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ABSTRACT

The desalination sector adopts Minimal Liquid Discharge (MLD) systems to become more circular, reduce brine discharge and enhance water recovery, which transforms them to multifunctional systems. This multifunctionality requires a methodologically consistent and goal-aligned approach to environmental impact assessment that recognises how different modelling choices are connected with specific decision contexts. A criterion LCA-based framework aligned with the ISO 14044 hierarchy and tailored specifically to desalination has been developed. It guides the selection of allocation approaches based on system characteristics, integration level, and assessment objectives and is applied to assess an MLD system which co-produces desalinated water, sodium chloride, magnesium hydroxide, calcium hydroxide, sodium sulphate and hydrochloric acid. Multifunctionality was handled with system expansion and partitioning (physical and economic) approaches, resulting in different functional units. For physical and economic partitioning, the MLD system is modelled from a process and system perspective. The results indicate that the MLD system has larger environmental benefits than the reference system with system expansion. When physical and economic partitioning under different perspectives are applied, they result in different environmental burdens per co-product. The MLD system performs better than the reference system (0.005 kg CO_2/kg desalinated water) only when process economic partitioning (0.003 kg CO_2/kg desalinated water) is applied. Whereas, the rest co-products perform better than reference products for all partitioning approaches applied. Our results highlight the potential of brine as a secondary source of products. This study underscores the importance of selecting appropriate allocation approaches, contributing to sustainable practices in the desalination sector.

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 pollution 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) (International Organization for Standardization, 2006a, 2006b). LCA considers inputs and outputs to evaluate the environmental impacts of a product system along its life cycle (International Organization for Standardization, 2006a, 2006b). Most of the LCA studies use a functional unit (FU) (i.e., 1 m^3 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 minimisation 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., 2017). Besides water recovery, if secondary product recovery from brine occurs, the

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Glossary

$Ca(OH)_2$ –	Calcium Hydroxide
EDBM –	Electrodialysis Bipolar Membrane
EF –	Economic factor
EFC –	Eutectic Freeze Crystalliser
EP –	Economic Partitioning
FU –	Functional Unit
GW –	Global Warming
HCl –	Hydrochloric Acid
ISO –	International Organization for Standardization
LCA –	Life Cycle Assessment
MED –	Multi-Effect Distillation
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
Na_2SO_4 –	Sodium Sulphate
NF –	Nanofiltration
PF –	Physical Factor
PP –	Physical Partitioning
RO –	Reverse Osmosis
TC –	Thermal Crystalliser
ZLD –	Zero Liquid Discharge

desalination system becomes a multifunctional system. Therefore, allocation is needed to assess environmentally 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 (International Organization for Standardization, 2006a) has acknowledged the complexity of the allocation issue 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 (International Organization for Standardization, 2006a). 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 (International Organization for Standardization, 2006a) 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 (International Organization for Standardization, 2006a). 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 (International Organization for Standardization, 2006a) 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 (International Organization for Standardization, 2006a), 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). Last, 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 the 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 a 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.

2. Methodology

2.1. Rationale for framework development

ISO 14044 describes a hierarchical approach to solve multi-functionality, 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.

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. Fig. 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

