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Yendery Ramírez Angel

WATER-ENERGY NEXUS FOR WASTE MINIMISATION IN THE MINING INDUSTRY

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Abstract

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Water and energy use are intrinsically intertwined and are critical factors influencing mining sustainability. The rising demand for metals and the decrease of ore grade cause the increase of water volume required and the waste amount generated. Moreover, the reprocessing of mine tailings for the recovery of valuable materials trigger consumption of water and energy. All those factors are a threat to sustainability.

The water-energy nexus in the mining industry has a significant impact on sustainability since decreasing waste by reusing, recycling, and reducing the water and energy consumption. Therefore, urge the need for suitable management of water and energy use that lead the way for sustainable mining industry in the context of the circular economy to attain the rising problems.

The dissertation aims to provide an insight into the decision-making process to ensure the sustainable operation of mining processes and the related reprocessing of production waste. It is obtained through a comprehensive assessment of technological, environmental, and economic aspects of the operations concerned. The water-energy nexus analysis is applied through the development of frameworks to facilitate and support the decision-making process of stakeholders, to improve the water and waste management in the mining industry that leads to a sustainable circular economy.

The main outputs of the dissertation are: The technology assessment provides an insight to decision-makers to aid them to improve technologies so that they can meet specific customers' demands; The environmental assessment offers a straightforward and fast analysis of the energy consumption influence in water treatment and distribution systems and its effect onto the environment, considering water distribution systems, water quality, and how energy affects these variables; The economic assessment of the feasibility of reprocessing mining tailings to recover critical raw materials, considering the uncertainties involved; and the water-energy nexus assessment on tailings facilities to found and optimised the trade-offs between water and energy. Therefore, obtaining the guidance for proper mine tailings and water management in the mining industry.

Keywords: Water-Energy Nexus, Mining Industry Sustainability, Circular Economy, Water Management, Waste Management, Technology Assessment, Environmental Assessment, Economic Assessment, Greenhouse Gas Emissions, Mine Tailings re-processing.

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Finally, a special thank you to Esteban, Vicente, and Matias, for experiencing with me every joy and every tear, for back me up, for lifting me every time I need it, for being there every day of this adventure with love and understanding.

Yendery Ramírez Angel
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Antofagasta, Chile

I am Not Alone

by Gabriela Mistral

The night, it is deserted
from the mountains to the sea.
But I, the one who rocks you,
I am not alone!

The sky, it is deserted
for the moon falls to the sea.
But I, the one who holds you,
I am not alone!

The world, it is deserted.
All flesh is sad you see.
But I, the one who hugs you,
I am not alone!

With love to Esteban, Vicente and Matías.

Contents

Publications

List of publications

This dissertation is based on the following articles. Publishers have been granted the right to include the papers in the dissertation. The first section of the dissertation comprises four publications listed below, with detailed descriptions of the author's contribution to the articles' research and writing.

I. Ramírez, Y., Cisternas, L. A., and Kraslawski, A. (2017). Application of House of Quality in assessment of seawater pre-treatment technologies. *Journal of Cleaner Production*, 148, pp. 223-232. JUFO 2
II. Ramírez, Y., Kraslawski, A., and Cisternas, L. A. (2019). Decision-support framework for environmental assessment of water treatment systems. *Journal of Cleaner Production*, 225, pp. 599-609. JUFO 2
III. Araya, N., Ramírez, Y., Cisternas, L.A. and Kraslawski, A. (2021). Feasibility of re-processing mine tailings to obtain critical raw materials using real options analysis. *Journal of Environmental Management*, 284, 112060. JUFO 1
IV. Araya, N., Ramírez, Y., Cisternas, L.A. and Kraslawski, A. (2021). Use of real options to enhance water-energy nexus in mine tailings management. *Applied Energy*, 303, 117626. JUFO 3

Author's contribution

The author is the principal investigator and corresponding author in articles I and II, co-author in papers III and IV.

In article I, the author was responsible for the research plan conceptualization of the idea, literature analysis, methodology, data collection, data analysis, and implementation, and writing the original draft. Professor Andrzej Kraslawski and Professor Luis A. Cisternas supervised idea conceptualisation and were involved in writing review and draft editing.

In article II, similar to the previous article, the author was responsible for the research plan, the idea conceptualization, literature survey, methodology, data collection, finding analysis and implementation, and writing the original draft. Professor Andrzej Kraslawski and Professor Luis A. Cisternas supervised the idea conceptualization and wrote a review and edited the manuscript.

Article III research was led by Dr Natalia Araya. The author contribute to the development of the idea conceptualization, was co-responsible for the literature survey, finding analysis, writing the original draft and contribute to the data collection and development of the research design and methods. Professor Andrzej Kraslawski supervised the research development and provide proofreading. Professor Luis A. Cisternas supervised the research process and assisted the methodology development.

Article IV is a collaborative work with Dr Natalia Araya. The author was responsible for the research plan, idea conceptualization, methodology, literature survey, setting the model, finding analysis, and writing the original draft. Dr Natalia Araya was responsible for the research plan, idea conceptualization, methodology, literature review, implemented the model and analysed its results, finding analysis, and writing the original draft. Professor Andrzej Kraslawski supervised the research process and provide proofreading. Professor Luis A. Cisternas supervised the research development and the statistical analysis model.

List of other publications

The author published the following publications during her time as a doctoral student. However, they are not related to the topics concerning this dissertation.

Ramírez, Y., & Cisternas, L. A. (2021). El nexo energía y agua de mar en el contexto de la economía circular. *Economía Circular en Procesos Mineros*. RIL Editores. ISBN: 978-84-18065-78-1. *Book Chapter in Spanish.*

Lam, E., Montofré, I., & Ramírez, Y. (2020). Mine tailings phytoremediation in arid and semiarid environments. *Phytorestoration of Abandoned Mining and Oil Drilling Sites*. Elsevier. ISBN: 978-012-82-1200-4. *Book Chapter.*

Montofré, I., Lam, E., Ramírez, Y., & Gálvez, M. (2020). Evaluation of copper tailing amendments through poultry waste and ammonium nitrate. *Environmental Geochemistry and Health*, 43, 2213-2230. DOI: 10.1007/s10653-020-00745-6

Lam, E., Zétola, V., Ramírez, Y., Montofré, I., & Pereira, F. (2020). Making Paving Stones from Copper Mine Tailings as Aggregates. *International Journal of Environmental Research and Public Health*, 17, 2448. DOI: 10.3390/ijerph17072448

Ramírez, Y., Araya, N., Cisternas, L. A., & Kraslawski, A. (2019). Water-energy Nexus in Mine Tailing Management for Integrated Mining System. *Foundations of Mineral Processing & Extractive Metallurgy* (FoMPEN 2019). *Conference.*

Lara, G., Moreno, L., Ramírez, Y., & Cisternas, L. A. (2018). Modeling an Airlift Reactor for the Growing of Microalgae. Th*e Open Journal of Chemical Engineering*. 12, 80-94. DOI: 10.2174/1874123101812010080.

Herrera, S., Cruz, C., Ramírez, Y., & Cisternas, L. (2016). Conceptual process design for Boric Acid: A case study for engineering education. *Computer Aided Chemical Engineering* (Vol. 38, pp. 1437-1442). Elsevier. DOI: 10.1016/B978-0-444-63428-3.50244-7. *Book Chapter.*

Ramírez, Y., Fuenzalida, Y., Díaz, A., Leyton, Y., & García, A. (2016). Improving dissolved air flotation (DAF) to promote the seawater use and water reuse. *Water in Mining 2016, 5th International Congress on water Management in Mining*, Santiago, Chile. GECAMIN. ISBN: 978-956-9393-45-7. *Conference.*

Ramírez, Y., Cruz, C., & Kraslawski, A. (2016). Evaluación tecnológica: el sustento para la toma de decisiones en el uso de agua de mar. *Agua de Mar Atacama: Oportunidades y avances para el uso sostenible del agua de mar en la minería*. RIL Editores. ISBN: 978-956-01-0388-8. *Book Chapter in Spanish.*

García, A., Lara, G., Ramírez, Y., Moreno, L., & Leyton Y. (2016). Remoción de impurezas usando flotación por aire disuelto para el tratamiento de agua de mar y efluentes mineros. *Agua de Mar Atacama: Oportunidades y avances para el uso sostenible del agua de mar en la minería*. RIL Editores. ISBN: 978-956-01-0388-8. *Book Chapter in Spanish.*

Pokhrel, C., Cruz C., Ramirez, Y., & Kraslawski, A. (2015). Adaptation of TRIZ contradiction matrix for solving problems in process engineering. *Chemical Engineering Research and Design*, 103, pp. 3-10. DOI: 10.1016/j.cherd.2015.10.012

Ramírez, Y., Cisternas, L., Lara, G., Moreno, L., & García, A. (2015). Dissolved Air Flotation (DAF) to Improve the Reuse of Water in Mining Operations. *Hydroprocess 2015, 7th International Seminar on Process Hydrometallurgy*, Antofagasta, Chile. GECAMIN. ISBN: 978-956-9393-32-7. *Conference*.

Nomenclature

Abbreviations

AMD	Acid Mine Drainage
CAPEX	Capital Expenditures
CBA	Cost Benefit Analysis
CE	Circular Economy
CRM	Critical Raw Materials
DAF	Dissolved Air Flotation
DCF	Discounted Cash Flow
EIA	Environmental Impact Assessment
EU	European Union
FCM	Five Capitals Models
GHG	Greenhouse Gas
HOQ	House of Quality
LCA	Life Cycle Assessment
NPV	Net Present Value
OPEX	Operational Expenditures
ROA	Real Options Approach
TA	Technology Assessment
TBL	Triple Bottom Line
TSF	Tailings’ Storage Facility
UN	United Nations

1 Introduction

Energy and water are two essential resources and are requirements for human well-being and socioeconomic development (Fan *et al.*, 2019). Water is required for energy generation, and energy is needed for various processes related to water extraction, treatment, and distribution (Shrestha *et al.*, 2011). It is estimated that the global water demand is expected to increase by 55% by 2050, and the energy sector will maintain a high growth rate in the coming decades, with an estimated increase of over 80% globally (IRENA, 2015).

Therefore, the sustainability of energy and water are inextricably linked with each other. Intense utilization and degradation of these resources may occur due to changing climate, growing population, higher life quality, and increasing pollution, including greenhouse gas (GHG) emissions due to the burning of fossil fuels (Bukhary, Batista and Ahmad, 2020). The issues related to the growing demand for energy and water are considered problems of front and centre in the Sustainable Development Goals (SDG 6 and SDG 7) proposed by the United Nations (UN) (United Nations, 2016).

As two essential resources that underpin socioeconomic development and human well-being, energy and water are inseparably related. The energy necessary for supplying, treating, and using water and electricity is responsible for the most impacts of water treatment, particularly in desalination processes, because these are more energy-intensive than conventional water treatment processes. It is crucial to analyse the energy sources diversity given the effects of water treatment and consumption on the environment so that stakeholders can make informed decisions and expand public awareness (Ramírez, Kraslawski and Cisternas, 2019).

1.1 Background

Water scarcity occurs more frequently in arid regions. The pollution and use of underground aquifers and surface waters have reduced the quantity and quality of natural water resources available in many countries. More than 1 billion people lack drinking water, and approximately 40% of the world's population lives in regions with water shortages. Therefore, a trend arises towards intensifying desalination across the globe to reduce current and future water scarcity (Valavala *et al.*, 2011).

Northern Chile is an area with significant needs for water sources. Overexploitation of natural water resources combined with increased water demand has led to higher requirements for alternative water sources. Desalination and water reuse have been successfully incorporated to provide additional water to meet the mining industry's needs. Currently, the efforts are dedicated to promoting the use of seawater in mining operations, which is expensive and energy-intensive because these operations are placed at a significant altitude from sea level and a great distance from the coast. Water transportation is one of the main components of water supply costs and has a greater impact than water treatment. Water resources in northern Chile are insufficient to meet ecological, municipal, and industrial needs. In the future, the country's 70% of desalination capacity will meet the mining industry's needs.

Chile's primary metallic and non-metallic ore deposits are copper, gold, silver, iron, and salt lake minerals (Cisternas and Gálvez, 2014), and the larger mineral extraction plants are in the driest non-artic desert on earth, the Atacama Desert, where the country offers 6400 kilometres of seashore. Therefore, the use of seawater is mandatory (Cisternas and Gálvez, 2018). Nowadays, the processing of copper oxide ore is decreasing, and the extraction of copper sulphur ore is rising, which means the amount of water needed to produce the same mass of copper is larger (Mudd, 2010). Worldwide, mining operations can be found in a full spectrum of hydrological contexts, where local climate and hydrology dictate the requirements for the mining operation and the influence on water-related impacts on mines, communities, ecosystems, and industries (Northey *et al.*, 2016a).

Increasing pressure on water resources leads to a growing reliance on seawater desalination for the provision of freshwater (Ramírez, Cisternas and Kraslawski, 2017). The decision to use a specific desalination technique is influenced by the water profile to be treated, considering, for example, feed water salinity, product quality demand, and site-specific factors, such as labour costs, available area, energy cost and local electricity demand. Reverse osmosis is currently the leading technology for seawater desalination, and it is still quite expensive to meet the general needs of a mining site. Although, some mining processes do not require high-quality reverse osmosis water.

Mining comprises both mineral exploitation and processing operations has been historically one of the industrial activities that have contributed the most to humanity's economic development. Mining has served as the basis of several industries, including aerospace, automotive, ceramics, chemical, construction, cosmetics, energy, pharmaceutical, electronics, detergents, glass, metals, paints, paper, plastics, and fertilizers (Dubiński, 2013).

Currently, the higher demands for renewable energy technologies require more metal and non-metal mineral resources, which will increase the climate impact of resources (Suh *et al.*, 2017) and rising population pressures. To implement effectively green technologies, it is necessary that the mining industry and regulators accurately and transparently account for GHG emissions to implement mitigation strategies (Azadi *et al.*, 2020).

1.2 Motivation and Scope

Energy, water, and GHG emissions are among the most critical factors influencing sustainability due to the rapid industrialization and urbanization guiding severe environmental issues. The balance between environment, economy, and society is the consumption of energy and resources and the elimination of waste in a city, an integrated concept for sustainability (Yang *et al.*, 2018).

Several types of atmospheric emissions may affect the air quality during a mine operation. Generally, the most important emissions are CO, NOx, SOx, and other gases associated with fuels. Likewise, particulate material emissions are liberated, especially during the initial process stages (drilling, blasting, stockpiling, comminution, etc.), where the material presents relatively low moisture content. GHG emissions are also associated with mining through the consumption of fossil fuels in transportation and power generation (Ali *et al.*, 2017). Additionally, blasting with explosives, and fugitive methane emissions of varying intensity in coal extraction, depending on the mining method, mine depth, coal characteristics, and gas content in the mineral deposit.

The extraction and processing of metals from mined ores have an associated environmental cost. In 2011, metals were responsible for 18% of resource-related climate change and 39 % of particle matter health impacts. Considering the period 2000-2015, the climate change and particle matter health impacts of metals doubled. Impacts due to toxicity also increased in the same period but at a slower pace (Oberle *et al.*, 2019).

Nevertheless, the mining industry can also help mitigate climate change, for instance, by making available mineral resources for the development of clean technologies (Ali *et al.*, 2017), reforestation of areas affected by mining. The effective implementation of the latter at a regional scale has been questioned. Still, it has also been suggested to improve it through greater involvement with local communities, aiming to achieve a fairer distribution of responsibilities and economic benefits associated with a potential global carbon trading scheme (Hirons *et al.*, 2014).

The vulnerability and adaptability of mining operations to the effects of climate change potential risks must be considered before the beginning of a mining operation. For instance, in the global production of copper, where a significant part of the resources is located in zones with a high risk of water shortage, exploitation operations can become unfeasible (Northey *et al.*, 2017). This is predominantly relevant in developing countries with growing mining activity within their territories, coupled with the risks of water scarcity and other socio-environmental concerns in these regions. The interest in this topic by the mineral sector is still limited to the perceived distance in a time of the predicted impacts and the lack of long-term planning vision (Segura-Salazar and Tavares, 2018).

1.2.1 **Water in the Mining Industry**

The limited water supplies and increased risk of climate change affect the interactions between the mining industry and water resources globally. The interactions are often complex and site-specific (Northey *et al.*, 2017). On a global scale, mining is a relatively small water consumer, however at a local scale can be a major water consumer (Northey *et al.*, 2016b). In some cases, mining can be dominating, e.g., in the arid Antofagasta region in Chile, approximately 65% of water is used in mining operations (Donoso et al., 2013) and the same region, Las Luces plant is has operated only with seawater since 1995 (Moreno *et al.*, 2011). By 2031, Chile's mining water consumption is expected to be 23.3 m^3/sec, with 10.9 m^3/sec of seawater and a peak of 11.3 m^3/sec of seawater in 2030.

However, for the Antofagasta region is expected that 66% of the water consumption comes from seawater (Cochilco, 2021).

