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Brine Valorisation - Recovery of minerals and metals from brines of seawater desalination plants

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European foreword

This CEN Workshop Agreement has been developed in accordance with the CEN-CENELEC Guide 29 “CEN/CENELEC Workshop Agreements – A rapid prototyping to standardization” and with the relevant provisions of CEN/CENELEC Internal Regulations - Part 2. It was approved by a Workshop of representatives of interested parties on 2024-09-25, the constitution of which was supported by CEN following the public call for participation made on 2023-12-19. However, this CEN Workshop Agreement does not necessarily include all relevant stakeholders.

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1 Scope

According to the European Critical Raw Material Act, the diversification of raw material supply chains is fostered.

The Sea4Value project contributes to the diversification of raw materials sourcing and aims to secure the supply of raw materials from already existing sources.

Brines produced in seawater desalination plants are multi-mineral and are an enormous potential source of minerals and metals as 19,744 plants are installed worldwide. By now, these brines are not broadly used for the extraction of (critical) raw materials, instead the brines are discarded. See Figure 1.

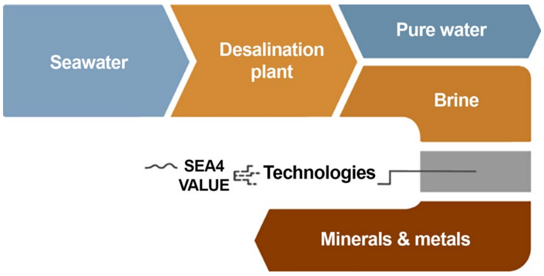

Figure 1 — Applying a circular supply model: Seawater brines as a resource of raw materials recovery

The EU-funded Sea4Value project is the first attempt to recover minerals and metals from brines produced in seawater desalination plants (SWDP) in a cost-effective way. The main focus is on separating, concentrating and crystallising Molybdenum, Magnesium, Scandium, Vanadium, Gallium, Boron, Indium, Lithium, Rubidium and Calcium from brines, where they can be found in low concentrations. To do that, a multimineral and modular process is developed for brine valorisation. The implementation of brine valorisation in seawater desalination plants offers new business opportunities, which can bring value to markets, environment, and society.

With this CEN Workshop, brine valorisation, i.e. brine mining, is to be standardised so that it can serve as a building block for a secure supply of raw materials in the future. To achieve this, it is necessary to remove the barriers to the introduction of a new process and new raw materials by ensuring reliability, knowledge transfer, and quality. Common standards help remove technical barriers to trade, open up markets and make businesses more competitive.

This CEN Workshop Agreement (CWA) which has been developed by the CEN Workshop aims to provide guidance and recommendations on best practices for sustainable brine valorisation to ensure transfer of innovation into practice. The guidance refers on the processing of brines to recover minerals and metals and on the properties of the recovered minerals and metals.

In order to achieve a common understanding, a language for describing brine valorisation needs to be developed as well as terms and system boundaries of brine valorisation need to be defined.

Moreover, the CWA describes, explains, and agrees on the core process steps of brine valorisation. This includes advice on the fundamental prerequisites; pre-treatment, key (technologic) elements/methods and post-treatment are specified and recommendations for planning, design, implementation and operation are given.

The CWA provides recommendations on good practice approaches, advice on the requirements of circularity in SWDP as well as considerations on environmental and economic impacts and evaluation. Besides the recommendations for the process of brine valorisation, recommendations are also be made for the recovered product, the minerals and metals, to ensure that the new products meet the market demand.

The CEN Workshop Agreement is intended to be used by operators of seawater desalination plants, engineering companies, end-users, traders and distributer of recovered minerals and metals as well as government and environmental authorities.

The CWA does not provide guidance and recommendations for sustainable valorisation of brines that are not produced in seawater desalination plants.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their contents constitute requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at https://www.electropedia.org/

— ISO Online browsing platform: available at https://www.iso.org/obp

3.1
brine from desalination plants

process to obtain fresh water from seawater or brackish water (which is not directly usable due to its high salinity). In all cases, in addition to the fresh water, a stream of water (by-products) is obtained that contains the salts separated from the seawater or brackish water, at a higher concentration than the initial one, and which is called reject or brine.

Traditionally, this brine is returned to the sea, which has to be managed correctly to avoid environmental impacts. However, what has often been considered a mere waste product, brine, has enormous potential that can be harnessed in a sustainable way.

3.2
brine treatment

treatment which involves brine concentration and chemical treatment technologies like multi-effect distillation, reactive and evaporative crystallization to manage brine efficiently, maximizing water yield, extract minerals and metals and minimizing environmental impacts

3.3
brine valorisation

production of salts and chemicals from brine concentrate that provide economic value for other industries. It involves the extraction of highly concentrated saltwater solutions from natural or anthropic sources like salt lakes, underground reservoirs or desalination plants. When it comes to seawater brine valorisation, it specifically refers to the production of salts and chemicals from the saline stream (brine) separated from seawater during the desalination process. This process allows to obtain valuable metals and minerals from seawater. Examples include extracting NaCl, Mg, Br, among others.

3.4
brownfield sites

previously developed lands that have existing structures or infrastructure

3.5
by-product

by-product or byproduct is a secondary product derived from a production process, manufacturing process or chemical reaction; it is not the primary product or service being produced. The brine produced in a seawater desalination process is consider as a by-product

3.6
circular economy

system where the value of products, materials and resources is maintained in the economy for as long as possible, and the generation of waste is minimised, making an essential contribution to the EU's efforts to develop a sustainable, low carbon, resource efficient and competitive economy

3.7
closed-loop recycling

sustainable concept embraced by various industries, aiming to reduce environmental impact by reusing waste materials to create the same product and/or use them within the process they originated from. This controlled recycling process, characterized by restoring and regenerating materials/compounds, ensures that resources are kept at their highest utility and value. Unlike open-loop recycling, where origin and quality of the products to be recycled is not always well known, closed-loop recycling aims to recycle indefinitely without high mass/volume loses and minimizing degradation of original properties. Closed loop recycling not only benefits the environment by reducing landfill waste but also contributes to limiting environmental impacts associated with the extraction/production of virgin materials/compounds. In essence, closed-loop recycling is a crucial strategy for businesses looking to enhance sustainability, reduce environmental impact, and promote resource efficiency through circular economy practices

[SOURCE: CWA 17354:2018]

3.8
desalination

process of removing salt and impurities from seawater or brackish water to produce freshwater for various uses

3.9
energy efficiency

ratio of output of performance, service, goods or energy, to input of energy

[SOURCE: CWA 17354:2018]

3.10
greenfield sites

undeveloped land that has not previously been built on

3.11
Minimum Liquid Discharge (MLD)

approach that focuses on reducing the volume of liquid waste generated e.g. during desalination processes by applying different brine treatment techniques to recover up to 70% of water (Li et al., 2019). Seeks to minimize solid waste generation penalising water reclamation

3.12
R9 Circular strategies

concept of recycling and recovering materials from waste to be reprocessed into new products, materials, or substances for various purposes in order to promote circularity in the economy by minimizing waste and maximizing resource efficiency. This approach is part of a broader framework known as the 9R Framework, which includes Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover.

3.13
Sea4Value project (S4V)

EU-funded research project focuses on exploring the waste brines/waste streams of seawater desalination plants as a sustainable source for recovering raw materials. By implementing radical and novel processes in seawater desalination plants, it aims to develop, and upscale innovative technologies and it seeks to recover valuable minerals and metals efficiently while promoting sustainable practices. It does not only address the challenge of resource scarcity but also aligns with the principles of circular economy by promoting the recovery and reuse of valuable minerals and metals from waste streams

3.14
Zero Liquid Discharge (ZLD)

more advanced approach where no liquid waste is discharged, aiming to recover up to 97% of water and salts for reuse (Li et al., 2019). It not only reduces environmental impact but also allows for the recovery and revaluation of valuable resources present in brine solutions by its mining. Seeks to maximize water recovery but also generates large quantities of difficult-to-manage solid waste

Table 1 – List of acronyms

BC	Brine Concentration
BPED	Electrodialysis with bipolar membranes
CAPEX	Capital Expenditure
CWV	Circular Water Value
EDR	Electrodialysis reversal
FO	Forward Osmosis
IX	Ion exchange
LSRRO	Low-salt-rejection reverse osmosis.
M&M	Minerals and Metals
MD	Membrane distillation
MLD	Minimum Liquid Discharge
MV	Multivalent
NDSX	Non-dispersive solvent extraction
NF	Nanofiltration
OARO	Osmotically Assisted Reverse Osmosis
OPEX	Operating Expenditure
PV	Polyvalent
RO	Reverse Osmosis

SRM	Secondary raw materials
SW	Seawater
SWDP	Seawater desalination plant
SWRO	Seawater Reverse Osmosis
SX	Solvent extraction
TDS	Total Dissolved Solids
UBC	Ultra Brine Concentration
UHP	Ultra-high pressure
ZLD	Zero Liquid Discharge

4 General aspects and description of brine valorisation from sea water desalination plants

4.1 General aspects, goal and scope of brine valorisation from SWDP

4.1.1 Goal of brine valorisation

The primary goal of brine valorisation is to extract specific minerals or elements dissolved in the brine. The brine may be from seawater desalination plants, other surface water, groundwater, or hyper-saline solutions from several industries (for example, textile industries or saltworks).

4.1.2 Difference between sea mining and brine valorisation from SWDP

In contrast to this sea mining, also known as deep-sea mining, refers to the extraction of minerals and resources from the seabed. Sea mining process involves accessing mineral deposits located on the ocean floor. Accordingly, these are two different extraction methods that should not be confused with each other.

4.1.3 Guidelines for distinguishing between brine valorisation unit and desalination plant

Desalination is the process of removing salt and other minerals and metals from seawater or brackish water to produce freshwater suitable for human consumption, irrigation or for utilizing it in industrial processes.

Desalination and brine valorisation from SWDP are two separate processes, but they are related in terms of the management of seawater resources and the extraction of valuable minerals. Some desalination plants may produce concentrated brine as a byproduct. This brine can potentially be used for brine valorisation to extract valuable minerals and metals, thereby providing an additional revenue stream and reducing environmental impact. Brine valorisation operations may require freshwater for processing or other purposes. In areas where freshwater is scarce, desalination plants could provide in addition to the brine a source of freshwater for brine valorisation operations. Brine valorisation begins, where the brine serves as the input stream to the brine valorisation unit.

4.1.4 Ownership of brines from SWDP

There are different types of ownership of brines from SWDP, such as:

- public ownership: in many countries, natural resources such as brines from SWDP are considered the property of the state or government. This means that the government holds ownership rights over brines found within its territorial waters or on public lands. The government may grant licenses or permits to companies or individuals for the extraction of minerals and metals from these brines, often under specific regulations and conditions;

- private ownership: in some cases, brines from SWDP may be owned by private individuals or companies, particularly if they are found on privately owned land or if mineral rights have been acquired through legal means. Private ownership of brines from SWDP may come with the right to extract minerals and metals from the brine and profit from their sale, subject to relevant laws and regulations;
- common ownership: in certain situations, brines from SWDP may be considered a common resource, meaning that they are owned collectively by the public or by specific communities. In such cases, the use and management of brines may be governed by customary laws, traditional practices, or community agreements;
- international waters: brines from SWDP found in international waters, beyond the jurisdiction of any single country, may be subject to international agreements and regulations governing the exploitation of marine resources. Ownership and rights to exploit such resources are often determined through international treaties and conventions.

4.2 Drivers for brine valorisation from SWDP

4.2.1 Motivation and benefits of brine valorisation from SWDP

4.2.1.1 Environmental aspects of brine discharge

Desalination generates a reject water with a higher concentration of salts than the original seawater, which is generally released into the sea. However, various scientific evidence shows that by taking the appropriate logistical and technological measures, complete dilution of the discharge is achieved within a few metres of the discharge, without significantly affecting the surrounding organisms and ecosystem (see Bibliography).

Unlike traditional mining operations that require extensive land clearing and excavation, brine valorisation from SWDP typically involves minimal land surface disturbance. This can lead to reduced habitat destruction and ecosystem rupture compared to land-based mining activities. So, the extraction of valuable minerals and metals from brines, which are byproducts, that is the utilization of these brines, reduces the need for further extraction of minerals and metals from terrestrial sources, which can help preserve land-based ecosystems.

Brine valorisation from SWDP often occurs in regions where freshwater resources are limited. By using saline water sources, it reduces the demand for freshwater in industrial processes, such as mineral extraction, thereby conserving precious freshwater resources for other uses like agriculture and drinking water.

Some brine valorisation operations may utilize renewable energy sources, such as solar or wind power, to run their operations. This can help reducing environmental impact such as greenhouse gas emissions and dependence on fossil fuels, contributing to efforts to mitigate climate change.

4.2.1.2 Diversification of raw material supply

Brine valorisation from SWDP provides access to minerals and metals that may not be readily available through traditional land-based mining methods. For example, brines can contain valuable minerals and metals such as lithium, potassium, magnesium, and various halogens like bromine and iodine, which may not be abundant in terrestrial ore deposits.

Brine valorisation from SWDP offers an alternative source of critical minerals and metals that are essential for various industries, including renewable energy, electronics manufacturing, and pharmaceuticals. By tapping into brine resources, countries can reduce their dependence on traditional mining sources and enhance their resilience to supply chain disruptions.

Seawater desalination plants producing brines are often found in different geographic regions compared to traditional mineral and metal deposits. This geographic diversity helps diversify the sources of raw materials, reducing the risk of supply disruptions due to geopolitical factors, natural disasters, or other unforeseen events.

4.2.1.3 Economical aspects and new business opportunities of SWDP

Brine from SWDP contains valuable minerals and metals such as lithium, potassium, magnesium, and rare earth elements. Recovering these minerals and metals from brine produced at SWDP presents an opportunity for businesses to tap into new sources of raw materials for various industries, including battery manufacturing, electronics, and renewable energy.

Developing efficient and environmentally sustainable methods for brine valorisation from SWDP requires technological innovation. Businesses involved in research and development of brine extraction technologies, such as advanced filtration systems or selective ion-exchange processes, can capitalize on the demand for more efficient and cost-effective mining techniques.

Brine valorisation from SWDP requires infrastructure such as pipelines, and processing facilities. Businesses involved in the design, construction, and maintenance of these infrastructure projects can benefit from the demand for new infrastructure to support brine valorisation operations.

Businesses offering regulatory compliance services, environmental impact assessments, and consulting expertise in navigating the regulatory landscape can find new opportunities in supporting projects for brine valorisation from SWDP.