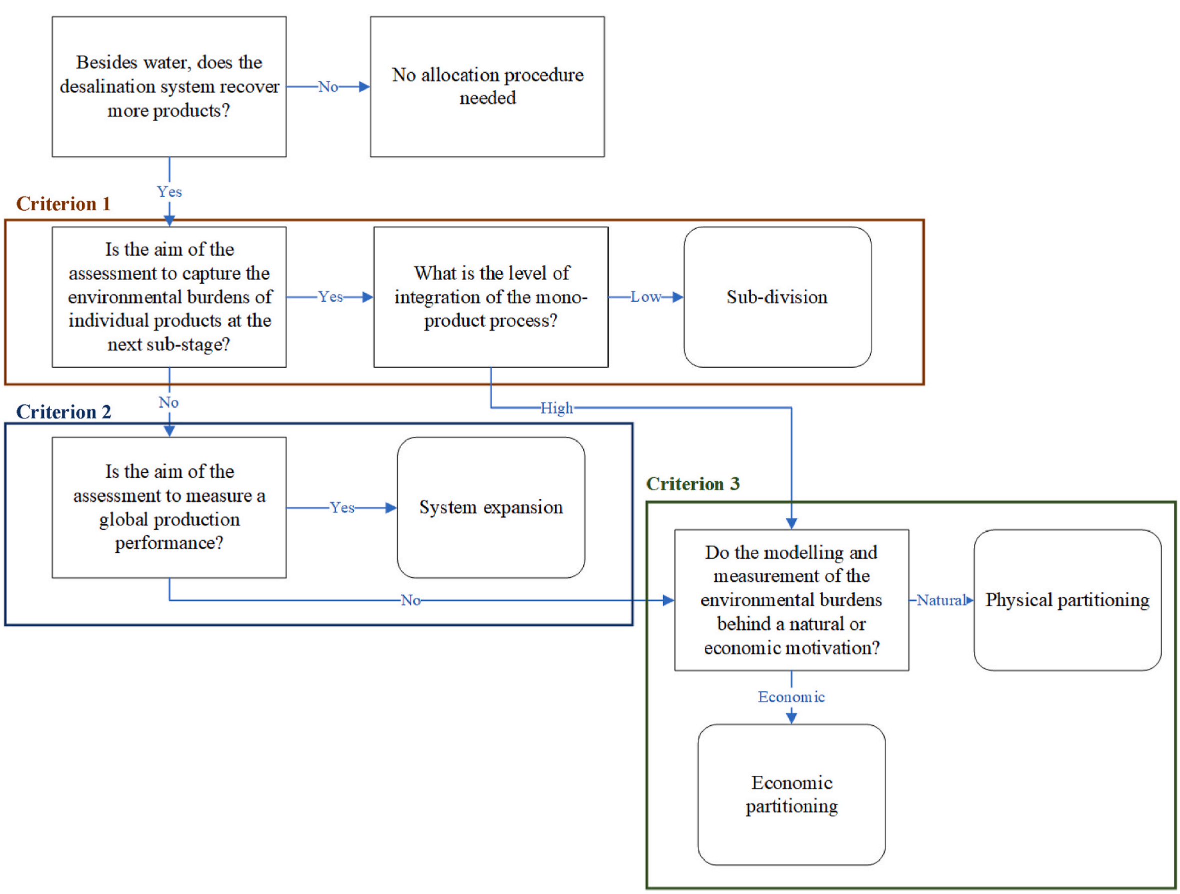

Fig. 1. – The criterion LCA-based framework for multifunctional desalination systems.

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.

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 Fig. 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 (Fig. 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.

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 (Fig. 4). However, reference products are required for each co-product, which could complicate the design of the reference system (Fig. 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. Fig. 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.

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 (Fig. 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 ($Mg(OH)_2$), calcium hydroxide ($Ca(OH)_2$), sodium sulphate (Na_2SO_4) and hydrochloric acid (HCl).

The seawater enters the MLD systems and is softened by the MMF,

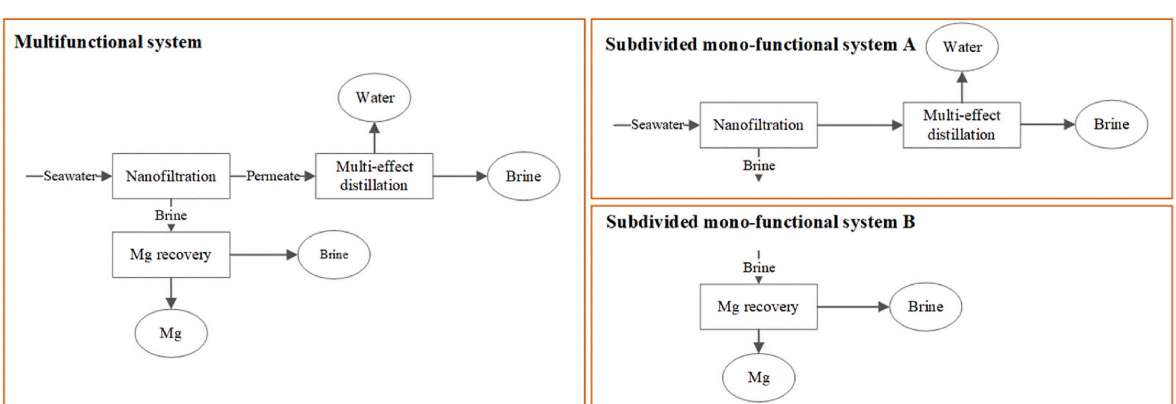

Fig. 2. – Example of an applied subdivision approach to a multifunctional desalination system.