Flotation is the most common technique used for concentrating the ore, and it is one of the biggest water-consuming unit processes in the mine (Gunson *et al.*, 2012). In Chile, over 70% of water in the copper mining operations is consumed in flotation (Donoso *et al.*, 2013). Tools for reducing waste rock dilution and ore losses minimise the use of energy, water, and consumables concerning final valuable products and side rock (Lessard, De Bakker and McHugh, 2014). However, ore sorting and thus ore quality will affect the water quality in the subsequent flotation process (Foggiatto *et al.*, 2014).

Some other examples of seawater used in mining operations are extraction of copper, cobalt, zinc, and manganese by El Boleo, Mexico; copper and molybdenum by Sierra Gorda SCM, Chile; lead and zinc by Black Angel, Greenland; copper and gold by Batu Hijau, Indonesia; iodine by Minera Algorta Norte S.A., Chile; and copper by Minera Michilla, Antucoya, Minera Las Luces, among other, Chile. Additionally, saline water has been used for nickel and copper by Mount Keith and uranium by Beverly Uranium Mine, both in Australia (Cisternas and Gálvez, 2018).

The seawater must first be collected from the seashore, where it can be pre-treated or desalinated, transported through a pumping system, and finally arrive at the place to be used. Therefore, different aspects are relevant, such as the decision to use desalinated or raw seawater, the transport system effect, environmental elements, corrosion on the transport system and mining operations, the impact of seawater on metallurgical recovery, among other issues (Cisternas and Gálvez, 2018). In other cases, mining companies had to reduce water consumption because the water crisis had a more significant effect on mining companies' business than anticipated (Askham and Van der Poll, 2017).

The pressure to save more water and build zero-emission concentrators has become even more critical due to further depletion of freshwater resources, competition by other industries, farmers, local communities, and environmental pollution issues (Ridoutt and Pfister, 2010). The problem is acute for the mining sector since a given plant needs to secure a stable water supply (Thomashausen, Maennling and Mebratu-Tsegaye, 2018) and limit its discharges (Mudd, 2010). Meanwhile, it cannot change its location to adapt to the regional water composition and availability (Askham and Van der Poll, 2017). Hence, the economic value of water depends on water availability at the site (Ossa-Moreno *et al.*, 2018).

1.2.2 **Energy in the Mining Industry**

The energy requirements and cost of minerals and metals are affected by the different production routes of commodities, from ore mineralogy and grade, mining type and available technologies to resources for mining and processing. The three principal energy sources are diesel, grid electricity, and explosives. Where explosives are used for rock fracture, diesel is used for transportation or mobile machinery, and electricity is used for running machines, plants, and equipment in various stages of the mining operations. While explosives account for the lowest energy-related emissions, diesel and electricity consumption contribute substantially to mining's GHG emissions (Azadi *et al.*, 2020). These emissions attributable to the life of each mineral and metal will differ widely. For instance, in copper mining, crushing and grinding are the most energy-intensive in the production chain and the main contributors to GHG emissions (Azadi *et al.*, 2020).

Mineral and metallurgical processing operations such as grinding, flotation, roasting, and smelting consume a remarkable amount of energy. Land clearing, drilling, blasting, crushing, and hauling require considerable energy in the mining stage. For underground mining, compared with surface mining, there are additional energy requirements for ventilation, degasification, or water pumping. Transportation of the ore to the processing plants and refineries also adds to the energy-related emissions. Depending on the commodity type, it can be the most emission-intensive and expensive production stage. Although it was traditionally considered a less energy-intensive stage of the mineral life cycle, ore processing has become one of the most challenging stages for optimising and minimising the climate change effects of mining. Finally, with the progressive development of a CE, it has become clear that future development of industry-wide emissions- and energy-saving technologies can benefit from optimum waste management (Azadi *et al.*, 2020).

The mining sector heavily depends on energy usage, so energy consumption is a substantial part of the mineral and metal industries' GHG emissions and climate change effects (Azadi *et al.*, 2020). Although GHG emissions are only one aspect of mining impacts, heavy metal emissions, landscape changes, and access to local resources like water are others. Research on decision-making to use renewable energy in mining present a practical decision rule based on a principle of indifference between renewable energy and fossil fuel technologies and on proper time management to conclude that the decisions are based on capital and operational costs.

In the copper industry, the GHG emissions can also arise from the decomposition of carbonate minerals (siderite and calcite) during weathering and neutralization of waste rock, mine tailings, acid leaching and metallurgical processing. The emissions from carbonate mineral decomposition, generally substantial, are rarely quantified within the copper industry. Additionally, mines produce a mineral concentrate (20–40% copper) then transport it to centralized smelting and refining facilities to produce refined copper products (Azadi *et al.*, 2020).

Despite the urgent need to reduce energy consumption and achieve decarbonization in mining industries, some barriers constrain this change. The efforts to decrease energy usage are challenged by declining ore grades and increasing strip ratios (Mudd, 2007; Norgate and Haque, 2010). This change is due to the additional amounts of ore that must be mined and processed to deliver similar quantities of concentrates and metals and the increased depth of surface mines. It makes the mining operation life cycle more energy-intensive, with an increased carbon footprint of the produced minerals and metals.

Furthermore, the growing demands for minerals and metals due to the rising living standards have contributed to increased mining activities. These changes require other infrastructure, adding further to the demand for minerals and metals (Azadi *et al.*, 2020).

The potential co-benefits of energy saving, and water conservation are not considered when setting energy targets. If an in-depth understanding exists on energy and water use conditions and the water-energy nexus arise, the opportunity for simultaneously achieving energy savings and water conservation (Fan *et al.*, 2019). Generally, the correlation between water and energy policy can be explained by the interdependence between water-intensive and energy-intensive industries. Consequently, considerable water conservation can be achieved thanks to the transition into low-carbon productions and vice versa. E.g., China's energy sectors are challenged by climate change mitigation and water security to be developed in a low-carbon and low-water fashion. The co-benefits and trade-off management are of great importance for the energy system's robustness and sustainability (Fan, Kong and Zhang, 2018).

Energy input is needed in every system stage, such as wastewater collection, physical treatment, chemical treatment, sludge treatment, and discharge. For instance, wastewater treatment accounts for about 3% of the electrical energy load in developed countries. Also, electricity is utilized as the only energy source for pumping and carrying wastewater through tubes and the operation of most treatment equipment (Feng and Chen, 2016).

1.2.3 Sustainability in the Mining Industry

UN has been on the leading role in spreading Sustainable Development. Meeting the SDGs simultaneously is complex, given the multiple trade-offs involved between them. UN seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future, relating present and future generations (especially the poorest people), i.e., intragenerational and intergenerational equity. Additionally, several of these goals can increase the use of resources, e.g., water and energy (Segura-Salazar and Tavares, 2018).

Contrasting to the unrestricted growth of the mining industry in the past, some governments and institutions have been promoting the vision of the Club of Rome, which postulates that economic development is based on the continuous increase in extraction of primary mineral resources is not sustainable. The result is that the concepts of sustainability and sustainable development have since become progressively incorporated as a priority topic in regional and national government agendas in several developed and developing countries. Mining and mineral processing operations present low conversion efficiencies, high energy intensity, large volumes of tailings and emissions, and several impacts whose magnitudes generally increase as the production scale intensifies and run-of-mine ore grades drop. All of these contribute remarkably to the ongoing debate whether mining may or not be rigorously considered sustainable (Segura-Salazar and Tavares, 2018).

Sustainability has been commonly approached in mineral and metal processing from two perspectives focused on resource use and management and minimising the impacts of the production process (McLellan *et al.*, 2009). The life cycle concept in mining operations has been considered from two different perspectives, intersecting the mine operation stage: the Life Cycle of the Mining Project, related to the life of a mine and includes the phases from exploration until mine closure (Durucan, Korre and Munoz-Melendez, 2006; McLellan *et al.*, 2009; Bond, 2014; Pimentel, Gonzalez and Barbosa, 2016) even post-rehabilitation (Espinoza and Morris, 2017), and the Life Cycle of the Product associated to the value chain of a particular mineral resource or commodity, Life Cycle Thinking (McLellan *et al.*, 2009; Fleury and Davies, 2012; Pimentel, Gonzalez and Barbosa, 2016).

Compared to the other resource industries such as forestry, aquaculture, and agriculture, the mining industry is perceived as one of the least committed to sustainable development (Worrall *et al.*, 2009). A particular mining operation generally lasts from about one to several decades, until a point is reached when exploiting the mineral resource becomes unfeasible either due to the characteristics of the mineral deposit, the metal prices, or even due to government instabilities or impacts to communities and the environment (Segura-Salazar and Tavares, 2018).

Global extraction of natural resources increased from 27.1 billion tons to 92.1 billion tons between 1970 and 2017. In the same period, the average person consumed 65% more natural resources in 2017 than 50 years ago, despite an increase in per capita GDP of only 50 % (Oberle *et al.*, 2019). However, this activity has also been causing a series of social and environmental impacts that must be avoided in the future, changing the business-as-usual development model (Segura-Salazar and Tavares, 2018).

The mining and processing of copper and precious metals cause high toxicity impacts compared to their production amounts. Sulfidic mining tailings are the primary source of toxicity impacts for both metals. Processed materials are stored in tailing impoundment dams but can nevertheless involve continuous leaching of pollutants into the soil and groundwater and might additionally present risks of contamination from spills in case of failure (Beylot and Villeneuve, 2017). The predominant contribution of tailings to toxicity impacts can also be related to the large amounts of rock processed per mass of refined metal (Oberle *et al.*, 2019).

Metal ores (iron, aluminium, copper, and other non-ferrous metals) accounted globally for 9.5% of material extraction in 1970, then grew slightly to around 10% in 2017, representing an average growth of 2.7% per year highlighted the importance of metals for many consumer goods. The ferrous ores' extraction grew much faster, at a yearly average of 3.5% than non-ferrous ores, which grew at 2.3% per year. The high average growth rates for ferrous metals and non-metallic minerals construction reflect the major urban and transport infrastructure development in transitioning countries (Oberle *et al.*, 2019).

The climate change impacts on mining are often not fully accounted for, although the environmental effects of mineral extraction are widely studied (Azadi *et al.*, 2020). GHG emissions related to primary mineral and metal production were equivalent to approximately 10% of the total global energy related GHG emissions in 2018. In Chile, fuel consumption increased by 130% for copper mining, and electricity consumption increased by 32% per unit of mined copper from 2001 to 2017, due primarily to decreasing ore grade (Azadi *et al.*, 2020).

The minerals' industry has been subjected to growing pressures by governments and society towards adopting more sustainable practices. To better understand the potential impacts, either positive or negative, that may be related to the extractive activities, as well as responding to these pressures, and there has been a significant growth of interest in sustainability in the mining industry (Worrall *et al.*, 2009; Fitzpatrick, Fonseca and McAllister, 2011). Various initiatives have been proposed to deal with diverse aspects of sustainability in the mining sector (Fitzpatrick, Fonseca and McAllister, 2011; Moran *et al.*, 2014).

1.3 Research Gap

The boosted stress on natural resources emphasises the need to improve the understanding of these resources using data to ensure equitable and safe access to natural resources for humans and the environment (Chini and Stillwell, 2018). The complex relationships between the environment and humankind are being studied and modelled at multiple scales over the interdependence analyses involved in the management of water, energy, minerals, soil, and food (Giurco *et al.*, 2014; Hamiche, Stambouli and Flazi, 2016; Tan and Zhi, 2016; Zhang and Vesselinov, 2016; Tokimatsu *et al.*, 2017; Dai *et al.*, 2018). There are ongoing debates on managing mineral resources from a more holistic standpoint, which considers potential scarcity for future generations and strategies for efficient use of resources and recycling (Segura-Salazar and Tavares, 2018).

Water accessibility and cost are critical features for the economic and environmental viability of current and new mining projects (Oyarzún and Oyarzún, 2011). The mining industry interaction with water resources is highly complex and site-specific, where impacts on hydrology and water quality can be found throughout all stages of mine's life (Northey *et al.*, 2016a). The impacts of mining relating to water consumption and how these are managed can influence the development and maintenance of social licence to operate. Sustainable assessments involve developing and examining the vast amount of data to generate a set of viable alternatives for decision-makers to judge. Therefore, strategic decisions and compromises must be made to assess a system, with clearly delimited boundaries, without disturbing its interactions with the outside world and observing the consequences of the assessment results.

Efficient management of energy, water and waste in the mining operations associated with these impacts becomes even more critical from the standpoint of sustainability due to the progressive decline in average run-of-mine ore grades (Caron, Durand and Asselin, 2016; Pimentel, Gonzalez and Barbosa, 2016). The trend towards highlighting the reduction of environmental impacts per tonnage of product and not in absolute terms has also been observed (Segura-Salazar and Tavares, 2018). However, this approach would lead to misinterpretations concerning the management of the impacts, since efficiency improvements are challenged by the rebound effects associated with the rate and the magnitude of the natural resources use, as a function of the demand for consumption of goods and services (McLellan *et al.*, 2009).

Demand for large amounts of high-quality water requires a more comprehensive analysis of how water treatment processes are managed. Looking for new sources or improved treatment methods while testing new technologies or improvements to existing ones is expensive and time-consuming. Technology Assessment (TA) covers all the critical areas involved in the analysis to provide an unbiased decision-making process. However, TA methods lacked benchmark technologies designed to have similar results but operated via different process mechanisms. The technologies have independent variables that differ from one another. Ergo, the input water quality of the reference cases - the basis of the TA - varies. Still, output water quality demand, investment cost, operational cost, effectiveness, and operational simplicity are suitable for comparisons (Ramírez, Cisternas and Kraslawski, 2017).

Environmental assessments involve the elaboration and analysis of a large amount of data. Decision-makers must manage considerable amounts of information just to obtain a viable set of alternatives. Individual tools have limitations considering boundary conditions, spatial specifications, interventions, and types of impact. Nevertheless, integrated tools intensify complexities and problems in modelling or analysing all rising and interactive environmental effects (Chen, Ngo and Guo, 2012) and call for substantial effort to meet methodological requirements (Svanström *et al.*, 2014). The assessment methods require extensive data and information, and some authors propose to rice the number of variables to improve the framework's effectiveness (Cominola *et al.*, 2015). Although, more indicators do not necessarily lead to a better average result since weighing the indicators and deciding about their relative importance may increase the uncertainty (Strezov, Evans and Evans, 2017).

It is necessary to develop tools that enable a quantitatively analyse of relative environmental impacts for pro-ecological measures to be taken to replace current practices; to improve implementation of the concepts and approaches of Cleaner Production, i.e. application of the overall preventive environmental management strategy for processes and products (Fijał, 2007). There is a lack of reliable environmental assessments with consistent data (Lundie and Peters, 2005; Andersen *et al.*, 2012). In particular, the challenge to a comprehensive environmental evaluation of energy and water is that it requires exhaustive data collection (Fan *et al.*, 2019).

Therefore, there was a lack of a decision-support method to environmentally assess the influence of energy consumption in water treatment systems (energy-for-water component of water-energy nexus) and its impact onto the environment, since water quality needs, water distribution systems, and how different energy combination setups affect these variables. Thus, a framework that provides a fast and straightforward analysis facilitates obtaining results that endorse the decision-making process (Ramírez, Kraslawski and Cisternas, 2019).

The valorisation of mine tailings is a critical component to achieve CE in the mining industry, which needs to improve its processes to minimise the environmental impacts of mining waste (Lèbre, Corder and Golev, 2017; Tayebi-Khorami *et al.*, 2019). The valorisation of tailings is still in the early stages. Nevertheless, it is expected to improve since tailings processing management may be minor related to the operation's OPEX and CAPEX, and tailings are a significant liability issue to the mining companies. New approaches are needed to prevent the challenges related to tailings storage and recover the potential business value related to tailings (Kinnunen and Kaksonen, 2019). Also, the concentration of critical material found in mine tailings is low, the technologies needed for its extraction are underdeveloped, and the uncertainty of the metal market price rice the uncertainty of the project. Therefore, a flexible economic evaluation that considers the high uncertainty variables found in these projects was missing (Araya, Ramírez, Kraslawski, *et al.*, 2021).

An economic approach was missing that allows a flexible assessment of investment decisions when traditional methods indicate that a project is not economically attractive. For instance, a strategy re-evaluates the project to determine whether the project development option is financially feasible. There are many opportunities for projects improvement that may eventually lead to the successful valorisation of mining waste (Araya, Ramírez, Kraslawski, *et al.*, 2021).

Closing the water loops in mining requires developing new methods to control and optimise water qualities for all process steps. The closure of water cycles will inevitably result in process disturbance and instability. Complete water recycling requires new holistic water management in mining. However, closing the water loop may turn into a loss of information and understanding of what flows inside and outside a given plant. The objective is then to determine how much and which kind of water can be extracted from (or discharged to) the surrounding water resources, stored, or recirculated internally, and in which internal unit operations. Therefore, tailings and mine water issues should be considered simultaneously, not separately. Ore sorting affects the ore quality, which further affects the water quality in flotation and tailings in further applications or disposal. The closed water loops are only possible when the tailings are filtered and stacked dry (Kinnunen *et al.*, 2021).

