\ [€/yr] = 0,031\ [€/m^3] * Water\ Capacity\ [m^3/day] * 365\ [days/yr] \quad [33]$$

$$Chemical\ Costs\ [€/yr] = 0,0223\ [€/m^3] * Water\ Capacity\ [m^3/day] * 365\ [days/yr] \quad [34]$$

The chemical equation of Morgante et al. (2024-a) is to elaborate for the feasibility phase to be able to solve equation 35 for chemical costs.

Chemical Costs = (Costpre−Chlorine · Qpre−Chlorine + Costantiscalant · Qantiscalant + Costantifoaming · Qantifoaming + CostCa(OH)2 · QCa(OH)2 + Costpolyelectrolyte · Qpolyelectrolyte + CostCO2 · QCO2 + Costpost−Chlorine · Qpost−Chlorine)Noper, hours [35]

Organic contamination has a significant impact on scaling and fouling in seawater desalination systems. This issue is mitigated by dosing chlorine into the feed water, which helps reduce biological growth and organic fouling (Membrane Scientist, 2025). For MED systems, between 0.25 and 4.0 mg of chlorine per litre of seawater is typically added to control these effects (Mika et al., 2024). The industrial price of chlorine in Europe is estimated at €0.35 per kilogram (Business Analyst, n.d.). Based on this price and the chlorine dosage range, the calculated chlorine cost is approximately €0.0014 per cubic metre of treated water. The detailed calculation is provided in Appendix I.

It is important to note that this cost only reflects the chlorine component and does not include other antiscalants such as polyphosphates, phosphonates, or carboxylic acids, which are also commonly used in desalination processes. To ensure accurate chemical dosing, the coefficient used in this study is derived from Ellersdorfer et al. (2023), who analysed a desalination plant supplying water to an electrolyser which is similar to the application considered in this research.

Table 26 : MED Chemicals

MLD	Chemicals	Valuation	Resource
MED	Chemicals	0,031 $€/m^3$	(Ellersdorfer et al., 2023)
MED	Chemicals	0,0223 $€/m^3$	(Malik et al., 2023)

MED	Chemicals	0,025 €/m^3	(Moharram et al., 2021)
MED	Chemicals	0,030 €/m^3	(Christ et al., 2015)
MED	Chlorine	0.25–4.0 mg per liter of feed water	
		0.25–4.0 mg per 0,001 m^3 of feed water	(Mika et al., 2024)

6.4.11 MED : Indirect Operational Costs

The indirect costs include utilities, plant administration, and insurance. As mentioned, utilities encompass services such as the fire department and security to maintain the plant. Malik et al. (2022) combine maintenance and insurance costs into a single cost item, providing a consistent basis in accordance with the indirect costs of this study. The following equation 36 is used to calculate the indirect operational costs.

Dastgerdi and Chua (2018) estimated the costs of maintenance and insurance to be 1.5% of the total capex. However, in this percentage the spare costs were also included. Therefore, it is crucial to determine which elements fall under the indirect operational costs, especially since spare parts are already covered in a separate section in this study.

For this study, the 1,5 % indirect operational costs only include the maintenance and the insurance. Moharram et al. estimate the operating and maintenance costs at 2.0%. However, this is considered too high, as Dastgerdi and Chua (2018) use a lower value of 1.5% for maintenance and spare parts in their study. An overview is given in table 27.

$$IOC\ [€/yr] = 1,5\% * TCC\ [€/yr] \quad [36]$$

Table 27 : MED OPEX Indirect Costs

MLD	OPEX	Valuation	Resource
MED	Indirect Costs	1.5% of CAPEX	(Malik et al., 2023)
MED	Indirect Costs	1.5% of CAPEX	(Dastgerdi and Chua, 2018)
MED	Indirect Costs	2,0 % of CAPEX	(Moharram et al., 2021)

6.4.12 MED : LCOW Benefits

It is only assumed that the earnings of the MED plant are the earnings generated from the demineralised water because the LCOH is no direct revenue of the first MLD system. The benefit is given in table 28. The formula is given in equation 37. The WMP stands for Water Market Price. The WMP is a knowledge gap in the literature review. Therefore, an expert interview was conducted that determined the WMP between €5 and €10 per m³ (Strategic Manager, 2025). Given the relatively small scale of the plant, production costs are expected to be higher which suggests that the price will likely be closer to €10 per m³. The LCOW is calculated with a WMP of €5 and €10 in Appendix I.

$$LCOW\ [€/yr] = 365\ [day/yr] * Water\ Production\ [kg/day] * WMP\ [€/m^3] \quad [37]$$

Table 28 : MLD 1 : LCOW

MLD	Benefit	Water [m3/day]	Resource
MED	Water Production	1.000	Calculation

6.4.13 MED : Environmental Impact Benefits

No information was provided about the environmental benefits, and this is easy to explain. The MLD process is not designed to isolate salts or reduce environmental impact. The MLD produces a more concentrated brine compared to standard demineralisation technologies, but unfortunately, it cannot isolate salts using MED technology alone. As a result, all the brine will be disposed of at sea which leads to the same environmental effects. Therefore, the first MLD process does not offer any environmental benefits, and the same permits required for standard demineralisation technology must be obtained. The MLD technology becomes valuable in terms of this cost item when combined with other technologies as shown in figure 15.

6.5 Summary MED Costs

A challenge arises when estimating the CAPEX for the MED system. The literature review does not thoroughly specify the land, equipment and building costs. This is because the cost items are highly specific. Only a general equation is determined in the literature review to estimate the total CAPEX (Kosmadakis et al., 2018). While this equation is not intended for use in the CBA, it can provide a useful benchmark. However, it tends to overestimate the costs of a 1.000 m^3/day plant, for the 25 years that the plant is in use, between 23 and 13 billion euros.

The alternative solution to use the DACE price booklet, excludes important elements such as electro and mechanical costs. Therefore, an expert interview was conducted to fill this important gap in the literature by determining the land costs, a combined cost for the equipment cost item, and the building costs.

The CAPEX is expressed as a single price index. To convert this into annual costs, a discount rate is applied. The equation 38 shows the discount rate. In this equation, P represents the initial investment either the CAPEX items, r is the discount rate, which has been already set at 2.25%, and n denotes the lifetime of each asset. The value of n varies depending on the type of capital investment. The MED system is assumed to have a lifespan of 25 years but this does not directly correspond to the lifespan of each individual cost component.(Ellersdorfer et al., 2023).

$$Yearly\ CAPEX\ costs\ [€/yr] = P[€] * \frac{r*(1+r)^n}{(1+r)^n-1} \quad [38]$$

The annual land cost in table 29 is difficult to determine precisely, as purchased land does not depreciate or have a defined lifespan. To enable discounting over time, it is assumed that the land cost is spread over the operational lifetime of the building. Buildings are assumed to have a lifetime of 30 years (Morgante et al., 2024-b). The indirect costs are also taken to be 30 years as the field supervision and insurance were invested for the construction of the building. The equipment has a lifetime of 15 years.

To be clear about the fuel costs, here is an overview;

1. The seawater costs are the extraction costs, which are zero.
2. Steam costs are the waste heat costs from the Botlek, which are benchmarked against the natural gas costs for an E-boiler.
3. The waste heat for seawater costs is the waste heat from the condenser of the MED and is therefore also zero.

Table 29: Summary Annual Costs MED CAPEX, OPEX and Benefits

MED CAPEX	**Costs [€]**	**Lifetime [years]**	**Costs [€/yr]**
Land Costs	3.274.629 [€]	30	151.285,71 [€/yr]
Equipment Costs	5.500.000 [€]	15	436.086,89 [€/yr]
Building Costs	0 [€]	30	0 [€/yr]
Indirect Costs	550.000 [€]	30	25.409,64 [€/yr]
MED OPEX	**Costs**		
Spare Parts Costs			222.204,11 [€/yr]
Fuel : Seawater Costs			0 [€/yr]
Fuel : Steam Costs			1.971.000 [€/yr]
Fuel : Waste Heat for Seawater Costs			0 [€/yr]
Electricity Costs			176.010,30 [€/yr]
Labour Costs			100.000 [€/yr]
Chemicals Costs			37.712,90 [€/yr]
Indirect Operations Costs			82.500 [€/yr]
MED Benefits	**Profit**		
Hydrogen			-
Environmental Impact			-
Demineralised Water			3.650.000 [€/yr]

6.6 MED Limitations: Sensitivity Analysis

The literature review on MED technology presents several limitations. This section discusses these limitations to ensure transparency, clarify the scope of the findings, identify remaining knowledge gaps for future research, and justify the choices made in forming the results.

One key aspect is the uncertainty in cost estimation throughout the project phases. The MLD process is defined during the feasibility study, where the total CAPEX can vary significantly, up to 50% higher or 30% lower than the final cost (Business Developer, 2025). As the project progresses into the basic and detailed engineering phase, this margin of error narrows which is shown in figure 37. Even during the construction phase, cost fluctuations remain possible with variations of up to 15% higher or 5% lower. It is important to mention that even these interval ranges have a confidence interval of

80%. The funnel graph illustrates the phase in which the indicative CBA is conducted, as well as the degree of uncertainty still present in the calculations.

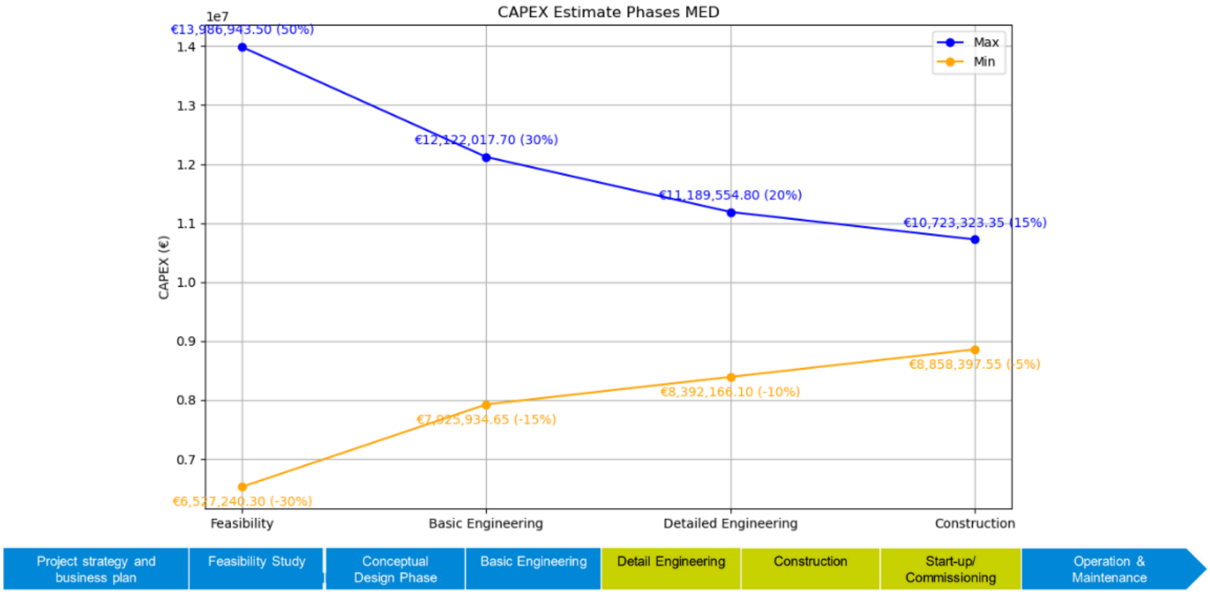


Figure 37 : MED CAPEX Estimates

A sensitivity analysis was conducted to identify the most relevant cost categories and to assess the impact of potential changes in these costs. In the study by Ellersdorfer, a sensitivity analysis was performed using a variation range of 20% more and 20% less. The same fluctuation range is applied in this study.

In figure 38 it is shown that the steam costs have the most impact on the yearly costs of the MED. The building costs are zero as no building is required for the MED technology. The seawater and waste heat costs are also zero. The seawater can be withdrawn without any additional costs because the needed seawater capacity is below 1800 m³/h. The waste heat is from the AWE and does not require purchase costs as it is part of the operation.

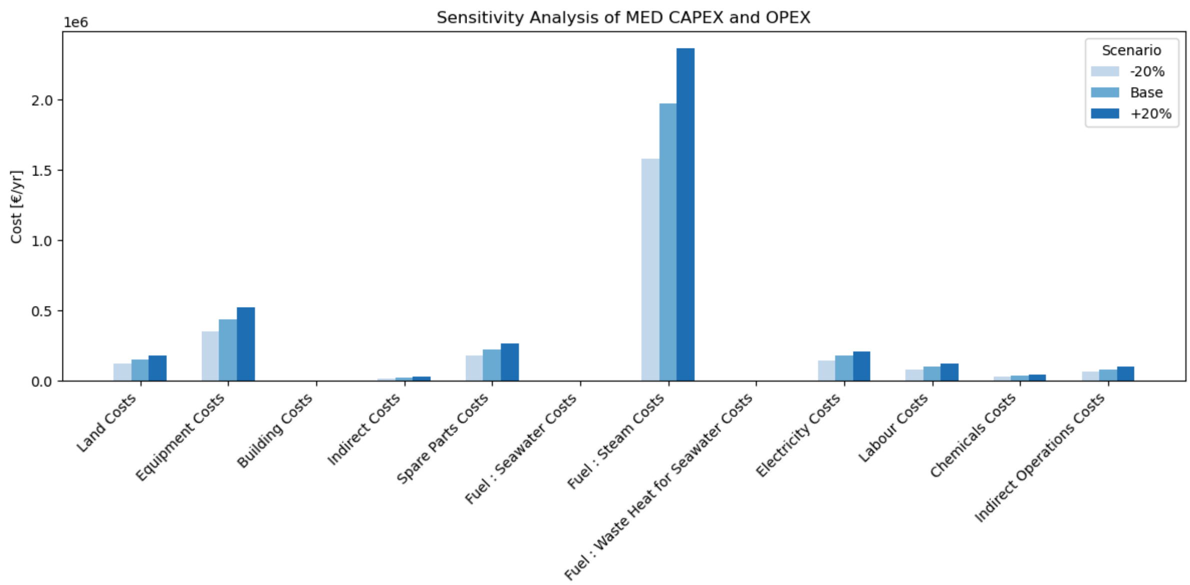


Figure 38 : Sensitivity Analysis MED CAPEX and OPEX per year

The steam costs could have been zero if the plant had been located in Emmen for example (Product Specialist, 2025). In this study, choosing steam from Emmen would have raised the piping costs between €200,000 and €300,000. The sensitivity analysis would then resemble figure 39 below. These piping costs would have been included in the CAPEX for equipment. In this case, the equipment costs would have been most expensive.

The steam costs could also be zero if the waste heat from the electrolyser was used (Ellersdorfer et al., 2023). Only, the AWE does not have the right temperature to function as 70°C steam for the MED.

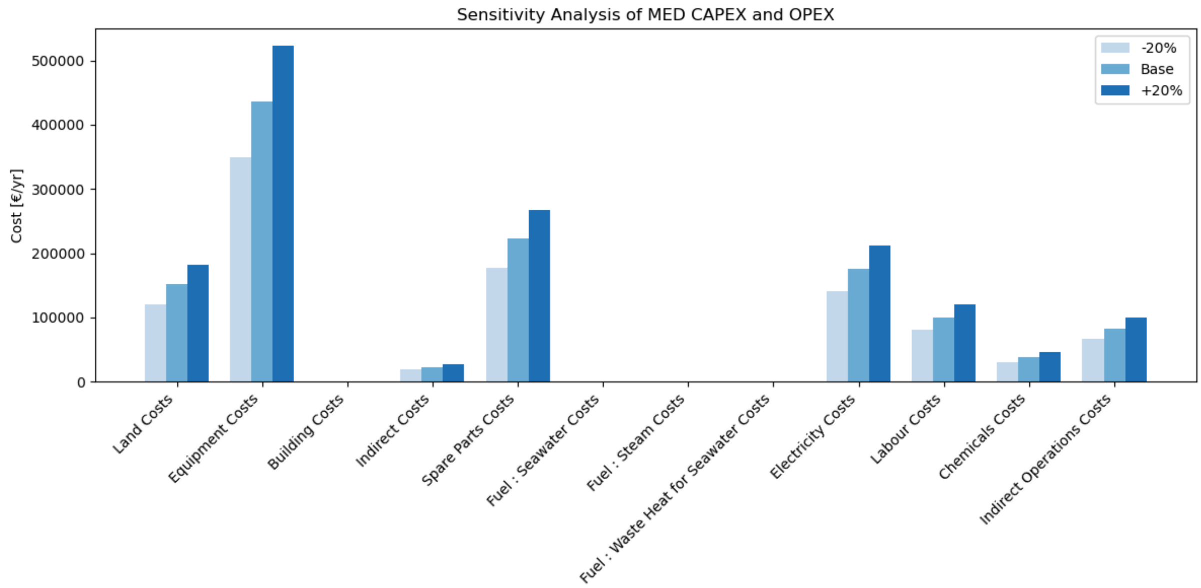


Figure 39 : Sensitivity Analysis MED CAPEX and OPEX per year with Zero Steam Costs

In this study, the benefits of the CBA are attributed to hydrogen and ultrapure water production. The MED process generates more ultrapure water than needed for the hydrogen production. Therefore, a secondary revenue stream can be derived from its sale. However, as illustrated in the figure 40 below, the projected hydrogen profits appear disproportionately high. This flaw arises because attributing hydrogen as a direct benefit to the MLD process is misleading. In reality, hydrogen production is part of the broader AWE system, which must be considered in its entirety to accurately assess costs and benefits.

To maintain relevance, only the footprint of the AWE system is included to make sure enough space was included for the first CBA. Nevertheless, many critical elements required for hydrogen production via AWE are excluded from this analysis, as they fall outside the scope of this research. Therefore, the representation of hydrogen as a benefit is not accurate, and only the profits from ultrapure water should be considered in the final evaluation.

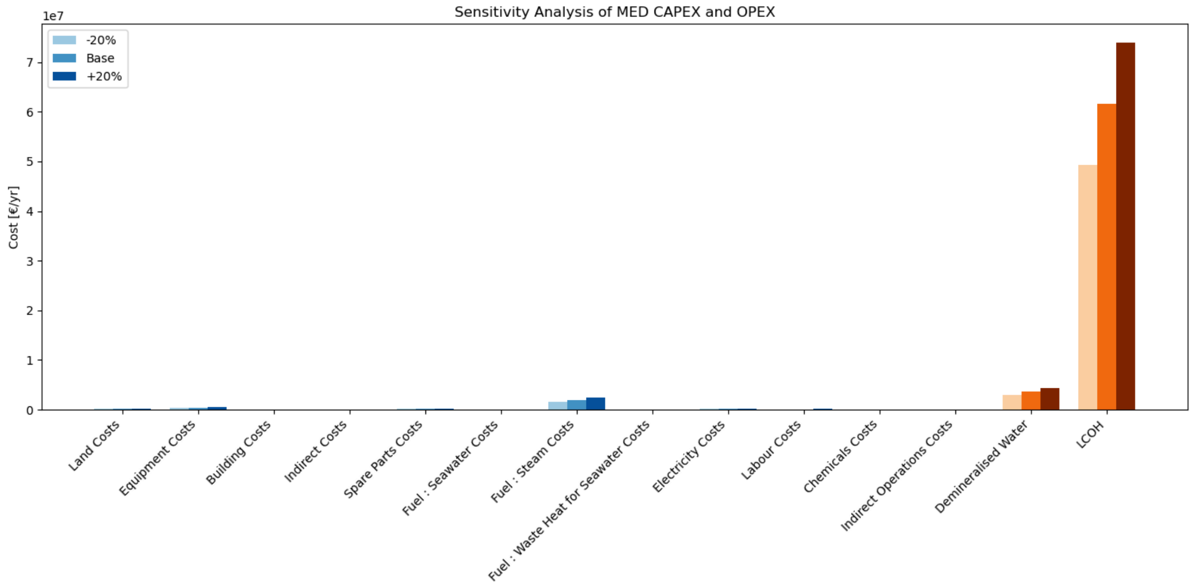


Figure 40 : Sensitivity Analysis MED CAPEX and OPEX per year with Hydrogen

The only benefit from the first MLD system is the ultrapure water with a WMP of €10. In figure 41 it is shown that the benefits are now more proportional. It seems from the yearly costs, that the first MLD is profitable. However, the exact NPV will be determined in chapter 9.

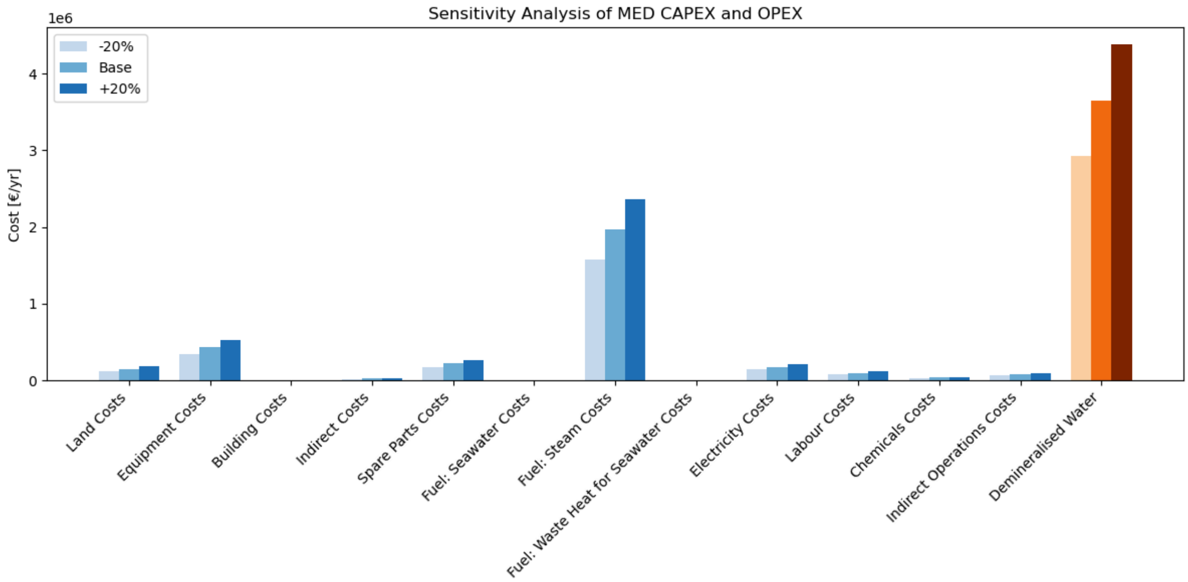


Figure 41 : Sensitivity Analysis MED CAPEX and OPEX per year with €10 *LCOW*

Figure 42 below presents the sensitivity analysis assuming a WMP of €5. The new LCOW is highlighted in slightly lighter orange bars. This significantly reduces the annual benefit. However, this value is likely not representative for smaller MED units such as the one analyzed in this study. Small MEDs typically have higher WMPs compared to the larger-scale units discussed in the literature review.

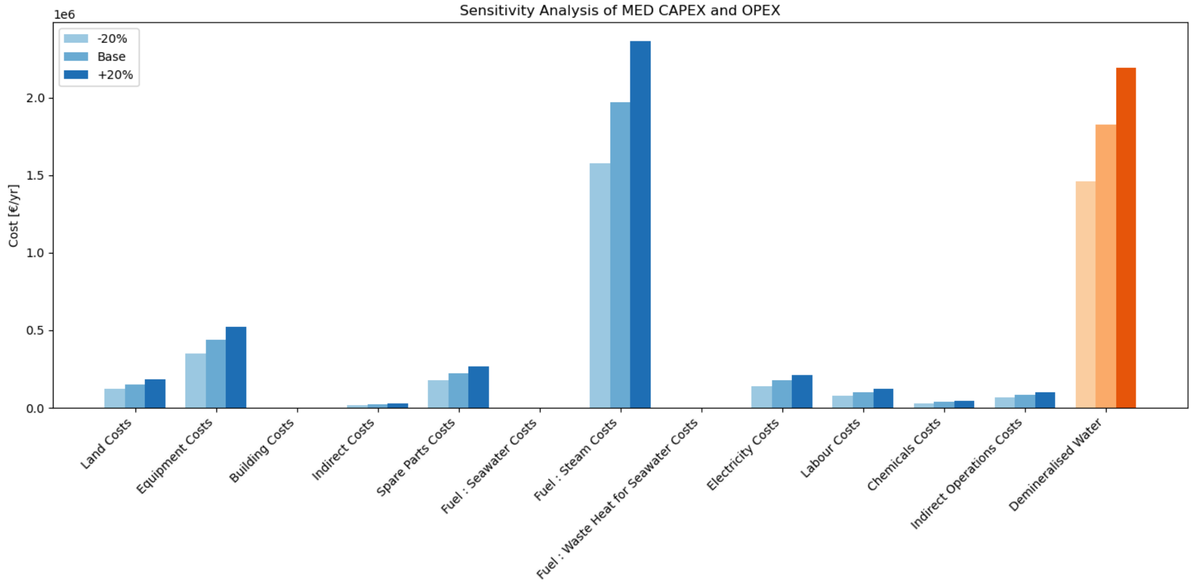


Figure 42 : Sensitivity Analysis MED CAPEX and OPEX per year with €5 LCOW

7. Literature Review NF

After determining the cost items for the MLD process with MED, it is important to determine the cost items for NF to be able to make the second CBA on two water desalination technologies. Therefore, a second literature review is conducted. A literature review is a helpful tool for researchers to obtain a well-structured overview of the literature and assists in making the knowledge gap explicit (Van Wee and Bannister, 2015).

NF is effective at removing multivalent ions, but it is not capable of producing ultrapure water required for AWE. Therefore, this review aims to assess the role and performance of NF technology within MLD or ZLD systems. The objectives of this literature review are:

1. To explore the potential functions that NF membranes can fulfill within MLD or ZLD processes.
2. To examine how similar cost elements have been calculated in previous studies, providing a methodological foundation for this research.
3. To identify the key parameters and assumptions used in those calculations, which are essential for building a reliable cost model.
4. Determine which cost items are a knowledge gap in the literature which need to be filled with expert interviews.

The definition of concepts from this literature review are the same concepts from the MED literature review. The methodology section outlines the approach used to conduct the literature review, followed by a presentation of the key findings. To support clarity and consistency, the review also addresses any limitations in the available literature and highlights areas where data is insufficient or inconsistent. To enhance the robustness of the findings, the results of the literature review are validated through semi-structured interviews with experts. These interviews not only confirm the assumptions and data used but also help to fill in any knowledge gaps not covered by existing literature.

7.1 Definition of Concepts

This section defines the key concepts that form the foundation of the literature review for the NF technology. The key concepts taken into account are those variables that affect the operating and capital costs of the NF water desalination. The concepts in this literature review are identical to the literature review of MED. The CAPEX are land, equipment, buildings and indirect costs. The OPEX are spare parts, fuel, electricity, labor, chemicals, and indirect costs. The benefits are not included as the NF does not produce purified water ready for sale, only softened water for further production. The definition of concepts regarding CAPEX and OPEX could be read in chapter 6.1 Definition of Concepts. This consistency is necessary to determine the values of the NF and to be able to determine the MLD effects in combination with MED.

7.2 Methodology

A literature review is conducted to summarize and evaluate a body of writing about a specific topic, which in this case is the characteristics of NF technology (Knopf, 2006). This will assist in formulating a well-considered analysis of the capital and operational costs of the membrane water desalination. The literature review adopted a structured approach. Scientific articles are collected through the databases Google Scholar and Scopus. These databases offer a wide variety of scientific articles on NF, so a screening is necessary to determine the relevant studies.

In Table 30 below, the used search terms are listed to show how the scope was narrowed. The final two search strings are used because the amount of hits did not really change much but resulted in a couple of additional articles relevant for the review. Electrolysers are not included as a search term because the focus should be on NF and a direct combination with an electrolyser is not possible, as previously determined.

Table 30 : Search Terms Used for the Literature Review NF

#	Search Strings	# Google Scholar	# Scopus
1	Nanofiltration	344.000	18.010
2	Nanofiltration AND Seawater Desalination	38.000	485
3	Nanofiltration AND Seawater Desalination AND Techno-Economic Analysis	2.640	7
4	Nanofiltration AND Seawater Desalination AND Techno-Economic Analysis AND Hydrogen Production	2.630	0

To manage the wide variety of results from the Google Scholar database, an initial delimitation was made by only including the first 20 articles from the two strings, after determining that the articles need to be published after 2021 to collect the most relevant data. This does not count for articles found through snowballing. The first 20 articles were reviewed because no single researcher or research group stood out. Morgante is used three times but wrote the articles with different research groups.

The articles all need to be written in English, and duplicates from both databases will be removed. After removing the duplicates, all papers should be peer reviewed which was the case for this literature review. After the initial delimitation, the actual screening will be conducted to collect the relevant data by assessing the title, publication year, and number of citations. Next, the abstract and keywords of the remaining articles will be reviewed. Finally, the introduction, discussion, and conclusion will be examined to select the most relevant articles. This resulted in 7 articles from Google Scholar, two articles were added because of snowballing, and two extra articles were concluded from the MED literature review which addressed very relevant information for the NF technology equations and parameters.

From the Scopus database, only the third search string yielded results of seven articles. The fourth search string did not yield any results. Given the limited number of articles, all seven were reviewed. Of these, four were relevant from which two were duplicates from Google Scholar. This resulted in two new relevant articles being included in the review. The complete literature review process is illustrated in Figure 43.

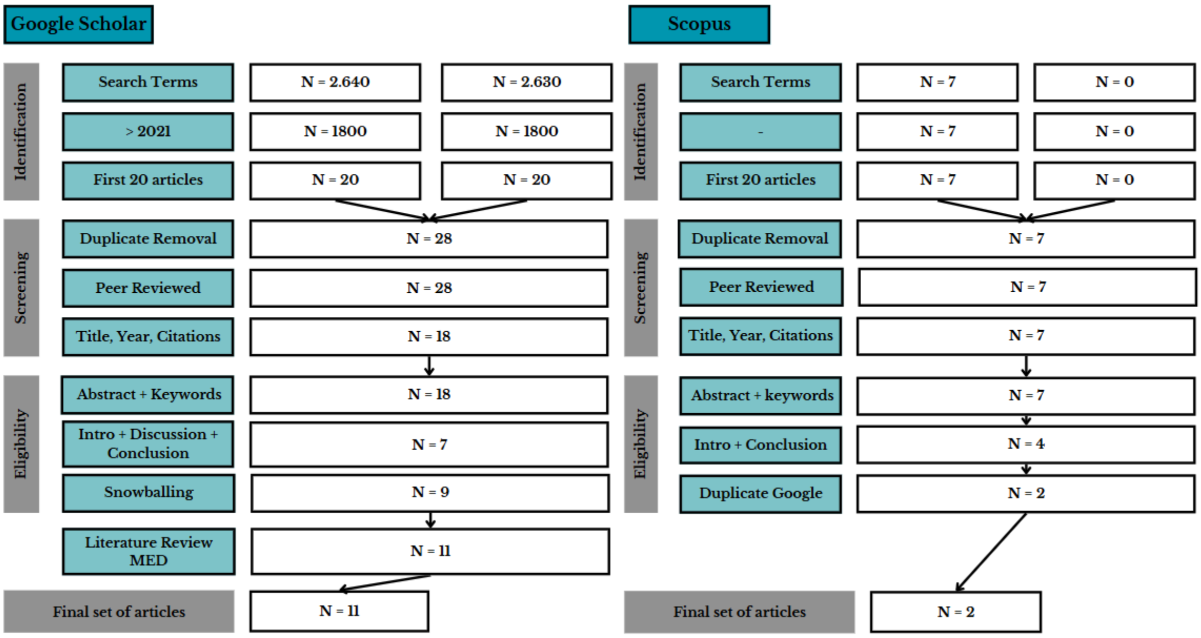


Figure 43 : NF Literature Review Process

7.3 Results NF

The results of the literature review highlight the various applications and characteristics of NF systems. It becomes evident that NF is commonly used for partial hardness removal and softening the water. Table 31 outlines the specific purposes for which NF is applied and explores the range of operational parameters associated with each application. The various implementations of NF may explain the variations in reported parameters of the literature review. For instance, NF systems treating SWRO brine must operate under higher salinity conditions compared to those treating seawater or even groundwater.