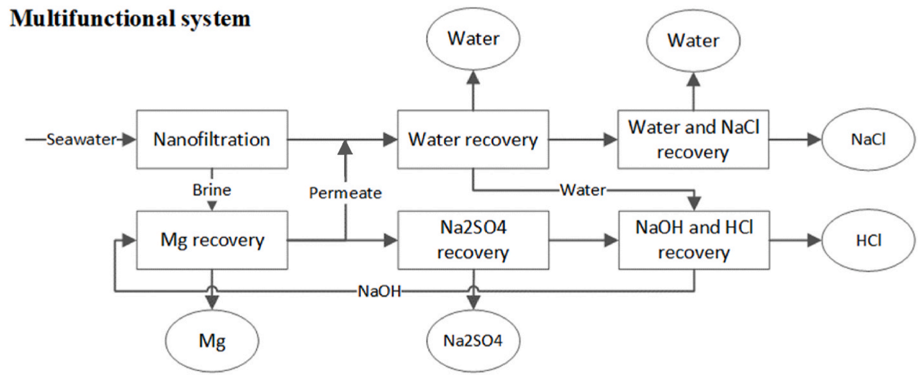

Fig. 3. – Example of multifunctional desalination system with a high level of integration. All the co-product processes are interdependent in a closed loop. The water recovery process is connected to the NaOH and HCl recovery process which is connected to the Mg recovery which is connected to the water recovery process.

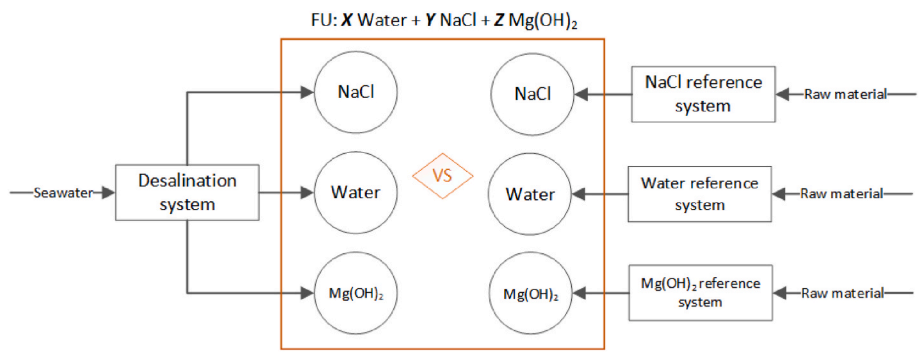

Fig. 4. – Example of a system expansion approach. The FU is expanded to the stoichiometry of the production, and the impacts are compared with the same FU for reference systems.

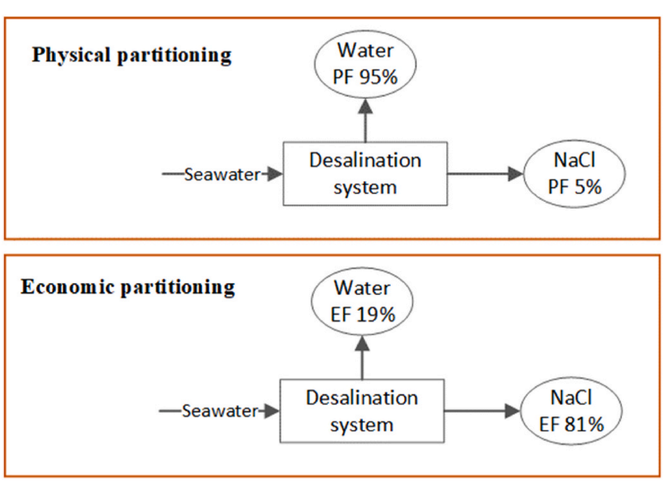

Fig. 5. – Example of applying physical and economic partitioning in the assessment of a multifunctional system that produces water and NaCl. The percentages are physical (PF) and economic (EF) factors, they do not regard co-products production.