Furthermore, there is a very scarce understanding of the final balance of a fully recycled water system. The end-of-pipe management usually considers the effluents and wastes valueless, only increasing extra costs (Zotter, 2004). However, the water and waste streams contain a value, which can be utilized. Metals content from recycled water can be recovered (Shadrunova and Orekhova, 2015). Water can be modified to be suitable to specific process steps that will improve the economic value of the ore (Kinnunen *et al.*, 2021).

The economic assessment was missing for sustainable mine tailings and water management to be used in the mining industry to evaluate the relationship between water supply and dewatering technologies and optimise energy and water consumption. Assess the economic output of several options to supply water and treat mine tailings allows identifying and transparent presentation of investments and management options. Investments in mining are characterized by huge uncertainty due to the market conditions, technical issues, and complexity of new projects. Therefore, it was the need for a flexible method to choose between different water management options, as a combination of different water treatments for the water supply and dewatering technologies to the mine, highly influenced by the energy consumption, and to provide an analysis of consequences of delaying or speeding up managerial decisions and that could contribute to the reduction of financial and operational risks (Araya, Ramírez, Cisternas, *et al.*, 2021).

1.4 Study Purpose Objectives and Research Questions

The dissertation aims to provide an insight into the decision-making process to ensure the sustainable operation of mining processes and the related reprocessing of production waste. It is obtained through a comprehensive assessment of technological, environmental, and economic aspects of the operations concerned. The water-energy nexus analysis is applied through the development of frameworks, to facilitate and support the decision-making process to improve the water and waste management in the mining industry that leads to a circular economy.

1. Conduct a technology assessment of desalination pretreatment processes.
   1.1. Is DAF a suitable technology for seawater desalination pretreatment?
   1.2. How does DAF can be improved to meet stakeholders demands?
2. Provide an analysis of the influence of energy consumption in water treatment systems (water-energy nexus) and its impact on the environment.
   2.1. How energy consumption affects the environment due to water treatment and distribution systems?
   2.2. What is the relationship between water and energy in the copper mining industry for different tailing disposal methods?
3. Provide an analysis of plausible alternatives to promote the circular economy model in the mining industry
   3.1. How can water treatment and distribution systems' environmental impacts be reduced?
   3.2. What alternatives can promote the circular economy model in the mining industry?

1.5 Dissertation Outline and Structure

This thesis title Water-Energy Nexus for Waste Minimisation in the Mining Industry presents the work done during the PhD studies. This PhD dissertation was written under a joint supervision (cotutelle) agreement between Universidad de Antofagasta, Chile, and LUT University, Finland.

This dissertation involves five chapters. Each chapter is divided into several sub-sections. The first chapter contains the research background, the motivation and scope behind the research, the definitions of the objectives concerning the study, and the dissertation outline. The second chapter discusses previous research as the State of Art, giving an overview of the literary contexts. The third chapter, the research methodology, explains how these methodologies are used to serve the research objectives. The fourth chapter provides overviews of the publications included and their respective results and discussions. The fifth chapter provides the main contributions of the study, limitations and future work concerning the research.

2 State of the Art

2.1 Sustainability Science

Agenda 21 and the Berlin Guidelines (Berlin Round Table on Mining and the Environment established by the UN and the German Foundation for International Development) defined fundamental principles for mining throughout its life cycle, such as regulatory frameworks, environmental management, socioeconomic impact assessment, continuous participation of the communities and stakeholders, and technology transfer for environmental impact mitigation, among others (Segura-Salazar and Tavares, 2018).

The concepts and models such as Sustainable Development and Five Capitals Models (FCM: Natural, Human, Social, Manufacture, and Financial Capitals) have been gradually developed and incorporated in sustainability science from an overall economic and anthropocentric perspective. Meanwhile, the applications of the models can make the transition to sustainability easier, the misinterpretations, giving greater attention to financial aspects (as in the business-as-usual model) and deepening the current ecological imbalance and social inequity. In Weak Sustainability, the capitals may be interchangeable, as contrary to Strong Sustainability, emphasizes nature as fundamental and even irreplaceable by other “capitals” (Kuhlman and Farrington, 2010).

2.1.1 Sustainability in the Mining Industry

Sustainability in the supply and demand of mineral goods is becoming progressively more relevant from the geopolitical standpoint. The difficulty in finding high-quality mineable resources in strong mining economies leads to several new exploitation projects in developing countries (Moran *et al.*, 2014) and regions with poor governance (Segura-Salazar and Tavares, 2018). Although, a positive correlation has been reported between the exploitation of mineral resources and the economic growth in some countries such as Chile, Indonesia, Botswana, China, and India, being the last two the greatest responsibility for the significant increase in the rate of exploitation of minerals that started in the 1980s (Dubiński, 2013).

There are different interpretations of sustainability and sustainable development in the minerals’ industry, which have been based mainly on the original definition from the Brundtland Commission and in either one of the two main sustainability frameworks: Triple bottom line (TBL) and FCM. The Brundtland Report defined sustainable development as the development that meets the present generation needs without compromising the future generation's ability to meet their own needs (Brundtland Commission, 1987). The definition contains two key concepts: the “needs”, particularly the essential needs of the world's poor, which requires priority, and the restrictions imposed by the state of social organization and technology on the ability of the environment to meet present and future needs (Musango and Brent, 2011).

While there are some points of convergence regarding the need to adopt a more systemic approach to sustainability in the mineral sector in different domains and contexts, there is still disagreement regarding which dimensions of sustainability must be explicitly considered. Although there is a consensus on the importance of the environmental, economic, social, and governance aspects at the public and private levels, where the role of responsible and sustainable technological innovation for the minerals' industry has been largely underestimated (Segura-Salazar and Tavares, 2018).

Sustainability challenges in the minerals' industry are based on the interacting elements: society (community, workers, NGOs, etc.), economic system (or economy), natural environment (ecosphere = geosphere + biosphere), technology (artificial environment, artefacts or Technosphere), and governance (public/political and private/corporate leadership). These components interact and must be balanced in different time scales and spatial locations (Segura-Salazar and Tavares, 2018).

Resource efficiency in mining supports climate change mitigation through reduced and cleaner production to meet the exact demand. Developments had been made in ore processing (Zhang *et al.*, 2015; Behera and Mulaba-Bafubiandi, 2017; Rahman, Pudasainee and Gupta, 2017; Yang *et al.*, 2019; Lishchuk *et al.*, 2020), mining waste management (Edraki *et al.*, 2014; Sun *et al.*, 2018; Park *et al.*, 2019; Qi and Fourie, 2019; Clarkson and Williams, 2020), reprocessing and recycling (Falagán, Grail and Johnson, 2017; Peelman *et al.*, 2018; Botelho Junior, Dreisinger and Espinosa, 2019; Naidu *et al.*, 2019), and technologies (Azadi *et al.*, 2020).

Mineral depletion is a recurrent concern in natural resources' management. Minerals stand as primary inputs in technological development and improve standards of human living. Given the wide use of minerals in modern society, long-term mineral depletion is critical for policymakers and society (Castillo and Eggert, 2020) where the society covered scarcities as one or a combination of approaches: developing new mineral sources and energy resources, using more efficiently resources and developing substitute sources of energy or materials (Castillo and Eggert, 2020).

The rational acquisition and use of natural resources are central to sustainable mineral development (Dubiński, 2013). Despite increasing extraction costs, the finite nature of minerals is still unclear (Mudd, 2013). Mineral depletion may start to occur sooner than expected, advising policymakers to take planned and coordinated actions at a global scale, interfering in mineral markets to promote sustainable development goals (Ali *et al.*, 2017), to control environmental losses and correct the trend, according to the society's perspective, of private actors to underinvest in technological innovation (Tilton *et al.*, 2018).

Three types of scarcities of mineral resources have been reported: absolute, related to the geological aspects; temporary, when the supply is smaller than the demand; and structural, when some metals are coproduced along the production chain of other metals and their suppliers do not necessarily respond to market demand (Segura-Salazar and

Tavares, 2018). In general, the perception of scarcity may be more associated with the time (Ali *et al.*, 2017) and the large investment of new extractive operations demand, as well as to the management of the impacts related to the exploitation and use of minerals, rather than to the actual availability of mineral deposits. A significant part of the mineral resources has not been explored for geopolitical and economic reasons and geographic inaccessibility. It has been mainly focused on high-grade deposits (Segura-Salazar and Tavares, 2018). For instance, copper, whose relative abundance contrasts with the supply risks associated with the high demand for it, the difficulty in replacing it, the progressive drop in run-of-mine ore grades on a global scale, and the geopolitical and climate change risks (Ali *et al.*, 2017; Northey *et al.*, 2017).

The degree of criticality of minerals has been recently defined considering criteria such as supply risk, vulnerability to supply restriction and environmental implications. Criticality and scarcity concepts have been related to society's value on each resource in terms of their usefulness. One of the most critical resources is energy, which relies heavily on socioeconomic development. Growing production may not meet current and future global demands in the next two decades. Energy consumption becomes even more critical considering that most energy sources are still non-renewable. There is a high demand for energy and mineral resources in developing alternative energy sources (Brown *et al.*, 2014).

Recycling represents one possible pathway towards decreased environmental impacts deriving from metal use and reducing minerals’ criticality. Metals are ideal candidates for closing material loops in a CE approach. They can be melted and reused indefinitely if alloys are not contaminated by weakening or toxic elements. In general, secondary production considerably reduces the environmental impacts of metal use because it avoids the impacts of the extraction and processing of ores (Oberle *et al.*, 2019).

More sustainable use of mineral resources is possible, as extracting minerals' environmental and social costs are compensated and satisfy all stakeholders. Mining activities must be carried out to minimise all possible impacts caused during all stages of its life cycle through practical and proactive environmental management. The strategy should go beyond meeting local environmental standards, given the global scope of these activities and the wide variability of environmental legislation worldwide, particularly in developing countries where it is not often as rigorous. It is also necessary to increase the durability of products, dematerialising products and services while maintaining their functionality, replacing potentially key materials, and closing the life cycle of materials through increased recycling and reuse rates (Segura-Salazar and Tavares, 2018).

2.1.2 Environmental Impacts of Mining

The environmental impacts caused by mining are often associated with the physical changes in the mining area and the impact of the activity on the soil, water, and air. The soil can be potentially impacted by tailings containing chemical reagents. Heavy metal wastes can contaminate the soil and water by natural processes such as erosion, rains, and flooding, thus affecting the ecosystems nearby. This becomes critical given the unpredictable nature of such events globally due to climate change. Alteration in the natural landscape is unavoidable in mining. This can impact the environment and create discomfort to the population, mainly when communities already inhabit the area where a new mining project is to be established. However, this impact can be mitigated from the beginning of the operation and after its closure by restoring the degraded area to preserve natural species and the soil for future activity. In underground mining, the landscape and soil can also be impacted by land subsidence, depending on the area topography and its surroundings (Bian *et al.*, 2010). Impacts from mining activity associated with deforestation have also been reported (Horsley *et al.*, 2015).

As the consumption and demand for natural resources increase and the run-of-mine ore grades drop, mining projects are pressed towards increasing their scale so that potentially impacted areas and mining waste volumes will increase accordingly (Adiansyah *et al.*, 2015a). Tailings can be disposed in different forms, preferentially removing a significant part of the water associated with them. Still, the most common method remains disposal in tailings dams (Schoenberger, 2016). Removing water from the tailings and recycling are steps forward in sustainable mining. In addition to conventional tailings, there are also technologies and existing applications for thickened tailings and tailings paste (Adiansyah *et al.*, 2015b) (up to 70–80% of solids, 30–50% of solids in current operations).

The advantages of removing thickened tailings are the recovery of water and process reagents and the possibility for mine backfill, reduction in Acid mine drainage (AMD) potential, and risk for a dam failure. Reducing the water content in the tailings can increase water efficiency and recycling and reduce the risks associated with dam failures (Adiansyah *et al.*, 2015b). The production of thickened tailings and the corresponding recovery of more water is a more energy-efficient option than the production of conventional tailings with the needed water make-up (Ihle and Kracht, 2018). As the water and electricity costs are expected to increase, the high-density tailings' disposal options are getting more interesting and economical.

Considering the growing trend in mining waste generation in a business-as-usual scenario, the risk of collapse of these dams may increase. This is the main source of environmental and socio-environmental disasters associated with mining activities (Edraki *et al.*, 2014; Schoenberger, 2016). Effective on-site waste management is critical to the sustainability of the minerals' industry. The presence of a robust regulatory environment is a crucial factor in preventing these disasters. This requires a greater commitment from the mining companies to meet high standards of safety related to waste management and mine area rehabilitation in the context of each region, which can be planned from the design stage of the mine and processing plant and executed until the end of the productive cycle (Segura-Salazar and Tavares, 2018).

Ore sorting decreases the volume of mine tailings and water use, where ore has a crucial effect on water and tailings quality (Kinnunen *et al.*, 2021). Ore sorting aims to remove the non-valuable material initially at a coarse particle size to avoid barren processing material below the cut-off grade. The processing would cost more than the value of the metal (Gülcan and Gülsoy, 2017). Therefore, sorting reduces the amount of material to be milled and thus the energy costs (Lessard, De Bakker and McHugh, 2014). Also, it reduces the water consumption at the beneficiation plant, enables selective beneficiation, and produces coarse dry waste (Foggiatto *et al.*, 2014). While the head grade of the feed increases, water, energy, and reagent consumption decrease (Lessard *et al.*, 2016). Water consumption per ton of product declines when fewer tons of ore at a higher grade are processed.

For sulphidic ores and sulphidic host rock, a subaerial deposition of tailings will lead to oxidation of the sulphides and the subsequent formation of AMD. Therefore, the deposition of these tailings is one of the significant challenges when closing water loops in the mineral processing plant. However, if the tailings contain considerable aluminium and silicon, they could be used as solid precursor materials for alkali-activated materials or geopolymers (Ahmari and Zhang, 2012; Gitari *et al.*, 2018; Manjarrez and Zhang, 2018). As a result, these tailings can be used for various applications rather than deposited as waste material (Lam *et al.*, 2020; Marín *et al.*, 2021). However, when economically and technically feasible, the principle of alkali-activated tailings can also be applied for construction purposes at the mine site or elsewhere, potentially generating additional value from the tailings. From the perspective of the mine operator, the best-case scenario is a complete valorisation of the tailings, preferably with no deposition at the surface level. Besides an ecological benefit, this could also result in an additional economic value for tailings management (Kinnunen *et al.*, 2021).

2.1.3 Social License to Operate and Legal Requirements

The social license is related to the technological aspects. It can be considered from the conceptual design stage of a mining operation through research and development to anticipate possible concerns and expectations from stakeholders about incorporating new technologies, according to each operation's different contexts (political, geographic, geological, and social). Besides the "social license to operate" concept, the social dimension has been gaining more attention in the minerals' industry context through the concept of "responsible mining", considered more comprehensive in the production chain than the former. However, it cannot deal with matters such as the consumption and discarding of products, the total reductions in the use of resources, the availability of secondary mineral resources and the rebound effect (Giurco *et al.*, 2014).

For social acceptance, the increased demand of communities worldwide to be involved in the decision-making processes for local mining projects, have a greater share of benefits and obtain assurances of safe and responsible mineral development (Prno, 2013). At the same time, legal compliance with state environmental regulations is not considered entirely sufficient in satisfying societies' expectations concerning mining (Mancini *et al.*, 2018).

Some critical factors for obtaining and maintaining the "social license to operate" are the involvement of all stakeholders, including communities, local authorities, workers, government, industry, NGOs, universities, shareholders, contractors, etc. (Azapagic, 2004); definition of strategies for effective communication and participation of the public, creating good long-term and collaborative relationships between the stakeholders (Prno, 2013); and fairer distribution of the costs and benefits that arise from mining activities (Fleury and Davies, 2012; Prno, 2013).

The implementation of leading practices can improve the sustainability of mine sites when environment, economics, community, safety, and resource efficiency are considered. It is also evident that impacts over the entire life cycle of a mine operation need to be considered, including the supply chains for additives and energy used in the mine (Mancini *et al.*, 2018).

From the social standpoint, one of the main origins of conflicts between mine projects and communities is the perception of the competition for water in terms of quantity and quality. Such a situation worsens in periods of severe drought like the one experienced in the Andean region from 2010 to 2020 (Kinnunen *et al.*, 2021). Technological progress, legal requirements, and the principles of sustainable development force the water supply service providers to ensure the continuous water supply of suitable quality for human consumption (Kończak and Janson, 2021).

Wise water governance is no longer exclusive of government domain, even though water is and, in general, will remain a public resource (Chile is an exception) with the government in a primary role. With most water being used for producing consumer goods and with product supply chains becoming complex and global. The rising awareness that companies, consumers, and investors have a key role. The interest in sustainable water use grows quickly in civil society and business communities (Hoekstra, Chapagain and Zhang, 2016).

