

**CIRCULARITY AND SUSTAINABILITY
MEASUREMENT AND ASSESSMENT OF WATER
AND RESOURCE SYSTEMS INTEGRATION**

**A Thesis Submitted for the
Degree of Doctor of Philosophy**

By

João Miguel dos Santos Ribeiro

**Department of Civil and Environmental
Engineering, Brunel University London**

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Dedicated to my friend Ricardo Marques

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Abstract

Decoupling resource consumption from economic growth and development is essential for long-term sustainability. Water, being a critical resource for sustaining ecosystems and supporting human health and well-being, holds significant social and economic value. However, due to linear consumption practices, water stress is becoming increasingly prevalent, leading to disruptions in essential services. Desalination has emerged as a prominent solution to address water scarcity and meet the growing demand for water across various sectors. Despite its potential, desalination faces significant environmental and economic challenges. While assessment methodologies have been widely employed to evaluate the environmental, economic, and social impacts of desalination systems, they often focus primarily on consequential effects. As the desalination industry embraces circular strategies like Minimal Liquid Discharge (MLD) and Zero Liquid Discharge (ZLD), there is an increasing need to evaluate the intrinsic circularity of these systems. Integrating this assessment is crucial for ensuring that desalination aligns effectively with Circular Economy (CE) principles, promoting long-term sustainability. To address this need, a systematic and comprehensive methodological approach was developed to measure the intrinsic circularity of desalination systems. This approach incorporates CE principles, such as resource flow traceability, which assigns circular and linear properties to flows associated with the desalination process, and assesses the circular value created by actions implemented in the system. The method identifies benefits and hotspots in various system configurations, including conventional desalination, MLD, and ZLD systems. Furthermore, by adopting MLD and ZLD strategies to reduce brine discharge and improve water recovery, the desalination sector is transforming into multifunctional product systems. A criterion-based Life Cycle Assessment framework was developed and applied to evaluate these multifunctional desalination systems. The results revealed that different assessment approaches (e.g., global vs. individual co-production) yield varying outcomes. However, the analysis demonstrated that brine, as a secondary product, can alleviate environmental pressures associated with conventional systems, such as those in the mining and chemical industries. Additionally, a circularity assessment conducted on the integration of desalination systems into the ceramic industry highlighted optimisation opportunities through scenario analysis. Ultimately, this research provides valuable insights into the performance and

impact of water and resource recovery systems, like desalination, in contributing to sustainability.

Table of Contents

Acknowledgements	v
Abstract.....	vii
Table of Contents	ix
List of Figures.....	xiii
List of Tables	xvi
List of Abbreviations	xix
1 Introduction	1
1.1 Research motivation	1
1.2 Overview of the research programme	5
1.2.1 Research questions addressed	5
1.2.2 Aims and objectives	6
1.2.3 Thesis outline	7
2 Literature Review	10
2.1 Introduction – desalination sector challenges and progress	10
2.2 Methodology	13
2.2.1 Water Systems Assessment.....	13
2.2.2 Current methodologies for assessing the desalination sector	14
2.2.3 Circular Economy and desalination sector	15
2.2.4 How can Intrinsic circularity be measured?.....	17
2.2.5 Sustainability assessment.....	24
2.2.6 Multifunctionality	25

3	Towards Circular Desalination: A New Methodology for Measuring and Assessing Resource Flows and Circular Actions.....	26
3.1	Introduction	26
3.2	Methodology	28
3.3	Resource flow characterisation	29
3.3.1	Water inflow	29
3.3.2	Water outflow	31
3.3.3	Ions inflow	33
3.3.4	Ions outflow	35
3.4	Resource flow indicators	37
3.5	Circular actions	39
3.5.1	Actions that create added value	40
3.5.2	Actions that contribute to value retention	41
3.5.3	Actions that contribute to value recovery	42
3.5.4	Actions that regenerate lost values	42
3.6	Circular action indicators	43
3.7	Application of Developed Methodology	47
3.8	Circularity indicators.....	48
3.8.1	Resource flow indicators and calculation	48
3.8.2	Circular actions and calculation.....	51
3.9	Scenario analysis	54
3.9.1	Scenario 1.....	55
3.9.2	Scenario 2.....	57
3.9.3	Scenario 3.....	57
3.10	Summary of main findings	60

4	Environmental Impact Assessment of Multifunctional Desalination Systems	61
4.1	Introduction	61
4.2	Methodology	64
4.2.1	Rationale for Framework development	64
4.2.2	Framework for dealing with multifunctionality.....	65
4.2.3	Case study - MLD system.....	70
4.2.4	Goal and scope	72
4.2.5	Multifunctionality	72
4.2.6	Impact assessment.....	76
4.2.7	Life Cycle Inventory (LCI).....	76
4.2.8	Assumptions.....	78
4.3	Results and discussion.....	79
4.3.1	System expansion (criterion 2)	79
4.3.2	Partitioning (criterion 3)	81
4.4	Limitations	85
4.5	Summary of main findings.....	86
5	Circularity Assessment of Industrial Heat Exchanger and Water Treatment Systems	
	Integration	87
5.1	Introduction	87
5.2	Methodology	90
5.2.1	Circularity framework.....	90
5.2.2	Case study	91
5.2.3	System development	92
5.2.4	Resource flows.....	95
5.2.5	Circular action.....	97

5.2.6	Circularity measurement.....	98
5.2.7	Circularity assessment	101
5.3	Results and discussion.....	101
5.3.1	Circularity assessment	101
5.4	Summary of main findings.....	107
6	Conclusions and Recommendations for Future Work.....	108
6.1	Conclusion.....	108
6.1.1	Research question 1	108
6.1.2	Research question 2	110
6.1.3	Research question 3	111
6.1.4	Research question 4	113
6.2	Recommendations for Future Work.....	114
	References.....	117
	List of Publications	133
A	Appendix.....	136
B	Appendix.....	153
C	Appendix.....	163

List of Figures

Figure 1.1 – Thesis philosophy.....	9
Figure 2.1 – Conventional desalination system (a) and ZLD/MLD (b) systems concepts.....	16
Figure 2.2 – Circularity assessment framework	19
Figure 2.3 – The conceptual desalination life cycle stages.....	20
Figure 3.1 – MLD system scheme, inputs and outputs. Blue: seawater; Dark blue: concentrate; Light blue: permeate; Yellow: electricity; Orange: waste heat; Purple: chemicals; Grey: Products	48
Figure 3.2 – Circular water and ions inflow (a), outflow (b), total circular flow (c), recovery efficiency (d), and renewable and recovered energy contribution (e) indicators for the MLD system.	50
Figure 4.1 – The criterion LCA-based framework for multifunctional desalination systems.	66
Figure 4.2 – Example of an applied subdivision approach to a multifunctional desalination system.	67
Figure 4.3 – Example of multifunctional desalination system with a high level of integration. All the co-product processes are interdependent in a closed loop. The water recovery process is connected to the NaOH and HCl recovery process which is connected to the Mg recovery which is connected to the water recovery process.	68
Figure 4.4 – Example of a system expansion approach. The FU is expanded to the stoichiometry of the production, and the impacts are compared with the same FU for reference systems.	68
Figure 4.5 – Example of applying physical and economic partitioning in the assessment of a multifunctional system that produces water and NaCl. The percentages are physical (PF) and economic (EF) factors, they do not regard co-product production.	70
Figure 4.6 – MLD system scheme: Blue colours represent the seawater and intermediate flows (Seawater, concentrate and permeate); purple colour represents chemicals/consumables	

flows (NaOH, HCl and antiscalant flows); yellow colour represents the electricity flows while the orange represents the waste heat flow; grey colour represents the co-products flows (desalinated water, NaCl, $Mg(OH)_2$, $Ca(OH)_2$, Na_2SO_4 and HCl).	71
Figure 4.7 – Boundaries of the MLD system.....	73
Figure 4.8 – Boundaries of system expansion reference scenario.	73
Figure 4.9 – Global Warming (a), Fine Particulate Matter Formation (b), Terrestrial Ecotoxicity (c), Terrestrial Acidification (d), Marine Ecotoxicity (e) and Fossil Resource Scarcity (f) impacts of the MLD and reference systems with the system expansion.	80
Figure 4.10 – Contribution analysis of Global Warming results of the MLD products with different approaches using physical partitioning (PP) and economic partitioning (EP).....	82
Figure 4.11 – Individual comparison of Global warming results of the desalinated water (a), NaCl (b), $Mg(OH)_2$ (c), $Ca(OH)_2$ (d), Na_2SO_4 (e) and HCl (f) products of the MLD system with different approaches using physical (PP) and economic partitioning (EP), and the corresponding reference products.	85
Figure 5.1 – Methodological framework for measuring and assessing circularity adapted from Nika et al. (2022).	91
Figure 5.2 – Processes and flows of the ceramic industry under investigation. RE: renewable and recovered energy; NRE: non-renewable energy.	92
Figure 5.3 – Processes and flows of the ceramic industry with the iWAYs systems integration under assessment (Scenario A). RE: renewable and recovered energy; NRE: non-renewable energy.....	94
Figure 5.4 – Processes and flows of the ceramic industry with the iWAYs systems and rooftop runoff rainwater harvesting integration under assessment (Scenario B). RE: renewable and recovered energy; NRE: non-renewable energy.....	95
Figure 5.5 – CWI, CWO, CWF, WWR, REC, WUI (a) and OWC (b) scores for baseline, scenario A and B.	103
Figure 5.6 – Water cost saving (a), fuel cost saving (b), total saved cost (b) and CO_2 reduction (c) indicators for scenarios A and B.	103

Figure 5.7 – Average, maximum and minimum for the WWR indicator (a) and the monetary value of the recovered water (condensed and rainwater) (b) during the year.....	105
Figure 5.8 – Average, maximum and minimum for the WWR indicator and the monetary value of the recovered water (condensate water and rainwater) in all the annual months. Scenario 1 (no NF use) (a and c) and scenario 2 (no UF and NF use) (b and d). The red line in figures c and d means when the recovered water overtakes the freshwater demand.....	106
Figure B.1 – Endpoint categories of the MLD system (FU = 1 kg of water + 0.0484 kg of NaCl + 0.0037 kg of Mg(OH) ₂ + 0.0004 kg of Ca(OH) ₂ + 0.0093 kg of Na ₂ SO ₄ + 0.0579 kg of HCl).	153
Figure B.2 – Contribution analysis of the resources to the MLD system.	159

List of Tables

Table 3.1 – Resource flow indicators selected for the circularity measurement and the respective equations.	39
Table 3.2 – CE actions, indicators and equations for desalination systems.	46
Table 3.3 – Comparison of the ion concentration of seawater and discharge, and the linear fraction of the ions in the discharge flow.....	50
Table 3.4 – Circular Material Productivity and Value-based resource efficiency indicators for the MLD system.....	51
Table 3.5 – Score of the circular action indicators for the MLD system.....	53
Table 3.6– Brackish water composition.....	55
Table 3.7 – Resource flow characterisation and circular actions results of the three scenarios.	59
Table 4.1 – Physical factors (PF) and economic factors (EF) of the system approach for the MLD system.....	74
Table 4.2 – Physical factors (PF) and economic factors (EF) of the process approach for the MLD processes.	75
Table 4.3 – Life cycle inventory of the MLD system for 1 year of operation.....	77
Table 5.1 – Operational and maintenance characteristics and requirements of the UF and NF units.....	94
Table 5.2 – Resource flow indicators.	97
Table 5.3 – Circular actions, indicators and equation.....	98
Table 5.4 – The estimated potential collected rooftop runoff rainwater for the ceramic industry.	100
Table 5.5 – Prices and cost data for calculation of economic indicators.	101
Table A.1 – Factors considered for the investment calculation.....	136
Table A.2 – Multi-media filtration mass and energy balances.	136

Table A.3 – Nanofiltration mass and energy balances.	137
Table A.4 – Operational data of the Nanofiltration process.	138
Table A.5 – Multi-effect distillation mass and energy balances.....	139
Table A.6 – Operational data of the Multi-effect distillation process.	140
Table A.7 – Thermal crystalliser mass and energy balances.	141
Table A.8 – Operational data of the Thermal Crystalliser.....	142
Table A.9 – Multiple feed plug flow reactor mass and energy balance.	143
Table A.10 – Operational data of the Multiple feed plug flow reactor.....	144
Table A.11 – Nanofiltration 2 mass and energy balances.	144
Table A.12 – Operational data of the Nanofiltration 2.	145
Table A.13 – Eutectic freeze crystalliser mass and energy balances.....	146
Table A.14 – Electrodialysis with bipolar membrane mass and energy balances.	147
Table A.15 – Operational data of the Electrodialysis with bipolar membrane.....	148
Table A.16 – Costs of the resources used in the circularity assessment.	149
Table A.17 – Water and ions inflow characterisation for the MLD system.	150
Table A.18 – Water and ions outflow characterisation for the MLD system.	151
Table A.19 – Global warming contribution analysis.	152
Table B.20 - Reference system for desalinated water production.	153
Table B.21 – Reference system for NaCl production (Ecoinvent process name: sodium chloride production, powder RER).	154
Table B.22 – Reference system for Mg(OH) ₂ production (Ecoinvent process name: magnesium oxide production RER; it is not the complete process of Mg(OH) ₂ , it stops in the MgO production).	155
Table B.23 – Reference system for Ca(OH) ₂ production (Ecoinvent process name: limestone quarry operation CH (process I); limestone production, crushed, washed CH (process II);	

quicklime production, in pieces, loose CH (process III); lime production, hydrated, loose weight CH (process IV)).	156
Table B.24 – Reference system for the Na ₂ SO ₄ production (Ecoinvent process name: sodium sulfate production, from natural sources RER).	157
Table B.25 – Reference scenario for the HCl production (Ecoinvent process name: hydrochloric acid production, from the reaction of hydrogen with chlorine RER).	158
Table B.26 – Non-Normalised environmental results of system expansion approach of the MLD system.	158
Table B.27 – Non-normalized environmental impacts of the process physical partitioning of the MLD system.	159
Table B.28 – Non-normalized environmental impacts of the process economic partitioning of the MLD system.	160
Table B.29 – Non-normalized environmental impacts of the system physical partitioning of the MLD system.	160
Table B.30 – Non-normalized environmental impacts for the system economic partitioning of the MLD system.	161
Table B.31 – Non-normalized environmental impacts of the reference scenarios.	162
Table C.32 – Freshwater and rainwater quality	163

List of Abbreviations

BCR – Benefit-Cost Ratio

Ca(OH)₂ – Calcium Hydroxide

CE – Circular Economy

CPCI – Circular Process Chemical Intensity

CWI – Circular Water Inflow

CWO – Circular Water Outflow

EDBM – Electrodialysis Bipolar Membrane

EF – Economic factor

EFC – Eutectic Freeze Crystalliser

EP – Economic Partitioning

FU – Functional Unit

GHG – Greenhouse Gases

GW – Global Warming

HCl – Hydrochloric Acid

HPCE – Heat Pipe Condenser Economiser

HPHE – Heat Pipe Heat Exchanger

ISO – International Organization for Standardization

LCA – Life Cycle Assessment

LCC – Life Cycle Costing

MCDM – Multi-criteria Decision Making

MED – Multi-Effect Distillation

MFA – Material Flow Analysis

MF-PFR – Multi-feed Plug Flow Reactor

Mg(OH)₂ – Magnesium Hydroxide

MLD – Minimal Liquid Discharge

MMF – Multi-Media Filtration

NaCl – Sodium Chloride

NaOH – Sodium Hydroxide

NF – Nanofiltration

OWC – Onsite Water Circularity

PF – Physical Factor

PP – Physical Partitioning

REC - Recovered Energy Contribution

RO – Reverse Osmosis

RPCI – Renewable Process Chemical Intensity

SA – Sustainability assessment

SDGs – Sustainable Development Goals

SFA – Substance Flow Analysis

SLCA – Social Life Cycle Assessment

TC – Thermal Crystalliser

TEA – Techno-Economic Analysis

UF – Ultrafiltration

WEE – Waste Eco-Efficiency

WUI – Waste Utilisation Index

WWR – Water Withdrawal Reduction

WWTP – Wastewater Treatment Plant

ZLD – Zero Liquid Discharge

1 Introduction

1.1 Research motivation

Nowadays, socio-economic systems are based on linear economy principles, meaning that a product is manufactured, consumed and disposed of. This linear production concept sustains unneeded resource losses in many ways: production chain and end-of-life waste, highly intensive energy use and damage to ecosystems (Michelini et al., 2017).

Imprudent resource consumption must be decoupled from economic growth and development. The Circular Economy (CE), as an alternative model to the linear economy model, encourages resource efficiency, to decrease waste generation and to improve environmental, economic and social sustainability (Nika et al., 2020). The CE concept has received interest on the agenda of policymakers to address sustainability issues. This is clear in the European Circular Economy package and the Chinese Circular Economy Promotion Law. CE turned out to be and still is an important area of research for academia as the number of articles and journals on this subject has increased in the last decade. CE carries opportunities which have also gained attention from companies and their stakeholders due to their associated value (Geissdoerfer et al., 2017). It is aligned with different United Nations' Sustainable Development Goals (SDGs), and different action plans for CE and reports on its potential for business have been issued (Alaerts et al., 2019).

In a similar way to materials, water has a linear usage. Take, use and discharge is a common strategy applied in the water sector (Arup, 2019). Water is abstracted from rivers, reservoirs, and groundwater aquifers; used by agriculture, industry, society and the environment; and then released to the water basin directly or via a treatment facility. This current scenario is often inefficient as water is lost, polluted and wasted (Frijns et al., 2024). Water, as a resource, is arguably the most vital for sustaining ecosystems and the services which are given for human health and well-being (UNEP, 2009), and therefore it has a high value (e.g. social and economic) as a universal resource. Moreover, water has a material and energy carrier function (Nika et al., 2020). Activities such as domestic, agricultural and industrial sectors demand water, and in most places of the world, the demand is met by abstracting groundwater.

Currently, the availability of freshwater has turned out to be an important problem in many parts of the world. Water demand is greater than the natural recharge capacity of groundwater sources. If no changes occur, the global water demand is predicted to exceed viable resources by 40% by 2030 (Wintgens et al., 2016). In Europe, water stress affects 20% of the European territory and 30% of the European population. In Southern Europe, countries like Greece and Cyprus have to deal with severe water stress problems with water consumed by different sectors – agriculture, public water supply and tourism – therefore causing pressure on water resource availability. In other parts of Europe, water stress situations are not so frequent, however occasionally they occur in specific hotspots due to the pressure caused by water use for electricity production, the industrial sector, public water supply and mining operations (EEA, 2021). In worldwide terms, a country is considered “water-stressed” if per capita available water resources are in the range of 1000–1700 m³/year and “water-scarce” if they are less than 1000 m³/year (Damkjaer and Taylor, 2017).

A transformative change in the use of new practice models is required to maximize the obtaining of value from water cycles at all scales such as river basins, city, industrial units and buildings to increase the efficiency of utilisation of water resources and to prevent further degradation of the environment (Arup, 2019). Three CE principles applicable to water systems were defined by the Ellen MacArthur Foundation:

- (1) Design out waste and pollution by optimising the amount of energy, minerals and chemicals used in the operation of water systems and the consumptive use of water within the sub-basins to adjacent sub-basins like agriculture. Implementation of solutions which have productivity without using water;
- (2) Keep products and materials in use through the optimisation of resource yield and value generated in the interfaces of water systems with other systems;
- (3) Regenerate natural systems by maximising environmental flows via water use reduction, preserving and enhancing the natural capital and ensuring minimal disruption of natural water systems from human interactions and usage.

Although CE concepts are increasingly well-established, they continue mainly in the early stages of implementation in most sectors. Technological progress has accelerated the implementation of CE models in some areas, but progress is often slow. The main challenges

to achieving a CE are not only technological but also governance related. For example, in the water sector, emerging technologies allow the recovery of many resources, however, concerns over economic feasibility can discourage their uptake, with uncertainty around the application of policy and regulatory frameworks, and there is a need for long-term engagement with key stakeholders and the wider public. In addition, it is also becoming apparent that circular water systems challenge current water governance practices. Water governance is defined by the Organisation for Economic Co-operation and Development as ‘the range of political, institutional, and administrative rules, practices, and processes (formal and informal) through which decisions are taken and implemented, stakeholders can articulate their interests and have their concerns considered, and decision-makers are held accountable for water management’ (Frijns et al., 2024).

Despite the challenges, CE can guide water innovations to technology and regulations which aid activities for water reuse and recycling. In the last 25 years, many important factors have highlighted the importance of recovering resources from wastewater. Even though waste recycling and value-adding techniques are gradually being implemented across Europe, harmonization is needed as the level of implementation is not consistent (Koseoglu-Imer et al., 2023). The resilience of water resources can be increased by diversifying management strategies. These strategies embrace green solutions, such as forest and wetland conservation, and grey solutions, such as increasing supplies (desalination, wastewater reuse), enhancing storage in surface reservoirs and depleted aquifers, and transporting water (Scanlon et al., 2023).

To fill the gap in the water balance, a nonconventional water resource practice named desalination is gaining importance in the world (Xevgenos et al., 2019). Among the water supply enhancement systems, desalination of seawater and brackish water has received the most attention and is increasingly seen as a feasible option to meet primarily domestic and municipal needs (Jones et al., 2019).

Recent studies suggest that more than 21,000 seawater desalination plants exist around the world. Together they produce around 99,000,000 cubic meters of desalinated water daily (Eyl-Mazzega and Cassignol, 2022). In 2019, the market value of desalinated water was 12.8 billion dollars (Panagopoulos and Haralambous, 2020). The water from a desalination plant can be consumed by different applications such as municipal use, industries, power stations, irrigation, tourism and others (Xevgenos et al., 2016). Countries like Saudi Arabia, the United Arab

Emirates, Kuwait, and Israel have been heavily dependent on desalination for the last five decades. About 60 to 80% of the water for domestic use in these countries is obtained from seawater desalination (Ayaz et al., 2022).

Despite being an attractive market, desalination still embraces different challenges at environmental and economic levels. Desalination is a water treatment that is often chemically, energetically and operationally intensive, therefore requiring a significant injection of capital, engineering expertise and infrastructure (Shannon et al., 2008). Moreover, current desalination plants are not qualified to reduce brine discharge. Desalination technologies are classified into two categories: membrane-based technologies and thermal-based technologies (Panagopoulos, 2021a) which have a water production efficiency between 40-55% and 25-30%, respectively. This means that the residue of the water is not recovered and is lost as brine. It was calculated that the amount of global brine produced is more than 150 million cubic meters per day (Eyl-Mazzega and Cassignol, 2022). Several plants and facilities located on the coast for seawater desalination frequently discharge brine back into the sea, potentially instigating problems with the ecosystem and the environment. There are different options to deal with the brine such as sewage, ocean or surface water discharge, injection into deep wells, and evaporation ponds (Ogunbiyi et al., 2021). However, conventional treatment strategies sometimes may fail to meet strict regulations and fit the purpose of a circular economy (Cipolletta et al., 2021).

Although desalination is increasingly being more extensively implemented (Panagopoulos and Giannika, 2023), there are still barriers to its adoption around the world due to its cost, energy requirements, low expertise and footprint (Salinas-Rodriguez et al., 2021). Additionally, emerging technologies (e.g. vapour compressor, electrodialysis, membrane distillation, and others) are being studied in order to become part of the desalination group of technologies. Moreover, Minimal Liquid Discharge (MLD) and Zero Liquid Discharge (ZLD) strategies seem to promote the circular economy, which is a sustainable step and economic model, that the European Union has engaged (Panagopoulos and Giannika, 2023). Therefore, it is indispensable to assess desalination technologies/systems and their environmental, economic and social impacts. Several works have assessed desalination systems through a techno-economic approach (Morgante et al., 2022; Panagopoulos, 2022, 2021) and sustainability framework by integrating environmental, economic and social aspects (Ibrahim et al., 2018).

What seems lacking are studies that measure the intrinsic circularity performance of desalination systems while moving the desalination sector towards sustainability. The application of the concept of circular economy is an acknowledged method to achieve sustainability development (Micari et al., 2020). Geissdoerfer et al., (2017) conclude that it is essential to understand the relationship between the Circular Economy and sustainability and their influences on performance e.g. innovative systems by investigation. Additionally, it is important to analyse how these intrinsic circularity aspects or circular initiatives perform against the triple bottom line, which after the World Summit in 2022 is referred to as the balanced integration of economic, environmental and social performance.

1.2 Overview of the research programme

1.2.1 Research questions addressed

1. How are desalination systems currently evaluated and assessed in terms of performance and sustainability? In what ways is the circular economy incorporated and measured within desalination systems? Is there an issue from a life cycle assessment perspective when multifunctional desalination systems are observed? **(Chapter 2)**
2. How can resource flows be tracked in the desalination systems? How does measuring the performance of the value chain of a desalination system provide insightful information for decision-making? Which are the main hotspots in the desalination systems? **(Chapter 3)**
3. How is multifunctionality addressed in the desalination systems? How do different approaches impact the environmental burden of products and co-products from multifunctional desalination systems? Can the recovery of co-products from brine become a secondary source of minerals with a lower environmental burden than conventional minerals? **(Chapter 4)**
4. Does the resource flow traceability and circular action performance measurement support the integration and optimisation of systems in a ceramic industry? **(Chapter 5)**

1.2.2 Aims and objectives

The desalination sector is focusing on introducing systems that reduce energy consumption and increase productivity. Moreover, the recovery of resources from brine through Zero Liquid Discharge (ZLD) and Minimal Liquid Discharge (MLD) concepts have been recognised as promising steps to move the sector towards sustainability. The literature shows that the assessment of desalination systems focuses on consequential aspects, such as environmental and economic performance, leaving intrinsic circularity aspects out of the assessment. The traceability of resources is not straightforward, and it requires definitions to assign circular and linear properties to the resource flows within a desalination system.

Furthermore, resource recovery from the brine generates multi-functional systems, meaning that co-production is observed. However, the lack of assessments focused on the co-production of desalination systems and the potential impacts of different approaches (e.g., system expansion, partitioning) raises an important question: How should the multifunctionality of desalination systems be addressed?

The industrial sector has been integrating circular strategies to reduce freshwater withdrawal and non-renewable energy consumption. Therefore, it is required to integrate resource traceability and the measurement of the value created in order to understand the impact of such circular strategies in the industries.

Therefore, the goal of this thesis is to develop and apply comprehensive methodological assessment approaches that can facilitate the characterisation, planning and optimisation of desalination systems. A crucial aspect is to identify hotspots and benefits objectively. This includes providing robust and clear definitions for classifying resources, enabling the traceability of linear and circular flows in desalination systems, and measuring the performance of circular actions to calculate the created circular value. Through scenario analysis, valuable insights can be extracted from the resource flow classification and circular action performance to support decision-making. It is also important for the goal of this thesis to demonstrate the impact of multifunctionality on environmental assessment and investigate if the recovery of products from brine is environmentally competitive against conventional practices.

1.2.3 Thesis outline

The thesis consists of several chapters, including an analysis of the challenges and advancements in the desalination sector, the development of a comprehensive methodology for evaluating the intrinsic circularity of desalination systems, an investigation into assessing the environmental impact of multifunctional desalination systems, and a circularity assessment of water systems and heat pipe heat exchangers in industrial applications.

Chapter 2: Moving the desalination sector towards Circular Economy: challenges, progress and assessment.

This chapter discusses the various challenges that the desalination sector faces. Resource demand and waste production are the key barriers the sector aims to overcome by adopting circular and sustainable strategies. Chapter 2 describes the concepts of Minimal Liquid Discharge (MLD) and Zero Liquid Discharge (ZLD) as strategies to guide the sector towards a Circular Economy (CE) and sustainability. While both strategies have been promoted as circular, only their consequential aspects have been measured. The lack of intrinsic circularity measurement in order to support the sustainable transition of the sector is highlighted. Therefore, methodologies and tools with the potential to calculate the intrinsic circularity value of desalination systems in a systematic format are identified and described. The chapter also discusses the importance of combining intrinsic and consequential assessments for the desalination sector.

Chapter 3: Towards Circular Desalination: A New Methodology for Measuring and Assessing Resource Flows and Circular Actions

This chapter proposes a novel framework for assessing the circular CE performance of desalination systems. Definitions for classifying resource flows are presented, enabling the traceability of both linear and circular flows. Additionally, circular actions are identified, facilitating the measurement of the circular performance (value created) of desalination systems. Resource flow characterisation and circular actions are assessed through specific indicators. By integrating a systemic indicator selection and calculation approach, this methodology aims to provide a comprehensive evaluation of the intrinsic circularity of desalination systems. A scenario analysis is also applied to determine whether the methodology can capture changes in the system and be applied to various desalination schemes, such as

conventional and ZLD. The objective is to optimise desalination systems and integrate circularity and sustainability indicators, allowing desalination plants to quantify and proactively improve their impact on resource efficiency, carbon footprint reduction, energy and chemical consumption and material circularity effectively.

Chapter 4: Environmental Impact Assessment of Multifunctional Desalination Systems

Chapter 4 evaluates the environmental performance of desalination processes using LCA. The desalination sector adopts MLD and ZLD systems to enhance circularity by reducing brine discharge and improving water recovery, thus transforming these systems into multifunctional product systems. Therefore, the co-production of valuable recovered products requires a fair environmental impact assessment. A criterion-based LCA framework, aligned with the International Organization for Standardization (ISO) 14044 hierarchy, is developed and applied to assess a multifunctional desalination system that co-produces desalinated water, sodium chloride, magnesium hydroxide, calcium hydroxide, sodium sulphate, and hydrochloric acid. Multifunctionality is addressed using system expansion and partitioning (both physical and economic) approaches, leading to different functional units. Various modelling perspectives are explored for the two partitioning approaches. Additionally, a main objective is to investigate the potential of brine as a secondary source of chemical products.

Chapter 5: Circularity Assessment of Industrial Heat Exchanger and Water Treatment Systems Integration

Lastly, resource flow classification and circular action identification approach were applied to the integration of a Heat Pipe Heat Exchanger and a water treatment system in a ceramic industry. Additionally, rooftop rainwater harvesting is integrated into the industry and included in the assessment. A benchmark assessment is conducted by comparing the industry with and without the integration of the Heat Pipe Heat Exchanger, water treatment system, and rainwater harvesting. Furthermore, a scenario analysis is performed to identify strategies for improving circular actions.

Figure 1.1 illustrates the main objective of the thesis and the connection between the chapters. Chapter 2 presents the methods used to measure the challenges and progress within the desalination sector, highlighting what is still required to incorporate in assessment methodologies for intrinsic analysis. In chapter 3, a comprehensive methodology is developed

for resource traceability and value created calculation in desalination systems, enabling benefits and hotspot identification and system optimisation through the incorporation of indicators. In chapter 4, the issue of allocation arising from desalination systems with co-production is addressed, allowing the measurement of the environmental impacts of the products from brine and comparison of them with the conventional products. The final chapter integrates the knowledge from Chapters 2 and 3 to assess the circularity of system integration within an industrial context.

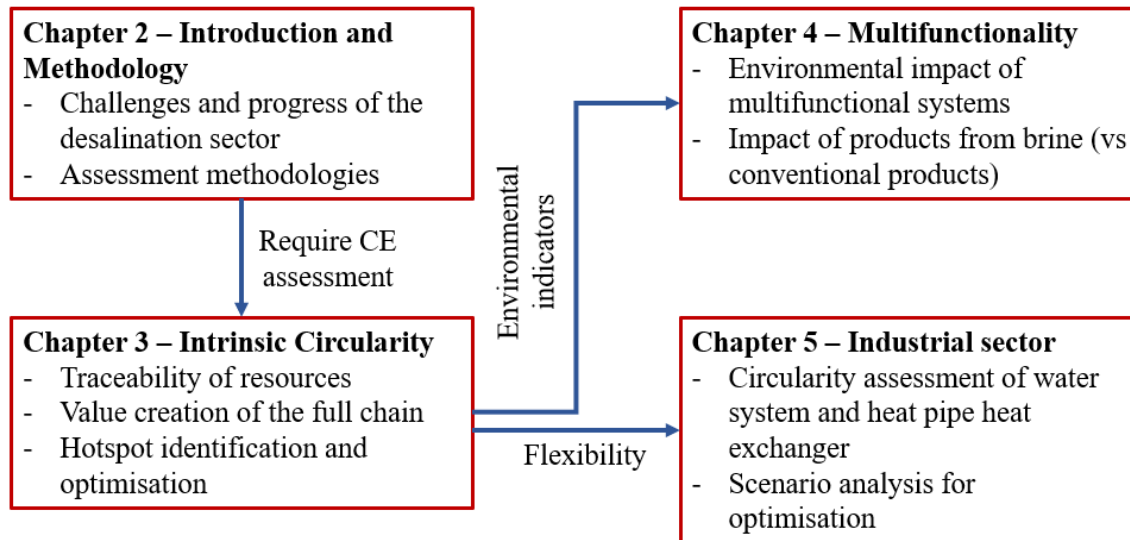


Figure 1.1 – Thesis philosophy.

2 Literature Review

2.1 Introduction – desalination sector challenges and progress

The drastic incremental demand for desalinated water may result in several problems (Alawad et al., 2023) due to specific challenges, mostly associated with relatively high economic costs and diverse environmental concerns (Jones et al., 2019). Additionally, social impacts related to the desalination sector have been addressed, however the social perspective as a barrier is still underrepresented (Tsalidis et al., 2023).

Desalination is an energy-intensive approach for water production, and the fast increase of installed capacity has created an increasing consumption of resources like energy (Jia et al., 2019). Energy demand is the leading cause of the negative environmental impact of desalination (Lee and Jepson, 2021) due to the power production from fossil fuels which emits large amounts of greenhouse gases (i.e., CO₂, CO, SO₂, NO₂, and NO) (Alawad et al., 2023). The energy consumption also impacts the economic performance of a desalination facility, as desalination comes with high energy costs (Li et al., 2018). However, the cost of energy consumption varies on the location, technology implemented and specific energy consumption (Eke et al., 2020).

Another relevant negative aspect of the desalination sector is the waste generated from separating the salt from water. Brine, the by-product of desalination operations, can cause significant adverse effects on marine life and the environment when discharged to the sea (Ogunbiyi et al., 2021). The high salinity content might decrease growth or even increase mortality of flora and fauna (Zhou et al., 2013). Moreover, its safe disposal remains a specific problem and a major technical and economic challenge (Jones et al., 2019). Different brine disposal methods like landfill, evaporation ponds, subsurface injection, sewer disposal, and surface water discharge can affect the cost level of the operation (Shokri and Sanavi Fard, 2023).

In addition, brine can contain residues of chemicals used in the pre-treatment stage of a desalination plant. Chemicals such as antiscalants, biofouling control additives, contaminants from corrosion and others may have significant interim and enduring effects on marine

biodiversity if released in marine ecosystems (Ihsanullah et al., 2021). In addition to the environmental issue, chemicals increase the operational costs of the desalination sector.

New developments in the desalination sector (i.e. technology level) have offered new concepts and approaches to be utilised as a strategic factor to move this type of water supply towards sustainability (Ihsanullah et al., 2021). The supply of clean and sustainable water is one of the primacies of the Sustainable Development Goals (SDGs) (Mironenko et al., 2015), meaning the fulfilment of the necessities of the present without compromising the options of future generations. For the desalination sector, specific commitments to achieve sustainable development include protecting marine species and habitats, building climate resilience in marine ecosystems, maintaining fisheries productivity, and avoiding adverse effects of land-based sources of pollution (Dawoud et al., 2020). According to UNEP-MAP, brine effluent is one of the major emerging threats to the Mediterranean sea environment (Xevgenos et al., 2019). To minimize or even eliminate the need to dispose of brine, the concept of Minimal Liquid Discharge (MLD) and Zero Liquid Discharge (ZLD) systems can lead the way. In addition, the recovery of valuable resources from brine such as minerals, metals and gases is possible (Ayaz et al., 2022). The field of resource recovery from brine (previously regarded as waste) has received attention and was initially proposed in the 1970s, and little progress was achieved in that field up until 2001 (Ogunbiyi et al., 2021). Progress in resource recovery technology in the latest decade has made the recovery of minerals and metals from desalination brine more cost-competitive in comparison to terrestrial mining (Sharkh et al., 2022). Therefore, brine should be classified as an important source of materials and no longer as waste to be disposed of. Magnesium is the most interesting cation in terms of industrial importance and value, which is part of brine composition. It is subjected to a high risk of supply interruption and high economic importance; therefore, magnesium is classified as a “critical raw material” by the European Commission among the 30 most critical raw materials and the value of searching for different ways for its supply is recognised (Fontana et al., 2023).

In addition to water and valuable resource recovery from brine, there is a large potential to harvest energy from brine. The utilisation of osmotic pressure (resulting from the release of Gibbs-free energy due to the mixing of two liquid streams of different salinity levels) has been gaining interest over the last decades (Ogunbiyi et al., 2021). Moreover, integrating desalination technologies with renewable energy sources has the potential to supply sustainable

water for future requirements (Shahzad et al., 2017). Decarbonisation of desalination is a necessary feature of reducing carbon dioxide emissions and mitigating climate change. The European Commission continuously guides policies to increase the share of renewable energy sources by setting targets and capping greenhouse gas (GHG) emissions. Solar energy is of special interest as it is the most abundant permanent source of energy on earth, although other sources of renewable energy such as hydro, wind and geothermal have also been explored (Ahmed et al., 2019). Also, waste heat recovery has received attention as an energy source for thermal desalination technologies like Multi-Effect Distillation (MED). This type of desalination technology can be integrated with low-temperature heat sources as it requires a low top brine temperature. Low grade heat is obtainable in cogeneration plants with diesel generators, steam turbines, nuclear power reactors, and gas turbine power plants. Waste heat can also be recovered from industrial cooling water and exhaust gases, solid waste incinerators, solar ponds and geothermal waters (Liponi et al., 2020).

Another goal is to integrate recycling and reusing processes by recovering products from brine, which then can be recirculated within the desalination system to reduce the use of external chemicals. Pre-treatment and concentration processes are both included in the ZLD and MLD systems. Mostly, gravity settling and filtration for settleable solids are common pre-treatment processes, as well as pH adjustments, nanofiltration, and chemical precipitation. Importantly, these pre-treatment processes also include cleaning steps (e.g. membranes), which are critical for improving performance and extending the life of the process but necessitate the use of chemicals (e.g. hydrochloric acid (HCl)) (Culcasi et al., 2022). Few studies in the literature have shown the potential of recovering chemicals from brine such as sodium hydroxide (NaOH) and HCl, which are integrated with, for example, chemical precipitation-based technologies (Morgante et al., 2024; Zhang et al., 2017). To recover magnesium from brine, magnesium can be precipitated through NaOH addition, however, it increases operational costs (Morgante et al., 2022) and potentially environmental-related issues, unless the NaOH is recovered from brine and recirculated as in (Morgante et al., 2024).