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, $Mg(OH)_2$ and $Ca(OH)_2$ are precipitated through the addition of sodium hydroxide (NaOH) in a two-phase cycle. The N_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 2465 m^3/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 $Mg(OH)_2$ and $Ca(OH)_2$.

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 3 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 $Mg(OH)_2$, Ca $(OH)_2$ 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.

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 to demonstrate 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.

2.5. Multifunctionality

The framework presents different approaches to deal with the multifunctionality issue. In this work, system expansion and partitioning are

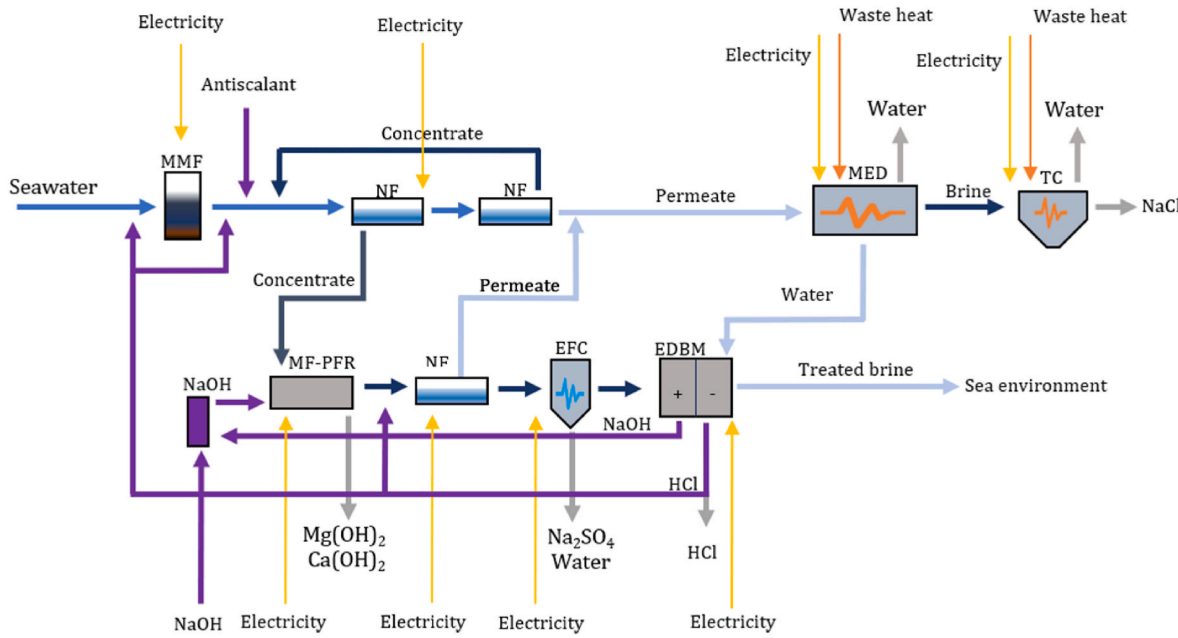

Fig. 6. – MLD system scheme: Blue colours represent the seawater and intermediate flows (Seawater, concentrate and permeate); purple colour represents chemicals/consumables flows (NaOH, HCl and antiscalant flows); yellow colour represents the electricity flows while the orange represents the waste heat flow; grey colour represents the co-products flows (desalinated water, NaCl, $Mg(OH)_2$, $Ca(OH)_2$, Na_2SO_4 and HCl).

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.