A unified policy framework for water and energy can be beneficial considering the high interrelationship of the two resources. Water fees can contribute to industrial water conservation, but the effect is limited under the current water fee level. The carbon tax adoption might further improve water-saving benefits. Furthermore, water fees and a higher carbon tax can also enhance GHG emission reduction goals (Fan, Kong and Zhang, 2018). Changes in policies and resource utilization regarding energy and water affect GHG emissions and contribute to environmental pollution (Nair *et al.*, 2014; Gu *et al.*, 2016).

2.2 Water-Energy Nexus

Nexus is defined as the interlinkage between different resources or an analysis method to quantify the links between the nexus nodes, i.e., energy, water, food, and carbon emissions (Zhang *et al.*, 2018). Circular Economy (CE) is focused on resource circularity, while the focus of Nexus is on understanding and analysing interlinkages between resources. Notwithstanding this distinction, both concepts share common aims of resource sustainability and waste minimisation (Parsa, Van De Wiel and Schmutz, 2021).

The Nexus concept has gained adhesion in scholarly literature and policy settings after World Economic Forum's 2011 report on water, energy, food and climate nexus (World Economic Forum, 2011) and Hoff's background paper for the Bonn 2011 Conference on energy, water, and food security nexus (Hoff, 2011), emerging Nexus as new approach sustainability.

In recent studies, the interdependence between the three environmental factors has been increasingly emphasized. In particular, the majority of researchers have focused on the environmental factor nexus within an individual sector (Ackerman and Fisher, 2013; Nair *et al.*, 2014; Liu *et al.*, 2015; Nogueira Vilanova and Perrella Balestieri, 2015; DeNooyer *et al.*, 2016; Thiede *et al.*, 2016; Feng and Chen, 2016; Gu *et al.*, 2016; Hennig, 2016; Valek, Sušnik and Grafakos, 2017; Wang *et al.*, 2017; Wu and Chen, 2017; Helmbrecht, Pastor and Moya, 2017; Lee *et al.*, 2017). For instance, the water pressure in energy sectors (e.g., thermoelectric power industry, hydropower industry, solar power industry, etc.) has been widely studied, and suggestions for water-saving were proposed from the perspective of technology improvement, policymaking, and trading patterns, among others (Liu *et al.*, 2015; Okadera *et al.*, 2015; DeNooyer *et al.*, 2016; Hennig, 2016; Wu and Chen, 2017). Whereas, the trade-offs were investigated between energy and water in the water sector, based on the consideration that the water withdrawal, supply, distribution processes, and wastewater treatment require large amounts of energy (Nogueira Vilanova and Perrella Balestieri, 2015; Feng and Chen, 2016; Helmbrecht, Pastor and Moya, 2017; Lee *et al.*, 2017; Valek, Sušnik and Grafakos, 2017). And a few researchers considered GHG emissions for nexus analysis in energy or water systems (Ackerman and Fisher, 2013; Nair *et al.*, 2014; Gu *et al.*, 2016). In addition, some researchers focused on the energy-water-carbon nexus within other industries, e.g., the manufacturing industry, the steel industry, and the service industry (Dawadi and Ahmad, 2013; Venkatesh, Chan and Brattebø, 2014; Thiede *et al.*, 2016; Becken and McLennan, 2017; Wang *et al.*, 2017; Chhipi-Shrestha, Hewage and Sadiq, 2017; Pinto *et al.*, 2017; Yang *et al.*, 2018; Meng *et al.*, 2019; Tamaddun, Kalra and Ahmad, 2019; Bukhary, Batista and Ahmad, 2020; Ravar *et al.*, 2020).

To achieve sustainability, economic viability, and reduction of environmental impacts, a comprehensive understanding of the nexus between water and energy is essential. The nexus approach involves understanding the interdependencies and linkages between water and energy on multiple spatial and temporal scales, finding solutions in an integrated manner to assist in decision-making about resource utilization and development, and ensuring resource sustainability (Chhipi-Shrestha, Hewage and Sadiq, 2017).

Economic growth, coupled with population expansion and rapid urbanization, will impose great pressure on water and energy resources (Fan, Kong and Zhang, 2018). Given the concerns on water and energy crisis, a growing emphasis, particularly by scholars, has been placed upon the nexus thinking of the two resources concerning utilization pattern and corresponding policymaking, which promises renewed opportunities to create pathways for sustainable resource management (Scott *et al.*, 2011; Qin *et al.*, 2015). The concept of the water-energy nexus provides an opportunity to consider energy savings and water conservation simultaneously (Fan *et al.*, 2019), this concept can focus on efficiently managing both resources through a systematic analysis of the interactions between energy and water (Fan *et al.*, 2019).

The nexus thinking indicates that the development plan of one sector can impose significant implications on the other, either positive or negative, implying both co-benefit and the trade-off will exist in future development pathways of the two resources. Therefore, integrative policymaking aims to identify the leverage point to manage the co-benefits and trade-offs and optimise the interconnections within water and carbon pricing policies (Fan, Kong and Zhang, 2018). Energy and water are fundamental inputs for production. In these two sectors, the co-benefit may exist in the parallel production chains of industrial sectors. This refers to the considerable water conservation benefits achieved via industry transition into a low-carbon development pathway (and vice versa) due to significant interdependence among water-intensive industries and energy-intensive industries (Fan, Kong and Zhang, 2018).

In general, water-energy nexus-related studies fall into two major categories. One focuses on the water requirement of the energy system and its impact on water resources. For instance, increased energy consumption and GHG emissions during the water supply and treatment processes (Siddiqi and Anadon, 2011; Cheung, Mui and Wong, 2013), water resource constraints for the coal industry (Shang *et al.*, 2017), cooling water for coal-based power generation (Ali and Kumar, 2015), and water issues associated with renewable energy such as hydropower (Gjorgiev and Sansavini, 2017), wind power (Yang and Chen, 2016), and solar power (Wu and Chen, 2017). And water-energy nexus studies focuses on the energy requirement of water systems (Ghaffarpour *et al.*, 2018), renewable energy-based water treatment technologies (Wang, He and Liu, 2018). Energy requirements for water production, treatment, end-use, reclamation, and disposal (Plappally and Lienhard V, 2012), and energy efficiency of thermal power technology (Wang and Wang, 2017), limited water endowment and increased water demand for energy extraction, processing and conversion, including fossil fuel production (Shang *et al.*, 2018), bioenergy production (Gerbens-Leenes *et al.*, 2012; Pacetti, Lombardi and Federici, 2015), and power generation (Ackerman and Fisher, 2013), highlighting the water guarantee in energy system sustainable development, quantification of the water use of the UK electricity sector (Byers, Hall and Amezaga, 2014), among others. Although some works are focus outside the energy and water industry. Recycling water, using saline water, and developing new technologies that use less water are proposals to alleviate freshwater use in extracting fuel from oil sand (Ali and Kumar, 2017).

It is recognized that energy is required to extract, transport, treat, store, deliver, utilize, and dispose of water (Plappally and Lienhard V, 2012). The water treatment process becomes part of the water-energy nexus as energy is consumed to treat and distribute the water. The source of the raw water may be surface or ground. Energy may also be expended during the raw water extraction from the ground, lakes or rivers, and then during the conveyance to water treatment facilities (Valek, Sušnik and Grafakos, 2017). After the community uses the supplied water, generated wastewater is collected and treated at wastewater treatment plants, which requires further energy expenditure. Operations related to water treatment and distribution are energy-intensive. According to a study by the UN Organization, globally, about 8% of the total energy consumption is related to water pumping, treatment, and distribution (Bukhary, Batista and Ahmad, 2020).

The energy requirements related to water supply and treatment may vary due to sources water characteristics, source water intakes, contaminant levels, and efficiency of the motors used in water supply and treatment equipment. Therefore, the nexus is unique for each case and influenced by the climate, the energy and water technologies used, and the geographical location (Venkatesh, Chan and Brattebø, 2014). Energy consumption related to water treatment is affected by the growing population, increasing water demands and changing climate (Brown, Mahat and Ramirez, 2019; Hashempour *et al.*, 2020). The changing climate may disrupt the water supply and affect water availability and quality (Ifaei, Safder and Yoo, 2019). Then, there has been an increased emphasis on the placement of stricter water quality standards, in recent years, as well as the use of improved technologies for drinking water treatment for the removal of pharmaceuticals, disinfection by-products, and endocrine disrupters, among others (Amoueyan *et al.*, 2017, 2019, 2020). However, the advanced treatment technologies, including ozonation, ultrafiltration, and RO, which can meet such standards, are energy-intensive (Taylor, Ahmadiannamini and Hiibel, 2019; Bailey, Ahmad and Batista, 2020). The approach of using renewable energies can potentially be used to meet the rising energy requirements of the water sector (Rothausen and Conway, 2011).

The boosted stress on natural resources emphasises the need to improve the understanding of these resources using data to ensure equitable and safe access to natural resources for humans and the environment. The inclusion of water-energy nexus principles into modelling frameworks enables more understanding and better decision-making. The complexity can be reduced by dividing the analysis of the water-energy nexus into two components: energy-for-water and water-for-energy (Chini and Stillwell, 2018). By working with only one component, energy-for-water manages more variables and better analyses the system in question and its interactions.

2.3 Circular Economy

A CE is an economic system that substitutes the ‘end-of-life’ concept with reducing, reusing, recovering and recycling materials in production, distribution and consumption processes to accomplish sustainable development (Kirchherr, Reike and Hekkert, 2017). The CE concept has its theoretical roots in the academic field of environmental economics, gradually emerging in the 1960s in response to the rising concerns about inconsistencies between economic growth and environmental sustainability (Wiesmeth, 2021). The more technical-practical perception of the CE approach is deeply grounded in industrial ecology and its engineering, science and technology (Wiesmeth, 2021), thriving after being adopted by China in 2002 and later EU as a new development strategy (Kalmykova, Sadagopan and Rosado, 2018).

In a CE, resource use is improved by minimising the extraction of natural resources, maximising waste prevention, and optimising the environmental, social, material and economic values throughout the lifecycles of materials, components and products (Velenturf and Purnell, 2021). The concept CE boost economic performance without consuming resources at a rate that exceeds the Earth's capacity (Stahel, 2010). CE achieves the decoupling of value creation from the consumption of finite resources by leveraging a range of efficiency, productivity, and restorative-oriented strategies (circular strategies) to keep products, components, and materials in use for longer (Foundation, 2015). Therefore, CE holds great promise as a contributor to sustainability (Ghisellini, Cialani and Ulgiati, 2016) and directly impacts multiple UN's Sustainable Development Goals (Schroeder, Anggraeni and Weber, 2019). However, the adoption of CE and sustainable strategies by industry has so far been modest (Circle Economy, 2021), and scarce progress is observed in the decoupling from linear resource consumption (Kristoffersen *et al.*, 2021).

The CE has been receiving attention from academia (Ghisellini, Cialani and Ulgiati, 2016), governments (e.g., China's CE Promotion Law and EC Working Package), and companies (Foundation, 2015) as an alternative to the prevalent economic development model: linear economy, otherwise known as the take, make and dispose model (Ranta *et al.*, 2018).

A multitude of perspectives exists about how to incorporate the CE into concrete actions at the firm level. The definition provided by the European Union (EU) Commission (European Commission, 2015) gives minimal direction to concrete operations. While academically, the concept is rooted in industrial ecology (Yuan, Bi and Moriguichi, 2008), product-service systems (Tukker, 2015), industrial symbiosis (Geng *et al.*, 2012), remanufacturing (Linder and Williander, 2017), corporate responsibility (Murray, Skene and Haynes, 2017), and sharing economy (Preston, 2012) among others (Ranta *et al.*, 2018).

The CE is often considered through the 3R principles: reuse, reduce, and recycle (Yong, 2007; Preston, 2012; Su *et al.*, 2013). Reuse principle states that components or products, not consider as waste, are used again with the purpose for which they were conceived, which means to use fewer resources, less energy, and less labour than that required to produce new products from virgin materials or even to recycle and dispose of products (Castellani, Sala and Mirabella, 2015). The reduction principle implies using minimal energy inputs, raw materials, and waste by implementing better technologies, simplifying packaging, and using more power-efficient appliances (Su *et al.*, 2013). The recycling principle refers to a recovery operation where waste materials are reprocessed into materials, products, or substances, whether for the original or other purposes, plus reprocessing of organic material without energy recovery nor materials that are to be used fuels or for backfilling operations. Recycling is often discussed almost synonymously with the CE, and waste policies have included a strong focus on improving recycling rates (Ranta *et al.*, 2018).

The 3R principles and implications for progressing them demonstrate that the CE's manufacturing and waste management sectors are major industries. However, the sectors have different approaches toward 3R principles because of their position in the value chain. Product manufacturers produce goods fromthe traditional value chain perspective, while waste management (i.e., integrator) companies deal with their disposal. In a profit-maximizing logic, reduce, reuse, and recycle have different impacts on actors in other parts of the value chain. Manufacturers that implement CE initiatives that fulfil some or all aspects of the 3R principles pursue benefits in terms of competitive advantage, although indirectly (Knight and Jenkins, 2009). Reduce principle is aligned with this approach (Ayres and Van Den Bergh, 2005), but organizing and designing reuse and recycling are not (Knight and Jenkins, 2009). At the same time, waste management companies seek to improve their processes with CE initiatives and direct business benefits. They are arranged in line with the 3R principles and thus have fewer conflicting business goals (Geng *et al.*, 2009).

Managing for TBL by creating economic, social, and ecological value is on the business plan. Although, it is challenging to address non-economic issues. Businesses are designed to maximize profit and are less aligned with global ecological and social challenges. Looking at time-tested patterns and strategies from natural ecosystems that operate using, reusing, and repurposing materials and components sustainably may allow for innovative and effective solutions for businesses to begin addressing these global challenges (Tate *et al.*, 2019).

The importance of feedback loops lies at the centre of CE thinking: stocks and flows of resources interact with each other in CE. Therefore, the product and system level, i.e., the interaction of a product with economic and ecological systems, must be considered along its entire lifecycle. Any organisation moving to a CE must acknowledge its interaction with the broader system (De Angelis, 2021).

Successful CE initiatives typically involve various economic and societal stakeholders that need to work together to enable the materials circular flow and related efficiency benefits (Geng *et al.*, 2012). Specifically, literature has shown that applied CE initiatives often needed societal support, including legislative and financial subsidies (Levänen, 2015; Fei *et al.*, 2016). Likewise, recent research has highlighted the role of wider institutional issues such as cultural aspects and norms in determining the transition toward more sustainable options and the CE principles adoption (Levänen, 2015). However, the central focus of the CE literature has been on technical issues, such as material flows and technologies (Mathews and Tan, 2016).

CE can contribute positively to most sustainable development goals, but sustainable development and CE are on diverging pathways. While the sustainable development agenda puts people front and centre with economic prosperity recognised as a means for living fulfilling lives in harmony with nature, CE remains fixated on technological solutions, driven by a promise of traditional economic growth. CE must be fully integrated with sustainable development. This necessitates a profound reconsideration of CE, broadening its scope from closed-loop recycling and short-term economic gains towards a transformed economy that organises access to resources to maintain or enhance social well-being and environmental quality. Superficial changes like accommodate recycling to prevailing economic models will not suffice (Velenturf and Purnell, 2021).

2.3.1 Circular Economy in Business

CE is a production and consumption paradigm for sustainable development (Bansal, 2019), drawing on different schools of thought as highlighted in extant literature (Geisendorf and Pietrulla, 2018). As an economy nested within ecology, aiming to eliminate the concept of waste and offer opportunities for innovation and growth (EMF and McKinsey, 2012). Namely, the CE approach refers to an economic system designed to be restorative and generative (Preston, 2012). The system maintains the value of materials, products, and resources in the economy for as long as possible and minimises waste generation (European Commission, 2015). CE theory proposes that growing resource efficiency and waste reduction throughout the lifecycle of produced goods are unexplored economic opportunities that have the potential for economic growth (Ghisellini, Cialani and Ulgiati, 2016). This central connexion between economic potential and environmental sustainability has generated major interest in CE initiatives globally (Geng *et al.*, 2012; European Commission, 2015; Mathews and Tan, 2016), and an ever-increasing number of academic publications, introduced in national and supranational policies, and gaining prominence in the corporate arena (De Angelis, 2021).

The three main principles that underline CE thinking are preserving and enhancing natural capital, optimising resources productivity, and fostering the elimination of all negative environmental externalities associated with production and consumption systems (EMF et al., 2015). A fundamental step to progress towards a CE is business model innovation, due to CE is an industrial system that is regenerative or restorative by intention and design that replaces the end-of-life with restoration, moves towards renewable energy use, while eliminates the toxic chemicals used, which impairs reuse and aims for the waste elimination through the superior design of materials, products, systems, and within this, business models (De Angelis, 2021).