4.2.1.4 Social impact, acceptance of brine valorisation from SWDP and incentives for governance

The acceptance of brine valorisation from SWDP often depends on how well the brine valorisation companies or entities engage with local communities. Effective communication, transparency, and consultation with stakeholders can help address concerns, build trust, and foster acceptance of the valorisation project.

Brine valorisation projects can provide employment opportunities for local residents, including jobs in brine valorisation operations, infrastructure development, and support services. The creation of job opportunities can have positive social impacts.

Brine valorisation could cause environmental impact, and therefore a robust environmental management practices should be applied.

Brine valorisation projects present an opportunity to collaborate with local communities by respecting areas of cultural significance, such as sacred sites, archaeological sites, and traditional fishing grounds. Prioritizing the protection of cultural heritage helps foster social acceptance and strengthens positive relationships with communities.

4.3 Fundamental prerequisites for brine valorisation from SWDP

4.3.1 Minimum criteria to engage in brine valorisation

The brine shall contain a sufficiently high concentration of valuable minerals and metals to justify the cost of extraction and processing. The presence or the recovery of minerals and metals such as lithium, potassium, magnesium, or rare earth elements in the brine in economically significant quantities is essential for the viability of brine valorisation operations.

The cost of extracting minerals and metals from the brine shall be economically feasible, taking into account factors such as extraction technology, processing methods, energy costs, labour costs, and market prices for the extracted minerals and metals. The projected revenue from mineral and metals sales should exceed the costs of brine valorisation and processing to ensure profitability.

Access to necessary infrastructure, such as transportation networks, water supply, energy sources, and processing facilities, is crucial for brine valorisation operations. The availability of infrastructure can significantly impact the feasibility and cost-effectiveness of brine valorisation projects.

Compliance with regulatory requirements and permitting processes is essential for brine valorisation projects to proceed legally and responsibly. Brine valorisation companies shall obtain the necessary permits, licenses, and approvals from regulatory authorities and adhere to environmental, health, safety, and social standards.

Brine valorisation operations shall mitigate potential environmental impacts, such as habitat disruption, water pollution, and ecosystem degradation. Implementing environmental management practices, mitigation measures, and monitoring programs is essential for minimizing environmental risks and ensuring sustainable operations.

There should be sufficient market demand for the extracted minerals and metals to justify investment in brine valorisation projects. Understanding market dynamics, trends, and potential customers for the extracted minerals and metals is crucial for assessing the economic viability of brine valorisation operations.

Brine valorisation companies shall conduct comprehensive risk assessments to identify and manage potential risks and uncertainties associated with brine valorisation projects. Factors such as geological uncertainties, market volatility, regulatory changes, and social acceptance shall be considered in assessing project viability.

4.3.2 Additional factors for brine valorisation from SWDP

Reducing the overall cost of desalination through energy-efficient processes and the integration of renewable energy sources can enhance the economics of brine valorisation. Additionally, developing integrated resource recovery systems that combine desalination with mineral and metal extraction, wastewater treatment, and resource recovery, while leveraging high market demand and favourable commodity prices for minerals and metals like lithium, magnesium, potassium, and rare earth elements, can increase the attractiveness of brine valorisation. Factors that should be considered include regulatory support and incentives for sustainable practices, addressing environmental concerns related to brine disposal, and ongoing research and development. Scalability and modular systems that can be adapted to various desalination plants, public-private partnerships for shared investments, and the engagement of local communities and stakeholders are essential for ensuring social acceptance and support.

4.3.3 Recommendations on dealing with low concentration of elements to be recovered

Dealing with the low concentration of elements in brines from SWDP requires innovative and efficient strategies to make the extraction process economically viable. Recommendations include implementing pre-concentration techniques like evaporation ponds or multiple-effect distillation (MED) and using membrane distillation to enhance brine concentration. Selective extraction methods such as ion exchange resins, electrodialysis, reactive crystallization and solvent extraction can target specific ions. Advanced adsorbents, including nanomaterials and functionalized adsorbents, improve extraction efficiency. Combining technologies in hybrid systems and designing multi-stage processes can enhance overall recovery rates. Conducting market analysis and collaborating with other industries can improve economic feasibility, while advanced monitoring and control systems optimize processes.

4.3.4 Necessary infrastructure for the installation of brine valorisation units

Here are the different types of infrastructure required for the installation of brine mining valorisation units:

- pumping stations: lift brine to the surface;
- transportation: pipelines move brine to processing facilities;
- location or space for the facility: sufficient space to set up the equipment, with an enclosure if necessary. Civil Works is required at the location;
- processing facilities: various methods extract minerals and metals, including evaporation ponds, reactive precipitation, membrane treatment, ion exchange, crystallization, and electrolysis;
- storage: minerals and metals are stored before further processing or transport;
- transport infrastructure: trucks, trains, or ships may transport minerals and metals to other locations;
- monitoring and control: continuous oversight ensures efficiency, quality, and regulatory compliance;
- utilities: supply with energy (including renewable energy), water, roads, gas, safety.

5 Description and explanation of core process steps of brine valorisation from SWDP

5.1 General

This clause has as the objective to provide guidance and recommendations on best practices for the processing of brines from SWDP to recover minerals & metals (M&M). There is a variety of technologies available for recovering M&M from brines for different purposes. The technologies considered include state-of-the-art as well as novel techniques developed during S4V for the selective extraction of target elements. The selection of the specific technology depends on the minerals and metals targeted.

Regardless of the technologies used for brine treatment, four stages can be identified: brine pre-treatment, concentration, compound recovery and purification. The following technologies are some examples of potential viable technologies separated by stages with focus on critical raw materials (CRM).

Table 2 — Four stages of brine treatment with viable technologies by stages with focus on CRM

Stage number	Stage name	Technologies
Stage 1	Brine pre-treatment	Nanofiltration (NF) Softening: calcium removal/ recovery step
Stage 2	Brine concentration	Thermal evaporation systems Advanced evaporation with corrosion-resistant and cost-effective polymer-based construction materials Osmotically assisted reverse osmosis (OARO) Low-salt-rejection reverse osmosis (LSRRO) Membrane distillation (MD) Electrodialysis reversal (EDR) Forward osmosis (FO) Membrane crystallisation (MD/ FO)
Stage 3	Compound recovery	Crystallization of Brines (evaporation ponds; reactive; thermal; freeze; solvent; membrane (MD/ FO)) Electrodialysis with bipolar membranes (BPED)
Stage 4	Compound purification	Mechanical separation Washing (Controlled) crystallization Leaching Recrystallization Ion exchanges Chemical treatment

There are two different approaches and process schemes for target element extraction from seawater:

- starting from seawater;
- starting from brine from SWDP.

Independently of the approaches selected, there are certain process steps that need to be followed in to efficiently concentrate the mentioned streams. Figure 2 shows a conceptual design for brine valorisation and recovery of CRM.

5.2 Possible treatment pathways

After producing a brine stream in the desalination stage, a pre-treatment stage should be carried with a first calcium removal/recovery step due to the high scaling nature of Ca salts. Once the brine is free of calcium one of two routes should be followed, where the calcium-free brine goes through:

- a concentration stage from 58 — 70 g/L TDS to 233 g/L TDS;
- a nanofiltration stage to produce two streams, a permeate stream rich mainly in monovalent ions and a reject stream where with mainly mono and multivalent ions. Subsequently, the permeate stream can be concentrated from 58 — 70 g/L TDS to 233 g/L TDS allowing for a more selective recovery of compounds compared to the previous solution.

Figure 2 depicts the conventional desalination of seawater with a basic pretreatment followed by a reverse osmosis step. For brine valorisation purposes, the reverse osmosis brine should be further treated by removing its scaling potential by removing Ca content, which forms low solubility salts and would be detrimental for the process. In locations where cheap land is available and the weather conditions allow for the functioning of evaporative basins, the calcium softening, and concentration steps can be accomplished at once into saltworks ponds, along with NaCl crystallization. In some cases, magnesium minerals can also be produced in the ponds.

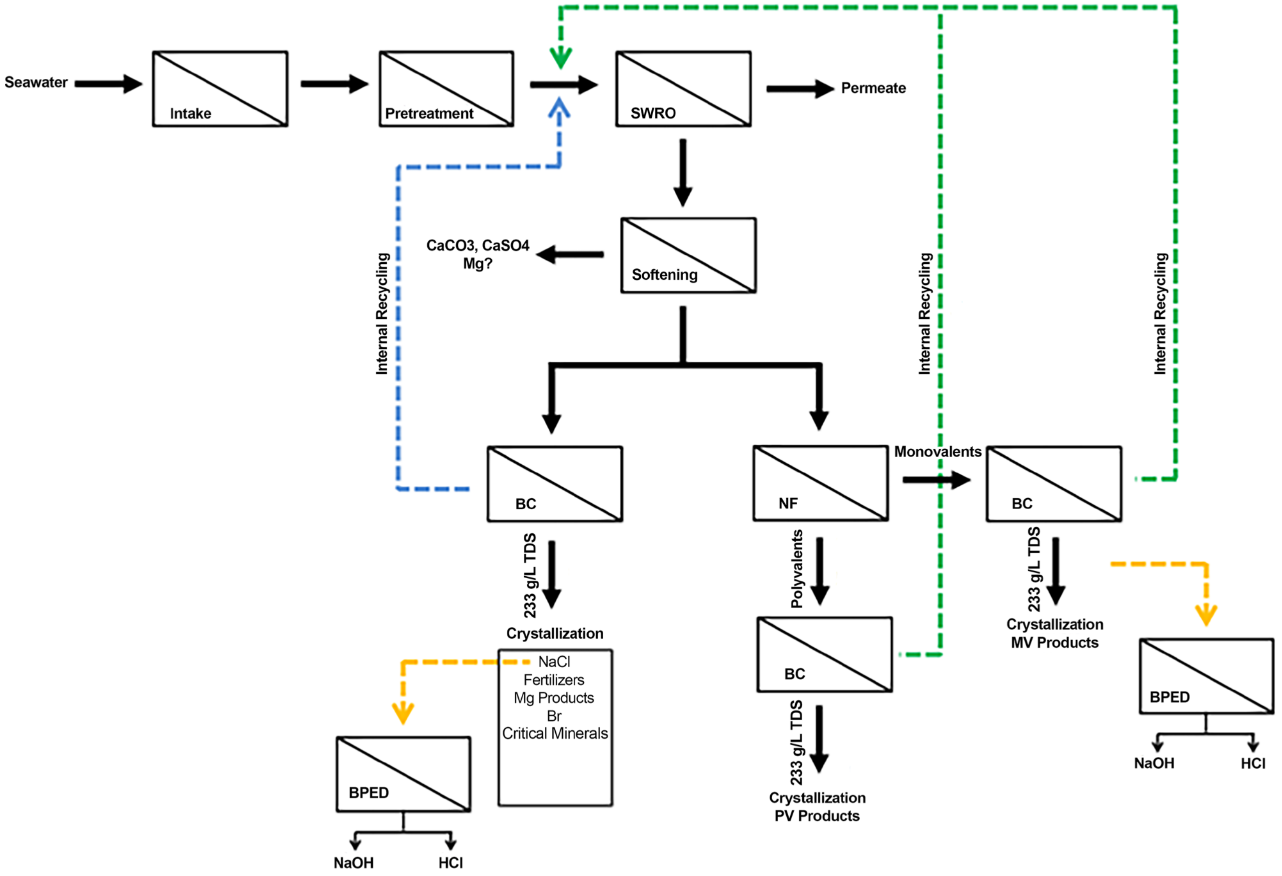

Figure 2 — Process scheme for brine valorisation with two optional flow paths after the softening step: (a) brine concentration (BC) and fractional crystallization (state-of-the-art at industrial scale); (b) nanofiltration (NF), brine concentration, extraction and purification steps for targeted minerals and metals at low concentrations.

5.3 Core process steps of brine valorisation

The desalination processes produce brine, which serves as an input for the brine valorisation facility. During brine valorisation treatment processes for the recovery of CRM, these comprise a sequence of treatment operations needed. The following list is the description of the core process steps:

- softening process: the brine produced by the SWRO can be separated using a softening process (that can consist of Nanofiltration (NF) membranes), with the objective of separating a divalent ions stream from a monovalent ions stream. Depending on which parameter needs to be optimized (OPEX or CAPEX), the softening process can be placed before the SWRO or after the SWRO (as shown in Figure 2);

- concentration process: this could be done using OARO or LSRRO membranes, so that brine salinity can be increased from 8% to 12% during the brine concentration step, and from 12% to 22% during the ultra brine concentration step;

- crystallization: the high salinity streams (that is, 22% TDS) can be fed directly to the crystallizer. The calcium softening by crystallization of carbonates and sulphates and the concentration steps can be accomplished at once into the crystallization step, along with NaCl crystallization. In some cases, magnesium minerals can also be produced in the ponds. In addition, crystallization can include reactive crystallization of selected minerals (for example, magnesium hydroxide);
- separation: brine streams can be separated using different mechanical or chemical approaches;
- solids extraction: this is where species can be separated in a solid form. Examples include filter presses or centrifuges;
- purification, post-treatment methods.

Figure 3 shows a brine treatment scheme including the S4V concept. In this scenario, after the brine treatment concentration and separation steps, three product lines can be obtained: 1) CRM metals, 2) fertilizers after crystallization and 3) chemicals (that is, NaOH and HCl) production by EDBM technique.