Table 31 : Overview of NF Applications

#	Article/concept	SW Treatment	SWRO Brine Treatment	SWRO Brine Treatment for MED	IEX Brine Treatment for MED	Groundwater Treatment	Treatment Effect and Fouling Property	SW Pretreatment for MSF	Seawater Treatment with MLD including NF-MED for Salt Mining	Seawater Treatment with MLD including NF-MED for Fresh Water
1	(Lopez et al., 2025)	X	X							
2	(Micari et al., 2019)				X					
3	(Bindels et al., 2020)		X							
4	(Morgante et al., 2024-b)	X	X							
5	(Figueira et al., 2023)		X							
6	(Morgante et al., 2022)			X						
7	(Van der Bruggen et al., 2001)					X				
8	(Zhou et al., 2023)						X			
9	(Hafiz et al., 2023)							X		
10	(Zouhri et al., 2024)	X								
11	(Abdelhay et al., 2022)		X						X	X

12	(Morgante et al., 2024-a)								X	
13	(Scelfo et al., 2025)								X	

Once the NF applications are determined, the CAPEX and OPEX can be determined. The table 32 below gives an overview of the cost items discussed in the literature and which items are left out of the analysis, the knowledge gaps. These knowledge gaps need to be filled to give a good indication of the impact of adding the NF to the MLD process. The knowledge gaps are filled with expert interviews. In the following sections of this chapter, the choices for the calculations and parameters are discussed and explained.

Table 32 : Results Literature Review MED

#	Article/concept	Land	Equipment	Buildings	CAPEX Indirect Costs	Spare Parts	Fuel	Electricity	Labour	Chemicals	OPEX Indirect Costs
1	(Lopez et al., 2025)		X	X	X			X		X	X
2	(Micari et al., 2019)		X	X	X			X		X	X
3	(Bindels et al., 2020)	X			X		X	X	X	X	
4	Morgante et al., 2024-b)		X	X	X			X		X	X
5	(Figueira et al., 2023)		X	X	X			X	X	X	X
6	(Morgante et al., 2022)		X	X				X		X	X
7	(Van der Bruggen et al., 2001)		X	X	X			X			X
8	(Zhou et al., 2023)		X					X		X	
9	(Hafiz et al., 2023)		X	X	X						

10	(Zouhri et al., 2024)		X	X	X	X		X	X	X	X
11	(Abdelhay et al., 2022)						X	X			
12	(Morgante et al., 2024-a)		X					X			
13	(Scelfo et al., 2025)							X	X		

7.4 Determination of the NF parameters

7.4.1 NF : Land Costs

The literature review did not give any indications on the land costs. This is, as previously discussed, because the location chosen is highly specific and determines the land costs. Again, to determine the land costs, the footprint of the needed water desalination technologies is multiplied by the costs per m^2 of the chosen area. By using the same method, the CBAs can be fairly compared. The equation is shown in equation 39.

$$LC\ NF\ [€] = NF\ [m^2] * Land\ Price\ [€/m^2] \quad [39]$$

The land requirement for an NF system depends on the specific configuration and layout of the installation. An expert interview was conducted with a process advisor to determine the land size. An indication is given in table 33. It should be mentioned that this is an indication and very specific for every NF installation (Process Advisor, 2025). The worst-case scenario is taken, so enough space is accounted for.

Table 33 : NF Land Area

MLD	Technology	Area $[m^2]$	Resource
MED	NF	155	(Process Advisor, 2025)

7.4.2 NF : Equipment Costs

The equipment needed for the NF is determined through civil investment, mechanical instruments and electrotechnical investments (Figueira et al., 2023; López et al., 2025). The civil investment contains the facility to host the NF unit and is therefore better suited under building. The mechanical instruments include the pumps, filters and piping among other things. Besides the mechanical instruments, there are electrotechnical investments. The electrotechnical investment provides the energy supply, control systems and electronic devices. In this study, the civil investments are considered as a separate cost element in the CBA under building costs. However, it is acknowledged that civil costs can also be categorized under equipment costs (Project Manager, 2025).

Below, the mechanical equation 40 and the electro equation 41 are determined from López et al. and Micari et al. regarding mechanical and electrotechnical costs. In these equations, Qfeed represents the inlet flow rate, Pfeed denotes the operating pressure of the feed stream, and n stands for the number of membranes required for the NF system.

$$Cmech\ [€] = 4329,6 * Qfeed^{0,85}\ [m^3/h] + 1089,6 * n \quad [40]$$

$$Celectro\ [€] = 1.68 * 10^6 + 64,8 * Pfeed\ [bar] * Qfeed\ [m^3/h] \quad [41]$$

For the equations different parameters are given in the literature review only referencing previous scientific work determining the parameters without further explanation (López et al., 2025). For example, Figueira et al. uses the same equations but with slightly different parameters as shown in table 34 below. The equations lead back to the work of Van der Bruggen et al. from 2001. These are quite old parameters and are used for ground water desalination.

Therefore, for this study, more recent parameters are chosen which are also the most in line with the MLD process of this study. These parameters are collected from Morgante et al. about an NF membrane as pretreatment for seawater followed by an MED which is corresponding with López et al. and Micari et al.

Table 34 : NF Equipment Equations

MLD	Equation	Resource
NF	$Cmech\,[€] = 4329,6 * Qfeed^{0,85}\,[m^3/h] + 1089,6 * n$	(López et al., 2025; Micari et al., 2019; Morgante et al., 2022)
	$Celectro\,[€] = 1.68 * 10^6 + 64,8 * Pfeed\,[bar] * Qfeed\,[m^3/h]$	
	$Cmembrane\,[€] = 1200\,[€] * n$	
NF	$Cmech\,[€] = 4069,8 * Qfeed^{0,85}\,[m^3/h] + 1024,2 * n$	(Figueira et al., 2023)
	$Celectro\,[€] = 1.57 * 10^6 + 60,9 * Pfeed\,[bar] * Qfeed\,[m^3/h]$	
	$Cmembrane\,[€] = 1128\,[€] * n$	
NF	$Cmech\,[€] = 862 * Qfeed^{0,85}\,[m^3/h] + 908 * n$	(Van der Bruggen et al., 2001)
	$Celectro\,[€] = 1.4 * 10^6 + 54 * Pfeed\,[bar] * Qfeed\,[m^3/h]$	
	$Cmembrane\,[€] = 1000\,[€] * n$	

The membranes have their own equation 42 below. The membrane costs differ per chosen NF membrane. For example, NF270 is assumed to be 1128€, and PROXS2 is assumed to be 2256€ (Figueira et al., 2023). An medium is taken of 1200€ (López et al., 2025; Micari et al., 2019; Morgante et al., 2022)

$$Cmembrane\,[€] = Membrane\ Costs\,[€] * n \qquad [42]$$

7.4.3 NF : Building Costs

The construction cost of the NF system is determined using a civil investment formula, as shown in equation 43 below (Morgante et al., 2022; López et al., 2025; Micari et al., 2019). Civil investments refer to the infrastructure required to house the NF unit which means the buildings where the plant will be installed. The term Qfeed represents the inlet flow rate. The n denotes the number of membrane modules required. Again, the equation of Morgante et al. is chosen. An overview of found equations is given in table 35.

$$Ccivil\,[€] = 1034,4 * Qfeed\,[m^3/h] + 1487 * n \qquad [43]$$

Table 35 : Determination NF Building Costs

MLD	Equation	Resource
NF	$Ccivil\,[€] = 1034,4 * Qfeed\,[m^3/h] + 1487 * n$	(López et al., 2025; Micari et al., 2019; Morgante et al., 2022)
NF	$Ccivil\,[€] = 972,3 * Qfeed\,[m^3/h] + 1397,8 * n$	(Figueira et al., 2023)
NF	$Ccivil\,[€] = 862 * Qfeed\,[m^3/h] + 1239 * n$	(Van der Bruggen et al., 2001)

7.4.4 NF : Indirect Capital Costs

Indirect costs include elements such as field supervision, construction equipment, and insurance. According to the literature review, indirect costs encompass freight, insurance, and contingency charges which aligns well with this definition. In their analysis, indirect costs are calculated as 10% of the direct costs as shown in equation 44 (Morgante et al., 2022; López et al., 2025; Micari et al., 2019). Direct costs cover equipment and building expenses, but exclude land costs. This exclusion is justified because insurance and contingency charges do not apply to land. The equipment and building needs to be insured for when equipment is stolen or lost in an accident. Contingency charges are allocated to equipment to cover potential breakages or the need for additional materials.

$$Cindirect\ costs\,[€] = 10\% * (Ccivil + Cmech + Celectro + Cmembrane) \qquad [44]$$

Table 36 presents two percentage values derived from the literature review. While these values vary across sources, the most recent and methodologically consistent equation has been selected. This choice aligns with the approach used in previously referenced studies, ensuring both relevance and continuity in the analysis.

Table 36 : NF Indirect Capital Equation

MLD	Equation	Resource
MLD	$Cindirect\ costs\,[€] = 10\%\,(Equipment\ and\ Building)$	(López et al., 2025; Micari et al., 2019; Figueira et al., 2023)
MLD	$Cindirect\ costs\,[€] = 20\%\,(Equipment\ and\ Building)$	(Van der Bruggen et al., 2023)

7.4.5 NF : Spare Parts Costs

The spare costs is the first element of the OPEX, from now on the costs are determined in $€/yr$ or need to be altered to be able to compare the different costs. For the spare parts, nothing was mentioned in the literature review, so this gap will be filled with an expert interview.

The spare parts consist of three categories; commissioning, operational spares, and critical spares (Consultancy Manager, 2025). the categories can be ranked high or low in costs. The commissioning is also called the start-up which is the consumables and wear items needed for initial commissioning and early-life failures. The technology is one of the oldest water desalinations, so the commissioning is ranked low.

Operational spare parts refer to components that are expected to wear out or require replacement within the first 2 to 5 years of operation (Consultancy Manager, 2025). In the case of NF systems, the membranes typically need to be replaced every five years, with the indication that the feedwater is properly pretreated before entering the membrane unit (Membrane Scientist, 2025). Because membrane replacement is a foreseeable event, the commissioning costs are relatively high, reflecting the likelihood of future replacements.

Critical spares are high-cost or long-lead-time components that are essential to keep on hand in order to prevent extended downtime in case of failure. For large-scale NF installations, it is not uncommon to install an additional parallel membrane unit. This allows the system to continue operating while one membrane module is being cleaned or repaired (Process Advisor, 2025). This stems from the relatively frequent cleaning of the membranes. As a result, it is common practice to ensure that such critical spares are readily available on-site (Project Manager, 2025). In total, the cost of spare parts is estimated at 5% of the total CAPEX for the MED system, as shown in Table 37. So, the following equation 45 is determined for the spare part costs.

$$Cspare\ parts\ [€/yr] = 5\% * TCC \qquad [45]$$

Table 37 : NF Spare Parts

Spare Part Category	Low [%]	High [%]
Commissioning	1	2
Operational Spares	1	3
Critical Spares	0,5	1

7.4.6 NF : Fuel Costs

For the NF system, seawater is the only input considered as a fuel. The volume of seawater required depends on the recovery rate of the membrane system. During the literature review, several recovery rates were identified, as shown in table 38. A 70% recovery rate was selected for the NF membrane, based on the assumptions discussed in the Preconcentration: Nanofiltration section. At this recovery rate, the NF system needs to pump approximately 4,761.43 m^3 of seawater per day. This volume is well below the maximum intake limit of 1,800 m^3 per hour permitted in the North Sea, as specified by the BAL guidelines (BAL, n.d.). Therefore, no additional costs are associated with seawater withdrawal in this case.

Table 38 : Determination NF Fuel Costs

MLD	Fuel	Recovery rate [%]	Resource
NF	Seawater	60	(López et al., 2025)
NF	Seawater	80	(Micari et al., 2019)
NF	Seawater	40	(Figueira et al., 2023)
NF	Seawater	80-90	(Membrane Scientist, 2025)

7.4.7 NF : Electricity Costs

For the electricity consumption only energy for the pumps is included. There are two different ways to determine the electricity costs. The first equation 46 determines the electricity costs through multiplying the local electricity price with the pump consumption and the amount of operational hours (Figueira et al., 2023).

$$Cel\ [€/yr]\ =\ Electricity\ Price\ [€/kWh]\ *\ Pcons\ [kW]\ *\ Operational\ Hours\ [h/y] \qquad [46]$$

The table 39 below, shows the relevant parameters for determining the electricity cost of the NF membrane. In this study, wind energy is assumed to be available for 9.6 hours per day, while the remaining 14.4 hours rely on grey electricity to ensure continuous operation of the MED system. This approach maximises the production of ultrapure water throughout the day. The wind electricity costs are €0,06 per kWh and the grey energy is €0,383 per kWh. The pump consumption is 2 kWh per m^3. Every hour the NF pumps 198,39m^3, so the total pump consumption is 396,78 kW. The NF is 8000 hours operational per year.

Table 39 : NF Electricity

MLD	Electricity	Parameter	Resource
NF	Electricity Price	0,06 [€ /kWh]	(De Vries, 2023)
NF	Electricity Price	0,383 [€ /kWh]	(CBS, 2025)
NF	Pcons	2 [kWh/m^3]	(Membrane Scientist, 2025)
NF	Operational Hours	8000 [h/yr]	(Figueira et al., 2023)

A second equation was also determined in the literature review. This equation is explained in Appendix J. However, as this is the feasibility phase and not all elements of the equations could be filled with the collected data from the literature review and the interviews, the equation 46 was chosen for this study.

7.4.8 NF : Labour Costs

For labour costs, the same rule of thumb used for the MED system is applied, as suggested by Figueira et al., which assumes the need for one full-time employee per year. However, based on insights from expert interviews, the previously assumed annual cost of €47,000 is considered too low. According to a Project Manager (2025), a more realistic estimate is approximately €100,000 per year for a qualified full-time operator. An overview of this adjustment is provided in table 40.

$$Clabour\ [€/yr]\ =\ 100.000\ [€/yr] \qquad [47]$$

Table 40 : NF Labour

MLD	OPEX	Valuation	Resource
NF	Labour	47.000 [€]	(Figueira et al., 2023)
NF	Labour	100.000 [€]	(Project Manager, 2025)

NF	Labour	0.007 - 0.1 [€/m3]	(Bindels et al., 2020)

7.4.9 NF : Chemical Costs

To calculate the chemical costs, there are two equations to use. The first equation 48 takes a medium valuation of the chemicals costs per m^3 and multiplies these by the NF permeate and the operational hours (Figueira et al., 2023; Morgante et al., 2024-b). The costs per m^3 are differently valued in the literature review as shown in table 41. To stay in line with the chosen factors from the previous cost items, the 0,052 €/m^3 coefficient is used.

$$Cchemicals\ [€/yr]\ =\ Cchem, nf\ [€/m^3]\ *\ Vpermeate\ [m^3/yr]\ *\ Noper, hours\ [h/yr] \quad [48]$$

Table 41 : NF Chemicals

MLD	OPEX	Parameter	Resource
NF	Chemicals	0,052 €/m^3	(López et al., 2025; Figueira et al., 2023)
NF	Chemicals	0,020–0,025 €/m^3	(Micari et al., 2019; Van der Bruggen et al., 2001)
NF	Chemicals	0,023 €/m^3	(Morgante et al., 2024-b)
NF	Chemicals	0.024 to 0.05 €/m^3	(Bindels et al., 2020)

If the exact chemical composition is known, the second equation 49 can be used. The formula determines the chemical costs through the acids and base chemicals used (Zhou et al., 2023). The amount of chemicals is multiplied by the number of Cleaning-In-Places (CIPs) and the unit costs of the determined chemicals. However, for this study the exact chemical composition is not determined.

$$Cchemicals\ =\ Cf_c\ *\ N_{CIP}\ *\ (C_{acid}\ *\ V_{acid}\ +\ C_{base}\ *\ V_{base}) \quad [49]$$

7.4.10 NF : Indirect Operational Costs

The indirect operational costs include elements such as the utilities, plant administration, and insurance. However, this is an overarching term to include indirect costs. In the literature review this is determined by maintenance which suits the description. The indirect costs are taken to be 2% of the CAPEX costs and are shown in the equation 50. No other indications were determined as mentioned in table 42.

$$Cindirect\ Costs\ [€/yr]\ =\ 2\%\ *\ CAPEX\ NF\ [€] \quad [50]$$

Table 42 : NF : Indirect Operational Costs

MLD	OPEX	Parameter	Resource
NF	Indirect Costs	2 % of CAPEX	(López et al., 2025; Micari et al., 2019; Figueira et al., 2023 ;

			Morgante et al., 2024-b; Van der Bruggen et al., 2001)
NF	Indirect Costs	0,5% of CAPEX	(Bindels et al., 2020)

7.5 Summary NF Costs

In this section the CAPEX and OPEX costs are summarised. After determining the equations and the needed parameters from the literature review an overview can be made of the costs for an NF that fits the needs of the MED. Table 43 shows the costs and the calculations are determined in Appendix J. The summary does not contain the benefits, as the NF is not capable of producing hydrogen or demineralised water ready to sell.

The CAPEX is expressed as a single price index. To convert this into annual costs, a discount rate is applied. The equation 51 shows the discount rate. In this equation, P represents the initial investment either the CAPEX items, r is the discount rate, which has been already set at 2.25%, and n denotes the lifetime of each asset. The value of n varies depending on the type of capital investment. Buildings are assumed to have a lifetime of 30 years, equipment is assumed to last 15 years, and membrane modules are replaced every 5 years (Morgante et al., 2024-b; Membrane Scientist, 2025). The indirect costs are taken to be 30 years, as the insurance for example needs to count until the last day of the building. Table 43 also shows the CAPEX costs per year.

$$Yearly\ CAPEX\ costs\ [€/yr] = P[€] * \frac{r*(1+r)^n}{(1+r)^n - 1} \quad [51]$$

The annual land cost in table 43 is difficult to determine precisely, as purchased land does not depreciate or have a defined lifespan. To enable discounting over time, it is assumed that the land cost is spread over the operational lifetime of the building. In this case, a 30-year period is used for the calculation.

Table 43 : Summary Annual Costs NF CAPEX and OPEX

NF CAPEX	**Costs [€]**	**Lifetime [Years]**	**Cost [€/yr]**
Land Costs	12.245 [€]	30	565,71 [€/yr]
Equipment Mechanical Costs	605. 289, 24 [€]	15	47. 992, 49 [€/yr]
Equipment Electro Costs	2.194.226,88 [€]	15	173.977,01 [€/yr]
Equipment Membrane Costs	238.800 [€]	5	51.031,61 [€/yr]
Building Costs	501.130,63 [€]	30	23.151,91 [€/yr]
Indirect Costs	353.944,68 [€]	30	16.352,01 [€/yr]
NF OPEX	**Costs**		
Spare Parts	177.442,51 [€/yr]		
Fuel : Seawater	0 [€/yr]		

Electricity	766.661,49 [€/yr]
Labour	100.000 [€/yr]
Chemicals	57.772 [€/yr]
Indirect Operations	77.867,83[€/yr]
NF Benefits	**Profit**
Hydrogen	-
Environmental Impact	-
Demineralised Water	-

7.6 NF Limitations: Sensitivity Analysis

The literature review on NF technology presents several limitations. This section outlines these to ensure transparency, clarify the scope of the findings, identify remaining knowledge gaps for future research, and justify the methodological choices made in shaping the results.

One key aspect is the uncertainty in cost estimation throughout the project phases. This lack of specificity is not unusual at this stage, as the current analysis is a feasibility study (Business Developer, 2025). At this point in the feasibility process, CAPEX estimates can vary significantly. The CAPEX costs can be up to 50% higher or 30% lower than calculated. This range reflects an accuracy level of approximately 80% confidence. Figure 44 illustrates how cost estimates become more precise as the project progresses through the development phases. The funnel graph illustrates the phase in which the indicative CBA is conducted, as well as the degree of uncertainty still present in the calculations.

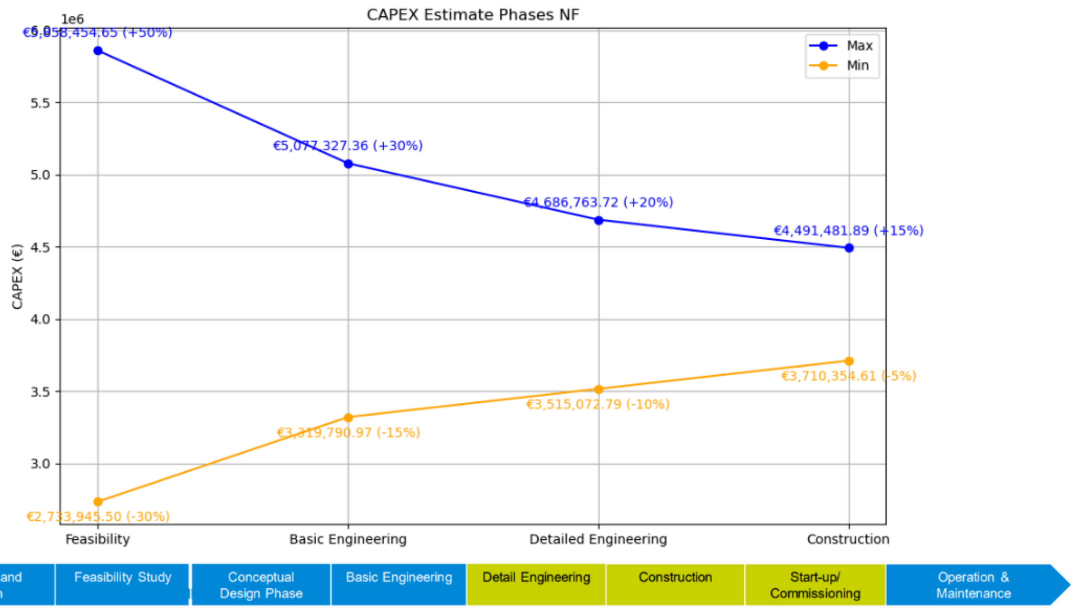


Figure 44 : NF CAPEX Estimates

Even though the feasibility study has some lack of specificity, a sensitivity analysis can be performed to identify the key drivers of the NF (Eldersdorfer et al., 2023). Figure 45 below shows which cost items have a severe impact on the total costs of the MLD system each year. For example, electricity costs have a significant impact due to the high energy demand required to overcome osmotic pressure.

The sensitivity analysis presented here applies only to the NF technology and does not yet reflect a fully operational MLD system capable of producing demineralised water of sufficient purity for use as feedstock in hydrogen production. Therefore, the potential benefits of hydrogen, environmental impact and demineralised water are not included in this analysis. It has also been previously established that hydrogen should not be considered a direct benefit within the context of the MLD process, as it is not a realistic output.

This limited scope of only NF explains why land costs appear relatively low, because they account only for the footprint of the NF unit. Seawater costs are shown as zero, since in the Netherlands there are no charges associated with extracting the required volume of seawater for the installation of this study.

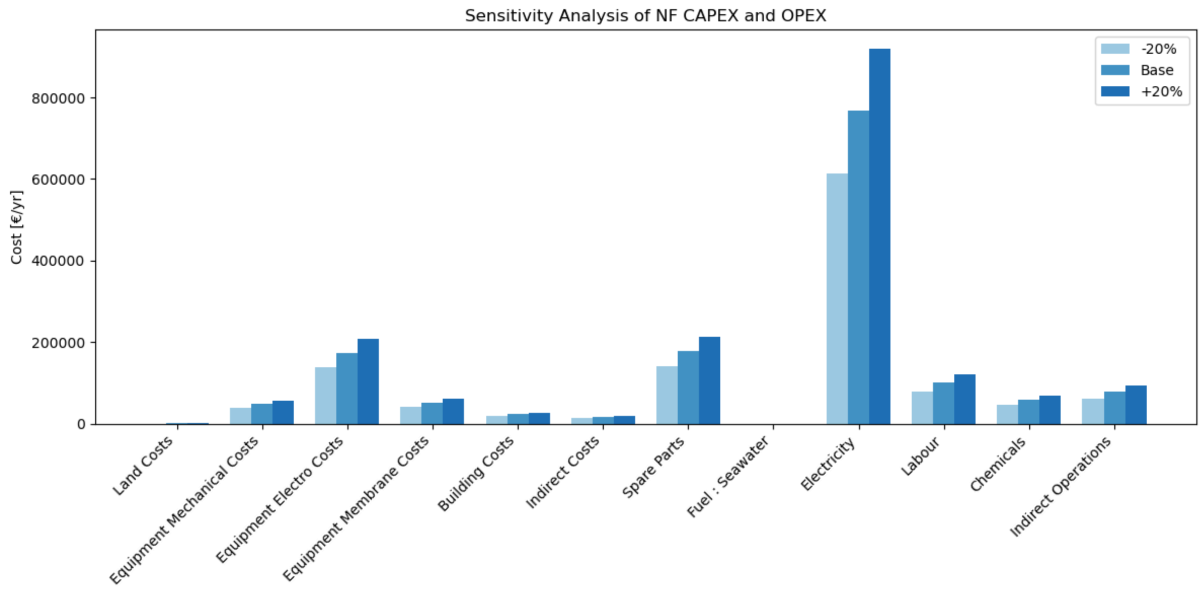


Figure 45 : Sensitivity Analysis NF CAPEX and OPEX per year

Figure 46 below presents a sensitivity analysis of the NF process when powered only by green energy. The energy calculations are shown in Appendix J. The difference between using a mixed energy source and fully green energy is clearly significant when comparing both graphs.

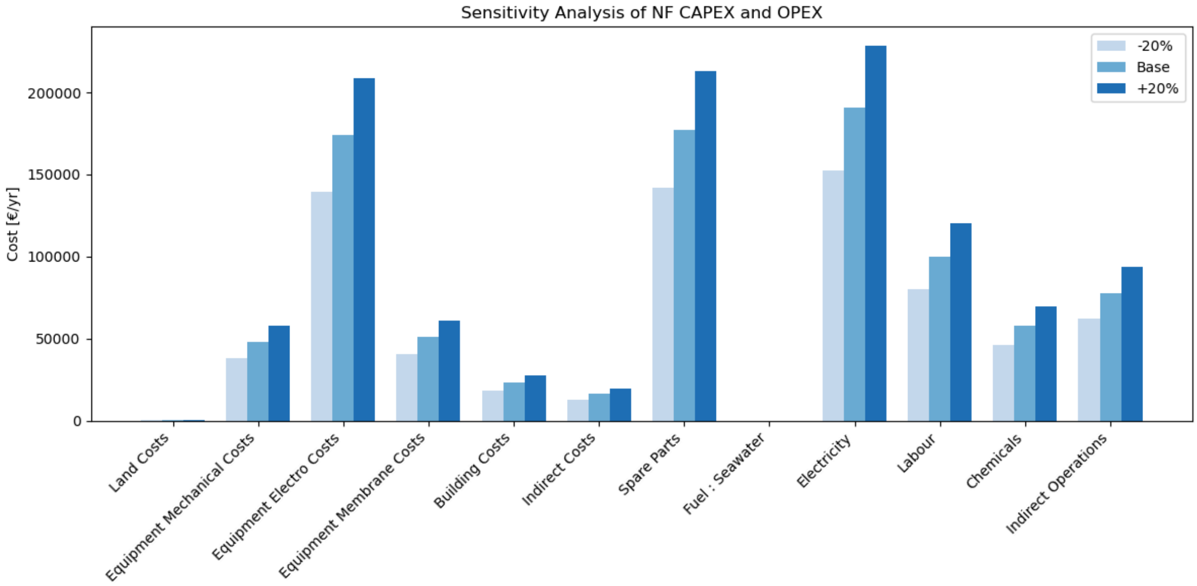


Figure 46 : Sensitivity Analysis NF CAPEX and OPEX per year with only Green Energy

8. Literature Review NF-MED

The chapter will dive into the entire second MLD process, combining MMF, NF and MED to produce demineralised water for the AWE. The flowchart is given in figure 47 below. The pretreatment will remain the same to protect the filter of the NF and the MED. The literature reviews are combined to determine the parameters and the limitations. The elements of the literature reviews will be verified with semi-structured interviews of experts. Elements that were not possible to find during the literature review will also be determined by the semi-structured interviews with experts.

However, since the NF-MED system is relatively new, not all experts were familiar with the specific combination of technologies. This gave the main challenge of this research. It required integrating each expert's individual area of expertise to construct realistic and reliable data.

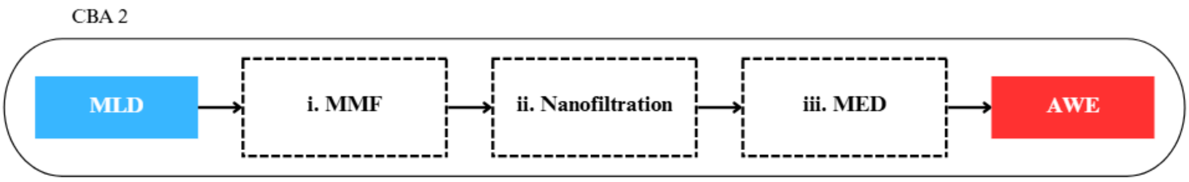


Figure 47 : CBA 2 with MMF, NF, MED, and AWE

NF is employed as a preconcentration to be able to increase the TBT to 125 °C (Ortega-Delgado et al., 2022; Hamed, 2005). Studies indicate that higher TBT significantly enhances the thermal efficiency of MED systems. TBT is one of the most critical parameters influencing MED performance (Xu et al., 2022). However, limited research has been conducted on the NF–MED configuration, and expert knowledge on this hybrid system is also scarce. The research that has been done on this hybrid water desalination, determines that NF is the best technology to couple with a thermal process (Filippini et al., 2022). To assess its potential impact, this study draws on literature from chapter 6 and 7, and NF–MSF systems. The MSF thermal desalination shares similar principles but MED generally requires less energy due to the steam reuse in each effect.

8.1 MLD Process with NF and MED

In this section all the changed parameters and operating processes are determined. This assists in calculation the cost items for the second CBA. Currently, the MED operates at 70°C with 9 effects which serves as the economic baseline for the first MLD system. The key operational changes of the second MLD, as extensively discussed in Chapter 4, are summarized below.

8.1.1 Recovery Rate Increase

The NF technology reduces the salts in the feedwater before it goes into the MED, therefore the MED can concentrate the brine further without scaling. This increases the recovery rate to 75% up to 87,5%. as explained and calculated in 4.4.1 Operation Scale MED. As the NF separates the salts, the MED system does not require additional chemical dosing, as NF effectively removes most bivalent ions (Ortega-Delgado et al., 2022).

When the production capacity increases from 1000 m³/day to 2500 m³/day, the steam and energy requirements also increase. This is because more water needs to be evaporated and more distillate needs to be pumped and handled in the MED system.

At a constant operating temperature of 70°C, this higher output requires a proportional increase in heat input. However, NF is used as a pretreatment which reduces the scaling. This allows the MED system to operate at higher temperatures of 125°C, which increases the GOR. A higher GOR means more distillate can be produced per unit of steam, so the specific heat input per m³ of water will reduce. As a result, even though the total production increases, the system can become more energy-efficient overall.

8.1.2 Temperature Increase

The demineralised water gives the second MLD system the chance to operate at 125°C also with 9 effects (Ortega-Delgado et al., 2022). When operating at higher temperatures, less effects and a decreased heat exchange is possible. This will reduce the CAPEX costs of the MED. However, for this study, the operational scale will stay the same as for the standalone MED and determine the synergy effects from the revenue of the MLD systems. A concern is that the materials of the MED must be resistant to these higher temperatures.

The NF membrane is able to reduce the bivalent ions between 90% and 99% and the monovalent ions between 10% and 60% in the seawater depending on the tight or loose membrane type (Van der Bruggen, 2013). This reduces scaling in the thermal systems and allows the desalination technology to work at 125°C with a pressure of 2,3 bar (Farahat et al., 2022; Kretzschmar and Wagner, 2024). Otherwise the water will all be evaporated before entering the other effects.