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

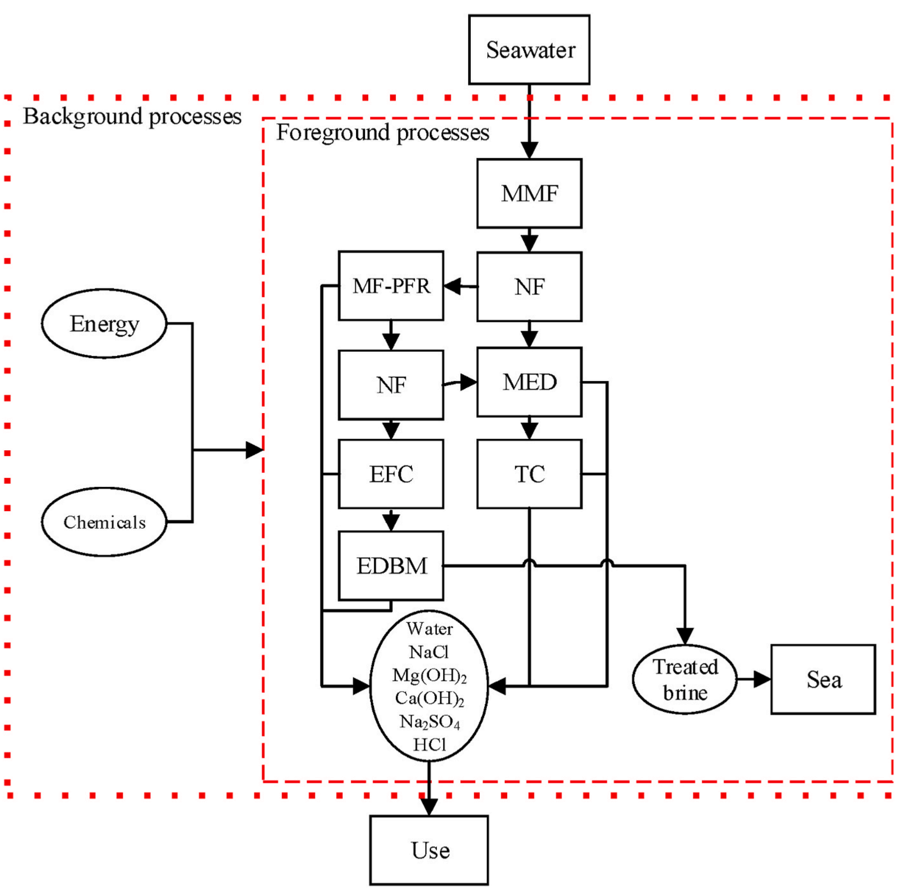

Fig. 7. – Boundaries of the MLD system.

NaCl + 0.0037 kg of $Mg(OH)_2$ + 0.0004 kg of $Ca(OH)_2$ + 0.0093 kg of Na_2SO_4 + 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 Fig. 7. The reference system boundaries are shown in Fig. 8. In addition to the conventional reverse osmosis system, the reference systems producing NaCl, $Mg(OH)_2$, $Ca(OH)_2$, Na_2SO_4 and HCl are considered.

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 modelling different 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 (Tables 1 and 2).

2.6. Impact assessment

The ReCiPe2016 Life Cycle Impact Assessment (LCIA) 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 (Fig. S1). 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.

2.7. Life Cycle Inventory (LCI)

Table 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, $Mg(OH)_2$, $Ca(OH)_2$, Na_2SO_4 and HCl, are presented in Tables S1, S2, S3, S4, S5 and S6, respectively. For consistency, the construction phases of all inventories (i.e. MLD and reference systems) were excluded. Additionally, due to the complexity of flows and internal recirculations, the mass balance check of the MLD system is included in Table S7 of the Supplementary Material.

Table 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
$Mg(OH)_2$	2970	1000	0.0033	0.2156
$Ca(OH)_2$	360	125	0.0004	0.0033
Na_2SO_4	7530	148	0.0083	0.0809
HCl	46,830	125	0.0517	0.4249

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.

3. Results and discussion

The MLD system under examination has a high level of integration because all the processes of the 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 (Table S1).