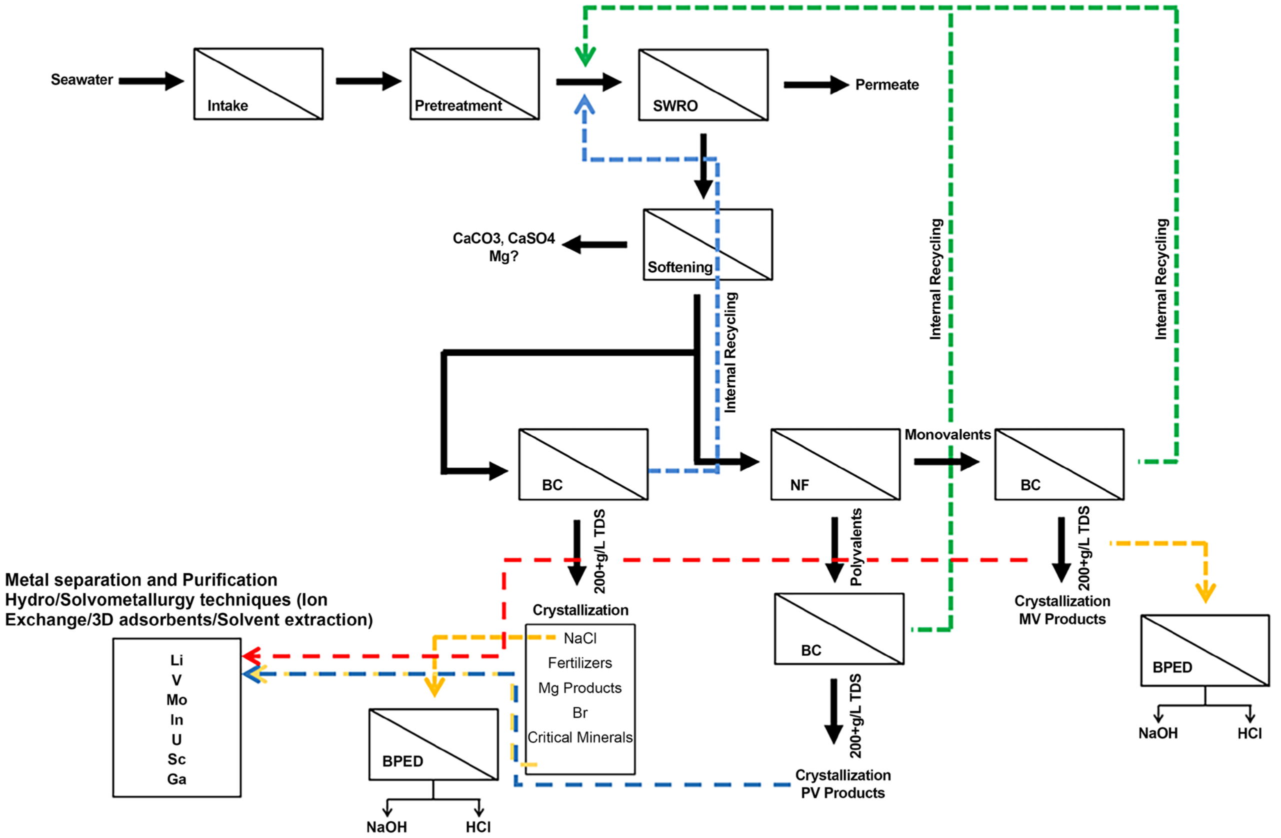

Figure 3 — Concept design of process flow for the concentration of brine streams deriving from the desalination of seawater and the incorporation of innovative techniques for CRM recovery (Sea4Value project concept)

5.4 Brine treatment stages

5.4.1 Early considerations during brine valorisation

The elemental analysis of brine, including its constituent species, pH, and conductivity, enables the determination of the most precise techniques for metal separation and purification.

The following steps shall be undertaken to ensure an in-depth knowledge of the brine matrix characteristics and handling requirements:

a) determine the brine analysis and composition;

   1) determine the physico-chemical characteristics (for example, pH, temperature, conductivity, total dissolved solids, chemical composition, specific species);

   2) consider other parameters such as sampling and pretreatment of the samples for the analysis;

b) define the quality parameters of a brine;

   1) determine the handling of the brine (storage, piping) and safe handling;

   2) determine which targeted salts and minerals to recover, which generally include NaCl, Mg salts ($MgCl_2$ Mg(OH)2 $MgSO_4$), KCl, Na_2SO_4, K_2SO_4, lithium, bromine, boron, iodine, trace minerals (including iron, manganese, zinc, and copper).

Other operational factors shall also be considered early in the process of brine treatment, such as:

- cleaning procedures: identify the proper ways of cleaning procedures for making easier applications of brine valorisation (use of antiscalants);
- procedures to avoid scaling problems.

To quantify the extraction efficiency of a specific technique, extraction efficiency should be calculated.: this metric quantifies the percentage of target metal successfully recovered from the brine. It is calculated as the ratio of recovered metal to the initial metal content in the brine:

$$\text{Extraction efficiency [\%]} = \frac{Recovered\ Metal(g)}{Initial\ metal\,content\ \ in\ brine(g)} \times 100$$

Other parameters could be quantified depending on the specific process, such as metal purity, solvent losses, energy consumption per unit of metal recovered, and operational costs might be relevant.

Other key considerations involve:

- salt composition: with calcium removed, attention shifts to other valuable salts and minerals present in the brine;
- recovery methods: various methods such as precipitation, crystallization, and ion exchange can be employed depending on the specific salt or mineral targeted;
- market demand: recovery depends on demand and market value for specific salts and minerals;
- environmental impact: proper management of residual brine and by-products is crucial to minimize environmental consequences.

5.4.2 Guidelines for the brine pre-treatment: softening and separation of brines from SWDP prior recovery of CRM

5.4.2.1 General

Brine pretreatment should be considered to ensure an optimum performance of the subsequent processing steps. In general, pretreatments should be used to increase metal and mineral concentration in brines during brine valorisation, while minimizing the loss of valuable minerals and metals. This can be achieved through a combination of techniques that:

— liberate target metals and minerals from their host matrix;

— remove impurities and contaminants;

— enhance the efficiency of subsequent processing steps.

A softening step is key. When it comes to Ca removal, it could be preferred to precipitate it as $CaCO_3$ to ensure that sulphates are available for the formation of fertilizers. In addition, each treatment step will be suited with an internal recycling stream that can help reducing the system size. Ultimately, side streams can be treated with Bipolar ED to produce chemicals to be used onsite. Finally, the recovery of Salts & Minerals using Crystallization can also be beneficial.

5.4.2.2 Pretreatment of SWRO Brines: Methods for softening

5.4.2.2.1 Calcium removal or recovery

Calcium removal and recovery should be included as a step in brine treatment to prevent precipitation and formation of scaling in the subsequent treatment stages.

Removing the calcium from the brine as a pretreatment for the following steps or for recovering it into a valuable product can be done in several ways, such as:

a) chemical precipitation:

   1) lime softening: lime ($Ca(OH)_2$) is added to precipitate calcium as $CaCO_3$. The pH adjusts, settling is allowed and finally filtration follows;

   2) soda ash softening: sodium carbonate (Na_2CO_3) is used to precipitate calcium as $CaCO_3$;

   3) calcium sulphate precipitation: either sulfuric acid (H_2SO_4) or sodium sulphate (Na_2SO_4) is added to precipitate calcium as $CaSO_4$. The formed precipitate is removed via sedimentation or filtration.

b) ion exchange:

   1) cation exchange resins: brine is passed through resins that exchange Ca^{2+} for Na^+ or H^+ ions. The resin can be regenerated periodically with acid or salt solution;

   2) softening filters: ion-exchange materials such as zeolites or similar materials in filters are used to remove calcium.

c) membrane processes:

   1) nanofiltration (NF): NF membranes reject divalent ions like calcium, reducing its concentration in the permeate stream;

   2) electrodialysis (ED): ion-selective membranes and an electric field are used to separate calcium ions;

   3) secondary RO system: a second RO stage with calcium-rejecting membranes. This is also referred as a selective NF stage.

d) electrochemical processes:

   1) electrocoagulation: during electrocoagulation, hydroxyl ions are electrochemically generated through water splitting at the cathode, precipitating calcium as calcium carbonate ($CaCO_3$).

e) saturation by concentration:

   1) calcium can be separated in the form of carbonates and sulphates in saltworks ponds.

5.4.2.2.2 Practical considerations with calcium removal or recovery

There are some practical considerations that should be considered when precipitating calcium, although combining methods may be necessary to achieve the desired calcium removal:

— initial calcium concentration: higher levels of calcium may need more intensive treatment;

— final use of brine determines the appropriate method;

— cost and efficiency: balance between cost and removal efficiency;

— environmental impact: consider the environmental effects of the chosen methods.

5.4.2.2.3 Magnesium removal or recovery

Magnesium (Mg) removal and recovery should be included as a step in brine treatment to prevent precipitation and formation of scaling in the subsequent treatment stages. Magnesium can also be precipitated out as magnesium hydroxide ($Mg(OH)_2$) through chemical precipitation. This process involves:

a) chemical addition: adding a chemical reagent, such as lime ($Ca(OH)_2$) or sodium hydroxide (NaOH), to the brine;

b) reaction: the added chemical reacts with magnesium ions (Mg^{2+}) in the brine to form insoluble magnesium hydroxide: Mg2++2OH−→Mg(OH)2Mg2++2OH−→Mg(OH)2

c) precipitation: magnesium hydroxide precipitates out of the solution and can be removed through settling, filtration, or centrifugation membrane processes:

   1) nanofiltration (NF): NF membranes reject divalent ions like magnesium, reducing its concentration in the permeate stream;

   2) electrodialysis (ED): ion-selective membranes and an electric field are used to separate magnesium ions;

   3) secondary RO system: employ a second RO stage with magnesium-rejecting membranes. This is also referred as a selective NF stage.

Some of the advantages of magnesium precipitation are:

— effective removal of magnesium from the brine, which could facilitate the recovery of magnesium;

— may simplify downstream processes by reducing magnesium content in the brine;

— utilizes common chemicals and relatively simple process steps.

However, some considerations should be taken into account during magnesium precipitation:

— pH control: proper pH adjustment is necessary for efficient precipitation;

— impurity formation: care shall be taken to prevent the formation of unwanted by-products;

— efficiency: the efficiency of magnesium precipitation may vary depending on factors such as brine composition and temperature.

By incorporating magnesium precipitation as an additional option for brine softening, operators can choose the most suitable method based on factors such as cost, efficiency, and downstream processing requirements.

Pretreatment of SWRO brines: separation methods

During the pretreatment of brine for valorisation purposes, separation of monovalent from multivalent ions is a potential option. This is mostly accomplished by membrane separation such as nanofiltration (NF). Target specific salts and minerals can be extracted from the resulting streams, mostly purified monovalent and polyvalent streams, by means of crystallization or other options such as solvent ion extraction.

The different membrane separation methods are listed below:

— nanofiltration (NF): NF membranes separate multivalent from monovalent ions generating a concentrated ion-rich that can be further treated. This is also referred as a selective NF stage or secondary RO system;

— electrodialysis (ED): ion-selective membranes and an electric field are used to separate calcium ions.

5.4.3 Guidelines for the SWDP brines concentration

After the softening and separation processing steps, there are two possible treatment routes for further valorising the brines. One is to concentrate the brine stream using a brine concentrator and mainly removing water. Brine concentrators reduce the volume of brine from desalination and industrial processes. Examples of different types of brine concentrators, which selection depends on several factors, include:

a) Thermal concentrators/crystallizers:

   1) mechanical vapor compression (MVC) evaporators: although energy efficient, it requires the use of electricity;

   2) multi effect evaporation (MEE): although energy efficient, it needs a heat source;

   3) saltworks ponds: viable where saltworks already exist or when cheap land is available, and weather conditions allow for it.

Due to the high chloride content and the elevated temperatures in the evaporator/crystallizer the brine is very corrosive. A proper selection of the construction materials of the thermal brine concentrators and crystallizers is of utmost importance to avoid corrosion, related maintenance costs and reduced lifetime. Highly corrosion-resistant metals, for example, stainless steel 316L, duplex, super duplex or hyper duplex stainless steels, titanium and nickel-based alloys, can be used. Advanced corrosion-resistant materials should be considered, such as polymer composite tubes with enhanced thermal conductivity for the heat transfer surface and fibre-reinforced resins for the shell, tube plates and other evaporator/crystallizer parts:

a) thermal crystallizer feed optimal concentration[1] :

1) the optimal concentration of a thermal crystallizer feed depends on various factors such as the solubility of the salts present in the feed, the desired crystal size and purity, and the specific operating conditions of the crystallization process;

i. the concentration of the feed solution should be slightly below the saturation point to promote nucleation and crystal growth. However, it should not be too dilute to minimize energy consumption and maximize throughput;

ii. in general, concentrations around 200-250 g/L are commonly used in industrial crystallization processes, but the exact value may vary depending on the specific requirements of the application;

2) the design of a crystallizer shall reduce or eliminate all feed chemical components that can affect the operation by generating scaling or implying the use of high-quality construction materials to avoid corrosion.

EXAMPLE If there is a significant amount of alkalinity in the feed which could cause calcium carbonate scaling problems once the brine is concentrated in the evaporators, the design may include a decarbonation step by adding sulphuric acid (carbonate to CO_2 at acid pH), CO_2 deaeration before the evaporator and pH adjustment with NaOH once the carbonate has been removed.

b) membrane-based concentrators:

1) reverse osmosis (RO): reverse osmosis is a technology that is based on using a semi-permeable membrane to selectively separate a solute from a solvent. In water treatment applications, the solvent is typically water, and the solutes are typically dissolved ions, including sometimes some total organic carbon (TOC). Reverse osmosis can be used to also remove micro-pollutants from water, and it is widely used to obtain desalinated water, as the most effective technology, from a capital and operating cost perspective. Reverse osmosis membranes elements tend to be standardized in the industry. They are typically referred as 8-inch elements, which means they are spiral-wound membranes in a cylindric shape, which have 8-inch diameter, and 40-inch wide. They have a feed side, and a permeate and reject or concentrate side. The feed side is where the water to be treated is fed into the membrane. The permeate side is the purified water, which has a lower salinity than the water treated. The concentrate side is where the water with higher salinity concentration is produced. Depending on the application of RO technologies, one can be interested into purifying water (the permeate side of the membrane), or into concentrating salts (the concentrate part of the membrane). Typically, reverse osmosis technologies can be divided into the different categories listed below, depending on the salinity they treat:

i. brackish water reverse osmosis (BWRO): these membranes are 8-inch spiral-wound membranes elements, which usually treat river water-like water types (also called brackish water), which tend to have a salinity below seawater salinity (around 3,5-4% salinity). These membranes are used to concentrate salts up to 4% salinities;

ii. seawater reverse osmosis (SWRO): these membranes are 8-inch spiral-wound membranes elements, which usually treat river seawater-like water types, which tend to have a seawater

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[1] While the Mediterranean Sea area is rich in active saltworks that can host a circular economy symbiosis between desalination and salt production, many European countries often lack the climate conditions or necessary land availability to apply the evaporation ponds option for the recovery of salts and minerals from brines. In these instances, thermal crystallization sshould be used.