8.1.3 Merging of Literature Reviews

Table 44 below presents an overview of the annual costs associated with both MED and NF systems. A decision must be made to either select one of the cost structures or develop a new combined cost item. For instance, land costs could be combined by adding the NF footprint to the MMF, MED and AWE footprint. However, the land footprint should also be altered a little bit, as the MMF needs to filter more water for the second MLD compared to the first MLD.

An important factor to consider is the number of operational hours. The NF membranes require a lot of maintenance. According to the literature review, the NF system is assumed to operate for approximately 8.000 hours per year (Membrane Scientist, 2025; Figueira et al., 2023). Since the MED system is dependent on the NF unit for pretreatment, it cannot operate independently. As a result, the total operational time of the MED system will also be limited by the availability of the NF system. This will lead to a lower overall operational time.

Table 44 : Overview Annual Costs MED and NF

CAPEX	MED Costs	NF Costs	Synergy
Land Costs	3.274.629 [€]	12.245 [€]	Combine
Equipment Mechanical Costs	5.500.000 [€/yr]	605.289,24 [€]	SUM
Equipment Electro Costs		2.194.226,88 [€]	SUM
Equipment Membrane Costs		238.800 [€]	SUM
Building Costs	0 [€/yr]	501.130,63 [€]	SUM

Indirect Costs	500.000 [€/yr]	353.944,68 [€]	10% CAPEX
OPEX	**MED Costs [€/yr]**	**NF Costs [€/yr]**	**Synergy**
Spare Parts	222.204,11 [€/yr]	177.442,51 [€/yr]	5% CAPEX
Fuel : Seawater	0 [€/yr]	0 [€/yr]	SUM
Fuel : Steam	1.971.000 [€/yr]	-	MED only
Fuel : Waste Heat for Seawater	0 [€/yr]	-	MED only
Electricity	176.010,30 [€/yr]	766.661,49 [€/yr]	SUM
Labour	100.000 [€/yr]	100.000 [€/yr]	100.000 [€/yr]
Chemicals	37.712,90 [€/yr]	57.772 [€/yr]	SUM
Indirect Operations	82.500 [€/yr]	77.867,83[€/yr]	2% CAPEX
MED Benefits	**Profit**		**Synergy**
Hydrogen	-	-	-
Environmental Impact	-	-	-
Demineralised Water	3.650.000 [€/yr]	-	Calculate

8.2. Determination of the NF-MED parameters

In determining the cost parameters for the NF–MED system, only those cost components that require adjustment or new estimation will be discussed. Several cost items, such as equipment, construction, fuel for seawater intake, and chemicals, can be summed from the individual NF and MED systems without any modification. However, certain elements are specific to the MED process and must be altered to fit the hybrid configuration.

8.2.1 NF-MED : Land Costs

The NF system in the NF-MED configuration requires an MMF capable of producing 4,761.43 m³ of filtered seawater per day. To achieve this, the MMF must process a total of 5,290.27 m³/day, which corresponds to a flow rate of approximately 220.42 m³/h. This MMF is larger than the one used in the first MLD configuration, which only included an MED unit. The reason for the increased size is that the NF unit is now added as a preconcentration step, operating with a recovery rate of 70%. As a result, more seawater must be filtered to produce the required 3,333 m³/day of feedwater for the MED system. The footprint of the second MMF is presented in Table X. Also, the figure 48 below gives a visual representation.

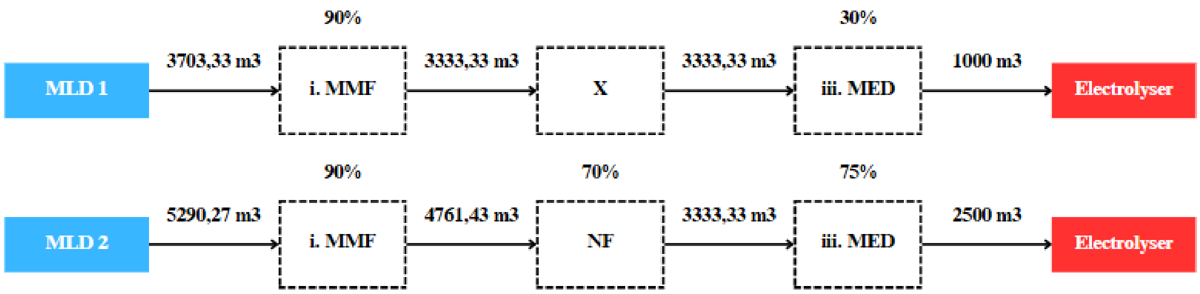


Figure 48 : Reason for different operation scales for the MMFs

The footprint for NF, MED and AWE will be added to the footprint of the new MMF. An overview of the footprints and the total footprint is presented in Table 45 below.

Table 45 : NF-MED Land Area

MLD	Technology	Area $[m^2]$	Resource
NF-MED	MMF	16 * 13 = 208	(Process Engineer, 2025)
NF-MED	NF	155	(Process Advisor, 2025)
NF-MED	MED	330	(Tendering Manager, 2025)
NF-MED	AWE	40.953	(Business Developer, 2025)
NF-MED	Total	41.646	(Process Engineer, 2025; Process Advisor, 2025; Tendering Manager, 2025; Business Developer, 2025)

8.2.2 NF-MED : Equipment Costs

The equipment costs are derived by adding up the individual estimates from both the NF and MED systems. While some process-related costs are not included in this calculation, a sensitivity analysis is provided at the end of the study to account for potential variations in these cost components. The equipment cost estimations are represented by equations X.

$$Cequipment\ NF\ MED\ [€] = Cmech\ NF\ [€] + Celectro\ NF[€] + Cmembrane\ [€] + Cequipment\ MED\ [€] \quad [52]$$

8.2.3 NF-MED : Building Costs

The building costs only include the NF building. This is because the MMF and MED units do not require a building (Project Manager, 2025). The AWE unit does require a building due to its 100 MW capacity, which exceeds the capacity of a container. This component falls outside the scope of this analysis, as previously discussed. Therefore, for the NF–MED building costs, the building costs are assumed to be equivalent to those of the NF system alone. These costs are represented by equation 53 below.

$$Ccivil\ NF\ MED[€] = Ccivil\ NF\ [€] \quad [53]$$

8.2.4 NF-MED : Indirect Capital Costs

In this analysis, indirect costs are determined as 10% of the CAPEX. The choice has been made to exclude land costs from this calculation. The reason for this is that land costs are not included in the literature review and are therefore excluded to maintain consistency with the sources used. The 10% is thus calculated solely on the cost items that are explained in the literature, such as equipment, civil, mechanical, electrical, and membrane costs. This approach ensures a transparent and consistent cost estimate, incorporating only the reliably established components. The exact cost items included in this calculation are presented in equation 54.

$$Cindirect\ costs\ NF\ MED\ [€] = 10\% * (Cequipment\ MED\ [€] + Cbuilding\ MED\ [€] + Ccivil\ NF\ [€] + Cmech\ NF\ [€] + Celectro\ NF\ [€] + Cmembrane\ [€] \quad [54]$$

8.2.5 NF-MED : Spare Costs

The spare parts costs are determined based on table 46. There are three key elements that influence the percentage allocated to spare parts: commissioning, operational spares, and critical spares (Consultancy Manager, 2025). These categories can vary in cost impact. Commissioning spares include consumables and wear items required during the initial commissioning phase and to address early-life failures. Although MED is one of the oldest desalination technologies, the specific combination with NF is relatively new, which results in high commissioning costs.

Operational spares refer to components expected to wear out or require replacement within the first 2 to 5 years of operation. Membranes typically need to be replaced within this period depending on maintenance practices and is the reason for the high percentage (Membrane Scientist, 2025). Critical spares are cost components that are essential to avoid prolonged downtime in case of a failure. An example is the feedwater pump not working anymore which halts the entire process. Therefore, it is standard practice to keep such spares readily available (Project Manager, 2025). Given the importance and cost of these components, the NF-MED configuration is assigned the maximum spare parts cost percentage of 6%. The equation 55 is given below.

$$Cspare\ parts\ NF\ MED\ [€] = 6\% * (NF\ MED\ CAPEX\ [€]) \quad [55]$$

Table 46 : NF-MED Spare Parts

Spare Part Category	Low [%]	High [%]
Commissioning	1	2
Operational Spares	1	3
Critical Spares	0,5	1

8.2.6 NF-MED : Fuel Costs

There are three types of fuel to consider; seawater, waste heat for the seawater, and steam for the MED. The NF does not use additional heat, so only the heat for the MED is needed for the calculations. The NF-MED does not need to pay for the seawater because this is only required starting from an intake flow of 1.800 m^3/h (BAL, n.d.). The MMF needs to pump 5,290.27 m^3 a day, which is less than the 1800 m^3/h allowed in the North Sea as indicated by the BAL, so no costs are associated with the withdrawal of seawater. The waste heat costs are also zero, because the heat to adjust the seawater to the right temperature is taken from the condenser.

There are three main ways to determine the steam price for the plant (Product Specialist, 2025). In some locations, such as Emmen, steam may be offered free of charge. However, the piping costs would be high because the plant is located in Rotterdam. An alternative would be to install an E-boiler, but this option is also costly because the installation and operational setup is already around €500.000, and additional sensible heat is required to heat the water.

In other locations waste heat has to be bought (Product Specialist, 2025). The steam price can be benchmarked against the cost of natural gas used to power an E-boiler. Therefore, the actual steam price is expected to fall somewhere between zero and the equivalent gas price. To ensure an inclusive estimate in this study, the same approach is used as for the MLD with a single MED. The highest possible steam price within that range has been used.

To produce 2500 m³ of distillate water per day, the MED system requires more steam compared to a lower production rate for the standalone MED. This increases operational costs. However, when operating at a higher temperature of 125°C, the GOR can increase up to 16 (Xu et al., 2022). A higher GOR means that more distillate is produced per unit of steam. This improves the thermal efficiency and reduces the total steam requirement. The calculation used to determine the benchmarked gas cost is provided in Appendix K.

8.2.7 NF-MED : Electricity Costs

The NF and MED systems are equipped with their own pumps to circulate water through the processes. Due to the nature of reverse osmosis, the NF system requires significantly more energy compared to MED. Both systems rely on a combination of green and grey electricity sources because the wind energy can only assist for 9,6 hours (Arunachalam et al., 2024).

In addition, the MLD system must be designed to operate for approximately 8.000 hours per year and must pump 2500 m³ of distillate water per day. Less hours are calculated, because the NF membranes require regular cleaning to maintain the performance and extend the lifetime of the membrane (Membrane Scientist, 2025). The new electricity calculations with 8000 operational hours are represented in Appendix K. The total electricity consumption of the system can be summed up which is shown in equation 56 and represents the combined energy costs.

$$Mixed\ \ Energy\ Price\ [€/yr]\ =\ Mixed\ NF\ Energy\ Price\ [€/yr]\ +\ Mixed\ MED\ Energy\ Price\ [€/yr]\quad [56]$$

8.2.8 NF-MED : Labour Costs

To estimate the labour costs, various calculation methods are available. However, for the first MLD installation, the cost was based on one full-time employee (Malik et al., 2023; Project Manager, 2025). The same approach and equation is applied for this cost component and is represented below as equation 57.

$$Clabour\ NF\ MED\ [€/yr]\ =\ Annual\ Wage\ [€/yr]\quad [57]$$

8.2.9 NF-MED : Chemical Costs

The NF and MED both require chemicals to prevent scaling. Although the MED operates at higher temperatures, it does not lead to increased chemical costs because the NF membranes effectively mitigates the scaling risks (Ortega-Delgado et al., 2022). As a result, the chemical costs remain consistent for both systems and leads to the formulation of equation 58 which only sums the chemical costs of both technologies. However, the 8.000 operational hours need to be taken into account again with the calculations which are represented in Appendix K.

$$Cchemical\ NF\ MED\ [€/yr] = Cchemicals\ NF\ [€/yr] + Cchemical\ MED [€/yr] \quad [58]$$

8.2.10 NF-MED : Indirect Operational Costs

For the NF the indirect operational costs are 2% of the total CAPEX, but the MED only indicates 1,5% of total CAPEX. To go from the worst case scenario, 2% of the total CAPEX is taken.

$$Cindirect\ NF\ MED\ Costs\ [€/yr] = 2\% \ * \ CAPEX\ NF\ MED\ [€] \quad [59]$$

8.2.11 NF-MED : LCOW Benefits

In the previous CBA, it is determined that the hydrogen production is no direct result from the MLD process, so only the ultrapure water is taken to be the benefit of the MLD systems. The NF-MED combination results in a higher thermal efficiency, so less heat is needed to produce 1.000m^3. However, the amount of ultrapure water will rise because the recovery rate will be between 75% and 87,5% (Morgante et al., 2024). The recovery rate of 75% is taken which will result in 2500 m^3 of ultra pure water a day. The equation 60 is given below to determine the new LCOW. The calculation is done in Appendix K.

$$LCOW\ [€/yr] = Operational\ days\ [day/yr] \ * \ Demineralised\ \ Production\ [m^3/day] \ * \ WMP\ [€/kg] \quad [60]$$

8.2.12 NF-MED : Environmental Impact Benefits

No information was provided about the environmental benefits for the same reason no environmental benefits were provided for the first MLD. The MLD process is not designed to isolate salts or reduce environmental impact. The second MLD produces a more concentrated brine compared to the first MLD, but unfortunately, it cannot isolate the salts. Therefore, a more concentrated brine still will have to be disposed into the sea.

As a result, the brine will lead to the same environmental effects. Therefore, the NF-MED process does not offer any environmental benefits, and the same permits required for standard demineralization technology must be obtained. The MLD technology becomes valuable in terms of this cost item when combined with other technologies as shown in figure 15.

8.3 Summary NF-MED Costs

In this section the CAPEX and OPEX costs are summarised for the NF-MED. After determining the equations and the needed parameters from the literature reviews an overview can be made of the costs. Table 47 shows the costs and the calculations are determined in Appendix K. The summary only contains the demineralised water as a benefit.

The CAPEX is expressed as a single price index. To convert this into annual costs, the discount rate of 2,25% is applied. The equation 61 shows the discount rate. In this equation, P represents the initial investment of the CAPEX item, r is the discount rate, and n denotes the lifetime of each asset. The value of n varies depending on the type of capital investment. Buildings are assumed to have a lifetime of 30 years, NF equipment is assumed to last 15 years, and membrane modules are replaced every 5 years (Morgante et al., 2024-b; Membrane Scientist, 2025). The MED equipment will use the same lifetime as the NF equipment, because the same type of equipment is needed such as pumps. The indirect costs are taken to be 30 years, as the insurance for example needs to count until the last day of the building. Table 47 also shows the CAPEX costs per year with this information.

$$Yearly\ CAPEX\ costs\ [€/yr] = P[€] * \frac{r * (1+r)^n}{(1+r)^n - 1} \qquad [61]$$

The annual land cost in table 43 is difficult to determine precisely, as purchased land does not depreciate or have a defined lifespan. To enable discounting over time, it is assumed that the land cost is spread over the operational lifetime of the building. In this case, a 30 year period is used for the calculation.

Table 47 : Summary Annual Costs NF-MED CAPEX, OPEX and Benefits

NF-MED CAPEX	**Costs [€]**	**Lifetime [Years]**	**Costs $[€/yr]$**
Land Costs	3.290.034	30	151.997,41 [€/yr]
Equipment MED Costs	5.500.000	15	436.086,89 [€/yr]
Equipment Mechanical Costs	605.289,24	15	47.992,49 [€/yr]
Equipment Electro Costs	2.194.226,88	15	173.977,01 [€/yr]
Equipment Membrane Costs	238.800	5	51.031,61 [€/yr]
Building Costs	501.130,63	30	23.151,91 [€/yr]
Indirect Capital Costs	903.944,68	30	41.761,65 [€/yr]
NF-MED OPEX	**Costs $[€/yr]$**		
Spare Parts Costs	739.768,85 $[€/yr]$		
Fuel : Seawater Costs	0 $[€/yr]$		
Fuel : Steam Costs	3.375.329,96$[€/yr]$		
Fuel : Waste Heat for Seawater Costs	0 $[€/yr]$		
Electricity Costs	1.168.507,47 $[€/yr]$		
Labour Costs	100.000 $[€/yr]$		
Chemicals Costs	92.214,24 $[€/yr]$		

Indirect Operations Costs	85.511,51 [€/yr]
MED Benefits	**Profit**
Hydrogen	-
Environmental Impact	-
LCOW	8.333.333,33 [€/yr]

8.4 NF-MED Limitations: Sensitivity Analysis

The literature review on NF-MED technology presents several limitations. This section discusses these limitations to ensure transparency, clarify the scope of the findings, identify remaining knowledge gaps for future research, and justify the choices made in forming the results.

The key limitation that applied to the first MLD also applies to this MLD. The estimated costs are based on the feasibility phase. At this stage, cost estimates can still vary between 50% more or 30% less. Figure 49 illustrates how cost estimates become more precise as the project progresses through the development phases. The funnel graph illustrates the phase in which the indicative CBA is conducted, as well as the degree of uncertainty still present in the calculations. The figure shows the funnel graph, illustrated in the same way as in figure 37 and figure 44. However, the graph differs in that the CAPEX values are higher.

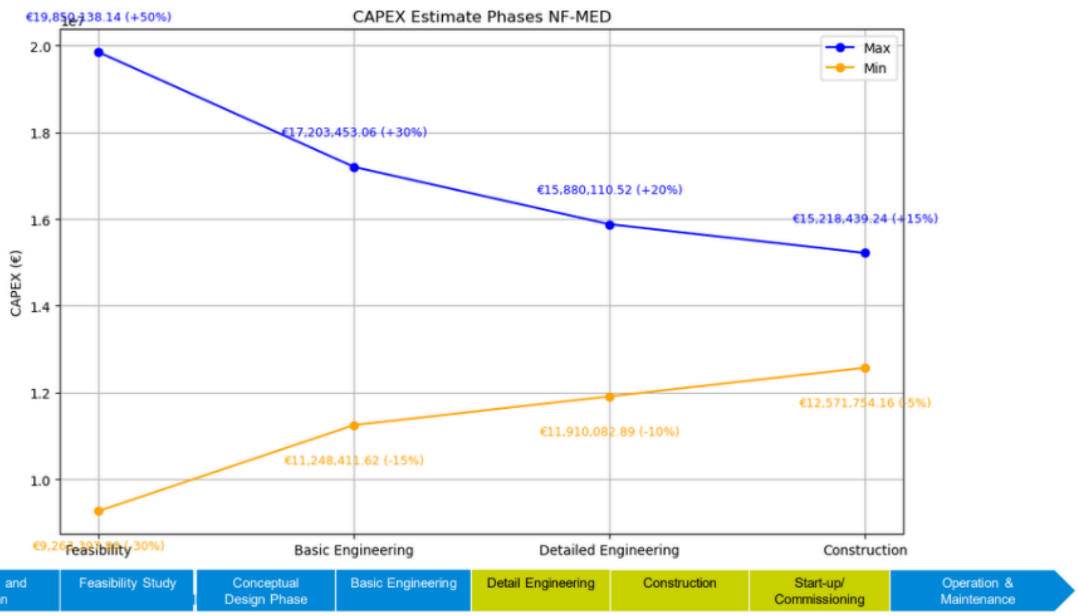


Figure 49 : NF-MED CAPEX Estimates

A sensitivity analysis was conducted in the same manner as performed by Ellerdorfer et al. and in the first MLD study using the standalone MED. This analysis focuses on the annual costs of the NF-MED installation and is shown in figure 50. Conducting a sensitivity analysis is essential because combining different water desalination technologies can introduce unforeseen process costs. These costs may not be fully understood or predictable during the early design phases. A sensitivity analysis helps identify which cost factors have the greatest impact on the overall system performance and allows for better informed decision-making.

Once again, steam costs have the greatest impact, followed by electricity and spare parts costs. The spare parts costs are noticeably higher for the NF-MED system, as this combination is relatively new in the industry. As a result, higher spare parts costs were assumed to account for potential unforeseen issues. Steam and electricity costs have increased due to the system operating at a higher capacity of 2.500 m³ per day instead of the 1.000 m³ per day for the initial MLD with the standalone MED.

Hydrogen costs are not included in this analysis, as the associated benefits are not directly linked to the MLD system. Including these costs would disproportionately show the results and lead to an unfair comparison. The environmental impact is also not represented, because the brine is still disposed of into the sea and does not resemble a benefit.

The WMP is set at €10 as previously determined, because the MED is a small plant (Strategic Account Manager, 2025). The WMP will decrease to €5 if the installation is bigger. In figure 50, the LCOW may appear to show a financial benefit. However, the MLD also represents annual costs. To provide a more accurate assessment, Chapter 10 presents the NPV of the NF-MED system.

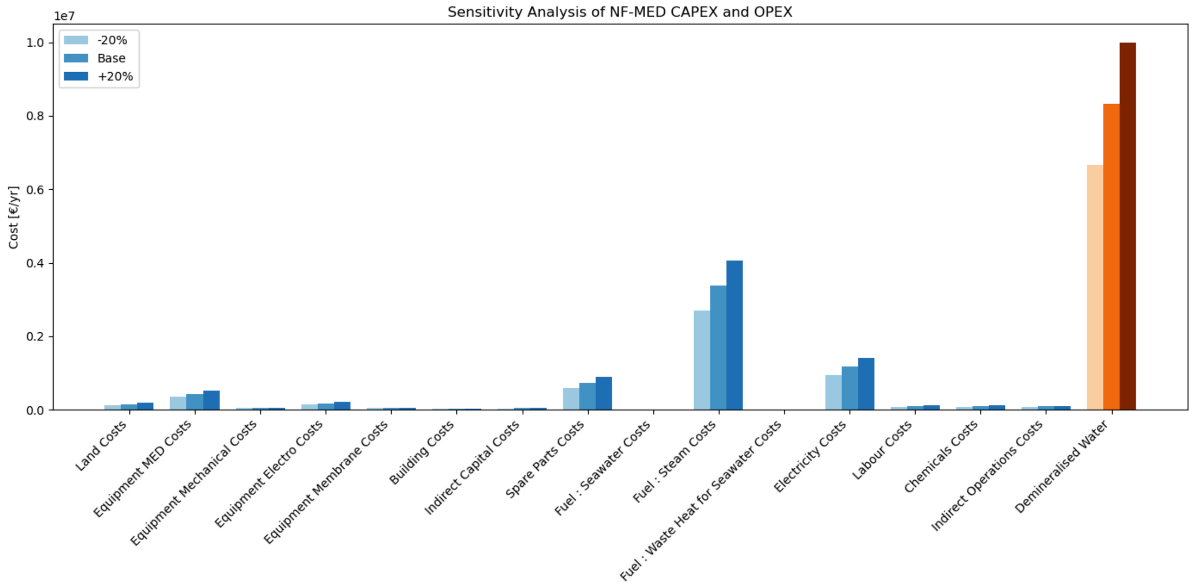


Figure 50 : Sensitivity Analysis NF-MED CAPEX and OPEX per year with LCOW

Figure 51 below presents the sensitivity analysis excluding the benefit of LCOW, in order to highlight the costs which are not really visible in the previous figure with LCOW. It is evident that steam costs have the most significant influence on the total annual costs. Seawater costs are shown as zero, as the extraction of seawater for this plant is free of charge. Similarly, waste heat is also considered free, since the MED condenser is capable of heating the seawater without additional expenses.

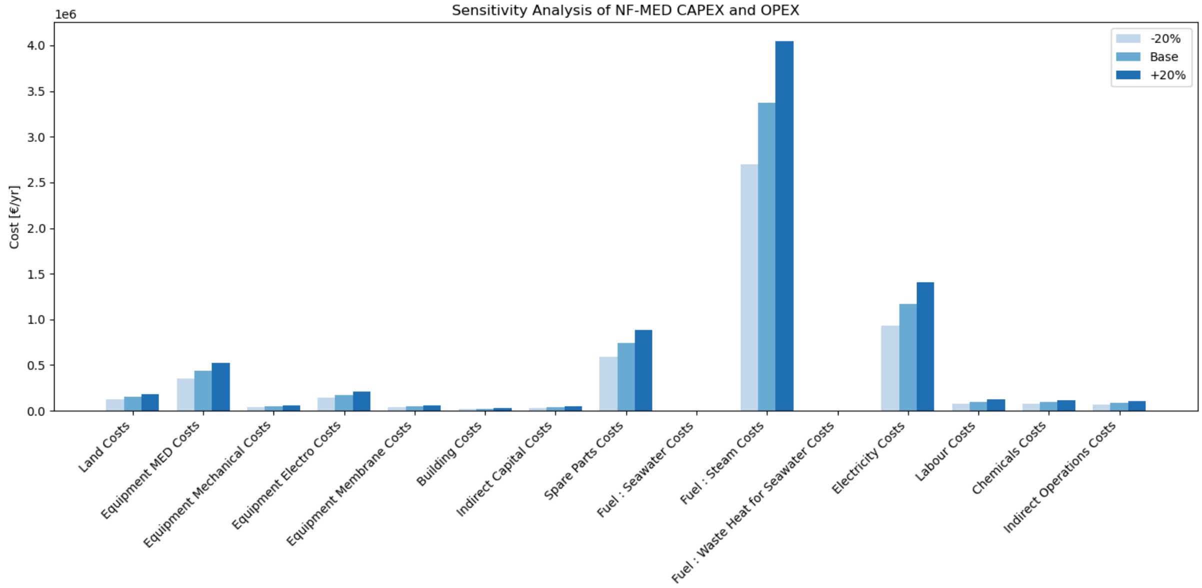


Figure 51 : Sensitivity Analysis NF-MED CAPEX and OPEX per year without LCOW

Figure 52 below illustrates the cost scenario if the plant were to be located in Emmen, a location where steam is free of charge. While this location offers relatively low costs, it may not be ideal. The MLD plant must be located near a facility that requires ultrapure water, such as the Conversion Park in the Botlek. The plant could potentially be located elsewhere with greater flexibility and reduced costs, if the process can instead operate at 70 °C and the electrolyser technology allows for the use of waste heat. It is therefore important to consider the significance of operating at 125 °C.

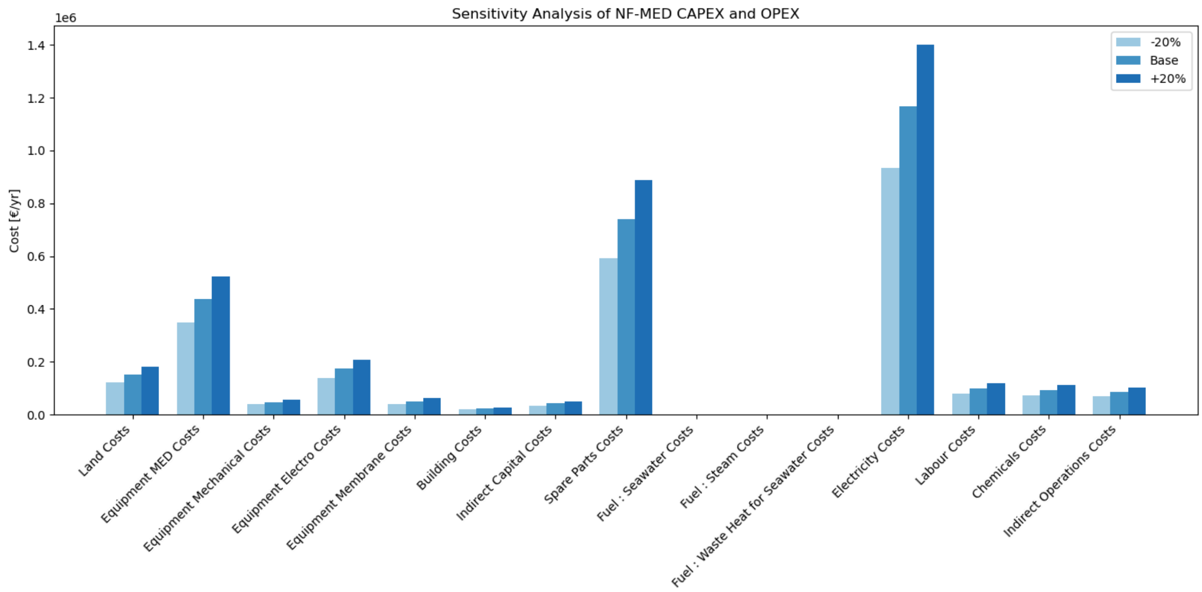


Figure 52 : Sensitivity Analysis NF-MED CAPEX and OPEX per year without steam costs

9. CBA MED

Chapter 6 presents a literature review aimed at identifying the appropriate methods for determining cost items and selecting the most relevant parameters for the MED process. The defined parameters are listed in table 48.

Table 48 : MED Economic Parameters

Variable	Value	Resource
Plant Lifetime [years]	25	(Ellersdorfer et al., 2023)
Recovery Rate [%]	30	(Ortega-Delgado et al., 2022; Ellersdorfer et al., 2023)
Operating Steam Temperature [°C]	70	(Dastgerdi and Chua, 2018)
Availability [%]	95	(Dastgerdi and Chua, 2018; Malik et al., 2023)
Land Costs [$€/m^2$]	79	(Gemeente Rotterdam, 2024)
Indirect Costs	10% CAPEX [-land]	(Morgante et al., 2022; López et al., 2025; Micari et al., 2019)
Spare Parts Costs	3% CAPEX	(Consultancy Manager, 2025)
GOR	8,13	(Malik et al., 2022; Mistry et al., 2013)
Seawater Costs [€/year]	0	(BAL, n.d.)
Electricity Costs [$€/kWh$]	0,06 for wind energy and 0,383 for grey energy	(De Vries, 2023; CBS, 2025)
Labour Costs [€/year]	100.000	(Project Manager, 2025)
Chemical Costs [$€/m^3$]	0,031 for MED	(Ellersdorfer et al., 2023)
Indirect Operation Costs [€/year]	1,5% CAPEX [-land]	(Malik et al., 2023, Dastgerdi and Chua, 2028)

A funnel diagram illustrates that the current CAPEX estimates are still in the feasibility phase and are expected to become more accurate as the project goes through the development stages. A sensitivity analysis highlights which cost components have the greatest influence during a typical production year. Based on these insights, a comprehensive overview of the CBA for the MED system is provided in table X.

Table 49 outlines the costs associated with operating the MED technology over a 30 year period. The equipment costs need to be paid twice, because the lifetime is 15 years (Morgante et al., 2024-b). With equation 62, the annual OPEX and benefits are discounted to their present value in the first operational year. The discount rate is 2,25% (Rijkswaterstaat, n.d.). The NPV stands for the net present value and is the final indicator of the CBA (Mouter, 2019). This allows for a clear assessment of the CBA. If the resulting net value is positive, the investment is considered economically viable. A negative outcome would indicate that the investment is not justified. The NPV is positive, so the investment is justified.

$$NPV = \sum_{t=1}^{t} \frac{C}{(1+r)^t} \qquad [62]$$

Table 49 : CBA MED

CAPEX	
Land Costs	€3.274.629,00
Equipment Costs	€9.439.244,52
Building Costs	€0,00
Indirect Capital Costs	€550.000,00
OPEX	
Spare Parts Costs	€4.809.681,25
Seawater Costs	€0,00
Steam Costs	€42.662.945,13
Waste Heat for Seawater Costs	€0,00
Electricity Costs	€3.809.801,00
Labour Costs	€2.164.532,98
Chemicals Costs	€816.308,16
Indirect Operational Costs	€1.785.739,71
Benefits	
Ultrapure Water	€78.789.000,65
Environmental Impact	€0,00
CBA MED	
Total	€9.476.118,90

10. CBA NF-MED

Chapter 6, 7 and 8 presents a literature review aimed at identifying the appropriate methods for determining cost items and selecting the most relevant parameters for the NF-MED process. The defined parameters are listed in table 50.