CE has been focused more on the environmental and economic benefits, whereby CE can facilitate economic growth through creating new job and businesses opportunities, saving material cost, decreasing price volatility, and improving the supply security, while reducing the environmental costs (Del Borghi, Moreschi and Gallo, 2020). CE definition is most frequently portrayed as a combination of reducing, reuse and recycle activities (Kirchherr, Reike and Hekkert, 2017; Tate *et al.*, 2019). CE aims to the recoupling economy with ecology (EMF et al., 2015). When translating this principle into practice, a company may be faced with the choice of dismissing old materials with renewable and better performing materials from an environmental sustainability point of view. This could result in increased costs (e.g., R&D, testing, development) and thereby in reduced profitability in the short term (De Angelis, 2021).

CE has been recognised as a sustainable substitute to the current linear economic model. Thus far, research on the CE has focused on better conserving the value in material flows. Currently, CE is being adopted as a sustainable development strategy (e.g., EU and China). Comparing and identifying the barriers and drivers to CE implementation would be beneficial for the development path acceleration. CE's general drivers from each institutional environment support recycling as the primary CE action, whereas support for other CE types seems to be lacking.

Moreover, increased recycling efforts have primarily driven regulatory measures on both the integrator and manufacturer sides. Likewise, identified normative indicators point toward recycling while increasing reuse faces cultural-cognitive barriers. To increase institutional support for CE and fulfil its capacity as a sustainable growth model, expanded institutional support for reducing the products produced and materials used and increasing reuse is needed (Ranta *et al.*, 2018).

CE has a significant sustainability potential while generating new business opportunities, limiting material costs and price volatility (Kalmykova, Sadagopan and Rosado, 2018), reducing import dependency, and increasing resource security (Mathews and Tan, 2016; Stahel, 2016). Global GHG emissions could be reduced by as much as 63% by 2050 through the uptake of low-carbon and resource-efficient strategies (Circle Economy, 2021). Additionally, improvements to the quality of life and the creation of new jobs have been suggested as a social benefit (Mathews and Tan, 2016; Kalmykova, Sadagopan and Rosado, 2018). Although environmental drivers for CE include the decarbonisation potential making use of this opportunity requires the whole system thinking to avoid simply shifting emissions from one part of the system to another (Velenturf and Purnell, 2021).

CE has the potential to improve resource management. The business models based on CE principles can replace linear operating industrial models with cyclical, closed-loop production systems based on the no-waste principle existing in nature, which has the potential to address the severe shortcomings of linear production and consumption systems (De Angelis, 2021)- placed as a technology-focused concept that can create economic gains while alleviating pressure on the environment. Though, concerns have increased regarding some purported CE practices being promoted as 'sustainable' yet resulting in detrimental impacts on the environment and society (Velenturf and Purnell, 2021). Although, the shift to a CE is not straightforward, and the current transitional phases may collide against many rooted features of the highly successful and much older linear economy model (Hopkinson *et al.*, 2018). There are conflicting targets and trade-offs between circularity and sustainability (Paiho *et al.*, 2020), and that circular does not necessarily mean environmentally sustainable (Parsa, Van De Wiel and Schmutz, 2021).

2.3.2 Closing the Loop in Mining

Closing the water loop in the mining industry can carry many challenges. Recycling water minimises pollutants' release into nearby waters and lowers freshwater withdrawals (Lutandula and Mwana, 2014). Particularly because the most critical aspect in water recirculation is to ensure that the quality of process waters is kept constant, and new technologies and solutions to address water issues targeting closed water loops are needed in mining operations.

Given the potential increase in capital and operating costs associated with better waste management, the development of a mine should not be justified in mineral deposits that are not profitable enough or when the area has a particularly fragile environment (Schoenberger, 2016). On the other hand, under certain circumstances, such as the Chilean context, disposal of mining tailings at higher solids concentrations is not necessarily more operationally expensive than conventional technologies. It may even bring additional benefits in terms of water recovery (Ihle and Kracht, 2018). For efficient and proactive management of waste rock and tailings. It is based on reduction, reprocessing, stockpiling, reuse, and remediation strategies, which allow dealing with these materials as a problem and a future economic and environmental opportunity. This has become more critical given the high frequency of premature mine closures (Laurence, 2011), causing the sudden interruption in the life cycle management of these operations. Economically, a possible advantage of using wastes as resources is the potential reduction in processing costs. Tailings are deposited on the ground surface and have fine sizes, thus reducing the processing costs associated with blasting and comminution (Segura-Salazar and Tavares, 2018).

For many projects in the mining sector, access to water is critical for feasibility (Nguyen *et al.*, 2014). Since mining is a water-intensive industry, reducing water consumption is crucial in achieving the sustainability targets (Gunson *et al.*, 2012). The challenge in mining is one should be able to control the quantity and quality of water intake and effluents. When the water loops in the mining industry are closed, new methods for water quality control and optimisation at each process step are required, which also facilitates the recovery of additional valuable elements. Mine sites recycle water and valorise tailings for an improved environmental and economic results, increase the social licence to operate (Kinnunen *et al.*, 2021).

The approach behind any attempt at increasing the water recirculation rate at a given mining plant must integrate several interrelated variables. As a scarce or abundant resource, the availability status of water is frequently the first item to consider. It is defined by the surrounding environment of the mine by hydrogeological setting and climatic conditions, and diverse competitive uses. Inside the plant, water streams of various qualities and volumes are handled: freshwater from the pits or surrounding watercourses; process waters produced during the plant operation, which must be treated before discharge; and wastewaters from tailings deposits, dams, and seepage waters, which may, or may not, need treatment. When treatments are required must be designed based on water quality, bearing in mind that quality is defined by the chemical composition of the water and the specifications of the processing unit where it is recirculated. In addition to the water requirements of unit operations, evaporation, seepage, or retention in tailings and concentrates occur (Gunson *et al.*, 2012; Ihle and Kracht, 2018).

Without recirculation, complex physicochemical, concentration-dependent, and transient-time interactions already occur at the flotation stage between the dissolved inorganic and organic reagents, colloidal species, microorganisms, and solid-liquid gas-liquid interfaces, all mediated by pH, redox potential, electrical conductivity, and temperature. The direct consequence of recycling water in the process is increasing the ionic concentration over time (Kinnunen et al., 2021). And water recycling may impact plant performance due to increased dissolved ions and high ionic strength (Corin et al., 2011). Previous research has shown positive, negative, and no clear effects of water recycling and increased ionic concentration on flotation. There were positive impacts of water recycling, e.g. chalcopyrite, galena, and sphalerite recoveries were higher in reused process water than tap water (Ikumapayi and Rao, 2015). Pyrite flotation from tailings remained unaffected throughout ten cycles using recycled water, even though the concentrations of several elements increased over time (Nuorivaara *et al.*, 2019). No apparent effect of water quality on the flotation of pyrite between tap water and synthetic process water (Rabieh, Albijanic and Eksteen, 2017).

However, most studies have shown negative effects on flotation with recycled water. The effect of calcium and sulphate ions on the flotation of galena since these ions are very common elements in the process of water when sulphide minerals are floated. Calcium was shown to adsorb onto the surfaces, reducing the xanthate adsorption on galena and affected its flotation negatively (Ikumapayi *et al.*, 2012). Gypsum in recycled water has been shown to decrease the flotation recovery in sphalerite flotation due to retarded uptake of copper and SIPX (Deng, Liu and Xu, 2013). Likewise, a change in ionic strength of the plant water affected the competitive adsorption of xanthate ions and cations on the mineral surface (Moimane, Corin and Wiese, 2016). Bicarbonate ions in the recycled water disturbed the flotation process of oxidized ores of copper and cobalt by depressing the minerals containing the metals of interest (Lutandula and Mwana, 2014). The accumulation of thiosulphate ions decreases copper and cobalt recovery in the flotation of oxidized ore (Shengo, Gaydardzhiev and Kalenga, 2014). The appearance of maximum ionic strength, the effects become constant and stable, although the grades slightly decreased due to more naturally floatable gangue introduction to the final concentrate (Corin *et al.*, 2011).

Additionally, there is a clear need to understand the potential accumulation of microorganisms and their effects on the closed water system (Kinnunen, Miettinen and Bomberg, 2020). The presence of microorganisms in the water can decrease flotation efficiency. Bacteria-laden water can be received when using treated effluent in the processes (Liu, Moran and Vink, 2013), or bacteria may start to accumulate when the water is recycled in the process. On the other hand, microorganisms may also positively affect flotation (Kinnunen *et al.*, 2021).

To accelerate the transition to CE, policymakers of each analysed region should extend support for reuse schemes and take-back programs enabling reuse. This could be done by creating requirements for products reuse and incentivizing the emerging reuse efforts. Since normative and cultural-cognitive support for the CE remains similarly recycling-focused, increasing awareness of the other CE methods, e.g., increasing their visibility in education and establishing certification schemes like those in recycling, is as significant as legislative measures (Ranta *et al.*, 2018).

However, closing loops does not necessarily guarantee environmental sustainability because materials reusing and recycling may only shift the burden by increasing energy and water consumption or GHG emission (Del Borghi, Moreschi and Gallo, 2020). The Nexus literature has echoed this as a silo mindset that fails to account for the complex interconnections and potential synergies and trade-offs between the sub-systems (Lehmann, 2018).

2.4 Circular Economy and the Nexus

CE and nexus are considered promising solutions for resource sustainability. While CE aims to design waste by reducing, reusing, recycling, and recovering materials, the nexus approach is interested in minimising waste and inefficiencies by focusing on the interlinkages between resources. Both concepts have evolved separately, with limited academic work to analyse their relationship (Parsa, Van De Wiel and Schmutz, 2021). The UN Environment Programme (Swilling *et al.*, 2013) defines CE as an economy that balances economic development with resources and environmental protection (Lehmann, 2018). In contrast, Nexus is more considered as one concept that can put the social and environmental aspects into perspective (Endo *et al.*, 2017; Udugama *et al.*, 2020).

Sustainability of resources and waste minimisation is the common goal of both CE and Nexus. Nexus aims to integrate resource management processes that increase the efficiency of natural resource use and infrastructural systems, transform planning practice and reduce GHG emissions and waste generation (Lehmann, 2018). Similarly, CE aims to keep the added value in products, materials, and resources for as long as possible and minimise waste generation. From a technological perspective, CE is widely recognised as an operationalization tool (Kirchherr, Reike and Hekkert, 2017; Chen *et al.*, 2020) or strategy for sustainable development. Contrariwise, Nexus is being promoted as a conceptual tool to achieve sustainable development (Biggs *et al.*, 2015; Lehmann, 2018). The integration of both concepts can have a synergistic output towards optimising resources and minimising waste- The potential highlights the importance of defining the CE-Nexus relationship and their integration.

Individually, CE and Nexus have received much academic attention, and their respective literature has been extensively reviewed for CE (Geissdoerfer *et al.*, 2017; Kirchherr, Reike and Hekkert, 2017; Kalmykova, Sadagopan and Rosado, 2018; Zhang *et al.*, 2018; Calisto Friant, Vermeulen and Salomone, 2020; Schöggl, Stumpf and Baumgartner, 2020) and for Nexus approach (Albrecht, Crootof and Scott, 2018; Ghodsvali, Krishnamurthy and de Vries, 2019; Jabbour *et al.*, 2019). Although, the interrelationship has received less attention (Parsa, Van De Wiel and Schmutz, 2021).

While the CE literature mainly concentrates on material loops, the lack of a nexus approach can shift the environmental pressure to other sectors by increasing other resources' consumption (water and energy) or GHG emissions. A Nexus approach is necessary for CE to avoid this pitfall. A common realistic approach to CE always indicates that a minimum of raw materials and resources is required and maximum recycling to meet the demands. Design and pre-production are critical to circularity for adopting a lifecycle approach, followed by 'production and processing', 'distribution and supply' and 'use and reuse' stages. Using different technologies, the generated waste after 'use and reuse' can be recycled or incinerated for energy recovery. However, there is always a portion of 'undeniable waste and pollution' throughout the process (Parsa, Van De Wiel and Schmutz, 2021).

Contrary to CE, Nexus is highly concentrated on interlinkages between resources and the impacts from/on other resources. Each nexus resource is affected by other resources while simultaneously having effects on them. This, however, provides a very generic and simplistic sense of the complex interlinkages between resources. Integrating a lifecycle-based CE with this generic nexus framework enables us to see a more detailed picture of the impacts from/on other resources throughout their lifecycle. Hence, a more accurate understanding and analysis of the nexus complexities moves from nexus thinking to nexus action (Simpson and Jewitt, 2019), which is considered a fundamental challenge in the nexus literature.

Integrating the CE with Nexus thinking helps to see the bilateral importance of Nexus resources in a CE that has been neglected. While CE is excessively focused on material circularity, it is hardly acknowledged that any step in CE requires some sort of scarce Nexus resources (energy and water). Not only does CE use such resources, but any looping action has accumulative impacts on the sustainability of these resources (Parsa, Van De Wiel and Schmutz, 2021).

2.5 Water and Waste Management

The depletion of natural resources continues to accelerate. At the same time, paradoxically, mountains of waste still accumulate (Velenturf and Purnell, 2017). Hence, it is logical that a CE should strive to minimise resource exploitation and maximise waste prevention. But given the great risks to the stability of an environment that is amenable to the thriving of the human species caused by depletion and pollution (Rockström *et al.*, 2009; Steffen *et al.*, 2015). CE should strive to restore and regenerate the environment by contributing to sustainability from the whole system perspective of optimising social, environmental, technical and economic values of materials and products in society (Velenturf and Purnell, 2021).

Tailings storage is the most significant water sink in most mines (Gunson *et al.*, 2012), with over 50% of water losses coming from the water trapped in the pores in the tailings (Donoso *et al.*, 2013). Tailings' disposal thus needs close attention in the mine water management (Gunson *et al.*, 2012). Tailings and mine water issues should be considered simultaneously, not separately. The solutions are anticipated to influence mining operations during the lifecycle since they provide input to the mine site planning and processes and the closure and rehabilitation (Kinnunen *et al.*, 2021). Lack of proper waste management can lead to environmental disasters, e.g. The collapse of two tailings dams in operation by Samarco in Mariana, Brazil (owned by Vale and BHP, both companies associated with ICMM), identified as the largest environmental disaster caused by mining in the country (Schoenberger, 2016).

Efficient water management strategies aimed to minimise its local demand through technologies that allow decreasing or eliminating the consumption and further treatment and maximizing its recovery and reuse (Pimentel, Gonzalez and Barbosa, 2016). Therefore, water management strategies are an important future challenge for the minerals' industry, especially in fragile areas with a shortage and competition for this resource. The integrated optimisation of water and energy has become particularly relevant. It is only recently being addressed, e.g., in cases such as the need to use seawater from remote sources in mining operations developed in arid zones of Chile (Ihle and Kracht, 2018). Concerning the water quality, one of the most important impacts is the AMD, which is caused by the oxidation of sulphide minerals contained in rocks and tailings exposed to contact with water. AMD can be mitigated through bioremediation and the incorporation of fully automated wastewater treatment facilities (Segura-Salazar and Tavares, 2018).

Lack of proper water management can lead to large volumes of water loss. For instance, the total amount of water withdrawals for Alberta's petroleum sector is not higher in its absolute amount than other sectors. Most of the amount withdrawn is consumed and not returned to the source. Moreover, most of the water demand in Alberta's oil sands is from a single river basin due to the location of the activities (Ali and Kumar, 2017).

The impacts on water resources are diverse, in both quantitative and qualitative terms. The first is due to depletion, while the second is associated with increasing turbidity, conductivity, contamination by ions, elements and chemical compounds associated with the processed ores and reagents used in the process. The water demand can be huge during the lifetime of a mine, especially in mineral processing (Ihle and Kracht, 2018), as well as in dust control, depending on several factors such as climate conditions, mineralogy and ore grade, the scale of operation and proportion of water recovered in products and tailings (Northey *et al.*, 2017). Identifying, evaluating, and managing water-related risks have emerged as major concerns for companies (Vlachos and Aivazidou, 2018).

Transparency issues regarding corporate water use entail significant efforts before companies contribute to efficient water management at a supply chain scale (Hoekstra, Chapagain and Zhang, 2016).

2.5.1 Technology Assessment

To determine the conceptual basis of sustainability, both theoretical and practical contributions to sustainability have been developed from static/absolute to dynamic/relative. Static conceptualization assumes no change in time with the object artefact itself and among other artefacts in its environment. An assessment takes place under the assumption of the completeness of scientific knowledge and taking into account current socio-cultural values, technological limitations and resource limitations. The dynamic conceptualization assumes that internal and external changes will take place. Therefore, to conduct a TA that considers all aspects of sustainability, it is important to recognize the complexity and co-evolution of technology within sustainability subsystems (Faber, Jorna and Van Engelen, 2005).

The concept of TA is to provide knowledge and orientation for acting and decision-making concerning technology and its implementation in society (Bechmann *et al.*, 2007). TA in management is a systematic effort to forecast the consequences of introducing a particular technology in all spheres likely to interrelate. TA is making technological choices preceded by a thorough analysis of all the implications the choice might have (Braun, 1998).