    like salinity (above 3,5-4% salinity). These membranes are used to concentrate salts from 4% salinity up to 8% salinity;

    iii. ultra high pressure RO (UHPRO): UHPRO is an advanced desalination technology that operates at significantly higher pressures than conventional reverse osmosis systems, often exceeding 100 bar. This process effectively separates water from dissolved salts and contaminants by forcing brine through a semi-permeable membrane, resulting in highly concentrated brine and purified water. UHPRO is particularly effective for treating high-salinity brines, as the increased pressure enhances the permeate flux and improves salt rejection rates. By achieving brine concentrations greater than 200 g/L, UHPRO not only reduces the volume of waste but also facilitates the recovery of valuable minerals. The technology is characterized by its energy efficiency and potential for resource recovery, making it a promising option for various applications, including industrial wastewater treatment and saline water management;

2) forward osmosis (FO): FO is a water treatment process that uses a semi-permeable membrane to draw water from a dilute solution, such as brine, into a concentrated solution known as the draw solution. By leveraging osmotic pressure differences, water moves across the membrane while leaving salts and impurities behind in the brine, effectively concentrating it. FO can achieve concentrations of around 100 to 200 g/L for brines, depending on the specific draw solution used and operational conditions. This concentration reduction makes the brine more manageable for disposal or further treatment. Additionally, FO typically requires less energy than traditional desalination methods, making it an attractive option for concentrating brines in various applications, including wastewater treatment and resource recovery;

3) osmotically assisted RO (OARO): OARO is a hybrid water treatment process that combines elements of forward osmosis and reverse osmosis to enhance the concentration of brines. In OARO, a dilute feed solution, such as brine, is first drawn through a semi-permeable membrane into a more concentrated draw solution, which creates an osmotic pressure gradient. This initial step allows for a significant volume reduction of the brine. Subsequently, the concentrated solution is processed through reverse osmosis, where additional water is removed, resulting in even higher concentration levels. OARO can achieve brine concentrations exceeding 200 g/L, depending on the operational conditions and specific draw solutions used. This method not only improves the efficiency of brine management but also reduces energy consumption compared to conventional desalination techniques;

4) low salt rejecting reverse osmosis (LSRRO): LSRRO uses loose, or open RO membranes. The goal of this process is to have a standard RO membrane that provides a permeate with high salinity. As the permeate has a high salinity, the difference between the permeate salinity, compared to the salinity in the feed-concentrate channel is reduced. This has the consequence of reducing the osmotic pressure of the membrane. This enables operating at a pressure below 80 bar, where no ultra-high pressure (UHP) equipment is required. This process enables to concentrate salts up to 22% salinity. Sometimes this process is also called “de-watering” process, as water is removed from the brine as it gets concentrated;

5) electrodialysis reversal (EDR): EDR is an electrochemical process used to desalinate water and concentrate brines by utilizing ion-exchange membranes and an applied electric field. In EDR, alternating stacks of cation and anion exchange membranes create separate flow paths for positively and negatively charged ions. When an electric current is applied, cations migrate toward the negatively charged electrode, while anions move toward the positively charged electrode. This movement allows for the selective removal of salts from the feed solution, resulting in a concentrated brine stream. EDR can effectively reach concentrations of around 100 to 200 g/L, depending on the feed composition and operating conditions. The process is

advantageous for its lower energy consumption and ability to handle fluctuating salinity levels, making it a suitable option for brine concentration and resource recovery in various applications;

6) membrane distillation (MD): MD is a thermally driven separation process that uses hydrophobic membranes to separate water vapor from liquid solutions, such as brines. In MD, a temperature difference is created across the membrane, causing water to evaporate from the warmer side (the feed solution) and condense on the cooler side (the permeate side). The membrane allows only water vapor to pass through while rejecting salts and other contaminants, resulting in a concentrated brine on the feed side. MD can achieve high concentrations, often exceeding 200 g/L, depending on the feed temperature and other operational conditions. This technology is particularly advantageous for its ability to operate at low temperatures and pressures, making it energy-efficient and suitable for a variety of applications, including wastewater treatment and resource recovery from brines;

7) photothermal membrane distillation for seawater desalination is an improved type of MD, studied during the Sea4Value project concept development.

The selection of the appropriate technology for treating brine streams depend on several key factors:

- brine characteristics: the salinity and composition of the brine shall be assessed for effective treatment;
- energy availability: the availability of energy sources—such as heat, electricity, or osmotic draw solutions—shall be assessed for process efficiency;
- scale and capacity: the project size and the volume of brine requiring treatment influences the choice of technology;
- cost considerations: a thorough evaluation of both initial capital expenditures (CAPEX) and ongoing operational expenses (OPEX) shall be undertaken;
- integration: the compatibility of the chosen technology with existing infrastructure shall be taken into account to ensure seamless implementation;
- by carefully considering these factors, project planners can identify the most suitable brine concentration technology for their specific needs.

5.4.4 Guidelines for the recovery and purification of salts, minerals and metals with concentrated brines

5.4.4.1 General considerations

The recovery and purification of salts, minerals and metals from the concentrated brine with brine valorisation can be done by different treatment techniques. Additionally, the specific purification methods selected depends on the recovered metal and its intended use. Here are some general options:

- SX/NDSX/IX may be employed for additional purification after initial M&M recovery;
- crystallization or recrystallization can enhance the purity of recovered metal salts;
- electrorefining purifies the metal using electrolysis and is applicable for certain metals;

5.4.4.2 Fractional thermal crystallization

5.4.4.2.1 General

Fractional crystallization is a process used to recover salts and minerals from concentrated seawater brine by exploiting the differences in solubility of various salts at different temperatures. Fractional crystallization is an effective method for recovering valuable salts and minerals from concentrated seawater brine, but it requires careful control and optimization to achieve the desired results efficiently and sustainably. The process is typically made up of the following steps:

a) step 1 is pre-concentration: seawater is first desalinated through a process like reverse osmosis (RO) to produce a concentrated brine with a high salt content;

b) step 2 is heat exchange: the concentrated brine is heated using waste heat or other energy sources. As the temperature increases, the solubility of salts in the brine decreases;

c) step 3 is nucleation and crystal formation: industrial crystallization involves the formation of solid crystals from a supersaturated solution or melt. Nucleation should be considered in this process, as it determines the initial formation of crystal nuclei, which then grow into larger crystals. There are two main types of nucleation in industrial crystallization:

    1) primary nucleation occurs in the absence of existing crystals;

    2) secondary nucleation occurs in the presence of existing crystals (parent crystals) of the same material.

d) step 4 is fractional crystallization:

    1) as the crystals form, they are separated from the remaining liquid using filtration or settling;

    2) the remaining liquid, or mother liquor, is further concentrated by removing water through evaporation or other means;

    3) the process is repeated in multiple stages, each with different temperature and concentration conditions;

    4) by adjusting the temperature and concentration conditions in each stage, different salts can be selectively crystallized and recovered;

    5) the crystals harvested from each stage contain a mixture of salts and minerals;

    6) these crystals can be further processed to separate and purify individual salts through methods like washing, dissolution, and recrystallization;

    7) the recovered salts can be used in various industrial applications, such as chemical manufacturing, agriculture, or road de-icing.

The brine recovered after the separation of the crystals is called Mother Liquor (ML) and is returned to the crystallizer. If the ML contains any impurities that could damage the equipment or affect the quality of the product, a purge shall be provided to regulate these quantities and, therefore, to obtain high purity crystals:

— crystals quality: there are standards for the quality of the crystals depending on the market and application. For example, table salt shall have a minimum content of sodium chloride of 97% on a dry basis, with a limited number of impurities and a specific granulometry to be marketed. This may vary according to specific customer requirements;

- temperature control: precise control of temperature shall be considered to selectively crystallize desired salts;
- solubility differences: the solubility of various salts at different temperatures shall be accounted to optimise the process;
- energy efficiency: utilizing waste heat or other energy sources can enhance the efficiency of the process.

During fractional crystallization, several key operational factors shall be carefully managed to optimize the recovery of salts from brines:

- counterflows: counterflow techniques shall be implemented to enhance mass transfer and improve the efficiency of the crystallization process. By directing the flow of the feed solution in the opposite direction to the flow of the crystallized solids, it maximizes contact time and allows for better heat and mass transfer. This configuration helps in achieving a higher purity of the crystallized salts and reducing the impurities that may co-crystallize with the desired salts;
- purging: the crystallization system shall be regularly purged to maintain optimal operating conditions and prevent the buildup of impurities. Purging involves the removal of a portion of the crystallization slurry, which can help to eliminate undesired salts and improve the overall quality of the crystallized product. It also aids in controlling the concentration of the brine, ensuring that supersaturation levels remain conducive to effective crystallization. Careful management of purging rates contributes to the balance of recovery and purity;
- temperature control: precise temperature control shall be maintained throughout the crystallization process. Variations in temperature can affect solubility and the rate of crystallization, leading to inconsistent product quality;
- nucleation control: the rate of nucleation can significantly impact the size and purity of the crystals formed. Managing factors such as supersaturation and seeding can help optimize the crystallization process, promoting the growth of larger, purer crystals;
- stirring and agitation: proper stirring and agitation shall be undertaken to ensure uniform distribution of temperature and concentration within the crystallization vessel. This promotes even growth of crystals and prevents the formation of agglomerates or fines;
- residence time: the length of time that the brine solution remains in the crystallization system can influence the purity and yield of the salts recovered. Adequate residence time allows for sufficient crystallization while preventing excessive co-precipitation of impurities.

By carefully considering these operational factors, the fractional crystallization process can be optimized, leading to effective salt recovery and improved product quality from brine solutions.

5.4.4.2.2 Unusable salt sidestreams

One common challenge in fraction crystallization is the generation of "unusable salt sidestreams". These sidestreams are typically by-products of the crystallization process that contain salts (often mixed or impure) in concentrations that are not economically or practically useful. They can be a mix of different salts or salts contaminated with impurities, making them difficult to recycle or repurpose. Some of the common salts produced as sidestreams include:

— mixed or low-purity salts: different salts crystallize together or become contaminated with non-target compounds;

— minority salts: salts present in lower concentrations, which crystallize later in the process and don't have significant industrial value;

— impure salts: contamination from other substances or residual solvents can make salts unusable for high-purity applications.

These unusable sidestreams can lead to several issues, such as:

— environmental concerns: disposal of these salts, especially in large quantities, can be harmful to ecosystems, particularly if they end up in water bodies;

— economic losses: if the salts cannot be sold or reused, industries incur additional costs for waste management and disposal.

5.4.4.2.3 Strategies to reduce unusable salt sidestreams

Several approaches should be used to minimize the generation of unusable salt sidestreams during fractional crystallization:

— improved process control: optimization of crystallization conditions: by carefully controlling temperature, pH, and supersaturation levels, it is possible to promote the formation of high-purity target salts and suppress the formation of unwanted salts. For example, cooling rates and solvent composition can be adjusted to selectively crystallize specific salts;

— selective crystallization: using multistage crystallization processes can allow for more precise separation of different salts. By dividing the crystallization process into steps, each salt can be recovered at its optimal crystallization point, reducing cross-contamination;

— use of anti-solvents or additives: certain anti-solvents or crystallization additives can modify the solubility of salts, helping to drive selective crystallization. For instance, adding a compound that reduces the solubility of a specific salt can cause it to crystallize earlier, leaving others in solution for further processing;

— hybrid or multi-stage systems: coupling crystallization with other processes: In some cases, combining fractional crystallization with other separation techniques (e.g., membrane filtration, ion exchange) can help purify streams or extract valuable salts before they become unusable;

— sequential recovery: a multi-stage recovery system can be used to separate and recover different salts at various points in the process. For example, one stage may recover sodium chloride, and a subsequent stage may focus on other salts like magnesium sulphate;

— recycling of sidestreams: in some cases, sidestreams can be recycled back into the process, either by re-dissolving the mixed salts or blending them with fresh feed material. This can help minimize waste and make use of materials that would otherwise be discarded;

- valorisation of sidestreams: developing secondary markets: Finding alternative uses for unusable salt sidestreams can help mitigate disposal issues. For example, some impure salts may be repurposed for industrial uses such as de-icing, water softening, or even as raw materials for chemical processes;
- salt blending: mixing unusable salts with other by-products can create products for niche markets, particularly if the purity requirements for these applications are lower.

In addition, some advanced separation technologies exist, for example:

- membrane distillation and electrodialysis: these technologies can help separate salts in solution before crystallization, reducing the number of salts that end up in unusable sidestreams;
- hybrid crystallization with forward osmosis: integrating newer techniques, like forward osmosis, with traditional crystallization can help concentrate the solution in a more controlled manner, reducing the formation of unusable by-products.

Unusable salt sidestreams from fractional crystallization pose both environmental and economic challenges, but they can be mitigated through improved process control, innovative separation techniques, recycling strategies, and finding alternative uses for by-products. By optimizing the crystallization process and combining it with other separation methods, industries can reduce waste, recover valuable salts, and minimize the environmental impact.

5.4.4.2.4 Saltworks ponds

In saltworks ponds, the process of fractional crystallization explained in the previous subclauses is implemented in a series of consecutive shallow basins. The driving force of the process is the difference in vapor pressure from the ponds to the atmosphere sustained by solar and wind energy.

In the typical layout, the ponds can be grouped in four orders according to the different evaporation stages of the production process, each order being characterized by a well-defined density range:

- evaporation zone I, “cold ponds” or “first-entry ponds”, where seawater or seawater brines are received. Typical density raises up from 1.016 kg/L to 1.025 kg/L;
- evaporation zone II, “driving ponds”, which are fed by the cold ones. The density grows from 1.025 kg/L° to 1.100 kg/L. In addition to the transition metals (usually present as trace elements), carbonates can precipitate;
- evaporation zones III and IV, “hot ponds” or “evaporative ponds”, made by several small and shallow ponds. Carbonates and sulphates of calcium reach the saturation point and precipitate. The water reaches the saturation of halite (1.250 kg/L);
- crystallizers, “crystallizing ponds”, where table-salt crystallizes. They are very shallow (10–25 cm) with very flat floor. By keeping brine density below 30°Bé, Mg salts precipitation is controlled, thus enhancing the quality of the NaCl produced.

5.4.4.3 Solvent extraction

In addition to crystallization and evaporation ponds, solvent extraction is another option for targeted ion extraction from brines. Solvent extraction, also known as liquid-liquid extraction, involves the transfer of ions from one liquid phase (the brine) to another immiscible liquid phase (the solvent: extractant and diluent). Solvent extraction offers a viable option for targeted ion extraction from brines, especially when high selectivity and continuous operation are required. However, it should be adopted after careful process design and consideration of environmental factors.