2.2 Methodology

2.2.1 *Water Systems Assessment*

Traditional water management developments, including freshwater supply, water treatment systems, wastewater management, flood mitigation, irrigation, and drainage, have primarily been addressed from a technical civil engineering perspective. However, such developments have increased economic, environmental and societal implications, and this is causing a change in the focus of water management advances. The traditional emphasis on technological optimisation is being converted to include concerns for ecological sustainability, economic balance, technical endurance, and societal acceptance (Bernhardi et al., 2000). Establishing a healthy water cycle is the fundamental approach to fixing water crises and achieving the sustainable usage of water resources (Zhang and Xiong, 2006). Furthermore, the CE concept can maximise the value derived from every resource within the water cycle, supporting the sustainable development of water management systems.

Several tools have been employed to assess the sustainability of water management systems from economic, environmental, and social perspectives. Two main methods for sustainable water management assessment are indicators and indices; and integrated estimation. Water indicators and indices accommodate simple, measurable, and inclusive communication information. A numerical outcome that easily provides relative capacity through situations is the advantage of the indicator method. However, compared with integrated estimations, the indicator method quantifies fewer elements. Integrated estimations use a complete system which includes, for example, cost-benefit analysis, risk analysis and system dynamics models. Systems dynamics models are applied through a framework established on feasibility loops in order to examine water system agreement, usage, and economics, and to understand water system reliability (Javadinejad et al., 2019).

Nika et al., (2022) proposed a novel methodology that integrates an indicator selection process and further benchmark and dynamic assessments for water systems. However, the incorporation of CE concepts like resource flows and circular actions takes the methodology to a higher-level regarding rigour and element coverage. The indicator selection process is composed of three dimensions, which are indicators for circular actions (performance),

resource flow circularity (resources, energy, water and waste) and sustainability impacts (social, environmental and economic). The methodology allows through the indicators, a comparison between a traditional water system and a potential circular water system, and it is also capable of capturing the impact of changes on the water system under investigation. (Renfrew et al., 2024c) developed a framework where CE indicators and sustainability indicators are integrated for a holistic assessment of urban Wastewater Treatment Plants (WWTP). The methodology shows innovation as it integrates clear and robust definitions developed by Renfrew et al., (2024a) that characterise the circular and linear resources flowing through the wastewater treatment system, allowing the traceability of resources like water, carbon and nutrients, showing potential disruptions between human and natural systems.

It seems the WWTP sector has embraced the concept of CE and its analysis and planning sooner than others like the desalination sector. Like the transition of WWTP to Water Resource Recovery Facilities, which consists of expanding functions, and increasing CE strategies to achieve sustainability, the desalination sector is also expanding its functions through potential CE strategies like MLD and ZLD.

2.2.2 Current methodologies for assessing the desalination sector

The desalination technologies are categorised into two groups which are membrane desalination (e.g. Reverse Osmosis (RO)) and thermal desalination (e.g. MED). In addition, there are emerging technologies like membrane distillation and forward osmosis which are under the development phase (Eke et al., 2020). As all desalination technologies are suitable for many end-user applications such as industrial, community and household activities, the selection of an appropriate desalination technology for a particular application is a difficult exercise (Vivekh et al., 2017). The end-users often take into consideration several aspects in the process of selecting desalination technologies such as the production cost, water recovery efficiency, environmental impacts, water purity, energy consumption, and technology reliability (Wang et al., 2019). The feasibility of desalination plants and processes was primarily judged on economics and production reliability with minimal attention to externalities (e.g. GHG emissions). The ‘cost’ of externalities was internalised only when government regulations were created and imposed. However, the production of desalinated water was so overwhelmingly important, and plant capacity so relatively small, that regulations

and enforcement were often of secondary importance (Lior, 2017). Methodological assessments have been applied in the desalination sector to measure such aspects of the processes and externalities.

Assessment modelling can integrate all aspects including technical, economic, environmental, social, and regulatory trends in order to achieve future planning and process improvement (Eke et al., 2020). The techno-economic assessment analyses the consumption of resources (e.g. energy) and the production (e.g. productivity), and the economic performance seeking costs and profits optimisation. A different economic method is the Life Cycle Costing (LCC) analysis, which is a useful methodology for assessing the desalination system's economic viability and implementation strategy (Gao et al., 2021), and the costs of the whole system and product life cycle (Termes-Rifé et al., 2013). Environmentally, Life Cycle Assessment (LCA) is the approach for analysing the environmental consequences of systems and products making it highly relevant for desalination (Alhaj et al., 2022). Regarding social consequences, the Social Life Cycle Assessment (SLCA) is applied as it assesses the social and socio-economic impacts of products. It is in its infancy; however, it has been promoted for use in the holistic approaches of life cycle sustainability assessment (Tsalidis et al., 2023). These types of analyses and assessments help in the planning, selection, operational phases and optimisation of desalination systems and processes under a sustainability scope.

2.2.3 Circular Economy and desalination sector

Under the scope of the sustainability pillars, the consequences of the desalination sector have been intensively measured, assessed and catalogued. However, a shift in the sector is happening which consists of adopting CE concepts such as increasing resources and systems efficiency, closing resource loops and avoiding pollution. They fit the CE principles created for sustainable water management by Arup, Antea Group and Ellen MacArthur Foundation which are Designing out Externalities, Keep Resources in Use and Regenerate Natural Capital (Arup, 2019).

In 2020, the European Commission adopted a new CE action plan from the European Green Deal. Particularly, wastewater (e.g. brine) recycling and reuse is an optimistic solution that can be achieved using the ZLD or MLD concept, enabling the European Union targets to be met (Culcasi et al., 2022). Due to the conservation and protection of water bodies, and water

situations like shortages, brine has received attention worldwide. Review articles have been published in the last few years focusing on brine management, ZLD and MLD and product recovery. Developments on analysis under the circular economy umbrella are required as the ZLD and MLD systems potentially facilitate the transition to a circular economy, wherein waste generation is minimised, carbon dioxide emissions are reduced, and resource usage is more competent (Panagopoulos and Giannika, 2022). Figure 2.1 shows the difference between a conventional desalination system (Figure 2.1 – a) that uses fossil energy, dispose brine and has low water recovery rate, and an MLD/ZLD system (Figure 2.1 – b) that integrates renewable energy, recovers valuable products from brine and has a high water recovery rate.

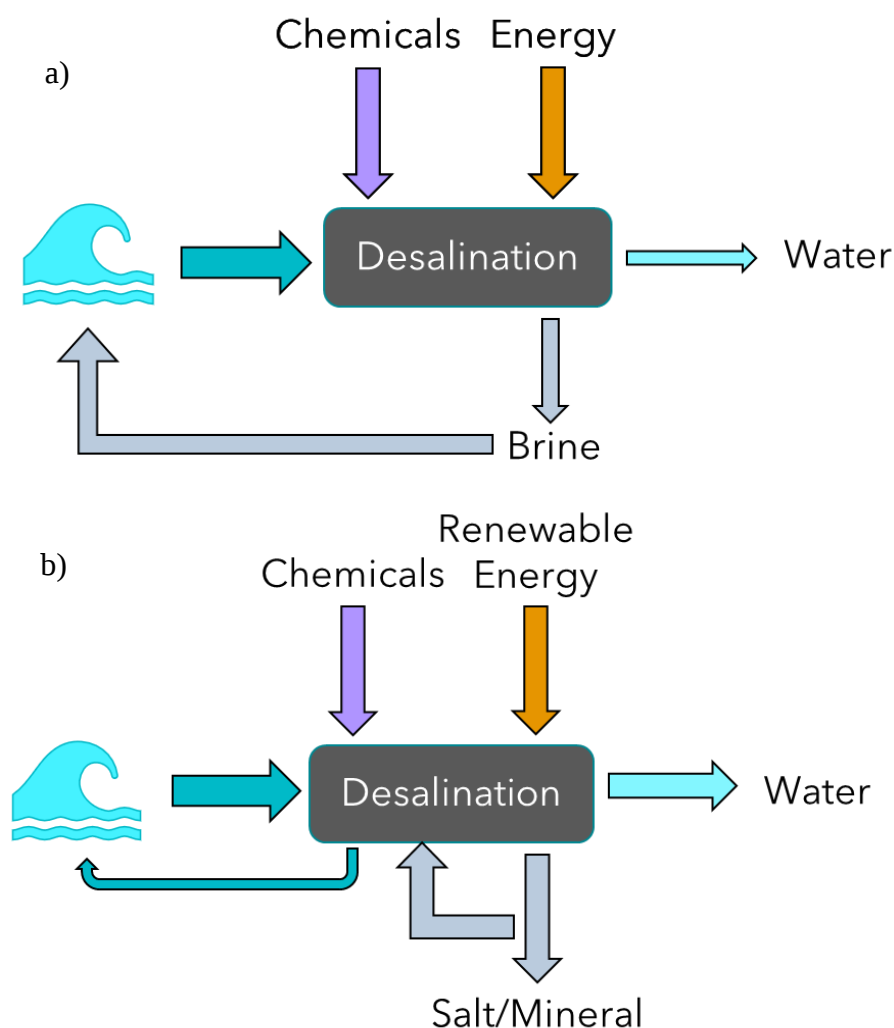


Figure 2.1 – Conventional desalination system (a) and ZLD/MLD (b) systems concepts.

Despite the efforts to promote the circular shifting of the desalination sector, assessment methodologies under the scope of circularity that perform a critical and comparative analysis by measuring the intrinsic circularity value of ZLD and MLD systems for multiple value-added product recovery do not exist. The intrinsic circularity value aims to increase circular sourcing, and productivity, and reduce the demand for resources and waste generation through closing loops. The ultimate goal of intrinsic performance is reducing the negative consequences of the sector. However, in some cases, improving intrinsic circularity performance might generate negative environmental impacts along the life cycle (Saidani et al., 2017) making the assessment of circularity important for the trade-off identification. This is relevant as it has been assumed that MLD and ZLD systems are inherently circular, however, there are important aspects to take into consideration when planning or operating a desalination system. Generally, there are different variations in the design, plan and operation of ZLD systems and therefore, each system is unique. For instance, brine concentrators and crystallisers, where distillate is condensed and collected, are thermal processes which demand a substantial amount of energy. On the other hand, processes like RO consumes significantly less energy. The disadvantages of membrane technologies are membrane fouling and also its replacement and disposal (Ogunbiyi et al., 2021). Such aspects and others require attention as they impact the intrinsic performance of the system, hence circularity performance.

2.2.4 How can Intrinsic circularity be measured?

The engineering and technological characteristics are no longer barriers that obstruct the circular transition, in reality, it is a non-existence of planning and performance analysis and cautious company culture viewing circular investments as economically unfavourable in the short term. Without a dedicated methodology for measuring the value creation of processes, it is not easy to build business cases and persuade companies to invest in circular solutions (product, technology, process, service, or strategy). In fact, there is limited research on how the CE provides a competitive advantage, emphasising the need for assessments that prove the economic viability of circular activities and measure their multi-dimensional benefits (Renfrew et al., 2024c).

Recently, the International Standardized Organization published the ISO 59000 family of standards, which was designed to harmonise the understanding of the CE and to support its implementation and measurement (ISO 59020, 2024). However, ISO 59000 lacks the provision of specific directions for water systems, and so far, no study which applies it has been published. To effectively describe the performance of a water system and enable the circularity assessment, covering all different aspects, integration of methods, models and metrics is needed.

Two fundamental steps are required for the development of an assessment (Figure 2.2), which are the definition of the goal and scope of the assessment. This is in alignment with the requirements of standardised methodologies like ISO 14040 (ISO 14040, 2006). After defining the goal and scope of the assessment, system mapping and modelling are required. The system mapping enables the understanding of important characteristics of the system under investigation. It facilitates the acquisition of data and modelling of the system for building the system resource flows and inventories (mass balances). The development of process models enables Material Flow Analysis (MFA) and Substance Flow Analysis (SFA) to understand how resources flow within the system (Renfrew et al., 2024b). MFA and SFA are widely used to assess circularity for systematically quantifying the flows and stocks of materials in systems, differentiating between flows of goods (e.g. water) and flows of substances contained within these goods (e.g. sodium) (Nika et al., 2020). The MFA and SFA are combined with assessment methods and models. The assessment methods and models provide valuable information on the performance of systems via indicators usage (Iacovidou et al., 2017). In order to measure the intrinsic circularity performance of system (e.g. desalination systems) indicators are selected that focus on resource circularity and productivity (Renfrew et al., 2024c). Nowadays, it has been commonly acknowledged that to promote CE, the introduction of monitoring and evaluation tools like indicators to measure circularity becomes essential (Saidani et al., 2017). An indicator is a variable number or a function of variables, which provides information about “intrinsic” circularity or the consequences relevant to decision-making. The indicators are calculated through the models that are mathematical descriptions (Moraga et al., 2019) of the system behaviour and resource flows. Hence, the indicators are the visual results of the methodological assessment. The circularity assessment can be differentiated between benchmark and dynamic assessment. Benchmark assessment uses static data and/or models to evaluate the system and compare it with the baseline scenario, while dynamic assessment

focuses on the optimisation of the system by using scenario analysis, continuous monitoring data and/or dynamic modelling (Nika et al., 2022). The assessment must allow the measurement of the intrinsic circularity value of the water system.

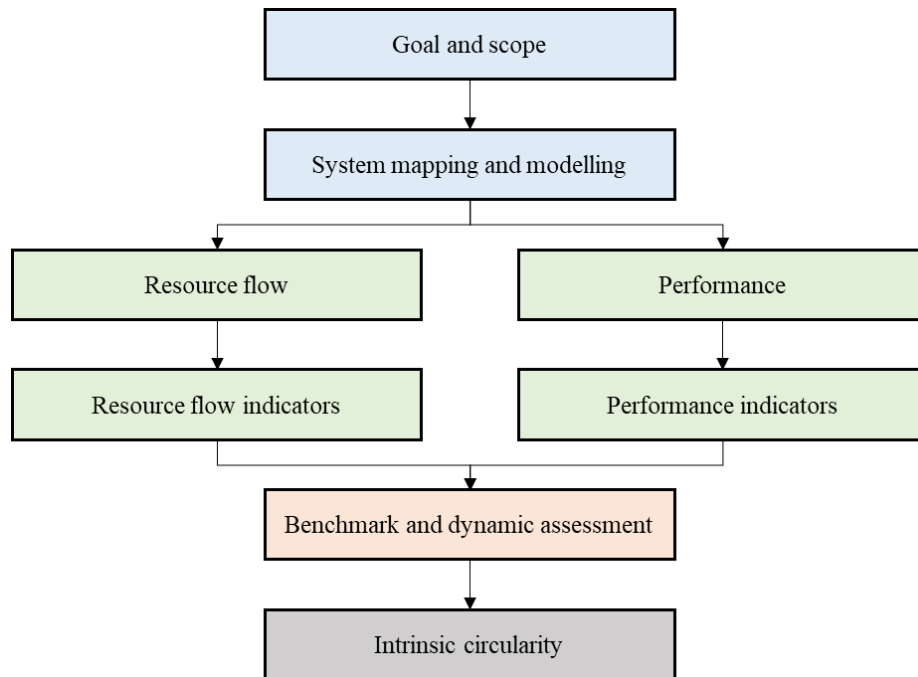


Figure 2.2 – Circularity assessment framework.

The described systematic methodology for measuring intrinsic circularity is based on the work developed by Nika et al., (2022) and Renfrew et al., (2024b). The first author developed a CE framework which focuses on water systems and their interaction with ecosystems. (Nika et al., 2022) applied the framework to a nature-based solution for wastewater treatment and considered the energy, waste and ecosystems nexus. Renfrew et al., (2024b) developed an intrinsic and consequential circularity framework for assessing urban WWTP. Successfully, the framework can overcome the gap between current circularity and sustainability assessments by systematically linking changes in physical resource circularity with resultant sustainable value creation, to harmonise the assessment of wastewater treatment processes. The development of an indicator taxonomy facilitated a robust assessment through the use of three typologies, namely resource flow, circular action, and sustainability indicators. Due to the impact of both the work and the results achieved, this study strongly believes that both can support the development of a circularity assessment methodology for the desalination sector (Chapter 3).

2.2.4.1 Assessment definition

The definition of the goal and scope of the assessment aims to establish the extent of the analysis and specify the methods to be used in the subsequent phases (Reap et al., 2008). The goal outlines the intended purpose of the assessment. In the desalination sector, possible goals could include measuring the intrinsic circularity performance of a novel or conventional desalination system, analysing changes within a desalination system, or comparing different desalination systems. The scope of the assessment defines the system under investigation and its boundaries. These boundaries can encompass the entire life cycle of the desalination system or be limited to specific life cycle stages. The full life cycle of desalination includes seawater abstraction, the desalination process, the distribution of desalinated water, the disposal of undesirable outputs (e.g., brine), the use of desalinated water, and the construction of the required infrastructure (Figure 2.3). However, the scope can be narrowed to focus on particular stages. For instance, if the goal is to evaluate the circularity performance of two different desalination systems in terms of minimising externalities, such as waste generation, the stages of distribution and use might be excluded from the assessment boundaries.

This part of the circularity assessment may also include functional units, allocation methods, limitations and data requirements, if necessary (Renfrew et al., 2024c).

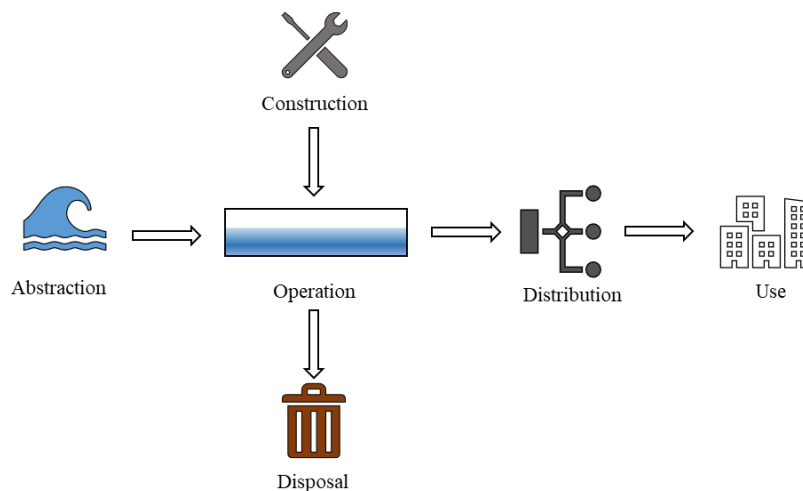


Figure 2.3 – The conceptual desalination life cycle stages.

2.2.4.2 Modelling

The assessment effectiveness relies on the accurate understanding and description of the system. The description is made through inventories with data. After mapping the system, the inventories are built with observed data, which is collected during the desalination system operation or with data generated from modelling practice, which simulates the behaviour of the system. Also, secondary data from reference studies can support the development of the inventories.

Modelling allows better prediction and control of system performance and helps our knowledge of everyday processes. However, developing suitable models needs a certain level of knowledge of the mechanism(s) being investigated (Ahmed et al., 2019). In addition, they require input data to be fed process performance parameters to run the calculation of the model equations. Process simulation and manual calculations are also used in ex-ante assessment (e.g. Life cycle analysis) to project and simulate lab/pilot scale systems to industrial scale systems (Tsoy et al., 2020). From a CE perspective, the development of process models allows the MFA and SFA to understand how resources flow within systems. It supports the characterisation of the resource flows which is required for robust calculation of the assessment indicators (Renfrew et al., 2024c).

2.2.4.3 Material and Substance Flow Analysis

Seawater contains large amounts of dissolved ions (Bardi, 2010), within a range of 30,000-45,000 mg/L of Total Dissolved Solids (TDS) (Greenlee et al., 2009). Seawater is composed mainly of monovalent ions such as potassium (K^+), bicarbonate (HCO_3^-), sodium (Na^+), chlorine (Cl^-), fluorine (F^-) and bromine (Br^-), and divalent ions such as calcium (Ca^{2+}), magnesium (Mg^{2+}), strontium (Sr^{2+}) and sulphates (SO_4^{2-}) (Sharkh et al., 2022). Sodium (Na), magnesium (Mg), calcium (Ca) and potassium are the metal elements with the high concentration levels (Bardi, 2010). Brackish water is slightly salty and found in estuaries as surface water and in salty aquifers as groundwater. The most common desalination processes treat brackish water with TDS concentrations within 1,000-10,000 mg/L TDS. Brackish water contains low organic content and low particulate or colloidal pollutants. Its components' concentrations can range significantly from source to source (Greenlee et al., 2009).

The transition of the desalination sector into facilities that recover valuable products that contain the ions that are part of the water source (e.g. seawater) requires monitoring and analysis of the materials and substances that flow through the desalination system. The MFA and SFA enable the tracking of the flows, providing insights on the origin and fate of the goods. For the desalination sector, MFA traces the water flows while the SFA traces the ion flows such as sodium, chlorine and magnesium.

Then, a classification approach is applied to all the modelled resource flows, which consists of designating circular and linear properties.

2.2.4.4 Resource characterisation

The characteristics of flows cause confusion when defining and assigning circular properties. Characteristics such as raw material, virgin, biogenic, by-product, and renewable are often used in CE literature to define resources, some of which reveal intrinsic circular properties whilst others necessitate further investigation of resource characteristics (Renfrew et al., 2024b). Wbcsd (2022) developed indicators that measure the fraction of circular water inflow and outflow, which require assigning the amount of circular water withdrawn and discharged. The report classifies seawater and third-party reclaimed water (industrial wastewater) as circular, and collected rainwater, water from a local watershed and surface water as potential circular, however, it depends on catchment replenishment cycles. (Renfrew et al., 2024b) developed a classification approach based on robust definitions for the urban wastewater sector which classifies the water flow of the wastewater as circular. Regarding the water outflow, it is classified as circular if, when returned to the local watershed, its quality is equal to the quality of the water of the local watershed (Renfrew et al., 2024a; Wbcsd, 2022). A classification approach is also developed for circular material flows, and Renfrew et al., (2024a) proposed circular and linear definitions for the classification of elements such as carbon, nitrogen and phosphorus. For the desalination sector, no standard definitions exist for the flow material. Therefore, in sections 3.3.3 and 3.3.4 definitions for classifying the circular and linear ion flows are proposed based on criteria which consider the abstraction impact on the source and the characteristics of the source (limited or not), and the products and discharged streams, as well as their impact on the destination based on the quality and function.

2.2.4.5 Circular actions

Circular actions indicate the strategies or solutions implemented to enable the realisation of CE and its principles (Nika et al., 2022). Several studies have identified CE actions. The most common in the CE literature include Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover (known as the R-strategies); however, some of these actions refer to general resources and types of industrial production that do not fit the water context. For example, Repair, Refurbish and Remanufacture are strategies for manufactured products, while Repurpose refers to the use of discarded products to make new ones (Morsetto et al., 2022).

The identification of circular actions specifies what needs to be measured and assessed, enabling the selection of appropriate circularity indicators (Nika et al., 2022). For the desalination sector, the actions should aim at the reduction of demand for resources which impact the life cycle (decreasing chemical and energy demand) while maintaining a strong yield of desalinated water recovery. Moreover, the desalination sector must endorse actions that respect regional communities' needs by having a positive impact on the environment and society, thus contributing as much as possible to the active protection and regeneration of natural ecosystems like marine environments and a reduction of harmful or hazardous substances. Also, they must impact the developing production processes of products and services and the generation of waste to a minimum. The actions on waste generation must be directed in favour of the greatest extent of generating economic products like salts, minerals and chemicals. This would have the potential to create multi-functional desalination systems (Nika et al., 2022).

2.2.4.6 Circularity assessment

The circularity assessment stage is the evaluation of the results of the circularity measurement. It should result in a comprehensive statement about the circularity performance of the system. The circularity performance is the degree to which a set of circularity aspects align with the core objectives and principles of a CE. In addition, it should enable a good understanding of the performance while providing full transparency regarding uncertainties and data gaps. Where possible, the circularity measurement and assessment should allow comparability to other similar or related systems whether internal or external to the system in focus (ISO 59020,

2024). This means the circularity assessment methodology must be applicable to different desalination systems for performance comparison. Additionally, it must be allowed to capture the change when operational parameters alter (e.g. feedstock type or flowrates).

2.2.5 Sustainability assessment

To complement circularity assessment, other methods that measure and assess sustainability impacts can be performed (ISO 59020, 2024), as the implementation of circular strategies affects the sustainable development of the desalination sector. The sustainability performance of desalination systems has received increasing attention in recent years (Aziz and Hanafiah, 2021). Sustainability assessment (SA) is a broad and growing field within sustainability research. It includes a range of approaches to support decision-making towards sustainability. SA has mainly emerged as a broadening of impact assessment methods to cover the three pillars of sustainable development (Troullaki et al., 2021) which are the environmental, economic and social dimensions (Opher et al., 2019) making SA one of the most complex types of assessment methodologies (Sala et al., 2015). Therefore, for desalination systems, it is important to consider the three dimensions and their impacts on sustainability. This can be done by applying a systemic and integrated sustainability assessment that considers all dimensions related to the desalination process, which will allow the assessment of the currently used technologies or emerging alternatives to have an accurate decision regarding their relative sustainability (Ibrahim et al., 2018). To perform SA, life cycle-based methods can be used as they have received wide acceptance and have been considered important (Troullaki et al., 2021). One of the methods accepted is LCA and it has been widely used to assess the environmental impact of desalination systems (Aziz and Hanafiah, 2021). LCC is another accepted method as well as the more recent method, the SLCA. These three methods have been integrated to form the Life Cycle Sustainability Assessment (Troullaki et al., 2021).

SA frameworks have been developed to assess the sustainability of desalination systems (Afgan and Darwish, 2011; Ibrahim et al., 2018; Lior, 2017), however, they have applied different methods and indicators, which results in unharmonised frameworks. Additionally, the most sustainable dimension assessed of the desalination sector is the environmental dimension, and little attention was given to evaluating the impact of other sustainability aspects (i.e., economic and social) (Ibrahim et al., 2018).

Despite the environmental dimensions being the most assessed, the desalination sector is moving towards CE, meaning a multi-functional system might be observed. Therefore, special attention is required in order to perform a fair environmental assessment of the co-production burdens.

2.2.6 Multifunctionality

The concept of multifunctionality for the desalination sector is observed when the function is not limited to only the recovery of water but also to the recovery of other products. Many novel technologies can be incorporated into, for example, ZLD systems to create multiple streams, allowing for the extraction of various common salts as well as precious metals such as lithium, rubidium and others (Panagopoulos, 2022) from brine. However, incorporating more technologies increases resource demand for energy for the full desalination system. Therefore, to achieve sustainable brine management, all the elements of water, energy and mineral recovery must be considered in an economically feasible way (Ogunbiyi et al., 2021). In addition, environmental impacts have to be expanded or allocated to the co-production of the multifunctional desalination system. From a methodological point of view, multifunctional systems represent an issue regarding the apportionment of the environmental burden to each co-function/co-product. Therefore, there is a need to investigate and explore how the multifunctionality issue must be handled for the desalination sector (Chapter 4).

3 Towards Circular Desalination: A New Methodology for Measuring and Assessing Resource Flows and Circular Actions

3.1 Introduction

Desalination delivers significant societal benefits by furnishing a constant supply of high-quality drinking water to preserve existing natural freshwater resources, generating wider environmental, socio-economic and health rewards. However, there is a debate about the potential adverse impacts of desalination (Ihsanullah et al., 2021), particularly concerning resource consumption, productivity and brine management. Desalination is an energy-intensive process and conventional processes increase greenhouse gas emissions due to a heavy reliance on fossil fuels. Thus, increasing the use of green energy is a key goal to enhance the sustainability of the sector (Ayaz et al., 2022). Moreover, the average global freshwater recovery rate in desalination operations is around 40%, resulting in the production of large amounts of brine, which is a major challenge for the sector. The goal is to maximise water production while minimising brine volumes (Cipolletta et al., 2021), thus avoiding harmful discharges. Brine contains high salt concentrations as well as toxic and non-toxic chemicals, which can cause pollution and negatively impact the marine environment (Panagopoulos and Haralambous, 2020). These adverse impacts are often associated with linear economy practices.

Transitioning to a circular water economy is essential, where water is continuously regenerated and reused, and any by-products are transformed into resources for other economic gains (Mauter and Fiske, 2020). The Circular Economy (CE) model offers a paradigm shift in this regard, potentially redefining the value proposition of desalination systems to ensure they achieve their primary purpose in a sustainable manner (Arup, 2019). Within this model, the water sector emphasises sustainable resource use, recovery processes, and integrated water and energy management (Kabir et al., 2024). In desalination, practices such as brine management, valorisation and resource recovery, or Zero Liquid Discharge (ZLD) and Minimal Liquid discharge (MLD), are gaining attention as potential strategies to tackle the negative impacts of desalination systems. Although these strategies are promoted as circular approaches, their

performance analysis primarily focuses on techno-economic or environmental aspects (Micari et al., 2020; Cipolletta et al., 2021; Panagopoulos, 2021; Morgante et al., 2022). This means the consequential impacts (sustainability dimensions) have been assessed for circular approaches like MLD and ZLD concepts. However, current methodologies do not capture the intrinsic circularity; the latter makes them incomplete for planning and assessing circular strategies. Intrinsic circularity is assessed by analysing resource flow traceability and circular actions.

Resource traceability enhances understanding and transparency in circularity by tracking the origins and destinations of flows, including water intake sources like seawater and brackish water, as well as energy and chemical consumption. This allows for the characterisation of linear and circular aspects of resource flows, enabling an investigation into potential disruptions when implementing circular solutions to close resource loops within human-managed systems and their interactions with the natural environment. Desalination generates brine which is often considered waste and is discharged into the environment. Current CE definitions categorise this as a linear flow with no economic value. However, when ZLD/MLD processes are applied, brine can become a valuable by-product (resource). Therefore, robust definitions are needed to track and define the linear and circular resource flows within desalination systems and integrate them within circularity analysis. Despite this, resource traceability principles are not commonly incorporated in the assessment of biotic/water resource circularity (Renfrew et al., 2024b). Additionally, circular actions are the strategies that the desalination sector can implement to realise CE principles. Actions, such as optimisation of resource consumption (e.g. fossil fuel use), minimisation of brine generation to avoid pollution, and recovering resources have the potential to create value. The identification of circular actions determines what needs to be measured and assessed, making it is crucial for the selection of appropriate circularity indicators (Nika et al., 2022).

A comprehensive circularity analysis requires the development of CE metrics and indicators to measure intrinsic aspects and evaluate the circularity of resource loops and the progress of CE actions in a specific system (Nika et al., 2022). The International Standard Organisation developed a circularity measurement taxonomy, providing a structure to measure resource flows and the extent to which circular goals and actions of the system contribute to the circularity performance of the target system at a specific time. However, this taxonomy is more

applicable to companies than to water systems (ISO 59020, 2024). Nika et al., (2020) developed a Multi-Sector Water Circularity Assessment framework for evaluating the circularity of complex water systems under the Water-Energy-Food-Ecosystems nexus. This framework covers all the socio-economic and non-economic sectors of the nexus, their incorporated resources, the three CE principles and additional economic, environmental and social aspects. However, it primarily focuses on sectors interconnected with water systems. Renfrew et al., (2024b) developed a method to assess the intrinsic circularity and consequential impacts, offering a holistic circularity assessment that provides definitions for resource flow characterisation and an approach for identifying circular actions. However, their methodology is limited to urban wastewater systems and does not extend to water supply systems such as desalination.

The current study proposes a novel methodology for resource flow characterisation and the identification of circular actions. Through systemic indicator selection and calculation, the methodology enables the measurement and assessment of the intrinsic circularity value and performance of desalination systems. The methodology focuses on intrinsic circularity, addressing aspects such as resource flow classification and circular actions, which provide critical insights during the planning and implementation phases of circular strategies. While the methodology centres on intrinsic circularity, its objective is to complement consequential assessment methodologies, such as LCA, which are well-established and extensively documented in the literature. Together, these complementary approaches support a more comprehensive understanding of the circular economy and overall sustainability of desalination systems.

3.2 Methodology

The methodology proposed in this study is designed to assign circularity definitions to all resources involved in desalination systems. It defines criteria to characterise resource flows, such as water and ions, which are integral to any desalination system. This approach allows for the classification of resource flows as either circular or linear. Additionally, the methodology emphasises actions that facilitate the implementation of CE principles within desalination systems. Indicators are selected for each dimension, the resource flow characterisation and circular actions. To demonstrate its adaptability, the methodology has been applied to three

distinct configurations: MLD, ZLD, and conventional desalination systems. This ensures its relevance across the entire desalination sector.

3.3 Resource flow characterisation

The methodology proposed in this study provides a universal framework for characterising resource flows like water and ions, and assessing circularity in desalination systems, irrespective of their configuration (e.g., conventional, MLD, ZLD) or feedwater source (e.g., seawater, brackish water, municipal wastewater). To accommodate system-specific variations and local environmental conditions, the criteria for resource flow classification are designed to be flexible and adaptable. Certain criteria, such as abstraction impacts or discharge quality requirements, are influenced by local factors, including environmental conditions, replenishment rates, and regulatory standards. For instance, sustainable abstraction thresholds for brackish water or acceptable salinity increases for brine discharge can vary depending on the region. As such, the methodology considers that users can customise the thresholds based on regional guidelines or site-specific data. This flexibility ensures the methodology's applicability across diverse desalination systems and operational contexts, supporting meaningful comparisons and encouraging broader adoption.

3.3.1 Water inflow

The water circular inflow definition should be aligned with circular sourcing criteria, following the concept of sustainable abstraction of water (seawater, brackish). The criterion demands that for a sustainable balance between water consumers and the environment to be established, there is a need for abstraction that remains within the replenishment capacities of the natural environment and does not damage the quality of ecosystems (Warwick, 2012). Hence, the natural renewability of the source is considered. Moreover, any water losses that occur between water abstraction and transportation to the desalination system must be considered.

3.3.1.1 Seawater

As a primary unconventional water resource, seawater desalination has been acknowledged to support the UN's Sustainable Development Goal 6: "Ensure availability and sustainable management of water and sanitation for all". Seawater desalination, as a nearly unlimited and

climate-independent source of water, can fulfil water supplies faster than the hydrological cycle (Ayaz et al., 2022). Using a size perspective and comparing the sea with for example groundwater reservoirs, the sea is larger and an open source of water with a higher and “unbreakable” natural replenishment rate. Therefore, seawater is classified as a circular water source. However, if during its abstraction and transportation any losses occur, the fraction lost must be classified as linear.

3.3.1.2 Brackish water

Brackish water is found in estuaries as surface water and in salty aquifers as groundwater. Using the perspective above for seawater, brackish water can be found in smaller proximate sources compared with seawater sources. In the case of water abstraction, if the desalination process leads to the depletion of the local water table, which occurs when water is abstracted at a higher rate than its natural replenishment, the water inflow is characterised as linear. This definition accounts for the total abstraction by all users of the brackish water source (e.g., agriculture or industrial use), not just the desalination plant. It also considers the variability of the natural recharge rate, which can fluctuate significantly due to climate conditions, particularly in drought-prone regions. Climate change further exacerbates this variability, increasing the likelihood of periods with insufficient recharge. As such, a comprehensive assessment of brackish water circularity requires integrated resource management, regular monitoring of abstraction and recharge rates, and adaptive management strategies to ensure sustainable use.

3.3.1.3 Nontraditional water source (municipal and industrial wastewater)

Most nontraditional desalination water sources are small scale, geographically dispersed, chemically heterogeneous, and far more temporally varied than traditional freshwater or seawater sources (Mauter and Fiske, 2020). For municipal wastewater, the definitions proposed by Renfrew et al., 2024a are applied. Regarding industrial wastewater, the water content which enters the system and is available for treatment and further use so can be considered circular as it comes from waste, while the content which is unrecoverable and thus lost must be classified as linear.

3.3.1.4 Water (for chemicals)

Another water inflow that has to be characterised is that contained in chemicals such as acids, bases and other (e.g. ferric) solutions that are used in pre-treatment steps or for process maintenance. The water used in chemical preparation is often distilled after its abstraction. If the chemical is mixed in water coming from a freshwater source and the abstraction rate is higher than the natural replenishment, the water inflow must be classified as linear. Nevertheless, compared with the scale of seawater abstraction and freshwater production, the volume of water in the chemicals employed could be very small (<1%) and potentially negligible.

3.3.2 Water outflow

3.3.2.1 Desalinated water (product)

For the desalinated water (product), the flow is circular as long as it complies with the qualitative requirements of the intended application. The application includes (however, not limited to) water body replenishment/restoration and socio-economic activities such as municipal, agricultural or industrial water utilisation. If the desalinated water is discharged to a water body, the quality of the water must enable replenishment and/or restoration. The accumulation of components that are harmful to the water body and local environment must be avoided. However, the most common purpose of desalinated water is for socio-economic activities in which the water must follow specific guidelines (e.g. guidelines for drinking water), whilst reducing overexploitation of virgin water and freshwater sources.

The World Health Organization provides guidelines for drinking water quality (WHO, 2017), which can be addressed by municipalities. Microbial, chemical, radiological and acceptability aspects and health-based target and water safety plans are components that must be established for a safe drinking water use. Australia and New Zealand have guidelines for fresh and marine water quality which cover primary industries such as agriculture, livestock, aquaculture and human consumption of aquatic foods, and also drinking water (Anzecc and Armcanz, 2018). The Food and Agriculture Organization of the United Nations and the International Water Management Institute published a book which provides the latest information on the water quality requirements for crops, livestock and aquaculture (Drechsel et al., 2023). Attention is

needed regarding the use of desalinated water in agriculture as pure water damages crops. Therefore, a post-treatment strategy for remineralisation and nutrition of desalinated water, including the addition of minerals and nutrients or mixing different water sources, might be required. The industrial sector often requires water with particular properties concerning water solubility, carriage potential or heat exchanging potential (Magara, 2020).

If the desalinated water does not have the appropriate quality for use, causing an increment of specific risks or unintended consequences such as public health issues, crop damage or industrial machinery failure, it is classified as a linear water flow. Also, if any losses occur between the desalination system and the intended destination, the fraction lost is classified as a linear flow.