TA first was defined as a policy studies class that tries to analyse the broadest possible scope of impacts on society by introducing new technology. Its objective is to inform the policy process by presenting an analysed set of alternatives, options, and consequences (Coates, 1976). The concept of TA first emerged in the USA at the end of the 1960s, when large-scale technology applications began to affect the citizens' lives. These developments, driven by market forces and governmental support, all have the primary intention to change life quality positively. But questions were raised about possible secondary adverse effects of new technologies on safety, health, employment, and so on (Braun, 1998; Tran, 2007).

TA is an essential area in technology management that has received increasing attention among researchers, including academics and practitioners in the technology and engineering management discipline. Although, the dominant actors in the field have been parliamentary and policy-making bodies (Tran, 2007). TA has evolved through various stages over the last decades (Tran and Daim, 2008) with its shifts in perspectives, focus, and approaches observed (Ramírez, Cisternas and Kraslawski, 2017).

The approaches and methods available for a purposeful look at the consequences of technological change include structural modelling and system dynamics, impact analysis, scenario analysis, risk assessment, decision analysis, environmental concerns and integrated TA, and emerging technologies (Tran and Daim, 2008). However, there are no universal tools or methods that can be applied in all TA studies. In general, a TA model needs to be customized before applying to a particular context (Yoon, Shin and Lee, 2018). Furthermore, TA is an evolving area that continuously brings in new issues and challenges to the researchers that require the improvisation of new methodologies and approaches to meet the new demand of the field (Tran, 2007).

TA in the private sector is the process of examining the impacts of technology new to the company on the individual company and society as a whole. TA meant to refer to public or private decision-making for resource allocations but has evolved to be a general rubric to assess various aspects of technology. TA enables the evaluation of the aggregated technology capabilities and, ultimately, the effective technology planning (Yoon, Shin and Lee, 2018). The impact analysis is explicit, systematic, integrated, and future-oriented, focusing on the company's direction to pursue the technology. TA represents an integrative tool for technological planning related to the firm’s future (Maloney, 1982).

Achieve technological competitiveness over competitors is a significant factor in the survival and sustainable growth in fierce competition in a globalised market. It is essential to understand the current level of technology, which indicates the technological capabilities and resources required for continuous R&D activities to acquire a competitive advantage. The public bodies have suggested various tools for evaluating organizational technology capabilities in terms of evaluation criteria, evaluation system, and evaluation programs, recognizing the importance of TA. The evaluation tools allow exploring solutions for improving organizational performance, to support innovation by analysing patterns of innovation in the organization, and to provide best practices of other leading organizations to be used as a source of technological innovation management and sustainable growth (Yoon, Shin and Lee, 2018).

The need for TA comes from the belief that new discoveries and technologies are essential for society, not just for scientists and engineers, and that technological progress entails ethical dilemmas (Decker and Ladikas, 2004). Technologies have a substantial impact on company performance due to their effect on manufacturing costs, efficiency, productivity, quality, flexibility, possibility to manufacture/deliver product and finally to satisfy many crucial customer needs, e.g., functional features. Technologies are important resources that often have a critical impact on the competitiveness of enterprises. Therefore, technologies are often treated as strategic resources of companies and enablers of achievement and preservation of strategic advantage, new ways of acting, and increased flexibility. During the development of technology, developers face a double-bind problem of an information problem: it is difficult to assess the impact of technology in the early stages of its development, before a sufficient number of applications appears, allowing gathering data for an objective and comprehensive examination of the impact of technology; and a feasibility problem: control or change in technology becomes difficult or even impossible when the technology is mature and already has numerous applications (Gladysz and Kluczek, 2017).

Production-based or technology-related measures effectively influence direct energy consumption and water use, whereas consumption-based or end-use steps are better suited for controlling indirect energy consumption and water use (Fan *et al.*, 2019). TA covers all the critical areas involved in the analysis to provide an unbiased decision-making process (Ramírez, Cisternas and Kraslawski, 2017).

2.5.2 Environmental Assessment

The long-term viability of the natural environment should be maintained to support long-term development by supplying resources and taking up emissions. This should result in the protection and efficient utilisation of environmental resources (Balkema *et al.*, 2002).

Environmental assessments are procedures and methods with the scope of identifying, describing, and evaluating the causes and effects of environmental impacts of technical systems. Previous research studies on pollutant emissions, the volume of waste produced or discharged effluent documented the relationships between manufacturing activity and deterioration in environmental quality. This increases the pressure on companies and industrial regions to significantly improve their environmental and economic performance (Fijał, 2007). Hence, a key step in assessing human-driven environmental problems is to understand pressures from human events and impacts on social practices through the adoption of suitable environmental assessment tools (Walmsley, 2002).

The environmental impact model purpose is to assist users in estimating and analysing cradle-to-gate environmental impacts of products (Gao *et al.*, 2016). Environmental impact assessment (EIA) is defined as a compulsory assessment practice that analyses and estimates the human activities impacts that may have on the environment. EIA uses different types of instruments and applies to different types of activities and has as a result in the form of an environmental impact statement. For the EIA, there are available both quantitative and qualitative impact assessment methods used to assign (qualitatively) or compute (quantitatively) numerical values for the environmental impacts (Ness *et al.*, 2007; Buytaert *et al.*, 2011; Singh, Strømman and Hertwich, 2012).

Several methods are employed, mainly using the procedures of EIA to evaluate planned projects. EIA study safeguards the sustainable use of technology by investigating and mitigating the impacts of a major project, while the benefits and impacts of different options should be balanced on the scale of regional management plans (Lattemann and Höpner, 2008). Life Cycle Assessment (LCA) is an EIA related to the whole life cycle of the product. Both methods are based on an assessment of predicted environmental impacts related to the evaluated product. Regardless of the facility to be assessed, both methods use the same or similar tools, including checklists, matrix methods, networks, histograms, or multi-criteria decision-making models. In both methods, an assessment includes important components such as the technology's environmental characteristics and the product's environmental characteristics (Fijał, 2007).

LCA follows the international standards ISO 14040:2006, ISO 14044:2006 and the International Life Cycle Data Systems (ILCD) Handbook (European Commission Joint Research Centre 2010). LCA maps the resource use and emissions from a studied system. Generally, the life cycle of a product or a service and recalculates them into different types of environmental impact referred to as impact categories (Bertanza *et al.*, 2015). LCA advantages are the numerical characterization of impacts based on cause-effect relationships and the definition and characterization of multiple environmental impacts (Corominas *et al.*, 2013; Zhang *et al.*, 2015).

LCA is an exhaustive tool for collecting and evaluating data about waste generation, collection, and treatment. LCA considers the production, use and disposal phases of products, including raw materials, energy demand, emissions and wastes and has been internationally standardised to ensure comparability of results (ISO, 2006). Commonly, there are four steps in LCA: defining the study goal and scope, conducting an inventory analysis, conducting an EIA, and interpreting the results (ISO, 2006).

LCA is one of the most important tools to assess the environmental impact of products and processes throughout their lifetimes (Tarnacki *et al.*, 2012). LCA has been used in different studies for evaluating at the system level (Kirkeby *et al.*, 2006; Yan Zhao *et al.*, 2009; Corominas *et al.*, 2013; Loubet *et al.*, 2014; Zang *et al.*, 2015) and at the technology level (Manfredi and Christensen, 2009; Yan Zhao *et al.*, 2009; Rodríguez *et al.*, 2012).

There are also some drawbacks of LCA refer to the data quality needed for a thorough LCA study and generates numerous results that can be difficult to be interpreted (Balkema *et al.*, 2002; Gutiérrez *et al.*, 2009). The data aggregation into the standardized environmental impact categories means a loss of insight into the emissions. Furthermore, additional indicators are needed to measure sustainability as LCA limits itself to a restricted set of technical and environmental aspects (Balkema *et al.*, 2002). Additionally, some methodological issues in completely describing water-related impacts within the well-established life cycle impact methodologies (Koehler, 2008; Corominas *et al.*, 2013).

An integrated water resources management is important to develop and use impact evaluation methods that can capture (by identification, description and quantification) as easily as possible the complexity of the water-related impacts associated with wastewater treatment and discharges (Teodosiu *et al.*, 2016).

Several studies have assessed the technical, economic, environmental and social performance of water systems at different scales such as stormwater recycling, greywater recycling, truck distribution (Poustie *et al.*, 2015), wastewater treatment (Maurer, 2009; Lee *et al.*, 2013), desalination (Shahabi *et al.*, 2017) and rainwater tank (Morales-Pinzón *et al.*, 2012) employing a range of different quantitative and qualitative methods. These methods include mathematical optimisation (Al-Nory and Graves, 2013), multi-criteria decision analysis (Poustie *et al.*, 2015), sustainability analysis (Muga and Mihelcic, 2008; Avram, Stroud and Xirouchakis, 2011; Zhao *et al.*, 2012; Zhang and Haapala, 2015; Al-

Kalbani *et al.*, 2016; Gao *et al.*, 2016), specific Net Present Value (NPV) (Maurer, 2009), and statistical analysis (Morales-Pinzón *et al.*, 2012). Although research on product water footprint assessment has rapidly increased during the last decade (Zhang *et al.*, 2017), there is an absence of systemic integration of the water footprint aspect into the entire supply chain spectrum (Aivazidou *et al.*, 2016).

Design tools are needed to manage the manufacturing industries effects on the economy and environment, which will help engineers to evaluate manufacturing costs and environmental impacts in early design (Gao *et al.*, 2016). Economic manufacturing development often has resulted in environmental problems and concerns (Gutowski *et al.*, 2005). A key step in assessing human-driven environmental problems is to understand pressures from human activities and impacts on social processes through the adoption of appropriate environmental assessment tools (Walmsley, 2002).

The application of environmental sustainability criteria is essential to identify the real environmental impacts from treatment processes. The life-cycle perspective entails the consideration of direct impacts associated with the discharge of treated effluent (end-of-pipe approach), combined with indirect impacts associated with the inputs (materials and energy use) and outputs (emissions and waste generated) (Garrido-Baserba *et al.*, 2016).

2.5.3 **Economic Assessment**

Economic sustainability implies that the entity pays for itself, with costs not exceeding benefits. It mainly focuses on increasing human well-being through optimal allocation and distribution of scarce resources to meet and satisfy human needs. This approach should include all resources, including those associated with social and environmental values. However, in practice, most assessments include only the financial costs and benefits (Balkema et al., 2002).

The sustainability assessment based on economic theory considers that sustainability can be integrated into decision-making expressed in money terms. In theory, all types of costs and benefits can be considered. The tools balance the expected costs and benefits and often are the first step in a project, i.e., cost-benefit analysis, life cycle costing, and total cost assessment. Yet, these tools are mostly used as a one-dimensional technique incorporating only financial costs and benefits in practice because most social and environmental costs are difficult to quantify (Balkema et al., 2002).

The quantification of environmental and socio-cultural indicators into monetary values is a part of the decision-making process since it includes normative choices such as fixing values and weighting factors of different indicators. In a perfect market economy, prices would reflect the value of things as perceived by society. In practice, the water sector prices must be regulated by governmental organisations with taxes and subsidies. Therefore, an in-depth economic analysis of the sustainability of water supply and wastewater treatment could provide valuable insight into the real cost of water services (Balkema et al., 2002).

Traditional economic assessment methods, such as discounted cash flow (DCF) and Cost-Benefit Analysis (CBA), are limited in their effectiveness in handling the type of non-probabilistic uncertainties (Watkiss et al., 2015). DCF estimates investments NPV, the most widely used decision-making tool for various investment projects, but not for highly volatile investments (Kim, Park and Kim, 2017).

An investment decision represents a real option execution, and the option execution, the corresponding NPV of the option, will be realized. However, the option execution is related to the opportunity cost generation since the investor abandons the possibility to make the investment decision later, which is linked to enhancing future data (Hull, 2018). Furthermore, the decision analysis will improve if the uncertainty of future conditions can explicitly incorporate in estimating the economic value of adaptation investments. Also, these uncertainties may diminish over time due to improvements in forecasting techniques and the availability of observational data (Dawson *et al.*, 2018).

The Real Options Approach (ROA) is based on the notion that managerial decisions often have similar features as decisions on the exercise of financial options. The term was originally coined in the 70s (Myers, 1977) to describe investment opportunities as options on physical assets rather than financial assets. Just as a financial option gives its owner the right, but not the obligation to buy or sell a financial asset, ROA describes possible managerial actions that will only be taken under favourable circumstances. Furthermore, the manager can decide at which point in time they want to invest (Wörsdörfer, Lier and Crasselt, 2017).

ROA highlights three interactive aspects of investing that influence investor decision. The first aspect is that investments are partially or totally irreversible and therefore, investment costs are at least partially lost. The second is that future cash flows from the investment are uncertain. The third is that investors can choose when they want to invest based on several factors. In NPV, the investment is reversible or, if it is irreversible, the decision is "now or never". This assumption implies that the investor cannot wait and learn more about a given investment opportunity before making an investment decision. The act of investing is effectively exercising an investor's option to invest and eliminates the possibility and potential value of waiting for more information to evaluate the investment opportunity (Dixit and Pindyck, 1994).

In the case of an investment with options, ROA is a method in investment decision-making that supports a more accurate appraisal of the project's value, assessing the investors' flexibility, and can be applied at different stages of a project (Locatelli, Invernizzi and Mancini, 2016), as compared to traditional methods (K. Kim *et al.*, 2017). ROA considers managerial flexibility and the volatility of a project's cash flow (Dai, Sun and Guo, 2016; Y. Kim *et al.*, 2017), namely, through the identification of deferred benefits of waiting for new information it can promote the delaying of adaptation responses if the benefits of the new information outweigh the costs of waiting (Watkiss *et al.*, 2015; Dawson *et al.*, 2018).

In the literature, different types of real options have been described (Trigeorgis, 1996). A distinction can be made between investment options (call options) and disinvestment options (put options). Another difference is whether the situation concerns the timing of an initial investment decision (option to wait, option to defer) or possible adjustments to a project after the initial investment. These adjustments can be the expansion of the project (option to expand), a reduction of size (option to contract), the termination of the project (option to abandon) or changes of the operating mode (option to switch) (Wörsdörfer, Lier and Crasselt, 2017; Olaniyi and Prause, 2020).

Before the end of the options, life is reached, the value of an option is determined by discounting expected future payoffs. Because the asymmetric risk structure of options conflicts with the assumptions to be fulfilled for using a single risk-adjusted discount rate for all periods and in all possible states of nature, other approaches to incorporate risk must be used. Most commonly, the risk-neutral valuation method is used. This method transforms the expected payoff into a certainty equivalent of the expected payoff, which then can be discounted with the risk-free interest rate. Valuation models such as the Black/Scholes model (Black and Scholes, 1973) and the binomial valuation model (Cox, Ross and Rubinstein, 1979) are based on this risk adjustment method.

The investment projects ROA is the extension of financial options theory on real property. The options trading approach into investment appraisal uses option pricing to assess an investment from the project zero points. By including a constant price variation of the asset, the option's exercise price, the money value of the time, and the option's closure (expiration) value, the ROA can calculate the price of a call option and put option (Black and Scholes, 1973).

The Black-Scholes model (Black and Scholes, 1973) and other continuous-time models assume that the exercise decision is made at the end of the options' life. Discrete-time models assume that uncertainty resolves in steps rather than continuously. If time steps are chosen to be short, the resulting distribution of future values closely resembles the distribution resulting from a continuous stochastic process (Wörsdörfer, Lier and Crasselt, 2017).

The validity of ROA in informing real-world decisions depends partly on the degree to which learning is possible. The operation of conventional ROA also depends on attaching objective probabilities to the alternative scenarios of benefits/costs (Dawson *et al.*, 2018). Previous studies undertake simulation exercises that impose hypothetical assumptions regarding rates of learning and decision time-frames to demonstrate the ROA principles (A. Kontogianni *et al.*, 2014; Woodward, Kapelan and Gouldby, 2014). Consequently, it is relatively straightforward to show that including a time-dynamic dimension in the economic analysis is likely to be beneficial (Dawson *et al.*, 2018). Studies on economic assessment for adaptation investment with high uncertainty recommend ROA as a methodology that also evaluates economic feasibility (Harrison, Whittington and Wallace, 2003; Dashchenko, 2006; Lier, Wörsdörfer and Grünewald, 2012; Gersonius *et al.*, 2013; A Kontogianni *et al.*, 2014; Woodward, Kapelan and Gouldby, 2014; Jeon, Lee and Shin, 2015; Seifert *et al.*, 2015; Kim, Park and Kim, 2017; Kim and Kim, 2018; Kim *et al.*, 2019).

3 Research Methodology

This section describes the overall research methodology applied, data collection, data analysis and the limitations presented by the study.

3.1 Research Approach

Even though water scarcity is an acute problem for mining companies located in the northern region of Chile, additionally is expected that the growing demands of minerals and the decreasing mineral concentration worsen this problem. This research problem has been documented by scientific research giving a great insight by the literature review in the field of water issues in the mining process. Therefore, the research approach selection was based on the research problems.