The process consists of three key treatment steps:

- contact: the brine is mixed with an organic solvent that contains an extractant that selectively binds to the target ions, forming a complex;
- phase separation: the solvent phase, now containing the target ions, is separated from the brine based on gravity after mixing;
- stripping: the target ions are then stripped from the solvent phase into a suitable aqueous solution, forming a concentrated extract by mixing and phase separation.

Some of the advantages of solvent extraction are:

- highly selective extraction of specific ions;
- it can handle high salinity brines;
- it allows for continuous operation and scalability;
- the solvent can be recycled.

Some of the considerations should be considered when applying solvent extraction, such as:

- it requires careful selection of solvent and extraction conditions to achieve high efficiency;
- it requires energy due to the need for mixing;
- it requires the management of solvent waste and environmental impact. Organic solvents with a high flashpoint (preferably above 70°C) should be chosen to minimize the risk of evaporation, which could potentially lead to hazardous situations.

Furthermore, it is important to highlight that there are techniques under development aimed at addressing, eliminating, minimizing, and/or preventing the environmental risks associated with metal purification. Some of these techniques include the use of non-contaminating solvents, such as ionic liquids, as well as methods in which solvents and brines are not mixed (such as the non-dispersive solvent extraction — NDSX — process). These advancements promise to contribute to a more sustainable and responsible mining industry in the future.

5.4.4.4 Solvent crystallization

Solvent crystallization through the absorption of water from the solvent and the precipitation of all remaining ions as one mass is a variation of the solvent crystallization process. This method involves the use of a solvent that has a high affinity for water, causing it to absorb water molecules from the brine solution. As a result, the concentration of dissolved salts and minerals in the remaining solvent increases until reaching saturation, leading to the precipitation of all remaining ions as a single mass of crystals. The process is typically made up of the following steps:

- solvent selection: a solvent with a high affinity for water should be chosen for the process. Common solvents used in this method include organic solvents such as acetone, ethanol, or methanol;
- brine-solvent mixing: the concentrated brine solution is mixed with the selected solvent. The solvent's affinity for water causes it to absorb water molecules from the brine solution, thereby increasing the concentration of dissolved salts and minerals in the remaining solvent;
- water absorption: as water is absorbed by the solvent, the concentration of dissolved salts and minerals in the brine solution increases. Eventually, the solvent becomes saturated with dissolved ions, reaching a point where no more water can be absorbed;

- precipitation: once the solvent becomes saturated, the remaining ions in the solution begin to precipitate out of the solvent as a single mass of crystals. Since the solvent has absorbed water, the remaining ions may precipitate together rather than forming separate crystals;

- crystal formation: the precipitated crystals are typically harvested from the solvent solution using filtration, centrifugation, or other separation techniques. The crystals may undergo washing or drying steps to remove residual solvent and impurities;

- solvent recovery: the solvent recovered from the crystallization process can be recycled and reused in subsequent operations. Solvent recovery techniques such as distillation or filtration are employed to separate the solvent from the crystalline product;

- solvent crystallization can be used in brines to produce mixed salts.

5.4.4.5 Selective capture of ions

There are many developments in active materials and fibres that selectively capture ions from metal-rich fluids such as geothermal brines, oil/gas produced water and industrial waste streams. They can extract lithium and other precious metals directly from brines.

These technologies find applications like extraction of lithium from natural lithium rich brines while avoiding heavy mining works.

5.4.4.6 Bipolar electrodialysis

To further process the softened brine, Bipolar electrodialysis (BPED) can be applied to the concentrated NaCl streams to produce chemicals. BPED utilizes an electric field to selectively transport ions through ion-selective membranes, separating them from the brine stream. Bipolar membranes generate H+ and OH^- ions.

The process consists of the following treatment steps:

- brine injection: concentrated NaCl solution is introduced into the BPED stack;

- ion migration: under the electric field, sodium ions (Na^+) migrate towards the cathode, while chloride ions (Cl^-) migrate towards the anode;

- water splitting: bipolar membranes permit the water splitting in its contact region. Thus, H+ and OH^- ions are separated while current is applied between the electrodes of the BPED stack;

- selective separation: ion-exchange membranes (cationic and anionic) within the stack selectively allow for the transport of ions. For instance, cations can only pass through cationic exchange membranes, but not anionic ones, while anions can cross anionic exchange membranes, but not the cationic ones;

- product collection: sodium hydroxide (NaOH) and hydrochloric acid (HCl) are produced due to the union of cations (Na+) with OH^- and anions (Cl^-) with the H+ produced in the bipolar membrane.

By applying BPED to concentrated NaCl streams, valuable chemicals such as sodium hydroxide and hydrochloric acid can be produced, which have diverse industrial applications. The market demand for these products exists across various industries, providing opportunities for sales and distribution. However, there should be a careful consideration of energy consumption, maintenance requirements, waste management, and market demand for commercial success, as shown in Table 3.

Table 3—Products and uses from BPED

Compound	Uses	Commercial applications
Sodium Hydroxide (NaOH)	Used in various industries, including chemical manufacturing, pulp and paper production, soap making, and water treatment.	Produced NaOH can be sold directly to industrial consumers or used as a raw material in the production of other chemicals.
Hydrochloric Acid (HCl)	Widely used in chemical synthesis, metal cleaning, food processing, and pH control in various industrial processes.	Produced HCl can be sold to various industries for use in manufacturing processes or as a cleaning agent.

When applying BPED, the following points should be considered:

— energy consumption: BPED implies significant electricity consumption for operation, impacting on operational costs;

— maintenance: membrane fouling and scaling may occur, requiring periodic cleaning and maintenance and replacing;

— waste management: proper management of waste streams generated during the process is essential to minimize environmental impact;

— CAPEX: commercial viability depends on market demand, pricing, and competition in the industry.

5.4.4.7 Hydrometallurgical processes

Several hydrometallurgical processes can be used individually or combined for brine-based M&M recovery. These techniques selectively separate target metals using organic solvents or ion-exchange resins. Here are some examples of the different hydrometallurgical processes that can be used:

— solvent extraction, non-dispersive solvent extraction & ion exchange (SX/NDSX/IX): these techniques selectively separate target metals using organic solvents or ion-exchange resins (for example, for lithium extraction);

— precipitation: adjusting brine chemistry can induce targeted metal precipitation as solids for further processing (for example, for magnesium removal);

— electrodeposition: applying electrical current recovers metals from solution onto a cathode. (for example, for final metal purification).

It should consider some issues for selective M&M extraction to elucidate whether the specific technique is feasible for the application intended:

— selectivity: the chosen technology should selectively target the desired M&M while minimizing co-extraction of impurities;

— efficiency: high extraction efficiency minimizes metal losses and maximizes resource recovery;

— scalability: the technology should be adaptable for large-scale industrial applications;

— energy consumption: minimizing energy requirements reduces operational costs and environmental impact;

- chemical compatibility: brine chemistry should be compatible with chosen reagents or membranes.

Using hydrometallurgical processes can bring several benefits, such as:

- high purity metals for various applications;
- efficient and environmentally friendly processing;
- valuable resource recovery and valorisation.

Hydrometallurgical processes have several applications, such as:

- brine valorisation and mineral processing;
- recycling and waste treatment;
- production of high-purity metals for electronics, batteries, and other industries.

5.4.4.8 Membrane crystallization

Membrane crystallization, particularly when combined with techniques like membrane distillation (MD) or forward osmosis (FO), offers an innovative approach for recovering salts from concentrated brines. In this process, the selective permeability of membranes allows water vapor to pass through while retaining dissolved salts, leading to the crystallization of salts as the solution becomes supersaturated. The integration of MD or FO enhances the efficiency of the process by facilitating water removal under low-energy conditions, which can be particularly beneficial for high-salinity solutions. This method not only concentrates the brine but also promotes the formation of high-purity salt crystals, making it suitable for resource recovery applications. By recovering salts such as sodium chloride, potassium sulphate, and magnesium compounds, membrane crystallization can contribute to sustainable practices in industries like desalination, mining, and wastewater treatment, turning waste into valuable resources while minimizing environmental impact.

5.4.5 Guidelines for the purification of recovered products

The objective during separation and recovery (purification) is to obtain metals or their metallic compounds/concentrate with a degree of purity that allows their use and valorisation.

Separation and recovery can bring several benefits, such as:

- high purity metals for various applications;
- efficient and environmentally friendly processing;
- valuable resource recovery and valorisation.

Separation and recovery have several applications, such as:

- brine valorisation and mineral processing;
- recycling and waste treatment;
- production of high-purity metals for electronics, batteries, and other industries.

The specific purification methods selected depends on the recovered metal and its intended use:

- SX/NDSX/IX can be employed for additional purification after initial M&M recovery;
- crystallization and recrystallization can enhance the purity of recovered metal salts;

- electrorefining is applicable for the purification of certain metals using electrolysis.

5.4.6 Guidelines for the management of residual brine in minimum liquid discharge

The residual brine from minimum liquid discharge should be managed properly to minimise environmental consequences. At the same time, brine treatment can bring some benefits, such as:

- waste brine management: the treated brine, depleted of target M&M, can potentially be reinjected back into the source formation or used for other industrial applications;
- solid waste valorisation: the precipitates or other solid wastes may be further processed to recover additional valuable resources.

6 Good practice approaches for planning, designing, implementing and operation of brine valorisation in SWDP

6.1 Relevant factors

Before planning, designing, implementing, and operating a brine valorisation process in SWDP, all the relevant factors shall be evaluated.

The following relevant factors for evaluating brine valorisation operations shall be considered:

- market value: the current and potential market value of the extracted M&M, indicating the economic significance of the project;
- market demand: the existing and anticipated demand for the extracted M&M in the market, influencing the overall market share and revenue potential;
- market potential: the growth prospects and market trends for the extracted M&M over the next 10-20 years, considering evolving industrial needs;
- shipping costs: the costs associated with transporting extracted M&M to market destinations, impacting on overall operational expenses;
- offtaker deals: agreements or contracts with off-takers, representing commitments from buyers to purchase the extracted M&M;
- infrastructure availability: the presence and adequacy of necessary infrastructure, such as transportation, power, and water supply, to support valorisation operations;
- technology efficiency: the effectiveness and efficiency of the brine extraction and processing technologies used, influencing overall operational productivity;
- political stability: the stability of the political environment in the region where the brine valorisation operations are located, as political factors can impact project continuity;
- resource resilience: the resilience and sustainability of the brine resource, indicating the long-term viability of the extraction operations;
- technological innovation: the incorporation of innovative technologies in brine valorisation operations, impacting efficiency, and potentially providing a competitive advantage;
- supply chain security: the security and reliability of the supply chain, encompassing the entire process from extraction to delivery of M&M to end-users;

- currency and economic stability: the stability of currencies and economic conditions in both the source and destination countries for the extracted M&M;
- green tax: potential taxes or levies related to environmental impact, reflecting the cost of mitigating environmental consequences;
- outlier events: consideration of unexpected events or risks that could impact the operation, requiring risk management strategies. These factors collectively contribute to a comprehensive evaluation of the feasibility, sustainability, and overall attractiveness of brine valorisation operations.

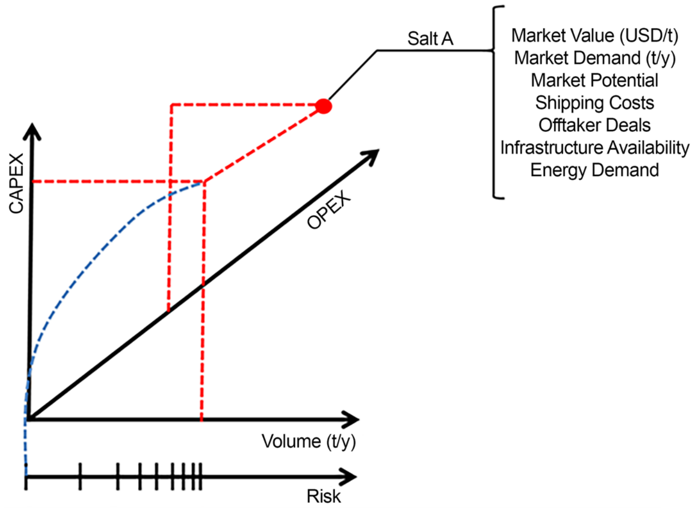

Figure 4 — Building of a business case for the recovery of Salt A from a brine by a tri-axis consideration of CAPEX, OPEX & relative product volume. Parallel we calculate also the relative operational/ commercial risks and the parameters discussed above

6.2 Recommendations for planning brine valorisation process in SWDP

When planning the brine valorisation process in seawater desalination plants (SWDP), once all the relevant factors have been identified, there are several key factors that shall be considered to ensure the economic viability, environmental sustainability, and operational efficiency of the project. Below are a series of actions that should guide the planning process:

- identify all the factors that can affect the viability of the process. Examples of this are the size of desalination plant, the market/end users demand, the quality and composition of the brines, the pretreatment processes in the desalination plant, the energy sources (for instance, land energy costs and type of energy available, such as renewable or fossil-based sources);
- identify whether brine valorisation is for green (a new desalination plant with brine valorisation) or brown (valorisation the upgrade of an existing desalination plant) field desalination plants;
- identify which critical M&M are to be mined and what to do with the remaining sub-products;
- identify focusing on recovering one/multiple M&M to recover;
- identify governance and regulation scenarios in brine management;
- identify brine valorisation process operators and brine owners;
- consider whether the brine valorisation process shall be flexible or fixed;

— identify if the recovered material is intended to be commercialized as a final product or as an intermediate product to another industry.

6.3 Recommendations for designing

When designing a brine valorisation process in SWDP, the following actions should be evaluated:

— identify the pretreatment process according to type of brine, quality, etc., for example to avoid scaling of the specific technology selected for the downstream process;

— identify the concentration process according to the type of material to recover, energy considerations, ZLD as opposed to minimum liquid discharge approaches;

— identify recovery processes for the targeted materials;

— identify the purification steps required to enhance the quality of the targeted product to commercialize;

— adopt a continuous process to reduce costs (which is strongly recommended in comparison to batch process);

— select the pretreatment, concentration, recovery and purification technologies with a lower environmental impact (see clause 7);

— identify the possible synergies with the existing desalination plants or industries (for example, chemical industry) in which the brine valorisation unit is intended to be implemented.

6.4 Recommendations on products to recover by brine valorisation in SWDP

6.4.1 Salts and minerals

The present subclause comprises a selection of salts and minerals that may be recovered from seawater brine during brine valorisation in SWDP. The list illustrates the range of potential substances for extraction, thereby establishing a foundation for subsequent analysis and decision-making within the valorisation process. With calcium recovered through the upstream softening step, various salts and minerals can be recovered from seawater brine (see Table 4).