Table 50 : NF-MED Economic Parameters

Variable	Value	Resource
Plant Lifetime [years]	25	(Ellersdorfer et al., 2023)
Recovery Rate [%]	30	(Ortega-Delgado et al., 2022; Ellersdorfer et al., 2023)
Operating Steam Temperature [°C]	125	(Ortega-Delgado et al., 2022)
Availability [hours]	8000	(Dastgerdi and Chua, 2018; Malik et al., 2023)
Land Costs [$€/m^2$]	79	(Gemeente Rotterdam, 2024)
Indirect Costs	10% CAPEX [-land]	(Morgante et al., 2022; López et al., 2025; Micari et al., 2019)
Spare Parts Costs	6% CAPEX	(Consultancy Manager, 2025)
GOR	16	(Xu et al., 2022)
Seawater Costs [€/year]	0	(BAL, n.d.)
Electricity Costs [$€/kWh$]	0,06 for wind energy and 0,383 for grey energy	(De Vries, 2023; CBS, 2025)
Labour Costs [€/year]	100.000	(Project Manager, 2025)
Chemical Costs [$€/m^3$]	0,052 for NF and 0,031 for MED	(López et al., 2025; Figueira et al., 2023; Ellersdorfer et al., 2023)
Indirect Operation Costs [€/year]	2,0% CAPEX [-land]	(López et al., 2025; Micari et al., 2019; Figueira et al., 2023 ; Morgante et al., 2024-b; Van der Bruggen et al., 2001)

A funnel diagram illustrates that the current CAPEX estimates are still in the feasibility phase and are expected to become more accurate as the project goes through the development stages. A sensitivity analysis highlights which cost components have the greatest influence during a typical production year. Based on these insights, a comprehensive overview of the CBA for the NF-MED system is provided in table 51.

Table 51 outlines the costs associated with operating the NF-MED technology over a 30 year period. The equipment costs need to be paid twice, because the lifetime is 15 years (Morgante et al., 2024-b). The membrane costs even need to be paid 5 times, because the lifetime is 5 years. With equation 63, the annual OPEX and benefits are discounted to their present value in the first operational year. The discount rate is 2,25% (Rijkswaterstaat, n.d.). The NPV stands for the net present value and is the final indicator of the CBA (Mouter, 2019). This allows for a clear assessment of the CBA. If the resulting net value is positive, the investment is considered economically viable. A negative outcome would indicate that the investment is not justified. The NPV is positive, so the investment is justified and even more profitable than the MLD with the standalone MED. It is notable that the second MLD has a higher CAPEX, operates less days but has significantly higher profits.

$$NPV = \sum_{t=1}^{t} \frac{C}{(1+r)^{t}} \quad [63]$$

Table 51 : CBA NF-MED

CAPEX	
Land Costs	€3.290.034,00
MED Equipment Costs	€14.653.682,48
NF Equipment Mechanical Costs	€1.038.813,30
NF Equipment Electro Costs	€3.765.789,83
NF Equipment Membrane Costs	€1.227.095,69
Building Costs	€501.130,63
Indirect Capital Costs	€903.944,68
OPEX	
Spare Parts Costs	€16.012.540,77
Seawater Costs	€0,00
Steam Costs	€73.060.130,33
Waste Heat for Seawater Costs	€0,00
Electricity Costs	€25.292.729,62
Labour Costs	€2.164.532,98
Chemicals Costs	€1.996.007,64
Indirect Operational Costs	€3.913.236,24
Benefits	
Ultrapure Water	€180.377.741,52
Environmental Impact	€0,00
CBA MED	
Total	€39.090.902,78

11. Discussion

This chapter reflects on the findings of the study by addressing each sub-question in a structured manner. It assesses the economic and environmental viability of MLD systems for ultrapure water production, compares the performance of standalone versus hybrid configurations, and reflects on broader implications for sustainability and policy. Key limitations are reviewed, and recommendations for future research are presented. However, first the results are determined.

11.1 Results

The conducted CBAs demonstrate that both the standalone MED system and the hybrid NF-MED configuration yield a positive NPV and confirm the economic feasibility of producing ultrapure water for green hydrogen production using MLD technologies. Notably, the NF-MED system achieves a considerably higher NPV despite having higher CAPEX and reduced operational hours due to NF maintenance. This result challenges the assumption that MLD systems are too expensive because of their energy demands and technological complexity.

For instance, the standalone MED configuration reaches break-even after 15 years, which is within expected 25 year operational lifetime (Ellersdorfer et al., 2023; Christ et al., 2015; Moharram et al., 2021). The hybrid NF-MED configuration does so after only 11 years. A visual overview is given in the figure 53 below. These outcomes can be largely attributed to the increase in water recovery from 30% to 75% and the higher operating temperatures from 70°C to 125°C that improved thermal efficiency that allows for higher operating temperatures (Morgante et al., 2024; Ortega-Delgado et al., 2022). Collectively, these efficiency gains enhance the overall system profitability.

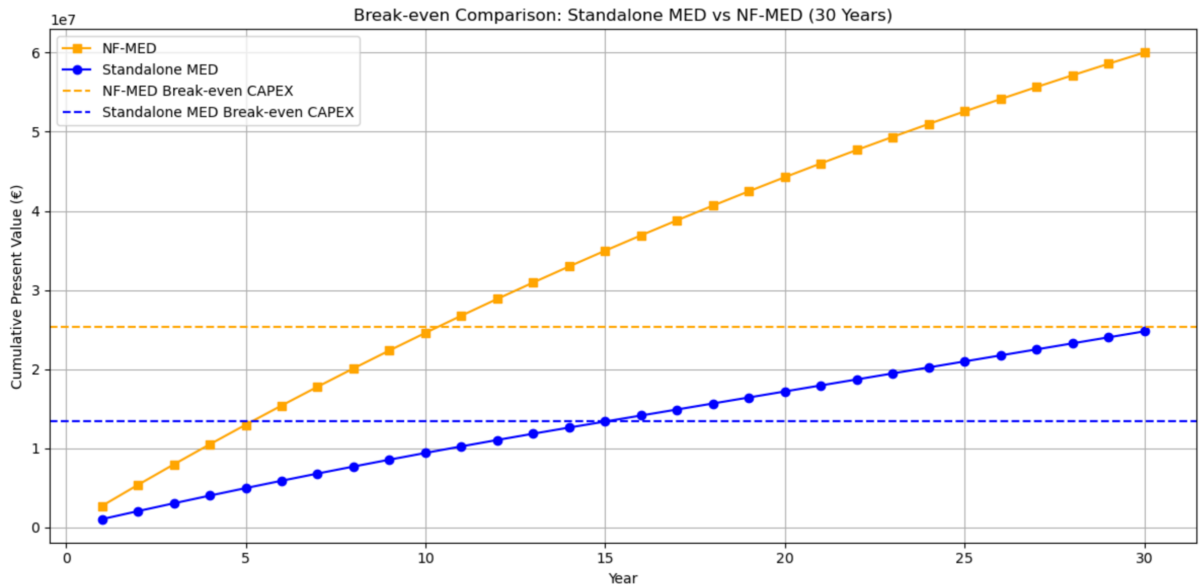


Figure 53 : Break-Even Comparison between Standalone MED and NF-MED

From a scientific perspective, this study will contribute to the societal challenge of water security and sustainable energy transition. By incorporating environmental impacts into the economic analysis, it addresses a critical gap in the current research strategies, which often relies solely on TEAs. The study aligns directly with the SDG 6 '*Clean Water and Sanitation'* and indirectly to SDG 7 '*Affordable and Clean Energy'* from the United Nations SDGs.

Policy implications of these findings are clear. Investing in MLD systems that utilize technologies in series can yield greater benefits, both economically and environmentally. Policymakers and stakeholders should therefore consider supporting such integrated systems, even if they require higher upfront investments. Over a 30 year operational period, the advantages in efficiency and resource recovery can outweigh the initial costs.

Nevertheless, several limitations must be acknowledged. The CBAs were based on specific assumptions regarding system performance and operational parameters. Even though the assumptions are grounded in the literature and expert interviews, it may not fully capture the variability encountered in real-world applications. Additionally, the analysis focused on a particular set of technologies and feedwater characteristics, which may limit the generalisability of the results for other MLD plants.

11.2 MLD Determination

The first sub-question set the technical and economic framework by clarifying the composition and selection criteria of the MLD system. Desk research and expert interviews confirmed that NF and MED technologies best meet the criteria of producing ultrapure water for hydrogen electrolysis and operational feasibility within available timeframes.

MED was chosen primarily for its ability to operate independently to produce ultrapure water and its higher thermal efficiency compared with other thermal processes like MSF (Panagopoulos et al., 2019). However, its reliance on steam, especially when steam is not freely available, remains a significant limitation in operational costs. NF serves as an effective preconcentration step by partially demineralising the seawater before the MED. Although NF also has drawbacks. The technology is an energy-intensive operation, has frequent membrane maintenance needs, and incomplete ion removal (Curto et al., 2021; Van Der Bruggen, 2013). Nevertheless, NF is preferred over RO due to its relatively lower energy demand among membrane-based desalination technologies (Shen et al., 2024).

Operational time is another critical factor. The NF-MED system operates around 8.000 hours annually which is equivalent to 333.33 days (López et al., 2025). Whereas, the standalone MED system operates around 347 days (Dastgerdi & Chua, 2018; Malik et al., 2023). Despite the reduced operational hours of the hybrid system, the second MLD revealed a higher NPV than the first MLD. This suggests that efficiency outperforms operational time.

In the literature, pretreatment was determined as a necessary component for both MLDs. Without filtration of the MMF, particles such as sand and sludge in seawater can damage the systems or result in extensive maintenance. The extensive maintenance reduces the operational efficiency. The inclusion of a third desalination technology such as MMF was determined necessary but was beyond the scope of this 21-week study. The relevance of a pretreatment can be researched and recommended in future research.

Post-treatment technologies are also essential for achieving the ultrapure water quality required for most electrolyser types (Tendering Manager, 2025). The extra technologies are needed, because it is hard to precisely determine the quality of the ultrapure water when using only the MED. This study used an AWE because it has less stringent purity requirements. Nonetheless, future research should consider integrating post-treatment stages to meet broader electrolyser specifications. If another electrolyser could be used, such as PEM, the waste heat from the electrolyser could be used as steam. This significantly reduces the OPEX costs.

A key limitation of the chosen NF-MED configuration is the lack of integrated environmental benefits. The hybrid system achieves a higher recovery rate and produces more concentrated brine. However, this brine is still discharged into the sea and damages the marine ecosystems within a 900 meter scope (Linden, 2024). The more concentrated brine does represent progress toward ZLD. Future studies should explore the potential reuse or treatment of concentrated brine to enhance the environmental profile of MLD systems.

11.3 CBA Evaluation

The second sub-question focuses on evaluating the environmental and economic costs associated with not implementing NF and MED technologies in seawater desalination for green hydrogen production. A CBA is selected as the most appropriate method to address the environmental and economic costs, as it allows for the monetisation of environmental benefits. To determine the value of implementing NF and MED technologies, it was first necessary to identify the relevant cost components and establish appropriate methods for their monetisation. However, conducting a CBA has its limitations. Two key limitations are relevant to the interpretation of the results and are discussed in the following section.

Firstly, the CBA is shaped by six normative value judgments (Mouter, 2019). These assumptions introduce a degree of subjectivity into the evaluation and may affect the robustness of the conclusions. In this context, a TEA offers a more empirically grounded approach. However, this study aimed to go beyond traditional TEAs by integrating environmental impacts into the assessment to offer a broader perspective on the MLD systems. Therefore, the six normative value judgements are introduced in the beginning of the thesis to show transparency.

Secondly, the CBAs conducted in this study are indicative. A comprehensive CBA would involve identifying and quantifying all relevant effects (Romijn and Renes, 2013). This is not feasible, as this study is limited to 21 weeks. Instead, the indicative CBA focused on the most significant and influential cost items to be able to make a well considered choice. The omission of minor cost items is unlikely to significantly change the overall conclusions.

This evaluation highlights the difficulty to balance conducting research within time and produce results that are relevant and true for policymakers and stakeholders.

11.4 Literature Review MED

The third sub-question aimed to determine the technical and economic costs associated with implementing the MED technology within an MLD system for ultrapure water production. To address this, a mixed-method approach was adopted. A combination was made with a literature review and expert interviews. This resulted in a comprehensive overview of the cost items relevant to MED.

One key insight from this analysis was that hydrogen production itself is not a direct output of the MLD system. Producing hydrogen requires a separate set of cost items associated with the operation of an AWE. The costs of the AWE are not in the scope of this research. Therefore, including hydrogen profits would have given disproportionate results. Only the LCOW is included in the CBAs.

To ensure a more transparent evaluation, a sensitivity analysis was conducted. A sensitivity analysis shows what will happen to the cost items if the operation turns out to be different. But above all, the sensitivity analysis shows the most relevant cost items of the operation. This revealed that steam costs were the most significant cost driver of the standalone MED. This is in accordance with the literature review on MLD and ZLD technologies (Mohammadi et al., 2020). These costs were benchmarked against the natural gas prices required to operate an electric boiler (Product Specialist, 2025).

The steam costs may be lower, depending on the availability of waste heat or alternative energy sources. This could reduce the overall OPEX costs. The location of the plant is therefore a very important aspect. Not only for steam, but also the land costs could be significantly reduced when operating in a cheapest city such as Eemshaven (Product Specialist, 2025). However, the location must be in need of ultrapure water, otherwise the implementation is redundant.

The reliability of the data from the literature review has limitations. Much of the data from the literature is specific for that research. The interpretation of the data requires adaptation to fit the scope of this study. Fortunately, expert interviews provided valuable validation and helped ensure that the interpretations were applicable to this MED. However, the results are in the feasibility phase. This means that the costs could still increase by 50% or decrease by 30%. Even this scope indication has an accuracy of 80%.

The strategic manager (2025) assumed that the market price for ultrapure water ranges between €5 and €10 per m^3. For this study, €10 is more appropriate due to the small operational scale of the MED system (Strategic Manager, 2025).

11.5 Literature Review NF

The fourth sub-question aimed to assess the technical and economic costs of implementing NF technology within a seawater desalination process. A literature review was conducted using the same methodological structure as applied in the MED evaluation.

The results confirmed that electricity is a major cost driver for NF systems (Shen et al., 2024). This is due to the energy needs of the high-pressure pumps to force seawater through the membrane, also called reverse osmosis. Unlike MED, NF does not require steam. In the sensitivity analysis, this reduces the need for thermal energy sources but shifts the entire energy demand to electricity.

To reflect on the available data, a funnel diagram was developed to illustrate that the findings are situated within the feasibility phase. Although the literature data was benchmarked against expert interviews, the resulting cost estimates remain indicative. Only through further development phases can more precise data be obtained. Nevertheless, the results provide a solid foundation for identifying the most significant cost components and for making an investment decision.

11.6 Combined Evaluation of NF-MED

The fifth sub-question is aimed to determine the technical and economic costs of implementing the combined NF-MED configuration. This required integrating the findings from the previous literature reviews and expert interviews to construct a comprehensive cost model. Each cost item had to be carefully assessed as some were specific to one desalination technology and others required recalculation due to changing system characteristics.

As expected, the CAPEX increased, since two desalination technologies had to be installed. This means that the OPEX and the resulting benefits determine whether the synergy between NF and MED is economically viable. For the OPEX costs, steam costs were again the most significant. These were benchmarked against the natural gas costs required to operate an electric boiler for this MLD (Product Specialist, 2025). In practice, steam costs could be lower. However, the worst-case scenario was taken into account to be inclusive.

Besides higher costs, the NF-MED system also introduced a notable improvement in the recovery rate from 30% to 75% (Morgante et al., 2024-a). This improvement is attributed to the ability of the NF to remove salts prior to MED treatment. This addition decreases scaling and enables higher water recovery. This pretreatment effect also allowed the MED to operate at higher temperatures, increasing from 70°C to 125°C (Xu et al., 2022). Higher operating temperatures improve the GOR. A higher GOR enhances thermal efficiency and reduces the amount of steam required per unit of ultrapure water produced. These dynamics were confirmed in the sensitivity analysis.

Although steam consumption increased due to the higher volume of ultrapure water produced of 2.500 m^3, the costs were not extensively higher. The improved thermal efficiency at 125°C helped mitigate the additional steam demand and costs. The sensitivity analysis shows the increase of yearly steam and energy costs compared to the standalone MED. Luckily, the higher operating temperature reduces the costs of the steam to €3.375.329,96 a year instead of €6.641.9993.358 a year. Besides the steam consumption, the electricity consumption also increased due to the energy requirements to pump the larger volumes of water through the system. In contrast, chemical costs remained stable, because NF effectively removed particles that would otherwise contribute to scaling at higher temperatures.

In conclusion, the elevated operating temperature helped reduce the relative cost of steam, while the enhanced recovery rate increased revenue potential. Moreover, the recovery rate could expand to 87,5%, which could increase the benefit even further. The recovery rate is determined by the CF. The CF of NF-MED is between 4 and 8. For this literature review, a CF of 4 was considered to stay in line with the worst-case scenario, but could therefore be higher. These decisions underscore the importance of a sensitivity analysis.

11.7 CBA of MLD with standalone MED

The sixth sub-question aims to evaluate the CBA of implementing a standalone MED system as the first MLD configuration. The results showed a positive NPV and indicates that the system is economically viable under the given assumptions.

Among the various cost components, steam emerged as the most impactful over the capital and operational cost. Two alternative strategies were identified that could significantly reduce steam costs. First, in certain regions of the Netherlands industrial heat is exchanged at no cost, such as in Emmen (Product Specialist, 2025). However, if the location does not require ultrapure water, additional CAPEX would be required to install and maintain pipelines for water transport.

The second and potentially more promising option involves utilising waste heat from the electrolyser itself. If the MED and AWE are located in the same area, the MED system with the electrolyser could allow for direct use of residual heat and substantially improve the NPV. However, the feasibility of this approach remains uncertain. Some literature and expert interviews suggest that the waste heat from an AWE may be sufficient (Tendering Manager, 2025). Others indicate that only PEM or SOEC technologies generate waste heat at temperatures high enough to be reused effectively (Business Developer, 2025).

This uncertainty highlights an important topic for future research. A more detailed technical and economic assessment of waste heat integration could provide valuable insights into optimising the cost-benefit of MLD configurations.

11.8 CBA Items of the MLD with NF-MED

The final sub-question aims to evaluate the CBA of the complete NF-MED system as the second MLD configuration. The results revealed that this configuration yielded the highest NPV and outperforms the standalone MED system by approximately €30 million. The NF-MED technology also recovers the CAPEX costs within 11 years, compared with the 15 years it takes the standalone MED. This significant increase in profitability is primarily attributed to two factors. The first factor is the reduced steam costs due to improved thermal efficiency at higher operating temperatures and the second factor is a substantially higher water recovery rate (Morgante et al., 2024-a). This indicates that the current results may underestimate the full potential of the NF-MED configuration.

Although the literature often characterises MLD systems as expensive, this study demonstrates that they can also be profitable. The positive outcome is largely the result of careful technology selection and parameter optimisation tailored to the specific operational context. Nevertheless, it is important to acknowledge that certain cost elements may vary in practice. Increases in key cost drivers, such as electricity or steam, could reduce the NPV and should be considered.

12. Future Research

This literature review was constrained by the scope of the study and therefore several interesting topics got excluded for further investigation. Some of these were already introduced in previous sections, but are elaborated here as key recommendations for future research.

An important future research is the integration of several steps to build a more comprehensive MLD for hydrogen production, but also for salt recovery to be able to use the method CBA with environmental impacts to its full potential. A key step for the salt recovery is the crystallisation step. In the current Nf-MED, the system only concentrates the brine with reducing its volume but not reusing its components. Including a crystallisation step could transform the concentrated brine into valuable byproducts.

This would not only enhance the environmental sustainability of the system but also introduce new economic value streams. The use of shadow pricing could help quantify these environmental benefits within the CBA framework and further distinguish a CBA from a TEA method. Additionally, a WTP survey could be conducted to assess whether plant operators are prepared to invest more in systems with environmental benefits. If the plant operators are willing to pay more, this would increase the environmental benefit of the CBA.

In addition, the integration of a post-treatment step ensures the production of ultrapure water but also opens the door to using the waste heat from PEM or SOEC. Unlike AWE, which generates low thermal energy, PEM and SOEC systems can provide usable heat. This heat could be recovered and reused and leads to reductions in steam generation costs.

Finally, this study has already indicated that intermittent operation could offer economic advantages (Arunachalam et al., 2024). This is particularly relevant because the production of hydrogen is very expensive. By operating the plant during periods of extensive renewable energy, it may be possible to benefit from negative electricity prices. This would enable the production of ultrapure water at significantly lower costs.

Moreover, if the system were to operate only on green electricity, the annual operational costs for the NF membranes could be reduced by nearly €500,000. Since NF membranes require a lot of energy input to overcome osmotic pressure, they represent a significant portion of the OPEX. Intermittent operation could therefore offer a promising strategy to mitigate these costs. The use of battery storage could further enhance this flexibility.

13. Policy Letter

Policy Letter: Evaluating MLD Technologies for Hydrogen Production

Step 1 : Problem Analysis
Hydrogen is a cornerstone of the global energy transition. However, producing green hydrogen via electrolysis requires large volumes of ultrapure water and clashes with water being a growing scarce resource. With already 2.7 billion people affected by water scarcity each year, freshwater use in hydrogen production increases global resource inequality. Seawater desalination is a potential solution but leads to the discharge of brine, which has a high salinity and therefore threatens marine ecosystems. Sustainable brine management technologies are urgently needed.

Step 2 : Baseline Alternative
The baseline scenario assumes continued reliance on traditional water desalination technologies without additional brine treatment. In this scenario, brine that is produced by seawater is discharged back into the sea, and the environmental impacts are not internalised in investment decisions. This results in impairment of marine life.

Step 3 : Policy Alternative
The policy alternative evaluates the implementation of MLD systems, specifically a hybrid system combining NF and MED, to produce ultrapure water while minimizing brine discharge. MLD offers an intermediate solution with more concentrated brine which is suitable for further processing than traditional methods and fewer technological challenges than ZLD.

Step 4 : Identification of Effects
The implementation of an NF-MED MLD system results in the following societal effects:

- Increased CAPEX and OPEX
- More concentrated brine discharge
- Increased water recovery per m³ of seawater, rising from 30% to 75%
- Higher operating temperatures which reduces steam costs, from 70°C to 125°C
- Lower dependency on freshwater resources
- Contribution to SDG 6 '*Clean Water and Sanitation*' and SDG 7 '*Affordable and Clean Energy*'

Step 5 : Monetisation of Effects
The cost components of the NF-MED system were derived from literature and validated through expert interviews. The interviews also filled the knowledge gaps in the literature for certain cost items. The environmental benefits are monetised using shadow pricing but the willingness-to-pay estimates could better determine the value of environmental benefits.

Step 6 : Net Present Value
The NPV was calculated over a 30 year horizon using a social discount rate of 2.25%. The results show that the NF-MED system achieves a higher positive NPV than a stand-alone MED system. The stand-alone MED breaks even after 15 years and NF-MED breaks even after 11 years.

Step 7 : Sensitivity Analysis
The analysis tested the impact of:

- Variations in energy prices
- Variations in steam prices
- Variations in WMP
- Technological synergy effects
- The possible impact of reusing brine to reduce environmental impacts

Step 8 : Conclusions and Policy Recommendations
This study finds that the NF-MED-based MLD system outweighs their costs under realistic technical and environmental assumptions. Based on this conclusion, we recommend:

- Use CBAs, not just TEAs, as the standard evaluation framework for water and energy infrastructure with major sustainability impacts.
- Internalise environmental impact by applying brine discharge levies or stricter regulatory standards so individuals feel more responsible to change.
- Introduce financial incentives, such as capital subsidies to accelerate the adoption of the MLD or even a ZLD.

By adopting NF-MED MLD systems for hydrogen production in a water scarce growing planet, policymakers can address carbon-neutral fuels, water security, and environmental protection.

Sincerely,
Megan Knape
TU Delft – MSc Complex Systems Engineering and Management

Conclusion

This study wants to research the technical and societal costs and benefits of MLD technologies for hydrogen production. Specifically for this study the hybrid combination of NF and MED is examined. Through a structured mixed-method approach based on seven sub-questions, this research provides an answer to the main research question.

Sub-question 1 identified the technical and economic characteristics of NF and MED. The characteristics of the MLD determine the foundation for the entire analysis. NF acts as a preconcentration step and this technology reduces the scaling risk of the salts in the seawater before MED completes the desalination process through thermal evaporation. Together, they form a hybrid MLD system that reaches a water recovery rate of 75%. This is a promising recovery rate compared to the 30% recovery rate of the stand-alone MED. This system was chosen to investigate the synergy effects of this fairly new combination and determine the cost and benefits within the 21 week research period.

Sub-question 2 addressed the environmental and social impacts of not implementing NF and MED, establishing the cost categories of the CBA. It concluded that brine disposal leads to significant harm to marine ecosystems. These externalities are often excluded in TEA and confirms the added value of a CBA that incorporates broader societal considerations. This sub-question defined the scope and structure of the CBA used in later stages.

Sub-questions 3 and 4 focused separately on the technical and economic costs of implementing MED and NF as water desalination technology. Sub-question 3 quantified the full CAPEX, OPEX and benefits of a stand-alone MED system. Sub-question 4 did the same for NF, only the NF had no benefits, so only CAPEX and OPEX were quantified. The NF cannot produce ultrapure water without other water desalinations. According to the literature reviews, the NF has lower operational costs compared to MED. This is mainly because the MED does not require steam costs. However, the energy costs are higher compared to the MED. These findings provided the input parameters for sub-question 5.

Sub-question 5 then examined the integrated NF-MED system. By combining the outputs of sub-questions 3 and 4, it became clear that NF significantly improves MED performance. The combined system yielded synergy effects such as higher recovery rates and lower specific energy consumption per m^3. These effects were critical for the comparative analysis in sub-questions 6 and 7.

Sub-question 6 evaluated the stand-alone MED system through a full CBA. The stand-alone MED does not reduce the brine and therefore the CBA does not include additional benefits from the environmental impact. However, the MED is technically feasible and resulted in a positive NPV. This baseline assists in determining the synergy effects of including the NF technology.

Sub-question 7 applied the same CBA framework to the NF-MED system and demonstrated a stronger business case. The hybrid system performed better than the stand-alone MED in terms of both environmental benefit and economic efficiency. The environmental benefit is that the NF-MED produces a more concentrated brine which is valuable for further processes. However, the NF-MED system does not reduce the environmental impact on its own. An additional technology is required to withdraw the salts. Economically, the use of demineralised water from NF reduces scaling in the MED unit and enables higher operating temperatures and increases the overall output of ultrapure water without extreme OPEX. The NPV of the hybrid system was significantly higher and justifies its adoption from a societal perspective.

Finally, all sub-questions are brought together to answer to the main research question: *"What are the societal costs and benefits of Minimal Liquid Discharge (MLD) technologies, with a focus on Nanofiltration (NF) and Multi-Effect Distillation (MED), for hydrogen production?"*. MLD technologies offer a more technically beneficial alternative for producing ultrapure water in hydrogen production than a stand-alone system. Besides, the MLD also offers a societal benefit with the production of more concentrated brine for further processes. While the upfront costs are high, the broader societal benefits can justify the investment. This conclusion can be strengthened when the environmental externalities are internalised through regulation or market incentives. The study concludes that hybrid MLD systems should be further explored, piloted, and supported as part of a sustainable hydrogen strategy.

Appendix

A. Literature List

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B. COSEM Concepts and Meaning

Table Appendix 1 : Key Concepts and Definitions

COSEM concepts	Relevance
Desalination	Desalination describes a process that aims to obtain fresh water from saline water resources, such as brackish water or seawater (Elsaid et al., 2020). Desalination is the solution for water scarcity but results in new environmental challenges.
Brine	Byproduct brine is the residue from desalination processes containing high salinity, high temperature, and dissolved chemicals (Giwa et al., 2017)). With the growing demand of water, increasing amounts of brine are being produced from the desalination plants leading to significant adverse impacts on the environment.
Zero Liquid Discharge (ZLD)	ZLD is seen as a promising method to reduce waste, reclaim resources, treat hazardous industrial effluents, and lessen the potential impact on water quality in producing freshwater (Yaqub et al., 2019). The technology is effective but very costly to implement.
Minimal Liquid Discharge (MLD)	MLD is similar to ZLD but uses only membrane-based technologies and has a greater amount of rejected brine than ZLD (Panagopoulos and Giannika., 2024-a)
Economic Assessment Study (EAS)	Economic assessment analysis is the process of identifying, calculating, and comparing the costs and benefits of a proposal, project, or intervention to evaluate its overall merit and feasibility. This type of analysis helps decision-makers understand the economic implications and potential impacts of their choices.
Cost-Benefit Analysis (CBA)	CBA is an economic assessment analysis and compares benefits and costs in evaluating the desirability of a project or programme and has a social nature (Mishan and Quah, 2020). CBA helps determine if a project is worthwhile and is a formal technique to make a well informed decision on the use of society's resources.
Techno-Economic Analysis (TEA)	TEA is an economic assessment analysis and is an important tool to evaluate the economic performance of industrial processes (Chai et al., 2022). The analysis focuses on CAPEX and OPEX but does not include a life cycle analysis and is therefore less inclusive about environmental impact.
Cost-Effectiveness Analysis (CEA)	CEA is an economic assessment analysis and compares costs with outcomes measured in natural units such as per life saved (Robinson, 1993). CEA compares outcomes to select the most cost-effective management strategy.
Life Cycle Analysis (LCA)	LCA is an economic assessment analysis and considers all costs incurred over the lifespan of an asset, project or investment (Ghaffour et al., 2013)

C. Abbreviations

Table Appendix 2 : Abbreviations

Abbreviation	Full Form
AVR	Afvalverwerking Rijnmond
CAPEX	Capital Expenditures
CBA	Cost-Benefit Analysis
CBS	Central Bureau of Statistics
CEA	Cost-Effectiveness Analysis
CF	Concentration Factor
COSEM	Complex System Engineering & Management
DWP	Demineralized Water Plant
EAS	Economic Assessment Study
HEX	Heat Exchanger
HMP	Hydrogen Market Price
IEX	Ion Exchange Resins
LCA	Life Cycle Analysis
LCOH	Levelized Cost of Hydrogen
LCOW	Levelized Cost of Water
MED	Multi-Effect Distillation
MF-PFR	Multiple Feed-Plug Flow Reactor
MLD	Minimal Liquid Discharge
MMF	Multi-Media Filter
MSF	Multi-Stage Flash
NPV	Net Present Value
NF	Nanofiltration
OPEX	Operational Expenditures
PSU	Practical Salinity Units
RO	Reverse Osmosis
RR	Recovery Rate

SECs	Specific Energy Consumptions
SDG	Sustainable Development Goals
SDI	Silt Density Index
STEC	Specific Thermal Energy Consumption
SW	Seawater
TBT	Top Brine Temperature
TCC	Total Capital Costs
TDS	Total Dissolved Solids
TEA	Techno-Economic Analysis
TOC	Total Operational Costs
WMP	Water Market Price
WTP	Willingness-To-Pay
ZLD	Zero Liquid Discharge

D. Parameter Units

Table Appendix 3 : Key Units

Units	Full Form
Dt,design	Total Production Rate
EUP	Electricity Unit Price
f	Plant Availability
GW	GigaWatt
MW	MegaWatt
NPPC	Normalised Pumping Power Consumption
p	Power Consumption
35 ‰	35 grams per 1000 grams

E. Research Approach

This research approach is a mixed method approach because multiple cost-benefit analyses will be conducted which is a quantitative method and interviews will be carried out which is a qualitative method (Creswell et al., 2011). Interviews are included to overcome the limitation of a quantitative approach. Quantitative research is a means for testing objective theories by examining the relationship among variables. These variables need to be data that can be analysed using statistical procedures. A cost-benefit analysis is designed to assign monetary values to the costs and benefits of a project and aims to quantify its performance in financial terms. This approach allows for a systematic comparison of the costs and benefits and facilitates informed decision-making based on quantitative data.