The selection of research methods was changing throughout the publications. A combination of research methods was used in this dissertation. Each scientific publication was based on a different methodology or a combination of methods, as shown in Figure 1. As presented in Figure 1, the dissertation was based on five methods: Quality function deployment (specifically HOQ), Decision-Support framework, Economic Risk framework, and Water Reduction Model (Gunson *et al.*, 2012).

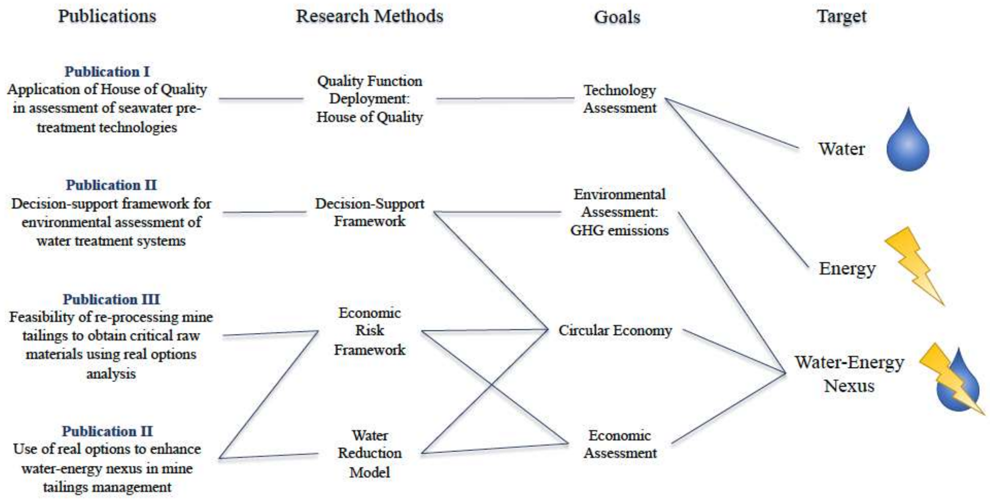

Figure 1: Methods applied throughout the dissertation.

3.1.1 Quality Function Deployment

Quality function deployment is a systematic method of ensuring that consumer needs are correctly interpreted (Yang *et al.*, 2021) and properly translated into technical specifications, thereby improving design quality and providing planned quality control from the earliest stages (Akao and Mazur, 2003). Quality function deployment is used in all the development of new products or services, also in the improvement of the product development process itself, allowing the early identification of areas of risk and opportunities for enhancement, by discovering the connection between the alternatives and their impacts (Ramírez, Cisternas and Kraslawski, 2017).

The application of HOQ warrants that the design or improvement of the product meets the demands of the customers (Shahin and Ebrahimi, 2021). The HOQ matrix is applied to analyse which technology is the most suitable for a particular case, based on the collection of data on the demand for water quality by customers and its translation into technical characteristics of the water (Hauser and Clausing, 1988). The use of HOQ allows identifying the aspects of the technology that need to be modified by the clients' preferences, allowing to achieve a competitive advantage over analogue technologies by better meeting the requirements of the market. The HOQ application shows which aspects of the evaluated technology need to be improved, based on customer demands and/or the performance of competing technologies, providing the first approach to improving a seawater pretreatment design or operational process. In addition, HOQ makes it possible to find a new application for the technology, according to the requirements of the market and the technical possibility of scaling up (Ramírez, Cisternas and Kraslawski, 2017).

3.1.2 **Decision-Support Framework**

The decision-support framework is based on the definition of the preliminary design of a treatment unit, which compromise the development of a flow sheet for mass balance calculation, quantitative characterization of water and sludge streams, and data collection (Svanström *et al.*, 2014). The framework is a strategy when environmental and ecological impacts do not apply to any market price mechanism. Thus, the non-market value quantification of natural resources can be assessed for decision-making purposes (Chang *et al.*, 2012).

The decision-support framework steps include delimitating borders, developing a scenario, collecting data, and assessing its performance. Where the performance assessment involves mass and energy consumption balance of all associated inputs, outputs, and storage. The energy consumption considers distance and efficiency as variables, calculated for the types of water demand. Finally, the last step consists of adding up all energy consumed in each system and then calculating the GHG emission per country based on the type and amount of generated energy, according to each scenario.

3.1.3 **Economic Risk Framework**

The economic risk framework proposes assess the feasibility of reprocessing mine tailings to obtain CRMs considering the uncertainties involved. The approach involves the application of Discounted Cash Flow (DCF), Real Options Analysis (ROA), and uncertainty and sensitivity analysis.

Suitable technology alternatives are needed to reprocess the mining waste stored in a Tailings' Storage Facility (TSF) to extract CRMs. If these technologies are not yet applicable on an industrial scale, then the technologies used to process primary minerals to obtain CRM are considered, as are the economics inputs such as CAPEX, OPEX and production. When it comes to mining waste, it is necessary to take into account certain aspects, such as a lower grade of the elements it contains. Additionally, mine tailings are found in the form of a paste or slurry, therefore, are no mining costs, which usually represent 43% of operating costs in a mine (Curry, Ismay and Jameson, 2014).

The CRM total mass is calculated based on the average concentration and mass in a TSF (Markovaara-Koivisto *et al.*, 2018; Araya, Kraslawski and Cisternas, 2020). The DCF method is used to estimate a project NPV for extracting one or more CRMs from one of the TSF understudy. The NPV is calculated with CAPEX and OPEX of a project comparable in terms of production capacity and ore grade. The criteria select the CRM to be extracted include concentration, total mass, and price (Araya, Ramírez, Kraslawski, *et al.*, 2021).

ROA is applied with the NPV obtained from the DCF method using the risk-neutral probability method. The risk-neutral probability allows for discounting the cash flows using a risk-free interest rate. Binomial tree analysis is used to apply the ROA. A binomial tree is constructed using the risk-neutral probability method presented, which involves adjusting the cash flows risk through the lattice with risk-neutral probabilities and discounting them at a risk-free rate (Araya, Ramírez, Kraslawski, *et al.*, 2021). To build a binomial tree and calculate the option value require risk-free rate, value of the underlying asset (present value of the expected free cash flows based on the DFC method), cost of exercising the option (investment required), life of the option, volatility factor (a measure of the variability of the underlying asset during its lifetime), and time frame (Kodukula and Papudesu, 2006).

Finally, the sensitivity and uncertainty analyses assess the uncertainties effect on NPV, Monte Carlo simulation is applied to perform uncertainty analysis and the Sobol' indices are calculated to perform global sensitivity analysis (Araya, Ramírez, Kraslawski, *et al.*, 2021).

3.1.4 Water Reduction Model

The water reduction model is based on the water reduction model introduced by Gunson *et al.* (2012). In general terms, the methodology can be described by the following stages (Araya, Ramírez, Cisternas, *et al.*, 2021):

- Boundaries delimitation of the studied system. It includes the selection of the dewatering technologies, types of water, size of mine, project lifespan, energy mix, among others.

- Modelling the quantity of water used in the system under study using a water reduction model.
- Calculating CAPEX and OPEX.
- Application of ROA, implementation of sensitivity and uncertainty analysis.
- Calculating energy consumption and GHG emissions.

ROA approach is used to assess the cost of each option by analysing each cost component, including the costs of technologies used for water and tailings management. The annual cost of each strategy is calculated for a project life of 20 years. CAPEX and OPEX costs uncertainties are considered in all options evaluated as these costs are subject to change. CAPEX and OPEX have uncertainties related to the price of electricity and water for the implemented technologies. The copper price is also an uncertainty considered in the process revenues.

Through ROA, Monte Carlo simulation is applied to perform uncertainty analysis and calculate Sobol' indices as global sensitivity analysis. The annual cost function is analysed, where its components are the CAPEX and OPEX for the different technologies included in each strategy, such as tailings dewatering technology, water treatment of the water supplied to the mine, and water transport from the water treatment located on the coast to the mine site.

The energy consumption of each tailings' dewatering technology is calculated and compared with the water recovered by each technology, in addition to the water supply and treatment for water management. Then, to calculate the GHG emissions, CO_2 equivalent emissions were determined for different percentages of the energy sources. CO_2 emissions vary within a certain range for each energy source; consequently, three cases of CO_2 emissions were used, minimum, median and maximum. Therefore, CO_2 equivalent emissions were estimated for each option.

3.2 Data Collection and Analysis

The data collected for each of the analyses was obtained from openly available data. These are secondary sources. Secondary sources are data that has been collected by others, not specifically for the research question under study (Harris, 2001). Secondary data is based on information that is available in the statistical information of published articles, data available in the text, tables, graphs, and appendices, that has been used effectively, but also can be based on the original data if the original data are available in an arcade (Church, 2002). There are many sources, including governments and regulatory agencies, public reports of companies, items from the press and other media, published academic research, and internal documents produced (Harris, 2001).

Secondary data has mainly been used in areas where there is a large amount of data, and the cost of its collection is particularly high (Church, 2002). Due to the high costs and logistical hurdles associated with the use of primary data and its collection, the reliance on secondary data such as claims or administrative data in comparative effectiveness research has increased enormously in recent years (Sun and Lipsitz, 2018). The advantage of secondary data acquisition is easy to access, saves time and resources, thus, giving more time for data analysis.

For publication I, the qualitative and quantitative data used for the analysis was obtained from scientific articles in the web of knowledge database search. Only one data was select to avoid consider twice the same information. A lissom version of the HOQ matrix was used to analyse the data to consider qualitative and quantitative data in the same evaluation.

Publication II quantitative data was extracted from peer-reviewed scientific publications, the International Energy Agency (IEA) database, The World Bank, and the OECD database. To evaluate the different ranges for each variable, propose three cases: best, worst and average. The data analysis was made by the decision-support framework develop to assess environmentally the diverse water treatment systems.

The quantitative data used in Publication III has been obtained from the SERNAGEOMIN (Chilean National Service of Geology and Mining) database and peer-review publications. The data analysis involved ROA using the binomial tree method, DCF, and uncertainty and sensitivity analysis of NPV.

For Publication IV, the quantitative data applied was obtained from peer-review publications, BHP reports, the International Energy Agency (IEA) database, and the SERNAGEOMIN (Chilean National Service of Geology and Mining) database. The data analysis was made by applying ROA and uncertainty and sensibility analysis using Monte Carlo.

4 Publications and Results Review

An overview of the publications is provided. It summarizes the objectives, findings, and contributions of individual publications included in this doctoral dissertation. The overall purpose of the dissertation is to address the issues related to water and energy in the mining industry with a focus on the sustainability aspects from the CE.

4.1 Publication I: *Application of House of Quality in assessment of seawater pretreatment technologies*

4.1.1 Research Objective

The objective of this publication was to conduct a TA by applying a lissom version of the House of Quality (HOQ) matrix. The assessment was applied to a Dissolved Air Flotation (DAF) system as a case study, which is used as a water pretreatment for Reverse Osmosis desalination systems. The DAF system technology was compared with other pretreatment processes, such as ultrafiltration, sedimentation, and granular media filtration. The comprehensive analysis provides insight to decision-makers to aid them to improve technologies so that they can meet specific customers' demands (Ramírez, Cisternas and Kraslawski, 2017).

4.1.2 Contributions

The HOQ offers a comprehensive analysis for decision-making in management. This article's main contribution is to show how to apply HOQ to compare water pretreatment technologies. These technologies are designed to have similar results; however, they operate via different process mechanisms, which means that the technologies have independent variables that differ from each other. The input water quality of the reference cases (the basis of the TA) varies. Still, output water quality demand, investment cost, operational cost, effectiveness, and operational simplicity are suitable for comparisons, identifying the system features, to which efforts should be funnelled (Ramírez, Cisternas and Kraslawski, 2017).

TA using HOQ identifies aspects of technology that need to be improved. HOQ matrix has been used to evaluate different processes, which deploy different operating mechanisms, but their input and output water is comparable, allowing assessing competing technologies. The HOQ matrix has proven to be an objective evaluation tool for managers, traditionally applies to product development, and provides the guidance to improve processes technologies based on customers' requirements and based on a comparative analysis of DAF as a pretreatment system with similar technologies. Other assessment tools are not available to achieve, so far, similar challenges, showing the specific characteristics that must be improved to develop, giving the direction in which this technology must evolve and allowing HOQ matrix to reflect flexibility through its evaluation expanding its application (Ramírez, Cisternas and Kraslawski, 2017).

4.2 Publication II: *Decision-support framework for environmental assessment of water treatment systems*

4.2.1 Research Objective

This article aims to provide a fast and straightforward analysis of the influence of energy consumption in water treatment and distribution systems (energy-for-water) and its impact on the environment, considering water distribution systems, water quality requirements, and how different energy combination mixes changed these variables (Ramírez, Kraslawski and Cisternas, 2019). The developed environmental assessment framework can represent a challenging geographic context, like the Northern Chilean one, with a long-distance between source and sink and high-altitude mountains.

This work aimed to show the permanent relationship between water and energy, studying the energy-for-water component of the water-energy nexus against GHG emissions and its variability throughout water treatment and distribution systems. The location of the water source and the final consumer cannot be changed. However, enhancements in the selection of technology, energy source, and the encouragement of water reuse, water recycling, and non-treated water for industrial processes can be improved to help reduce GHG emissions coming from water treatment processes and water distribution systems (Ramírez, Kraslawski and Cisternas, 2019).

4.2.2 Contributions

Based on a simplified decision-support framework, an environmental assessment of seawater treatment and distribution systems could be performed for different water quality requirements, topography scenarios, and energy mixes. The framework calculates GHG emissions and their environmental impact for a different location to compare the same scenario for every country, meanwhile demonstrating the unbreakable bond between water treatment and energy demand (Ramírez, Kraslawski and Cisternas, 2019).

The principal results are that energy-for-water GHG emissions can be decreased through the awareness-related actions reflected in the energy sources selection, changing water desalination process, optimising water intake, choosing water reuse, and using untreated seawater in industrial processes. The analysis showed that a diverse energy mix is the main factor affecting GHG emissions. The water source locations and end-users have the most significant impact on the environment if solely energy related GHG emissions are considered. Countries with the highest GHG emissions continue obtaining electricity from coal. Similarly, GHG emissions are inferior in countries using electricity from nuclear sources. Though, the dependence on nuclear energy depends on stakeholder endorsement (Ramírez, Kraslawski and Cisternas, 2019).

4.3 Publication III: *Feasibility of re-processing mine tailings to obtain critical raw materials using real options analysis*

4.3.1 Research Objective

This article proposes a framework to assess the feasibility of reprocessing mining tailings to recover critical raw materials (CRM), considering the uncertainties involved. The methodology is illustrated by the unique data set that applies to Chilean mining waste. The proposed approach was to use the DCF method in conjunction with a ROA and an uncertainty and sensitivity analysis. The framework could be applied to other tailings deposits for which geochemical data are available, *e.g.,* the content of CRM in mine tailings has already been measured in some deposits in Finland, Sweden, Portugal, Indonesia, and Mexico (Araya, Ramírez, Kraslawski, *et al.*, 2021).

4.3.2 Contributions

The novel contribution of this article is to consider the ROA and the Sensitivity and Uncertainty Analysis to give flexibility to the economic assessment of mining waste reprocessing, considering the associated uncertainties. The NPV, which is a measure used to assess the feasibility of a project, is calculated using the DCF method as a starting point and then using ROA, various outcomes are estimated for an investment project. The profitability of mining investments depends on variables that have a high level of uncertainty about the market prices of metals. In mining tailings reprocessing, technological developments and business models are still required. A Monte Carlo simulation is used to perform a sensitivity and uncertainty analysis to examine the influence of various variables on the NPV result (Araya, Ramírez, Kraslawski, *et al.*, 2021).

This article included risks and uncertainties in the evaluation of the reprocessing of clearing projects. The proposed approach allows a flexible evaluation of investment decisions. When conventional methods, such as the DCF method, indicate that a project is not economically attractive, a ROA reassesses the project by offering options such as waiting until the project is economically viable under consideration. The waiting option is an interesting alternative when it comes to mine tailings resource valorisation. This is due to the lack of technological development and economic business models to treat mine tailings as a source of CRM (Araya, Ramírez, Kraslawski, *et al.*, 2021).

4.4 Publication IV: *Use of real options to enhance water-energy nexus in mine tailings management*

4.4.1 Research Objective

Mining has a significant local impact on water resources. If mining companies are located in areas that suffer from water scarcity, water must be transported long distances and, in some cases, high altitudes above sea level. Correct mine tailings management can optimise energy and water use. The article aims to assess the water-energy nexus in copper mines, focus on tailings facilities to analyse the compromises between water and energy and propose tailings' sustainable management framework. The approach entails using real options to analyse the relationship between water supply and dewatering technologies and the economic output of every option (Araya, Ramírez, Cisternas, *et al.*, 2021).