3.3.2.2 Brine

The water recovery rate depends on the type of processes and configuration of the desalination system (e.g. MLD/ZLD). Different water recovery rates have been observed (from 25% to 99%) (Ogunbiyi et al., 2021; Morgante et al., 2022) and the water which is not recovered and ends up in the brine is considered a water loss. Therefore, the water outflow in the brine is classified as linear. As an ZLD system ensures no discharge occurs, no water flow in brine exists for classification.

3.3.2.3 Water in products

Water in products is not expected in conventional desalination systems as they recover water and discharge the brine. Therefore, this classification is not applied to systems that do not recover valuable products from brine. Products such as sodium decahydrate ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$), sodium hydroxide solution (NaOH) or hydrochloric acid solution (HCl) can be recovered from the brine and they contain water as part of their molecular structure or mixture composition. Therefore, the water content leaving the desalination system in such recovered products must be characterised. If the water content facilitates the required function of the recovered product and it comes from a circular water source (e.g. seawater) it is classified as a circular flow.

From a desalination functionality perspective, the water in these recovered products could be considered linear (similar to the water content in brine) because water is lost, as the main functionality of a desalination system is water production, not other by-products. However,

from a life cycle assessment perspective, if co-production is integrated within the desalination system, multifunctionality exists. This means that the function of the desalination system is water production and product recovery from brine, so this study agrees that the desired fraction of the water contained in the products recovered can be classified as circular. However, if the recovered products contain an excess of or insufficient water that reduces quality and results in a loss of function, the water is classified as linear.

3.3.3 *Ions inflow*

The mineral content (molecules and ions) of seawater and brackish water is continuously replenished through natural processes like rock weathering and the hydrological cycle. In seawater, the concentration of ions is dependent on two main aspects which are their crustal abundance and the existence of water-soluble species (Bardi, 2010). Therefore, the ions' circularity characterisation should address the renewability capacity of ions in the source.

Regarding other non-traditional water sources (i.e. industrial effluents), ion characterisation could be more complex due to varying contamination levels and composition depending on the upstream user. The characterisation of non-traditional water sources is not part of the study, as the methodology is applied to a desalination system for seawater and brackish water.

3.3.3.1 *Seawater*

The ocean contains an infinite source of resources that can be utilised for closing the cycle and achieving sustainability of industries (Bardi, 2010). Bardi, (2010) presented an estimation of the amount of dissolved metal ions in the ocean and mineral reserves on Earth. As an example, the estimation of the total oceanic abundance of magnesium and potassium ions are 1.68×10^{15} and 5.10×10^{14} tonnes, respectively, while the abundance of the same ions in the mineral reserves on land are 2.20×10^9 and 8.30×10^9 tonnes, respectively. An important factor is the availability, access and condition of the ions in seawater compared with mineral reserves on Earth, meaning seawater is observed as an "infinite water source". Thus, the ions that are part of the seawater composition can be considered a renewable material source. This is relevant as the abstraction and use of renewable materials where possible is one of the key CE principles (Arup, 2019).

In the past, many minerals have been extracted commercially from seawater (e.g. sodium chloride (NaCl), magnesium hydroxide ($\text{Mg}(\text{OH})_2$)). Nowadays, NaCl is produced from the mining of rock salt and evaporation of seawater or brine. Despite NaCl being a low-value product, its production is often located far from consumers. Therefore, transportation factors increase the price of NaCl, making it a decisive factor when attempting to secure resource supply (Sharkh et al., 2022). Increasing the production of circular products composed of ions from local desalination, which abstracts from more abundant sources, would therefore enhance the supply security of materials at risk.

The current study classifies the ions from seawater as circular. However, if during its abstraction and transportation, any losses occur, the fraction of ions lost must be classified as linear.

3.3.3.2 Brackish water

Regarding the inflow circularity of ions from brackish water, there are challenges related to the overexploitation of brackish water sources by the desalination sector. They are not infinite and abundant like seawater. Hence, ion depletion in brackish water sources due to its abstraction takes the same circular and linear characterisation applied to the brackish water resources (3.3.1.2). This means the ion fraction is circular unless the brackish water and consequently the ions are abstracted at a higher rate than their natural replenishment. In addition, if any volume of brackish water is lost during the abstraction and transportation, the fraction of ions in the lost volume is classified as linear.

3.3.3.3 Chemicals

Chemicals with different properties are used in desalination systems for a range of process functions, including pre-treatment (e.g., antiscalants, coagulants) and post-treatment (e.g., remineralisation agents, pH adjusters). Their circularity must be assessed based on their source and the potential for recycling or reuse. For instance, chemicals derived from renewable resources or those recovered and recirculated within the desalination system are classified as circular. Conversely, chemicals sourced from limited terrestrial deposits or lost in waste streams are classified as linear. This classification supports the assessment of intrinsic circularity by enabling the identification of opportunities for increased circularity through chemical reuse, internal recirculation, or shifts to renewable sources. By focusing on the origin,

use, and fate of chemicals, the methodology allows for comparing different desalination configurations and scenarios in terms of their chemical circularity.

3.3.4 Ions outflow

3.3.4.1 Brine

Concerning brine management, the most conventional practice is discharging it into water bodies or injecting it into inland wells. Therefore, the characteristics of the brine and receptor (e.g. water body) must be known. Brine characterisation typically includes total dissolved solids, density and discharge flow rate, while the characteristics of the water body are its physical features, volume and biological content (Giwa et al., 2017). This is especially important when discharging brine into confined water bodies such as the Persian Gulf. In such regions, unregulated brine disposal can increase salinity levels, negatively affecting the aquatic ecosystem and potentially reducing the availability and quality of seawater for desalination and other uses (Paparella et al., 2022). This, in turn, places additional energy and operational constraints on desalination facilities, as higher salinity levels increase energy demand for freshwater extraction (Christopoulos et al., 2018). Therefore, brine discharge must be carefully managed to ensure it does not compromise the characteristics of the receiving water body, following local regulations and permit limits. Adopting advanced brine management strategies, such as dilution with other effluents, or utilising ZLD technologies, could help mitigate these impacts and preserve water availability in sensitive regions. Additionally, chemicals used in the pre-treatment step that end up in the brine should be quantified and tracked. Therefore, brine is classified as linear when the requirements for discharging are not met; potentially causing negative impacts on the ecosystem and the environment of the receiving water.

3.3.4.2 Products

Seawater has received attention as a promising resource for accomplishing a sustainable water-energy-materials-food nexus (Diallo et al., 2015), as several products can be recovered from brine for use across multiple sectors. For instance, magnesium is one of the Critical Raw Materials for the European Union because of its high supply risk (Morgante et al., 2022), and it is one of the ions with high concentration in seawater (Bardi, 2010). The configuration of the desalination system enables the recovery of specific products. However, this is more likely to

occur in MLD and ZLD systems which can recover a range of products with different functions, rather than in desalination systems that only recover water and discharge brine.

From a system and sector perspective, the goal is to recover products to reduce waste generation. However, from a product and use perspective, the circularity of ions depends on other factors such as quality (e.g. purity, composition, contamination), downstream processing and final usage. The management of these products after being recovered from brine is out of the scope of the study, as the study focuses more on the transition of the desalination sector and technology performance towards CE. However, from a CE perspective, it is essential to ensure the safe and sustainable use (Caldeira et al., 2022) of products coming from brine, as contaminants like boron tend to end up in brine discharges with large environmental impacts. Therefore, under the scope of the study, ions recovered in products are characterised as circular. However, if an undesired contaminant is present in any product recovered from brine (e.g., magnesium in NaCl crystals) due to inefficient process operation, this must be accounted for in product circularity. If contamination reduces the product's quality (e.g., lowering its market price) and/or its intended function (e.g., altering its usability), the fraction of the product affected is classified as linear. For example, (Morgante et al., 2024) found purity levels of 90-98% for Mg(OH)_2 , 50-80% for calcium hydroxide (Ca(OH)_2), and higher than 99% for NaCl, with variations driven by operational conditions and the presence of carbonates in the feed. These variations highlight the role of process efficiency and feed composition in determining product circularity. Additionally, Morgante et al., (2022) demonstrated that separating magnesium and calcium ions before recovering sodium chloride improved the purity of the final product. Products with low purity, such as recovered salts from brine, are often sold at lower prices and have limited applications, illustrating how operational inefficiencies can impact circularity and economic value. Although the downstream purification of recovered products is outside the scope of this assessment, it is emphasised that maximising product quality and composition is essential for minimising energy, chemical, and transportation demands. Products with insufficient quality are less desirable in the market, and the additional investments and resource consumption for water recovery and brine valorisation at the desalination plant may not be justified. By focusing on flexibility, the methodology empowers users to define product-specific thresholds for purity based on their recovery processes and market needs.

3.4 Resource flow indicators

Resource flow indicators are used to describe the main resource flows which enter and leave the desalination system. They were categorised in resources, energy and economic which follows ISO 59020 (2024). The indicators should measure the intrinsic circularity of the desalination system and allow system comparisons (e.g. benchmark). The resource flow classification in section 3.3 combined with process mass and energy balances enables resource flow indicator calculation. In the desalination sector, resource flow indicators include resource input and output, energy and monetary flows. In the classification proposed in section 3.3, energy is not addressed because energy classification is already well defined in terms of renewability and circularity. The list of resource flow indicators and their equations are shown in Table 3.1.

The Circular Inflow and Outflow indicators for the water and ions are calculated using the classification discussed in section 3.3. The classification enables the characterisation and therefore the measurement of the circular flow fraction of water and relevant ion resources entering and leaving the desalination system. This helps assess the system's impact on the abstraction source and the destination of its outflows. It is relevant when comparing different scenarios or systems. Then, both indicators are aggregated in one indicator, Total Circular Flow. These resource flow indicators are standardised and aligned with the Circular Transition Indicator framework (wbcsd, 2022). The recovery efficiency indicator measures the efficiency of the system in recovering targeted resources.

The renewable energy contribution indicator considers the energy consumed from renewable sources. However, other sources of energy like waste heat generated from fossil sources are not classified as renewable energy but can be integrated within desalination systems, allowing the reduction of fossil fuel energy consumption which potentially reduces process carbon footprint and economic costs. In addition, the energy demand can be reduced by integrating energy recovery devices. These sources of energy are classified as circular because the energy is generated from waste, non-renewable and non-recoverable resource outflows from a process (ISO 59020, 2024). Therefore, this study proposes that the assessment of desalination systems requires a clear distinction between renewable and recovered energy contribution indicators. This distinction is critical because the energy demand and type of energy required vary

significantly depending on the desalination technology and feedwater source. For example, membrane processes such as reverse osmosis should prioritise renewable electricity (Ahmed et al., 2021) to reduce dependence on non-circular energy sources. Conversely, thermally driven processes like Multi-effect Distillation and Multi-stage Stage Flash distillation can utilise renewable thermal energy (Xevgenos et al., 2016) or waste heat (Morgante et al., 2024). By applying these indicators, assessors can differentiate energy sources, enabling the measurement and comparison of their effects on the intrinsic circularity of the system. Additionally, these indicators provide actionable insights into how energy strategies can be optimised based on the selected desalination technology and feedwater characteristics.

The economic resource indicators are calculated based on the monetary and mass values attributed to each specific flow considered in the equations. The Circular Material Productivity indicator shows the system's effectiveness in decoupling financial performance and linear resource consumption (ISO 59020, 2024). The economic efficiency of the desalination system is provided by calculating the indicator Value-based Resource Efficiency which divides the gross output (revenue) per energy and material (e.g. chemicals) costs.

Table 3.1 – Resource flow indicators selected for the circularity measurement and the respective equations.

Category	Indicator	Equation	Reference
Resource	Circular Inflow (as defined by classification approach) (%)	$\frac{\text{Mass Circular Inflow}}{\text{Total Mass of Inflow}}$	(wbcsd, 2022)
	Circular Outflow (as defined by classification approach) (%)	$\frac{\text{Mass Circular Outflow}}{\text{Total Mass of Outflow}}$	(wbcsd, 2022)
	Total Circular Flow (%)	$\frac{\text{Circular Inflow} + \text{Circular Outflow}}{2}$	(wbcsd, 2022)
	Recovery efficiency	$\left[1 - \left(\frac{\text{Mass inflow} - \text{Mass outflow}}{\text{Mass inflow}} \right) \right] \times 100$	Modified from (Morgante et al., 2024)
Energy	Renewable Energy Contribution (%)	$\frac{\text{Renewable Energy}}{\text{Total Energy Consumption}}$	(wbcsd, 2022)
	Recovered Energy Contribution (%)	$\frac{\text{Recovered Energy}}{\text{Total Energy Consumption}}$	Adapted from Renewable Energy Contribution
Economic	Circular Material Productivity (€/kg)	$\frac{\text{Total Revenue}}{\text{Mass of Linear Inflow}}$	(ISO 59020, 2024)
	Value-based Resource Efficiency (€/€)	$\frac{\text{Gross Output} - \text{Personnel and Service Costs}}{\text{Input Energy and Material Value}} - 1$	(Di Maio et al., 2017)

3.5 Circular actions

Circular actions aim for the creation of circular value in the complete value chain of the desalination system. The boundaries of the value chain include the consumption of resources, productivity, waste and product outflows, and the impact on ecosystems. Circular actions are implemented with the purpose of adding, retaining and recovering value resulting in the regeneration of value that is often lost due to linear and unsustainable activities. In this section

terms like repurposing and cascading are included to highlight the importance of CE terms to the desalination sector.

3.5.1 Actions that create added value

The desalination sector must allow the optimisation of processes to enable product and resource circulation and at the same time prevent the generation of waste and pollution. Process optimisation actions increase productivity by decreasing the demand for resources which results in cost savings and enhances the resilience of the system. Renewable energy integration with desalination aims to reduce fossil fuel energy consumption. It has been affirmed that renewable-energy driven desalination has significant potential, as the global production rate and cost of renewable improve at a fast pace (Alhaj et al., 2022). Circular actions in desalination processes should prioritise strategies that enable greener and more sustainable technologies (Ihsanullah et al., 2021). Circular actions in desalination processes should prioritise strategies to reduce reliance on virgin materials by optimising chemical use, recovery, and recycling. For example, Morgante et al. (2022) identified the high consumption of NaOH and HCl in recovering $\text{Mg}(\text{OH})_2$ and $\text{Ca}(\text{OH})_2$ from brine as a critical challenge, highlighting the need for more circular approaches. Strategies such as internal recirculation of NaOH and the integration of technologies that enable chemical recovery, as demonstrated by Zhang et al. (2017), can significantly enhance circularity while reducing operational costs. To complement these actions, exploring alternative sourcing strategies, such as renewable chemicals or biobased materials, can reduce dependency on finite resources. Such advances would not only improve circularity but also align desalination systems with broader sustainability goals by creating synergies between intrinsic and consequential circularity aspects. Such innovations illustrate how circular actions can lead to more sustainable desalination processes by closing material loops and enhancing the efficiency of resource use in line with circular economy principles.

The diversity of desalination technologies and production capabilities presents an opportunity for the desalination sector to create value by fostering industrial symbiosis through the physical exchange of resources. By integrating desalination systems with industrial processes, sectors like power generation, oil refineries, and the chemical industry can repurpose resources more effectively. For instance, waste heat from steam power plants, which would otherwise be lost to the atmosphere, can be used to power thermal desalination systems. This circular action

reduces facility costs and lowers energy consumption and environmental impacts, creating value for both the desalination sector and the industrial network (Ramin et al., 2024). Within a symbiotic environment, desalination systems treat industrial wastewater, including streams with heavy hydrocarbon pollutants and salts (Eke et al., 2020). This repurposing of waste heat and integration of desalination technologies ensures the efficient use of resources across industries, transforming waste into a valuable input. As a result, clean water is produced for power plants or other industrial processes, further enhancing resource efficiency and reducing reliance on external energy sources (Gadhamshetty et al., 2014). However, this symbiotic approach requires additional investment such as a waste heat recovery system, and furthermore its efficiency is an important factor (Elsaid et al., 2020). This means that the potential energy supplied by the industrial system must be commensurate to the demands of the desalination system, considering the technology (energy source, chemicals) and scale (energy consumption).

3.5.2 Actions that contribute to value retention

Circular actions in the desalination sector should focus on value retention by planning and investing in strategies that extend the life of resources. One key objective is to minimise the environmental impacts of brine, a by-product of desalination. Instead of conventional brine discharge, circular actions like brine reduction and repurposing can retain its function and economic value. The investigation of repurposing to promote a CE through effective brine management is essential (M.S. et al., 2024). By processing brine to recover valuable materials such as salts and minerals, these resources are reintroduced into industrial systems, extending their lifecycle and maintaining their economic contribution.

Furthermore, desalination plays a crucial role in supplying high-quality water to municipalities, industries, and agriculture, particularly in water-scarce regions. Circular actions, such as the integration of desalination systems to treat wastewater and recover water, allow the industrial sector to repurpose waste flows and reduce reliance on freshwater sources. The latter reduces operational costs and alleviates pressure on natural freshwater reserves, retaining the value of both water and by-products within human-managed systems and contributing to long-term resource sustainability.

3.5.3 Actions that contribute to value recovery

The MLD and ZLD concepts tend to follow a co-production scheme as several products like NaCl, $\text{Mg}(\text{OH})_2$ and $\text{Ca}(\text{OH})_2$ can be produced from seawater (Morgante et al., 2022). The flexibility and scale of desalination technologies allow the integration of processes in a cascading scheme. Thus, process outputs become inputs of another process for a material or product production often in decreasing quality and quantity (ISO 59004, 2024). Figure 3.1 shows an example of a cascading action, where processes generate products when receiving the output of a different process. Employing cascading actions allows a desalination system to recover more products rather than just water, and it has also the potential to increase the water recovery rate when elements in the brine are valorised.

Energy is also a resource which can be recovered from brine in the desalination system. Brine has a high osmotic pressure because of the salinity content, therefore it is a source of salinity gradient energy if mixed with fresh water (Ihsanullah et al., 2021). Also, in the case of a reverse osmosis process, a high-pressure exchanger can be integrated to receive the reverse osmosis concentrate (brine), and the pressure in the concentrate is pumped to the input of the reverse osmosis process, reducing the energy consumption of the high-pressure feed pump. This integration can lead to the reduction of energy consumption from 4 kWh/m^3 to 2 kWh/m^3 in a conventional seawater desalination system (Alhathal Alanezi et al., 2020).

3.5.4 Actions that regenerate lost values

Circular actions aimed at regenerating lost values in desalination systems focus on addressing the environmental adversities associated with traditional operations. One of the main challenges of desalination is its reliance on fossil fuels for energy, which contributes significantly to climate change. To recover lost environmental value, desalination systems can integrate renewable energy sources, such as solar or wind power, reducing the carbon footprint and moving the sector toward decarbonisation (Alhaj et al., 2022). This action directly mitigates the environmental impacts tied to energy consumption, which is a major factor in the overall sustainability of desalination systems. Additionally, recovering valuable products from brine, such as salts and minerals, can help avoid pollution and contamination from brine discharge, regenerating the lost ecological value that would otherwise be compromised by

brine disposal. However, it is important to note that product recovery may require additional resources like energy, which could impact the system's overall circularity performance. Careful management and optimisation of resource recovery processes can minimise these trade-offs and ensure that the regeneration of lost environmental value remains effective and sustainable.

3.6 Circular action indicators

The objective is to select a group of indicators that show if the value-creating goals of each action are achieved. The selection approach followed a step-wise approach which must represent the complete value chain meaning that each stage of a desalination system such as the consumption of resources, productivity, generation of waste, value created from recovering water and impact on ecosystems is addressed. First, the circular actions are identified for each stage, and they must enhance the circular performance of a stage of the desalination value chain. Then, using the circular actions the specific objectives are identified for the relevant stage of the value chain. Lastly, indicators are selected and they must ensure a consistent calculation and interpretation of the action performance.

Morgante et al., (2024) used circular indicators focused on waste reduction (Total Waste Reduction indicator), efficiency of recovery of valuable products from seawater (Resource Efficiency indicator), chemical use (Circular Chemical Inflow indicator) and energy (Energy-self Sufficiency indicator). The Resource Efficiency indicator focuses on the final products while this study uses the Resource Efficiency indicator on individual resources like water and ions. Despite the circular indicators calculation, the complete value chain is not addressed. Therefore, this study proposes a list of indicators to measure the value created by circular action implementation in the complete value chain of a desalination system (Table 3.2). The indicators selected for the circular sourcing action are the Circular Process Chemical Intensity (CPCI) and Renewable Process Chemical Intensity (RPCI) indicators. The CPCI measures the fraction of recycled or reused chemicals in the total mass of chemicals used. In this study, recycled or reused chemicals are defined as chemicals that are used and then recycled for internal use or reused again. The RPCI measures the fraction of renewable chemicals sourced in the total mass of chemicals used. If the desalination system does not employ circular or renewable chemicals, both indicators should score zero. However, as they reflect different characteristics of the same

chemical input variable the indicator results are dependent meaning there are multiple optimal results, specifically either indicator equalling one or the sum of both equalling one (as shown in Table 3.2). The renewable source (e.g. seawater) is defined based on the classification proposed.

In CE, significant benefits can be achieved by optimising systems for efficient productivity, mitigating intensive resource consumption and reducing waste generation. Therefore, in the process optimisation action, the objective is to measure how productive the system is in using resources such as feedstocks (e.g. seawater), energy and chemicals, and generating waste. In addition, it is important to measure the optimisation performance economically. Therefore, for this action, different indicators were used. The System Productivity indicator measures the capacity of the desalination system in producing products (e.g. water) and/or co-products (e.g. NaCl). The Energy and Chemical Demand indicators measure the amount of resources required to generate products and/or co-products. If they exist, internal energy and chemicals produced by the system are included in the equation. The Waste Reduction indicator is used to measure the efficiency of the system in avoiding waste generation. If a ZLD system is assessed, the score should be zero, as it focuses only on effluents, such as brine, that need to be disposed of. To track monetarily the desalination system performance, the economic indicator, the Benefit-Cost Ratio (BCR), is included. The indicator divides the present value of the expected benefits of selling desalinated water and any co-products per present value of costs. The calculation of the present value of costs includes the electricity and chemical costs of the system. Additionally, the Circular Water Value indicator is calculated (Xevgenos et al., 2024). In this study, the value gained (revenue) and treatment cost are calculated per mass of desalinated water produced. The treatment costs include the value of costs and the initial investment. The method used for the calculation of investment (provided in Appendix in Table A.1) was based on the method used in (Palmeros Parada et al., 2023). Table A.1 shows the parameters considered for the investment amortisation calculation, with an interest rate of 6% (Xevgenos et al., 2024) and a plant lifetime of 25 years.

The desalination sector aims to employ brine repurposing by recovering products (e.g. minerals), allowing the possibility of retaining value, reducing waste and generating economic value. This is measured by the Waste Eco-Efficiency (WEE) indicator. The previous action only occurs by designing a cascading desalination system, where processes receive the output

of other processes. The cascading scheme increases the recovery of water and co-products from brine and reduces brine volume. Therefore, a Value Created indicator is selected to measure the total value gained from the mass of water produced. The indicator only considers the mass of water produced, making it applicable to conventional desalination systems. A target of the desalination sector is to reduce environmental issues through regeneration and prevention actions. Therefore, Global Warming (GW) and Aquatic Eco-Toxicity impacts are measured. The GW is measured by life-cycle analysis using the Recipe method, and Aquatic Eco-Toxicity potential is measured based on the Zhou et al., (2013) method.

Table 3.2 – CE actions, indicators and equations for desalination systems.

CE action	Objective	Indicator	Equation	Aim
Circular sourcing	Reduce the consumption of linear and non-renewable chemicals	Circular Process Chemical Intensity	$\frac{\text{Recycled/reused chemicals}}{\text{Total mass of chemicals}}$	At least one indicator close to 1 or the sum of both indicators close to 1
		Renewable Process Chemical Intensity	$\frac{\text{Renewable chemicals}}{\text{Total mass of chemicals}}$	
Process optimisation	Operation of the system with high productivity, low demand for resources, low waste generation and strong benefits and value	System Productivity	$\frac{\text{Feedstock}}{\text{Mass of Products} + \text{mass of co-products}}$	Close to 1
		Energy Demand	$\frac{\text{Energy Demand} - \text{Internally Derived Energy}}{\text{Mass of Products} + \text{mass of co-products}}$	Reduce
		Chemical Demand	$\frac{\text{Chemical Demand} - \text{Internally Derived Chemicals}}{\text{Mass of Products} + \text{mass of co-products}}$	Reduce
		Waste Reduction	$\frac{\text{Mass of waste (discharge)}}{\text{Mass of feedstock}}$	Reduce
		Benefit-Cost Ratio	$\frac{\text{Present Value of expected benefits}}{\text{Present Value of costs}}$	Higher than 1
		Circular Water Value	$\frac{\text{Value gained (revenue)} - \text{treatment costs}}{\text{Mass of water (produced)}}$	Increase
Repurposing	Generate revenues with low mass of waste	Waste Eco-Efficiency (WEE)	$\frac{\text{Value gained (revenue)}}{\text{Mass of waste (discharge)}}$	Increase
Cascading	Generate value to the production of water from outflows	Value Created	$\frac{\text{Value gained (revenue)}}{\text{Mass of water (produced)}}$	Increase
Regeneration	Low footprint and eco-toxicity to ecosystems	Global Warming	Recipe method (midpoint impact) (Huijbregts et al., 2017)	Reduce
Prevention		Aquatic Eco-Toxicity Potential	(Zhou et al., 2013)	Reduce

3.7 Application of Developed Methodology

The desalination sector is moving towards CE, however, planning and analysis are required to integrate circular approaches. Therefore, the developed methodology aims to support the planning and analysis of desalination systems through the measurement of intrinsic circularity aspects. The measurement and assessment of intrinsic aspects intend to provide more supportive information on the consequential impacts through resource flow characterisation and indicators. The indicator results aim to guide good practice for the sector and support policy making. An MLD desalination system was assessed to demonstrate the potential of the developed methodology.

The MLD system under investigation was operated at pilot-scale at the power plant station of Lampedusa island under the scope of the project H2020 WATER-MINING (grant agreement No. 869474). The power plant produces electricity with diesel engines and also intakes seawater to produce water for the power plant and the population of the island. The MLD is composed of 7 processes (Figure 3.1) – i.e. Multimedia filtration (MMF), Nanofiltration (NF), Multi-effect distillation (MED), Thermal crystalliser (TC), Multiple feed plug flow reactor (MF-PFR), Eutectic freeze crystalliser (EFC) and Electrodialysis with bipolar membrane (EDBM). The generated products are desalinated water, sodium chloride (NaCl), magnesium hydroxide ($\text{Mg}(\text{OH})_2$), calcium hydroxide ($\text{Ca}(\text{OH})_2$), sodium sulphate (decahydrate) ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$) and hydrochloric acid (HCl). The EDBM produces NaOH and HCL, and both are used onsite in the system. Additionally, antiscalant and NaOH are sourced externally. The NaOH produced by the EDBM is not sufficient to cover the demand for $\text{Mg}(\text{OH})_2$ and $\text{Ca}(\text{OH})_2$. The thermal energy consumed by the MED and TC is supplied by the waste heat generated from the power plant's electricity production process. The integration of the waste heat supply is seen as an opportunity to reduce the environmental impacts of desalination operations.

respectively. The linear water inflow of the MLD is from the water fraction in the NaOH (1M) solution used to recover $\text{Mg}(\text{OH})_2$ and $\text{Ca}(\text{OH})_2$. As an assumption, the water used to prepare the solution comes from a freshwater source overexploited in a water-scarce region. This means that the integration of precipitation processes such as the MF-PFR which requires chemical solutions would reduce the inflow water circularity if the water source is linear. Regarding water outflow circularity, the MLD system has a linear water outflow of 8.8% which is the fraction of water lost in the discharge. The Table A.18 shows that the major circular water outflow is in the desalinated water (85.9%), and as the discharge flow contains water, increasing the amount of desalinated water produced by minimising the amount of discharge would potentially increase the circular water outflow. Therefore, the inflow and outflow water circularities are affected by the external source of water and the desalinated water recovery rate, respectively.

The ion inflows are classified as 100% circular except for the sodium inflow. The inflow of sodium is 10.3% linear since the sodium used in the NaOH solution is sourced from a limited terrestrial deposit source. The ion outflow is 100% circular only for sodium, chlorine and magnesium since they leave the system in the form of products and their concentration in the discharge meets the same or better quality as the discharge destination (sea). Calcium and sulphate leave the system in the form of products and the discharge, however, in the discharge stream, these ions have a higher concentration than the receiving destination (sea) (Table 3.3). Therefore, the fractions of these ions that exceed the seawater concentrations, meaning these resources do not meet the criterion for circular discharge and so are classified as linear.

The MLD system has a desalinated water recovery rate of 85.9% which is a good score compared to conventional reverse osmosis systems (40 to 55%, (Ogunbiyi et al., 2021)). The integration of processes like TC and EFC enables a higher recovery rate, as both processes produce NaCl and $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$, respectively, and recover water. Thus, the recovery of products from brine can enhance the water recovery rate. The MLD system recovers sodium, chlorine, magnesium, calcium and sulphate at an efficiency rate of 97.0%, 94.8%, 99.9%, 64.2% and 80.5%, respectively. Once ions are recovered in the form of products, the MLD system has the potential to become attractive as economic value can be created and disposal issues might be avoided. Regarding the circular energy contribution, the waste heat contributes

to 62.2% of the total energy consumed showing that waste heat is an important circular source to the thermal processes of the MLD system.

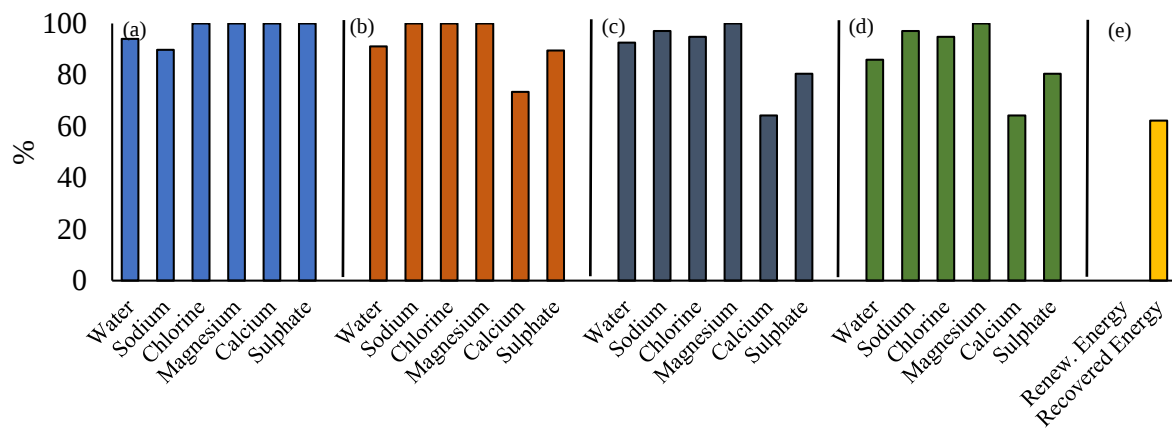


Figure 3.2 – Circular water and ions inflow (a), outflow (b), total circular flow (c), recovery efficiency (d), and renewable and recovered energy contribution (e) indicators for the MLD system.

Table 3.3 – Comparison of the ion concentration of seawater and discharge, and the linear fraction of the ions in the discharge flow.

Ion	Seawater	Discharge	Seawater	Discharge	Difference	Mass that is not circular	Discharge Linear %
Na	11.9	6.9	10,710,000	560,885	-	0	0
Cl	21.8	16.9	19,620,000	1,378,785	-	0	0
Mg	1.4	0.0	1,260,000	0	-	0	0
Ca	0.4	1.6	360,000	127,766	1.2	95,041	74
SO ₄	3.2	6.9	2,880,000	561,226	3.7	299,424	53
Unit	kg/m ³	kg/m ³	kg/y	kg/y	kg/m ³	kg/y	%

The Circularity Material Productivity indicator reveals that while the MLD system recirculates HCl and NaOH from the EDBM process, the system generates €3.8 in revenue per kilogram of linear resources consumed (Table 3.4). This linear consumption stems from the external NaOH required to recover Mg(OH)₂ and Ca(OH)₂. Monitoring this indicator over time is crucial, as an increase signifies financial growth and a reduction in reliance on linear resources (ISO 59020, 2024). The Value-based Resource Efficiency indicator shows the MLD system

operates economically, with high product recovery rates. However, due to the MLD system's reliance on emerging technologies (e.g. EDBM), there is room for process optimisation. Targeting operational costs for reduction could further improve the Value-based Resource Efficiency score.

Table 3.4 – Circular Material Productivity and Value-based resource efficiency indicators for the MLD system.

Indicator	Value	Unit
Circular Material Productivity	3.8	€/kg
Value-based Resource Efficiency	2.5	€/€

3.8.2 Circular actions and calculation

The circular action performance results calculated for the MLD system are shown in Table 3.5. The MLD system uses NaOH (1M) in the MF-PFR process to recover $\text{Mg}(\text{OH})_2$ and $\text{Ca}(\text{OH})_2$, and the EDBM recycles and returns NaOH (1M) to the MF-PFR. The CPCI is 0.68 kg per kg of total mass of chemical used. There is no renewable chemical contribution and the external source of NaOH is classified as linear, therefore the RPCI is not measured. Regarding process efficiency, the MLD system shows system productivity of 1.09 kg of seawater per kg of products and co-products meaning that the MLD system almost converts the total amount of feedstock into products. The ‘conversion’ requires 0.04 kWh, and 0.20 kg of chemicals per kg of products and co-products. The discharge is considered waste and the amount of waste leaving the system is 0.09 kg of waste per kg of seawater, meaning that only 9% of the feedstock is not recoverable. Considering the expected benefits and the operational costs, the BCR was calculated resulting in 3.17 euros of benefits per euro of costs. The economic performance of producing desalinated water, NaCl, $\text{Mg}(\text{OH})_2$, $\text{Ca}(\text{OH})_2$, $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ and HCl is also shown through the calculation of the Circular Water Value, for which the MLD system scores 9.01 euros of circular value per tonne of water. In addition, the calculation of the WEE (euros of revenue per kg of waste) and Value Created indicators (euros of revenue per kg of water produced) show the potential economic benefits of lower waste generation by recovering products from brine. It is worth mentioning that the Value Created indicator is

nearly two times higher than the Circular Water Value indicating that a significant proportion of revenue is consumed by the costs and investment. Despite the potential economic benefits, the MLD system emits 21.26 kg CO_{2eq}/tonne of water which is much higher than the conventional desalination system (the estimated greenhouse gas emissions footprint of seawater RO desalination (0.4–6.7 kg CO₂ eq/m³) (Jia et al., 2019). One reason is that the impacts of the processes that recover products from brine are allocated to water production. Thus, this higher impact is expected because more energy and chemicals are consumed by the MLD system compared with a conventional desalination system. The contribution of the energy and chemicals to the GW is shown in Appendix (Table A.19). Despite higher GW, the MLD system has less waste discharged avoiding pollution. The Aquatic Eco-toxicity Potential indicator shows that the MLD discharge emitted 11.93 Potential Affected Fraction.m³.d, which is lower than the emission of seawater of this study (18.06 Potential Affected Fraction.m³.d) measured for comparison.

Table 3.5 – Score of the circular action indicators for the MLD system.

Action	Indicator	MLD	Unit
Circular sourcing	Circular Chemical Intensity	0.68	kg/kg
	Renewable Chemical Intensity	0.00	kg/kg
Process optimisation	System Productivity	1.09	kg/kg
	Energy Demand	0.04	kWh/kg
	Chemical Demand	0.20	kg/kg
	Waste Generation	0.09	kg/kg
	Benefit-Cost ratio	3.17	€/€
	Circular Water Value	9.01	€/tonne
Repurposing	Waste Eco-efficiency	165.45	€/tonne
Cascading	Value Created	17.03	€/tonne
Regeneration	Global Warming	21.26	kg CO ₂ eq/tonne of water
Prevention	Aquatic Eco-Toxicity Potential	11.93	Potential Affected Fraction of species.m ³ .d

The circular action results for the MLD system indicate strong performance in circular chemical sourcing, productivity, and waste reduction. Strategically, this system demonstrates efficiency, economic benefits, and low pollution potential. However, it faces challenges with high resource demands, particularly for chemicals and energy. Chemical usage is a key area of concern, as 20% of the total production relies on external chemicals. Energy demand is another hotspot, while 62% of the energy is circular, the reliance on non-circular energy from the power station remains significant, contributing to a higher GW compared to conventional desalination systems. These types of desalination systems are energy-intensive as they include several

technologies, and as a result, they have a high carbon footprint when consuming energy from fossil fuels (Panagopoulos and Giannika, 2022). To address these issues, optimising the EDBM process to increase NaOH production could meet the chemical requirements for $\text{Mg}(\text{OH})_2$ and $\text{Ca}(\text{OH})_2$ recovery. This would enhance circular sourcing, reduce chemical costs, and improve both the BCR and Circular Water Value however, the Value Created would remain unchanged, as it does not take costs into account. Additionally, integrating renewable energy sources like solar power could lower energy costs and reduce the GW, which is a critical concern for both the MLD system and the desalination sector as a whole.

3.9 Scenario analysis

This study aims to support decision-making for the implementation and operation of desalination systems by assessing their intrinsic circularity value. In this analysis, the goal is to examine the mass balance and resource flows within the MLD system and explore how different operational scenarios affect circularity. Furthermore, it is intended to demonstrate the adaptability of the methodology to an MLD system that intakes different feedstock, to a conventional system that discharges brine to the sea and to a ZLD system that does not discharge any effluent to the sea. Therefore, three scenarios were developed to analyse the impact of changes in the system's inlet, chemical supply, and outlet, and to evaluate how these adjustments influence circular resource flows and actions. Each scenario explores the impacts of different operational strategies on circularity indicators and is compared with the baseline MLD system to assess the changes in intrinsic circularity. The operational parameters of the process's system of each scenario remain the same as the MLD system.

Scenario 1: MLD System with Brackish Water. Scenario 1 explores the MLD system in regions where only brackish water is available. The brackish water composition was taken from (Alghoul et al., 2009) for the same group of ions considered in the seawater (Table 3.6). The abstraction rate of the brackish water is not higher than the natural replenishment, therefore the source is classified as circular.

Table 3.6– Brackish water composition.