The quality of the results in quantitative research relies on the reliability and validity of the instruments used and can be a limitation as important insights might be missed (Creswell, Research Design, Chapter 1 on Research Approaches). However, by conducting interviews with water management consultants who work in the field, the static data can be analysed within real-life contexts to ensure that the CBA includes all relevant insights. This is a concurrent mixed method procedure which merges research results to form a complete analysis.

Research Questions

To address the main research question, *"What are the Societal Costs and Benefits of Minimal Liquid Discharge (MLD) technologies, with a focus on Nanofiltration (NF) and Multi-Effect Distillation (MED) for hydrogen production?"*, sub-questions must be formulated to add knowledge that contributes to answering the main question and achieving the research objective.

Research sub-questions

The table Appendix 4 below defines the six sub-questions and the contribution to the CBA to answer the research question. Table Appendix 4 also shows the research methods per sub-question.

Table Appendix 4 : Sub-questions and contribution to the Research Question

#	Sub-question	Technology	Contribution CBA
1	What are the technical and economic costs of implementing NF technologies?	Nanofiltration	CAPEX, OPEX
2	What are the technical and economic costs of implementing MED technologies?	Multi-Effect Distillation	CAPEX, OPEX
3	What are the environmental costs associated with not implementing Nanofiltration (NF) and Multi-Effect Distillation (MED) in seawater desalination for green hydrogen production?	Nanofiltration & Multi-Effect Distillation	Environmental Impact
4	What is the cost-benefit analysis of implementing NF technologies?	Nanofiltration	CAPEX, OPEX, Revenue, Environmental Impact

5	What is the cost-benefit analysis of implementing MED technologies?	Multi-Effect Distillation	CAPEX, OPEX, Revenue, Environmental Impact
6	What is the cost-benefit analysis of the Minimal Liquid Discharge technology NF-MED?	NF-MED	CAPEX, OPEX, Revenue, Environmental Impact

1. What are the technical and economic costs of implementing NF technologies?

The first research question involves conducting a literature review to provide a comprehensive overview of all technical and economic costs associated with implementing NF technology. This research question will contribute to the CBA elements CAPEX and OPEX. The sub-question contributes to the CBA but also gives the opportunity to compare TEA results with CBA results. It is important to realise that the MLD systems from the literature review will not be exactly the same as the NF-MED system from this research, so the comparison needs to be made based on the elements that are not included in a TEA and are included in a CBA. In this case that will be the environmental impact and the benefit element revenue from water sales for hydrogen production.

2. What are the technical and economic costs of implementing MED technologies?

The second research question will involve conducting a literature review to provide a comprehensive overview of all technical and economic costs associated with implementing MED technology. This research question will have the same contribution to the research as sub-question one, only for MED instead of NF.

3. What are the environmental costs associated with not implementing Nanofiltration (NF) and Multi-Effect Distillation (MED) in seawater desalination for green hydrogen production?

The third research question is a desk research to determine environmental costs related to not implementing NF and MED. The CBA has internal and external parameters (Ghafourian et al. 2022). CAPEX and OPEX are internal parameters and the environmental costs are external. An externality occurs when producing or consuming a good or service and it causes a positive or negative impact on the third parties that are not directly linked to its creation. The environmental impact of brine on marine life is an externality. The problem of external impact is that they do not have commonly approved monetary value. There are several economic estimation methods to overcome this hurdle. For this study, shadow pricing is chosen as an economic estimation method with a damage cost approach. This approach calculates the costs that will be made to recover environmental impacts of brine and will be determined as the monetary value. Firstly, the environmental impacts of brine disposal then needs to be determined when returned to sea as shown in figure Appendix 1. The environmental impacts are expected to reach a zone of 900 meters (Linden, 2024).

Source of Impact		Impact	
Source	**Characteristics**	**Adverse Effect**	**Level of Impact**
Brine	Increased Temperature	Thermal Pollution	Medium
		Reduction of Dissolved oxygen of receiving water bodies	
		Harmful effects to non thermal tolerant species	
	Increased concentration/salinity	Harmful effects to salt intolerant species and particularly in benthic biota	Medium to High[1]

Figure Appendix 1 : Main impacts of brine discharge from desalination plants (NTUA and TINOS, 2016)

In the Netherlands, permits are required from Rijkswaterstaat to be allowed to discharge the brine at sea (Ministerie van Infrastructuur en Waterstaat, 2024). The money collected from the permits will be used for the damage costs (Ghafourian et al. 2022). The willingness-to-pay for a ZLD or MLD technology from companies is reflected in the costs associated with obtaining the necessary permits. For sustainability purposes, companies might be willing to pay more than the permit costs which could be researched through a survey *(NTUA and TINOS, 2016)*. However, because of the length of this study this is relevant for a future study. A visual representation is shown in figure Appendix 2 about the WTP and additional WTP from companies.

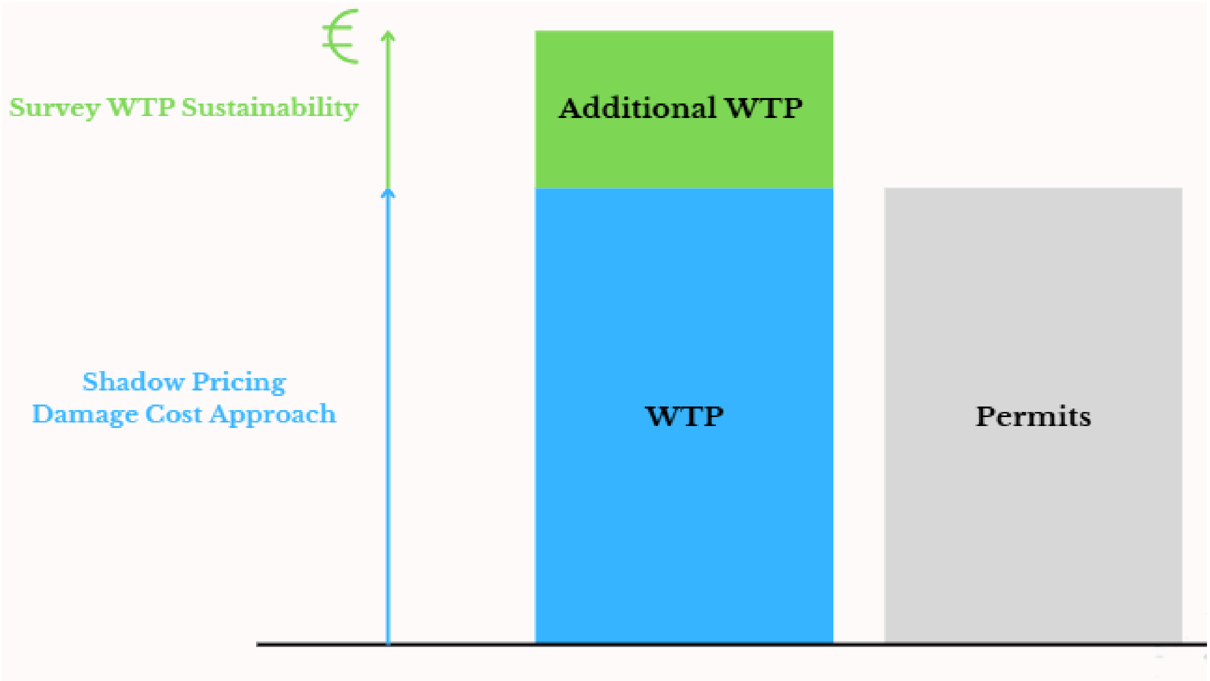

Figure Appendix 2 : WTP for companies regarding MLD technologies

4. What is the cost-benefit analysis of implementing NF technologies?

Sub-questions 1 and 3 contribute to answering the fourth sub-question. For this sub-question, a singular CBA will be conducted for NF. The first step involves desk research to identify all relevant elements and their monetary terms. The second step includes conducting interviews with experts to validate the desk research findings with real-world insights. This research question will contribute to the research question, to show the performance of a single technology before analysing the performance of a hybrid desalination process.

It is important to mention that the revenue sales from the CBA only include water sales and not the sales of minerals because the focus is on water feedstock for hydrogen and not mining. Mining mineral sales are difficult because the seawater concentrations are hard to determine. Some in the highest concentration range are sodium, magnesium, calcium and potassium. Other more valuable elements present in seawater, such as lithium, however are much less concentrated and more difficult to extract (Morgante et al., 2024-a).

5. What is the cost-benefit analysis of implementing MED technologies?

Sub-questions 2 and 3 contribute to answering the fifth sub-question. For this sub-question, a singular CBA will be conducted for MED. The first step involves desk research to identify all relevant elements and their monetary terms. The second step includes conducting interviews with experts to validate the desk research findings with real-world insights. This research question will contribute to the research question, to show the performance of a single technology before analysing the performance of a hybrid desalination process.

6. What is the cost-benefit analysis of the Minimal Liquid Discharge technology NF-MED?

Sub-questions 4 and 5 contribute to answering the sixth question but also desk research is needed to determine the performance of the MLD technology. The performance will be different from the single technologies because of synergy elements. After determining the CBA, interviews are yet again needed to validate the desk research findings with real-world insights. This research question will contribute to the research question, to show the performance of an MLD over a single technology performance.

Table Appendix 5 : Overview of the sub-questions and the research methods.

RQ	Sub-question build up	Research Method	Data Source(s)	Data Type	Data Analysis Tools
1	Make use of the techno-economic assessment of previous research into these technologies.	Literature Review	Google Scholar & Scopus	Secondary	Excel
2	Make use of the techno-economic assessment of previous research into these technologies.	Literature Review	Google Scholar & Scopus	Secondary	Excel
3	What are the environmental costs associated with not implementing Nanofiltration (NF) and Multi-Effect Distillation (MED) in seawater desalination for green hydrogen production?	Desk Research	Google Scholar & Scopus	Secondary	Excel
4	Use the previous sub-questions to define the CBA.	Desk Research	Google Scholar & Scopus	Secondary	Excel
		Semi-structured Interview	Consultant Technical Consultancy	Primary	Teams
		Semi-structured Interview	Consultant Technical Consultancy	Primary	Teams
		Semi-structured Interview	Consultant Technical Consultancy	Primary	Teams
		Semi-structured Interview	Panagopoulos	Primary	Teams
		Semi-structured Interview	Evides	Primary	Teams
		Semi-structured Interview	Erik Roesink	Primary	Teams
5	Use the previous sub-questions to define the CBA.	Desk Research	Google Scholar & Scopus	Secondary	Excel

		Semi-structured Interview	Consultant Technical Consultancy	Primary	Teams
		Semi-structured Interview	Consultant Technical Consultancy	Primary	Teams
		Semi-structured Interview	Consultant Technical Consultancy	Primary	Teams
		Semi-structured Interview	Panagopoulos	Primary	Teams
		Semi-structured Interview	Evides	Primary	Teams
		Semi-structured Interview	Erik Roesink	Primary	Teams
6	Use the previous sub-questions to define the CBA.	Desk Research	Google Scholar & Scopus	Secondary	Excel
		Semi-structured Interview	Consultant Technical Consultancy	Primary	Teams
		Semi-structured Interview	Consultant Technical Consultancy	Primary	Teams
		Semi-structured Interview	Consultant Technical Consultancy	Primary	Teams
		Semi-structured Interview	Panagopoulos	Primary	Teams
		Semi-structured Interview	Evides	Primary	Teams
		Semi-structured Interview	Erik Roesink	Primary	Teams

3.4.2. Method Limitations

Figure Appendix 3 visualizes the steps derived from the sub-questions. The first two sub-questions feed sub-question 3. Sub-questions 1, 2, and 3 contribute to sub-questions 4 and 5. Finally, sub-questions 4 and 5 are used for sub-question 6. The limitations of this approach include the potential dominance of quantitative methods due to the first three questions being conducted quantitatively. Additionally, an extended project timeline poses another limitation. To mitigate this, a time table is created to reduce the possible impact of this limitation.

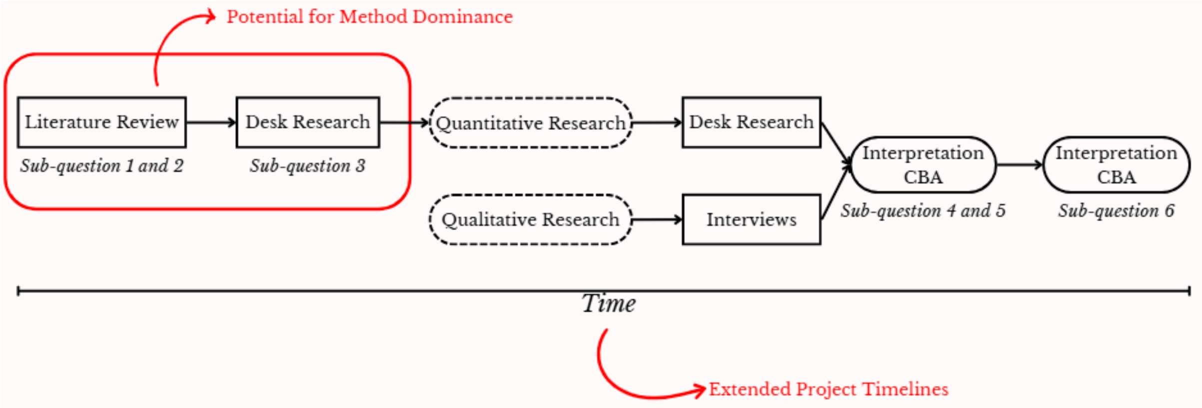

Figure Appendix 3 : Sub-questions flowchart and limitations

3.5 Data Analysis Tools

Table Appendix 5 presents the data analysis tools for all sub-questions. Excel will be used to analyse the CBA data which focuses on the technical, economic, and environmental elements of NF, MED, and NF-MED technologies to determine and calculate the associated costs and benefits.

Interviews will be conducted with the water company Evides and water consultants from a technical Consultant. Evides operates a Demineralized Water Plant (DWP) in the Botlek area which is a large-scale demonstration plant for zero brine. Erik Roesink is a professor at TU Twente and works for NX Filtration who are specialised in making the pretreatment nanofiltration. These interviews will provide real-world insights to validate the CBA and ensure all relevant factors are considered. Additionally, an interview with Panagopoulos would further support the development of the CBA because of his expertise on TEA for ZLD and MLD. The interviews will be semi-structured with open- and closed-ended questions. Interviews will be conducted in a manner that prioritises the interviewees preference in person or online. The data analysis tool Teams will be used for online interviews and for transcript of the conversation.

F. ZLD/MLD Trains

1. Alrashidi et al., 2024 ZLD/MLD train.

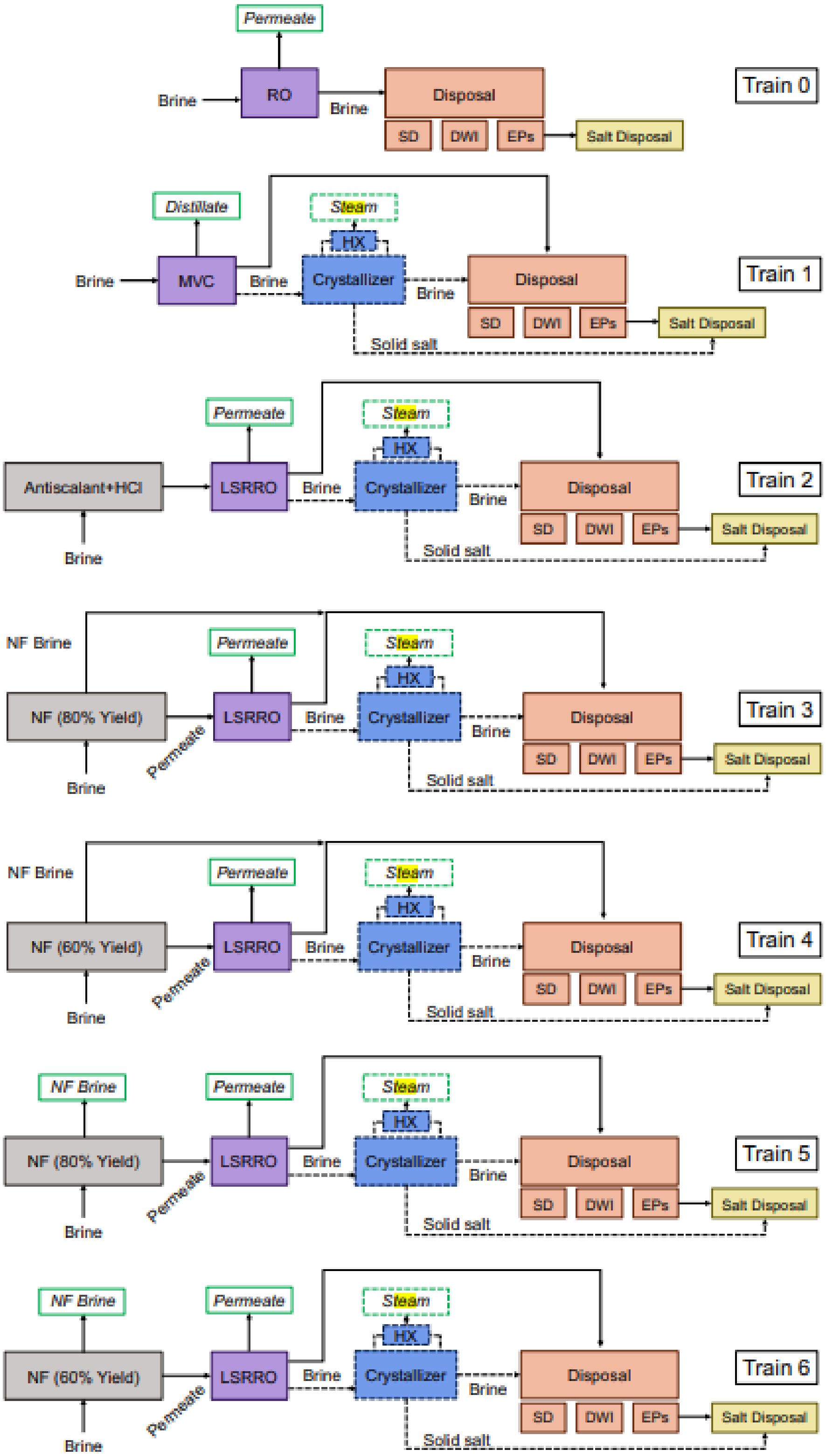

Figure Appendix 4 : Alrashidi et al., 2024 ZLD/MLD train

2. O'Connell et al., 2024 MLD/ZLD train.

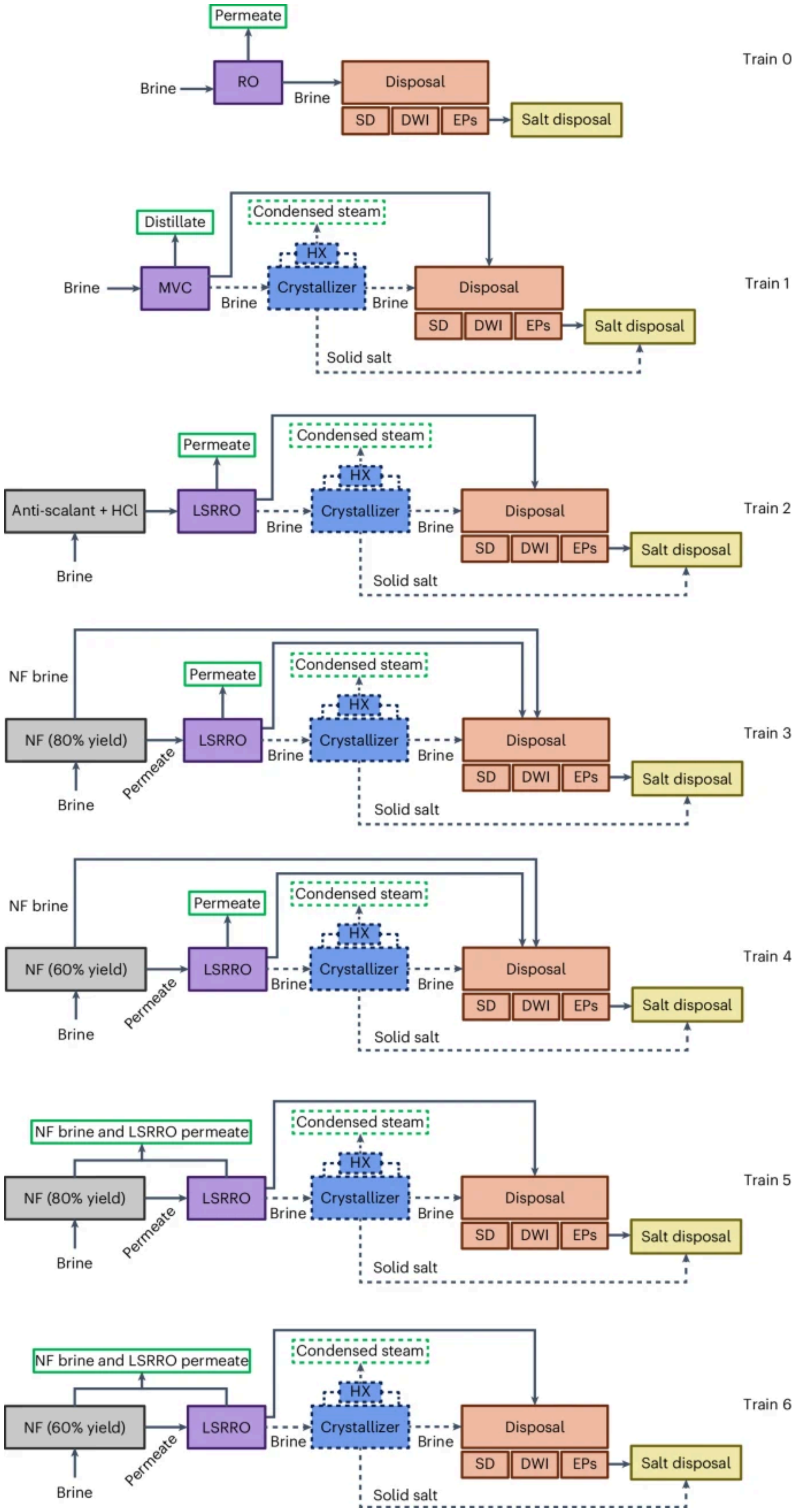

Figure Appendix 5 : O'Connell et al., 2024 MLD/ZLD train

G. Chapter 4 : Scale Operation of the Electrolyser and MED Parameters

1. The table below shows the scale of the MED unit to support an electrolyser of 100 MW

Table Appendix 6 : Electrolyser and MED parameters

AWE Parameters	**Calculations**	**Value**	**Unit**	**Remark**
Electrolysis		100	[MWh]	HyNetherlands Project
Electrolysis	100 [MWh] * 1000 [kWh/MWh] =	100000	[kWh]	1 MWh = 1000 kWh
Hydrogen	100000 [kWh] / 50 [kWh/kg] =	2000	[kg/h]	50 [kWh/kg H2]
MED Parameters	**Calculations**	**Value**	**Unit**	**Remark**
Hydrogen Water	2000 [kg/h] * 10 [L/kg] =	20000	[L/h]	10 [L/kg H2]
Hydrogen Water	20000 [L/h] / 1000 =	20	[m3/h]	1 m3 = 1000 L
Hydrogen Water	20.000 [m3/h] * 24 [h] =	480	[m3/day]	24 hours in a day
Cooling Water	2000 [kg] * 50 [L/kg] =	100000	[L/h]	50 [L/kg H2]
Cooling Water	100000 [L/h] / 1000 =	100	[m3/h]	1 m3 = 1000 L
Cooling Water	100 [m3/h] * 24 [h] =	2400	[m3/day]	24 hours in a day

2. The calculations for two 12,000 m³ MED units for the company AVR indicate that the MED plant could support an electrolyser capacity of 5 GW. The calculations are shown below.

$MED\ Water\ Capacity\ [m^3/day]\ =\ 12.000\ [m^3]\ *\ 2\ =\ 24.000\ [m^3]$
$MED\ Water\ Capacity\ [m^3/h]\ =\ 24.000\ [m^3/day]\ /\ 24\ [h/day]\ =\ 1000\ [m^3/h]$
$MED\ Water\ Capacity\ [L/h]\ =\ 1000\ [m^3/h]\ *\ 1000\ =\ 1.000.000\ [L/h]$
$Hydrogen\ production\ [kg\ H2]\ =\ 1.000.000\ [L/h]\ /\ 10\ [L/kg\ H2]\ =\ 100.000\ kg\ H2$
$Energy\ Need\ [kWh]\ =\ 100.000\ kg\ H2\ *\ 50\ kWh\ =\ 5.000.000\ kWh$
$Energy\ Need\ [GW]\ 5.000.000\ kWh\ /\ 1000.000\ =\ 5\ GW$

3. The table below shows the scale of the MED unit to support an AWE of 100 MW

Table Appendix 7 : AWE and MED parameters

AWE Parameters	**Calculations**	**Value**	**Unit**	**Remark**
Electrolyser		100	[MWh]	HyNetherlands Project
Electrolyser	100 [MWh] * 1000 [kWh/MWh] =	100000	[kWh]	1 MWh = 1000 kWh
Hydrogen	100000 [kWh] / 50 [kWh/kg] =	1818,181818	[kg/h]	55 [kWh/kg H2]
MED Parameters	**Calculations**	**Value**	**Unit**	**Remark**

Hydrogen Water	2000 [kg/h] * 10 [L/kg] =	18181,81818	[L/h]	10 [L/kg H2]
Hydrogen Water	20000 [L/h] / 1000 =	18,18181818	[m3/h]	1 m3 = 1000 L
Hydrogen Water	20.000 [m3/h] * 24 [h] =	436,3636364	[m3/day]	24 hours in a day
Cooling Water	2000 [kg] * 50 [L/kg] =	90909,09091	[L/h]	50 [L/kg H2]
Cooling Water	100000 [L/h] / 1000 =	90,90909091	[m3/h]	1 m3 = 1000 L
Cooling Water	100 [m3/h] * 24 [h] =	2181,818182	[m3/day]	24 hours in a day

H. Chapter 4 : Steam Calculations

1. $GOR = \frac{M_{distillate}}{M_{steam}}$

   $GOR = 8,13$

   $M_{distillate}\ [kg/day] = 1000\ m^3/day\ *\ 1000\ [kg/m^3] = 1.000.000\ [kg/day]$

   $M_{steam}\ [kg/day] = 1.000.000\ [kg/day]\ /\ 8,13 = 123.001,23\ [kg/day]$

2. $Q\ [kJ/day] = m\ [kg]\ *\ L_v\ [kJ/kg] = 2.333.100.000\ [kJ/day]$

   $m\ seawater\ [kg/day] = 1.000.000\ [kg/day]$

   $L_v\ [kJ/kg] = 2333,1\ [kJ/kg]$

   $Required\ Heat\ Input = \frac{Q}{GOR} = \frac{2.333.100.000}{8,13} = 286.974.170\ [kJ]$

   $Q\ [MWh/day] = 286.974.170\ [kJ]\ /\ 3.600.000\ [kj/MWh] = 79,72\ MWh/day$

You can then compare the cost to the cost of heating the water of an E-boiler with natural gas. The E-boiler has a capacity of 3 MWe (Product Specialist, 2025). These costs are calculated in the literature review in chapter 6.

I. Chapter 6 : MED CAPEX and OPEX Calculations

I. MED : CAPEX Calculations

1. $Cmed\ [€/m^3/day] = 3054D^{-0.0249} = 2.571,40$
   D = 1000 m^3/day

2. $Cmed\ [€/m^3/day] = 6291D^{-0.135}[(1 - fHEX) + fHEX\ (\frac{HEX\ area}{HEX\ area,ref})^{0.8}] = 2.475,82$
   D = 1000 m^3/day
   $fHEX$ = 0,4
   HEX area = 8841,0 m^2
   HEX area,ref = 8841,0 m^2
   Ts = 70 °C

3. $Cmed\ [€/m^3/day] = 6291D^{-0.135}[(1 - fHEX(\frac{N}{Nref})^{1.277}(\frac{Ts,ref}{Ts})^{1.048}] = 1.485,49$
   D = 1000 m^3/day
   $fHEX$ = 0,4
   N = 8
   N, ref = 8
   Ts,ref = 70 °C
   Ts = 70 °C

II. MED : Land Calculations

1. $Cland\ MED\ [€] = (MMF\ [m^2] + MED\ [m^2] + AWE\ [m^2]) * Land\ Price\ [EUR/m^2] = 3.274.629$

2. $MMF\ [€] = MMF\ [m^2] * Land\ Price\ [EUR/m^2] = 13.272$
   $MMF\ [m^2]$ = 168
   $Land\ Price\ [EUR/m^2]$ = 79

3. $MED\ [€] = MED\ [m^2] * Land\ Price\ [EUR/m^2] = 26.070$
   $MED\ [m^2] = 330$
   $Land\ Price\ [EUR/m^2] = 79$

4. $AWE\ [€] = AWE\ [m^2] * Land\ Price\ [EUR/m^2] = 3.235.287$
   $AWE\ [m^2] = 187\ [m] * 219\ [m] = 40.953$
   $Land\ Price\ [EUR/m^2] = 79$

5. $Cland\ MED\ [€/yr] = P * \frac{r * (1+r)^n}{(1+r)^n - 1} = 151.285,71$
   P [€] = 3.274.629
   R = 2,25%
   n = 30

III. MED : Equipment Calculations

1. $Cequipment\ MED\ [€]\ =\ 5.500.000$

2. $CEquipment\ MED\ [€/yr]\ =\ P\ *\ \frac{r*(1+r)^{n}}{(1+r)^{n}-1}\ =\ 436.086,89$

   P [€] = $5.500.000$
   R = 2,25%
   n = 15

IV. MED : Buildings Calculations

1. $Cbuilding\ MED\ [€]\ =\ 0$

2. $Cbuilding\ MED\ [€/yr]\ =\ P\ *\ \frac{r*(1+r)^{n}}{(1+r)^{n}-1}\ =\ 0$

   P [€] = 0
   R = 2,25%
   n = 30

V. MED : Indirect Capital Calculations

1. $Ccapex\ =\ Ccapex, d\ +\ Ccapex, ind$

2. $Cindirect\ costs\ MED\ [€]\ =\ 10\%\ *\ (Cequipment\ +\ Cbuilding)\ =\ 550.000$

   $Cequipment\ [€]\ =\ 5.500.000$
   $Cbuilding\ [€]\ =\ 0$

3. $Cindirect\ costs\ MED\ [€/yr]\ =\ P\ *\ \frac{r*(1+r)^{n}}{(1+r)^{n}-1}$ = 25.409,64

   P [€] = 550.000
   R = 2,25%
   n = 30

VI. MED : Spare Parts Calculations

1. $Cspare\ parts\ MED\ [€]\ =\ 3\%\ *\ (Cland\ +\ Cequipment\ +\ Cbuilding)\ =\ 222.204,11$
   $Cland\ [€]\ =\ 3.244.403,60$
   $Cequipment\ [€]\ =\ 3.784.000$
   $Cbuilding\ [€]\ =\ 0$

   The land costs are included, because for the spare parts the geographic location is important and part of the CAPEX.

VII. MED : Fuel Calculations

1. $CSteam\ Fuel\ MED\ =\ 3,15\ [€/m^3]$
$Households\ pay\ a\ maximum\ of\ \ 43,79\ €/GJ\ of\ heat$
$1\ [kW]\ =\ 0,0036\ [GJ]$
$To\ produce\ one\ m^3\ of\ water,\ 20\ kW\ is\ required$
$0,0036\ [GJ/kW]\ *\ 20\ [kW/m^3]\ =\ 0,072\ [GJ/m^3]$
$0,072\ [GJ/m^3]\ *\ 43,79\ [€/GJ]\ =\ 3,15\ [€/m^3]$

2. $Steam\ Costs\ [€/m^3/day]\ =\ Water\ Capacity\ [m^3/day]\ *\ Steam\ Costs\ [€/m^3]$
$Steam\ Costs\ [€/m^3/day]\ =\ 3333\ *\ 3,15\ =\ 10.498,95$

3. $Csteam\ [€/yr]\ =\ 3,15\ [€/m^3]\ *\ 3333\ [m^3/day]\ *\ 365\ =\ €3.832.117$

This steam price per year is way too high. This is because a consumer price is taken for district heating.