Table 4 — List of salts and minerals that can be recovered from seawater brine

Salt/Mineral	Characteristics
Sodium Chloride ($NaCl$)	Used in food production (for example, seasoning), chemical manufacturing, water softening, and de-icing roads. Low quality $NaCl$ can be used in animal food and for chlor-alkali industry.
Magnesium Chloride ($MgCl_2$)	Used in the production of magnesium metal, as a de-icer, and in various industrial processes
Magnesium Sulfate ($MgSO_4$)	Commonly known as Epsom salt, it is used in agriculture, medicine, cosmetics, and as a drying agent
Magnesium Hydroxide ($Mg(OH)_2$)	Commonly known as brucite, it is used as flame retardant and neutralizing agent
Potassium Chloride (KCl)	Used as a fertilizer, in the chemical industry, and in food processing

Salt/Mineral	Characteristics
Sodium Sulphate (Na_2SO_4)	Used in the detergent industry, glass manufacturing, and as a filler in paper and textiles
Potassium Sulphate (K_2SO_4)	Used as a fertilizer in agriculture and in industrial applications such as glass manufacturing, pharmaceuticals, and potassium alum production
Lithium, Bromine, Boron, Iodine	Recovered for various industrial applications including batteries, flame retardants, agriculture, and pharmaceuticals
Various Trace Minerals (for example vanadium, manganese, zinc, gallium, indium, molybdenum, rubidium and copper)	Used with industrial and nutritional applications

6.4.2 Key considerations

There are a few key considerations that shall be considered when recovering salts and minerals from recovered from seawater brine:

— salt composition: with calcium removed, attention shifts to other valuable salts and minerals present in the brine;

— recovery methods: various methods such as precipitation, crystallization, and ion exchange can be employed depending on the specific salt or mineral;

— market demand: recovery depends on demand and market value for specific salts and minerals;

— environmental impact: proper management of residual brine and by-products is crucial to minimize environmental consequences.

— in addition, while the concept of full salts, minerals and metals recovery from brines holds promise, it may not be feasible in every case due to varying parameters and availabilities because of various reasons, such as brine composition. The composition of brine varies depending on factors such as the source (seawater, industrial effluent.) and the treatment process used. Some brines may contain a limited range of salts and minerals, making full recovery less economically viable;

— infrastructure and logistics: the availability of infrastructure and logistical support plays a crucial role in determining the feasibility of salts and minerals recovery. Access to transportation, energy sources, and water resources can significantly impact the cost and efficiency of extraction processes. Additionally, shipping costs for delivering the produced salts and minerals to potential clients, especially if they are located far away, can add to the overall expenses;

— local market demand: the demand and market value for recovered salts and minerals vary depending on factors such as industrial applications, regional preferences, and pricing dynamics. In some cases, the market demand may not justify the investment required for full recovery;

— regulatory and environmental factors: regulatory requirements and environmental considerations may impose constraints on brine treatment and disposal. Compliance with regulations related to waste management, water discharge, and environmental impact can influence the feasibility of salts and minerals recovery;

— economic viability: the economic viability of salts and minerals recovery depends on factors such as capital investment, operational costs, revenue potential, return on investment, and shipping costs for delivering the produced salts and minerals to potential clients. Each case of brine concentration shall be evaluated based on its unique economic parameters to determine the feasibility of full recovery.

6.5 Other recommendations for brine valorisation in SWDP

Before implementing central and decentral treatment of the minerals and metals coming from the process, it shall be considered that brine valorisation presents significant challenges for smaller local projects in Europe. These projects often face limitations in processing diverse brine compositions, accessing critical infrastructure, complying with regulatory standards, and achieving economies of scale necessary for profitability. However, a potential solution to these challenges lies in the concept of Central Separation Hubs. By centralizing processing facilities, infrastructure, market access, regulatory compliance efforts, and technological innovation, these hubs offer a promising approach to overcome the barriers faced by smaller local projects in brine valorisation.

Hubs for centralizing brine treatment/salts around Europe (as shown in Figure 5) should be established to avoid dealing with smaller volumes in small-scale units which might have added difficulties. Sometimes local parameters do not make it economically feasible to recover all or none of the products on each of the sites. Nevertheless, shipping the mixed salts to a central recovery unit that can separate the products and distribute them can be cost-effective.

NOTE Roughly speaking, above 150 million litres per day could potentially be cost-effective, while anything below 1,000m^3/h would not be economically feasible for recovering NaCl alone.

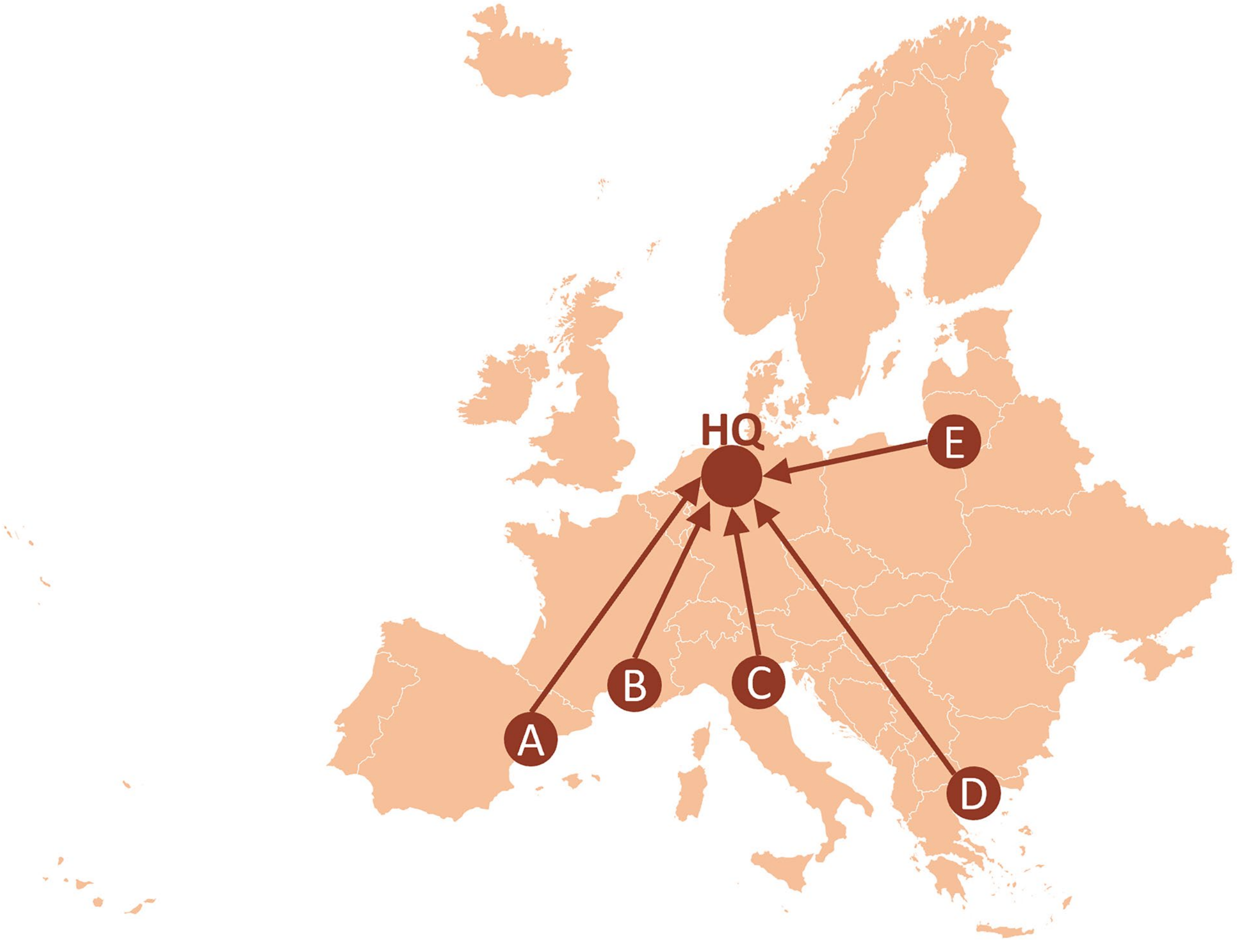

Figure 5 — Example of a central separation hub (HQ) for brine valorisation. The recovery of salts and minerals is directly dependent on the relative volumes of the products on each site (A-E).

The following are some recommendations on decision-making criteria and steps related to the above:

a) undertake a pre-study for centralised or decentralised solutions;

b) assess the following criteria to decide whether central or decentral treatment would be sustainable (at the economic, social and ecological level):

    1) volume produced;

    2) location of the desalination plant;

    3) logistics (long distance to carry heavy load);

c) decide on the brine valorisation steps;

d) consider the option for a decentralized or centralized treatment plant (for example, the use of hubs):

    1) central separation hub;

    2) on site of the desalination hub.

7 Good practice approaches and recommendations for circularity and environmental aspects

7.1 Circularity in desalination

Although the S4V project is centred around boosting brine valorisation, the dependence and potential interconnectedness with desalination plants makes it unavoidable to consider the advantages that S4V technology would offer to brackish and seawater desalination industry. S4V has the potential to promote circularity in the desalination industry by achieving both higher freshwater water yields and harnessing brine, a byproduct not currently valorised. In addition, brine poses potential environmental challenges given that its uncontrolled disposal (hyper-saline stream) can cause damage to the vicinity ecosystems of discharge points. Nevertheless, most of current brine disposal occurs under controlled conditions and with the use of diffusers, which minimise those potential impacts.

The optimization of mass and energy balance in desalination processes through the reintroduction of waste streams and consumables is a cornerstone of circular economy principles. This approach not only minimizes resource depletion but also significantly reduces environmental impact and operational costs. By closing material loops and maximizing the utility of resources, desalination plants can achieve higher levels of efficiency and sustainability. Reimagining waste/byproducts streams as potential resources can boost industries seeking innovative solutions that not only address waste management challenges, but also create new value chains and business opportunities. In the desalination field, the reintegration of waste materials (such as the use of regenerated membranes) together with the valorisation of byproducts which are currently underused (such as the elements obtained in S4V brine valorisation) helps eliminating the concept of "waste" altogether. It helps transforming what was once considered a liability into an asset and establish a new source of valuable materials which in other cases would be disposed back into the sea. In addition, it improves SWDP water harvesting and supports the achievement of a process close to zero liquid discharge and a zero-waste process. S4V is an example of circular economy in and of itself. However, actions shall be considered in each of the processes, such as during the optimization of energy and materials by applying the closed-loop re-use/recycling approach (such as recycling solvents and other chemicals within the same process or by using waste/by-products outputs from one as input for others, etc). To do this, the use of eco-design concepts as well as ex-ante environmental impact assessments in parallel to the development/optimization phase of each of the are important tools to guide and control the circularity and environmental impact of the developments. This practice aligns with the circular economy's goal of keeping products, components, and materials at their highest utility and value for as long as possible. This holistic approach to resource management is essential for transitioning from a linear "take-make-dispose" model to a more sustainable and regenerative circular economy.

7.2 Environmental impact

Brine valorisation, while offering advantages over traditional evaporative methods, still poses several potential environmental risks. The primary concerns include soil and atmosphere contamination because of the use of solvents and reagents in the concentration and extraction processes that may result in soil and water pollution if not properly managed. To measure these impacts, a comprehensive environmental monitoring program should be implemented to minimize potential environmental impacts. For that purpose, several strategies can be employed:

— closed-loop systems: implement technologies that recycle and reuse process waste/by-products streams to reduce chemical consumption and minimize its discharge into the environment;

— selective extraction: utilize advanced separation techniques to target specific ions, reducing the overall volume of brine processed and minimizing waste generation;

— renewable energy and waste heat integration: power extraction and processing operations with renewable energy sources to reduce environmental impact;

— proper waste management: develop comprehensive plans for the safe disposal or reuse of waste products, including spent solvents and exhausted brine.

By adopting these measures and maintaining rigorous environmental monitoring, the chemical brine valorisation industry can work towards more sustainable practices while meeting the growing demand for valuable minerals and metals.

Life Cycle Assessment (LCA) methodology can play a crucial role in evaluating and improving the environmental performance of chemical brine valorisation operations. LCA provides a holistic view of the environmental impacts throughout the entire life cycle of the valorisation process, from raw material extraction to end-of-life disposal. Furthermore, the development of Product Category Rules (PCRs) specific to chemical brine valorisation would establish a standardized framework for conducting LCAs in this industry. PCRs would ensure consistency in impact assessment methods, system boundaries, and data quality requirements across different companies and projects. This standardization would not only facilitate fair comparisons between different mining operations but also foster healthy competition in environmental performance, ultimately driving the industry towards more sustainable practices.

Reference scenarios can be used to gain insight into S4V's potential environmental impact to the field of CRMs and other minerals and metals obtaining processes. The reference scenarios primarily involve land-based mining for the CRMs that are recovered in the S4V project. The processes were selected according to the series EN ISO 14040, which recommends identifying generic processes in LCA databases when primary data is not available (commonly identified as proxy processes). Hence, production processes for the same or similar products to those to be obtained in S4V have been identified. For preliminary or prospective analysis when a LCA is developed in its early stages, the strategy of extrapolation from data of similar processes is useful to 'fill out gaps'. The process used for extrapolation should follow the precepts of representativeness (technological coverage), geography and temporal scope.

When performing LCA to brine valorisation, it should be considered the allocation procedure given the multiproduct (by-products and co-products) process that S4V represents. Allocation should be avoided, if possible, by dividing the unit process into necessary number of sub-processes. When allocation is needed, and physical relationships alone cannot be used or could undermine the market importance of the assessed products, mass allocation should be discarded by the economic allocation, which shall be used and documented. For this, and although the existing and unavoidable controversial issue regarding the choice between physical (mass) and economic allocation, the LCA of the Sea4Value's brine refining processes would make use of the economic allocation procedure to allocate the environmental impact of the Sea4Value's brine refining process to each of the co-products and by-products obtained. In addition, to minimise the influence of one-off swings in market prices, the use of average prices over several years can be considered. This decision is further reinforced by the fact that revenue is a driving force of value recovery without which the proposed processes would not take place and therefore, economic incentives drive environmental impacts.

8 Factors enabling market entry of the recovered minerals and metals

8.1 General Introduction

This clause delves into the multifaceted factors enabling the market entry of the recovered minerals and metals, emphasizing the pivotal roles played by legal, social, environmental, technological, and economic dimensions.