Ion	Concentration	Unit
Sodium	1,125	mg/L
Chlorine	1,483	mg/L
Magnesium	192	mg/L
Calcium	142	mg/L
Sulphate	340	mg/L

Scenario 2: Conventional Desalination System with Brine Discharge. Scenario 2 represents a conventional desalination system configuration where brine is discharged without extensive resource recovery. This is simulated by interrupting the external NaOH supply, halting brine valorisation processes such as the recovery of $\text{Mg}(\text{OH})_2$, $\text{Ca}(\text{OH})_2$, $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$, and HCl. The focus is on understanding the impact of limited circular actions, as the system recovers only water and NaCl while discharging brine to the sea.

Scenario 3: Zero Liquid Discharge (ZLD) System. Scenario 3 explores a ZLD configuration, designed for regions where freshwater scarcity necessitates the elimination of effluent discharge. In this scenario, the effluent from the MLD system is recirculated back into the MED process, ensuring complete recovery of water and ions. This highlights the methodology's applicability to systems aiming for complete resource closure.

More information on resource inputs, assumptions and expected outcomes can be found in Appendix (Table A.20). The results of the scenarios 1, 2 and 3 are shown in Table 3.7.

3.9.1 Scenario 1

In Scenario 1, replacing seawater with brackish water increases the Water Circular Inflow but decreases the Sodium Circular Inflow. This is because the NaOH solution produced by the EDBM process has a lower concentration (0.5M) with brackish water compared to 1M in the baseline MLD scenario. As a result, Scenario 1 requires more external sodium relative to water

for the recovery of magnesium and calcium. The same applies to the HCl solution, where the concentration is lower (0.3M). Therefore, external HCl is required and chlorine is sourced from a limited terrestrial deposit making this inflow linear.

For Water Circular Outflow, Scenario 1 shows a slight increase in desalinated water recovery due to the lower salinity of brackish water. However, the Ions Outflow Circularity decreases, as the brine discharge has a higher salinity than the brackish water source.

Regarding circular actions, Scenario 1 performs better in circular sourcing than the MLD scenario. Despite having lower sodium and chlorine circularity, the lower magnesium and calcium content in brackish water requires fewer external chemicals. Scenario 1 also demonstrates slightly better productivity, as the lower ion concentration in brackish water improves water recovery, reducing both energy and chemical demand, as well as waste generation.

However, the lower ion concentration means fewer minerals are recovered from the brine, leading to a lower BCR. The Circular Water Value is also significantly reduced, as mineral products generally have a higher market value than desalinated water. Additionally, the WEE and Value Created indicators show less effective repurposing and cascading actions compared to the MLD scenario, indicating weaker brine recovery performance.

Despite these trade-offs, Scenario 1 performs better in terms of regeneration (GW) and prevention (Aquatic Eco-toxicity), offering benefits for climate and ecosystem protection.

This analysis highlights that salinity content is crucial for MLD planning, as it impacts both economic performance and resource demands. However, brackish water, while less demanding on resources, provides greater benefits for climate change mitigation and ecosystem health.

These results indicate that the utilisation of brackish water sources results in a reduction of circularity performance when using this specific MLD technology configuration. Therefore, project planners and plant operators in areas with both readily available seawater and brackish water may favour the use of seawater to enhance circular value. However, it is worth noting that the MLD technology may not be optimal for brackish water desalination, meaning in these scenarios alternate technologies should be assessed and compared to find the optimal process.

3.9.2 Scenario 2

In Scenario 2, if the NaOH supply is interrupted, the MF-PFR, EFC, and EDBM processes stop. As a result, both the Water and Sodium Circular Inflow increase since no external NaOH is supplied. The only remaining chemical input is a small amount of HCl, meaning there is no circular sourcing of chemicals. Additionally, the Circular Outflow decreases because brine is generated and discharged without being valorised. This scenario also leads to lower productivity, as more feedstock is needed to produce the same amount of products. Without recovering $\text{Mg}(\text{OH})_2$, $\text{Ca}(\text{OH})_2$, $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$, and HCl from brine, the energy and chemical demand decrease, but waste generation increases due to the unprocessed brine. Although operational costs are reduced by stopping the operation of these processes, resulting in a higher BCR, the Circular Water Value decreases, highlighting the importance of recovering these products in the circularity value of the water of the MLD system. Scenario 2 also shows lower performance in repurposing and cascading actions, as fewer products are recovered from brine. While the scenario results in lower CO_2 emissions due to reduced energy and chemical use, the increased brine discharge leads to a higher Aquatic Eco-toxicity impact, indicating poor performance in preventing harm to ecosystems. This scenario emphasises the strategic importance of ensuring a secure NaOH supply for the MLD system, as the circularity and overall value of the system are heavily dependent on the recovery of products from brine.

3.9.3 Scenario 3

In Scenario 3, to eliminate discharge from desalination, the effluent from the EDBM process is recirculated to the inlet of the MED process. This recirculation does not affect the Circular Inflow, as it does not change the main seawater intake or the MF-PFR process. However, it transforms Scenario 3 into a fully circular outflow system, meaning there is no discharge.

This scenario results in better productivity than the MLD scenario, as all outputs are products. The energy and chemical demand per unit of production is slightly lower because more products are recovered, and no waste is generated due to the effluent recirculation. The BCR is also slightly higher due to increased productivity, which boosts net present benefits. However, the Circular Water Value decreases as operational costs rise with the additional desalinated water, and the indicator does not account for co-products. Since there is no waste

generation, the WEE is not measured. The cascading action performance increases, as Scenario 3 has an increase in desalinated water recovery of 10.1% and NaCl recovery of 3.3%. This means that the increase of water and NaCl produced has an impact on the identified CE cascading action of increasing the recovery value. Regarding CO₂ emissions, Scenario 3 performs better than the MLD scenario, as more water is recovered with less energy and chemical consumption. Finally, since there is no discharge, the aquatic eco-toxicity potential is not measured. Overall, Scenario 3 demonstrates that the system maintains strong intrinsic circularity without generating brine, addressing a key regulatory and environmental concern for the desalination sector.

Table 3.7 – Resource flow characterisation and circular actions results of the three scenarios.

Resource	Indicator	MLD	Scenario 1	Scenario 2	Scenario 3	Unit
Water	Circular Inflow	94.0	97.3	99.9	94.0	%
Sodium		89.7	68.1	100.0	89.7	
Chlorine		100.0	61.7	99.9	100.0	
Magnesium		100.0	100.0	100.0	100.00	
Calcium		100.0	100.0	100.0	100.0	
Sulphate		100.0	100.0	100.0	100.0	
Water	Circular Outflow	91.2	95.7	74.0	100.0	%
Sodium		100.0	97.8	92.8	100.0	
Chlorine		100.0	95.3	84.9	100.00	
Magnesium		100.0	100.0	27.7	100.0	
Calcium		73.4	69.6	30.7	100.0	
Sulphate		89.6	84.8	26.1	100.0	
Action	Indicator	MLD	Scenario 1	Scenario 2	Scenario 3	Unit
Circular sourcing	Circular process chemical intensity	0.681	0.744	0	0.681	kg/kg
Process optimisation	System productivity	1.086	1.044	1.362	0.995	kg/kg
	Energy demand	0.037	0.029	0.025	0.036	kWh/kg
	Chemical demand	0.203	0.079	0.001	0.186	kg/kg
	Waste generation	0.092	0.044	0.344	0.000	kg/kg
	Cost-benefit ratio	3.172	2.580	8.055	3.211	€/€
	Circular water value	9.013	0.750	1.556	7.881	€/tonne

Repurposing	Waste eco-efficiency	165.452	146.918	11.149	-	€/tonne
Cascading	Value-created	17.034	6.741	4.197	24.007	€/tonne
Regeneration	Global warming	21.261	9.565	1.941	16.038	kg CO ₂ eq/tonne of water
Prevention	Aquatic Eco-Toxicity Potential	11.927	4.847	31.979	0.000	Potential Affected Fraction.m ³ .d

3.10 Summary of main findings

- There is a lack of methodologies to quantitatively assess the intrinsic circularity of desalination systems, particularly in terms of resource flow traceability and circular actions. This chapter proposes a new framework for evaluating the circular economy performance of desalination systems.
- The framework integrates a systemic indicator selection and calculation approach, enabling a comprehensive evaluation of intrinsic circularity.
- The methodology was applied to assess a desalination system, identifying key hotspots such as high energy and chemical demand, offering opportunities for optimisation. Furthermore, the system demonstrated 94% circular water inflow, 91.2% circular water outflow and 85.9% water recovery rate.
- A scenario analysis showed the methodology's ability to capture system changes and provided detailed insights into the resource recovery process. It also demonstrated that the methodology can be applied to various desalination schemes (e.g., Minimal Liquid Discharge, Conventional, Zero Liquid Discharge).
- The research advances the planning and strategic implementation of circular strategies in desalination and emphasises the role of intrinsic circularity for sustainable water supply.

4 Environmental Impact Assessment of Multifunctional Desalination Systems

4.1 Introduction

Desalination is considered the main technological intervention which can address the growing pressure on freshwater resources from increasing urban demands and water deficits due to climate change. However, many impediments to desalination integration are highlighted by critics, which are polluting outflows and carbon emissions (Lee and Jepson, 2021). Desalination has adverse impacts on the marine environment, air quality and society (Ihsanullah et al., 2021). Life Cycle Assessment (LCA) is the dominant tool to evaluate the environmental impacts of desalination processes (Lee and Jepson, 2021). LCA is standardised by International Standard Organization (ISO) (ISO 14040, 2006a; ISO 14044 2006b). LCA considers inputs and outputs to evaluate the environmental impacts of a product system along its life cycle (ISO 14040, 2006a; ISO 14044 2006b). Most of the LCA studies use a functional unit (FU) (i.e., 1 m³ of desalinated water) for a conventional desalination system which produces desalinated water. The desalination sector is embracing the minimal liquid discharge (MLD) and zero liquid discharge (ZLD) configurations. Both configurations are under investigation for brine rejection minimization and water recovery. The feasibility of the MLD and ZLD systems has been assessed through LCA and techno-economic assessment (Panagopoulos and Haralambous, 2020). Both concepts show high water recovery rates (95-99%) from wastewater (i.e., brine). In addition, desalination systems can be designed for recovering water as well as profitable products from brine with reasonable operating costs and energy consumption, which will support the development of the desalination industry (Giwa et al., 2017b). Besides water recovery, if secondary product recovery from brine occurs, the desalination system becomes a multifunctional system. Therefore, allocation is needed to assess environmentally impact of the desalination system due to the water recovery and the co-products recovery from brine.

Allocation is often required due to the co-production or recycling within the systems which makes them multifunctional (Schrijvers et al., 2020). In several production systems, multifunctional processes are present within the product's life cycle. The major issue tackled

in multifunctional processes is how the impact of inputs and outputs should be distributed among co-functions (Ijassi et al., 2021). ISO 14044 (ISO 14044, 2006b) has acknowledged the complexity of allocation issues in LCA and presented a hierarchy to follow. The hierarchy describes subdivision as the first step to avoid applying allocation. If this is impossible, system expansion method is required. Alternatively, partitioning based on the physical properties of flows (e.g. mass, volume, energy) is described. If a physical relationship cannot be established, economic partitioning is the alternative option.

In subdivision, the multifunctional-product system is divided into monofunctional-product sub-systems for assessing each output separately (ISO 14044, 2006b). However, it is not common for the existence of multifunctional systems where an allocation issue is handled with subdivision as the sub-systems are inherently multifunctional (Li et al., 2020). ISO endorses the use of system expansion to deal with multifunctionality (ISO 14044, 2006b) or when the aim of the assessment is not to assess each product individually (Svanes et al., 2011; Moretti et al., 2020). System expansion results in redefining the FU to include the additional functions related to the co-products (ISO 14044, 2006b). System expansion can only be applied to process-oriented LCA, as products are assessed in a global FU. A process-oriented LCA can be applied when the interest of the assessment is the optimisation of the obtention process (Schrijvers et al., 2020).

When system subdivision and expansion cannot be applied, LCA practitioners should apply physical partitioning using physical properties of the outputs to calculate allocation factors and distribute environmental impacts to those outputs. ISO (ISO 14044, 2006b) instructs that an underlying physical relationship should be reflected by the allocation of the inputs and outputs of a system between its products or functions (Pelletier et al., 2015). Moreover, it was found that physical partitioning is commonly used to maintain the natural science basis and physical realism of the LCA systems (Schrijvers et al., 2016). Svanes et al., (2011) recommend physical partitioning for performance tracking of multifunctional systems because it is based on measurable physical relationships and does not depend on market fluctuations, unlike economic partitioning. It is suggested by some authors that if physical partitioning does not reflect the causal relationship, an alternative allocation approach should be applied that better captures the causal relationship (Pelletier et al., 2015). In that case, economic partitioning might solve the causal issue. Pelletier et al. (2015) emphasise that economic allocation is not

biophysically causal and therefore is not appropriate in natural science-oriented LCAs. However, in socio-economic contexts, economic allocation may offer insight into market-driven causality and support specific decision-making needs. Economic partitioning is based on the gross sales value and total amount of products produced (ISO 14044, 2006b), thus addressing the economic motivation behind the multifunctional process (Wardenaar et al., 2012). However, economic partitioning might not be appropriate for performance tracking (or system optimisation) due to the product prices non-existent relationship and proportion with the physical properties of the system. In addition, product price volatility might hide real improvements in environmental performance or the contrary, a reduced environmental performance, in a certain period (Svanes et al., 2011). Furthermore, price variations that can occur among different locations are sometimes set as a drawback of economic partitioning (Wardenaar et al., 2012). Lastly, economic partitioning relates better to the societal cause of the ‘emissions’, i.e., the demand for a product (Pelletier et al., 2015).

Several LCA practitioners affirm that applying allocation is challenging, as many allocation procedures exist, with guidelines diverging on recommendations, and all allocation methods seem to be in line with the ISO (Schrijvers et al., 2020). However, some authors made the decision not to follow the ISO hierarchy (Moretti et al., 2020) because it is not clear for interpretation nor straightforward to use (Pelletier et al., 2015). Others decided on the allocation method arbitrarily, and others chose the method that is commonly used in similar case studies found in the literature (Moretti et al., 2020). However, a recent review of LCA studies (Lai et al., 2021) focusing on the multifunctionality issues in the context of primary metals co-production showed that in most studies the choice of allocation approach was not justified.

The multifunctionality issue of the MLD concept has not been addressed by the research community. Lee and Jepson, 2021 examined the application of LCA for the desalination sector. However, the concept of diverse brine disposal methods was not discussed, therefore multifunctionality and allocation issues were not covered. This shows a gap and need for future LCA research. Tsalidis et al., (2022) performed an LCA study on a system that treats brine from active coal mining which consists of common desalination processes such as nanofiltration, reverse osmosis and crystallisation. As the system is a multifunctional processes system, mass and economic partitioning are applied. The authors show the effects of the

allocation methods on the outcome of the results but without emphasising the motivation of each method.

This study aims to investigate the different approaches to dealing with the desalination multifunctionality. Therefore, the study proposes a framework that aligns with the ISO hierarchy for dealing with multifunctionality focusing on the MLD concept. The framework guides the selection of allocation approaches based on system characteristics, integration level, and assessment objectives and is applied to an MLD system and its co-products allowing a further discussion on motivations for selecting the different allocation approaches.

4.2 Methodology

4.2.1 Rationale for Framework development

ISO 14044 describes a hierarchical approach to solve multifunctionality, which includes subdivision, system expansion and partitioning. However, it does not provide sector-specific criteria to be applied in systems such as desalination, where multifunctionality is observed from the co-production of water and products from brine. The transformation of a monofunctional desalination (water-only system) into a multifunctional system can be driven by various motivations, such as reducing brine volume, complying with regulations or pursuing economic value through co-product recovery. Despite the motivation, the environmental burden is extended to include the co-production of water and products from brine, which is an issue underexplored in the desalination sector. Therefore, the rationale behind the development of the framework is to bridge the ISO hierarchy and the desalination system and products. Solving of multifunctionality issue can be challenging, hence it became necessary to develop desalination-specific decision criteria. Criteria set aligned with the ISO hierarchy were established and tailored for the desalination systems and products. The main goal is to guide the selection of allocation approaches based on criteria that consider system characteristics, integration level, and assessment objectives and motivation. Three main criteria were developed to bridge the general ISO hierarchy with the operational characteristics and motivations of multifunctional desalination:

- Criterion 1 – addresses cases where the aim is to measure the environmental burdens of individual co-products. If the level of integration between sub-processes is low, subdivision is advised;
- Criteria 2 – applies when the aim is to measure the environmental burdens of the global production performance of the system. System expansion is described;
- Criterion 3 – if subdivision (criteria 1) cannot be applied and the assessment does not focus on the global performance (criteria 2), partitioning is used. Depending on the motivation:
 - Physical partitioning is appropriate if the aim is to maintain physical causality.
 - Economic partitioning is recommended if the aim is to enable decision-making based on economic relevance.

4.2.2 Framework for dealing with multifunctionality

A criterion-based framework aligned with ISO 14044 was developed as the basis of LCA for desalination systems, which are a type of production system. Figure 4.1 presents the developed framework that handles multifunctionality at different condition levels such as the aim and motivation of the assessment. The developed framework was applied to a case study of a circular desalination plant in Lampedusa, Italy. The framework starts with the definition of the functionality of the desalination system under investigation. If the only function is to produce desalinated water and the resulting brine is disposed for treatment or to the sea, no multifunctional issue exists. On the other hand, if the desalination system is a co-product system, a multifunctionality exists. Criterion 1 applies when the aim of the assessment is to measure the environmental impacts of each co-product individually. Criterion 2 applies when the objective is to evaluate the global environmental performance of the entire desalination system, meaning the impacts associated with producing all co-products together, in the fixed proportions (co-production stoichiometry) dictated by the system's integrated process. When criteria 1 and 2 cannot be followed, criterion 3 is suggested. It recommends applying partitioning based on the motivation. If the assessment seeks to reflect the physical processes and functioning of the desalination system, physical partitioning should be applied. This approach maintains the link between the system's physical characteristics and the distribution

of environmental impacts. Alternatively, if the purpose of the assessment is to understand how environmental impacts might be distributed according to the economic relevance or value of co-products, economic partitioning may be more suitable. In this case, the allocation is based on market values and reflects a socio-economic perspective, often relevant in decision-making contexts where profitability or investment prioritisation is of interest. The rationale behind this criterion is to offer flexibility depending on whether the analysis is driven by natural science or socio-economic reasoning. This consideration is particularly important in desalination systems, where the co-products can vary significantly in both mass and economic value, which in turn can strongly influence the outcomes of the environmental assessment.

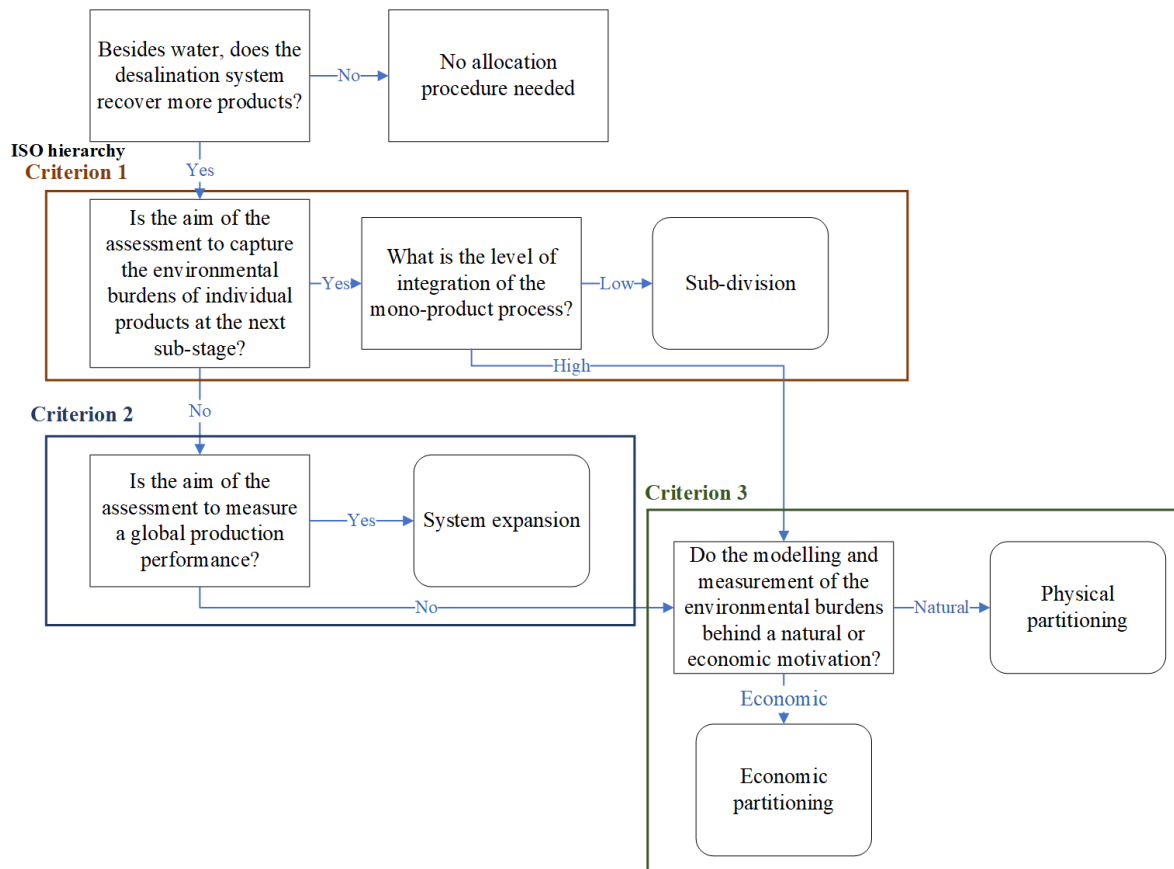


Figure 4.1 – The criterion LCA-based framework for multifunctional desalination systems.

4.2.2.1 Criterion 1 - Subdivision

In a multifunctional desalination system, co-products may be assessed individually by subdividing the desalination system into monofunctional-product sub-systems if no interdependency between inputs and outputs among sub-systems exists. In Figure 4.2, an

example of a subdivision scenario is shown. The multifunctional system was subdivided into two subdivided mono-functional systems, one that produces water, and the other which valorises brine by recovering magnesium. However, if the multifunctional desalination system has a higher integration level, subdivision cannot be applied as interdependencies exist among processes making the subdivided mono-functional systems inherently multifunctional (Figure 4.3). Therefore, if the assessment aims to assess products individually and the integration level of the processes of the system is low, the subdivision is applicable. If the aim is not to assess the co-products individually or the allocation issue cannot be eliminated with subdivision, the LCA practitioner is advised to move to criteria 2 or 3, respectively.

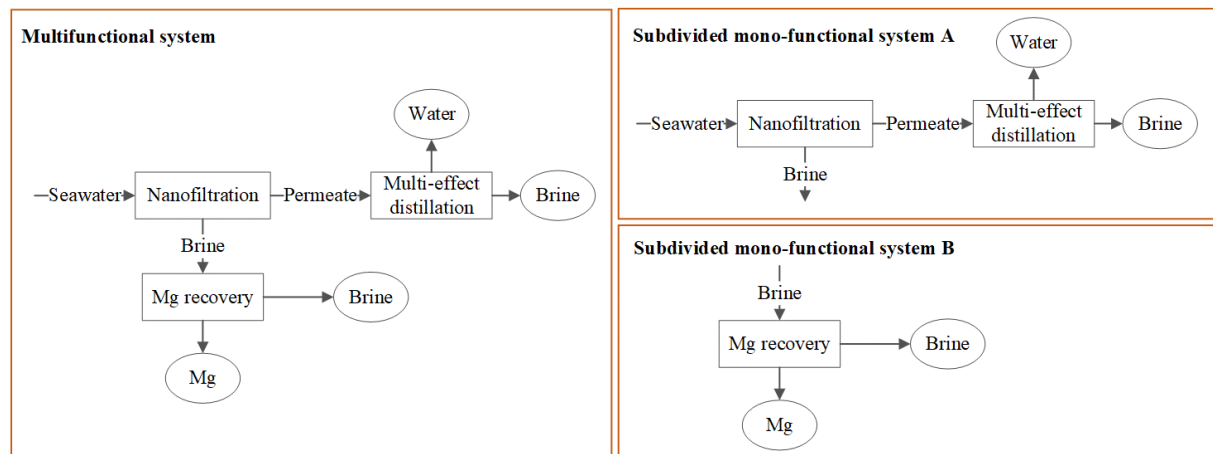


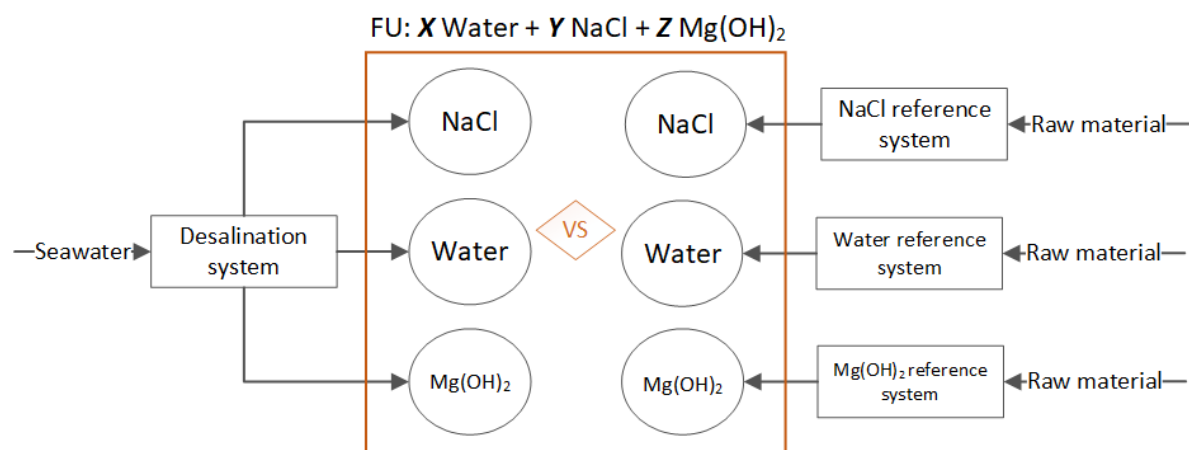
Figure 4.2 – Example of an applied subdivision approach to a multifunctional desalination system.

The diagram illustrates a multifunctional system for seawater desalination and resource recovery. The process begins with Seawater entering a Nanofiltration unit. The Nanofiltration unit produces Brine, which is sent to Mg recovery, and Permeate, which is sent to Water recovery. The Mg recovery unit produces Mg and NaOH. The Water recovery unit produces Water and sends Water to NaOH and HCl recovery. The NaOH and HCl recovery unit produces NaOH and HCl. The NaOH is then sent to Na₂SO₄ recovery, which produces Na₂SO₄. The Na₂SO₄ recovery unit also sends NaOH to the NaOH and HCl recovery unit. The NaOH and HCl recovery unit also produces NaCl.

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graph LR; Seawater --> NF[Nanofiltration]; NF -- Brine --> Mg[Mg recovery]; NF -- Permeate --> WR[Water recovery]; Mg --> MgOut((Mg)); Mg -- NaOH --> Na2SO4[Na2SO4 recovery]; WR -- Water --> WR2[Water and NaCl recovery]; WR -- Water --> NaOH_HCl[NaOH and HCl recovery]; NaOH_HCl -- NaOH --> Na2SO4; NaOH_HCl -- HCl --> HClOut((HCl)); NaOH_HCl -- NaCl --> NaClOut((NaCl)); Na2SO4 --> Na2SO4Out((Na2SO4));
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4.2.2.2 Criterion 2 – System expansion

If the assessment aims to measure the global performance of recovering water and secondary resources from brine, system expansion should be applied. System expansion assesses the multifunctional desalination system and results in modifying the FU to include the recovery of all co-products based on the production stoichiometry of the multifunctional system (Figure 4.4). However, reference products are required for each co-product, which could complicate the design of the reference system (Figure 4.4).



68

4.2.2.3 Criterion 3 – Partitioning

Physical partitioning is applied when the assessment aims to keep the natural science and physical characteristics which affect the system production or co-products. On the other hand, if a “fair” allocation of impacts is required, following socioeconomic causality and incentivising certain behaviours, economic partitioning is applied (Schrijvers et al., 2016). Therefore, the developed framework addresses motivation as the point for selecting the partitioning approach. Attributing the burden to co-products through physical or economic partitioning can generate different environmental impact indicator results. This can be seen in the assessment of a multifunctional desalination system when co-products have different mass and market prices. Figure 4.5 presents an example of a desalination system that has a stoichiometric production of 1 kg of water and 0.05 kg of sodium chloride (NaCl), with a water price of 0.83 €/tonne and NaCl price of 66 €/tonne. The calculated allocation factors of both products for physical and economic partitioning are 95% for water and 5% for NaCl, and 19% for water and 81% for NaCl, respectively. The application of physical partitioning results in distributing environmental impacts mainly to water. This approach attributes a low environmental burden of the system to the NaCl, which could be a good choice for a comparative study with the reference scenario of NaCl (e.g. mining). In contrast, the economic partitioning attributes a significant burden to the NaCl which can make NaCl appear less environmentally favourable, potentially discouraging its recovery and leading to brine disposal instead, which may be environmentally negative. However, in cases where the recovery of NaCl is economically motivated, economic partitioning may be the more appropriate choice. This illustrates how the selection of an allocation method can influence the interpretation of results and should be aligned with the broader goals of the assessment.

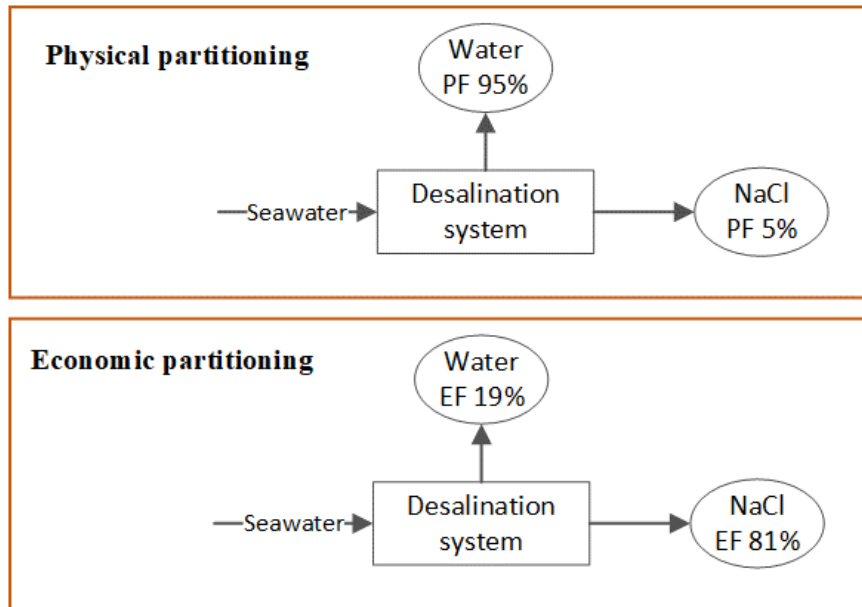


Figure 4.5 – Example of applying physical and economic partitioning in the assessment of a multifunctional system that produces water and NaCl. The percentages are physical (PF) and economic (EF) factors, they do not regard co-product production.

4.2.3 Case study - MLD system

Lampedusa is a small remote Italian island located between Sicily and northern Africa which depends on one single power plant for its electricity generation (from oil) and a desalination plant for drinking water production. Furthermore, the power plant operates a reverse osmosis unit to produce process water for the steam cycle and brine that is locally discharged. The power plant plans to invest in a circular MLD system to reduce the brine discharge and recover secondary resources from the brine. The MLD system consists of seven processes (Figure 4.6) – i.e. Multimedia filtration (MMF), Nanofiltration (NF), Multi-effect distillation (MED), Thermal crystalliser (TC), Multiple feed plug flow reactor (MF-PFR), Eutectic freeze crystalliser (EFC) and Electrodialysis with bipolar membrane (EDBM). The resulting co-products are desalinated water, NaCl, magnesium hydroxide ($\text{Mg}(\text{OH})_2$), calcium hydroxide ($\text{Ca}(\text{OH})_2$), sodium sulphate (Na_2SO_4) and hydrochloric acid (HCl).

The seawater enters the MLD systems and is softened by the MMF, and it is pumped to the NF process where divalent and monovalent ions are selectively separated. The permeate containing the monovalent ions goes to the MED and the concentrate composed of divalent ions goes to

the MF-PFR. The desalinated water is produced by the MED, TC and EFC processes. The TC also recovers NaCl from the brine coming from the MED. In the MF-PFR, $\text{Mg}(\text{OH})_2$ and $\text{Ca}(\text{OH})_2$ are precipitated through the addition of sodium hydroxide (NaOH) in a two-phase cycle. The Na_2SO_4 is recovered in the EFC process, the EDBM recovers NaOH and HCl, and both are used onsite in the process. In particular, NaOH is recovered and entirely consumed by the MF-PFR unit. The flowrate of raw seawater is $2,465 \text{ m}^3/\text{d}$, and waste heat is considered to cover the thermal energy demand of the MED and TC. Additionally, antiscalant and NaOH are sourced externally because the NaOH produced in the EDBM is not sufficient to cover the demand for $\text{Mg}(\text{OH})_2$ and $\text{Ca}(\text{OH})_2$.

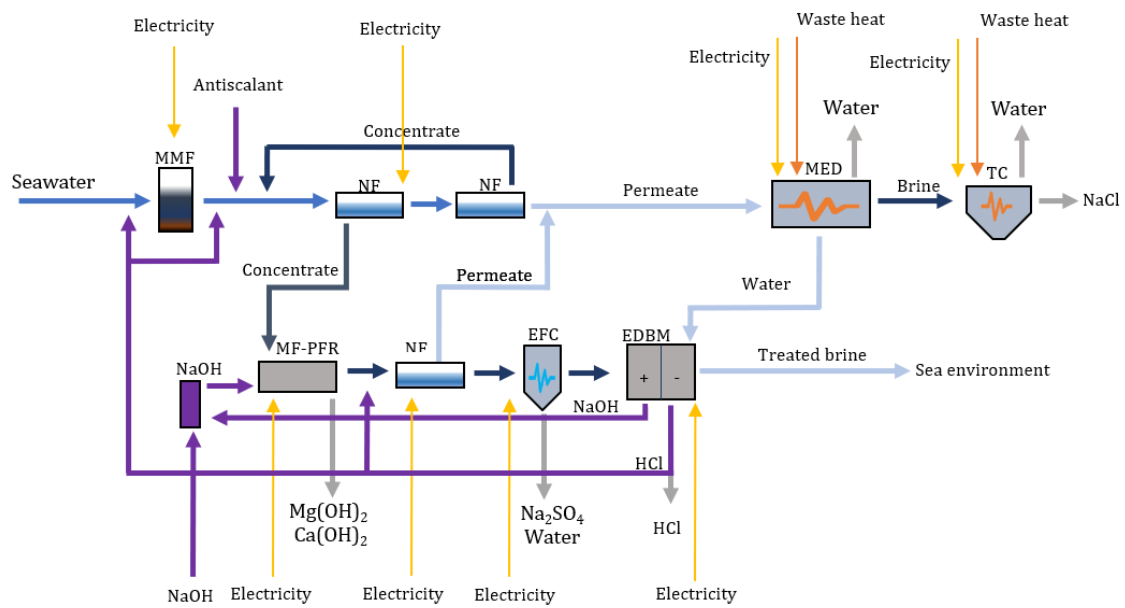


Figure 4.6 – MLD system scheme: Blue colours represent the seawater and intermediate flows (Seawater, concentrate and permeate); purple colour represents chemicals/consumables flows (NaOH, HCl and antiscalant flows); yellow colour represents the electricity flows while the orange represents the waste heat flow; grey colour represents the co-products flows (desalinated water, NaCl, $\text{Mg}(\text{OH})_2$, $\text{Ca}(\text{OH})_2$, Na_2SO_4 and HCl).

A conventional reverse osmosis plant is the reference system for desalinated water production. This reference scenario was based on literature data (Fayyaz et al., 2023). Additionally, reference systems of other co-products (recovered from brine) are considered and data are collected from the Ecoinvent database (Wernet et al., 2016). The NaCl reference system consists of extracting NaCl from the ground and seawater (51/49 ratio) for NaCl powder production. The $\text{Mg}(\text{OH})_2$, $\text{Ca}(\text{OH})_2$ and Na_2SO_4 reference systems consist of extracting

magnesite, calcite and Gaulb's salt from the ground. The HCl reference system consists of a chemical reaction using hydrogen, nitrogen and chlorine. As the reference scenarios represent monofunctional system, allocation was not required.

4.2.4 Goal and scope

The goal of the assessment is to calculate the environmental impacts of the MLD system and its co-products and compare them with the reference systems through different motivations which allow a demonstration of the use of the framework proposed. The scope of the assessment is cradle-to-gate, i.e., from the inflow of seawater to the desalination plant exit. In addition, the abstraction of seawater and the construction phase of the system are excluded from the assessment.

4.2.5 Multifunctionality

The framework presents different approaches to deal with the multifunctionality issue. In this work, system expansion and partitioning are considered when the motivation is to assess the global performance of the MLD system (co-production stoichiometry) and the co-products individually, respectively. Both have different boundaries and functional units.

4.2.5.1 System expansion

For the system expansion approach, the boundaries and FU are expanded to include all the co-products according to the production stoichiometry of the MLD system. The FU is 1 kg of water + 0.0484 kg of NaCl + 0.0037 kg of Mg(OH)₂ + 0.0004 kg of Ca(OH)₂ + 0.0093 kg of Na₂SO₄ + 0.0579 kg of HCl. In the system expansion, the intermediate flows of recovered resources that act as consumables, such as HCl and NaOH (produced by the EDBM), are not considered by the study. Therefore, the impacts of the EDBM are allocated totally to the HCl product because system expansion has a global functional unit to the co-products that exit the MLD system, and it leaves out the outflows produced (e.g. NaOH), which are recirculated and considered as consumables. The boundaries of the MLD system are shown in Figure 4.7. The reference system boundaries are shown in Figure 4.8. In addition to the conventional reverse osmosis system, the reference systems producing NaCl, Mg(OH)₂, Ca(OH)₂, Na₂SO₄ and HCl are considered.