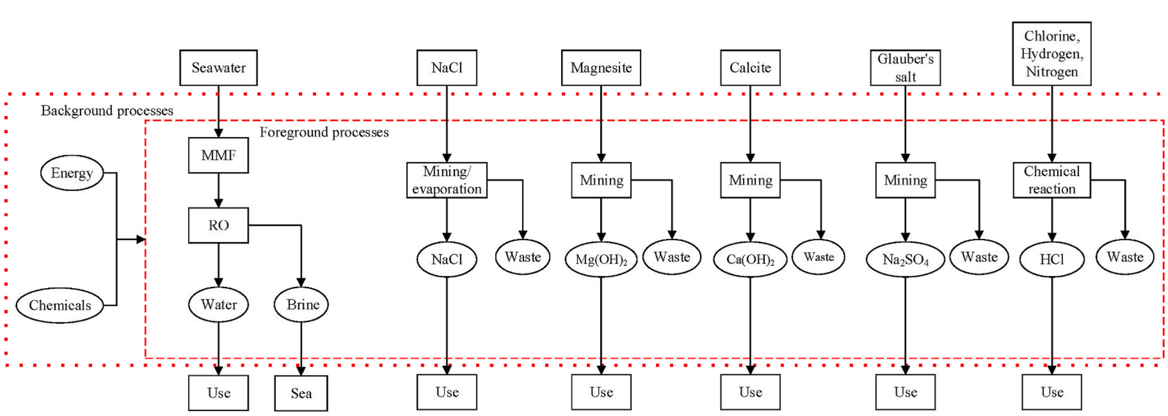

Fig. 8. – Boundaries of system expansion reference scenario.

Table 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**
$Mg(OH)_2$	2970	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_2SO_4	7530	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

3.1. System expansion (criterion 2)

Fig. 9 presents the normalised results of system expansion for the MLD and reference systems. Non-normalised results can be found in the Supplementary Material, Table S8. 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 (Fig. 9 – c and e).

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 %) (Fig. S2). The integration of other types of renewable energy (e.g. solar) with the 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 %).

The 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.

3.2. Partitioning (criterion 3)

3.2.1. Process and system approach with physical and economic partitioning

Fig. 10 presents the normalised results of one kg of co-product according to the physical and economic partitioning. Non-normalised results can be found in Tables S9, S10, S11, S12 and S14 of the Supplementary Material. The results indicate different relative contributions of the co-products which are affected by the approaches applied, which have different sets of partitioning factors (Tables 1 and 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 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 Na_2SO_4 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 Na_2SO_4 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 Na_2SO_4 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 the 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).

Table 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
Electricity	226	MWh	Na2SO4	7,530	tonne
			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
Desalinated water MED	163,165	tonne	Hydrochloric acid (1M) NF	355	tonne
			Hydrochloric acid (1M) MFPFR	39,414	tonne
			Sodium hydroxide (1M) MF-PFR	85,085	tonne