8.2 Legal factors

8.2.1 General

Legislation and directives have been developed and are being developed at European Union level to support the market entry of metals and minerals extracted from brines of seawater desalination plants. These mandates identify both critical and strategic materials, and, to ensure future supply meets future demand, set benchmarks for the annual consumption of materials coming from local extraction as well as recycled materials. Member states are required to adopt laws and directives into their national legal systems. Metals and minerals extracted from brine valorisation projects are required to be correctly classified as recycled or circular to benefit from these legislations.

The form and purity requirements of products extracted from seawater desalination brines are defined by standards or legislation governing the application. Some standards also define the production processes that are acceptable to generate the mineral or metal. To ensure that the products extracted from seawater desalination brines can be used in the intended application, they should refer to these standards and legislation or should be updated.

Products that are extracted from seawater brines by means of chemical reactions, or precipitations shall be registered and comply with the requirements of the current legislation[2].

During the development and implementation of seawater desalination and brine valorisation projects, there shall be a careful consideration of the regulatory landscape, involving international and national laws, ownership rights, waste classification criteria, and intellectual property protection to ensure compliance, promote sustainable practices, and maximize resource recovery opportunities. Some examples of these are:

— relevant laws and regulations: include initiatives such as the EU Green Deal (promoting a resource-efficient circular economy), the Critical Raw Material Act (identifying critical raw materials and encouraging alternative, sustainable sources), and the European Raw Materials Alliance (ERMA);

— specific legislation: national and EU-level legislation that impacts the extraction and use of minerals and metals from brines;

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[2] The current legislation on this topic is Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC.

- waste criteria and treatment standards: regulations defining the classification and treatment requirements for materials extracted from brines;
- country-specific regulations: legal requirements and criteria that vary depending on the country;
- classification of by-products: ensuring that extracted materials are classified as by-products rather than waste, which provides regulatory and economic advantages;
- intellectual property (IP) protection: safeguarding proprietary extraction technologies through patents, trademarks, or trade secrets;
- challenges in policy implementation: long timelines for recommending and incorporating new policies at the EU level;
- ownership rights of brines: clarifying ownership of brines and the rights to the minerals and metals contained within them;
- the European Union introduces directives that encourage member states to increase the use of recovered or recycled materials in finished products. Each Member State is then required to implement these directives by incorporating them into their national laws;
- laws that promote or mandate the use of recycled materials in production processes;
- regulations that restrict or impose taxes on the discharge of brines;
- legislation that imposes taxes on the use of imported or non-circular materials;
- classification of metals and minerals extracted from brines as recycled or circular materials to benefit from relevant regulations and incentives.

8.2.2 Considerations and recommendations

Based on the legal aspects identified in clause 8.2.1, the following considerations should be considered:

- it should be ensured that brine valorisation is recognised as an acceptable production method for all intended applications. For example, food monographs often specify the approved manufacturing processes;
- it shall be ensured that recycled materials meet the same purity standards as virgin materials, as defined by norms and regulations specific to each application;
- it should be clarified, prior to initiating a brine valorisation project, the ownership of the brine, as well as the rights to the metals and minerals contained within it;
- it shall be ensured compliance with EU regulations for any chemical reactions used in the extraction process;
- it should be ensured that the consortium follows appropriate procedures for environmental protection, health, and safety according to the objective of current regulations ;
- it should be ensured that the appropriate procedures related to environmental protection, health, and safety are followed;
- it shall be ensured that local laws and regulations are consulted to confirm the suitability of materials for the intended application;

- it should be ensured that the main aspects of intellectual property (IP) protection are considered. Such aspects include, for example, securing patents, trademarks, or trade secrets for proprietary technologies, which can provide a competitive advantage and protect investments in research and development;

- it should be ensured an engagement with regulatory authorities to advocate for policies that support the development of mineral recovery from brines, such as incentives or streamlined permitting processes.

A few key recommendations can be deduced from the current clause:

- ensure proper classification of recovered materials: classify metals and minerals extracted from brines as recycled or circular materials to benefit from relevant European Union regulations and incentives, such as the Critical Raw Materials Act and EU Green Deal directives;

- secure compliance with regulatory standards: engage early with regulatory authorities to confirm compliance with registration requirements, purity standards, and application-specific norms, ensuring that recovered materials meet legal and industry requirements for their intended applications;

- clarify ownership and IP rights: establish clear ownership of brine resources and secure intellectual property rights for innovative extraction technologies to protect investments and avoid legal disputes over material rights.

8.3 Social factors

8.3.1 General

Achieving social acceptance and fostering community engagement should be accounted for to gain public support and ensure the success of brine valorisation projects. Introducing sustainability certification standards can further enhance market entry by highlighting the lower environmental impact of brine-derived materials compared to conventional land-based mining. The following key social considerations should be addressed.

8.3.2 Public acceptance

Public perception significantly influences the success of any project. If communities understand the benefits of recovering minerals and metals from seawater desalination brines—such as reduced environmental impact and promoting resource sustainability—they are more likely to support the initiative. Public acceptance can be improved through effective communication, transparency regarding project goals and methods, and addressing any concerns or misconceptions. Local authorities can aid in this process by sharing material safety data sheets and product quality measurements to assure potential buyers of the product’s safety and quality. In summary, there are three key aspects that should be addressed:

- education and awareness: providing educational resources to inform the public about the benefits and safety of recovered materials;

- community engagement: actively involving local communities in project discussions and decision-making;

- risk communication: clearly communicating potential risks and how they are mitigated.

8.3.3 Public benefits

Emphasizing the economic benefits of brine valorisation, such as increased tax revenue and job creation, can generate support from both the public and policymakers. However, it is crucial to ensure that these benefits are equitably distributed and that local communities also gain tangible advantages from the project. To ensure this, the following aspects should be addressed:

- economic opportunities: creating local jobs and supporting regional economic growth;
- revenue sharing: allocating a portion of the project's revenue to community development initiatives.

8.3.4 Social acceptance and environmental impact

Communities may oppose projects if they perceive potential negative impacts on their environment or quality of life, commonly referred to as "Not In My Backyard" (NIMBY) sentiment. To address these concerns, rigorous environmental impact assessments should be conducted, sustainable practices should be implemented, and communities should be engaged to understand and address their concerns. Involving local stakeholders in the decision-making process and providing direct benefits to the community can further encourage acceptance. In summary, there are three key aspects that should be addressed:

- environmental mitigation: implementing measures to minimize environmental impact;
- stakeholder consultation: consulting with local stakeholders to address concerns and incorporate feedback;
- community benefits: offering tangible benefits to local communities, such as infrastructure improvements or environmental initiatives.

8.3.5 Sustainability certification

Obtaining a sustainability certification can differentiate brine-recovered minerals and metals as more environmentally friendly compared to materials sourced from traditional mining. A green label or certification indicating compliance with environmental standards can help market entry by signalling to consumers and businesses that the products are ethically sourced and environmentally responsible. Certification schemes, such as eco-labels or responsible sourcing certifications, can provide assurance, increase demand, and enhance competitiveness:

- sustainability standards: meeting established environmental and ethical standards;
- market differentiation: using certifications to position products as environmentally superior and responsible.

8.3.6 Transparency and compliance

Adherence to existing laws, norms, and regulations can build credibility and trust, which are essential for gaining social acceptance. Transparent reporting and compliance with regulatory standards can reassure the public and stakeholders about the project's commitment to safety and sustainability.

8.3.7 Ethical sourcing

Ethical considerations, such as respect for human rights, fair labour standards, and fair trade practices, should be considered to attract both consumers and investors. Adopting responsible sourcing policies and adhering to international ethical standards can differentiate brine-mined products and enhance their market appeal.

8.3.8 Key recommendations for the factor social acceptance

There are three key recommendations that should be followed when addressing social factors in brine valorisation from SWDP:

- promote sustainability certification: obtain sustainability certifications for brine-mined materials to differentiate them as environmentally friendly alternatives to traditional mined resources, enhancing market entry and acceptance among consumers and businesses;
- enhance community engagement and transparency: foster public acceptance by maintaining transparent communication, actively engaging with local communities, addressing concerns related to environmental impact, safety, and project benefits through education, outreach, and stakeholder consultation;
- highlight economic and social benefits: emphasize the local economic benefits of brine valorisation, such as job creation and increased tax revenue, and ensure equitable distribution of these benefits to gain support from both the public and policymakers.

8.4 Technological factors

8.4.1 General

The technological parameters affecting the market entry of recovered raw materials from seawater desalination brine are critical to determining the feasibility and sustainability of this unique sector. This clause delves into the main relevant technological considerations, ranging from ensuring high product purity and scalability to leveraging advanced extraction methods and integrating these technologies into existing infrastructure, providing a comprehensive framework for successful implementation and market adoption.

8.4.2 Quality and purity

The quality of the end products and intermediates affects the market entry of recovered raw materials. High purity levels should be achieved to meet industry standards and customer requirements. Therefore, advanced purification technologies should be integrated into the recovery process to ensure that the extracted minerals and metals meet the necessary quality benchmarks.

8.4.3 Scale-up

Transitioning from laboratory-scale experiments to industrial-scale production is a significant challenge. The scalability of the recovery process shall be addressed to ensure that the specific technology can be economically viable on a larger scale. This involves optimizing the process parameters, designing scalable equipment, and ensuring that the process can handle the variability of raw materials.

8.4.4 Development of novel materials and processes

The development of novel materials and processes should be considered to increase resource efficiency:

- materials and processes with high selectivity for target ions reduce the need for extensive purification and lowers the overall reagent usage;
- methods that minimize the use of chemical reagents can significantly reduce operational costs and environmental impact;
- energy-efficient technologies make the recovery process more sustainable and cost-effective.

8.4.5 Technologies for improved selectivity and efficiency

The following technologies should be considered when addressing selectivity and efficiency in brine valorisation from SWDP:

- nanofiltration (NF) can be used as a pretreatment step to improve the selectivity of monovalent and divalent ions, enhancing the recovery process's overall efficiency;
- membrane distillation crystallization can achieve high concentration factors at lower energy consumption, making it an attractive option for brine valorisation;
- advanced polymer-multi-effect distillation incorporates advanced polymers to improve the efficiency of distillation processes.

8.4.6 Improved selectivity and extraction of metals

Selectivity and extraction of metals can be improved through several methods, such as:

- extraction with ionic liquids can offer high selectivity for specific metals, making them useful for targeted recovery;
- liquid membranes and solvent extraction can enhance the extraction efficiency of valuable metals from brine;
- electrodialysis (ED) with bipolar membranes can be employed for selective ion removal, improving the overall recovery efficiency;
- 3D adsorption modules can increase the surface area for adsorption, enhancing the extraction process.

8.4.7 Technology adaptations at the salt manufacturing site

Some technologies can also be applied directly to the salt manufacturing site with operations such as:

- adaptation of existing desalination plants that shall be modified to combine with brine valorisation technologies through, for instance, ensuring sufficient space and energy availability;
- valorisation assessment and optimisation of the energy balance and requirements should be undertaken to avoid excessive energy consumption;
- if the brine valorisation process significantly reduces volume and increases salinity, modifications in brine disposal technology shall be taken. This might involve enhancing the dilution processes at the seabed to manage the increased salinity levels; the adaptation of existing desalination plants for coupling with brine valorisation presents limitations. For instance, additional space and, especially, energy requirements might not be available. Nevertheless, there are other possible modifications needed in brine disposal technology if the brine valorisation process results in a significant reduction of volume and thus increase of salinity: more dilution at seabed might be required.

8.5 Economic factors

8.5.1 Transportation

The transportation of metals and minerals plays an important role in the global supply chain. It is important to link the resource-rich regions with the regions where resources get used. The percentage of the cost constituted by cost of transportation can vary strongly depending on the product, such as mass, volume, density and hazardous properties, as well as other factors such as:

— regulation and documentation: different regions and countries might enforce different laws requiring varying documentation which can increase prices;

— packaging and handling: the packaging itself can vary strongly in price. Additionally, handling due to different sizes or safety considerations can increase handling time and prices;

— supply chain disruptions: costs can be increased due to delays, rerouting, and the need for alternative, often more expensive, shipping methods to maintain delivery schedules;

— safety and security: some products require special safety and security considerations which significantly increase prices.

Therefore, during market entry there should be some research on the main factors to consider when transporting products. to find the optimal routes featuring the most cost-effective transportation methods and models. There should be small distances between the producer and buyer to reduce fuel consumption and time. This allows to keep cost as well as environmental impacts low and reduces the amount of different regulations, needs for documentation and risks due to changing infrastructure and laws when crossing borders.

Besides the factors mentioned above, the actual state of the product also influences transportation costs. Thus, in addition to choosing the most efficient transportation method and distances, one should also select the most efficient and easiest product condition to transport. Therefore, the solved minerals and metals should be processed into solid state for transportation and selling. Due to lower prices, a low-quality product should usually be economically sold regionally to customers or middlemen that can improve quality, while high-quality products can be transported over longer distances to customers.

8.5.2 Recommendations for transportation

There are three key recommendations that should be followed when addressing transportation in brine valorisation from SWDP:

— optimize transportation routes and distances: transportation distances between producers and buyers should be minimised to reduce fuel consumption, transportation costs, and environmental impact, while also simplifying compliance with varying regional regulations;

— process recovered materials into solid form for transport: recovered minerals and metals should be in a solid state before transportation to reduce handling complexity, lower costs, and ensure safe and efficient transport, especially over long distances.

8.5.3 Price

8.5.3.1 General

The price of a product as well as the pricing strategy is one of the most important factors when entering a market. The price of a product will determine the sales volume and therefore also the profit gained with a specific product. The price of a product should be low enough to compete with similar products on the market but high enough to enable a viable business model. The following points should be considered for the market entry of circular brine valorisation products.

8.5.3.2 Prices of circular economy products

Thorough market research should be conducted for every single product that is to be produced and sold to understand general prices and market dynamics of the target market. It is possible that circular products have a higher production cost and therefore price than products produced in an established linear economy. To evaluate this for the product, the following factors should be considered:

- quality control and purity: brines show variations of unknown or unanalysed purities and impurities that should be treated differently. This might increase prices due to more complex and customized purification processes;
- technological challenges: development of new technologies demands investments and time to be cost-effective;
- scale and infrastructure: circular systems require new facilities, logistics and infrastructure networks while linear systems benefit from already established, optimized and scaled supply chains and infrastructure;

There are multiple ways to tackle these problems. One key player to enable a better position in the competition is the government, which may have interest in strengthening the circular economy transition due to reduced carbon emissions, less waste, and more resource security. Subsidies may also keep lower prices for virgin material prices, which conflicts with the support of circular products. Another player could be public capital. It should be investigated if public or private funding or subsidies are available for the targeted product and product market.