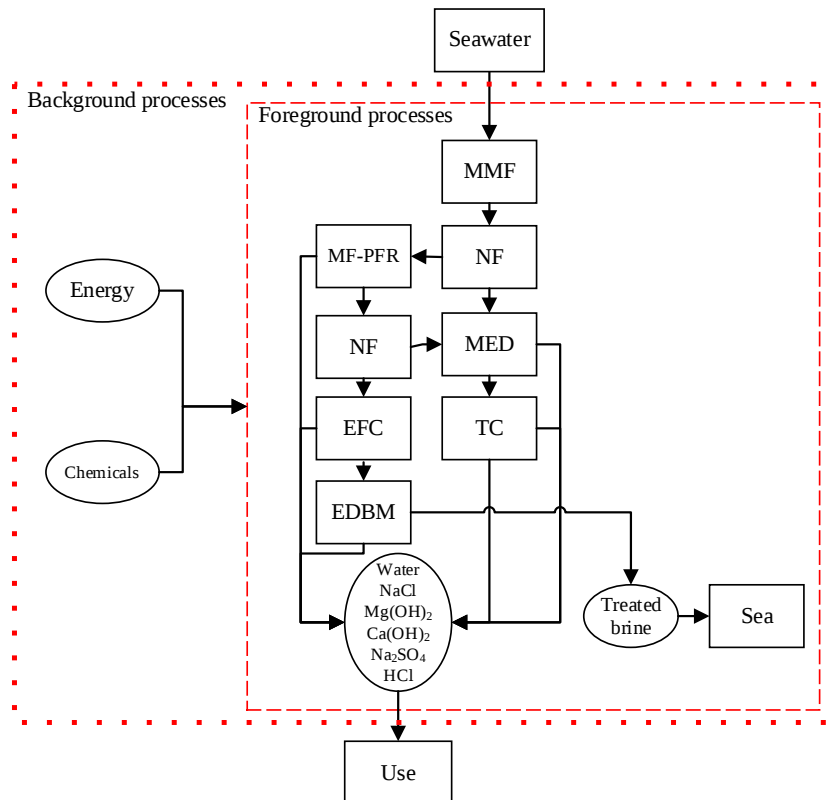


Figure 4.7 – Boundaries of the MLD system.

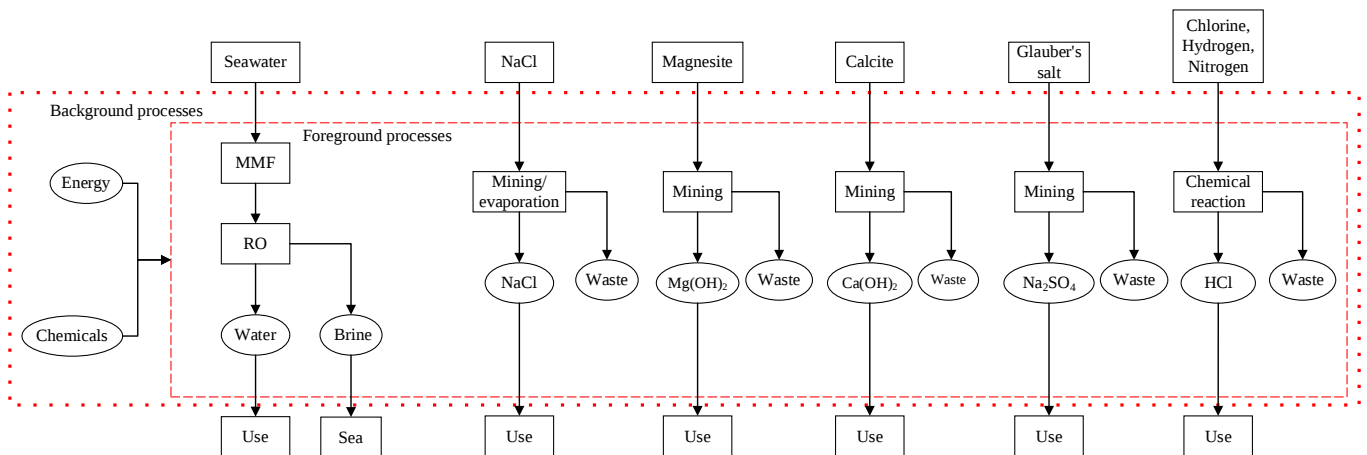


Figure 4.8 – Boundaries of system expansion reference scenario.

4.2.5.2 Partitioning

While in the system expansion, the impacts of the stoichiometry of the production are measured, in the partitioning each product is assessed individually. Additionally, two different modelling perspectives were applied. One perspective follows a black box approach which in this work is referred to as a system approach for the remainder of the study, as the impacts of the recirculation of consumables like the NaOH and HCl recirculated internally and the water from the MED to the EDBM are not modelled. The other perspective follows a white box perspective because the recirculated consumable flows are modelled and impacts are allocated to them. The objective is to understand how different modelling perspectives impact the results. In addition, physical and economic partitioning were applied. This generated in total four allocation factors (Table 4.1 and Table 4.2).

Table 4.1 – Physical factors (PF) and economic factors (EF) of the system approach for the MLD system.

Products	Quantity (tonne)	Price (€/tonne)	PF	EF
Desalinated water	808,792	1.5	0.8931	0.0881
NaCl	39,106	66	0.0432	0.1873
Mg(OH) ₂	2,970	1000	0.0033	0.2156
Ca(OH) ₂	360	125	0.0004	0.0033
Na ₂ SO ₄	7,530	148	0.0083	0.0809
HCl	46,830	125	0.0517	0.4249

Table 4.2 – Physical factors (PF) and economic factors (EF) of the process approach for the MLD processes.

NF Flows	Quantity (tonne)	Price (€/tonne)	PF	EF
Permeate	679,725	1.5	0.734	0.004
Concentrate	245,819	1000	0.266	0.996
MED Flows	Quantity (tonne)	Price (€/tonne)	PF	EF
Brine	139,252	66	0.149	0.885
Desalinated water	630,602	1.5	0.676	0.091
Desalinated water EDBM	163,135	1.5	0.175	0.024
TC flows	Quantity (tonne)	Price (€/tonne)	PF	EF
NaCl	39,106	66	0.281	0.945
Desalinated water	100,146	1.5	0.719	0.055
MF-PFR Flows	Quantity (tonne)	Price (€/tonne)	PF	EF
Mg(OH) ₂	2,970	1000	0.008	0.104
Ca(OH) ₂	360	125	0.001	0.002
Effluent	385,348	66	0.991	0.894
NF Flows	Quantity (tonne)	Price (€/tonne)	PF	EF
Permeate	253,264	1.5	0.596	0.015
Concentrate	171,499	148	0.404	0.985
EFC Flows	Quantity (tonne)	Price (€/tonne)	PF	EF
Na ₂ SO ₄	7,530	148	0.044	0.161
Effluent	85,924	66	0.501	0.822
Desalinated water	78,045	1.5	0.455	0.017
EDBM Flows	Quantity (tonne)	Price (€/tonne)	PF	EF

HCl	46,830	125	0.273	0.150
HCl MMF	0.04	125	0.000	0.000
HCl NF	355	125	0.002	0.001
HCl MF-PFR	39,414	125	0.230	0.127
NaOH MF-PFR	85,085	330	0.496	0.722

4.2.6 Impact assessment

The ReCiPe2016 Life Cycle Impact Assessment method (H) (Huijbregts et al., 2017) was used at the midpoint and endpoint level to evaluate these impacts. The endpoint impacts were calculated in order to measure the midpoint impacts with higher contribution (>10%), so the assessment focuses on those midpoint impacts (Figure B.1). Additionally, impacts of the reference system such as Marine and Terrestrial Ecotoxicity were included. The reason is that mining activities can induce local impacts on soil and water (Yao et al., 2021). Therefore, the impacts on which the assessment focuses are Global Warming, Fossil Resource Scarcity, Terrestrial Ecotoxicity, Marine Ecotoxicity, Fine Particle Matter Formation and Terrestrial Acidification.

4.2.7 Life Cycle Inventory (LCI)

Table 4.3 shows the LCI of the MLD processes. It consists of inputs and outputs. The recirculated consumable flows are represented in the EDBM process. The inventories of the reference system of the desalinated water, NaCl, Mg(OH)₂, Ca(OH)₂, Na₂SO₄ and HCl, are presented in Table B.20, Table B.21, Table B.22, Table B.23, Table B.24 and Table B.25, respectively.

Table 4.3 – Life cycle inventory of the MLD system for 1 year of operation.

Input	Value	Unit	Output	Value	Unit
MMF					
Seawater	925,129	tonne	Filtered seawater	925,129	tonne
Electricity	50	MWh			
NF					
Filtered seawater	925,129	tonne	Permeate	679,725	tonne
Electricity	591	MWh	Concentrate	245,819	tonne
Sodium tripolyphosphate	19	tonne			
MED					
Permeate NF 1	679,725	tonne	Desalinated water (for use)	630,602	tonne
Permeate NF 2	253,264	tonne	Brine	139,252	tonne
Electricity	1,016	MWh			
TC					
Brine	139,252	tonne	Desalinated water (for use)	100,146	tonne
Electricity	4,833	MWh	NaCl	39,106	tonne
MF-PFR					
Concentrate	245,819	tonne	Effluent	385,348	tonne
Electricity	723	MWh	Mg(OH) ₂	2,970	tonne
Sodium hydroxide	2,132	tonne	Ca(OH) ₂	360	tonne
NF					
Effluent	385,348	tonne	Permeate	253,264	tonne

Electricity	104	MWh	Concentrate	171,499	tonne
EFC					
Concentrate	171,499	tonne	Effluent	85,924	tonne
			Na ₂ SO ₄	7,530	tonne
Electricity	226	MWh	Desalinated water (for use)	78,045	tonne
EDBM					
Effluent	85,924	tonne	Hydrochloric acid (1M)	46,830	tonne
Electricity	9,817	MWh	Hydrochloric acid (1M) MMF	0.04	tonne
			Hydrochloric acid (1M) NF	355	tonne
Desalinated water MED	163,165	tonne	Hydrochloric acid (1M) MFPFR	39,414	tonne
			Sodium hydroxide (1M) MF-PFR	85,085	tonne

4.2.8 Assumptions

The following assumptions were made in preparing the assessment:

1. The waste heat was considered with zero burden because it was classified as waste. The waste heat results from the local power plant;
2. The antiscalant used in the NF process was Sodium tripolyphosphate.

4.3 Results and discussion

The MLD system under examination has a high level of integration because all the processes of MLD are interconnected to all the products. Therefore, criterion 1 cannot be applied to the MLD system.

The system expansion (criterion 2) is used to assess the global production of the MLD system and co-products. Global Warming, Fossil Resource Scarcity, Terrestrial Ecotoxicity, Marine Ecotoxicity, Fine Particle Matter Formation and Terrestrial Acidification impacts are calculated for global production.

In addition, as it is not possible to select criterion 1, criterion 3 is applied. In this study, the objective of the partitioning application is to understand the outcome of physical or economic motivation under different perspectives (process and system) in the MLD system assessment. Therefore, to avoid several different impact outcomes potentially resulting in complex discussions on the results, the partitioning analysis focuses only on the Global Warming impact. Global Warming was selected because it is one of the most calculated impact indicators in LCA. Lee and Jepson (2021) did a systematic review of LCA in desalination and found that all the LCA studies calculated the Global Warming. Additionally, the end-point results show a high contribution of Global warming (Figure B.1).

4.3.1 System expansion (criterion 2)

Figure 4.9 presents the normalised results of system expansion for the MLD and reference systems. Non-normalised results can be found in the Appendix, Table B.26. The calculation of the Global Warming, Fine Particulate Matter Formation, Terrestrial Ecotoxicity, Terrestrial Acidification, Marine Ecotoxicity and Fossil Resource Scarcity impacts shows the environmental benefits of the MLD system over the reference system. It should be highlighted that the reference system has considerably higher negative terrestrial and marine ecotoxicity impacts compared to the MLD system (Figure 4.9 – c and e).

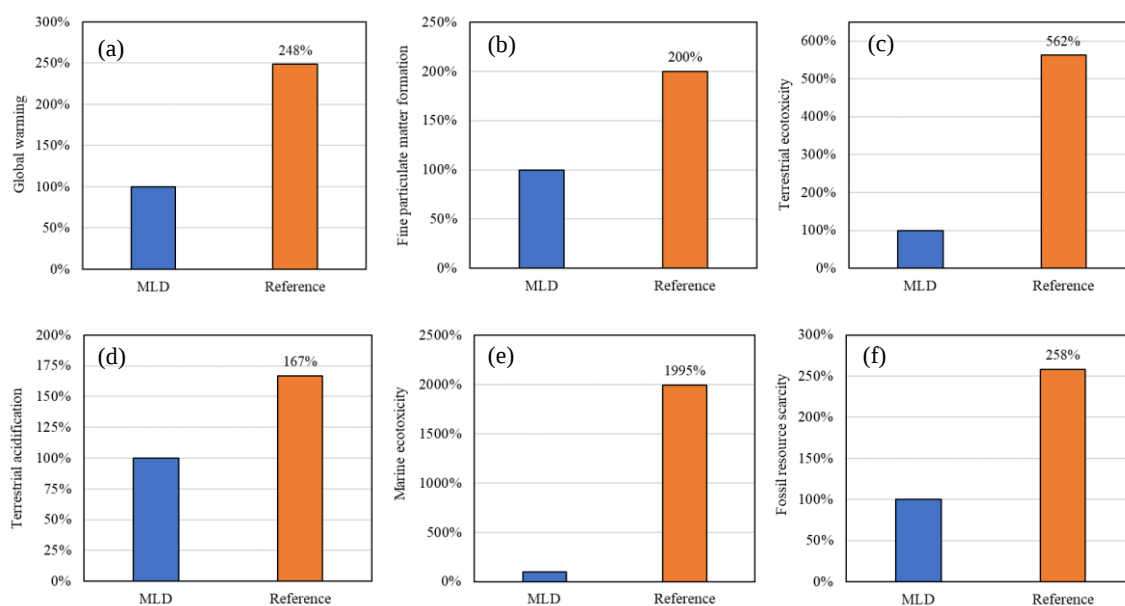


Figure 4.9 – Global Warming (a), Fine Particulate Matter Formation (b), Terrestrial Ecotoxicity (c), Terrestrial Acidification (d), Marine Ecotoxicity (e) and Fossil Resource Scarcity (f) impacts of the MLD and reference systems with the system expansion.

Regarding the MLD system, the oil-derived electricity consumption at the power station is the major contributor to Global Warming (82%), Fine Particulate Matter Formation (83%), Terrestrial Ecotoxicity (77%), Terrestrial Acidification (90%) and Fossil Resource Scarcity impacts (83%) (Figure B.2). The integration of other types of renewable energy (e.g. solar) with MLD is expected to decrease the contribution and consequently the overall impact. For the Marine Ecotoxicity category of the MLD system, the consumption of NaOH in the MF-PFR is the largest contributor (67%).

System expansion seems a reasonable option to assess desalination systems under the MLD and ZLD concepts as they tend to have more processes integrated than a conventional desalination system that only recovers water. The increment of processes potentially results in a higher burden to the environment, therefore it is appropriate to expand the boundaries of the reference system to include the reference system of the co-products recovered from brine. This definitely can change the perspectives of policymakers on preparing directives and action plans for the future of the desalination sector, as environmental benefits over reference systems are spotted.

4.3.2 Partitioning (criterion 3)

4.3.2.1 Process and system approach with physical and economic partitioning

Figure 4.10 presents the normalised results of one kg of co-product according to physical and economic partitioning. Non-normalised results can be found in Table B.27, Table B.28, Table B.29 and Table B.30 of the Appendix. The results indicate different relative contributions of the co-products which are affected by the approaches applied, which have different sets of partitioning factors (Table 4.1 and Table 4.2).

The desalinated water has the most impact contribution when system physical partitioning is applied because 89% of the co-production is desalinated water. This co-production ratio is enough for the desalinated water impact to represent almost 10% of the total impacts if system economic partitioning is used. It has no significant impact when the process economic partitioning is applied because of its market price of 1.5€/tonne which causes co-products like NaCl to have a higher burden. However, its impact increases to approximately 10% when the process physical partitioning is used because the impacts of the EFC and EDBM are allocated to the desalinated water due to the recirculation of NaOH and HCl from EDBM.

The NaCl shows a similar contribution to the total impact when process physical and economic partitioning and system physical partitioning are used. If the system economic partitioning is applied the contribution increases because its price and amount result in the third highest economic partitioning factor.

Mg(OH)₂, Ca(OH)₂ and Na₂SO₄ have a similar portion of impact if process physical partitioning is used, because energy and chemical impacts are allocated close to 100% to the effluent of the MF-PFR, and to the desalinated water and effluent of the EFC. The portion of impacts is different for the three co-products when process economic partitioning is applied because the market prices are different. From a system perspective, the system physical partitioning does not allocate impact to a large extent because the production of Mg(OH)₂, Ca(OH)₂ and Na₂SO₄ is much lower compared with the desalinated water, NaCl and HCl co-products. However, using system economic partitioning the portion of impacts for Mg(OH)₂ and Na₂SO₄ are large, while the environmental impact of Ca(OH)₂ is small because its production is much lower.

The HCl product increases the Global Warming impact for the process physical and economic partitioning because it is the last process. In addition, HCl receives significant impact contributions from the MF-PFR and EFC as their impacts are heavily allocated to effluents which end up in the EDBM process. In the system economic partitioning, the impacts of the EDBM are allocated 100% to the HCl because the recirculated HCL and NaOH are not modelled and the EDBM is very energy intensive. In addition, it has a much higher market value compared to the value of desalinated water. Therefore, HCl has the major portion of Global warming impact.

Regarding the physical and economic partitioning, the motivation and rationales must support the selection. From a desalination sector perspective and associated environmental issues, it is appropriate to affirm that physical partitioning is more reasonable to use because the main functionality of the desalination system is to produce water, and the other co-products which are recovered from waste, must have less burden than the main co-product. However, from an economic perspective, one of the motivations for the recovery of co-products from brine is the economic value generation. Therefore, the share of value attributable to the recovery of co-products establishes an appropriate basis for allocating responsibility for the related environmental burdens (Pelletier et al., 2015).

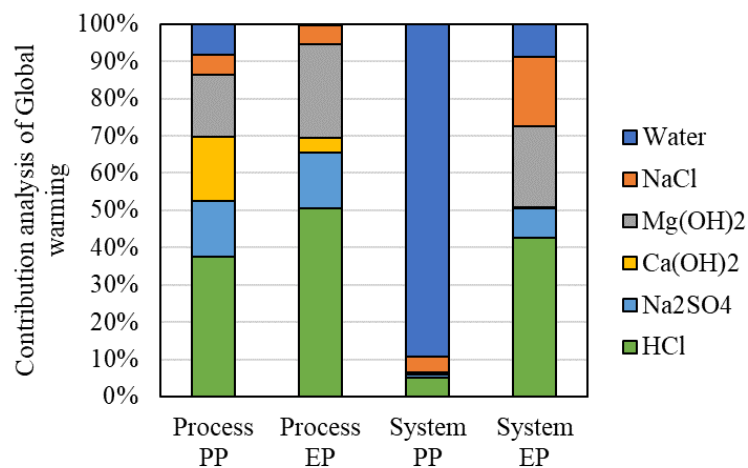


Figure 4.10 – Contribution analysis of Global Warming results of the MLD products with different approaches using physical partitioning (PP) and economic partitioning (EP).

4.3.2.2 Product analysis

Besides the analysis of different approaches for the multifunctionality issue, the study also compares each co-product individually with the corresponding reference product. Figure 4.11 shows the individual product comparison.

4.3.2.2.1 Desalinated water

For the desalinated water (Figure 4.11– a), the reference product system is conventional seawater reverse osmosis, which outperforms the MLD system when process physical partitioning, system physical partitioning and system economic partitioning are applied to calculate the Global Warming. This is mainly because the desalinated water of the MLD requires more energy and chemicals than the desalinated water of the conventional seawater reverse osmosis. However, if the process economic partitioning is used, the desalinated water of the MLD performs better than the reference desalinated water because the impacts are allocated to the MLD products and consumables like NaOH that have higher market prices. Moreover, the Global Warming from system physical partitioning is in the range of the reported carbon footprint of seawater RO desalination, which is 0.4–6.7 kg CO₂ eq/m³ (0.0004 – 0.0067 kg CO₂ eq/kg) (Jia et al., 2019)

4.3.2.2.2 NaCl, Mg(OH)₂, Ca(OH)₂, Na₂SO₄ and HCl

For co-products such as NaCl (Figure 4.11 – b), Mg(OH)₂ (Figure 4.11 – c), Na₂SO₄ (Figure 4.11 – e) and HCl (Figure 4.11 – f) where economic partitioning is applied, the Global Warming impact is closer to the reference products compared with the mass partitioning. However, the impact is still lower than the corresponding reference products. Regarding the Ca(OH)₂ recovered from the brine (Figure 4.11 – d), this has a significantly lower impact compared to the reference product. This is mainly because the reference Ca(OH)₂ production is more intensively composed of several production steps until the manufacturing of the Ca(OH)₂ (Table B.23).

The results show that the decisions of the different motivations, thus different partitioning methods and modelling perspectives, do not compromise the environmental benefit of recovering products from brine based on the operational level of the MLD system when the products are compared with the reference scenario. However, the decision on the partitioning

method generates a significant impact on the outcome of the LCA for the same product. For the MLD co-products, physical partitioning benefits the co-products recovered from brine because a lower environmental impact is allocated to them. In contrast, the economic partitioning (process) benefits the desalinated water. However, this difference between physical and economic partitioning might change when assessing and comparing different MLD schemes, technologies or brine management implementation.

An objectively accurate way to handle the multifunctionality issue does not exist, but the issue can be solved in a way that serves the aim of the LCA best. In a policy context, LCAs should contribute to long-term stability in the system, provide actors with equivalent and full information, and create a level playing field (Wardenaar et al., 2012). Therefore, preparing policies in which LCA is required to measure the environmental impacts of desalination systems, and allocation approaches are recommended, must take into consideration that several products can be recovered with different rates and market prices.

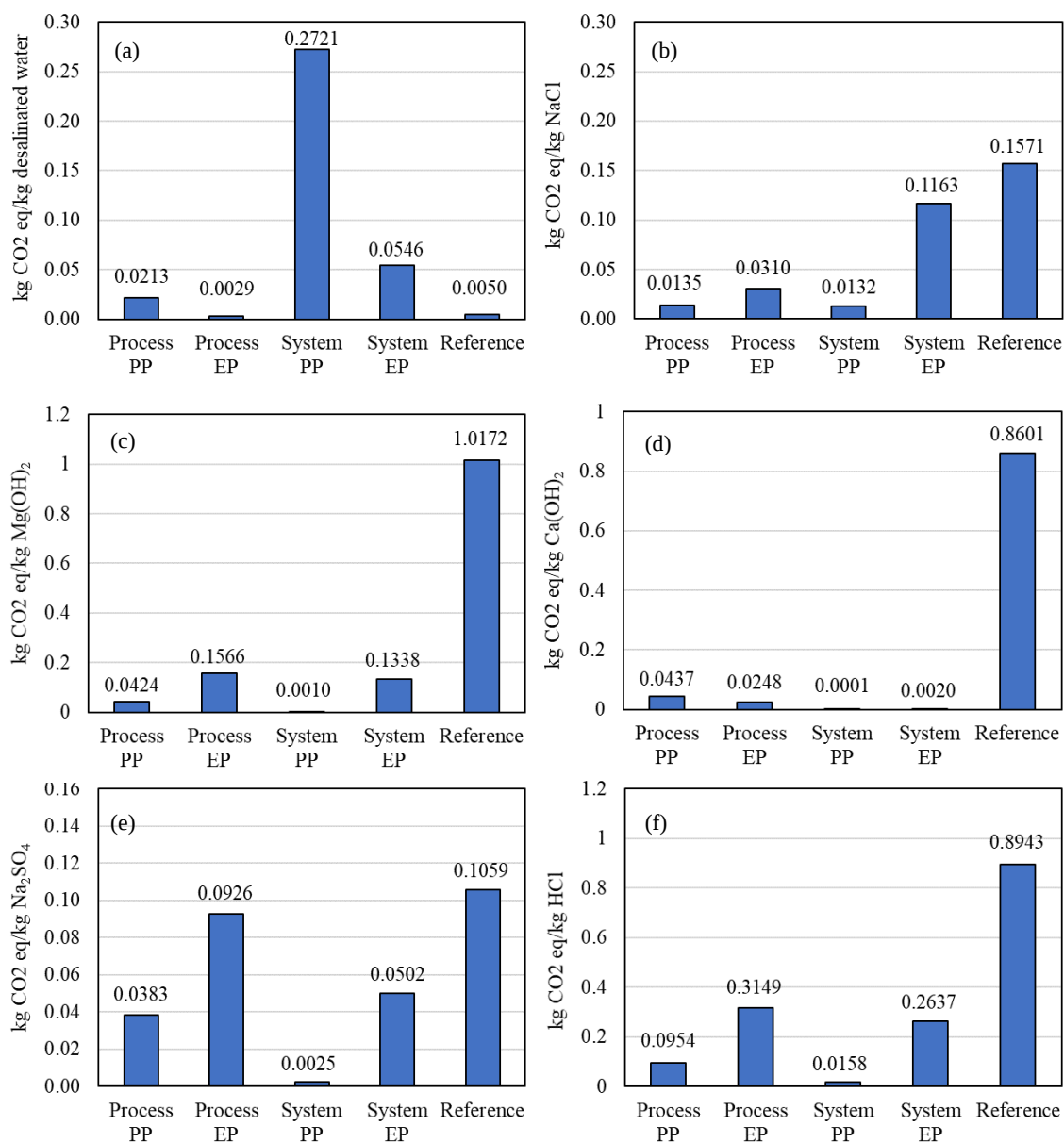


Figure 4.11 – Individual comparison of Global warming results of the desalinated water (a), NaCl (b), Mg(OH)₂ (c), Ca(OH)₂ (d), Na₂SO₄ (e) and HCl (f) products of the MLD system with different approaches using physical (PP) and economic partitioning (EP), and the corresponding reference products.

4.4 Limitations

A limitation of this study is the exclusion of all life cycle stages, such as construction and end-of-life. One of the reasons was the uncertainty about data regarding the construction of such MLD system, and the various applications for the co-products. For future research, the integration of the infrastructure of a multifunctional desalination system in the Life Cycle

Inventory would be valuable for understanding this stage's contribution to the environmental impacts of desalination co-products under different allocation approaches. Another limitation stems from the variation in operational conditions, which can affect the recovery rate of desalinated water and co-products, potentially influencing the results. Moreover, the assessments use fixed market values for the co-products, which restricts the economic partitioning approach, therefore the results. A sensitivity analysis would approach this limitation by highlighting how changes in recovery rates and market prices might impact the environmental performance of the MLD system, allowing for setting boundaries in its integration and operation.

4.5 Summary of main findings

- MLD systems are being adopted to enhance circularity by reducing brine discharge and increasing water recovery, converting them into multifunctional product systems. Therefore, a criterion LCA-based framework aligned with ISO 14044 was developed to assess the co-production of multifunctional desalination systems.
- Multifunctionality was handled using system expansion and partitioning (physical and economic) approaches, resulting in different functional units.
- Results show that the MLD system has larger environmental benefits than the reference system with system expansion. Applying physical and economic partitioning under different perspectives leads to different environmental burdens per co-product. The MLD system performs better than the reference system in CO₂ emissions when process economic partitioning is applied (0.003 kg CO₂/kg desalinated water).
- The co-products perform better than reference products under all partitioning approaches, highlighting the potential of brine as a secondary source of chemical products.
- This chapter emphasises the importance of selecting appropriate allocation approaches depending on the assessment's aim and motivation in order to support the desalination sector towards sustainability.

5 Circularity Assessment of Industrial Heat Exchanger and Water Treatment Systems Integration

5.1 Introduction

An increase in global water and energy demands is expected in the coming years due to overall growth in global consumption. However, the requirements and ability to meet these increases are likely to be hindered due to the ever-increasing reliance on (inter)dependencies between water, energy, and climate change (Rao et al., 2017). The global water demand is estimated to increase from 3,500 km³ per year in 2000 to approximately 5,500 km³ per year in 2050 (Willet et al., 2019), much due to overall population growth, urbanisation, migration and industrialisation – creating an ever-increasing need for freshwater resources (WWAP, 2015). The industrial sector is responsible for 12% of global water withdrawals, which is projected to increase by 400% in 2050, and result in severe consequences for the environment and ecosystems both locally and globally (Willet et al., 2019). Energy is another resource highly employed by the industrial sector, with 9,566 TWh of energy employed globally in 2019 (Urban, 2022) being a significant contributor to greenhouse gas emissions (Brodny and Tutak, 2022), and consequently climate change. Therefore, the European Union has identified climate and energy strategies with a focus on energy efficiency, decarbonisation and the development of renewable energy sources as a target to achieve carbon neutrality (Hafner and Raimondi, 2020).

As pressures mount on the world to transition to a Circular Economy (CE) and valorise all forms of resources by recovering, repurposing, recycling, upcycling, reusing, and others, innovative technologies will help pave the way. In order to demonstrate the decoupling of imprudent resource consumption from economic growth and development, the CE approach has been promoted to achieve resource efficiency, reduce waste production and improve environmental, economic and social sustainability (Nika et al., 2020). A CE action can be defined as an action that produces a circular intervention in a linear process or system to endorse circular principles. Circular principles are broadly accepted as those suggested by the Ellen MacArthur Foundation – “Design out waste externalities”, “Keep resources in use” and “Regenerate natural capital” (Arup, 2019). Moreover, CE principles have been employed to

tackle the over-consumption of resources, contributing to the Sustainable Development Goals (SDGs). When focusing on industrial economics, the CE was conceptualised as a strategy for waste prevention, regional job creation, resource efficiency, and dematerialisation of the industrial economy. Also, it emphasised the utilisation instead of ownership of goods as the most relevant sustainable business model for a loop economy, allowing industries to profit without externalising costs and risks associated with waste. The contemporary understanding of the Circular Economy and its practical applications to economic systems and industrial processes has evolved to incorporate different features and contributions from a variety of concepts that share the idea of closed loops (Geissdoerfer et al., 2017).

The United Nations developed the Sustainable Development Goals (SDGs) initiative which has set a goal for water, namely through Goal No. 6 – “Ensure availability and sustainable management of water and sanitation for all”. Thus, water recycling and reuse have been taken as one of the most important methods to achieve the goal. Due to the growth of freshwater scarcity and environmental protection concerns, water recycling and reuse as well as other resource recovery have been promoted in industries. Over the last decade, data have revealed that water recycling and reuse practices have improved exponentially (Ahmad et al., 2022). Nanofiltration method is employed in a variety of water and wastewater from different industrial applications for the selective removal of ions and organic compounds (Abdel-Fatah, 2018), and water purification (Tin et al., 2017). Moreover, two-stage ultrafiltration and nanofiltration have been investigated for recycling resources and water from different types of water and wastewater (Luo et al., 2011; Khosousi et al., 2023).

Regarding energy, SDGs have set a target for energy research and technology. The integration of waste heat recovery systems in industrial processes has been important as one of the major areas of research to decrease fuel consumption, mitigate harmful emissions and improve production efficiency. Industrial waste heat is the energy that is generated from industrial processes which is not harnessed in any practical way and is wasted or released into the environment. Waste Heat Recovery systems, like Heat Pipe Heat Exchangers (HPHE), are introduced in a system to promote optimum waste heat recovery efficiency (Jouhara et al., 2018), and are associated with nearly every industry, mostly in energy generation and heat exchange in general (Prajapati et al., 2024). Furthermore, the HPHE technology can mitigate

greenhouse gas emissions in industries which are highly dependent on natural gas consumption like ceramic industries (Jouhara et al., 2021).

Some industries generate gases (e.g. flue) that if released into the atmosphere contain a considerable amount of vapor form. If the gas temperature could be reduced below the dew point, the water vapor would begin to condense and sensible heat (convection), as well as latent heat (condensation) of the gas, could be recovered. Also, water in the form of condensate could be used repeatedly in the plant after its treatment (Poškas et al., 2024). This combination of resource recovery and use is being investigated due to their CE principles and benefits.

The CE strategies on water and energy endorsed by the industrial sector have gained momentum. By adopting CE principles, resource depletion and waste generation can be significantly reduced as materials are kept within the system for as long as possible. To transit towards a more circular and sustainable economic paradigm, it is imperative to assess the circularity potential within a specific industrial estate (Edirisinghe et al., 2024). Assessing the CE principles is important for the analysis of their true impact. It provides a way to understand how well different industries are integrating circular strategies into their processes, essentially demonstrating how industries are adapting to a more sustainable approach. Assessment methodologies measure the efficiency of the transition from a linear to a circular economy and identify strategies to improve (Vogiantzi and Tserpes, 2023). Measuring circularity requires selecting and validating CE indicators to assess the progress of identified CE actions in a specific system and sector (Moraga et al., 2019).

However, circularity assessment must also characterise and measure the impact of resource abstraction and outflow release on the origin and destination, respectively. Characterising linear and circular resource flows enables an understanding of potential disruptions when implementing circular actions to reduce resource depletion or close resource loops within the industries and their interactions with the natural environment.

Therefore, this work adapted a circularity assessment framework developed for water systems by Nika et al., (2022) as the framework incorporates resource flow characterisation and the measurement of the circular action performance. Additionally, the purpose of this work is to transfer this complete framework to the industrial sector. The adapted framework is hereby, applied for the assessment of a ceramic industry which integrated two systems in the production process intending to increase circularity by reducing freshwater and natural gas consumption.

5.2 Methodology

5.2.1 *Circularity framework*

The framework considered has been adapted from Nika et al., (2022) and encompasses five steps (Figure 5.1):

- 1) system development;
- 2) resource flows;
- 3) circular actions;
- 4) circularity measurement;
- 5) circularity assessment.

The first step regards the goal and scope definition, and the system boundaries under the scope. This definition enables the identification of the processes and resources that flow in and out of the assessment boundaries. The resource flow characterisation classifies the circular and linear flows that are part of the intervention in the industry. The flows can be materials, water, energy, waste or economic. Indicators are selected to differentiate the circular and linear fractions of the inflow and outflow. The circular actions are the strategies that the industrial sector can employ to accomplish CE principles. The identification of circular actions determines what needs to be measured and assessed, thus resulting in a crucial step for the selection of appropriate circularity indicators that translate those circular actions (Nika et al., 2022). In the circularity measurement step, data is collected to build the model for the material flow analysis that is used to calculate the indicators. The selected indicators should enable the assessment in the fifth step, where a benchmark and a scenario analysis are done. Benchmarking is performed when the goal of the assessment is to compare the CE actions integration in the industry with an identified and chosen baseline, and scenario analysis is more relevant when conducting optimisation steps of CE actions.

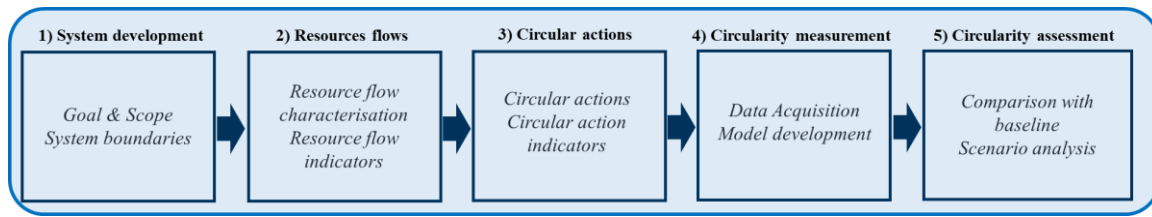


Figure 5.1 – Methodological framework for measuring and assessing circularity adapted from Nika et al. (2022).

5.2.2 Case study

The case study under investigation is a ceramic industry located in Modena, Italy, and produces a multitude of different ceramic products. The assessment focuses on the water and energy use, and waste in the exhaust gas generated in the production process (Figure 5.2). The products require different water volumes, and the water used can have different qualities which depends on the intended production batch and quality of the final product. Processes which consume the largest quantities of water are a) spray dryer, b) milling, and c) glazing. During milling, water is added to the powder mixture to facilitate the mixing of the ingredients and achieve fine grinding, resulting in a slip. This slip consists of water with varying properties (i.e. cleanest to dirtiest) depending on the colour desired (e.g. Dark ceramics, Grey ceramics and Light ceramics) and the source of water. Water is then removed (>90%) from the slip with a spray dryer unit and it is lost as water vapour in exhaust gas that is released through a chimney stack. Water is sourced from internal and external sources (Figure 5.2). The external water sources consist of wastewater and freshwater. Wastewater is obtained from third parties, i.e. industries, and it is treated by the onsite wastewater treatment plant (WWTP). The WWTP also receives wastewater produced by the ceramic industry (internal recirculation) and generates two flows: a purified water flow and a sludge flow which is reused by the industry. The sludge water is used directly in the milling phase when dark-scale ceramics are produced. The purified water can be used as a source for light-coloured ceramic production, however, this is rare and it is usually used for the production of grey-coloured ceramics. Freshwater is stored as clean water for industry use and when grey and light-coloured ceramics are produced. The consumption of fresh, purified and sludge water accounts for 77.6 %, 9.0% and 13.4% of the total water consumption of this ceramic industry, respectively. The exhaust gas that is released through a chimney stack to the environment is a mixture of various elements (e.g. organic matter,

nitrogen, bicarbonates, ions, etc), including water vapour (40,500 m³/year) and it is considered to have no value for the industry.

The industry generates electricity through a cogeneration system that uses natural gas (8.03% of the total energy consumed) and a photovoltaic panels system (0.05%). Moreover, it employs natural gas (88.61%) for heating purposes and grid electricity (3.31%) for the rest of its activities (e.g. lights and heating of boilers, spray dryer).