4. $GOR\ =\ \frac{M_{distillate}}{M_{steam}}$
$GOR\ =\ 8,13$
$M_{distillate}\ [kg/day]\ =\ 1000\ m^3/day\ *\ 1000\ [kg/m^3]\ =\ 1.000.000\ [kg/day]$
$M_{steam}\ [kg/day]\ =\ 1.000.000\ [kg/day]\ /\ 8,13\ =\ 123.001,23\ [kg/day]$

5. $Q\ [kJ/day]\ =\ m\ [kg]\ *\ L_v\ [kJ/kg]\ =\ 2.333.100.000\ [kJ/day]$
$m\ water\ [kg/day]\ =\ 1.000.000\ [kg/day]$
$L_v\ [kJ/kg]\ =\ 2333,1\ [kJ/kg]$

$Required\ Heat\ Input\ =\frac{Q}{GOR}\ =\ \frac{2.333.100.000}{8,13}\ =\ 286.974.170\ [kJ]$

$Q\ [MWh/day]\ =\ 286.974.170\ [kJ]\ /\ 3.600.000\ [kj/MWh]\ =\ 79,72\ MWh/day$

You can then compare the cost to the cost of heating the water of an E-boiler with natural gas. The E-boiler has a capacity of 3 MWe (Product Specialist, 2025).

6. $Csteam\ [€/yr]\ =\ Cgas\ [€/yr]\ =\ 1.971.000$
$Cgas\ [€/yr]\ =\ gas\ price\ [€/MWh]\ *\ boiler\ electrical\ capacity\ [MWh/day]\ *\ 365\ [days/yr]\ =\ 1.971.000$
$gas\ price\ [€/MWh]\ =\ 100\ [€/MWh]$
$boiler\ electrical\ capacity\ [MWh/day]\ =\ 75\ [\%]\ *\ 3\ [MWh]\ *\ 24\ [hours/day]\ =\ 54$

In this equation the steam price is benchmarked against the cost of natural gas used to power an E-boiler.

VIII. MED : Electricity Calculations

1. $Cel\ tot.\ green\ [€/yr]\ =\ 365\ [day/yr]\ *\ f\ *\ Dt,Design\ [m^3/day]\ *\ NPPC\ [kWh/m^3]\ *\ EUP\ [€/kWh]\ =\ 41.610$
Operational days $[day/yr]$ = 365
f = 95%
$Dt,Design\ [m^3/day]$= 1000

$NPPC\ [kWh/m^3] = 2$
$EUP\ [€/kWh] = 0,06$

2. $Cel\ tot\ grey\ [€/yr] = 365\ [day/yr] * f * Dt, Design\ [m^3/day] * NPPC\ [kWh/m^3] * EUP\ [€/kWh] = 265.610,50$
Operational days $[day/yr]$ = 365
f = 95%
$Dt, Design\ [m^3/day]$= 1000
$NPPC\ [kWh/m^3] = 2$
$EUP\ [€/kWh] = 0,383$

3. $Cel\ green\ [€/yr] = 146\ [day/yr] * f * Dt, Design\ [m^3/day] * NPPC\ [kWh/m^3] * EUP\ [€/kWh] = 16.644$
Operational days $[day/yr]$ = 365 * 0,40 = 146
f = 95%
$Dt, Design\ [m^3/day]$= 1000
$NPPC\ [kWh/m^3] = 2$
$EUP\ [€/kWh] = 0,06$

4. $Cel\ grey\ [€/yr] = 219\ [day/yr] * f * Dt, Design\ [m^3/day] * NPPC\ [kWh/m^3] * EUP\ [€/kWh] = 159.366,30$
Operational days $[day/yr]$ = 365 * 0,60 = 219
f = 95%
$Dt, Design\ [m^3/day]$= 1000
$NPPC\ [kWh/m^3] = 2$
$EUP\ [€/kWh] = 0,383$

5. $Cel\ green\ \&\ grey\ [€/yr] = Cel\ green\ [€/yr] + Cel\ grey\ [€/yr] = 176.010,30$

IX. MED : Labour Calculations

1. $Clabour\ MED\ [€/yr] = 100.000\ [€/yr]$

X. MED : Chemical Calculations

1. $Chemical\ Costs\ MED\ [€/yr] = 0,031\ [€/m^3] * Water\ Capacity\ [m^3/day] * 365\ [days/yr] = 37.712,895$
$Water\ Capacity\ [m^3/day]$ = 3333

XI. MED : Indirect Operational Calculations

1. $Cindirect\ cost\ MED\ [€] = 1,5\% * CAPEX\ [€] = 82.500$
$CAPEX\ [€] = Cequipment\ [€] + Cbuilding\ [€]$
$Cequipment\ [€] = 5.500.000$
$Cbuilding\ [€] = 0$

XII. LCOW Benefits

1. $LCOW\ MED\ [€/yr]\ =\ 365\ [day/yr]\ *\ Demineralised\ \ Production\ [m^3/day]\ *\ WMP\ [€/kg]\ =\ 1.825.000$
   $Demineralised\ \ Production\ [m^3/day]\ =\ 1.000$
   $WMP\ [€/m^3]\ =\ 5,00$

2. $LCOW\ MED\ [€/yr]\ =\ 365\ [day/yr]\ *\ Demineralised\ \ Production\ [m^3/day]\ *\ WMP\ [€/kg]\ =\ 3.650.000$
   $Demineralised\ \ Production\ [m^3/day]\ =\ 1000$
   $WMP\ [€/m^3]\ =\ 10,00$

J. Chapter 7 : NF CAPEX and OPEX Calculations

I. NF : Land Calculations

1. $Cland\ NF\ [€]\ =\ (NF\ [m^2])\ *\ Land\ Price\ [EUR/m^2]\ \ =\ 12.245$
   $NF\ [m^2]\ =\ 155$
   $Land\ Price\ [EUR/m^2\ ]$ = 79

2. $Cland\ NF\ [€/yr]\ =\ P\ *\ \frac{r*(1+r)^n}{(1+r)^n-1}\ =\ 565,71$
   P [€] = 12.245
   R = 2,25%
   n = 30

II. NF : Equipment Calculations

1. $Cmech\ NF\ [€]\ =\ 4329,6\ *Qfeed^{0,85}\ [m^3/h]\ +\ 1089,6\ *\ n\ =\ 605.289,24$
   $Qfeed\ \ [m^3/h]\ =\ 4761,43\ [m^3/day]\ /\ 24\ [h/day]\ =\ 198.39$
   $n\ =\ 199$

2. $Celectro\ NF\ [€]\ =\ 1.68\ *10^6\ +\ 64,8\ *\ Pfeed\ [bar]\ *\ Qfeed\ [m^3/h]\ =\ 2.194.226,88$
   $Pfeed\ \ [bar]\ =\ 40$
   $Qfeed\ \ [m^3/h]\ =\ 4761,43\ [m^3/day]\ /\ 24\ [h/day]\ =\ 198,39$

3. $Cmembrane\ [€]\ =\ Membrane\ Costs\ [€]\ *\ n\ =\ 238.800$
   $Membrane\ Costs$ [€] = 1.200
   $n\ =\ 199$

4. $Cmech\ NF\ [€/yr]\ =\ P\ *\ \frac{r*(1+r)^n}{(1+r)^n-1}\ =\ 47.992,49$
   P [€] = 605.289,24
   R = 2,25%
   n = 15

5. $Celectro\ NF\ [€/yr]\ =\ P\ *\ \frac{r*(1+r)^n}{(1+r)^n-1}\ =\ 173.977,01$
   P [€] = 2.194.226,88
   R = 2,25%
   n = 15

6. $Cmembrane\ [€/yr]\ =\ P\ *\ \frac{r*(1+r)^n}{(1+r)^n-1}\ =\ 51.031,61$
   P [€] = 238.800
   R = 2,25%
   n = 5

III. NF : Building Calculations

1. $Ccivil\ NF\ [€]\ =\ 1034,4\ *\ Qfeed\ [m^3/h]\ +\ 1487\ *\ n\ =\ 501.130,63$

   $Qfeed\ [m^3/h]\ =\ 4761,43\ [m^3/day]\ /\ 24\ [h/day]\ =\ 198,39$

   $n\ =\ 199$

2. $Ccivil\ NF\ [€/yr]\ =\ P\ *\ \frac{r * (1+r)^n}{(1+r)^n - 1}\ =\ 23.151,91$

   P [€] = $501.130,63$

   R = 2,25%

   n = 30

IV. NF : Indirect Capital Calculations

1. $Cindirect\ costs\ NF\ [€]\ =\ 10\%\ *\ (Ccivil\ +\ Cmech\ +\ Celectro\ +\ Cmembrane)$= 353.944,68

   $Ccivil\ NF\ [€]\ =\ 501.130,63$

   $Cmech\ NF\ [€]\ =\ 605.289,24$

   $Celectro\ NF\ [€]\ =\ 2.194.226,88$

   $Cmembrane\ [€]\ =\ 238.800$

2. $Cindirect\ costs\ NF\ [€/yr]\ =\ P\ *\ \frac{r * (1+r)^n}{(1+r)^n - 1}\ =\ 16.352,01$

   P [€] = $353.944,68$

   R = 2,25%

   n = 30

V. NF : Spare Parts Calculations

1. $Cspare\ parts\ NF[€]\ =\ 5\%\ *\ (C\ land\ +\ Ccivil\ +\ Cmech\ +\ Celectro\ +\ Cmembrane)\ =\ 177.442,51$

   The land costs are included, because for the spare parts the geographic location is important and part of the CAPEX.

VI. NF : Fuel Calculations

1. $CSeawater\ NF\ [€/yr]\ =\ 0$

VII. NF : Electricity Calculations

1. $Cel\ tot.green\ [€/yr]\ =\ Electricity\ \ Price\ \ [€/kWh]\ *\ Pcons\ [kW]\ *\ Operational\ Hours\ [h/yr]\ =\ 190.454,4$

   $Electricity\ \ Price\ \ [€/kWh]$ = 0,06

   $Pcons\ [kW]\ =\ 2\ [kWh/\ m^3]\ *\ 198,39\ [m^3/h]\ =\ 396,78$

   $Operational\ Hours\ \ [h/yr]$ = 8000

2. $Cel\ tot.grey\ [€/yr] = Electricity\ \ Price\ [€/kWh] * Pcons\ [kW] * Operational\ Hours\ [h/yr] = 1.215.733,$
   $Electricity\ \ Price\ [€/kWh]$ = 0,383
   $Pcons\ [kW] = 2\ [kWh/\ m^3] * 198,39\ [m^3/h] = 396,78$
   $Operational\ Hours\ \ [h/yr]$ = 8000

3. $Cel\ green\ [€/yr] = Electricity\ \ Price\ [€/kWh] * Pcons\ [kW] * Operational\ Hours\ [h/yr] = 83.419,03$
   $Electricity\ \ Price\ [€/kWh]$ = 0,06
   $Pcons\ [kW] = 2\ [kWh/\ m^3] * 198,39\ [m^3/h] = 396,78$
   $Operational\ Hours\ \ [h/yr]$ = 9,6 * 365 = 3.504

4. $Cel\ \ grey\ [€/yr] = Electricity\ \ Price\ [€/kWh] * Pcons\ [kW] * Operational\ Hours\ [h/yr] = 683.242,46$
   $Electricity\ \ Price\ [€/kWh]$ = 0,383
   $Pcons\ [kW] = 2\ [kWh/\ m^3] * 198,39\ [m^3/h] = 396,78$
   $Operational\ Hours\ \ [h/yr]$ = 8000 -3504 = 4.496

5. $Mixed\ Energy\ Price\ [€/yr] = Cel\ \ grey\ [€/yr] + Cel\ green\ [€/yr] = 766.661,49$

The second below determines the electricity costs in more detail by applying the electrical power conversion efficiency, the number of Cleaning-In-Place (CIP) and the hours per CIP (Zhou et al., 2023). The included table Appendix 8 shows the meaning behind the parameters of the equation.

$$Cel\ [€/yr] = \frac{Cfe}{n} * Pf_{avg} * Qf * (t_0 - N_{CIP} * t_{CIP})$$

Table Appendix 8 : NF Electricity Parameters (Zhou et al., 2023)

Parameter	Meaning	Unit	Parameter	Resource
Cfe	Unit Costs of Electrical Energy	[€ /kWh]	0,06	(De Vries, 2023)
n	Electrical Power Conversion Efficiency	-		
Pf_{avg}	Average Applied Pressure	[bar]	30-40	(Figueira et al., 2023; Membrane Scientist, 2025)
Qf	Flow Rate	$[m^3/yr]$	1.216.545	-
t_0	Operational Time	[h/yr]	8000	(Figueira et al., 2023)
N_{CIP}	Number of CIP	-	2 * 52 = 104	(Membrane Scientist, 2025; Process Advisor, 2025)
t_{CIP}	Duration of each CIP	[h/yr]	104 * 2 = 208	(Membrane Scientist, 2025; Process Advisor, 2025)

VIII. NF : Labour Calculations

1. $Clabour\ NF\ [€/yr] = 100.000\ [€/yr]$

IX. NF : Chemical Calculations

1. $Cchemicals\ NF\ [€/yr]\ =\ Cchem, nf\ [€/m^3]\ *\ Vpermeate\ [m^3/h]\ *\ Noper, hours\ [h/yr]\ =\ 57.772$
   $Cchem, nf\ [€/m^3]\ =\ 0,052$
   $Vpermeate\ [m^3/h]\ =\ 3333\ [m^3/day]\ /\ 24\ [h/day]\ =\ 138,88$
   $Noper, hours\ [h/yr]\ =\ 8000$

X. NF : Indirect Operational Calculations

1. $Cindirect\ Costs\ NF\ [€/yr]\ =\ 2\%\ *\ (Ccivil\ +\ Cmech\ +\ Celectro\ +\ Cmembrane)\ [€]\ =\ 77.867,83$
   $CAPEX\ NF\ [€]\ =\ (Ccivil\ +\ Cmech\ +\ Celectro\ +\ Cmembrane)\ [€]$
   $CAPEX\ NF$ [€] = 3.893.391,43

K. Chapter 8: NF-MED : CAPEX and OPEX Calculations

I. NF-MED : Land Calculations

1. $Cland\ NF\ MED\ [€] = (MMF\ [m^2] + NF\ [m^2] + MED\ [m^2] + AWE\ [m^2]) * Land\ Price\ [€/m^2] = 3.290.034$
   $MMF\ [m^2] = 208$
   $NF\ [m^2] = 155$
   $MED\ [m^2] = 330$
   $AWE\ [m^2] = 40.953$
   $Land\ Price\ [€/m^2] = 79$

2. $Cland\ NF\ MED\ [€/yr] = P * \frac{r*(1+r)^n}{(1+r)^n-1} = 151.997,41$
   P [€] = 3.290.034
   R = 2,25%
   n = 30

II. NF-MED : Equipment Calculations

1. $Cequipment\ NF\ MED = Cmech\ [€] + Celectro\ [€] + Cmembrane\ [€] + Cequipment\ MED\ [€] = 8.538.316,12$

2. $Cmech\ NF\ [€] = 4329,6 * Qfeed^{0,85}\ [m^3/h] + 1089,6 * n = 605.289,24$
   $Qfeed\ [m^3/h] = 4761,43\ [m^3/day]\ /\ 24\ [h/day] = 198.39$
   $n = 199$

3. $Celectro\ NF\ [€] = 1.68 * 10^6 + 64,8 * Pfeed\ [bar] * Qfeed\ [m^3/h] = 2.194.226,88$
   $Pfeed\ [bar] = 40$
   $Qfeed\ [m^3/h] = 4761,43\ [m^3/day]\ /\ 24\ [h/day] = 198,39$

4. $Cmembrane\ NF\ [€] = Membrane\ Costs\ [€] * n = 238.800$
   $Membrane\ Costs$ [€] = 1.200
   $n = 199$

5. $Cequipment\ MED\ [€] = 5.500.000$

6. $Cmech\ NF\ [€/yr] = P * \frac{r*(1+r)^n}{(1+r)^n-1} = 47.992,49$
   P [€] = 605.289,24
   R = 2,25%
   n = 15

7. $Celectro\ NF\ [€/yr] = P * \frac{r*(1+r)^n}{(1+r)^n-1} = 173.977,01$
   P [€] = 2.194.226,88
   R = 2,25%
   n = 15

8. $Cmembrane\ [€/yr] = P * \frac{r*(1+r)^n}{(1+r)^n-1} = 51.031,61$
   P [€] = 238.800
   R = 2,25%

n = 5

9. $Cequipment\ MED\ [€/yr]\ =\ P\ *\ \frac{r*(1+r)^n}{(1+r)^n-1}\ =\ 436.086,89$

P [€] = 5.500.000
R = 2,25%
n = 15

III. NF-MED : Building Calculations

1. $Ccivil\ NFMED[€]\ =\ Ccivil\ NF\ [€]\ +\ Cbuilding\ MED\ [€]\ =\ 501.130,63$

2. $Ccivil\ NF\ [€]\ =\ 1034,4\ *\ Qfeed\ [m^3/h]\ +\ 1487\ *\ n\ =\ 501.130,63$

$Qfeed\ [m^3/h]\ =\ 4761,43\ [m^3/day]\ /\ 24\ [h/day]\ =\ 198,39$

$n\ =\ 199$

3. $Cbuilding\ MED\ [€]\ =\ 0$

4. $Cequipment\ MED\ [€/yr]\ =\ P\ *\ \frac{r*(1+r)^n}{(1+r)^n-1}\ =\ 23.151,91$

P [€] = 501.130,63
R = 2,25%
n = 30

IV. NF-MED : Indirect Calculations

1. $Cindirect\ costs\ [€]\ =\ 10\%\ *\ (Cequipment\ +\ Cbuilding\ +\ Ccivil\ NF\ +\ Cmech\ NF\ +\ Celectro\ NF\ +\ Cmembrane)\ =\ 903.944,68$

$Cequipment\ MED\ [€]\ =\ 5.500.000$
$Cbuilding\ [€]\ =0$
$Ccivil\ NF\ [€]\ =\ 501.130,63$
$Cmech\ NF\ [€]\ =\ 605.289,24$
$Celectro\ NF\ [€]\ =\ 2.194.226,88$
$Cmembrane\ [€]\ =\ 238.800$

2. $Cindirect\ costs\ [€/yr]\ =\ P\ *\ \frac{r*(1+r)^n}{(1+r)^n-1}\ =\ 41.761,65$

P [€] = 903.944,68
R = 2,25%
n = 30

V. NF-MED : Spare Parts Calculations

1. $Cspare\ parts\ [€]\ =\ 6\%\ *\ (CAPEX\ NF\ MED\ [€])\ =\ 739.768,85$

$CAPEX\ NFMED\ [€]\ =\ (Cland\ +\ Cequipment\ +\ Cbuilding\ +\ Ccivil\ NF\ +\ Cmech\ NF\ +\ Celectro\ NF\ +\ Ccmembrane)$
$Cland\ NF\ MED\ [€]\ =\ 3.290.034$
$Cequipment\ MED\ =\ 5.500.000$
$Cbuilding\ [€]\ =0$
$Ccivil\ NF[€]\ =\ 501.130,63$
$Cmech\ [€]\ =\ 605.289,24$

$Celectro$ [€] $= 2.194.226,88$
$Cmembrane$ [€] $= 238.800$
CAPEX NF-MED [€] = 12.329.480,75

The land costs are included, because for the spare parts the geographic location is important and part of the CAPEX.

VI. NF-MED : Fuel Calculations

1. $CSeawater\ [€/yr] = 0$

2. $AWE\ Waste\ Heat\ Costs\ [€/m^3/day] = Water\ Capacity\ [m^3/day] * Waste\ Heat\ Costs\ [€/m^3] = 0$
$Water\ Capacity\ [m^3/day] = 0$
$Waste\ Heat\ Costs\ [€/m^3] = 0$

The NF-MED has a recovery rate of 75%, so 2500 m^3 distillate water is produced. The steam at 70°C has a GOR of 8,13.

3. $GOR = \frac{M_{distillate}}{M_{steam}}$
GOR = 8,13
$M_{distillate} = 2500\ [m^3/day] = 2.500.000\ [kg/day]$
$M_{steam} = 2.500.000\ [kg]\ /\ 8,13 = 307.503,075\ [kg/day]$

4. $Q\ [kJ/day] = m\ [kg/day] * L_v\ [kJ/kg] = 5.832.750.000\ [kJ/day]$
$m\ water\ [kg/day] = 2.500.000\ [kg/day]$
$L_v\ [kJ/kg] = 2333,1\ [kJ/kg]$

$Required\ Heat\ Input = \frac{Q}{GOR} = \frac{5.832.750.000}{8,13} = 717.435.424,40\ [kJ/day]$

$Q\ [MWh/day] = 717.435.424,40\ [kJ/day]\ /\ 3.600.000\ [kJ/MWh] = 199,29\ [MWh/day]$

5. $Csteam\ [€/yr] = Cgas\ [€/yr] = 6.641.9993.358$
$Cgas\ [€/yr] = gas\ price\ [€/MWh] * boiler\ electrical\ capacity\ [MWh/day] * 333,333 = 6.641.9993.358$
$gas\ price\ [€/MWh] = 100\ [€/MWh]$
$boiler\ electrical\ capacity\ [MWh/day] = 75\ [\%] * 11,07\ [MWe] * 24\ [hours/day] = 199,29$
8000 [operational hours] = 333,333 [days]

The NF-MED has a recovery rate of 75%, so 2500 m^3 distillate water is produced. The steam can increase to 125°C and has a GOR of 16. This shows that 50% of the steam is needed when the temperature rises.

6. $GOR = \frac{M_{distillate}}{M_{steam}}$
GOR = 16
$M_{distillate} = 2500\ [m^3/day] = 2.500.000\ [kg/day]$
$M_{steam} = 2.500.000\ [kg]\ /\ 16 = 156.250\ [kg/day]$

7. $Q\ [kJ] = m\ [kg] * L_v\ [kJ/kg] = 5.832.750.000\ [kJ/day]$
$m\ water\ [kg/day] = 2.500.000\ [kg/day]$
$L_v\ [kJ/kg] = 2333,1\ [kJ/kg]$

$Required\ Heat\ Input = \frac{Q}{GOR} = \frac{5.832.750.000}{16} = 364.546.875\ [kJ/day]$

$Q\ [MWh/day] = 364.546.875\ [kJ/day]\ /\ 3.600.000\ [kJ/MWh] = 101,26\ [MWh/day]$

8. $Csteam\ [€/yr] = Cgas\ [€/yr] = 3.375.329,96$
   $Cgas\ [€/yr] = gas\ price\ [€/MWh] * boiler\ electrical\ capacity\ [MWh/day] * 333,333 = 3.375.329,958$
   $gas\ price\ [€/MWh] = 100\ [€/MWh]$
   $boiler\ electrical\ capacity\ [MWh/day] = 75\ [\%] * 5,63\ [MWe] * 24\ [hours/day] = 101,26$
   8000 [operational hours] = 333,333 [days]

VII. NF-MED : Electricity Calculations

1. $Celec\ mixed\ NF\ MED\ [€/yr] = Mixed\ NF\ Energy\ Price\ [€/yr] + Mixed\ MED\ Energy\ Price\ [€/yr] = 1.168.507,47$

2. $Celec\ mixed\ NF\ [€/yr] = Cel\ grey\ [€/yr] + Cel\ green\ [€/yr] = 766.661,49$

3. $Celec\ mixed\ MED\ [€/yr] = Cel\ green\ [€/yr] + Cel\ grey\ [€/yr] = 401.845,98$

Wind energy is only 9,6 hours of wind which is 40% of the day.
NF-MED has 8000 operational hours, which is 333,33 days out of 365 days.

$Cel\ green\ MED\ [€/yr] = 133,33[day/yr] * f * Dt, Design\ [m^3/day] * NPPC\ [kWh/m^3] * EUP\ [€/kWh] = 37.999,62$
   Operational days $[day/yr]$ = 333,33 * 0,40 = 133,33
   f = 95%
   $Dt, Design\ [m^3/day]$= 2500
   $NPPC\ [kWh/m^3] = 2$
   $EUP\ [€/kWh] = 0,06$

$Cel\ grey\ MED\ [€/yr] = 200\ [day/yr] * f * Dt, Design\ [m^3/day] * NPPC\ [kWh/m^3] * EUP\ [€/kWh] = 363.846,36$
   Operational days $[day/yr]$ = 333,33 * 0,60 = 200
   f = 95%
   $Dt, Design\ [m^3/day]$= 2500
   $NPPC\ [kWh/m^3] = 2$
   $EUP\ [€/kWh] = 0,383$

$Cel\ green\ \&\ grey\ MED\ [€/yr] = Cel\ green\ [€/yr] + Cel\ grey\ [€/yr] = 401.845,98$

VIII. NF-MED : Labour Calculations

1. $Clabour\ NF\ MED\ [€/yr] = 100.000\ [€/yr]$

IX. NF-MED : Chemical Calculations

1. $Cchemical\ NF\ MED\ [€/yr] = Cchemicals\ NF\ [€/yr] + Cchemical\ MED[€/yr] = 92.214,24$
2. $Cchemicals\ NF\ [€/yr] = Cchem, nf\ [€/m^3] * Vpermeate\ [m^3/h] * Noper, hours\ [h/yr] = 57.772$
   $Cchem, nf\ [€/m^3] = 0,052$
   $Vpermeate\ [m^3/h] = 3333\ [m^3/day]\ /\ 24\ [h/day] = 138,88$
   $Noper, hours\ [h/yr] = 8000$

3. $Cchemical\ MED\ [€/yr]\ =\ 0,031\ [€/m^3]\ *\ Water\ Capacity\ [m^3/h]\ *\ Noper, hours\ [h/yr]\ =\ 34.442,24$
$Vpermeate\ [m^3/h]\ =\ 3333\ [m^3/day]\ /\ 24\ [h/day]\ =\ 138,88$
$Noper, hours\ [h/yr]\ =\ 8000$

X. NF-MED : Indirect Operational Calculations

XI. $Cindirect\ Costs\ NF\ MED\ [€/yr]\ =\ 2\%\ *\ CAPEX\ NF\ MED\ [€]\ =\ 180.788,94$
$CAPEX\ NF\ MED\ [€]\ =\ Cequipment\ +\ Cbuilding\ +\ Ccivil\ NF\ +\ Cmech\ NF\ +\ Celectro\ NF\ +\ Ccmembrane$
$Cequipment\ MED\ =\ 5.500.000$
$Cbuilding\ [€]\ =0$
$Ccivil\ NF[€]\ =\ 501.130,63$
$Cmech\ [€]\ =\ 605.289,24$
$Celectro\ [€]\ =\ 2.194.226,88$
$Cmembrane\ [€]\ =\ 238.800$
$CAPEX\ NF\ MED$ [€] = 9.039.446,75

XII. NF-MED : LCOW Calculations

1. $LCOW\ NF\ MED\ [€/yr]\ =\ Operational\ days\ [day/yr]\ *\ Demineralised\ Production\ [m^3/day]\ *\ WMP\ [€/kg]$
$LCOW\ NF\ MED\ [€/yr]\ =\ 8.333.333,33$
$Operational\ days\ [days/yr]\ =\ 8.000\ [hours/yr]\ /\ 24\ [hours/day]\ =\ 333,333$
$Demineralised\ Production\ [m^3/day]\ =\ 2500$
$WMP\ [€/m^3]\ =\ 10,00$

2. $LCOW\ NF\ MED\ [€/yr]\ =\ Operational\ days\ [day/yr]\ *\ Demineralised\ Production\ [m^3/day]\ *\ WMP\ [€/kg]$
$LCOW\ NF\ MED\ [€/yr]\ =\ 4.166.666,67$
$Operational\ days\ [days/yr]\ =\ 8.000\ [hours/yr]\ /\ 24\ [hours/day]\ =\ 333,333$
$Demineralised\ Production\ [m^3/day]\ =\ 2500$
$WMP\ [€/m^3]\ =\ 5,00$

L. Chapter 9 : MED CBA

I. *MED Land NPV = 3.274.629* [€]

II. $MED\ Equipment\ NPV\ =\ 5.500.000\ [€]\ +\ \frac{5.500.000}{(1+0,0225)^{15}}\ =\ 5.550.000\ +\ 3.939.244,52\ =\ 9.439.244,52\ [€]$

III. *MED Building NPV = 0* [€]

IV. *MED Indirect Capital NPV = 550.000* [€]

V. $MED\ Spare\ Parts\ NPV\ =\ \sum_{t=1}^{t}\frac{C}{(1+r)^{t}}\ =\ \sum_{t=1}^{30}\frac{222.204,11}{(1+0,0225)^{30}}\ =\ 4.809.681,25\ \ [€]$

VI. $MED\ Seawater\ NPV\ =\ \sum_{t=1}^{t}\frac{C}{(1+r)^{t}}\ =\ \sum_{t=1}^{30}\frac{0}{(1+0,0225)^{30}}\ =\ 0\ \ [€]$

VII. $MED\ Steam\ NPV\ =\ \sum_{t=1}^{t}\frac{C}{(1+r)^{t}}\ =\ \sum_{t=1}^{30}\frac{1.971.000}{(1+0,0225)^{30}}\ =\ 42.662.945,13\ [€]$

VIII. $MED\ Waste\ Heat\ for\ Seawater\ NPV\ =\ \sum_{t=1}^{t}\frac{C}{(1+r)^{t}}\ =\ \sum_{t=1}^{30}\frac{0}{(1+0,0225)^{30}}\ =\ 0\ \ [€]$

IX. $MED\ Electricity\ \ NPV\ =\ \sum_{t=1}^{t}\frac{C}{(1+r)^{t}}\ =\ \sum_{t=1}^{30}\frac{176.010,30}{(1+0,0225)^{30}}\ =\ 3.809.801,00\ [€]$

X. $MED\ Labour\ NPV\ =\ \sum_{t=1}^{t}\frac{C}{(1+r)^{t}}\ =\ \sum_{t=1}^{30}\frac{100.000}{(1+0,0225)^{30}}\ =\ 2.164.532,98\ [€]$

XI. $MED\ Chemicals\ \ NPV\ =\ \sum_{t=1}^{t}\frac{C}{(1+r)^{t}}\ =\ \sum_{t=1}^{30}\frac{37.712,90}{(1+0,0225)^{30}}\ =\ 816.308,16\ [€]$

XII. $MED\ Indirect\ Operational\ NPV\ =\ \sum_{t=1}^{t}\frac{C}{(1+r)^{t}}\ =\ \sum_{t=1}^{30}\frac{82.500}{(1+0,0225)^{30}}\ =\ 1.785.739,71\ [€]$

XIII. $MED\ Ultrapure\ Water\ NPV\ =\ \sum_{t=1}^{t}\frac{C}{(1+r)^{t}}\ =\ \sum_{t=1}^{30}\frac{3.650.000}{(1+0,0225)^{30}}\ =\ 78.789.000,65[€]$

M. Chapter 10 : NF-MED CBA

I. *NF-MED Land NPV = 3.290.034* [€]

II. $MED\ Equipment\ NPV = 8.538.316,12 + \frac{8.538.316,12}{(1+0,0225)^{15}} = 8.538.316,12 + 6.115.366,36 = 14.653.682,48$ [€]

III. $NF\ Equipment\ Mechanical\ NPV = 605.289,24 + \frac{605.289,24}{(1+0,0225)^{15}} = 605.289,24 + 433.524,06 = 1.038.813,30$[€]

IV. $NF\ Equipment\ Electro\ NPV = 2.194.226,88 + \frac{2.194.226,88}{(1+0,0225)^{15}} = 2.194.226,88 + 1.571.562,95 = 3.765.789,83$ [€]

V. $NF\ Equipment\ Membrane\ NPV = 238.800 + \frac{238.800}{(1+0,0225)^{5}} = 1.227.095,69$

VI. $NF\ MED\ Building\ NPV = 501.130,63$ [€]

VII. $MED\ Indirect\ Capital\ NPV = 903.944,68$ [€]

VIII. $MED\ Spare\ Parts\ NPV = \sum_{t=1}^{t} \frac{C}{(1+r)^t} = \sum_{t=1}^{30} \frac{739.768,85}{(1+0,0225)^{30}} = 16.012.540,77$ [€]