8.5.3.3 Long-term benefits

The circular economy benefits from the expansion and extension of facilities, logistics and infrastructure. Once those factors are established, the prices can continuously decrease until they are cheaper than virgin materials, as in the example of aluminium. This also increases the number of circular products available on the market and the trading volumes of said products. With growing production of minerals and metals from brine of SWDP, the price can be decreased even further.

One system that is beneficial for the price competitiveness of circular products is the emissions trading system established by single countries as well as institutions such as the EU. This system is based on the systematic reduction of price emissions to increase prices for virgin material products, which may produce more emissions, thereby making circular products relatively less expensive.

Another long-term benefit of the price of brine valorisation products is its relative resistance to external shocks. Geopolitical difficulties can often increase prices for materials, especially for materials whose production is dependent on single countries. This was seen for vanadium prices in the last decade, doubling in 2018 due to policy changes in China and fluctuation and price increases due to the start of the war in Ukraine in 2022. In these circumstances, the supply security competitiveness of the decentralized production of circular products such as brine valorisation products can be improved. This factor should be considered when planning to enter the market with a product that may be vulnerable to external fluctuations, as this can significantly impact pricing.

8.5.3.4 Dynamics of supply and demand for circular products

Market dynamics can change quickly through innovation and funding. Limited funding for new circular economic processes can further undermine the development of the technologies and therefore the transitioning to a circular economy. On the other hand, if a process can prove itself successful by successfully introducing products into the market, further demand and therefore funding can be obtained, thereby increasing production, decreasing prices and creating a positive feedback loop.

Therefore, it should be evaluated whether an increased production of certain materials will increase the demand and investments, factors that should be included when planning the market entry.

8.5.3.5 Concentrations vary in different brines

The concentrations of different materials can differ vastly in different brines. Concentration might be essential to achieve competitive prices as the extraction process and energy consumption get more effective and the price per kg of product decreases.

Therefore, the concentrations of different compounds in the targeted brines should be analysed to evaluate whether the compound is available in high enough concentrations to enable an efficient recovery and therefore price for the market entry to be competitive.

8.5.3.6 “Green premium”

It should be noted that the brine recovered materials, such as all circular materials do not always shall compete directly with the virgin materials produced in the linear economy. “Green” products can be more appealing to companies because of their image, their sustainable impact, the possibility of entering of new markets, and the planned or predicted regulatory changes for secure supply chains. This combined with a demand that surpasses the supply leads to companies deciding to pay the additional cost of choosing green or clean technologies or products, also called “green premium”. Therefore, an analysis should be carried out to see whether a green premium price top up is possible. This of course depends on the competition; if the product is already available “in green”, there should not be additional price increases.

Price is a factor that should be considered when entering a market with a new product. Potential higher prices as well as (political) benefits such as subsidies, green premium, future demand as well as other long-term benefits can influence the competitiveness of the product. Therefore, all the factors influencing the price of the products should be analysed to ensure a successful market entry.

8.5.3.7 Key recommendations

There are three key recommendations that should be followed when addressing price factors in brine valorisation from SWDP:

— conduct thorough market research for competitive pricing: perform detailed market research to understand pricing dynamics, evaluate production costs, and identify potential subsidies or funding opportunities to ensure that brine-mined products are competitively priced against traditional materials;

— leverage long-term economic benefits: highlight long-term benefits such as reduced dependence on fluctuating global supply chains and potential government incentives to position brine-mined materials as cost-effective and sustainable alternatives, especially in the face of future price increases for virgin materials due to stricter environmental regulations.

8.5.4 Market demand

8.5.4.1 Market screening and analysis

Mineral and metal raw materials are essential for industrial value creation, technological progress and the maintenance of our prosperity. The demand for certain critical and strategic minerals and metals will increase in the coming years as a result of sustainability targets set by policymakers and the resulting shift towards green technologies and increasing AI/digitalisation. Depending on which technical innovations, political guidelines or consumption patterns prevail, their demand for raw materials also develops differently. New and sustainable sources of raw materials should be developed to meet the growing demand as well as to drive forward a circular economy. The sustainable recovery of critical and strategic minerals and metals from seawater brines can provide an alternative source for the recovery of raw materials and contribute to meet the increasing demand.

To ensure a successful market entry for the recovered M&Ms, a market screening (target market and target customers) and a market analysis (market opportunities and market barriers, competitors) should be carried out in advance, as only high market demand and competitive prices (see clause 8.5.3) enables a product to enter the market. Market entry opportunities may vary from one EU country to another, depending on the respective prevailing markets.

The following factors should be considered in market analysis as basis for decisions for each product:

- market geo-distribution;
- market size;
- market application and customers (unmet needs);
- market competitors (price, quality), consolidation;
- existing enablers and barriers.

Subsequently, a SWOT analysis should be undertaken to determine the strengths, weaknesses, opportunities, and threats in relation to the market, taking into account the current market trends.

Depending on the product, further processing/purification can be appropriate for greater market opportunities and application potential.

When entering a market, the product should be promoted so that potential customers become aware of the product.

8.5.4.2 Key recommendations

The following recommendations that should be followed when undertaking a market analysis for each product of brine valorisation from SWDP:

- perform comprehensive market analysis to identify demand opportunities: conduct in-depth market screening and analysis to identify target customers, unmet needs, and potential applications for recovered minerals and metals, ensuring that products are introduced into markets with high demand and growth potential;
- adapt product offerings based on market needs and competitor analysis: continuously assess market trends, competitor strategies, and customer requirements to tailor product specifications, quality, and processing levels, thereby enhancing market fit and maximizing the potential for successful entry.

8.5.5 Regional products

8.5.5.1 General

In the dynamic global landscape of mineral and metal markets, the advent of innovative extraction technologies from seawater presents a transformative opportunity. This sub-clause explores the strategic advantages of prioritizing regional production over reliance on imports from distant locations. The emphasis on regional products, meaning those extracted and processed within a proximate geographic area, should consider factors such as:

- safe supply routes;
- abundant availability;

- the impact of established trading relationships;
- the critical role of supportive legislation.

Brine valorisation from SWDP as a method for acquiring minerals and metals offers a secure and reliable supply route. The abundance of brine from SWDP as a resource reduces dependence on unsecure supply, thereby mitigating risks associated with regional conflicts or political instability.

Over the past decade, improvements in resource recovery technology have enhanced the cost-efficiency of extracting minerals and metals from brine of SWDP, making it more competitive with traditional land-based mining. Despite these strengths, the path to market entry for minerals and metals extracted from brines of SWDP is full of challenges. One significant barrier stems from conventional mining operations' entrenched trade relationships and cost competitiveness. Overcoming these barriers would necessitate a concerted policy framework tailored to nurture and support this emerging industry. Targeted legislation can serve as a driving force in this attempt, encompassing subsidies to alleviate the financial burden of initial infrastructure investments, thereby narrowing the cost disparity with established mining operations. Tax breaks and incentives could further augment the economic viability of brine valorisation ventures. At the same time, import quotas or tariffs on competing minerals and metals may provide a temporal advantage for domestic industry growth and market penetration. However, these considerations should also take into account how they affect the market and the relationship with other market participants and should not conflict with other circular economy activities.

Beyond fiscal measures, policy advocacy plays a crucial role in highlighting the strategic and environmental merits of brine valorisation from SWDP to policymakers and stakeholders alike. The potential environmental benefits of the SWDP brine valorisation process should be brought to the forefront of policy discussions. However, the realization of brine valorisation from SWDP full potential is contingent upon ongoing research and development efforts to refine the efficiency and cost-effectiveness of the extraction processes. In conjunction with policy initiatives, a thorough market analysis should be undertaken to understand the dynamics of competitor pricing and identifying niche opportunities where minerals and metals recovered from brines from SWDP can offer distinct advantages. Collaboration with established industry players also offers strategic benefits, leveraging existing infrastructure and distribution networks to facilitate market entry and acceptance. In conclusion, by addressing the outlined challenges through targeted policy measures, technological advancements, and strategic market positioning, the recovery of minerals and metals from brines of SWDP presents a promising avenue toward securing a sustainable and diversified resource supply for the future.

8.5.5.2 Key recommendations

The following recommendations that should be followed when assessing the extraction of regional products through brine valorisation from SWDP:

- prioritize regional production to enhance supply security: emphasize the development of regional production capabilities to support the local economy, minimize supply chain risks, and enhance resilience against potential geopolitical or logistical disruptions;
- leverage supportive regional legislation and incentives: take advantage of local policies, subsidies, and incentives designed to promote regional production, which can help offset initial infrastructure costs and improve the economic viability of brine valorisation projects within the region.

8.5.6 The circular water value

8.5.6.1 General

The concept of Circular Water Value (CWV), developed within previous EU-funded projects[3] , represents the total economic value obtained by treating one cubic meter of a certain wastewater effluent with a given composition, through the recovery of certain secondary raw materials (SRM), establishing a circular water economy. This value is expressed in monetary terms (for example, euro per cubic meter) and represents the potential benefits derived from resource recovery in wastewater treatment. CWV is calculated by evaluating the quantities of valuable compounds (SRM) present in the wastewater and translating them into their respective economic values based on current market prices. CWV transcends traditional wastewater treatment, which predominantly emphasizes water purification and safe discharge. Instead, it includes the recovery and reuse of materials such as salts, minerals, and other chemicals, thereby transforming waste streams into valuable resources. The shift to CWV should be considered as it aligns with the principles of the circular economy, which seeks to minimize waste and optimize resource utilisation.

8.5.6.2 Application steps of the circular water value concept

8.5.6.2.1 Assessment of effluent composition

Initially, the composition and flow rates of the specific wastewater effluent should comprehensively be gathered. This data collection process ensures accuracy, with a charge balance performed to verify the integrity of the dataset in accordance with the electroneutrality condition.

8.5.6.2.2 Calculation of theoretical CWV

A process model, typically implemented using tools like MS Excel, is employed for calculating mass and energy balances across all flow streams of the effluent of interest. This includes the recovery assessment of various elements and compounds, including different water qualities such as drinking water and demineralized water. The theoretical CWV is derived when the weight of the SRM of interest in a given volume of effluent is quantified. This is done in two steps. First, the milliequivalent of the ion (element) of interest is calculated, which is used in the second step to calculate the mass of the SRM that can be recovered by treating a given volume of the effluent, based on the wastewater composition obtained according to clause 8.5.6.2.1.

8.5.6.2.3 Evaluation of treatment cost and net benefit

The evaluation of treatment costs and technologies in the context of CWV should be carried out for assessing the economic viability of implementing circular solutions like the CWV. The process begins with calculating the CWV and treatment costs on a per cubic meter basis. This assessment should focus on the potential economic benefits derived from the recovery of SRM and other valuable compounds from a given effluent.

To determine the treatment cost per cubic meter of a given effluent, both Capital Expenditure (CAPEX) and Operating Expenditure (OPEX) are considered. CAPEX includes direct and indirect capital costs, which are annualized using an amortization factor based on the annual interest rate and the plant's expected lifetime. This ensures that the long-term investment costs are appropriately accounted for over the lifespan of the treatment facility.

The amortization factor is calculated using a specific formula that incorporates the annual interest rate and the plant lifetime. By multiplying the total CAPEX by this amortization factor, the annualized CAPEX is obtained. This method converts the total capital investment into manageable annual costs, reflecting the capital recovery cost (CRC) commonly referenced in engineering literature.

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[3] The EU-funded projects that developed the concept of CWV are ZERO BRINE and LIFE BRINE-MINING.

$$a = \frac{i(1+i)^n}{(1+i)^n - 1}$$

where

a	is the amortization factor
i	is the annual interest rate
n	is the plant lifetime.

The total treatment cost per annum is then derived by adding the annualized CAPEX to the annual OPEX. This comprehensive total cost is divided by the annual volume of brine effluent that requires treatment, resulting in the cost per cubic meter of treated wastewater. This detailed financial analysis allows for a clear comparison between the CWV and the wastewater treatment cost, which should be conducted on an annual basis.

Comparing the CWV with the wastewater treatment value provides an evaluation of the economic sustainability of the business case. This approach ensures that both immediate operational costs and long-term investment costs are factored into the analysis, providing a comprehensive economic perspective on the feasibility and profitability of wastewater treatment solutions. Integrating CWV with detailed cost assessments helps optimise resource utilization, promote sustainability, and maximise economic returns from wastewater management practices.

8.5.6.2.4 Implementation and optimization

8.5.6.2.5 General

The practical implementation of the CWV concept shall be accompanied by a structured and methodical approach to ensure maximum efficacy and economic viability. Here, there are two key steps, pilot testing and validation and scale-up and full-scale implementation.

8.5.6.2.6 Pilot testing and validation

Initially, pilot testing should be conducted to validate theoretical calculations and treatment processes, collecting comprehensive data on effluent composition, recovery efficiency, and treatment costs, which informs the evaluation of treatment cost and net benefit (see clause 8.5.6.2.3). This phase allows for the fine-tuning of process parameters to enhance efficiency and identify potential issues, ensuring the reliability of the CWV model before scaling up to full-scale implementation.

8.5.6.2.7 Scale-up and full-scale implementation

Following successful pilot testing, the process should move to full-scale implementation, which includes optimising process parameters, selecting appropriate technologies, and designing and constructing the treatment facility. A detailed economic analysis should compare the CWV with overall treatment costs, considering both capital and operating expenditures and potential revenue from recovered materials. Additionally, environmental benefits such as reduced waste discharge and lower demand for virgin raw materials can be assessed, alongside ensuring compliance with regulatory standards to secure necessary permits and adhere to safety and environmental requirements. Post-implementation, continuous monitoring and feedback mechanisms are essential for maintaining and improving performance.

8.5.6.2.8 Key recommendations

The following recommendations can be deduced from using CWV in brine valorisation from SWDP:

- assess economic viability using the circular water value (CWV) concept: implement the CWV framework to evaluate the potential economic benefits of recovering valuable compounds from wastewater effluents, comparing these benefits against treatment costs to ensure the financial sustainability of brine valorisation projects;

- pilot and scale up CWV-based projects for maximum efficiency: conduct pilot testing to validate CWV calculations and refine treatment processes, followed by scaling up successful models to full-scale implementation, optimizing both operational efficiency and economic returns.

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