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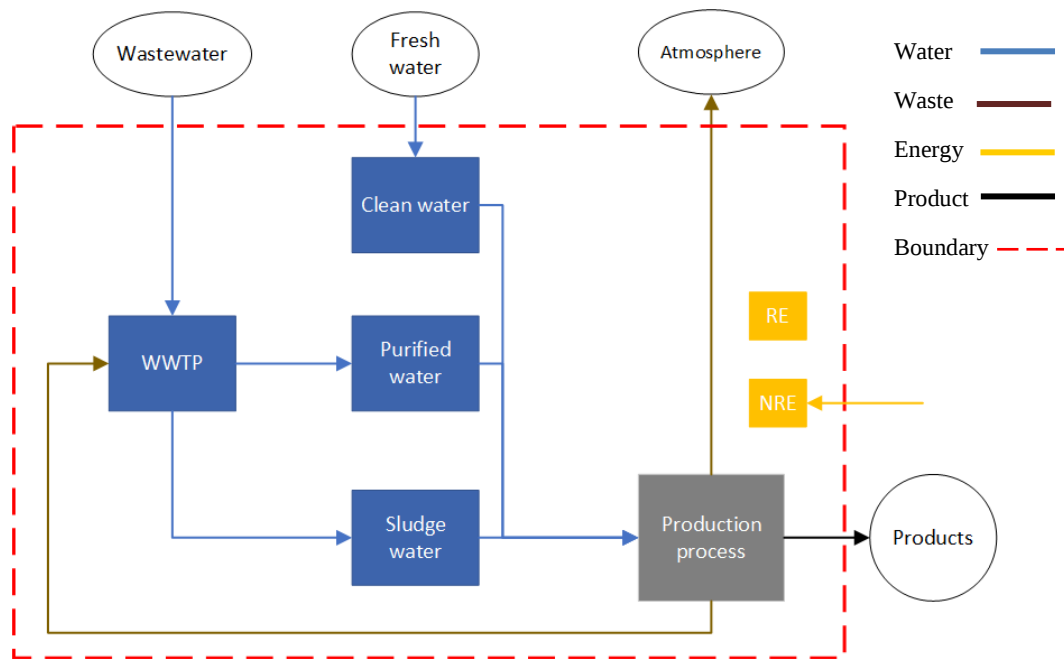


Figure 5.2 – Processes and flows of the ceramic industry under investigation. RE: renewable and recovered energy; NRE: non-renewable energy.

5.2.3 System development

Under the scope of the H2020 iWAYS project (grant no. 958274), two systems are integrated with the ceramic industry in order to reduce energy consumption from natural gas and water consumption from a freshwater source. The combination of the systems includes an energy and condensate water recovery system via a Heat Pipe Condenser Economiser (HPCE), and

consequent treatment of the recovered condensate via a water treatment system (Figure 5.3). A projected HPCE system of five units is located downstream of the spray dryer to receive the exhaust gas. The water vapour in the exhaust gas condensates through the operational dynamics of the HPCE system due to temperature difference, i.e. the HPCE is essentially divided into two sections, one where the vapour passes through a series of channels and progressively cools down. In the second section, a coolant liquid (insulated) flows through the HPCE to cool down the vapour as it flows through different channels. The thermal exchange between the vapour exhaust and the coolant liquid captures thermal energy by heating the coolant liquid which can then be reused to heat boilers or for other purposes. After treating the condensate, it is reused in the industry, for milling or glazing activities. The operational principles of the HPCE system are a maximum capacity of 6.5 MWh for energy recovery and 2.5 m³/h for condensate water recovery.

The water treatment system treats the recovered condensate from the HPCE system. It consists of an ultrafiltration (UF) followed by nanofiltration (NF). The UF unit is composed of four vertical hollow fibres and the NF unit is composed of three vertical hollow tubes. The operational characteristics of the water treatment process are shown in Table 5.1. The operational data was used to calculate the performance impacts of the water treatment process regarding water and energy flows within the assessment boundaries. The water treatment system receives a recoverable condensate rate of 21,900 m³/year and produces clean water, approx. 7,884 m³/year – best scenario. The clean water is stored in a purified water tank (Figure 5.3).

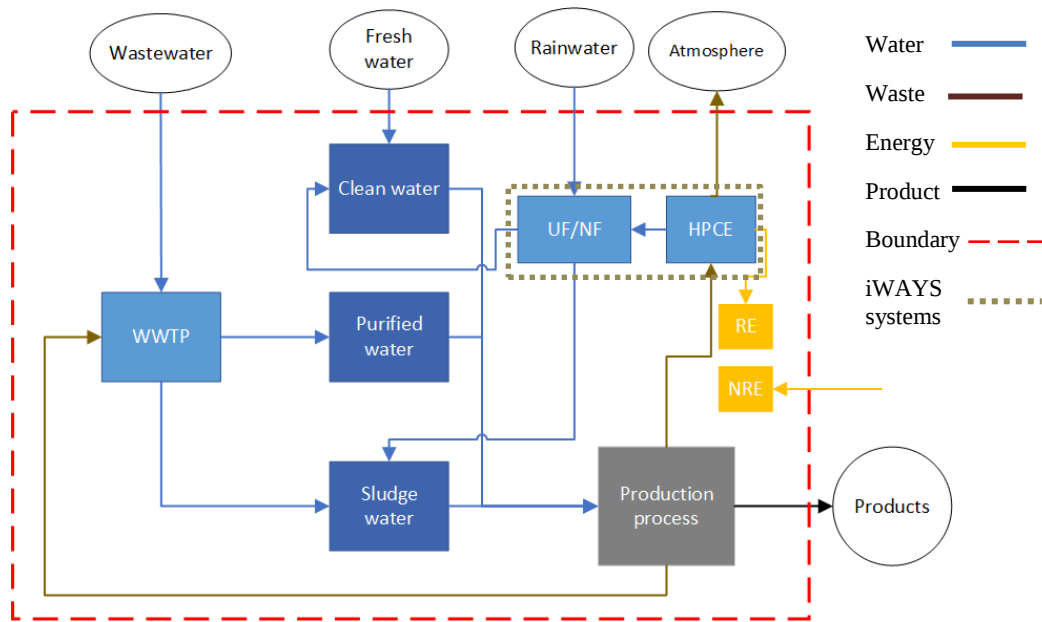


Figure 5.4 – Processes and flows of the ceramic industry with the iWAYS systems and rooftop runoff rainwater harvesting integration under assessment (Scenario B). RE: renewable and recovered energy; NRE: non-renewable energy.

The goal of the assessment is to measure the intrinsic circularity performances of both scenarios (A and B) and compare them with the scenario without integration. In addition, scenario analysis is performed to optimise the rainwater harvesting method. Therefore, the scope of the assessment focuses on the impact of the integration on freshwater consumption and natural gas resources which are aimed to be mitigated.

5.2.4 Resource flows

For the assessment of the integration of the HPCE and water treatment systems, the resource flow characterisation focuses on the water and energy flows within the boundaries of the assessment. Regarding the water inflows, the wastewater, freshwater, and rainwater are characterised as inputs to the system. Wastewater is classified as a circular flow, as it results from third parties and is reclaimed (wbcsd, 2022), while the freshwater is classified as a linear flow because it is sourced from an aquifer and is classified as a virgin source (Renfrew et al., 2024). Harvested rainwater which is renewed by precipitation and the natural water cycle is classified as a circular flow (ISO 59020, 2024). Regarding the water outflows, water leaving

the assessment boundaries is in the form of exhaust gas and in the product. The water in the exhaust gas is classified as a linear outflow because it is lost as a by-product of the industry production process (wbcsd, 2022). The water in the products is classified as circular outflow as it is part of the product's characteristics and function.

The industry with the integrated HPCE results in five energy sources. Energy from the HPCE and photovoltaic panel system is classified as circular flows as they are non-virgin and renewable respectively, while energy obtained from cogeneration and natural gas burning is classified as linear flows (from non-renewable material). Regarding energy from the grid, this is classified as both linear and circular flows, as the mix of the energy grid is diversified.

The resource flow indicators are shown in Table 5.2. For the water flows, the indicators selected are Circular Water Inflow (CWI) and Circular Water Outflow (CWO). The CWI measures the circular fraction that enters the boundaries of the assessment which is defined by the classification approach applied to the wastewater, freshwater and rainwater. The CWO measures the circular water fraction that leaves the boundaries and it is defined by the classification approach applied to the water in the exhaust gas and final product.

ISO 59020 (2024) proposes two indicators for energy. One calculates the percentage of the renewable energy contribution and the second is the percentage of energy recovered or generated from residual, non-renewable and non-recoverable resource outflows. The HPCE recovers waste heat from an outflow of the boundaries which is the exhaust gas, and it is not classified as renewable. However, the use of waste heat allows a decrease in the dependency on natural gas which is a non-renewable energy, thus classified as a linear flow. Therefore, the Recovered Energy Contribution (REC) indicator is used to calculate the fraction of energy recovered from outflows by the industry. As the HPCE and water treatment systems do not impact the renewable energy flow from the photovoltaic panels system, the percentage of renewable energy contribution is not measured.

Table 5.2 – Resource flow indicators.

Category	Indicator	Equation	Reference
Water	Water Circular Inflow (as defined by classification approach) (%)	$\frac{\text{Mass Circular Inflow}}{\text{Total Mass of Inflow}}$	(wbcsd, 2022; Renfrew et al., 2024; ISO 59020, 2024)
	Water Circular Outflow (as defined by classification approach) (%)	$\frac{\text{Mass Circular Outflow}}{\text{Total Mass of Outflow}}$	(wbcsd, 2022)
	Total Circular Flow (%)	$\frac{\text{Circular Inflow} + \text{Circular Outflow}}{2}$	(Renfrew et al., 2024)
Energy	Recovered Energy Contribution (%)	$\frac{\text{Recovered energy from outflow}}{\text{Total Energy Consumption}}$	(ISO 59020, 2024)

5.2.5 Circular action

The strategy of integrating the HPCE and water treatment systems in the industry aims to promote the following CE principles:

- Reducing freshwater withdrawal by recovering resource value through recycling water from the exhaust gas and by harvesting rooftop run-off rainwater;
- Reducing natural gas consumption by recovering resource value through recovering waste heat from the exhaust gas;
- Closing loops by retaining value through the utilisation of outflows.

The circular action indicators selected are shown in Table 5.3. Each circular action has a group of indicators in order to measure its performance. Moreover, economic indicators were selected as in addition to increasing the intrinsic circularity of the industry, the systems also aim to impose economic savings related to freshwater and natural gas consumption (Table 5.3).

The performance of the circular action on reducing freshwater withdrawal is measured by the indicators Onsite Water Circularity (OWC) and Water Withdrawal Reduction (WWR). The OWC indicator was selected because it measures the times that water is circulated onsite through recycling and reuse practices before it results in an outflow (wbcsd, 2022). If it is

higher than one it means water is recycled and reused on site. The WWR indicator measures the percentage of freshwater withdrawal reduction (Nika et al., 2022). In addition, the economic savings from reducing freshwater consumption is calculated by the Water Cost Saving indicator.

Regarding the circular action of reducing natural gas dependency by integrating the HPCE, the performance of the action is measured by the calculation of the reduction of CO₂ emissions and economic savings related to the reduction in natural gas consumption.

Through closing the exhaust gas loop by recovering heat and water, the focus is on heat and water vapour loss through the stack chimney and the wastewater produced that goes to the WWTP. The Waste Utilisation Index (WUI) indicates the amount of water vapour in the exhaust gas and the wastewater which is recovered to be used in the industry. To complement this, the Total Cost Saving indicator is used as the sum of Water and Energy Cost-Saving indicators, as the closing loop action allows to potentially reduce costs related to freshwater and energy consumption.

Table 5.3 – Circular actions, indicators and equation

Circular action	Indicator	Equation	Aim
Reducing freshwater withdrawal	Onsite Water Circularity (OWC)	$\frac{\text{Volume of water use} - \text{Total volume of water withdrawal}}{\text{Total volume of water withdrawal}} + 1$	Increase
	Withdrawal Reduction (WWR)	$\frac{WW_{\text{baseline}} - WW_{\text{circular action}}}{WW_{\text{baseline}}}$	Up to 100%
	Water Cost Saving	Volume of freshwater reduction $\times$ price of water	Increase
Reducing natural gas dependency	CO ₂ Emissions Reduction	Natural gas reduction $\times$ CO ₂ emission factor	Increase
	Energy Cost Saving	Natural gas reduction $\times$ price of natural gas	Increase
Closing loops	Waste Utilisation Index (WUI)	$\frac{\text{Amount of utilised waste}}{\text{Amount of utilised waste} + \text{Amount of generated waste}}$	Up to 100%
	Total Cost Saving	Water Cost Saving + Energy Cost Saving	Increase

5.2.6 Circularity measurement

The circularity measurement consists of collecting data in order to build the model that represents the integration of the HPCE and water treatment systems and the rooftop runoff

rainwater harvesting in the industry. The model contains the material flow analysis (MFA) required to calculate the resource flow and circular action indicators. Due to confidentiality, the MFA is not presented. Additionally, to calculate the indicators for Scenario B, a rainwater harvesting model was developed based on the rooftop area available for collecting rainwater (63,000 m²), and historical precipitation data in the region (Modena, Italy) was used – European Climate Assessment & Dataset (<http://www.ecad.eu>) (Klein Tank et al., 2002) (Table 5.4). Based on recorded historical precipitation data, potential rainwater harvesting volumes were calculated for the past 15 years (Table 5.4).

Table 5.4 – The estimated potential collected rooftop runoff rainwater for the ceramic industry.

Month	Average runoff rainwater (m ³)	Max runoff rainwater (m ³)	Min runoff rainwater (m ³)
January	2,428	7,069	126
February	4,296	9,778	315
March	3,624	8,921	176
April	3,389	7,472	25
May	4,052	12,323	1,058
June	4,229	11,416	441
July	1,649	6,023	0
August	2,265	6,728	0
September	3,607	8,921	491
October	4,171	9,387	529
November	5,045	10,760	1,184
December	2,227	7,459	0
TOTAL	40,981	106,256	4,374

The data used for the economic indicators for each circular action are given in Table 5.5. The costs of the natural gas and freshwater were collected at the beginning of this assessment, and it is worth mentioning that their cost values are subjected to change due to market volatility and inflation. Additionally, chemical costs of the water treatment system were included and the volume of chemicals used was registered during the operational campaign carried out in the iWAYS project. The emission factor of natural gas combustion, 1.9 kg CO₂ eq/m³, was used (EEA, 2024) to calculate the avoided CO₂ emissions due to replacing natural gas with waste heat.

Table 5.5 – Prices and cost data for calculation of economic indicators.

Parameter	Price	Unit	Source
Natural gas	7.82	€/kwh	(Statista, 2023)
Freshwater	1.05	€/m ³	Provided
Caustic soda	0.90	€/m ³	Provided
Citric acid	0.80	€/m ³	Provided
Sodium hypochlorite	0.60	€/m ³	Provided
Phosphonic acid	0.07	€/m ³	Provided

5.2.7 Circularity assessment

The circularity assessments were performed through 1) a benchmark assessment evaluating scenarios A and B against the baseline scenario, and 2) a scenario analysis which consists of analysing the effect of rainwater monthly variation and the impact of different rainwater management methods. The rainwater management methods investigated are: 1) treating the harvested rainwater only with the UF unit; and 2) no treatment for harvested meaning it is directly used in the production process of the industry.

5.3 Results and discussion

5.3.1 Circularity assessment

The circularity assessment consists of quantifying the benchmark and proposed solution through the selected indicators and comparing them with each other. Additionally, a scenario analysis is performed which consist of analysing changes in the rainwater management method.

5.3.1.1 Benchmark assessment of Scenario A and B

Figure 5.5 (a) shows the scores of CWI, CWO, CWF, WWR, REC and WUI indicator calculations, and Figure 5.5 (b) shows the OWC indicator for the baseline and scenarios A and B. The baseline scenario indicates a CWI score of 5.78% due to the intake of wastewater from third parties meaning the baseline has a large linear water withdrawal flow due to freshwater

consumption. Regarding the CWO, the baseline scores a value of 5.00% which is represented by the amount of water in the manufactured products. This means that a significant volume of water that exits the industry (or assessment boundaries) is classified as a linear flow as it is released and lost through the exhaust gas. The wastewater produced in the production process of the industry is pumped to the WWTP, therefore it is not considered an outflow because the flows are contained within the boundaries of the assessment. The OWC indicator shows that water is reused onsite 1.29 times before it leaves the industry as an outflow.

Scenario A slightly improves the CWI (6.28%) due to the recovered condensate water from the HPCE system. The CWO increases up to 10.27% due to the recovery of 21,900 m³/year of condensate water from the 40 530 m³/year of vapour water in the exhaust gas by the HPCE system. This contributes to a water withdrawal reduction of 7.97% from the freshwater source and an increase in the OWC indicator to 1.40.

Scenario B presents a significant increase in water circularity due to the employment of rooftop rainwater harvesting, which increased the CWF and the WWR indicators up to 33.73% and 22.88%, respectively. The increase in CWF is credited to the increase in CWI (61.19%) due to the estimated volume of 41,000 m³/year of rainwater harvested considering a rooftop area of 63,000 m². Additionally, the OWC increased from 1.40 to 1.79, indicating an increment in the number of times water is reused by the industry.

The REC shows that the Baseline has a 0.0%, scenarios A and B have a 20.01% and 19.98% of recovered energy employed. The integration of the HPCE system results in an increment of the circular energy portion by 20%. The small difference between scenarios A and B is due to the energy consumption of the iWAYS water treatment system. Scenario B recovers more water, therefore the water treatment system requires more energy, increasing the overall energy demand of the industry.

For the Baseline, the WUI is 36.07% because the industry already reuses wastewater generated from other industries and treats it in its onsite WWTP (or sometimes directly reuses the wastewater with no treatment required). Regarding scenarios A and B, the score is the same (70.62%) due to the recovery of condensate water from the exhaust gas occurring in both scenarios at the same rate.

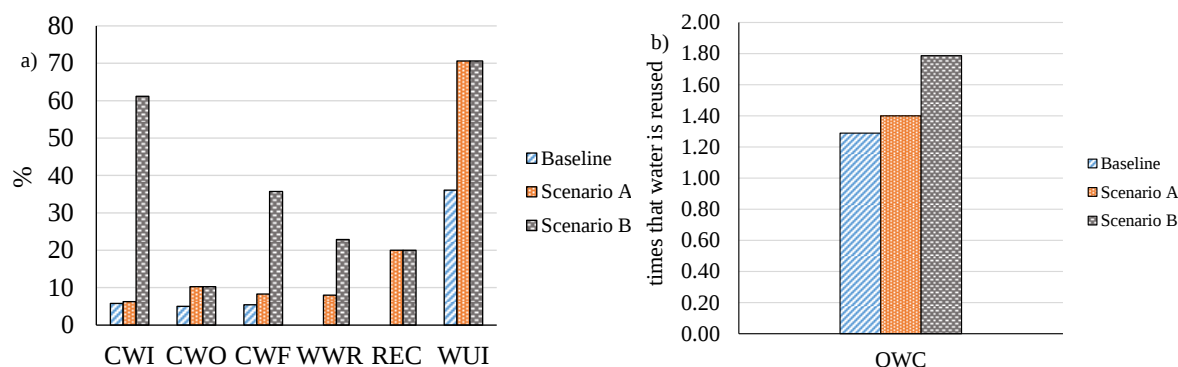


Figure 5.5 – CWI, CWO, CWF, WWR, REC, WUI (a) and OWC (b) scores for baseline, scenario A and B.

Economically, freshwater reduction shows that scenario A results in saving 8,270 € per year due to the water recovery from the exhaust gas compared to the baseline scenario (Figure 5.6 – a). Furthermore, scenario B demonstrates an increase in the water cost saving by 187% (23,760 €/year), in relation to the baseline scenario (Figure 5.6 – a). The assessment indicates a step towards decarbonisation by recovering waste heat from the exhaust gas, which results in avoiding 9,875 kg CO₂/year of emissions from natural gas combustion (Figure 5.6 – b). The circular action of reducing natural gas dependency by integrating the HPCE (scenario A) indicates a fuel cost saving of 4,378,400€ per year (Figure 5.6 – c). No differences are seen in scenario B because the rainwater harvesting integration does not affect the energy recovered by the HPCE system and natural gas consumption. Economically, the utilisation of the exhaust gas for recovering water and energy contributes to a total saving of 4,386,700 €/year, and the rooftop runoff rainwater harvesting integration contributes to a total saving of 4,402,150 €/year (Figure 5.6 – c).

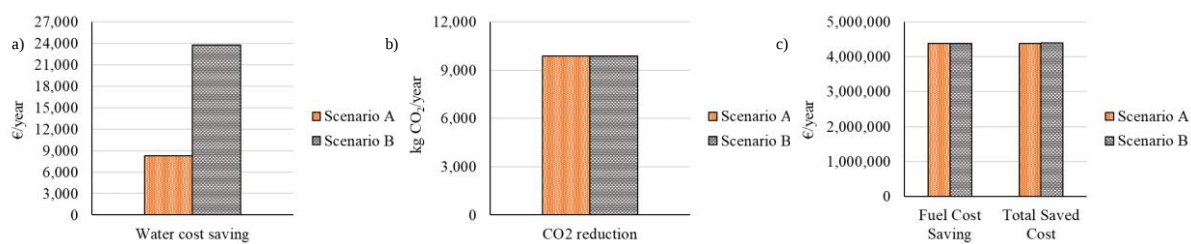


Figure 5.6 – Water cost saving (a), fuel cost saving (b), total saved cost (b) and CO₂ reduction (c) indicators for scenarios A and B.

The results indicate the HPCE system integration improves circularity flows related to energy more than to water. Additionally, it is the main contributor to the strong performance of the identified circular actions: reducing natural gas dependency and closing loops through decarbonisation. It is also the major contributor to the economic savings.

The lower impact of the HPCE system on the water circular flow and the action reducing freshwater withdrawal is associated with the demand of the industry for freshwater, which is almost 12 times higher than the recovered condensate water after the iWAYs water treatment system. However, it is still worth highlighting the slight improvement due to a novel design feature on the HPCE enabling condensate water recovery, as its main functionality is waste heat recovery from exhaust gases.

The water circular flow and the circular action reducing freshwater withdrawal have a significant improvement when rooftop runoff rainwater harvesting is integrated. However, its annual variation is expected to impact the water circularity flows and the circular action performance.

5.3.1.2 Annual rainwater variation and rainwater management methods impacts

Rainwater events are periodic and different each month in the industry region, thus impacting the potential harvesting rate (Table 5.4). Therefore, the impact of annual rainwater variation is measured. The indicators regarding the water withdrawal reduction (WWR), and the associated value creation of the economic savings generated by reducing freshwater withdrawal are considered for the analysis.

In Figure 5.7, the WWR indicator (Figure 5.7 – a) and the related monetary value of the total water recovered (condensed and rainwater) (Figure 5.7 – b) for each month are shown. The analysis shows that for February, May, June and November, a WWR score above 50% is achievable which represents a monetary water saving value of 4,390 €, 5,350 €, 5,005 € and 4,760 €, respectively. On the other hand, the WWR indicator shows the months with lower rainwater harvesting potential are July, August and December. Table 5.4 indicates that in the past, these three months have recorded no precipitation at all. Therefore, employing rooftop runoff rainwater harvesting shows that large and small freshwater reduction can be observed annually, meaning the benefits of this circular strategy are dependent on uncontrolled and external events.

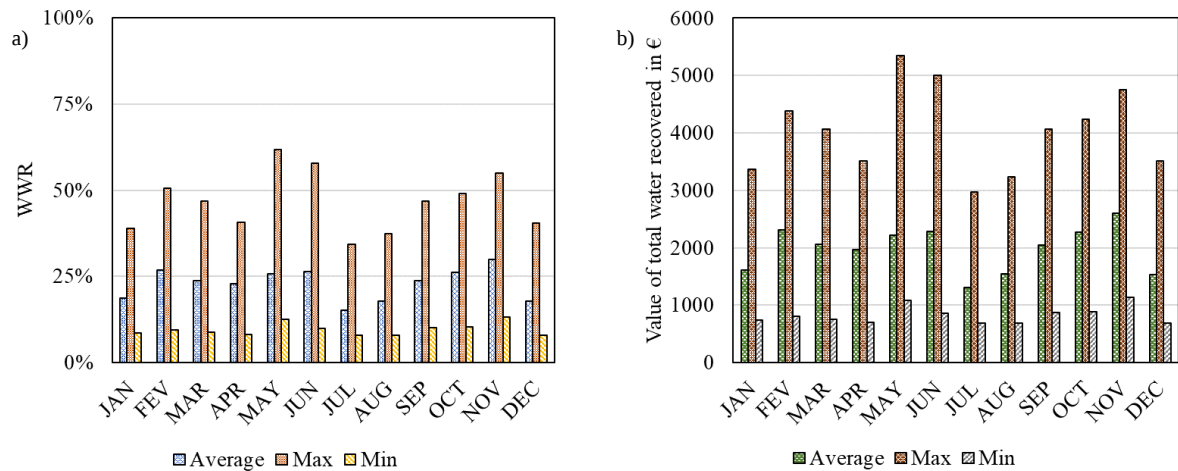


Figure 5.7 – Average, maximum and minimum for the WWR indicator (a) and the monetary value of the recovered water (condensed and rainwater) (b) during the year.

In fact, an option to increase the WWR indicator, resulting in water savings, would be to stop feeding harvested rainwater to the iWAYS water treatment system, as the UF and NF recovery efficiencies are 72 and 50%, respectively. The decision to treat harvested rainwater is mainly to remove algae that potentially might grow in the harvesting storage tanks, however, the rainwater composition was analysed and it has a good quality compared with the freshwater (Table C.32). Therefore, two scenarios were studied:

1. treating the harvested rainwater only with the UF unit;
2. absence of UF and NF – direct use of the harvested rainwater in the production process.

Under scenario 1, the WWR average is 39% (Figure 5.8 – a) demonstrating a strong improvement when compared to scenario B. Furthermore, the data shows if a rainfall event like the maximum registered in May, June and November occurs, the harvested rainwater and the recovered condensate water can cover all freshwater demand by the industry in those months.

Regarding scenario 2, the WWR indicator increased on average up to 49% annually. Thus, the potential of covering freshwater requirements with recovered water is extended to February, March, September, October and November (Figure 5.8 – b), alongside May and June.

From an economic perspective, scenarios 1 and 2 could lead to savings of on average 39,260 € and 51,308 € in freshwater consumption per year, respectively (Figure 5.8 – c and d). The excess of recovered water could be stored for further use, reducing the dependency on freshwater. Another option could be selling or sourcing the recovered water to another industry in the vicinity.

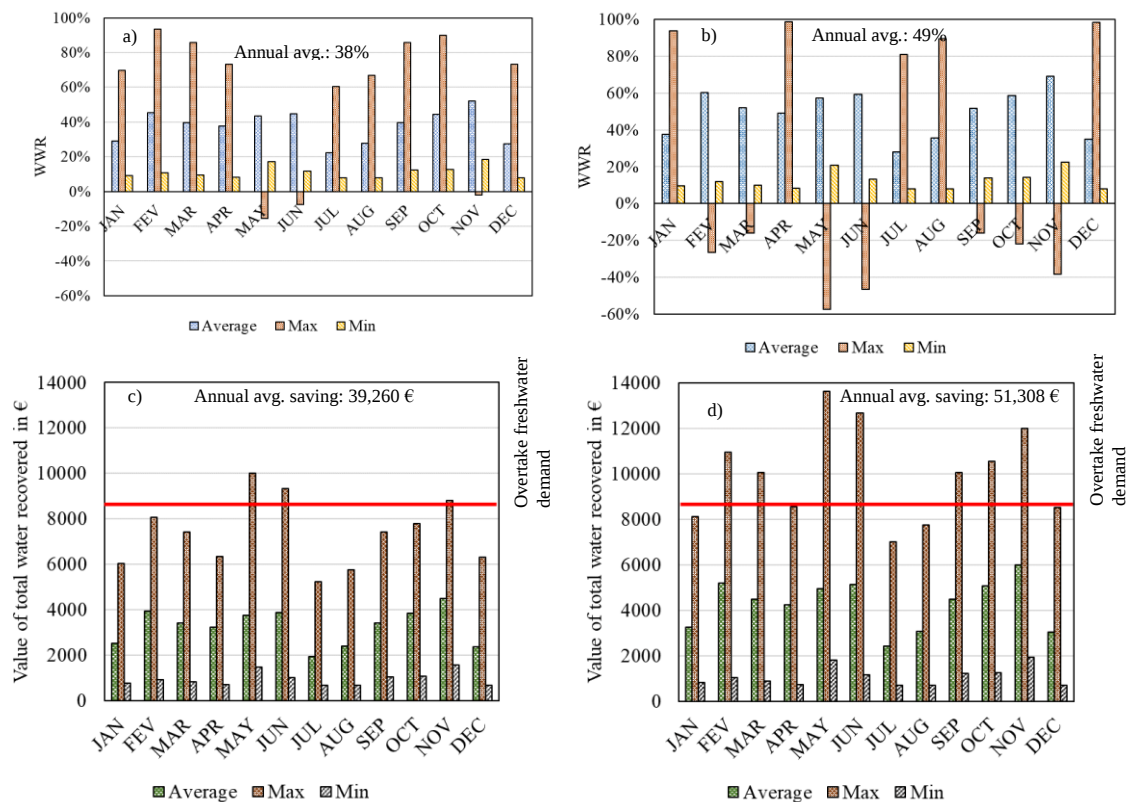


Figure 5.8 – Average, maximum and minimum for the WWR indicator and the monetary value of the recovered water (condensate water and rainwater) in all the annual months. Scenario 1 (no NF use) (a and c) and scenario 2 (no UF and NF use) (b and d). The red line in figures c and d means when the recovered water overtakes the freshwater demand.

5.4 Summary of main findings

- The industrial sector significantly contributes to global freshwater and energy consumption, impacting the environment. Therefore, industries are adopting strategies to shift from linear to circular practices, including water recycling and reusing to reduce freshwater consumption. One of the strategies is employing the Heat Pipe Heat Exchanger (HPHE) technology which has been effective in reducing natural gas consumption and mitigating greenhouse gas emissions;
- This study assesses the integration of a Heat Pipe Condenser Economiser, water treatment system, and rooftop rainwater harvesting in the ceramic industry. However, the current CE assessment methodologies do not fully account for interactions between human and natural systems, which could lead to potential disruptions. Therefore, this chapter uses CE methodologies and indicators to measure efficiency in transitioning from linear to circular practices and to measure the resource flows within the ceramic industry and natural systems;
- Results show that integrating these systems increased circular water and energy flows, reducing resource consumption and releases. Furthermore, CE actions improved performance over the baseline scenario and strategies to further optimise circular practices such as reducing freshwater withdrawal were identified.

6 Conclusions and Recommendations for Future Work

6.1 Conclusion

Desalination plays a crucial role in many regions and industries globally. However, given its environmental and economic implications, it is essential for the desalination sector to transition toward a Circular Economy (CE) and greater sustainability. The assessment methodologies developed and applied in this thesis provide valuable insights into desalination systems. The circularity assessment introduced in Chapter 3 can assist researchers and R&D industries in planning and identifying key areas for improvement within desalination systems. Furthermore, policymakers can benefit from this assessment, which tracks linear resource flows and highlights tangible value creation. Additionally, exploring various allocation methods can help policymakers understand how differing motivations—such as production rates (physical) and market price/demand (economic)—can influence environmental outcomes.

6.1.1 Research question 1

How are desalination systems currently evaluated and assessed in terms of performance and sustainability?

Evaluating and assessing desalination systems involves a range of methodologies aimed at measuring their performance across environmental, economic, and technical dimensions. While the assessment of social impacts is still in its early stages, it is increasingly recognised as a crucial component of comprehensive sustainability evaluations. Economic and techno-economic methodologies, such as Life Cycle Costing (LCC) and Techno-Economic Analysis (TEA), are widely used to assess the economic and technical performance of desalination systems. Historically, the feasibility of desalination plants and processes has been primarily evaluated based on economics and production reliability, with limited attention given to externalities. However, measuring the environmental impacts has become an essential task for the desalination sector. LCA is the most commonly employed methodology for evaluating environmental impacts. These methodologies are vital and provide valuable support in the transition of the desalination sector toward sustainability.

In what ways is the circular economy incorporated and measured within desalination systems?

Due to the conservation and protection of water bodies, and water situations like shortages, brine has received attention worldwide. The developments on transforming desalination systems into MLD and ZLD systems have been promoted as circular as they aim to close loops by minimising waste generation, maximise recovery efficiency and encourage reuse of materials. However, implementing CE principles might generate negative externalities, therefore, it is important to identify trade-offs as concepts like MLD and ZLD can look inherently to circularity. For the water sector, systematic and comprehensive methodologies for measuring the intrinsic circularity have been recently developed and applied, however, nothing is focusing on water supply systems like desalination systems. Therefore, it is urgent to develop a systematic and comprehensive assessment methodology under the scope of circularity that performs a critical and comparative analysis by measuring the intrinsic circularity value of desalination systems. Traceability of resource flows and value created calculation could support the identification of hotspots (negative externalities) caused by desalination systems in which circular performance is expected to be overserved, and in addition, both could enable system optimisation.

Is there an issue from a life cycle assessment perspective when multifunctional desalination systems are observed?

The concept of multifunctionality in the desalination sector extends beyond water recovery to include the extraction of additional products, such as common salts and valuable metals like lithium and rubidium, particularly through technologies like ZLD systems. However, incorporating multiple technologies increases the energy demand of the overall desalination process. Therefore, the environmental impacts of multifunctional systems need to be appropriately distributed among the various co-functions or co-products. This highlights the need for further investigation into how to address the challenges of multifunctionality in the desalination sector.

6.1.2 Research question 2

How can resource flows be tracked in the desalination systems? How does measuring the performance of the value chain of a desalination system provide insightful information for decision-making?

This thesis presents a novel methodology that systematically and comprehensively measures the intrinsic circularity of desalination systems, with a focus on resource flow traceability and the implementation of circular actions. The classification approach effectively differentiates between circular and linear resource flows, including water and ions, within desalination processes. The methodology enables the identification and evaluation of circular actions across the value chain through a set of targeted performance indicators. This allows for the identification of stages in the desalination system that are either overperforming or underperforming according to CE principles. Additionally, the methodology demonstrates flexibility in adapting to changing conditions, such as variations in feedstock, interruptions in resource supply, and different discharge strategies. This adaptability provides valuable insights into potential risks and benefits, aiding in strategic planning. Furthermore, scenario analysis illustrates that the methodology can be applied to various desalination systems, including conventional desalination (Scenario 2) and Zero Liquid Discharge (ZLD) systems (Scenario 3).

Which are the main hotspots in the desalination systems?

This work emphasises the importance of assessing intrinsic circularity to promote more sustainable desalination practices. Applying this methodology to an MLD system, valuable insights were measured, such as achieving 94% circular water inflow, 91.2% circular water outflow, and an 85.9% water recovery rate. These results highlight energy and chemical consumption as hotspots and, therefore, key areas for optimisation, as high CO₂ emissions are expected. In addition, the high costs were also identified as hotspots. This integrated approach supports informed decision-making, optimising resource use and minimising environmental footprints. However, the goal of this methodology is to complement, not replace, existing assessments, which typically take a more consequential perspective. Therefore, future research could focus on integrating circularity and sustainability indicators to create a more holistic assessment tool. This would provide more detailed results and reveal additional trade-offs,

thereby enhancing the strategic implementation of circular economy principles within the sector.

6.1.3 Research question 3

How is multifunctionality addressed in the desalination systems?

The desalination sector is increasingly adopting MLD systems to enhance circularity, reduce brine discharge, and improve water recovery, thereby transforming these systems into multifunctional product systems. This shift means that desalination systems are capable of producing multiple co-products in addition to desalinated water. As a result, the co-production of valuable recovered products requires a fair environmental impact assessment. In conventional desalination systems, environmental impacts are typically allocated to the desalinated water. However, for multifunctional desalination systems, the environmental impact must be distributed across each co-product, presenting a methodological challenge in allocating the environmental burden for each function. Moreover, assessing a multifunctional desalination system requires a benchmark scenario with an equal scope and functional unit for comparison. This should not pose a significant challenge for Life Cycle Assessment (LCA) of desalination systems, as the co-products derived from brine are made up of elements from the periodic table. These elements can also be obtained through conventional processes such as mining and other physical or chemical processes.

This issue has been addressed in several sectors, including energy, food, manufacturing, wastewater treatment, and biobased products, but it remains unaddressed in the desalination sector. It is well-known that applying allocation methods to resolve multi-functionality issues is challenging, and LCA practitioners often differ in their recommended guidelines. Some follow ISO recommendations, while others adopt different approaches. In many cases, the choice of methodology appears subjective, with some practitioners relying on similar studies. Given this, it is crucial to begin addressing this issue in the LCA of desalination systems. Rather than adding confusion to the field, it is important to approach this issue through a systematic and logical methodological framework.

How do different approaches impact the environmental burden of products and co-products from multifunctional desalination systems? Can the recovery of co-products from brine become

a secondary source of minerals with a lower environmental burden than conventional minerals?

The study developed and applied a criterion-based framework aligned with ISO 14044 to handle the multifunctionality issue of desalination systems. The developed framework guides the selection of allocation approaches such as subdivision, system expansion and partitioning based on criteria that consider system characteristics, integration level, and assessment objectives and motivation. An MLD system that co-produces desalinated water, NaCl, Mg(OH)_2 , Ca(OH)_2 , Na_2SO_4 and HCl was assessed and its multifunctionality issue was handled through the framework proposed. Due to the level of integration of the processes of the MLD system, subdivision could not be applied (criterion 1). First, criterion 2 was followed to assess the global production of the MLD system and compare it with the reference system. The results of criterion 2 showed the MLD system results in a better environmental performance than the reference system. The largest environmental benefits were the terrestrial and marine ecotoxicity.

Second, criterion 3 was followed, and physical and economic partitioning were applied with different modelling perspectives, process and system. The four partitioning approaches yielded different results. Both process and system economic partitioning resulted in benefits for desalinated water, while with the system of physical partitioning the desalinated water was the co-product with the highest impact. In contrast, the co-products Mg(OH)_2 , Na_2SO_4 and HCl showed lower environmental impacts only in system physical partitioning. The co-product Ca(OH)_2 is environmentally favourable when a system approach for both partitioning is applied. The selection of the partitioning approach and modelling perspective can thus affect conclusions about the environmental performance of individual products.

Comparing each co-product individually with the reference scenario, it was observed that only the process economic partitioning shows the benefits of the desalinated water of the MLD system over the reference system. The other co-products have environmental advantages over the reference system for all the allocation and modelling perspectives. This suggests that brine as a secondary source of products could reduce environmental pressure associated with the reference systems (e.g. mining and chemical industries).

In conclusion, the results of the partitioning approach show that recovery rates and market prices significantly influence the outcome of LCA results. This thesis emphasises that these

parameters must be considered when using LCA to inform policies in the desalination sector. Furthermore, the study suggests that future research should explore the role of factors such as the location of the desalination system and the demand for products recovered from brine. These factors could have a significant impact on LCA results, particularly when different allocation approaches are applied. The distribution of products and varying market prices around the world—which are influenced by demand—should be considered as important parameters in LCA studies of multifunctional systems.

6.1.4 Research question 4

Does the resource flow traceability and circular action performance measurement support the integration and optimisation of systems in a ceramic industry?