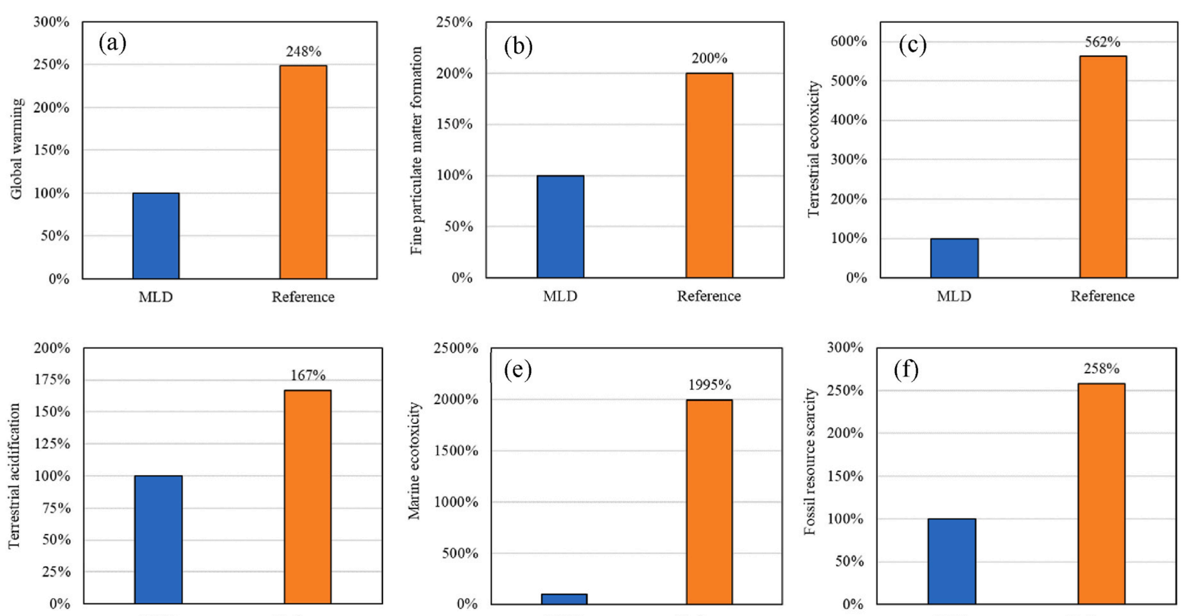

Fig. 9. – Global Warming (a), Fine Particulate Matter Formation (b), Terrestrial Ecotoxicity (c), Terrestrial Acidification (d), Marine Ecotoxicity (e) and Fossil Resource Scarcity (f) impacts of the MLD and reference systems with the system expansion.

3.2.2. *Product analysis*

Besides the analysis of different approaches for the multi-functionality issue, the study also compares each co-product individually with the corresponding reference product. Fig. 11 shows the individual product comparison.

3.2.2.1. Desalinated water. For the desalinated water (Fig. 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

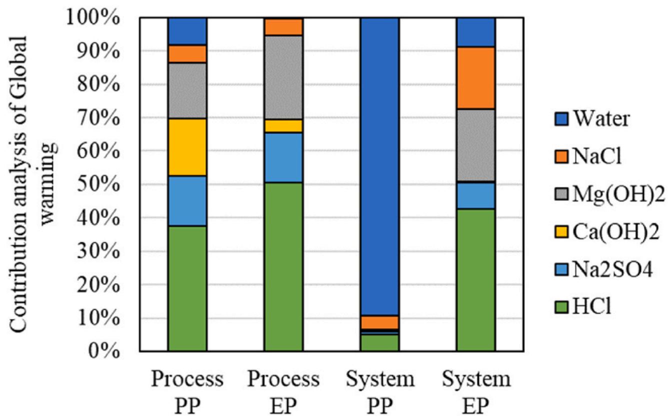

Fig. 10. – Contribution analysis of Global Warming results of the MLD products with different approaches using physical partitioning (PP) and economic partitioning (EP).

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 CO_2 eq/m^3 (0.0004–0.0067 kg CO_2 eq/kg) (Jia et al., 2019).

3.2.2.2. NaCl, $Mg(OH)_2$, $Ca(OH)_2$, Na_2SO_4 and HCl. For co-products such as NaCl (Fig. 11 – b), $Mg(OH)_2$ (Fig. 11 – c), Na_2SO_4 (Fig. 11 – e) and HCl (Fig. 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 (Fig. 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 S4).

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 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.

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.

5. Conclusion

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 that 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 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 show 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).

To conclude, the results of the partitioning approach indicate that recovery rate and market prices impact the outcome of the LCA results. This study shows that those parameters are important to be considered when LCA is used for preparing policies for the desalination sector. Additionally, the authors believe and leave as a thought for future investigation that the location of the desalination system and demand for products recovered from brine can also play a key role in the LCA results when applying different allocation approaches. The distribution of the products and different market prices around the world, in which the latter is affected by demand, can be important parameters to take into consideration for LCA studies of multifunctional systems. Further studies are needed to assess the impact of market price and location variations on LCA results for more effective policy coordination.

CRediT authorship contribution statement

J.M. Ribeiro: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **G.A. Tsalidis:**