IX. $MED\ Seawater\ NPV = \sum_{t=1}^{t} \frac{C}{(1+r)^t} = \sum_{t=1}^{30} \frac{0}{(1+0,0225)^{30}} = 0$ [€]

X. $MED\ Steam\ NPV = \sum_{t=1}^{t} \frac{C}{(1+r)^t} = \sum_{t=1}^{30} \frac{3.375.329,96}{(1+0,0225)^{30}} = 73.060.130,33$[€]

XI. $MED\ Waste\ Heat\ for\ Seawater\ NPV = \sum_{t=1}^{t} \frac{C}{(1+r)^t} = \sum_{t=1}^{30} \frac{0}{(1+0,0225)^{30}} = 0$ [€]

XII. $MED\ Electricity\ NPV = \sum_{t=1}^{t} \frac{C}{(1+r)^t} = \sum_{t=1}^{30} \frac{1.168.507,47}{(1+0,0225)^{30}} = 25.292.729,62$ [€]

XIII. $MED\ Labour\ NPV = \sum_{t=1}^{t} \frac{C}{(1+r)^t} = \sum_{t=1}^{30} \frac{100.000}{(1+0,0225)^{30}} = 2.164.532,98$ [€]

XIV. $MED\ Chemicals\ NPV = \sum_{t=1}^{t} \frac{C}{(1+r)^t} = \sum_{t=1}^{30} \frac{92.214,24}{(1+0,0225)^{30}} = 1.996.007,64$[€]

XV. $MED\ Indirect\ Operational\ NPV = \sum_{t=1}^{t} \frac{C}{(1+r)^t} = \sum_{t=1}^{30} \frac{180.788,94}{(1+0,0225)^{30}} = 3.913.236,24$[€]

XVI. $Ultrapure\ Water\ NPV = \sum_{t=1}^{t} \frac{C}{(1+r)^t} = \sum_{t=1}^{30} \frac{8.333.333}{(1+0,0225)^{30}} = 180.377.741,52$[€]

N. Break-Even Point MLD with Standalone MED

$$CAPEX\ MED = Cland\ NPV + Cequipment\ NPV + Cbuilding\ NPV + Cindirect\ costs\ NPV = 13.263.873,52$$

Table Appendix 9 : Break-Even Point MLD with Standalone MED

Year	Net Cash Flow [€]	Discounted Cash Flow [€]	Cumulative PV [€]
1	3.650.000 - 2.589.381,11 = 1.060.618,89	$\frac{1.060.618,89}{(1+0,0225)^{1}} = 1.037.280,09$	1.037.280,09
2	3.650.000 - 2.589.381,11 = 1.060.618,89	$\frac{1.060.618,89}{(1+0,0225)^{2}} = 1.014.454,85$	2.051.734,94
3	3.650.000 - 2.589.381,11 = 1.060.618,89	$\frac{1.060.618,89}{(1+0,0225)^{3}} = 992.131,89$	3.043.866,83
4	3.650.000 - 2.589.381,11 = 1.060.618,89	$\frac{1.060.618,89}{(1+0,0225)^{4}} = 970.300,13$	4.014.166,96
5	3.650.000 - 2.589.381,11 = 1.060.618,89	$\frac{1.060.618,89}{(1+0,0225)^{5}} = 948.948,79$	4.963.115,75
6	3.650.000 - 2.589.381,11 = 1.060.618,89	$\frac{1.060.618,89}{(1+0,0225)^{6}} = 928.067,27$	5.891.183,02
7	3.650.000 - 2.589.381,11 = 1.060.618,89	$\frac{1.060.618,89}{(1+0,0225)^{7}} = 907.645,25$	6.798.828,27
8	3.650.000 - 2.589.381,11 = 1.060.618,89	$\frac{1.060.618,89}{(1+0,0225)^{8}} = 887.672,62$	7.686.500,89
9	3.650.000 - 2.589.381,11 = 1.060.618,89	$\frac{1.060.618,89}{(1+0,0225)^{9}} = 868.139,48$	8.554.640,37
10	3.650.000 - 2.589.381,11 = 1.060.618,89	$\frac{1.060.618,89}{(1+0,0225)^{10}} = 849.036,17$	9.403.676,54
11	3.650.000 - 2.589.381,11 = 1.060.618,89	$\frac{1.060.618,89}{(1+0,0225)^{11}} = 830.353,22$	10.234.029,76

12	3.650.000 - 2.589.381,11 = 1.060.618,89	$\frac{1.060.618{,}89}{(1+0{,}0225)^{12}} = 812.081,39$	11.046.111,15
13	3.650.000 - 2.589.381,11 = 1.060.618,89	$\frac{1.060.618{,}89}{(1+0{,}0225)^{13}} = 794.211,63$	€11.840.322,78
14	3.650.000 - 2.589.381,11 = 1.060.618,89	$\frac{1.060.618{,}89}{(1+0{,}0225)^{14}} = 776.735,09$	€12.617.057,87
15	3.650.000 - 2.589.381,11 = 1.060.618,89	$\frac{1.060.618{,}89}{(1+0{,}0225)^{15}} = 759.643,12$	€13.376.700,98

O. Break-Even Point MLD with NF-MED

$$CAPEX\ NFMED = Cland\ NPV + Cequipment\ NPV + Cbuilding\ NPV + Cindirect\ costs\ NPV = 25.380.491,61$$

Table Appendix 10 : Break-Even Point MLD with NF-MED

Year	Net Cash Flow [€]	Discounted Cash Flow [€]	Cumulative PV [€]
1	8.333.333,33 - 5.561.332,03 = 2.772.001,30	$\frac{2.772.001,30}{(1+0,0225)^{1}} = 2.711.003,72$	2.711.003,72
2	8.333.333,33 - 5.561.332,03 = 2.772.001,30	$\frac{2.772.001,30}{(1+0,0225)^{2}} = 2.651.348,38$	5.362.352,09
3	8.333.333,33 - 5.561.332,03 = 2.772.001,30	$\frac{2.772.001,30}{(1+0,0225)^{3}} = 2.593.005,75$	7.955.357,84
4	8.333.333,33 - 5.561.332,03 = 2.772.001,30	$\frac{2.772.001,30}{(1+0,0225)^{4}} = 2.535.946,94$	10.491.304,79
5	8.333.333,33 - 5.561.332,03 = 2.772.001,30	$\frac{2.772.001,30}{(1+0,0225)^{5}} = 2.480.143,71$	12.971.448,49
6	8.333.333,33 - 5.561.332,03 = 2.772.001,30	$\frac{2.772.001,30}{(1+0,0225)^{6}} = 2.425.568,42$	15.397.016,91
7	8.333.333,33 - 5.561.332,03 = 2.772.001,30	$\frac{2.772.001,30}{(1+0,0225)^{7}} = 2.372.194,05$	17.769.210,97
8	8.333.333,33 - 5.561.332,03 = 2.772.001,30	$\frac{2.772.001,30}{(1+0,0225)^{8}} = 2.319.994,18$	20.089.205,15
9	8.333.333,33 - 5.561.332,03 = 2.772.001,30	$\frac{2.772.001,30}{(1+0,0225)^{9}} = 2.268.942,97$	22.358.148,12
10	8.333.333,33 - 5.561.332,03 = 2.772.001,30	$\frac{2.772.001,30}{(1+0,0225)^{10}} = 2.219.015,13$	24.577.163,25
11	8.333.333,33 - 5.561.332,03 = 2.772.001,30	$\frac{2.772.001,30}{(1+0,0225)^{11}} = 2.170.185,94$	26.747.349,19

P. DACE Cost and Value Booklet

Table Appendix 11 : Equipment costs MED

MED	Parameter	Low [€]	Medium [€]	High [€]	Resource
Feed Water Pump	Pump Capacity: 138,88 [m^3/h]	8.600	13.900	19.800	(DACE booklet, 2024)
Vacuum Pump	Pump Capacity: 138,88 [m^3/h]	15.000	25.000	35.000	(DACE booklet, 2024)
Heat Source Pump	Temperature : 70°C Pressure : 0,5 [bar]	10.000	17.500	25.000	(DACE booklet, 2024)
Brine Pump	Pump Capacity: 97,21[m^3/h]	6.700	10.700	17.700	(DACE booklet, 2024)
Distillate Pump	Pump Capacity: 41,67 [m^3/h]	4.800	8.600	14.300	(DACE booklet, 2024)
Electrical Motor	Pump Capacity: 138,88 [m^3/h] Pressure : 0,5 [bar]	460	610	765	(DACE booklet, 2024)
Heat Exchanger	8841,0 m^2	1790	2920	3250	(DACE booklet, 2024)

Table Appendix 12 : Equipment costs NF

NF	Parameter	Low [€]	Medium [€]	High [€]	Resource
Feed Water Pump	Pump Capacity: 198,39 [m^3/h]	8.600	13.900	19.800	(DACE booklet, 2024)
High Pressure Pump	Pump Capacity: 198,39 [m^3/h] Pressure : 30-40 [bar]	60.000	90.000	120.000	(DACE booklet, 2024)
Electrical Motor	Pump Capacity: 198,39 [m^3/h] Pressure : 30-40 [bar]	60.000	75.000	90.000	(DACE booklet, 2024)
Membrane	-	1000	1128	1200	(DACE booklet, 2024)
Brine Pump	Pump Capacity: 59,17 [m^3/h]	4.800	8.600	14.300	(DACE booklet, 2024)
Distillate Pump	Pump Capacity: 138,88 [m^3/h]	8.600	13.900	19.800	(DACE booklet, 2024)

Table Appendix 13 : Equipment costs NF-MED

NF-MED	Parameter	Low [€]	Medium [€]	High [€]	Resource
NF:					
Feed Water Pump	Pump Capacity: 198,39 [m^3/h] Pressure : 30-40 [bar]	10.200	12.200	17.100	(DACE booklet, 2024)
High Pressure Pump	Pump Capacity: 198,39 [m^3/h] Pressure : 30-40 [bar]	60.000	90.000	120.000	(DACE booklet, 2024)
Electrical Motor	Pump Capacity: 198,39 [m^3/h] Pressure : 30-40 [bar]	60.000	75.000	90.000	(DACE booklet, 2024)
Membrane	-	1000	1128	1200	(López et al., 2025; Figueira et al., 2023; Van der Bruggen et al., 2001)
Brine Pump	Pump Capacity: 59,17 [m^3/h]	8.800	10.700	14.300	(DACE booklet, 2024)
Distillate Pump	Pump Capacity: 138,88 [m^3/h]	9.700	11.800	16.100	(DACE booklet, 2024)
MED:					
Feed Water Pump	Pump Capacity: 138,88 [m^3/h]	8.600	13.900	19.800	(DACE booklet, 2024)
Vacuum Pump	Pump Capacity: 138,88 [m^3/h]	15.000	25.000	35.000	(DACE booklet, 2024)
Heat Source Pump	Temperature : 125°C	20.000	30.000	40.000	(DACE booklet, 2024)

	Pressure : 1,0 [bar]				
Brine Pump	Pump Capacity: 27,76 [m^3/h] Pressure : 1,0 [bar]	6.000	7.600	10.500	(DACE booklet, 2024)
Distillate Pump	Pump Capacity: 111,10 [m^3/h] Pressure : 1,0 [bar]	9.700	11.800	16.100	(DACE booklet, 2024)
Electrical Motor	Pump Capacity: 138,88 [m^3/h] Pressure : 1,0 [bar]	460	610	765	(DACE booklet, 2024)
Heat Exchanger	8841,0 m^2	1790	2920	3250	(DACE booklet, 2024)

Q. Interviews

To maintain the anonymity of the experts in this study, only a generic identifier is used to refer to each expert. Summaries of the interviews are included to reference the most important information used for this study.

1) Interview Summary Project Manager from Technical Consultancy - 07/05/2025

On the seventh of May an interview was conducted with a project manager from a technical consultancy agency to compare the indications given on the capital and operation costs of building a water desalination plant. During the interview the project manager gave insight on all the elements from the CBA and how these elements are determined in real life situations. The interview will be summarised according to the elements.

Land
Rotterdam is not the most suitable location to minimise the costs. Alternatives such as Eemshaven or Den Helder are more cost-effective. Given the high operational costs associated with hydrogen energy losses, it is crucial to consider these alternatives to keep expenses within acceptable limits. Additionally, exploring locations that offer subsidies for housing hydrogen production can be a beneficial strategy.

Equipment / Fuel
The list of equipment looks good, but you might want to consider an E-boiler since you already plan to use electrical energy for the pumps. Using waste energy from Shell or another company will incur costs, whereas if you are already utilising wind energy, you could also use it for the E-boiler. You could compare which option is more cost-effective. I also think that the heat of the Industry is not high enough to supply the MED with the right temperature steam. The use of the waste heat from the electrolyser could also be a good solution.

Building
There is not always a building needed. For example, an AWE is already in a container. The MED is a big tank. Even advantages are made to have unattended plants which could be monitored remotely. Only an administrative services department is needed. So the building costs could also be under equipment costs.

Indirect Costs
It is good to start with a rule of thumb regarding CAPEX costs;

1. 45 % is civil costs, the costs to build the plant
2. 30% mechanical engineering costs, the equipment such as the pumps
3. 25% electrical costs, 7% automation

The indirect costs such as insurance is more on the customers' sight and is not included with the costs of the engineer consultant.

Spare Parts
Spare parts are a complex subject. A plant owner can choose to invest in spare parts or pay a fee to have an intermediary store them. Spare parts are likely to be more about maintenance rather than full replacement of components, such as pumps. The decision to invest in spares depends on the importance of the spare part and the associated costs. A risk analysis should be conducted to assess the potential impact of your decision.

Electricity

Green energy will never be free, as energy providers will always seek to profit, even at prices as low as €0.06. As a plant owner, you can benefit from the system by running your water desalination operations when wind and solar energy are abundant. Energy suppliers are willing to pay for coal-fired power stations to shut down. As a water desalination owner, you should aim to produce water during these times, allowing the energy provider to pay you to operate your plant intermittently. Wind is a very good supplier for this, as in the Netherlands there is a lot of oversupply of wind energy.

Additionally, it is important to consider how the energy is supplied, whether directly from the wind farms in the North Sea or through the regular energy grid.

Labour

For labour it is quite easy, we take 100.000 euros for labour.

2) Interview Summary Business Developer from Technical Consultancy - 08/05/2025

On the eighth of May an interview was conducted with a business developer from a technical consultancy agency to indicate the needed equipment for the NF-MED water desalination plant. During the interview, the business developer gave insight on the equipment needed to run the plant.. The interview will be summarised according to the needed equipment.

Central or Local MED
The technology can benefit from a central water desalination installation, as the produced water can be distributed to various technologies. However, the downside of a central plant is that the electrolyser might be located away from the MED, preventing the waste heat from being redirected back to the MED.

Equipment
The equipment costs can be determined using the DACE price book. It is important to also consider the following:

- Piping for steam: Pressure and temperature are crucial parameters for determining the materials and costs of the piping.
- Pressure Equipment Directive: European guideline on pressure equipment.
- PID-controller: Proportional-Integral-Derivative controller.

Electrolyser
An AWE operates at a temperature of 40°C to 50°C, which may be challenging for heating seawater. An alternative solution, such as PEM, operates at 80°C and is ideal for using waste heat to heat seawater. A solid oxide electrolyser can even reach 350°C.
An AWE of 200 MW has dimensions of approximately 219.000 by 187.000 m2. A 100 MW electrolyser will be smaller but will require the same equipment and support, such as hydrogen compressors, hydrogen purification, and a control room.

Building
Typically, an AWE does not require a building as it is housed in a container. However, this AWE is so large that it cannot fit in a container and requires a building, which is more cost-effective.
Feasibility
The cost estimates for your MLD process can vary from reality, as it is only in the feasibility stage. At this stage, costs can be 50% higher or 30% lower. This represents an 80% confidence interval accuracy range, as illustrated in figure Appendix 6 below.

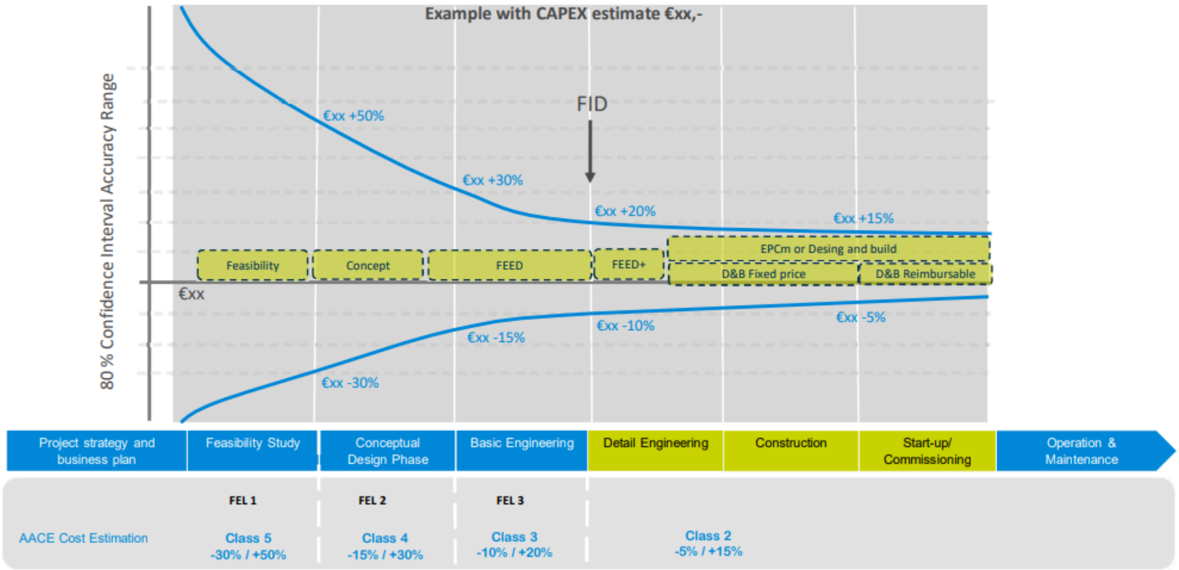

Figure Appendix 6 : Feasibility stage price indicators (Business Developer, 2025)

3) Interview Summary Consultancy Manager from Technical Consultancy - 12/05/2025

On the twelfth of May an interview was conducted with a Consultancy Manager to indicate the costs regarding spare parts for the MLD process. During the interview, the consultancy manager gave insight on their personal estimates on spare parts. The interview will be summarised according to the topics discussed.

Estimating OPEX Costs

OPEX costs encompass spare part costs and maintenance costs, which include personal costs, material costs, and external costs. There are three different baseline values used in benchmarks for estimating OPEX costs: Capital Expenditures (CAPEX), Asset Investment Value (AIV), and Plant Replacement Value (PRV).

1. CAPEX = Annual periodic investment in assets, such as construction or upgrades (current or specific year)
2. AIV = The total cumulative investment (historical cost) to build and commission assets. (total lifecycle investment)
3. PRV = The estimated cost to replace the plant today, considering inflation and modernization (present-day valuation)

For a newly built facility at commissioning, the three baselines are the same. So, CAPEX = AIV = PRV, assuming there are no inflation and modernization effects.

Maintenance Costs calculated from CAPEX

An expert from the technical consultancy suggests a maintenance value, or plant replacement value, of 3.3% of your total investment costs for the chemical industry. Figure Appendix 7 illustrates the percentages. Therefore, for maintenance costs, you could calculate 3.3% of the total CAPEX.

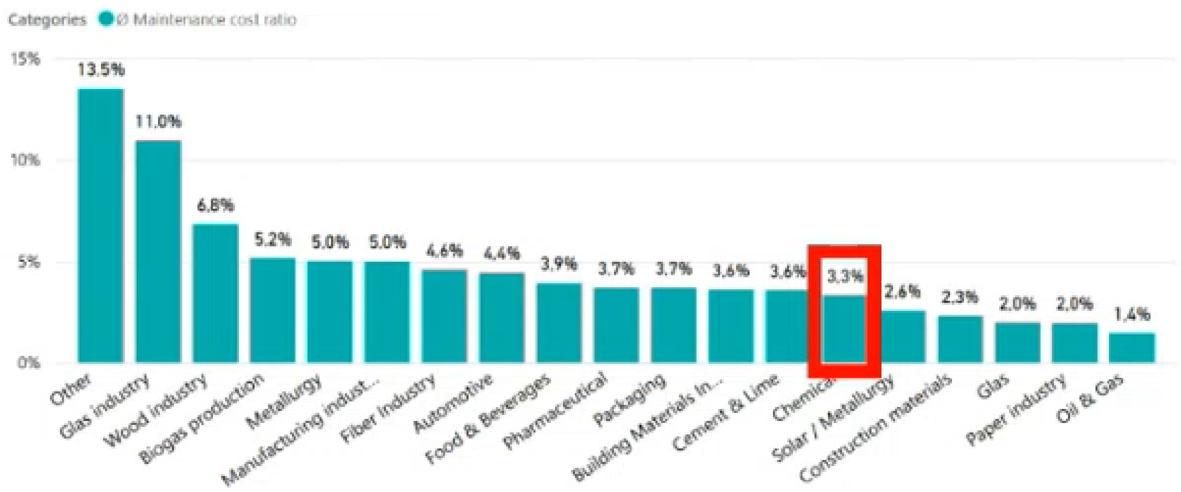

Figure Appendix 7 : Maintenance Cost Ratio

Maintenance costs depend on your facility's complexity, automation, equipment redundancy, asset age, maintenance philosophy, technical maturity, and geographic location. Depending on these factors, your maintenance costs can range from 2-3% (low) to 4-5% (high) of your CAPEX. This is shown in Table X.

Table Appendix 14 : Maintenance Estimation Percentage

	Low % (2-3% of AIV)	High % (4-5% of AIV)
Facility Complexity	Simple processes, minimal equipment types	Complex processes, diverse equipment types
Automation	High automation, fewer manual systems	Low automation, manual-intensive systems
Equipment Redundancy	Low redundancy, fewer backup systems	High redundancy, multiple backup systems
Asset Age	Newer assets, under warranty	Aging assets, increased failures
Maintenance Philosophy	Reactive maintenance (short term lower costs)	Proactive maintenance
Technology Maturity	Mature Technologies: Proven, well-established systems; spare parts and expertise are widely available.	Emerging Technologies: New or innovative systems; higher maintenance due to lack of familiarity, spare part availability, and teething issues.
Geographic Location	Low-cost regions	High-cost regions

Personal Costs, Material Costs and External Costs calculated from OPEX

Once the 3.3% is determined, there is a benchmark for the maintenance costs of the plant. The breakdown is as follows:

- Personal costs: 35-55%
- Material costs: 25-35%
- External costs: 15-35%

Spare Parts Costs calculated from CAPEX

Spare parts costs are also determined by a benchmark, as shown in Table X. These costs can be a low or high percentage of the total investment costs, influenced by three elements: commissioning, operational spares, and critical spares.

- Commissioning: Covers consumables and water items needed for initial commissioning and early-life failures.
- Operational Spares: Includes parts expected to wear out or require replacement during the first 2-5 years.
- Critical Spares: Long-lead-time or high-cost critical spares to avoid extended downtime in case of failure.

The total spare parts budget will be between 2.5% and 6.0% of the total CAPEX costs, or in this example, the total PRV

Table Appendix 15 : Indication on spare costs estimates

		PRV =	€ 65,000,000			
Spare Part Category	Percentage of PRV		Calculated costs		Purpose of Spares Category	Drivers for % (Low - High)
	Low	High	Low	High		
Commissioning/Start-Up	1.0%	2.0%	€ 650,000	€ 1,300,000	Covers consumables and wear items needed for initial commissioning and early-life failures.	**Low:** Proven equipment with minimal early failures. **High:** New or complex technology with high uncertainty in early operation.
Operational Spares	1.0%	3.0%	€ 650,000	€ 1,950,000	Includes parts expected to wear out or require replacement during the first 2-5 years.	**Low:** Stocking for only 2 years, simple operations, or standardized equipment with high reliability. **High:** Stocking for 5 years, continuous operations, high wear, or specialized equipment
Critical Spares / Insurance Spares	0.5%	1.0%	€ 325,000	€ 650,000	Long-lead-time or high-cost critical spares to avoid extended downtime in case of failure.	**Low:** Short lead times, redundant systems, or low downtime impact. **High:** Custom components, long lead times, or high financial loss from downtime
Total Spare Parts Budget	2.5%	6.0%	€ 1,625,000	€ 3,900,000		

4) Interview Summary Product Specialist from Technical Consultancy - 12/05/2025

On the thirst of June an interview was conducted with a tendering manager from a company dedicated to sustainable solutions for water including MEDS to indicate the CAPEX and OPEX of the MED for ultrapure water. During the interview, the tendering manager gave insight on their personal experience with MED and advice regarding the costs. The interview will be summarised according to the topics discussed about the E-boiler and the MED technology.

MED Temperature and Pressure

In each effect of the MED the water desalination is progressively operating at lower pressures and temperatures. This staged process allows the system to reuse heat efficiently, making it highly energy-efficient for desalination. To achieve evaporation at a temperature of 70 °C, the system must operate at a corresponding saturation pressure of approximately 0.3 bar. However, in practice, the pressure in the evaporation chambers is often around 0.5 bar. This total pressure includes not only the pressure from steam but also from non-condensable gases such as nitrogen and oxygen.

These gases are naturally present in seawater and are released when the water is heated. The dissolved gases in the seawater come out of solution and form bubbles when the temperature rises. This means that 10 to 20% of the total pressure in the effect may be due to air rather than steam. Since only the steam pressure contributes to the evaporation temperature, the presence of air effectively lowers the actual steam pressure and the temperature at which evaporation occurs. So the air contributes to the total pressure but does not increase the temperature and therefore could interfere with the operation at which the temperature is too low.

To maintain a true saturation state at 70 °C, the system must either increase the total pressure to compensate for the air content, potentially up to 1.6 or 1.7 bar, or remove the non-condensable gases from the effects. This is typically done using vacuum pumps or ejectors, which help maintain the low-pressure environment necessary for efficient evaporation. In some cases, the steam inlet to the first effect may not be pure steam but rather heated water. Regardless, the evaporation process relies on maintaining a pressure-temperature balance that allows seawater to boil at lower temperatures in each successive effect. This balance is only possible if non-condensable gases are continuously removed, ensuring that the pressure in each chamber accurately reflects the desired saturation conditions.

The E-boiler heats the incoming water, which may still contain dissolved gases. As the water is heated, these gases can form bubbles and disrupt the pressure balance in the effects. In contrast, when using waste heat steam as the energy source, the incoming water is typically much cleaner. This reduces the risk of gas bubble formation and results in more stable pressure conditions within the evaporation rooms.

Costs and Dependence

Heating water with an E-boiler requires a significant amount of energy, especially when compared to using waste heat, which is already available in the form of steam. Steam is an excellent energy carrier as each kilogram contains approximately 2500 kJ of thermal energy. Because of this high energy content, companies charge other companies for the use of waste heat. However, relying on waste heat from other companies introduces a dependency. The MED system will be reliant on the continuous operation of the external company supplying the steam. If that company undergoes maintenance or shuts down temporarily, the steam supply stops and the MED process must also be stopped.

Location and Dependence
To minimise energy losses during transport, the MED installation should be located as close as possible to the source of waste heat. In Eemshaven, there are two electric power plants that produce residual heat and could be a suitable partner for a nearby MED facility. One downside of relying on an electrical power plant is the increasing share of renewable energy sources, such as wind and solar. These sources reduce the need for conventional power plants during periods of high renewable output. As a result, power plants may be shut down or operate at reduced capacity.

However, this challenge also presents an opportunity for the MED system. In situations where there is an oversupply of electricity in the Netherlands, power plants are sometimes paid to reduce or stop production. The MED plant could also be paid to operate during these periods of surplus. This would allow the MED system to run intermittently using free electricity. In such cases, the E-boiler becomes a viable option again. The E-boiler can heat up within 3 minutes, even 1 minute. Which is a good characteristic for an intermittent operation. This approach is particularly attractive when the system is also used for hydrogen production, which is typically very energy-intensive and costly.

Clean Water
One major advantage of using steam from industrial waste heat is its purity. Steam is an extremely clean source, which eliminates the need for extensive water treatment before it enters the MED system. In contrast, raw water must first be purified when using an E-boiler which adds to operational costs. If saline water is used in the boiler, it leads to significant scaling and corrosion and a lot of maintenance is needed. This makes it an unsuitable option for efficient and reliable operation. When using fresh water, scaling is not such a big problem. Using clean industrial steam can therefore reduce both complexity and expenses.

MED Brine Impact
To produce 100% pure water through desalination, approximately 400% to 600% of seawater input is required. The remaining water, known as brine, is discharged back into the sea. While this discharge does increase local salinity, the overall environmental impact is relatively low.

Seawater naturally exhibits variations in TDS due to environmental factors such as currents, evaporation, and local geography. As a result, salinity levels can fluctuate and a localized increase is not unusual. Although this may temporarily affect the immediate area around the outfall, the salinity levels tend to normalize over time due to natural water movements.

Steam Decision for this Study

1. *Steam from Emmen*

In Emmen the steam is free. This is because there is an overload of steam available. The MED is placed in Rotterdam which makes the piping costs an important element of the steam costs. This is, however, a one time only CAPEX. It could be indicated that the piping is between 200.000 and 300.000 euros. The piping costs might even be higher than an E-boiler itself.

2. *E-boiler*

An E-boiler could be placed instead of using waste steam. The E-boiler itself costs 200.000 to 300.000 euros. Then the E-boiler must be installed, which costs 100.000 to 200.000 euros extra. This is all on top of the electricity needed to operate the E-boiler to produce steam for the MED installation.

3. *Waste Heat from the Botlek*

To estimate the cost of steam production, the energy consumption of the E-boiler can be compared to the cost of natural gas. This requires first calculating the total energy input needed to operate the boiler to produce enough steam to make $1000\ [m^3/day]$. Once the energy demand is known, it can be multiplied by the gas price per MWh to estimate the cost.

The boiler which is needed for this operation has the electrical capacity of 3 MWe. When the boiler operates the entire day, this is 72 MWe. The boiler operates at an efficiency of 75%. which means that 25% of the input is lost. The 20% is conversion losses and 5% maintenance losses. The gas price currently is €100 per MWh. So it can be taken that the gas price per day is €7200. This cost reflects the energy input required to produce the necessary amount of steam.Therefore, the daily cost of steam production via the boiler can be estimated for €7200 a day.

5) Interview Summary Process Advisor from a Water Company - 13/05/2025

On the thirteenth of may an interview was conducted with a process advisor from a water company. The process advisor gave insight on their demineralized plant and shared their personal experience with the operation of the plant. The plant used a RO and could assist in the operation of the NF for this study. The interview will be summarised according to the subjects discussed during the meeting.

RO vs. NF

RO membranes reject approximately 99% of dissolved ions, allowing only about 1% to pass through. In contrast, NF membranes allow around 5–7% of ions to pass, particularly monovalent ions. This means NF has slightly lower rejection performance compared to RO. However, NF technology has advanced significantly, and its ion rejection capabilities have improved compared to earlier literature values.

The pore size in RO membranes is much smaller, which means higher pressure is required to achieve the same water quality as NF. As a result, RO systems typically consume 2 to 3 times more energy than NF systems.

The recovery rate of NF systems is generally around 80%. While it is technically possible to increase this rate by adding more membrane stages, doing so leads to disproportionately higher energy consumption. For example:

- Increasing recovery from 50% to 80% may require about 50% more energy.
- But increasing from 80% to 90% could require up to 300% more energy, making it economically unfeasible.

Post Treatment

To achieve ultrapure water quality after the RO unit, an ion exchange system is required as a polishing step. Although RO membranes remove the majority of dissolved salts, a small percentage of 1% can still pass through. The ion exchange unit effectively removes these remaining ions, ensuring the final water meets ultrapure standards.