The assessment focused on the actions implemented, and also on the circular resources such as energy and water. To measure the circular flows, definitions were defined which classify in terms of linear and circular flows. The wastewater was classified as circular as it originated from a third party and is reclaimed, while the freshwater was classified as linear as it is sourced from an aquifer and is virgin. The rainwater was classified as circular as it is renewed by the natural cycle phenomenon of precipitation. The assessment also classified the water outflow of the industry. The water that leaves the exhaust gas and is lost was classified as linear. The water in the products was classified as circular as it is part of the product function. The assessment enables the measurement of the impact of the Heat Pipe Condenser Economiser and water treatment system in the industry. It showed that the integration has a higher impact on energy compared to water. The water circularity is only improved significantly if the rooftop rainwater harvesting is considered. This is also observed through the calculation of the economic savings to the industry.

It is relevant from a methodological assessment perspective that scenario analysis is possible for optimisation. The methodology allowed the assessment of different rainwater management approaches. The scenario analysis demonstrates that if the rooftop runoff rainwater is directly used without passing through the water treatment system, the impact on reducing the freshwater demand is significant and also increases the economic water saving to the industries. It also showed that in the months in which rainfall is greater, the water recovered can cover the demand for freshwater by the industry. The assessment methodology applied demonstrates the

capacity of measuring impacts of systems integration in an industry, which is useful for decision making on planning and optimisation.

6.2 Recommendations for Future Work

Throughout the study, both intrinsic and consequential aspects were inherently interconnected and explored. However, due to the multi-functionality issue, which is particularly relevant when assessing the environmental impact of co-production, and its lack of attention within the desalination sector's scientific community, it was decided to dedicate one chapter of this thesis solely to examining one specific dimension of sustainability. Therefore, it would be valuable to measure both aspects in a study and better understand the consequences of circular interventions and strategies within the desalination sector. Life cycle methodologies could be integrated with the circularity framework (Chapter 2) to provide a more holistic assessment, offering comprehensive insights to inform decision-making. This integration could further enhance the methodology's ability to identify trade-offs between intrinsic and consequential elements, enabling more robust and strategic planning under uncertain or complex conditions.

In addition to the consequential aspects of measurement, the concept behind the circular economy emphasises that companies have a responsibility to uphold the environmental and sustainability values of society. They must respond to a broad range of stakeholders, not just their closest shareholders (Lahti et al., 2018). The circularity framework proposed in Chapter 3 selects indicators based on CE reports and scientific papers that cover the full desalination sector and calculate circular value. However, each desalination system serves a specific purpose and involves unique participants. Each participant (e.g., company, stakeholder, or actor) who intends to implement circularity and sustainability has distinct concerns, needs, opportunities, goals, and risks. Therefore, the assessment process should align with these requirements and limitations to increase its relevance and facilitate successful implementation. A combined expert and participatory approach to selecting CE indicators would enable stakeholders and practitioners to make more informed decisions, based on representative indicators they have critically prioritised. Involving stakeholders in this participatory process is also expected to increase the adoption of holistic and systemic assessments of CE (Nika et al., 2020). If circularity and life cycle methodologies are integrated, and stakeholder input is prioritised, this approach will generate numerous trade-offs and increase complexity and

uncertainty. To address this, Multi-criteria Decision Making (MCDM) can support the analysis of these issues. Effective water management decisions require a deep understanding of how these systems operate (Blythe et al., 2017; Gittins et al., 2021). Depending on the MCDM application, the assessment goals will influence the key performance indicators used to guide the decision-making process (e.g. selection of process to be integrated in a desalination system or optimisation strategies) and final outcome (Renfrew et al., 2024a).

Besides the issue of assessing the environmental impact of multifunctional desalination systems which was investigated in chapter 4, there are emerging technologies for brine treatment and product recovery under investigation (Giwa et al., 2017). Emerging desalination technologies have the potential to compete with conventional technologies for seawater desalination, or to outperform these technologies in niche areas; however, their transition to full-scale employment depends on further scientific advances to achieve threshold performance and energy efficiency (Ahmed et al., 2021). This means a spectrum of different technological readiness levels exist. Environmental assessment of these emerging technologies in the early stages of development has gained increasing attention in recent years. Many novel technologies claim to be environmentally sustainable, but these claims need to be substantiated through early-stage environmental assessments. Identifying potential environmental impacts at an early stage allows for technology development to be directed toward improved environmental performance at relatively low costs (Tsoy et al., 2020). The primary goal of any ex-ante LCA is to compare the future potential environmental performance of new technologies against existing technologies. This provides valuable insights into the development of these technologies and helps guide research and development efforts (van der Giesen et al., 2020). In Chapters 3 and 4, upscaling techniques were applied to the MLD system to build inventories for the assessment, although this task is not emphasised. However, it is believed that conducting a deeper analysis through ex-ante LCA would be beneficial for optimising emerging desalination technologies and exploring potential scenarios for their future full-scale integration. Such an analysis would require data preparation, operational simulations, and analysis that could not be performed in this study. According to Arvidsson et al., (2018) “An LCA is prospective when the (emerging) technology studied is in an early phase of development (e.g. small-scale production), but the technology is modelled at a future, more-developed phase (e.g. large-scale production)”. This type of assessment integrates forecasting methodologies and the development of future scenarios. Prospective LCA could be especially

useful in guiding the development of emerging desalination technologies by anticipating unintended consequences and supporting the environmentally conscious design of future products. In chapter 4, the LCA conducted focuses on the environmental burden of the production phase of a desalination system. Therefore, a prospective assessment could scope the supply of products from brine and identify benefits and hotspots of a secondary supply chain of such products in different locations. Prospective assessment has been proven valuable in various applications, including assessing emerging technologies, future public policies, and future production and consumption systems (Mendoza Beltran et al., 2020).

Despite the desalination sector still requires future research and innovation, the ultimate goal of securing water sustainably is inevitable through circular strategies, and assessment methodologies will have a key role in monitoring externalities and in supporting the sector in relieving pressure on the environment, economy and society.

References

- Abdel-Fatah, M.A., 2018. Nanofiltration systems and applications in wastewater treatment: Review article. Ain Shams Engineering Journal. <https://doi.org/10.1016/j.asej.2018.08.001>
- Afgan, N.H., Darwish, M., 2011. Multi-criteria sustainability assessment of water desalination and energy systems — Kuwait case. Desalination Water Treat 25, 241–250. <https://doi.org/10.5004/dwt.2011.1764>
- Ahmed, F.E., Hashaikeh, R., Diabat, A., Hilal, N., 2019. Mathematical and optimization modelling in desalination: State-of-the-art and future direction. Desalination. <https://doi.org/10.1016/j.desal.2019.114092>
- Ahmed, F.E., Khalil, A., Hilal, N., 2021. Emerging desalination technologies: Current status, challenges and future trends. Desalination. <https://doi.org/10.1016/j.desal.2021.115183>
- Alaerts, L., Van Acker, K., Rousseau, S., De Jaeger, S., Moraga, G., Dewulf, J., De Meester, S., Van Passel, S., Compernelle, T., Bachus, K., Vrancken, K., Eyckmans, J., 2019. Towards a more direct policy feedback in circular economy monitoring via a societal needs perspective. Resour Conserv Recycl 149, 363–371. <https://doi.org/10.1016/j.resconrec.2019.06.004>
- Alawad, S.M., Mansour, R. Ben, Al-Sulaiman, F.A., Rehman, S., 2023. Renewable energy systems for water desalination applications: A comprehensive review. Energy Convers Manag. <https://doi.org/10.1016/j.enconman.2023.117035>
- Alghoul, M.A., Poovanaesvaran, P., Sopian, K., Sulaiman, M.Y., 2009. Review of brackish water reverse osmosis (BWRO) system designs. Renewable and Sustainable Energy Reviews. <https://doi.org/10.1016/j.rser.2009.03.013>
- Alhaj, M., Tahir, F., Al-Ghamdi, S.G., 2022. Life-cycle environmental assessment of solar-driven Multi-Effect Desalination (MED) plant. Desalination 524. <https://doi.org/10.1016/j.desal.2021.115451>
- Alanezi, A. A., Altaee, A., Sharif, A.O., 2020. The effect of energy recovery device and feed flow rate on the energy efficiency of reverse osmosis process. Chemical Engineering Research and Design 158, 12–23. <https://doi.org/10.1016/j.cherd.2020.03.018>

- ANZECC, ARMCANZ. 2018. Australia and New Zealand guidelines for fresh and marine water quality: Volume 1. Paper N°4.
- Arvidsson, R., Tillman, A.M., Sandén, B.A., Janssen, M., Nordelöf, A., Kushnir, D., Molander, S., 2018. Environmental Assessment of Emerging Technologies: Recommendations for Prospective LCA. *J Ind Ecol.* <https://doi.org/10.1111/jiec.12690>
- Arup, Antea Group, Ellen MacArthur Foundation, 2019. Water and Circular Economy: White Paper.
- Ayaz, M., Namazi, M.A., Din, M.A. ud, Ershath, M.I.M., Mansour, A., Aggoune, el H.M., 2022. Sustainable seawater desalination: Current status, environmental implications and future expectations. *Desalination.* <https://doi.org/10.1016/j.desal.2022.116022>
- Aziz, N.I.H.A., Hanafiah, M.M., 2021. Application of life cycle assessment for desalination: Progress, challenges and future directions. *Environmental Pollution.* <https://doi.org/10.1016/j.envpol.2020.115948>
- Bardi, U., 2010. Extracting minerals from seawater: An energy analysis. *Sustainability* 2, 980–992. <https://doi.org/10.3390/su2040980>
- Bernhardi, L., Beroggi, G.E.G., Moens, M.R., 2000. Sustainable Water Management through Flexible Method Management, *Water Resources Management* 14, 473–495. <https://doi.org/10.1023/A:1011105008526>
- Blythe, J., Nash, K., Yates, J., Cumming, G., 2017. Feedbacks as a bridging concept for advancing transdisciplinary sustainability research. *Curr Opin Environ Sustain.* <https://doi.org/10.1016/j.cosust.2017.05.004>
- Brodny, J., Tutak, M., 2022. Analysis of the efficiency and structure of energy consumption in the industrial sector in the European Union countries between 1995 and 2019. *Science of the Total Environment* 808. <https://doi.org/10.1016/j.scitotenv.2021.152052>
- Caldeira, Carla., Farcal, L.R., Garmendia Aguirre, Irantzu., Mancini, Lucia., Tosches, Davide., Amelio, Antonio., Rasmussen, Kirsten., Rauscher, Hubert., Riego Sintes, Juan., Sala, Serenella., 2022. Safe and sustainable by design chemicals and materials: framework for the definition of criteria and evaluation procedure for chemicals and materials. Publications Office of the European Union.

- Christopoulos, K., Pospotikis, N., Kostopoulos, E., Kondili, E., Kaldellis, J.K., 2018. Experimental analysis of the water salinity impact on the energy consumption of small desalination plants, in: *Procedia Structural Integrity*. Elsevier B.V., pp. 171–178. <https://doi.org/10.1016/j.prostr.2018.09.025>
- Cipolletta, G., Lancioni, N., Akyol, Ç., Eusebi, A.L., Fatone, F., 2021. Brine treatment technologies towards minimum/zero liquid discharge and resource recovery: State of the art and techno-economic assessment. *J Environ Manage.* <https://doi.org/10.1016/j.jenvman.2021.113681>
- Culcasi, A., Ktori, R., Pellegrino, A., Rodriguez-Pascual, M., van Loosdrecht, M.C.M., Tamburini, A., Cipollina, A., Xevgenos, D., Micale, G., 2022. Towards sustainable production of minerals and chemicals through seawater brine treatment using Eutectic freeze crystallization and Electrodialysis with bipolar membranes. *J Clean Prod* 368. <https://doi.org/10.1016/j.jclepro.2022.133143>
- Damkjaer, S., Taylor, R., 2017. The measurement of water scarcity: Defining a meaningful indicator. *Ambio*. <https://doi.org/10.1007/s13280-017-0912-z>
- Dawoud, M.A., Alaswad, S.O., Ewea, H.A., Dawoud, R.M., 2020. Towards sustainable desalination industry in Arab region: Challenges and opportunities. *Desalination Water Treat* 193, 1–10. <https://doi.org/10.5004/dwt.2020.25686>
- Diallo, M.S., Kotte, M.R., Cho, M., 2015. Mining Critical Metals and Elements from Seawater: Opportunities and Challenges. *Environ Sci Technol* 49, 9390–9399. <https://doi.org/10.1021/acs.est.5b00463>
- Di Maio, F., Rem, P.C., Baldé, K., Polder, M., 2017. Measuring resource efficiency and circular economy: A market value approach. *Resour Conserv Recycl* 122, 163–171. <https://doi.org/10.1016/j.resconrec.2017.02.009>
- Drechsel, P., Marjani Zadeh, S. & Pedrero, F. (eds). 2023. *Water quality in agriculture: Risks and risk mitigation*. Rome, FAO & IWMI. <https://doi.org/10.4060/cc7340en>
- Edirisinghe, L.G.L.M., de Alwis, A.A.P., Wijayasundara, M., Hemali, N.A., 2024. Quantifying circularity factor of waste: Assessing the circular economy potential of industrial zones. *Cleaner Environmental Systems* 12. <https://doi.org/10.1016/j.cesys.2023.100160>

- EEA, 2021 Water resources across Europe – Confronting water stress: an updated assessment, Publications Office of the European Union. <https://doi.org/10.2800/320975>
- Eke, J., Yusuf, A., Giwa, A., Sodiq, A., 2020. The global status of desalination: An assessment of current desalination technologies, plants and capacity. *Desalination* 495. <https://doi.org/10.1016/j.desal.2020.114633>
- Elsaid, K., Taha Sayed, E., Yousef, B.A.A., Kamal Hussien Rabaia, M., Ali Abdelkareem, M., Olabi, A.G., 2020. Recent progress on the utilization of waste heat for desalination: A review. *Energy Convers Manag.* <https://doi.org/10.1016/j.enconman.2020.113105>
- Eyl-Mazzega, M., Cassignol, E. 2023. The Geopolitics of Seawater Desalination. Policy Center for the New South. Morocco.
- Fayyaz, S., Khadem Masjedi, S., Kazemi, A., Khaki, E., Moeinaddini, M., Irving Olsen, S., 2023. Life cycle assessment of reverse osmosis for high-salinity seawater desalination process: Potable and industrial water production. *J Clean Prod* 382. <https://doi.org/10.1016/j.jclepro.2022.135299>
- Fontana, D., Forte, F., Pietrantonio, M., Pucciarmati, S., Marcoaldi, C., 2023. Magnesium recovery from seawater desalination brines: a technical review. *Environ Dev Sustain.* <https://doi.org/10.1007/s10668-022-02663-2>
- Frijns, J., Smith, H.M., Makropoulos, C., 2024. Enabling the uptake of circular water solutions. *Water Policy* 26, 94–110. <https://doi.org/10.2166/wp.2024.167>
- Gadhamshetty, V., Gude, V.G., Nirmalakhandan, N., 2014. Thermal energy storage system for energy conservation and water desalination in power plants. *Energy* 66, 938–949. <https://doi.org/10.1016/j.energy.2014.01.046>
- Gao, L., Liu, G., Zamyadi, A., Wang, Q., Li, M., 2021. Life-cycle cost analysis of a hybrid algae-based biological desalination – low pressure reverse osmosis system. *Water Res* 195. <https://doi.org/10.1016/j.watres.2021.116957>
- Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The Circular Economy – A new sustainability paradigm? *J Clean Prod.* <https://doi.org/10.1016/j.jclepro.2016.12.048>

- Gittins, J.R., Hemingway, J.R., Dajka, J.C., 2021. How a water-resources crisis highlights social-ecological disconnects. *Water Res.* <https://doi.org/10.1016/j.watres.2021.116937>
- Giwa, A., Dufour, V., Al Marzooqi, F., Al Kaabi, M., Hasan, S.W., 2017. Brine management methods: Recent innovations and current status. *Desalination*. <https://doi.org/10.1016/j.desal.2016.12.008>
- Greenlee, L.F., Lawler, D.F., Freeman, B.D., Marrot, B., Moulin, P., 2009. Reverse osmosis desalination: Water sources, technology, and today's challenges. *Water Res.* <https://doi.org/10.1016/j.watres.2009.03.010>
- Hafner, M., Raimondi, P.P., 2020. Priorities and challenges of the EU energy transition: From the European Green Package to the new Green Deal. *Russian Journal of Economics* 6, 374–389. <https://doi.org/10.32609/J.RUJE.6.55375>
- Huijbregts, M.A.J., Steinmann, Z.J.N., Elshout, P.M.F., Stam, G., Verones, F., Vieira, M., Zijp, M., Hollander, A., van Zelm, R., 2017. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. *International Journal of Life Cycle Assessment* 22, 138–147. <https://doi.org/10.1007/s11367-016-1246-y>
- Iacovidou, E., Velis, C.A., Purnell, P., Zwirner, O., Brown, A., Hahladakis, J., Millward-Hopkins, J., Williams, P.T., 2017. Metrics for optimising the multi-dimensional value of resources recovered from waste in a circular economy: A critical review. *J Clean Prod.* <https://doi.org/10.1016/j.jclepro.2017.07.100>
- Ibrahim, Y., Arafat, H.A., Mezher, T., AlMarzooqi, F., 2018. An integrated framework for sustainability assessment of seawater desalination. *Desalination* 447, 1–17. <https://doi.org/10.1016/j.desal.2018.08.019>
- Ihsanullah, I., Atieh, M.A., Sajid, M., Nazal, M.K., 2021. Desalination and environment: A critical analysis of impacts, mitigation strategies, and greener desalination technologies. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2021.146585>
- Ijassi, W., Ben Rejeb, H., Zwolinski, P., 2021. Environmental impact evaluation of co-products: decision-aid tool for allocation in LCA. *International Journal of Life Cycle Assessment* 26, 2199–2214. <https://doi.org/10.1007/s11367-021-01984-0>

- International Standards Organization, 2024. ISO/CD 59020 Circular Economy — Measuring and assessing circularity. 1st edition.
- International Organization for Standardization, 2006a. DIN EN ISO 14040:2006. Environmental Management - Life Cycle Assessment - Principles and Framework. Geneva, Switzerland
- International Organization for Standardization, 2006b. DIN EN ISO 14044:2006. Environmental management-Life cycle assessment-Requirements and guidelines, 1st ed. Geneva, Switzerland.
- Javadinejad, S., Ostad-Ali-Askari, K., Singh, V.P., Shayannejad, M., 2019. Reliable, Resilient, and Sustainable Water Management in Different Water Use Sectors. *Water Conservation Science and Engineering* 4, 133–148. <https://doi.org/10.1007/s41101-019-00073-6>
- Jia, X., Klemeš, J.J., Varbanov, P.S., Alwi, S.R.W., 2019. Analyzing the energy consumption, GHG emission, and cost of seawater desalination in China. *Energies (Basel)* 12. <https://doi.org/10.3390/en12030463>
- Jones, E., Qadir, M., van Vliet, M.T.H., Smakhtin, V., Kang, S. mu, 2019. The state of desalination and brine production: A global outlook. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2018.12.076>
- Jouhara, H., Bertrand, D., Axcell, B., Montorsi, L., Venturelli, M., Almahmoud, S., Milani, M., Ahmad, L., Chauhan, A., 2021. Investigation on a full-scale heat pipe heat exchanger in the ceramics industry for waste heat recovery. *Energy* 223. <https://doi.org/10.1016/j.energy.2021.120037>
- Jouhara, H., Khordehgah, N., Almahmoud, S., Delpech, B., Chauhan, A., Tassou, S.A., 2018. Waste heat recovery technologies and applications. *Thermal Science and Engineering Progress*. <https://doi.org/10.1016/j.tsep.2018.04.017>
- Kabir, M.M., Sabur, G.M., Akter, M.M., Nam, S.Y., Im, K.S., Tijing, L., Shon, H.K., 2024. Electrodialysis desalination, resource and energy recovery from water industries for a circular economy. *Desalination*. <https://doi.org/10.1016/j.desal.2023.117041>

- Khosousi, T., Ahmadzadeh, M., Sadeghi, M., 2023. Two-stage membrane process (UF/NF) for treatment of water process in the steel industry at a pilot scale. *Chemical Papers* 77, 4683–4691. <https://doi.org/10.1007/s11696-023-02817-0>
- Klein Tank, A.M.G., Wijngaard, J.B., Können, G.P., Böhm, R., Demarée, G., Gocheva, A., Mileta, M., Pashiardis, S., Hejkrlik, L., Kern-Hansen, C., Heino, R., Bessemoulin, P., Müller-Westermeier, G., Tzanakou, M., Szalai, S., Pálsdóttir, T., Fitzgerald, D., Rubin, S., Capaldo, M., Maugeri, M., Leitass, A., Bukantis, A., Aberfeld, R., Van Engelen, A.F.V., Forland, E., Miletus, M., Coelho, F., Mares, C., Razuvaev, V., Nieplova, E., Cegnar, T., Antonio López, J., Dahlström, B., Moberg, A., Kirchhofer, W., Ceylan, A., Pachaliuk, O., Alexander, L. V., Petrovic, P., 2002. Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment. *International Journal of Climatology* 22, 1441–1453. <https://doi.org/10.1002/joc.773>
- Koseoglu-Imer, D.Y., Oral, H.V., Coutinho Calheiros, C.S., Krzeminski, P., Güçlü, S., Pereira, S.A., Surmacz-Górska, J., Plaza, E., Samaras, P., Binder, P.M., van Hullebusch, E.D., Devolli, A., 2023. Current challenges and future perspectives for the full circular economy of water in European countries. *J Environ Manage.* <https://doi.org/10.1016/j.jenvman.2023.118627>
- Lahti, T., Wincent, J., Parida, V., 2018. A definition and theoretical review of the circular economy, value creation, and sustainable business models: Where are we now and where should research move in the future? *Sustainability* (Switzerland). <https://doi.org/10.3390/su10082799>
- Lai, F., Laurent, F., Beylot, A., Villeneuve, J., 2021. Solving multifunctionality in the carbon footprint assessment of primary metals production: Comparison of different approaches. *Miner Eng* 170. <https://doi.org/10.1016/j.mineng.2021.107053>
- Lee, K., Jepson, W., 2021. Environmental impact of desalination: A systematic review of Life Cycle Assessment. *Desalination*. <https://doi.org/10.1016/j.desal.2021.115066>
- Li, J., Zhang, S., Nie, Y., Ma, X., Xu, L., Wu, L., 2020. A holistic life cycle evaluation of coking production covering coke oven gas purification process based on the subdivision method. *J Clean Prod* 248. <https://doi.org/10.1016/j.jclepro.2019.119183>

- Lior, N., 2017. Sustainability as the quantitative norm for water desalination impacts. *Desalination* 401, 99–111. <https://doi.org/10.1016/j.desal.2016.08.008>
- Liponi, A., Wieland, C., Baccioli, A., 2020. Multi-effect distillation plants for small-scale seawater desalination: thermodynamic and economic improvement. *Energy Convers Manag* 205, 112337. <https://doi.org/10.1016/j.enconman.2019.112337>
- Li, Z., Siddiqi, A., Anadon, L.D., Narayanamurti, V., 2018. Towards sustainability in water-energy nexus: Ocean energy for seawater desalination. *Renewable and Sustainable Energy Reviews*. <https://doi.org/10.1016/j.rser.2017.10.087>
- Luo, J., Ding, L., Qi, B., Jaffrin, M.Y., Wan, Y., 2011. A two-stage ultrafiltration and nanofiltration process for recycling dairy wastewater. *Bioresour Technol* 102, 7437–7442. <https://doi.org/10.1016/j.biortech.2011.05.012>
- Magara, Y. 2020. Industrial Water. In (eds.) Kubota, S., Tsuchiya, Y. *Water Quality and Standards - Volume I*. EOLSS Publishers Company Limited. (pp 270).
- Mauter, M.S., Fiske, P.S., 2020. Desalination for a circular water economy. *Energy Environ Sci*. <https://doi.org/10.1039/d0ee01653e>
- Mendoza Beltran, A., Cox, B., Mutel, C., van Vuuren, D.P., Font Vivanco, D., Deetman, S., Edelenbosch, O.Y., Guinée, J., Tukker, A., 2020. When the Background Matters: Using Scenarios from Integrated Assessment Models in Prospective Life Cycle Assessment. *J Ind Ecol* 24, 64–79. <https://doi.org/10.1111/jiec.12825>
- Micari, M., Moser, M., Cipollina, A., Tamburini, A., Micale, G., Bertsch, V., 2020. Towards the implementation of circular economy in the water softening industry: A technical, economic and environmental analysis. *J Clean Prod* 255. <https://doi.org/10.1016/j.jclepro.2020.120291>
- Michellini, G., Moraes, R.N., Cunha, R.N., Costa, J.M.H., Ometto, A.R., 2017. From Linear to Circular Economy: PSS Conducting the Transition, in: *Procedia CIRP*. Elsevier B.V., pp. 2–6. <https://doi.org/10.1016/j.procir.2017.03.012>
- Mironenko, O., Lucas, P.L., Tarasova, N., Zlinszky, J., 2015. *Sustainable Development Goals: Why do We Need Them?*, Social Evolution & History. Uchitel' Publishing House.

- Moraga, G., Huysveld, S., Mathieux, F., Blengini, G.A., Alaerts, L., Van Acker, K., de Meester, S., Dewulf, J., 2019. Circular economy indicators: What do they measure? *Resour Conserv Recycl* 146, 452–461. <https://doi.org/10.1016/j.resconrec.2019.03.045>
- Moretti, C., Corona, B., Edwards, R., Junginger, M., Moro, A., Rocco, M., Shen, L., 2020. Reviewing ISO compliant multifunctionality practices in environmental life cycle modeling. *Energies* (Basel). <https://doi.org/10.3390/en13143579>
- Morgante, C., Vassallo, F., Cassaro, C., Virruso, G., Diamantidou, D., Van Linden, N., Trezzi, A., Xenogianni, C., Ktori, R., Rodriguez, M., Scelfo, G., Randazzo, S., Tamburini, A., Cipollina, A., Micale, G., Xevgenos, D., 2024. Pioneering minimum liquid discharge desalination: A pilot study in Lampedusa Island. *Desalination* 581. <https://doi.org/10.1016/j.desal.2024.117562>
- Morgante, C., Vassallo, F., Xevgenos, D., Cipollina, A., Micari, M., Tamburini, A., Micale, G., 2022. Valorisation of SWRO brines in a remote island through a circular approach: Techno-economic analysis and perspectives. *Desalination* 542. <https://doi.org/10.1016/j.desal.2022.116005>
- Morseletto, P., Mooren, C.E., Munaretto, S., 2022. Circular Economy of Water: Definition, Strategies and Challenges. *Circular Economy and Sustainability* 2, 1463–1477. <https://doi.org/10.1007/s43615-022-00165-x>
- M.S., S., Elmakki, T., Schipper, K., Ihm, S., Yoo, Y., Park, B., Park, H., Shon, H.K., Han, D.S., 2024. Integrated seawater hub: A nexus of sustainable water, energy, and resource generation. *Desalination*. <https://doi.org/10.1016/j.desal.2023.117065>
- Nika, C.E., Vasilaki, V., Expósito, A., Katsou, E., 2020. Water Cycle and Circular Economy: Developing a Circularity Assessment Framework for Complex Water Systems. *Water Res* 187. <https://doi.org/10.1016/j.watres.2020.116423>
- Nika, C.E., Vasilaki, V., Renfrew, D., Danishvar, M., Echchel, A., Katsou, E., 2022. Assessing circularity of multi-sectoral systems under the Water-Energy-Food-Ecosystems (WEFE) nexus. *Water Res* 221. <https://doi.org/10.1016/j.watres.2022.118842>
- Ogunbiyi, O., Saththasivam, J., Al-Masri, D., Manawi, Y., Lawler, J., Zhang, X., Liu, Z., 2021. Sustainable brine management from the perspectives of water, energy and mineral

recovery: A comprehensive review. Desalination 513.
<https://doi.org/10.1016/j.desal.2021.115055>

- Opher, T., Friedler, E., Shapira, A., 2019. Comparative life cycle sustainability assessment of urban water reuse at various centralization scales. *International Journal of Life Cycle Assessment* 24, 1319–1332. <https://doi.org/10.1007/s11367-018-1469-1>
- Palmeros Parada, M., Randazzo, S., Gamboa, G., Ktori, R., Bouchaut, B., Cipolina, A., Micale, G., Xevgenos, D., 2023. Resource recovery from desalination, the case of small islands. *Resour Conserv Recycl* 199. <https://doi.org/10.1016/j.resconrec.2023.107287>
- Panagopoulos, A., 2022. Techno-economic assessment of zero liquid discharge (ZLD) systems for sustainable treatment, minimization and valorization of seawater brine. *J Environ Manage* 306. <https://doi.org/10.1016/j.jenvman.2022.114488>
- Panagopoulos, A., 2021. Energetic, economic and environmental assessment of zero liquid discharge (ZLD) brackish water and seawater desalination systems. *Energy Convers Manag* 235. <https://doi.org/10.1016/j.enconman.2021.113957>
- Panagopoulos, A., Giannika, V., 2023. Study on the water resources and the opportunities for sustainable desalination & minimal/zero liquid discharge (MLD/ZLD) practices in Greece (Eastern Mediterranean). *Sustain Water Resour Manag* 9. <https://doi.org/10.1007/s40899-023-00884-5>
- Panagopoulos, A., Giannika, V., 2022. Comparative techno-economic and environmental analysis of minimal liquid discharge (MLD) and zero liquid discharge (ZLD) desalination systems for seawater brine treatment and valorization. *Sustainable Energy Technologies and Assessments* 53. <https://doi.org/10.1016/j.seta.2022.102477>
- Panagopoulos, A., Haralambous, K.J., 2020. Minimal Liquid Discharge (MLD) and Zero Liquid Discharge (ZLD) strategies for wastewater management and resource recovery- Analysis, challenges and prospects. *J Environ Chem Eng* 8. <https://doi.org/10.1016/j.jece.2020.104418>
- Paparella, F., D'Agostino, D., A. Burt, J., 2022. Long-term, basin-scale salinity impacts from desalination in the Arabian/Persian Gulf. *Sci Rep* 12. <https://doi.org/10.1038/s41598-022-25167-5>

- Pelletier, N., Ardente, F., Brandão, M., De Camillis, C., Pennington, D., 2015. Rationales for and limitations of preferred solutions for multi-functionality problems in LCA: is increased consistency possible? *International Journal of Life Cycle Assessment* 20, 74–86. <https://doi.org/10.1007/s11367-014-0812-4>
- Poškas, R., Sirvydas, A., Mingilaitė, L., Jouhara, H., Poškas, P., 2024. Experimental investigation of water vapor condensation from flue gas in different rows of a heat exchanger model. *Thermal Science and Engineering Progress* 47. <https://doi.org/10.1016/j.tsep.2023.102365>
- Prajapati, P., Raja, B.D., Patel, V., Jouhara, H., 2024. Energy-economic analysis and optimization of a shell and tube heat exchanger using a multi-objective heat transfer search algorithm. *Thermal Science and Engineering Progress* 56. <https://doi.org/10.1016/j.tsep.2024.103021>
- Ramin, E., Faria, L., Gargalo, C.L., Ramin, P., Flores-Alsina, X., Andersen, M.M., Gernaey, K. V., 2024. Water innovation in industrial symbiosis - A global review. *J Environ Manage.* <https://doi.org/10.1016/j.jenvman.2023.119578>
- Rao, P., Kostecki, R., Dale, L., Gadgil, A., 2017. Annual Review of Environment and Resources Technology and Engineering of the Water-Energy Nexus. <https://doi.org/10.1146/annurev-environ>
- Reap, J., Roman, F., Duncan, S., Bras, B., 2008. A survey of unresolved problems in life cycle assessment. Part 1: Goal and scope and inventory analysis. *International Journal of Life Cycle Assessment*. <https://doi.org/10.1007/s11367-008-0008-x>
- Renfrew, D., Vasilaki, V., Katsou, E., 2024a. Indicator based multi-criteria decision support systems for wastewater treatment plants. *Science of the Total Environment*. <https://doi.org/10.1016/j.scitotenv.2024.169903>
- Renfrew, D., Vasilaki, V., Nika, E., Harris, E., Katsou, E., 2024b. Tracing wastewater resources: Unravelling the circularity of waste using source, destination, and quality analysis. *Water Res* 250. <https://doi.org/10.1016/j.watres.2023.120901>

- Renfrew, D., Vasilaki, V., Nika, E., Tsalidis, G.A., Marin, E., Katsou, E., 2024c. Systematic assessment of wastewater resource circularity and sustainable value creation. *Water Res* 251. <https://doi.org/10.1016/j.watres.2024.121141>
- Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., 2017. How to assess product performance in the circular economy? Proposed requirements for the design of a circularity measurement framework. *Recycling* 2. <https://doi.org/10.3390/recycling2010006>
- Sala, S., Ciuffo, B., Nijkamp, P., 2015. A systemic framework for sustainability assessment. *Ecological Economics* 119, 314–325. <https://doi.org/10.1016/j.ecolecon.2015.09.015>
- Salinas Rodriguez, S. G., Schippers, J. C., Amy, G. L., Kim, I. S., Kennedy, M. D. (eds.) (2021). *Seawater Reverse Osmosis Desalination: Assessment and Pre-treatment of Fouling and Scaling*, London: IWA Publishing. doi: <https://doi.org/10.2166/9781780409863>
- Scanlon, B.R., Fakhreddine, S., Rateb, A., de Graaf, I., Famiglietti, J., Gleeson, T., Grafton, R.Q., Jobbagy, E., Kebede, S., Kolusu, S.R., Konikow, L.F., Long, D., Mekonnen, M., Schmied, H.M., Mukherjee, A., MacDonald, A., Reedy, R.C., Shamsudduha, M., Simmons, C.T., Sun, A., Taylor, R.G., Villholth, K.G., Vörösmarty, C.J., Zheng, C., 2023. Global water resources and the role of groundwater in a resilient water future. *Nat Rev Earth Environ* 4, 87–101. <https://doi.org/10.1038/s43017-022-00378-6>
- Schrijvers, D.L., Loubet, P., Sonnemann, G., 2016. Developing a systematic framework for consistent allocation in LCA. *International Journal of Life Cycle Assessment*. <https://doi.org/10.1007/s11367-016-1063-3>
- Schrijvers, D., Loubet, P., Sonnemann, G., 2020. Archetypes of goal and scope definitions for consistent allocation in LCA. *Sustainability* (Switzerland) 12. <https://doi.org/10.3390/su12145587>
- Shahzad, M.W., Burhan, M., Ang, L., Ng, K.C., 2017. Energy-water-environment nexus underpinning future desalination sustainability. *Desalination*. <https://doi.org/10.1016/j.desal.2017.03.009>

- Shannon, M.A., Bohn, P.W., Elimelech, M., Georgiadis, J.G., Mariñas, B.J., Mayes, A.M., 2008. Science and technology for water purification in the coming decades. *Nature*. <https://doi.org/10.1038/nature06599>
- Sharkh, B.A., Al-Amoudi, A.A., Farooque, M., Fellows, C.M., Ihm, S., Lee, S., Li, S., Voutchkov, N., 2022. Seawater desalination concentrate—a new frontier for sustainable mining of valuable minerals. *NPJ Clean Water*. <https://doi.org/10.1038/s41545-022-00153-6>
- Shokri, A., Sanavi Fard, M., 2023. Techno-economic assessment of water desalination: Future outlooks and challenges. *Process Safety and Environmental Protection*. <https://doi.org/10.1016/j.psep.2022.11.007>
- Statista, Natural gas prices for household consumers in Italy, <https://www.statista.com/statistics/785605/natural-gas-prices-for-household-consumers-in-italy/>, 2023 (accessed May 2023)
- Svanes, E., Vold, M., Hanssen, O.J., 2011. Effect of different allocation methods on LCA results of products from wild-caught fish and on the use of such results. *International Journal of Life Cycle Assessment* 16, 512–521. <https://doi.org/10.1007/s11367-011-0288-4>
- Termes-Rifé, M., Molinos-Senante, M., Hernández-Sancho, F., Sala-Garrido, R., 2013. Life Cycle Costing: a tool to manage the urban water cycle. *Journal of Water Supply: Research and Technology-Aqua* 62, 468–476. <https://doi.org/10.2166/aqua.2013.110>
- Tin, M.M.M., Anioke, G., Nakagoe, O., Tanabe, S., Kodamatani, H., Nghiem, L.D., Fujioka, T., 2017. Membrane fouling, chemical cleaning and separation performance assessment of a chlorine-resistant nanofiltration membrane for water recycling applications. *Sep Purif Technol* 189, 170–175. <https://doi.org/10.1016/j.seppur.2017.07.080>
- Troullaki, K., Rozakis, S., Kostakis, V., 2021. Bridging barriers in sustainability research: A review from sustainability science to life cycle sustainability assessment. *Ecological Economics*. <https://doi.org/10.1016/j.ecolecon.2021.107007>
- Tsalidis, G.A., Tourkodimitri, K.P., Mitko, K., Gzyl, G., Skalny, A., Posada, J.A., Xevgenos, D., 2022. Assessing the environmental performance of a novel coal mine brine treatment

- technique: A case in Poland. *J Clean Prod* 358. <https://doi.org/10.1016/j.jclepro.2022.131973>
- Tsalidis, G.A., Xevgenos, D., Ktori, R., Krishnan, A., Posada, J.A., 2023. Social life cycle assessment of a desalination and resource recovery plant on a remote island: Analysis of generic and site-specific perspectives. *Sustain Prod Consum* 37, 412–423. <https://doi.org/10.1016/j.spc.2023.03.017>
- Tsoy, N., Steubing, B., van der Giesen, C., Guinée, J., 2020. Upscaling methods used in ex ante life cycle assessment of emerging technologies: a review. *International Journal of Life Cycle Assessment*. <https://doi.org/10.1007/s11367-020-01796-8>
- UNEP 2009 Water security and ecosystem services: The critical connection. ISBN 978 - 92 - 807 - 3018 - 0
- Urban, W., 2022. Energy Savings in Production Processes as a Key Component of the Global Energy Problem—The Introduction to the Special Issue of Energies. *Energies* (Basel). <https://doi.org/10.3390/en15145158>
- van der Giesen, C., Cucurachi, S., Guinée, J., Kramer, G.J., Tukker, A., 2020. A critical view on the current application of LCA for new technologies and recommendations for improved practice. *J Clean Prod* 259. <https://doi.org/10.1016/j.jclepro.2020.120904>
- Vivekh, P., Sudhakar, M., Srinivas, M., Vishwanthkumar, V., 2017. Desalination technology selection using multi-criteria evaluation: TOPSIS and PROMETHEE-2. *International Journal of Low-Carbon Technologies* 12, 24–35. <https://doi.org/10.1093/ijlct/ctw001>
- Vogiantzi, C., Tserpes, K., 2023. On the Definition, Assessment, and Enhancement of Circular Economy across Various Industrial Sectors: A Literature Review and Recent Findings. *Sustainability* (Switzerland). <https://doi.org/10.3390/su152316532>
- Wang, Z., Wang, Y., Xu, G., Ren, J., 2019. Sustainable desalination process selection: Decision support framework under hybrid information. *Desalination* 465, 44–57. <https://doi.org/10.1016/j.desal.2019.04.022>
- Wardenaar, T., Van Ruijven, T., Beltran, A.M., Vad, K., Guinée, J., Heijungs, R., 2012. Differences between LCA for analysis and LCA for policy: A case study on the