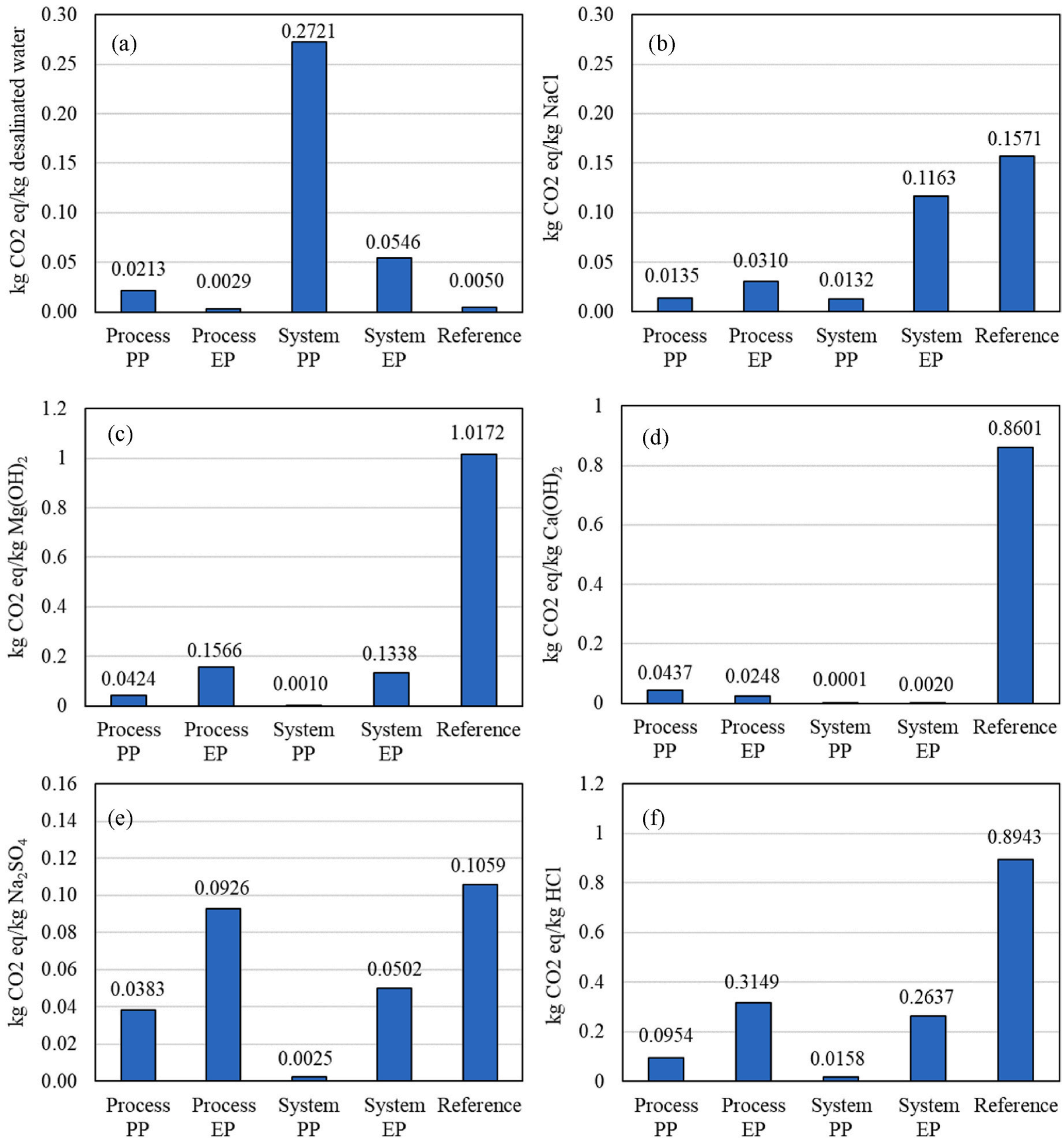

Fig. 11. – Individual comparison of Global Warming results of the desalinated water (a), NaCl (b), $Mg(OH)_2$ (c), $Ca(OH)_2$ (d), Na_2SO_4 (e) and HCl (f) products of the MLD system with different approaches using physical (PP) and economic partitioning (EP), and the corresponding reference products.

Writing – review & editing, Validation, Methodology, Formal analysis. **E. Nika:** Writing – review & editing, Investigation. **V. Vasilaki:** Writing – review & editing, Investigation. **D. Xevgenos:** Investigation, Funding acquisition. **H. Jouhara:** Writing – review & editing, Supervision, Investigation. **E. Katsou:** Writing – review & editing, Supervision, Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2025.100328.

Data availability

Data will be made available on request.

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