MED Pilot Parameters

MED pilot with two effects. The pilot MED was designed to operate with the optimised capacity of 0.120 m^3/h in a continuous operation.

Table Appendix 16 : MED Pilot Parameters

MED Parameter	**Unit**
Water Recovery	30 - 70 %
Required Power	2 kW
Heat Energy for 1000 kg recovered condensate	100 - 300 kW
TDS	< 0.2 mg/L
Steam	120-150 °C
Hot Water	90 °C

Equipment Costs	€130.000
Installation Costs	5 - 10 % of the Equipment Costs

NF Pilot Parameters
NF has the pore size in the range of 0.2 to 2 nm and it can be used to separate larger size molecules such as sugars and divalent salts while allowing passage of monovalent salts. The pilot NF was designed to operate with the optimised capacity of 1 m^3/h in a continuous operation.

The footprint is not included and very dependent on the specific technology. The NF for this thesis will have a footprint of approximately 155 m^2 for an NF with around 200 membranes.

Table Appendix 17 : NF Pilot Parameters

NF Parameter	**Unit**
Lifetime	5 years
Membrane Surface	40 m^2
Membrane Costs	€600
Membrane Water Production	0,5 - 1 m^3/h
Water Recovery	30 - 70 %
Chemicals	2 ml/h
Pump Power	8 kW
Pump Pressure	40 bar
Equipment Costs	€160.000
Installation Costs	10 % of the Equipment Costs
Maintenance costs per year	€3.000

Membrane Series
A specific type of membrane is used that achieves approximately 15% recovery per unit. To increase the overall water recovery, multiple membranes, typically 5 to 6, are installed in series. This setup results in a recovery rate of around 80%. While it is technically possible to add more membranes, 8 or 9, doing so would require a significantly larger pump to maintain the necessary pressure. Therefore, most systems are designed to operate at a practical recovery rate of 80% to 85%, balancing efficiency with equipment limitations.

If the system requires approximately 40 m^3/h of demineralized water, and each membrane allows at least 0.5 m^3/h to pass through, then a total of 80 membranes would be needed. This is considered a modest number, as some large-scale installations may contain up to 2,000 membranes.

Temperatures
In an ideal scenario, membrane systems operate at around 25 °C. However, when using seawater, this temperature is not always achievable, as the water can be significantly colder. Lower feedwater

temperatures can lead to reduced membrane performance and increased energy consumption, resulting in overall energy losses.

Chemicals

In membrane water treatment systems, scaling can occur in pipes and on membrane surfaces. To prevent rapid scaling, a chemical called an antiscalant is used. This slows down the crystallisation process, allowing the system to operate longer without requiring cleaning or maintenance. Without antiscalants, membranes can become clogged in as little as one day. When using seawater as feedwater instead of freshwater or brackish water, more chemicals are typically required. This is due to the higher salt content, which increases the risk of scaling and fouling. In addition to higher chemical demand, seawater systems also require more energy to operate.

Membrane systems require regular cleaning of 2 to 3 times per week, with each cleaning cycle lasting 3 to 4 hours. Warm water is typically needed for effective cleaning. To minimise downtime, larger facilities often install multiple NF skids. For example, a demineralized water plant may use 8 skids, with 6 in operation and 2 in cleaning or maintenance. This allows for continuous production by rotating between skids. However, this level of operation is often not feasible for smaller companies, which may need to shut down the entire system during cleaning.

Energy Consumption

Energy consumption is a big cost factor in membrane systems. One way to reduce operational costs is through intermittent operation. Facilities can lower both energy and chemical costs by running the system during the day with solar energy and storing the treated water in tanks for nighttime.

Disposal permit

To discharge brine into the sea, a one-time permit fee is required. The cost of this permit depends on several factors, including:

- The composition of the brine; salt concentration and the presence of heavy metals or chemicals
- The duration and volume of the discharge
- The environmental impact on the surrounding marine ecosystem
- Additionally, regulations often specify that the temperature of the discharged brine must not exceed 30 °C

6) Interview Summary Membrane Scientist - 13/05/2025

On the thirteenth of May an interview was conducted with a membrane scientist to indicate the needed parameters for the NF membrane for the MLD process. During the interview, the membrane scientists have insight on their personal experience with parameters to run an NF plant. The interview will be summarised according to the questions the membrane scientist could answer. Some questions were too specific to determine a well considered response.

1. What is the recovery rate?

The recovery rate is between 80% and 90%, depending on the type of membrane. With seawater, the recovery rate can be similar. However, the required pressure needs to be higher, around 30-40 bar.

2. How much electricity is needed to pump around the seawater?

An indication of 2 kW/m3 is a good indication for the MLD process.

3. How many membranes are needed in the MLD process?

A membrane can have a flow rate of 1 to 1.5 m^3/h, again depending on the type. The number of membranes required depends on the total water flow needed. For example, one membrane module can have a flow rate of 1000 L/h, which is equivalent to 1 m^3/h. By knowing the daily water flow, you can adjust the number of membranes accordingly.

4. How big are the NF membranes?

NF membranes can vary in size, but an indication of 30 to 40 m^2 is a good benchmark.

5. What kind of chemicals are used to keep the membranes clean?

The most impactful element for the membrane is organic contamination. Organic contamination can be treated with chlorine bleach, but it must be noted that chlorine is not good for the membranes. Therefore, thorough pretreatment of the seawater will yield better results. Peroxide can also be used, but it will have a similar effect on the membrane, reducing its lifespan.

6. When is maintenance needed on the membranes?

Every few days, the membrane requires maintenance. This results in a temporary halt in the NF process. This maintenance typically takes a couple of hours and impacts the operational hours of the membrane.

7. When do the membranes need to be replaced?

The membranes need to be replaced every 3 to 5 years. The replacement frequency depends on the pretreatment of the feedwater. With proper pretreatment, the membranes can operate for around five years, regardless of the type of feedwater. Even with seawater as the inlet, the membranes can last up to five years with good pretreatment.

8. What are the costs of a membrane?

A cost estimation of €500 to €600 is likely too low and should be adjusted to a higher amount.

1) <u>Interview Summary Tendering Manager MED from Company focused on sustainable solutions for water - 03/06/2025</u>

On the third of June an interview was conducted with a tendering manager from a company dedicated to sustainable solutions for water including MEDs to indicate the CAPEX and OPEX of the MED for ultrapure water. During the interview, the tendering manager gave insight on their personal experience with MED and advice regarding the costs. The interview will be summarised according to the topics discussed about the MED technology.

MED CAPEX

The MED system is designed with 9 effects, rather than the initially considered 8, to account for thermal losses and pressure drops. Based on this configuration, there are two possible approaches:

1. Option 1: A single unit with 9 effects with an estimated CAPEX of €5.5 million.
2. Option 2: Two units with 9 effects with a combined estimated CAPEX of €8.3 million.

The costs will increase if more effects are added to the system. For example, a unit with 20 effects would cost approximately €7 million for one unit and €11 million for two units

Land Costs

The figure Appendix 8 below represents the footprint for a two unit MED with each 9 effects.

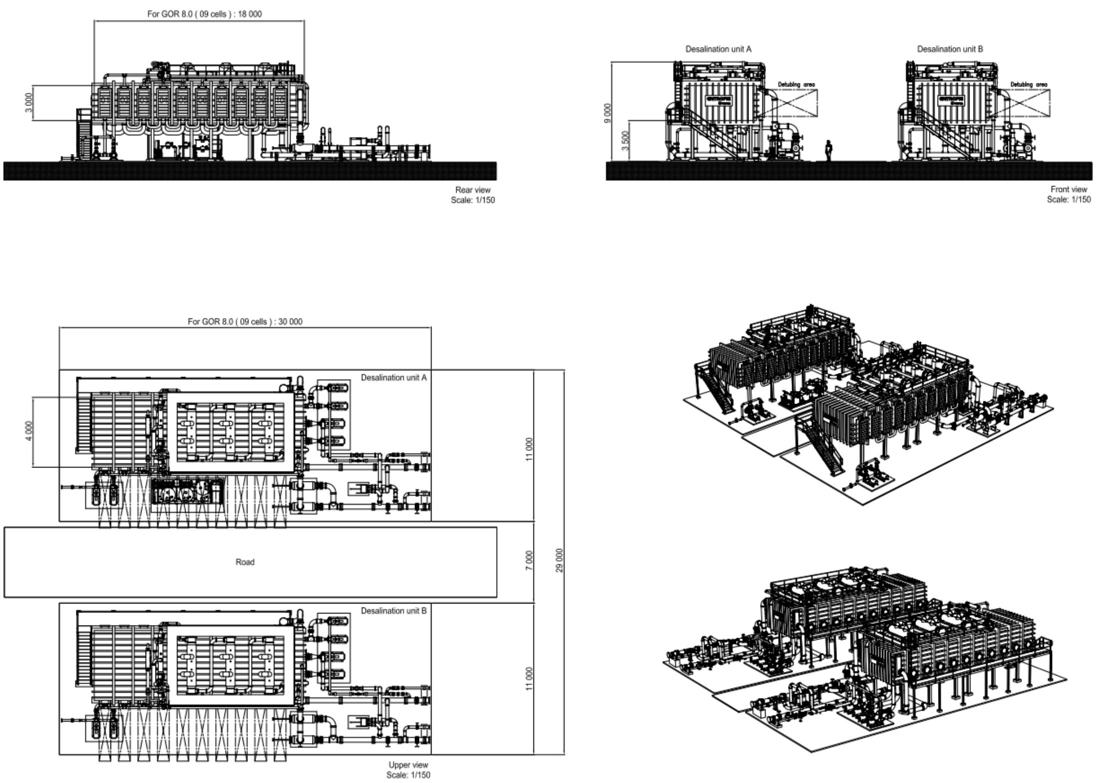

Figure Appendix 8 : MED footprint

The Shift from MED to RO

Thermal desalination technologies like MED are highly energy-intensive. In recent years, RO has significantly improved in efficiency and leads to a shift toward RO in many applications. However, there is still a profit for using MED, particularly where low-grade waste heat is available. MED systems can operate at temperatures as low as 60 °C, making them suitable for integration with processes that generate low-temperature waste heat, such as AWE. The market is increasingly favoring LT-MED over HT-MED for this reason.

Impact of the Nanofiltration

The integration of NF in desalination system presents several considerations:

- NF is not commonly used as pretreatment for MED for water desalination.
- Adding NF increases the capital and operational costs of the MLD system.
- NF helps reduce scaling in the MED unit, enabling operation at higher temperatures or higher concentration factors.
- However, higher operating temperatures may lead to increased costs for cleaning chemicals.

Waste Heat from the Electrolyser

LT-MED is particularly well-suited for utilizing waste heat from AWE systems, which typically operate at 55–60 °C. This waste heat can be recovered and used to drive the MED process:

- Approximately 80% of the waste heat from the electrolyser is sufficient to produce the full volume of ultrapure water required to feed the electrolyser.
- No additional waste heat sources are needed because AWE alone provides enough.
- In fact, the available waste heat is often more than sufficient, meaning that even a single MED unit can produce more water than the electrolyser consumes.
- If excess water is produced, a market or consumer base is needed to utilize or sell the surplus.

GOR & Effects

The GOR is defined as the amount of distillate produced per unit of steam input. For an easy comprehension, ignoring all pressure drops, thermal losses and boiling point elevations, the following could be said:

- One ton of steam evaporates one ton of seawater.
- In a pure MED, the GOR is directly linked to the number of effects. In this case, the 8 effects are required to achieve a GOR of 8. This is because the heat will be reused in the following effects.
- In real-world conditions, due to thermal losses and pressure drops, 9 to 10 effects may be necessary to reach the same performance.

MED Temperature differences

Each effect in an MED system typically operates with a temperature drop of 4°C to 5 °C. From the beginning till end of the effects the temperature will drop around 40 °C with 8 effects and 45°C with 9 effects.

A smaller temperature difference per effect (ΔT) requires a larger heat transfer surface area (S) to maintain the same heat flux. This is described by the following equation:

$$Heat\ Flux = K * S * \Delta T$$

K is the overall heat transfer coefficient. As ΔT decreases, S must increase to compensate, which leads to higher CAPEX due to the need for more extensive heat exchange surfaces.

Condenser

The vapor generated in the final effect is condensed in a condenser:

- A temperature difference between the condenser and the cooling water, for example seawater at 20 °C, is necessary for effective condensation.
- The primary function of the condenser is to condense vapor from the last effect.
- Using seawater as a cooling medium reduces the energy required to heat the feedwater.

Building Costs

No building costs are required because the MED can stand outside.

Chemicals

The OPEX for chemicals in a 9 effect MED system is approximately 0,03 €/m^3.

Electrical Power

The OPEX for electricity in a 9 effect MED system is approximately 1,1 kWh/m^3. This is based on the assumption that seawater is supplied to the MED unit at a pressure of around 4 barg.

Post-Treatment

Between the MED unit and the AWE system, post-treatment is required to ensure water purity:

- Determining the exact water quality requirements can be challenging, but ensuring sufficient purity is critical for long-term electrolyser performance.
- Electrodeionization (EDI) is typically used to polish the water to ultrapure standards.
- Although alkaline electrolysers require less pure water than PEM systems, post-treatment is still essential to prevent damage.

Cooling Water

You always need a cooling source;

- Both the MED and the electrolyser require cooling systems.
- Seawater is generally sufficient to cool the MED.

Conclusion

For producing ultrapure water for electrolysers, NF pretreatment to be able to operate at high temperatures is not necessary. LT-MED, powered by the waste heat from the electrolyser itself, offers a cost-effective and energy-efficient solution.

7) Interview Summary Strategic Account Manager from a Water Company - 03/06/2025

On the third of June an interview was conducted with a strategic account manager from a water company focused on purifying water. The strategic account manager was interviewed to gain insights into the pricing of purified water. Their personal experience and recommendations regarding cost considerations are essential for establishing a cost price that aligns with industry standards. The interview will be summarised according to the topics discussed about the MED technology.

Sales Price of Ultrapure Water

The cost of ultrapure water is highly dependent on the technology applied, making it challenging to determine a fixed price. Several factors influence the final cost, including:

1. The location of the plant
2. The technologies implemented
3. The quality of the inlet feedwater
4. The materials used in construction
5. The overall size and capacity of the plant

For this specific plant, an estimated price range for ultrapure water is between €5 and €10 per m^3. Given the relatively small scale of the plant, production costs are expected to be higher which suggests that the price will likely be closer to €10 per m^3.

While this estimate provides a general indication, a more accurate price can be determined by further analysing the factors mentioned above. Scaling up the plant would increase both CAPEX and OPEX, but could lead to lower unit costs for the ultrapure water.

8) Interview Summary Process Engineer from a Water Treatment Company - 17/06/2025

On the seventeenth of June an interview was conducted with a process engineer from a water treatment company specialised in MMFs. The process engineer was interviewed to gain insights of the footprint, energy requirements and profits of using a MMF. Their personal experience and recommendations regarding cost considerations are essential for establishing the MMF within the CBAs. The interview will be summarised according to the topics discussed about the MED technology.

Footprint

The footprint between the first and second MMF is different as the first MMF needs to filter 3.703,33 m^3 per day and the second MMF needs to filter 5.290,27 m^3 per day. Each MMF requires a minimum of two filters, with a third usually included to ensure continuous operation while one filter undergoes cleaning. Additionally, the footprint includes a tank for catching the backwash water. On both sides of the tank a pump is installed. The first pump performs the backwash and the second pump is to pump away the backwash water that is collected in the backwash tank. Figure Appendix 9 illustrates the layout of the first MMF installation and figure Appendix 10 illustrates the second layout of the MMF installation. The setup is the same, only the diameters shown in the plot plan are different.

Figure Appendix 9 below shows the first MMF. The MMF has the two mentioned backwash pumps, but also a blower which assists the backwash. The cleaning process is a combination of water and air. The diameter of every filter is 3,2 metres. However, the backwash tank takes up most space.

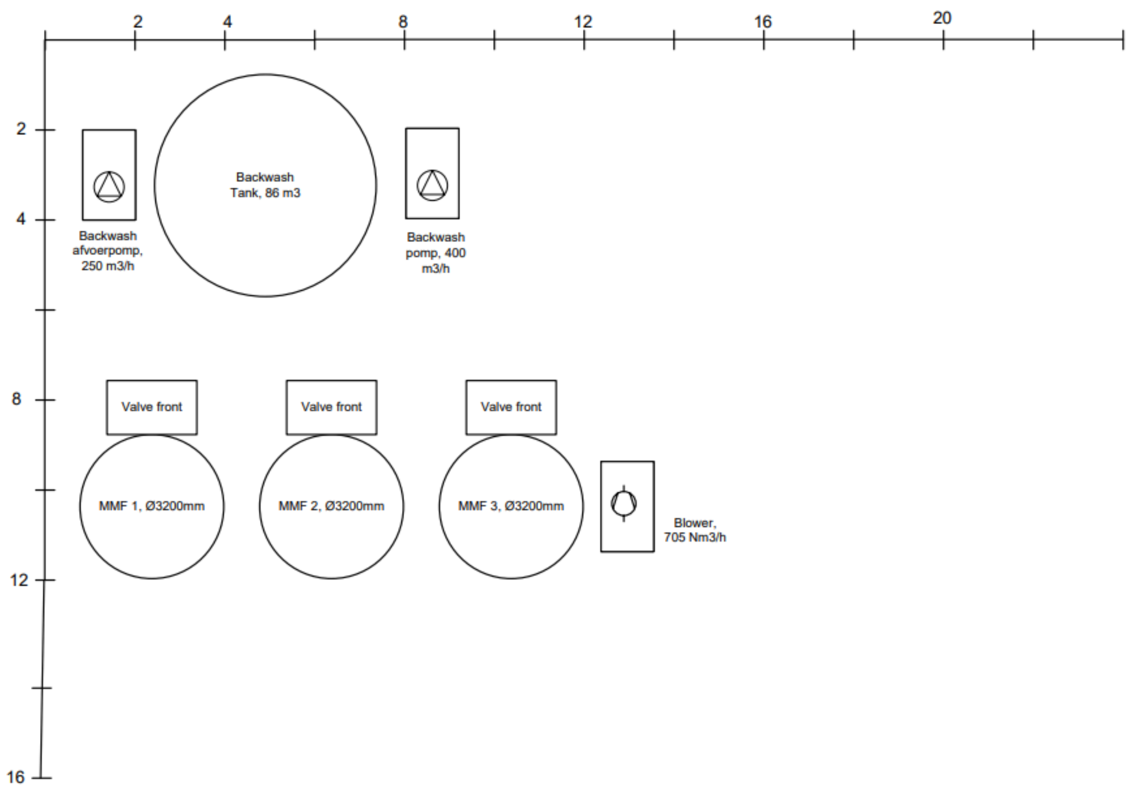

Figure Appendix 9 : MMF 1 Footprint

Figure Appendix 10 below shows the second MMF. The MMF has the same layout, only the dimensions are bigger as more seawater needs to be filtered. The MMF diameter of every filter is 3,8 metres instead of 3,2 metres. Again, the backwash tank takes up most space.

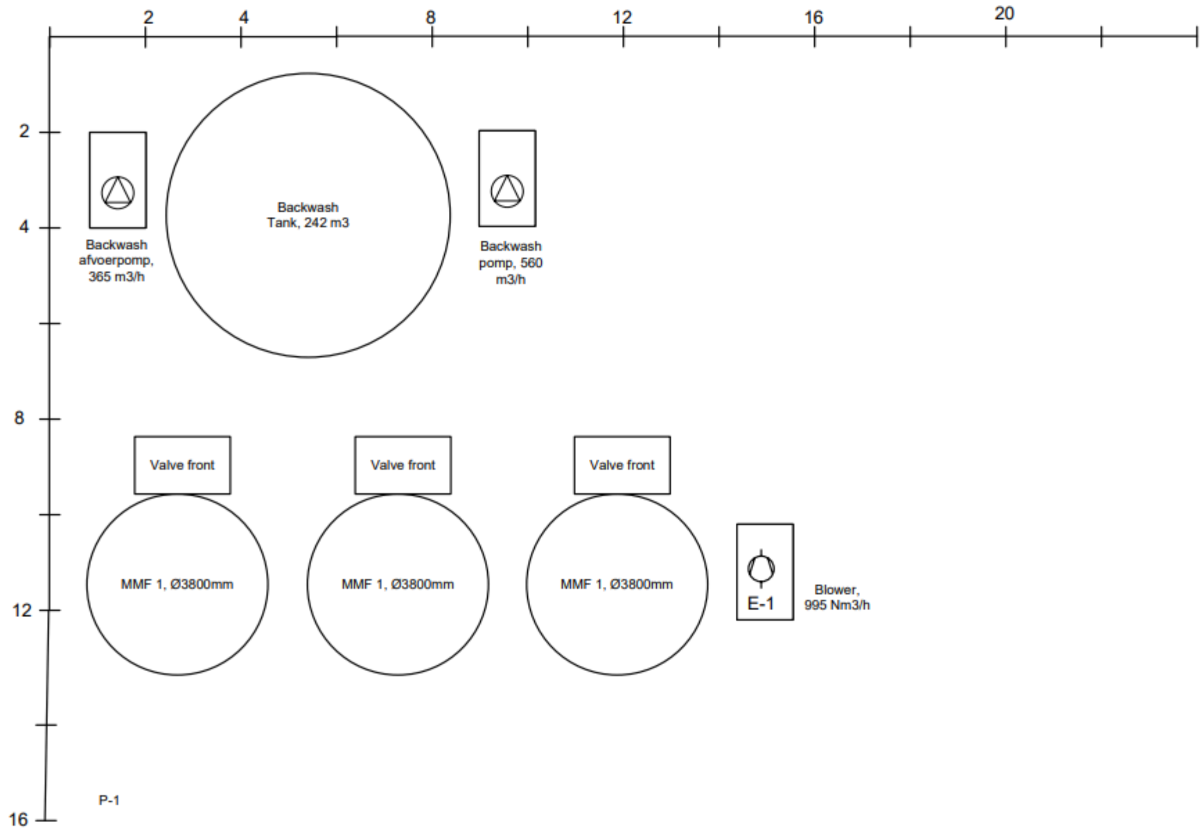

Figure Appendix 10 : MMF 2 Footprint

Energy requirements

The first and second CBAs utilize different MMF systems. In the first CBA, the MMF is required to filter 3.703.33 m³ of water per day. To circulate the water through the system, three types of pumps are used: the backwash pump, a second pump that drains the backwash water, and one feed pump. As shown in table Appendix 18, the feed pump consumes 13.37 kWh, the backwash pump consumes 20.79 kWh, and the backwash drainage pump consumes 15.11 kWh.

Table Appendix 18 : MMF 1 pumping requirements

Pumps & Motors (electrisch)													
Equipment		Load	Working point		Efficiencies					Power	Consumption	Costs	
No	Omschrijving	Hours	Flow	Δp_{tot}	$\eta_{equipment}$	η_{motor}	$\eta_{cos\ phi}$	$\eta_{control}$	η_{totaal}	P			
[-]	[-]	[uren/jaar]	[m3/h]	[bar]	[-]	[-]	[-]	[-]	[-]	[kW]	[kWh/jaar]	[€/kWh]	[€/jaar]
	Voedingspomp	8.000	154	2,00	0,75	0,9	1	0,95	0,64	13,37	106.948	0,25	26.737
	BW pomp	500	400,00	1,20	0,75	0,9	1	0,95	0,64	20,79	10.396	0,25	2.599
	BW afvoer pomp	1.000	260,00	1,20	0,75	0,9	0,85	1	0,57	15,11	15.105	0,25	3.776
	diversen	8.000								4,93	39.413	0,25	9.853
Sub-totaal 1											171.863	€	**42.966**

Blowers & Compressors (Isothermal)													
Equipment		Load	Flow 1		Mol massa	Pressure abs		Temp.	Eff.	Power	Consumption	Costs	
No	Omschrijving	Uren	Q	m	M	p1	p2	T	η_{totaal}	P			
[-]	[-]	[uren/jaar]	[Nm3/h]	[kg/s]	[g/mol]	[kPa]	[kPa]	[°C]	[-]	[kW]	[kWh/jaar]	[€/kWh]	[€/year]
	Blower spoeling	1.500	705,00	2,E-01	28,97	100,00	160	20	0,45	22,39	33.585	0,25	8.396
Sub-totaal 2												€	**8.396**

Total Energy				
No	Description			Total
[-]	[-]			[€/year]
Costs				
1	Energy			51.362
Total			€	**51.362**

The second MMF needs to filter 5.290,27 m^3 a day. The MMF uses the same three types of pumps but needs to filter more water. The calculations in table Appendix 19 below show that the feeding pump requires 19,10 kWh, the back wash pump requires 29,11 kWh, and the back wash drainage pump requires 21,09 kWh.

Table Appendix 19 : MMF 2 pumping requirements

Pumps & Motors (electrisch)													
Equipment		Load	Working point		Efficiencies					Power	Consumption	Costs	
No	Omschrijving	Hours	Flow	Δp_{tot}	$\eta_{equipment}$	η_{motor}	$\eta_{cos\ phi}$	$\eta_{control}$	η_{totaal}	P			
[-]	[-]	[uren/jaar]	[m3/h]	[bar]	[-]	[-]	[-]	[-]	[-]	[kW]	[kWh/jaar]	[€/kWh]	[€/jaar]
	Voedingspomp	8.000	220	2,00	0,75	0,9	1	0,95	0,64	19,10	152.777	0,25	38.194
	BW pomp	500	560,00	1,20	0,75	0,9	1	0,95	0,64	29,11	14.555	0,25	3.639
	BW afvoer pomp	1.000	363,00	1,20	0,75	0,9	0,85	1	0,57	21,09	21.089	0,25	5.272
	diversen	8.000								6,93	55.437	0,25	13.859
Sub-totaal 1											243.858	€	**60.964**

Blowers & Compressors (Isothermal)													
Equipment		Load	Flow 1		Mol massa	Pressure abs		Temp.	Eff.	Power	Consumption	Costs	
No	Omschrijving	Uren	Q	m	M	p1	p2	T	η_{totaal}	P			
[-]	[-]	[uren/jaar]	[Nm3/h]	[kg/s]	[g/mol]	[kPa]	[kPa]	[°C]	[-]	[kW]	[kWh/jaar]	[€/kWh]	[€/year]
	Blower spoeling	1.500	995,00	3,E-01	28,97	100,00	160	20	0,45	31,60	47.400	0,25	11.850
Sub-totaal 2												€	**11.850**

Total Energy				
No	Description			Total
[-]	[-]			[€/year]
Costs				
1	Energy			72.814
Total			€	**72.814**

Recovery Rate

The indicated recovery rate of 90% is accurate and could potentially be higher.

Advantage of the pretreatment of MMF

An advantage of using a MMF over other pretreatment methods such as UF is that it requires no chemicals and involves less maintenance. This not only reduces operational costs but also benefits the environment by minimizing the amount of chemicals discharged into the brine.

R. Dutch Regulations

Environmental Planning Act (Omgevingswet)

Env. & Planning Article	**Definition**	**Direct Link**
Article 1.6	" Everyone takes adequate care of the physical environment."	Artikel 1.6 Omgevingswet
Article 1.7	"Anyone who knows or can reasonably suspect that his activity may have adverse effects on the physical living environment, is obliged: a.to take all measures that can reasonably be required of him to prevent those consequences, b.insofar as those consequences cannot be prevented: to limit or undo those consequences as much as possible, c.if those consequences cannot be sufficiently mitigated: to refrain from that activity insofar as this can reasonably be required of him."	Artikel 1.7 Omgevingswet
Article 1.7a.	" 1. It is prohibited to carry out or refrain from carrying out an activity if the carrying out or refraining from carrying out such activity causes or threatens to cause significant adverse effects on the physical living environment. 2. The application of Subsection 1 will be elaborated or limited by order in council. The elaboration or limitation will in any case serve to implement the Environmental Criminal Law Directive and relate to: a.the extent of the adverse effects on the physical living environment, b.the cases in which the first paragraph applies. "	Artikel 1.7a Omgevingswet
Article 4.23	" (1) The rules referred to in Article 4.3 relating to discharge activities in a body of surface water or a water	government regulations concerning water-related activities

	treatment plant, water extraction activities and restricted area activities concerning a water control work or an installation, i.e., not a mining installation in a water control work, shall be laid down with a view to: … d. protecting the efficient operation of a water treatment plant …“	
Article 5.1	“ … (2) The following activities are prohibited without an environmental permit: … c. discharge activity to: 1. a body of surface water, 2. a water treatment plant, …”	Activities subject to the environmental permit under this Act
Article 5.36b	“ If the prohibition, as referred to in Article 5.1, paragraph one, to carry out a deposition activity at sea without an environmental permit by an amendment to Annex 4 to the London Protocol, applies to an activity for which an environmental permit for a discharge activity into a body of surface water or for an activity in restricted area with regard to a water control work as referred to in Article 5.1, paragraph two, has already been granted, that environmental permit shall apply as a permit for a deposition activity at sea, provided that that Annex to the London Protocol states that a permit may be granted for that activity.”	Conversion of an environmental permit into a permit for a water-related activity due to a new authorisation for a deposition activity at sea
Article 5.38	“ (1) To the extent that an environmental permit involves: a. deposition activity at sea, b. an environmentally harmful activity, unless it concerns a case designated by virtue of Article 5.26, paragraph four, c. discharge activity: 1. a body of surface water, 2. a water treatment plant, … “	Updating of environmental permits

Living Environment Activities Decree (Bkl)

Bkl Article	**Definition**	**Direct Link**
Article 2.11	Specific duty of care	Artikel 2.11 Besluit activiteiten leefomgeving
Article 3.1	“ 1. The discharge of substances, water or heat into a surface water body from	Artikel 3.1 Besluit activiteiten leefomgeving

	an environmentally harmful activity as referred to in this chapter is a discharge activity to a surface water body as referred to in Article 2.1. 2. The discharge of substances, water or heat to a purification plant originating from an environmentally harmful activity as referred to in this chapter is a discharge activity to a purification plant as referred to in Article 2.1."	
Article 16.1	"a. water abstraction activities for industrial uses of more than 150,000 m3/year of water or for public drinking water supply to the extent that it concerns: 1°.the extraction of groundwater by a facility intended for that purpose; …"	Artikel 16.1 Besluit activiteiten leefomgeving
Article 16.3	"This section applies to water abstraction activities for industrial uses of more than 150,000 m3/year of water or for public drinking water supply, to the extent that they involve: (a) the extraction of groundwater by a facility intended for that purpose; …"	Artikel 16.3 Besluit activiteiten leefomgeving
Article 16.4	" The prohibition referred to in Section 5.1(2) of the Act to carry out a water abstraction activity without a licence applies to the activities referred to in Section 16.3."	Artikel 16.4 Besluit activiteiten leefomgeving

Water Act (Waterwet)

WA Article	**Definition**	**Direct Link**
Article 7.1	" In this chapter and the provisions based thereon, unless otherwise provided, the following definitions shall apply: … Discharge: the introduction of waste, pollutants or harmful substances into a body of surface water; …"	Artikel 7.1 Waterwet
Article 7.2	" 1. Under the name pollution levy, a levy shall be levied with respect to discharging into a surface water body managed by the State.	Artikel 7.2 Waterwet

	2. With respect to discharges into a surface water body managed by a Water Board, the general board of such Water Board may levy a levy under the name of Pollution Levy. 3. The following may be subjected to the levy: … with regard to **discharging through a sewer or a purification technical work**: the person in charge of that sewer or purification technical work; …"	

Water Authorities Act (Waterschapswet)

WAA Article	**Definition**	**Direct Link**
Article 122c	"For the purposes of this chapter and the provisions based thereon, the following definitions shall apply: **purification technical work**: a work for purifying waste water or transporting waste water, other than a sewerage system; … "	Artikel 122c Waterschapswet
Article 122d	The Purification Levy	Artikel 122d Waterschapswet
Article 122e	" The levy is based on the quantity and quality of substances disposed of in a calendar year. "	Artikel 122e Waterschapswet
Article 122f	"One pollution unit represents with respect to: … the quantities by weight of the substance chloride 650 kilograms"	Artikel 122f Waterschapswet