- consequences of allocation choices in bio-energy policies. *International Journal of Life Cycle Assessment* 17, 1059–1067. <https://doi.org/10.1007/s11367-012-0431-x>
- Warwick, C., 2012. “Sustainable” water abstraction: Catchment abstraction management strategies in England and Wales. *Water Policy*. <https://doi.org/10.2166/wp.2011.116>
- wbcsd, 2022. Circular Transition Indicators v3.0 - Metrics for business, by business.
- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. *International Journal of Life Cycle Assessment* 21, 1218–1230. <https://doi.org/10.1007/s11367-016-1087-8>
- WHO. 2017. Guidelines for drinking-water quality: fourth edition incorporating the first addendum. Geneva: World Health Organization
- Willet, J., Wetser, K., Vreeburg, J., Rijnaarts, H.H.M., 2019. Review of methods to assess sustainability of industrial water use. *Water Resour Ind* 21. <https://doi.org/10.1016/j.wri.2019.100110>
- Wintgens, T. Nättorp, A., Elango, L., Asolekar, S. R. eds (2016) Natural Water Treatment Systems for Safe and Sustainable Water Supply in the Indian Context: *Saph Pani*. IWA Publishing Vol. 15. <https://doi.org/10.2166/9781780408392>
- WWAP (United Nations World Water Assessment Programme). 2015. The United Nations World Water Development Report 2015: Water for a Sustainable World. Paris, UNESCO. ISBN 978-92-3-100071-3
- Xevgenos, D., Bakogianni, D., Haralambous, K.-J., Loizidou, M., 2019. Integrated Brine Management: A Circular Economy Approach, in: *Smart Water Grids*. CRC Press, pp. 203–229. <https://doi.org/10.1201/b21948-8>
- Xevgenos, D., Moustakas, K., Malamis, D., Loizidou, M., 2016. An overview on desalination & sustainability: renewable energy-driven desalination and brine management. *Desalination Water Treat* 57, 2304–2314. <https://doi.org/10.1080/19443994.2014.984927>
- Xevgenos, D., Tourkodimitri, K.P., Mortou, M., Mitko, K., Sapoutzi, D., Stroutza, D., Turek, M., van Loosdrecht, M.C.M., 2024. The concept of circular water value and its role in the design and implementation of circular desalination projects. The case of coal mines in Poland. *Desalination* 579. <https://doi.org/10.1016/j.desal.2024.117501>

- Yao, K.A.F., Yao, B.K., Belcourt, O., Salze, D., Lasm, T., Lopez-Ferber, M., Junqua, G., 2021. Mining Impacts Assessment Using the LCA Methodology: Case Study of Afema Gold Mine in Ivory Coast. *Integr Environ Assess Manag* 17, 465–479. <https://doi.org/10.1002/ieam.4336>
- Zhang, J., Xiong, B.Y., 2006. Towards a healthy water cycle in China. *Water Science and Technology* 53, 9–15. <https://doi.org/10.2166/wst.2006.274>
- Zhang, W., Miao, M., Pan, J., Sotto, A., Shen, J., Gao, C., Van der Bruggen, B., 2017. Process Economic Evaluation of Resource Valorization of Seawater Concentrate by Membrane Technology. *ACS Sustain Chem Eng* 5, 5820–5830. <https://doi.org/10.1021/acssuschemeng.7b00555>
- Zhou, J., Chang, V.W.C., Fane, A.G., 2013. An improved life cycle impact assessment (LCIA) approach for assessing aquatic eco-toxic impact of brine disposal from seawater desalination plants. *Desalination* 308, 233–241. <https://doi.org/10.1016/j.desal.2012.07.039>

List of Publications

The thesis is based on the following publications and conference presentations:

Publications

- Dias, Daniel F. C.; Abily, Morgan; **Ribeiro, João M.**; Jouhara, Hussam; Katsou, Evina. (2024) Screening Rainwater Harvesting Potentialities in the EU Industrial Sector: A Framework for Site-Specific Assessment. *Water* 16, no. 12: 1758. <https://doi.org/10.3390/w16121758> (Co-author)
- **Ribeiro, João M.**; Renfrew, David; Nika, Eliza; Vasilaki, Vasileia; Katsou, Evina. (2025) Towards Circular Desalination: A New Methodology for Measuring and Assessing Resource Flows and Circular Action. *Water Research*, 274, 123126. <https://doi.org/10.1016/j.watres.2025.123126>
- Tsalidis, Georgios Archimidis; Dias, Daniel F. C.; Martins, Antonio; Vasilaki, Vasileia; **Ribeiro, João M.**; Katsou, Evina. (2025) Assessing the ISO Hierarchy Validity in Circular Wastewater Treatment Life Cycle Assessments: A Portuguese Case Study Resources, Conservation and Recycling, 215, 108146. <https://doi.org/10.1016/j.resconrec.2025.108146> (Co-author)
- **Ribeiro, João M.**; Tsalidis, Georgios Archimidis; Nika, Eliza; Vasilaki, Vasileia; Xevgenos, Dimitris; Jouhara, Hussam; Katsou, Evina. (2025) Environmental Impact Assessment of Multifunctional Desalination Systems, Volume 19, 100328. <https://doi.org/10.1016/j.cesys.2025.100328>
- **Ribeiro, João M.**; Dias, Daniel F. C.; Nika, Eliza; Delpech, Bertrand; Katsou, Evina; Jouhara, Hussam. (2025) Circularity Assessment of Industrial Heat Exchanger and Water Treatment Systems Integration. *Thermal Science and Engineering Progress*, Volume 62, 103661. <https://doi.org/10.1016/j.tsep.2025.103661>

Conference presentations

- **Ribeiro, João M.;** Nika, Eliza; Dias, Daniel F. C.; Katsou, Evina. (2022) A Circular Economy framework for assessing the impacts of treated wastewater use in agriculture. Work presented at BENELUX Young Water Professionals 7th Regional Conference, 4th – 6th of May 2022, Delft, the Netherlands.
- **Ribeiro, João M.;** Nika, Eliza; Ktori, Rodoula; Tsadilis, George; Ghafourian, Matia; Dias, Daniel F. C.; Xevgenos, Dimitris; Katsou, Evina. (2023) Circularity and sustainability assessment of a minimal liquid discharge desalination. Work presented at Water Innovation and Circularity Conference (WICC), 7th – 9th of June 2023, Athens, Greece.
- **Ribeiro, João M.;** Dias, Daniel F. C.; Delpech, Bertrand; Jouhara, Hussam; Katsou, Evina. (2023) Water-Waste-Energy Nexus modelling to support the implementation of Circular Actions: Industrial water and energy consumption. Work presented at 4th Symposium on Circular Economy and Sustainability, 19th – 21st June 2023, Heraklion, Greece.
- **Ribeiro, João M.;** Nika, Eliza; Ktori, Rodoula; Tsadilis, George; Ghafourian, Matia; Dias, Daniel F. C.; Xevgenos, Dimitris; Katsou, Evina. (2023) Circularity and sustainability assessment of a minimal liquid discharge desalination. Work presented IWA International Conference of eco-Technologies for Wastewater Treatment, 26th – 29th June 2023, Girona, Spain.
- **Ribeiro, João M.;** Dias, Daniel F. C.; Delpech, Bertrand; Katsou, Evina; Jouhara, Hussam. (2024) Circularity assessment of industrial sector: Industrial water and energy consumption. Work presented 10th International Conference on Material Science and Smart Materials, 15th – 17th of May 2024, Athens, Greece.
- **Ribeiro, João M.;** Nika, Eliza; Tsadilis, George; Dias, Daniel F. C.; Jouhara, Hussam; Katsou, Evina. (2024) Circularity and sustainability of Minimal Liquid Discharge Desalination system and products: assessment approaches and allocation methods.

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- **Ribeiro, João M.;** Dias, Daniel F. C.; Delpech, Bertrand; Katsou, Evina; Jouhara, Hussam. (2024) Circularity assessment of industrial heat exchanger and water treatment systems integration. Work presented at 16th International Conference on Sustainable Energy and Environmental Protection, 9th – 12th of September 2024, Vienna, Austria.

A Appendix

Table A.1 – Factors considered for the investment calculation.

Investment	
Equipment cost (direct cost)	
Installation cost (direct cost)	25% of purchased equipment cost
Building, process and auxiliary cost (direct cost)	20% of purchased equipment cost
Land cost (direct cost)	6% of purchased equipment cost
Indirect cost	15% of direct cost
Fixed capital investment	Direct +Indirect costs
Working capital	20% of total investment cost

Table A.2 – Multi-media filtration mass and energy balances.

Input - seawater			Output – filtered seawater		
Name	Value	Unit	Name	Value	Unit
Mass flow	925,129	tonne/y	Mass flow	925,484	tonne/y
Sodium	10,710	tonne/y	Sodium	10,710	tonne/y
Chlorine	19,620	tonne/y	Chlorine	19,620	tonne/y
Magnesium	1,260	tonne/y	Magnesium	1,260	tonne/y
Calcium	360	tonne/y	Calcium	360	tonne/y
Sulphate	2,880	tonne/y	Sulphate	2,880	tonne/y
HCl	0.04	tonne/y			
Energy	50	MWh/y			

Table A.3 – Nanofiltration mass and energy balances.

Input - filtered seawater			Output – permeate 1		
Name	Value	Unit	Name	Value	Unit
Mass flow	925,484	tonne/y	Mass flow	679,725	tonne/y
Sodium	10,710	tonne/y	Sodium	7,162	tonne/y
Chlorine	19,620	tonne/y	Chlorine	11,600	tonne/y
Magnesium	1,260	tonne/y	Magnesium	22	tonne/y
Calcium	360	tonne/y	Calcium	17	tonne/y
Sulphate	2,880	tonne/y	Sulphate	5	tonne/y
HCl	355	tonne/y	Output - concentrate		
Antiscalant	19	tonne/y	Mass flow	245,819	tonne/y
Energy	591	MWh/y	Sodium	3,548	tonne/y
			Chlorine	8,034	tonne/y
			Magnesium	1,238	tonne/y
			Calcium	343	tonne/y
			Sulphate	2,875	tonne/y

Table A.4 – Operational data of the Nanofiltration process.

Parameter	Value	Unit
Rejection Na	9	%
Rejection Cl	18	%
Rejection Mg	88	%
Rejection Ca	78	%
Rejection SO4	96	%
Water recovery	76	%
Temperature	20	°C
Drive-Pressure	2	bar

Table A.5 – Multi-effect distillation mass and energy balances.

Input – permeate 1 + 2			Output – desalinated water		
Name	Value	Unit	Name	Value	Unit
Mass flow	932,989	tonne/y	Mass flow	793,737	tonne/y
Sodium	10,300	tonne/y	Sodium	0	tonne/y
Chlorine	16,587	tonne/y	Chlorine	0	tonne/y
Magnesium	22	tonne/y	Magnesium	0	tonne/y
Calcium	36	tonne/y	Calcium	0	tonne/y
Sulphate	72	tonne/y	Sulphate	0	tonne/y
Energy	1,016	MWh/y	Output – brine		
			Mass flow	139,252	tonne/y
			Sodium	10,300	tonne/y
			Chlorine	16,587	tonne/y
			Magnesium	22	tonne/y
			Calcium	36	tonne/y
			Sulphate	72	tonne/y

Table A.6 – Operational data of the Multi-effect distillation process.

Parameter	Value	Unit
Concentration Factor	6.7	-
Temperature input	40	°C
Number of effects	2	-
Temperature in the last effect	44	°C
Steam temperature	70	°C
Cooling water in	32	°C
Cooling water out	42	°C

Table A.7 – Thermal crystalliser mass and energy balances.

Input - brine			Output – desalinated water		
Name	Value	Unit	Name	Value	Unit
Mass flow	139,252	tonne/y	Mass flow	100,146	tonne/y
Sodium	10,300	tonne/y	Sodium	0	tonne/y
Chlorine	16,587	tonne/y	Chlorine	0	tonne/y
Magnesium	22	tonne/y	Magnesium	0	tonne/y
Calcium	36	tonne/y	Calcium	0	tonne/y
Sulphate	72	tonne/y	Sulphate	0	tonne/y
Energy	171	MWh/y	Output – NaCl		
			Mass flow	39,106	tonne/y
			Sodium	10,300	tonne/y
			Chlorine	16,587	tonne/y
			Magnesium	22	tonne/y
			Calcium	36	tonne/y
			Sulphate	72	tonne/y

Table A.8 – Operational data of the Thermal Crystalliser

Parameter	Value	Unit
Salt moisture	20	-
Temperature input	40	°C
Temperature out	60	
Cooling water in	25	°C
Cooling water out	50	°C

Table A.9 – Multiple feed plug flow reactor mass and energy balance.

Input - concentrate			Output – Mg(OH) ₂		
Name	Value	Unit	Name	Value	Unit
Mass flow	245,819	tonne/y	Mass flow	2,970	tonne/y
Sodium	3,548	tonne/y	Sodium	0	tonne/y
Chlorine	8,034	tonne/y	Chlorine	0	tonne/y
Magnesium	1,238	tonne/y	Magnesium	1,238	tonne/y
Calcium	343	tonne/y	Calcium	0	tonne/y
Sulphate	2,875	tonne/y	Sulphate	0	tonne/y
NaOH	85,085	tonne/y	Output – Ca(OH) ₂		
Na	1,960	tonne/y	Mass flow	360	tonne/y
OH	1,450	tonne/y	Sodium	0	tonne/y
Water	81,676	tonne/y	Chlorine	0	tonne/y
NaOH	58,594	tonne/y	Magnesium	0	tonne/y
Na	1,226	tonne/y	Calcium	195	tonne/y
OH	907	tonne/y	Sulphate	0	tonne/y
Water	56,462	tonne/y	Output – effluent		
HCl	39414	tonne/y	Mass flow	385,348	tonne/y
Cl	1,320	tonne/y	Sodium	6,734	tonne/y
H	37	tonne/y	Chlorine	8,034	tonne/y
Water	38,057	tonne/y	Magnesium	0	tonne/y
Energy	171	MWh/y	Calcium	148	tonne/y
			Sulphate	2,875	tonne/y

Table A.10 – Operational data of the Multiple feed plug flow reactor.

Parameter	Value	Unit
pH (Mg step)	10.35	
pH (Ca step)	13	
NaOH molarity	1	M
Mg step recovery rate	95	%
Mg step recovery rate	56.9	%

Table A.11 – Nanofiltration 2 mass and energy balances.

Input – effluent			Output – permeate 2		
Name	Value	Unit	Name	Value	Unit
Mass flow	424,763	tonne/y	Mass flow	253,264	tonne/y
Sodium	6,734	tonne/y	Sodium	3,353	tonne/y
Chlorine	9,356	tonne/y	Chlorine	5,333	tonne/y
Magnesium	0	tonne/y	Magnesium	0	tonne/y
Calcium	148	tonne/y	Calcium	19	tonne/y
Sulphate	2,875	tonne/y	Sulphate	69	tonne/y
Energy	1,016	MWh/y	Output – concentrate 2		
			Mass flow	171,499	tonne/y
			Sodium	3,380	tonne/y
			Chlorine	4,023	tonne/y
			Magnesium	0	tonne/y
			Calcium	128	tonne/y
			Sulphate	2,806	tonne/y

Table A.12 – Operational data of the Nanofiltration 2.

Parameter	Value	Unit
Rejection Na	17	%
Rejection Cl	5	%
Rejection Mg	88	%
Rejection Ca	78	%
Rejection SO ₄	96	%
Water recovery	60	%
Temperature	20	°C
Drive-Pressure	2	bar

Table A.13 – Eutectic freeze crystalliser mass and energy balances.

Input – concentrate 2			Output – desalinated water		
Name	Value	Unit	Name	Value	Unit
Mass flow	171,499	tonne/y	Mass flow	78,045	tonne/y
Sodium	3,380	tonne/y	Sodium	0	tonne/y
Chlorine	4,023	tonne/y	Chlorine	0	tonne/y
Magnesium	0	tonne/y	Magnesium	0	tonne/y
Calcium	128	tonne/y	Calcium	0	tonne/y
Sulphate	2,806	tonne/y	Sulphate	0	tonne/y
Energy	226	MWh/y	Output – Na ₂ SO ₄		
			Mass flow	7,530	tonne/y
			Sodium	1,075	tonne/y
			Chlorine	0	tonne/y
			Magnesium	0	tonne/y
			Calcium	0	tonne/y
			Sulphate	2,245	tonne/y
			Water	4,210	tonne/y
			Output – effluent 2		
			Mass flow	85,924	tonne/y
			Sodium	2,306	tonne/y
			Chlorine	4,023	tonne/y
			Magnesium	0	tonne/y
			Calcium	128	tonne/y

			Sulphate	561	tonne/y
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Table A.14 – Electrodialysis with bipolar membrane mass and energy balances.

Input – effluent 2			Output – NaOH		
Name	Value	Unit	Name	Value	Unit
Mass flow	85,924	tonne/y	Mass flow	85,085	tonne/y
Sodium	2,306	tonne/y	Sodium	1,960	tonne/y
Chlorine	4,023	tonne/y	Chlorine	0	tonne/y
Magnesium	0	tonne/y	Magnesium	0	tonne/y
Calcium	128	tonne/y	Calcium	0	tonne/y
Sulphate	561	tonne/y	Sulphate	0	tonne/y
Water	163,135	tonne/y	Water	81,676	tonne/y
Energy	9,817	MWh/y	Output – HCl		
			Mass flow	86,599	tonne/y
			Sodium	0	tonne/y
			Chlorine	3,017	tonne/y
			Magnesium	0	tonne/y
			Calcium	0	tonne/y
			Sulphate	0	tonne/y
			Water	83,496	tonne/y
			Output – discharge		
			Mass flow	83,269	tonne/y
			Sodium	346	tonne/y

			Chlorine	1,006	tonne/y
			Magnesium	0	tonne/y
			Calcium	128	tonne/y
			Sulphate	561	tonne/y

Table A.15 – Operational data of the Electrodialysis with bipolar membrane.

Parameter	Value	Unit
Temperature	20	%
Sodium recovery efficiency	85	%
Chlorine recovery efficiency	75	%

Table A.16 – Costs of the resources used in the circularity assessment.

Resource	Value	Unit	Source
Desalinated water	1.5*	€/m ³	Lampedusa water authority
NaCl	66.0*	€/tonne	(Morgante et al., 2022)
Mg(OH) ₂	1,000.0*	€/tonne	(Morgante et al., 2022)
Ca(OH) ₂	125.0*	€/tonne	(Morgante et al., 2022)
Na ₂ SO ₄	115.0*	€/tonne	(Morgante et al., 2022)
HCl	125.0*	€/tonne	(Morgante et al., 2022)
NaOH	330.0*	€/tonne	(Morgante et al., 2022)
Electricity	0.2*	€/kWh	Lampedusa water authority

* The prices are subject to market fluctuations.

Table A.17 – Water and ions inflow characterisation for the MLD system.

Inflow	Stream	Source	Fraction	Characterisation
Water	Seawater	Sea	94.0%	Circular
	Water in NaOH (1M)	Groundwater	6.0%	Linear
Sodium	Seawater	Sea	89.7%	Circular
	NaOH (1M)	Terrestrial deposit	10.3%	Linear
Chlorine	Seawater	Sea	100.0%	Circular
Magnesium	Seawater	Sea	100.0%	Circular
Calcium	Seawater	Sea	100.0%	Circular
Sulphate	Seawater	Sea	100.0%	Circular

Table A.18 – Water and ions outflow characterisation for the MLD system.

Outflow	Stream	Destination	Fraction	Characterisation
Water	Desalinated water	Socio-economic activities	85.9%	Circular
	Discharge	Sea	8.8%	Linear
	Na ₂ SO ₄	Socio-economic activities	0.4%	Circular
	HCl	Socio-economic activities	4.8%	Circular
Sodium	Discharge	Sea	3.0%	Circular
	Na ₂ SO ₄	Socio-economic activities	9.2%	Circular
	NaCl	Socio-economic activities	87.9%	Circular
Chlorine	Discharge	Sea	5.2%	Circular
	HCl	Socio-economic activities	8.7%	Circular
	NaCl	Socio-economic activities	86.1%	Circular
Magnesium	Discharge	Sea	0.0%	Circular
	Mg(OH) ₂	Socio-economic activities	98.3%	Circular
	NaCl	Socio-economic activities	1.7%	Circular
Calcium	Discharge	Sea	9.2%	Circular
		Sea	26.6%	Linear
	Ca(OH) ₂	Socio-economic activities	54.2%	Circular
	NaCl	Socio-economic activities	10.0%	Circular
Sulphate	Discharge	Sea	9.1%	Circular
		Sea	10.4%	Linear
	Na ₂ SO ₄	Socio-economic activities	77.9%	Circular

	NaCl	Socio-economic activities	2.5%	Circular
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Table A.19 – Global warming contribution analysis.

Resource	Global warming (kg CO ₂ /tonne of water)
Energy	16.84
Antiscalant (Sodium tripolyphosphate)	0.12
NaOH	4.30

Table A.20 – Resources inputs, assumptions and expected outcomes of the three scenarios.

Scenario	Resource Inputs	Assumptions	Expected Outcomes
Scenario 1	Brackish water, NaOH, HCl, Antiscalant, Energy	Same energy type as the MLD system; Same origin of the chemicals as the MLD system	Demonstrate the impact of brackish water on the resource flows and ion recovery performance
Scenario 2	Seawater, HCl, Antiscalant, Energy	Same energy type as the MLD system; Same origin of the chemicals as the MLD system; The brine is discharged to the sea where the seawater is abstracted	Shows the impact of no brine valorisation
Scenario 3	Seawater, NaOH, Antiscalant, Energy	Same energy type as the MLD system; Same origin of the chemicals as the MLD system	Highlight the impact of achieving the ZLD

B Appendix

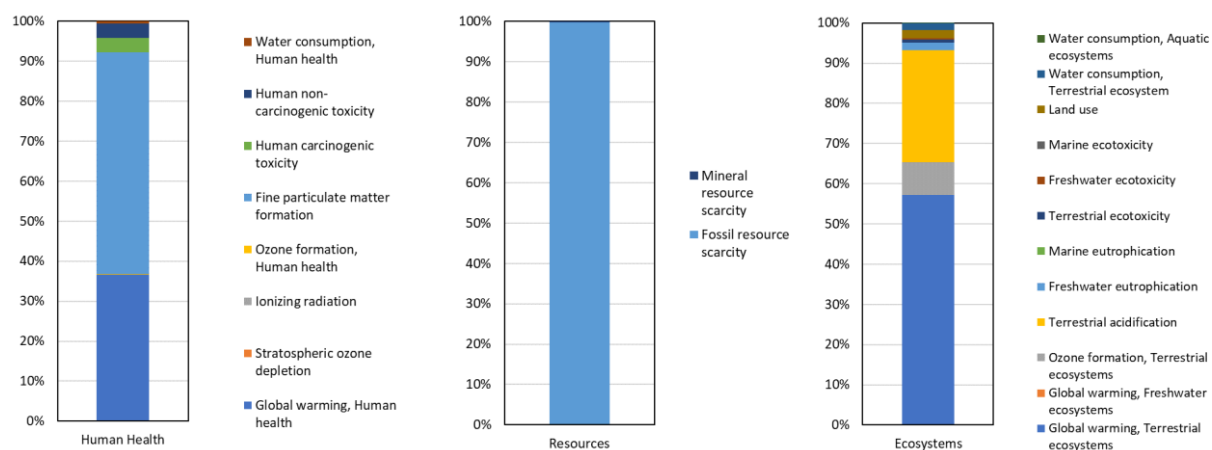


Figure B.1 – Endpoint categories of the MLD system (FU = 1 kg of water + 0.0484 kg of NaCl + 0.0037 kg of Mg(OH)₂ + 0.0004 kg of Ca(OH)₂ + 0.0093 kg of Na₂SO₄ + 0.0579 kg of HCl).

Table B.20 - Reference system for desalinated water production.

Input	Value	Unit	Output	Value	Unit
MMF					
Seawater	925,129	tonne	Filtered seawater	925,129	tonne
Electricity	50	MWh			
Hydrochloric acid	0.04	tonne			
Reverse osmosis					
Filtered seawater	925,129	tonne	Desalinated water	416,348	tonne
Electricity	1,621	MWh			
Sodium hypochlorite	0.00006	tonne			
Sulphuric acid	0.00025	tonne			
Sodium bisulfite	0.00001	tonne	Concentrate	508,870	tonne
Polycarboxylates	0.01359	tonne			

Iron(III) chloride	0.01306	tonne			
Calcium hypochlorite	0.00241	tonne			

Table B.21 – Reference system for NaCl production (Ecoinvent process name: sodium chloride production, powder RER).

Input	Value	Unit	Output	Value	Unit
Sodium chloride (from ground)	0.001000	tonne	NaCl	0.00100	tonne
Water	0.002690	tonne	Water	0.00180	tonne
Water	0.003820	tonne	Water	0.00086	tonne
Quicklime	0.000014	tonne	Decarbonising waste	0.00003	tonne
Soda ash	0.000013	tonne	Wastewater	0.00340	tonne
Diesel	0.001189	kWh			
Electricity	0.170000	kWh			
Heat	0.054722	kWh			

Table B.22 – Reference system for $\text{Mg}(\text{OH})_2$ production (Ecoinvent process name: magnesium oxide production RER; it is not the complete process of $\text{Mg}(\text{OH})_2$, it stops in the MgO production).

Input	Value	Unit	Output	Value	Unit
Magnesite	0.00227	tonne	$\text{Mg}(\text{OH})_2$	0.00100	tonne
Water	0.00263	tonne	Carbon dioxide	0.00091	tonne
Water	0.00006	tonne	Carbon monoxide	4.77E-06	tonne
Diesel	0.01447	kWh	Nitrogen oxides	3.36E-07	tonne
Electricity	0.20700	kWh	NM VOC	4.55E-08	tonne
Heat	0.00148	kWh	Particulates	0.00001	tonne
Heat	0.06844	kWh	Sulfur dioxide	3.36E-07	tonne
			Arsenic	1.85E-08	tonne
			Cadmium	1.85E-08	tonne
			Chromium VI	1.85E-08	tonne
			Chemical oxygen demand	0.00001	tonne
			Copper	9.24E-08	tonne
			Cyanide	1.85E-07	tonne
			Iron	6.47E-07	tonne
			Lead	3.70E-08	tonne
			Mercury	1.85E-09	tonne
			Nickel	9.24E-08	tonne
			Oils	1.85E-06	tonne
			Water, RER	0.00214	tonne

			Zinc	3.70E-07	tonne
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Table B.23 – Reference system for Ca(OH)₂ production (Ecoinvent process name: limestone quarry operation CH (process I); limestone production, crushed, washed CH (process II); quicklime production, in pieces, loose CH (process III); lime production, hydrated, loose weight CH (process IV)).

Input	Value	Unit	Output	Value	Unit
Process I					
Calcite	0.00173	tonne	Limestone	0.00173	tonne
Water	0.00004	tonne	Particulates	2.768E-07	tonne
Diesel	0.00865	kWh	Water	0.00004	tonne
Heat	0.00027	kWh			
Process II					
Limestone	0.00173	tonne	Limestone	0.00173	tonne
Water	0.00002	tonne	Particulates	3.014E-08	tonne
Electricity	0.00062	kWh	Water	0.00009	tonne
Electricity	0.00062	kWh	Water	0.00023	tonne
Heat	0.00068	kWh			
Process III					
Limestone	0.00173	tonne	Quicklime	0.00100	tonne
Fuel oil	0.00009	tonne	Carbon dioxide	0.00108	tonne
Electricity	0.04690	kWh	Carbon monoxide	4.77E-06	tonne
Electricity	0.04690	kWh	Nitrogen oxides	3.36E-07	tonne
			NM VOC	4.55E-08	tonne

			Particulate	6.82E-08	tonne
			Sulfur dioxide	3.36E-07	tonne
Process IV					
Quicklime	0.00077	tonne	Ca(OH) ₂	0.00100	tonne
Water	0.00060	tonne	Water	0.00009	tonne
Electricity	0.00636	kWh	Water	0.00051	tonne
Electricity	0.00636	kWh			
Heat	0.00039	kWh			

Table B.24 – Reference system for the Na₂SO₄ production (Ecoinvent process name: sodium sulfate production, from natural sources RER).

Input	Value	Unit	Output	Value	Unit
Glauber's salt	0.00105	tonne	Na ₂ SO ₄	0.00100	tonne
Diesel	0.00119	kWh	Sulfate	0.00003	tonne
Electricity	0.17000	kWh	Inert waste	0.00003	tonne
Heat	0.05028	kWh			

Table B.25 – Reference scenario for the HCl production (Ecoinvent process name: hydrochloric acid production, from the reaction of hydrogen with chlorine RER).

Input	Value	Unit	Output	Value	Unit
Chlorine	0.00098	tonne	HCl	0.00100	tonne
Hydrogen	0.00003	tonne	Chlorine	0.00002	tonne
Nitrogen	0.00002	tonne	Nitrogen	0.000019	tonne
Electricity	0.00042	kWh			

Table B.26 – Non-Normalised environmental results of system expansion approach of the MLD system.

Impact category	Unit	MLD	Reference
Global warming	kg CO ₂ eq	0.027965456	0.0694684
Fine particulate matter formation	kg PM2.5 eq	6.29893E-05	0.0001259
Terrestrial acidification	kg SO ₂ eq	0.000189473	0.0003166
Terrestrial ecotoxicity	kg 1,4-DCB	0.10106687	0.5683278
Marine ecotoxicity	kg 1,4-DCB	0.000502676	0.0100307
Fossil resource scarcity	kg oil eq	0.007233417	0.0186637

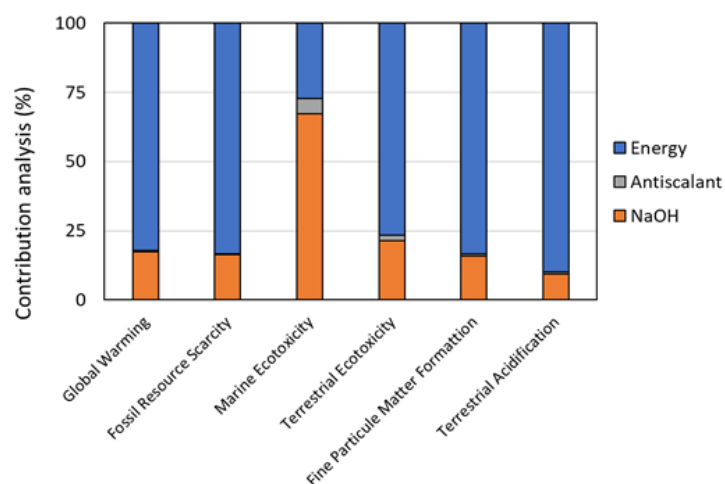


Figure B.2 – Contribution analysis of the resources to the MLD system.

Table B.27 – Non-normalized environmental impacts of the process physical partitioning of the MLD system.

Impact category	Unit	Desalinated water	NaCl	Mg(OH) ₂	Ca(OH) ₂	Na ₂ SO ₄	HCl
Global warming	kg CO ₂ eq	0.0212611	0.013455	0.042409	0.043734	0.038251	0.095378
Fine particulate matter formation	kg PM _{2.5} eq	4.7757E-05	3.037E-05	9.491E-05	9.787E-05	8.57E-05	0.0002172
Terrestrial acidification	kg SO ₂ eq	0.0001419	9.149E-05	0.0002788	0.0002875	0.000253	0.0006846
Terrestrial ecotoxicity	kg 1,4-DCB	0.0776253	0.0491922	0.1548006	0.1596381	0.1391344	0.3303612
Marine ecotoxicity	kg 1,4-DCB	0.000422	0.0002489	0.0008904	0.0009182	0.0007763	0.0009976
Fossil resource scarcity	kg oil eq	0.0054865	0.0034761	0.0109323	0.011274	0.0098692	0.024902

Table B.28 – Non-normalized environmental impacts of the process economic partitioning of the MLD system.

Impact category	Unit	Desalinated water	NaCl	Mg(OH) ₂	Ca(OH) ₂	Na ₂ SO ₄	HCl
Global warming	kg CO ₂ eq	0.00285599	0.030973	0.156570	0.024840	0.0926363	0.3149231
Fine particulate matter formation	kg PM _{2.5} eq	6.4448E-06	0.000135	0.00273	0.000433	0.0014863	0.0002663
Terrestrial acidification	kg SO ₂ eq	1.941E-05	0.000429	0.008090	0.001283	0.0044091	0.0008125
Terrestrial ecotoxicity	kg 1,4-DCB	0.0104427	0.226575	4.381254	0.695103	2.3827661	0.4162577
Marine ecotoxicity	kg 1,4-DCB	5.294E-05	0.000960	0.023398	0.003712	0.0126284	0.0017769
Fossil resource scarcity	kg oil eq	0.0007378	0.015025	0.314992	0.049975	0.1714694	0.0306592

Table B.29 – Non-normalized environmental impacts of the system physical partitioning of the MLD system.

Impact category	Unit	Desalinated water	NaCl	Mg(OH) ₂	Ca(OH) ₂	Na ₂ SO ₄	HCl
Global warming	kg CO ₂ eq	0.0076127	0.0067284	0.0103984	0.0107234	0.01072536	0.25851
Fine particulate matter formation	kg PM _{2.5} eq	1.6642E-05	1.499E-05	2.202E-05	2.271E-05	2.303E-05	0.0005896
Terrestrial acidification	kg SO ₂ eq	4.32E-05	4.212E-05	4.901E-05	5.054E-05	5.538E-05	0.0018739
Terrestrial ecotoxicity	kg 1,4-DCB	0.0307198	0.0264357	0.0439271	0.0452998	0.0437921	0.8862323
Marine ecotoxicity	kg 1,4-DCB	0.0002948	0.0002014	0.0005556	0.0005729	0.0004884	0.002317
Fossil resource scarcity	kg oil eq	0.0019178	0.001712	0.0025749	0.0026554	0.0026825	0.067625

Table B.30 – Non-normalized environmental impacts for the system economic partitioning of the MLD system.

Impact category	Unit	Desalinated water	NaCl	Mg(OH) ₂	Ca(OH) ₂	Na ₂ SO ₄	HCl
Global warming	kg CO ₂ eq	0.000629088	0.0309727	0.1565698	0.0248404	0.092636252	0.3149231
Fine particulate matter formation	kg PM _{2.5} eq	1.4017E-06	7.087E-05	0.0003377	5.357E-05	0.0002009	0.0007123
Terrestrial acidification	kg SO ₂ eq	3.986E-06	0.0002278	0.0008014	0.0001271	0.0004926	0.0021769
Terrestrial ecotoxicity	kg 1,4-DCB	0.0024038	0.1054527	0.6761111	0.1072676	0.3924554	1.1282412
Marine ecotoxicity	kg 1,4-DCB	1.699E-05	0.0002254	0.0079143	0.0012556	0.0043248	0.0049733
Fossil resource scarcity	kg oil eq	0.0001608	0.0081178	0.038811	0.0061575	0.0230806	0.0816617

Table B.31 – Non-normalized environmental impacts of the reference scenarios.

Impact category	Unit	Desalinated water	NaCl	Mg(OH) ₂	Ca(OH) ₂	Na ₂ SO ₄	HCl
Global warming	kg CO ₂ eq	0.0049886	0.15712343	1.01723618	0.86013294	0.1058708	0.894263912
Fine particulate matter formation	kg PM _{2.5} eq	1.3821E-05	0.00034199	0.00065217	0.00021186	0.0002192	0.001571058
Terrestrial acidification	kg SO ₂ eq	4.3879E-05	0.00088566	0.0010402	0.000598652	0.0005619	0.003809005
Terrestrial ecotoxicity	kg 1,4-DCB	0.02055235	2.90830885	0.16828103	0.122175929	1.469691	6.783998592
Marine ecotoxicity	kg 1,4-DCB	7.6083E-05	0.04694393	0.14322841	0.000909536	0.0248873	0.119632294
Fossil resource scarcity	kg oil eq	0.00140579	0.03679011	0.0281409	0.07496282	0.0270251	0.26063009

C Appendix

Table C.32 – Freshwater and rainwater quality

Parameter	Freshwater	Rainwater	Units
Chemical Oxygen Demand (COD)	10	9	mg/l
Total Suspended Solids (TSS)	4	< 4.0	mg/l
Ammonium Nitrogen (NH ₄ ⁺)	0.02	< 0.02	mg/l
Nitrites (NO ₂ ⁻)	0.02	< 0.02	mg/l
Nitrates (NO ₃ ⁻)	40.5	4.92	mg/l
Sulphates (SO ₄ ²⁻)	144.5	4.73	mg/l
Bicarbonates (HCO ₃ ⁻)	443.5	44	mg/l
Chloride (Cl ⁻)	101	1.14	mg/l
Fluoride (F ⁻)	0.1	0.131	mg/l
Aluminium (Al)	0.00275	0.0338	mg/l
Cadmium (Cd)	0.0001	< 0.0001	mg/l
Boron (B)	0.555	< 0.001	mg/l
Calcium (Ca)	252.5	12.2	mg/l
Iron (Fe)	0.0325	0.0127	mg/l
Magnesium (Mg)	33.8	0.388	mg/l
Manganese (Mn)	0.0015	0.00135	mg/l
Potassium (K)	3.95	0.87	mg/l
Silica (SiO ₂)	7.95	0.81	mg/l
Sodium (Na)	100.5	1.61	mg/l
Temperature	9.6	6.5	C
pH	7.2	7.1	-
Specific Electrical Conductivity	1229.5	75	μS/cm