A ROA consists in offering the choices that company management can take to expand, change, or delay investments based on market, economic, or technical conditions. ROA is applied to reduce the mining investments risk due to quantitative analysis of responses to unexpected market conditions. The current managerial evaluation methods allow optimising decisions under the existing investment alternatives and available capital resources. The method used provides a financial value and the decisions timing role, allowing a better assessment of uncertainty. Therefore, often it is identified as a source of additional value (Araya, Ramírez, Cisternas, *et al.*, 2021).

4.4.2 Contributions

The novelty of this study was to evaluate the economic performance of several water supply options and mine tailings treatment using a ROA. It enables the identification and straightforward presentation of existing investments and management options. The method applied provides the flexibility to choose between different water management options as it entails a combination of different water treatments to supply water to the mine. Investments in mining are distinguished by great uncertainty due to the nature of the markets and the complexity of new projects. The ROA allows to assess the uncertainty of each cost component and evaluate each option to decide. ROA permit to analyse the consequences of delaying or accelerating management decisions and help reduce financial and operational risks (Araya, Ramírez, Cisternas, *et al.*, 2021).

5 Summary

The route to sustainable CE comes with different challenges to the mining industry. The increased stress on natural resources and the social licence to operate defy mining businesses to constantly improve their processes through a sustainable path while being profitable. The increased demand for metals needs to the construction of renewable energy technologies and the need for waste reduction, i.e., tailings a mining liability, presents the challenge to finding new ways of business to find a sustainable CE.

The assessment of complex systems can be managed from different perspectives to attain various goals, be applied to other contexts, involve diverse stakeholders, and analyse every aspect involving a colossal challenge. However, after obtaining the result of any assessment, the final decision is made by humans to either consider these results as feasible or to go in a different direction.

The conclusions resulting from this dissertation are presented in the context of answers to the following research questions:

Objective 1: Conduct a technology assessment of desalination pretreatment processes.

Is DAF a suitable technology for seawater desalination pre-treatment? (Article I)

By performing a technology assessment to analyse seawater desalination pre-treatment technologies, comparing DAF, ultrafiltration, granular media filtration, and sedimentation. After the analysis performed by the HOQ matrix, the result showed that no technology presents a superior performance to all customers’ requirements (Ramírez, Cisternas and Kraslawski, 2017).

DAF performance is acceptable concerning customers' essential features relating to water quality, like fouling and water clearness (turbidity). Therefore, it is no need to focus the efforts on improving these characteristics. For the least important group of attributes: algal removal, operational cost, footprint, operational life and operational flexibility, DAF is less effective than other technologies. However, strategically there is no urgent need to improve these features (Ramírez, Cisternas and Kraslawski, 2017).

How does DAF can be improved to meet stakeholders demands? (Article I)

DAF system should improve the capacity to adjust to water quality changes, relating water quality, and improving energy consumption efficiency, relating equipment characteristics, where the former is the worst. These features are considered the second most important customers’ attribute. The efforts should be focused on these features. Water quality changes are a challenge to most technologies due to their variability mainly affected by weather conditions throughout the day and the seasons, where chemical conditioning control is essential to achieve better results. The higher energy consumption demand of DAF is due to its mechanism of generated microbubbles to separate the clarified water from the particles to be removed, efforts are made to operate the system under lower working pressures (Féris and Rubio, 1999), and to change the mechanism to generate microbubbles (Sadatomi *et al.*, 2012; Gordiychuk *et al.*, 2016; Ramírez, Cisternas and Kraslawski, 2017).

Objective 2: Provide an analysis of the influence of energy consumption in water treatment systems (water-energy nexus) and its impact onto the environment.

How energy consumption affects the environment due to water treatment and distribution systems? (Article II)

Energy consumption in water treatment and distribution systems depend on the technology selected, water source, selection energy sources, consumers' awareness, the promotion of water reuse, water recycling, and non-treated water for industrial processes. The energy-for-water relationship can be improved to help lower GHG emissions to diminish the environmental impact of the water supply chain. This work showed the lasting relationship between water and energy. Water and energy are inseparably associated, given the energy required for the processes of supplying, treating, and using water. Electricity is responsible for the most significant part of the impacts of water treatment, particularly in desalination processes, where energy requirements are higher than in conventional water treatment processes (Ramírez, Kraslawski and Cisternas, 2019).

What is the relationship between water and energy in the copper mining industry for different tailing disposal methods? (Article IV)

There is a trade-off between energy and water in choosing the tailings dewatering technology. Even though dewatering technologies are more expensive than conventional tailings' disposal in terms of CAPEX and OPEX, yet they reduce the raw water requirement of the mine. These technologies decrease the cost of water treatment and water transport to the mine site and ultimately reduce the overall cost of the mine site operation. Furthermore, the use of filtrated tailings and thickened tailings technologies, by removing additional water from the mine tailings, improves the stability of deposit, diminishes the risk of AMD, and reduces the deposit site volume as a mining liability (Araya, Ramírez, Cisternas, *et al.*, 2021).

Currently, some mine sites use a combination of water that includes recycled water, freshwater, and desalinated water. Water transportation and treatment are energy-intensive processes that generate a large amount of GHG and threaten the competitiveness of the copper price by increasing the production cost in mines geographically located in water scarcity places. For example, in Chile, mine plants use seawater and are located far away from the coast, and soon, seawater will be the primary water source for mining due to the scarcity of freshwater sources. Therefore, having filtrated tailings or thickened tailings could be more economically viable than conventional tailings' disposal due to the costs involved in transporting water to high altitudes. The costs of technologies to manage tailings are directly related to the energy they consume. Filtrated tailings are highly energy-intensive, but the final product is mine tailings with the lowest percentage of water, meaning that the raw water requirement of the mining plant decreases more considerably than when using conventional tailings' disposal (Araya, Ramírez, Cisternas, *et al.*, 2021).

Objective 3: Provide an analysis of plausible alternatives to promote the circular economy model in the mining industry

How can water treatment and distribution systems' environmental impacts be reduced? (Article II)

Energy-for-water GHG emissions can be reduced in the systems through awareness-related measurements relating to energy source selection, optimising water intake, opting for water reuse and water recycling, changing for less energy-intensive water desalination processes, and using untreated seawater when possible. The emissions can be reduced by countries opting for energy sources other than coal and opting for nuclear energy. However, the election of nuclear energy depends on stakeholders' approval (Ramírez, Kraslawski and Cisternas, 2019).

What alternatives can promote the circular economy model in the mining industry? (Article III)

The water reduction model investigated the uncertainties concerning costs of the different options of dewatering technologies for tailings management and water supply. These analyses on the overall cost of the system indicate that water transport costs are one of the biggest cost components; hence, efforts to reduce the water requirements are crucial. Since most water can be found in tailings, investing in dewatering technologies is vital to reduce the water requirement of the mine (Araya, Ramírez, Kraslawski, *et al.*, 2021).

Water is a scarce resource; efforts to reduce water content in tailings are crucial in lowering the demand for water in the mine sites. Mine tailings disposed of using the traditional disposal method contain approximately 70% of water. Switching from conventional tailings' disposal to thickened tailings or filtered tailings solutions would reduce the water requirement of the mine site even though it would increase the amounts of energy needed because these technologies are energy-intensive. However, if the water requirement is reduced, water treatment and transport costs are reduced, and less energy is required in these processes, which are also energy-intensive (Araya, Ramírez, Kraslawski, *et al.*, 2021).

Water-energy nexus is a major component of the total cost for different water supply management systems options in mines, including water used by the tailing dewatering technologies. However, energy is needed to transport water, desalinate or partially desalinate seawater, and in technologies used to recover water from the mine tailings (Araya, Ramírez, Kraslawski, *et al.*, 2021).

The amount of seawater used in the mining industry has been rising, and it is expected that the seawater demand will increase, intensifying the energy demand. Therefore, to reduce GHG emissions is mandatory to use low emitting sources of energy and improve the technologies to consume less energy to achieve the same or better results (Araya, Ramírez, Kraslawski, *et al.*, 2021).

5.1 Contribution of the study

The first contribution of this study was to technologically evaluate through the application of a lissom version of the HOQ matrix to overcome the challenges presented by the case study: the comparison of water pretreatment technologies, designed to have similar results via different process mechanisms, i.e., present different operational variables. The input water quality of the reference cases - the basis of the TA - varies. Still, output water quality demand, investment cost, operational cost, effectiveness, and operational simplicity were suitable for comparisons (Ramírez, Cisternas and Kraslawski, 2017).

Traditional environmental assessments involve the development and examination of a large amount of data. A daunting task where decision-makers must manage large amounts of information just to obtain feasible alternatives set. The second contribution is an environmental assessment develop through a decision-support framework that facilitates obtaining results to endorse the decision-making process. The strategy was to analyse the energy-for-water component of the water-energy nexus, not assessed in previous studies. The simplified decision-support framework environmentally assesses seawater treatment and distribution system for different water quality requirements, topography scenarios, and energy mixes, intending to estimate GHG emissions and their environmental consequences for every location to compare the same scenario for every country (Ramírez, Kraslawski and Cisternas, 2019).

The third contribution is the economic assessment to evaluate the economic risk related to the re-processing of mine tailings to obtain CRM. The framework, based on DCF and ROA, and uncertainty and sensitivity analysis, was performed to study the profitability of using mine tailings as a source of CRM in the Chilean mining industry. The originality of this approach entails enabling the investment decision-making, including the uncertainties related to a novel investment mining project, business model, technologies under development, and high uncertainty of the market price where the valorisation of mine tailings is a critical component to achieving a CE in the mining industry (Araya, Ramírez, Kraslawski, *et al.*, 2021).

Proper mine tailings management can optimise the use of water, as well as the use of energy. The fourth and final contribution is the water-energy nexus assessment, focusing on tailings facilities to determine the trade-offs between water and energy for sustainable mine tailings management. ROA is used to study the relationship between water supply and dewatering technologies and the economic output of every option. To offer company management choices to expand, change, or delay investments based on economic, technical, or market conditions. ROA gives the flexibility to choose between different management options allowing the analysis of consequences of delaying or speeding up managerial decisions and could contribute to the reduction of financial and operational risks, reducing the risk of mining investments due to the quantitative analysis (Araya, Ramírez, Cisternas, *et al.*, 2021).

5.2 Limitations of the study and suggestions for future work

This dissertation only considers the sustainability analysis of technology, environment, and economics, disregarding the social pillar. A social assessment should be considered for a sustainable CE in the mining industry, especially considering how important is the social licence to operate nowadays. Other limitations are:

- The water requirements are site-specific, and water availability has significant volatility over time. The virtual water problem must be analysed case by case and not compared in different years. Therefore, the assessment results may change to other cases and through time.
- The TA shows the characteristic to improve through the development of the technology under analysis by comparison with other existing competitors. The TA is analysed based on the market pull, disregarding the technology push that may arise through the innovation path, i.e., underdevelopment of technology.
- The limitations related to the environmental assessment come from its concept of a simplified framework, considering only the energy-for-water component of the water-energy nexus.
- The water-energy nexus assessment focuses on the mine tailings storage disregarding the mine process facilities that also contribute to the optimisation of water and energy consumption. However, the approach allows to analyse the problem in detail in order to avoid the additional disturbances.

Future research should consider the social and legal aspects of mine tailings re-processing since tailings are an environmental liability containing heavy metals that may spread during the process. In places like Chile, some tailings are owned by the state. Some can be found in urban zones and can represent additional challenges.

Future research should consider the legal and social aspects of water management in the context of water as private property in Chile. A very specific feature, however important to analyse the water as a human right and the water in the context of a free market.

Future studies should perform a technological and environmental assessment of mining processes, considering the energy-for-water aspect, to find the path to improve the water used, reuse, and recycle, reducing water consumption while increasing energy efficiency. The constant diminishes of ore mineral grade, water quality and quantity sources, stricter law and social standards demand better management of resources fulfilling sustainability principles.

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Application of House of Quality in assessment of seawater pre-treatment technologies

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Application of House of Quality in assessment of seawater pretreatment technologies

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ABSTRACT

Increasing pressure on water resources is leading to a growing reliance on seawater desalination for the provision of freshwater. Pretreatment of seawater is a major step in seawater desalination, which can mitigate problems with reverse osmosis (RO) membranes. No clearly superior pretreatment technology exists, due to the variation in input water quality, and furthermore, the pretreatment must be designed to be functional with input water quality characteristics that vary considerably over time.

The objective of this work is to conduct technology assessment by applying a lissome version of HOQ matrix developed in a case study of dissolved air flotation (DAF) system, which is used as water pretreatment for RO desalination systems. The DAF system technology is compared with other pretreatment processes such as ultrafiltration, sedimentation, and granular media filtration. General analysis provides insight to decision makers to help them improve technologies so that they could meet specific demands. HOQ offers a comparative analysis and identifies specific characteristics that must be improved to develop the chosen technology.

The HOQ provides a comprehensive analysis for decision making in management, showing that no pretreatment technologies present a superior performance vis-a-vis all customer attributes, however, it identifies the features of the system, to which efforts should be funneled. For DAF system, these are: water quality changes and energy consumption.

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1. Introduction

Steady growth in world population and increased industrial and agricultural activities necessitate better management of water resources. Currently, more than 80 countries experience water shortages that interfere with industrial activities and citizens' health and wellbeing (Drelich et al., 2012). Many interchangeable methods for improving water quality have been developed (Zaitsev and Dror, 2013) and approaches such as seawater desalinization and water reuse (or recycling) have been implemented. In some industrial operations, for example, mining operations, utilization of seawater without desalination treatment has been proposed (Castro, 2012) and combined with water reuse it may provide an environmentally-friendly option. Different processes require different water quality and the use of unnecessarily pure freshwater is undesirable as utilization of modified or lower quality process water can lead to lower operational costs. Water quality depends on many variables, such as chemical elements content, biological organisms, suspended matter, and physical and aesthetic characteristics, like color, taste, and odor (WHO, 2007; Zaitsev and Dror, 2013). One of the biggest challenges in water treatment processes is variation in water quality at the intake, manifested as variability in temperature, stream, salinity, organic load, among others, which alters the operational parameters of the treatment process, leading to a production of low water quality. In some cases, algal blooms have forced seawater reverse osmosis (RO) plants to reduce or shut down operations due to clogging and/or inadmissible quality feed water (Villacorte et al., 2015).

During the last decades several technologies have been created for improving water quality. However, each method has advantages and drawbacks concerning water quality, cost, and ecological impact (Zaitsev and Dror, 2013). These technological advancements

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have provided many options for design or improvement of a water treatment process. Therefore, a comprehensive research is needed to ensure that technology choices are the most appropriate for long-term decisions, especially about infrastructure selection, which can affect energy and water efficiency for decades to come (Stokes et al., 2014). Implementation of an eco-friendly technology or process improvement does not automatically lead to sustainable user performance (Etmannski and Darton, 2014). User's behavior will depend on changes in the context of environmental, socio-cultural, and economic interactions, in which the technology operates, although eco-friendly products can be economically viable for proactive manufacturers (Zhou and Schoenung, 2007) reducing costs of raw materials by using their process by-products.

Technology assessment includes a balance between costs and benefits, in terms of short-term local market economics, to recognize unanticipated impacts and affected parties. This assessment must be impartial to enrich the information for management decisions and to avoid missing opportunities that would benefit society (Hetman, 1973). In other words, technology assessment can be defined as it is indicated by Hetman (1973) as "the process of taking a purposeful look at the consequences of technological change".

The House of Quality (HOQ) methodology, which is a tool of quality function deployment, has been selected for technology assessment in this study. The HOQ is useful because it allows the interfunctional planning and communication on a conceptual diagram, based on customers' desires and tastes. (Hauser and Clausing, 1988). Consequently, to ensure process, service or activity quality for the end user, customers' opinions should be considered from the very beginning of product design or improvement process. Quality function deployment has been extensively implemented in manufacturing industries for product development and marketing, as well as in service industries to help in the design, development, and control of service quality (Lin and Pekkarinen, 2011).

The objective of this work is to assess technology by applying a lissome version of HOQ matrix developed in the case study of dissolved air flotation (DAF) system as a pretreatment for RO desalination with other pretreatment processes such as ultrafiltration, sedimentation, and granular media filtration. The main contribution of this paper is to show how to apply HOQ for comparison of water pretreatment technologies that are designed to have similar results but operate via different process mechanisms, which means that the technologies have independent variables that differ from each other. The input water quality of the reference cases - the basis of the technology assessment - varies, but output water quality demand, investment cost, operational cost, effectiveness, and operational simplicity are suitable for comparisons.

2. Methodology

2.1. Technology assessment

The evaluations of developments in technology, focusing on technical, economical and legal aspects are part of engineering work (Jischa, 1998). Nowadays, it is becoming increasingly imperative that engineers also consider sustainability aspects. Sustainability involves a complex interaction of environmental, social, economic and legal values, which poses a challenge for multidisciplinary team work as every aspect must be considered in detail and in its entirety. The sustainability part of technology assessment in this work aims to minimize dangerous or potentially dangerous operations. It should be noted that such operations are currently legal, but legislation may change, and the tendency is to adopt stricter regulation, which would render obsolete any assessment analysis conducted on the basis of presently binding legislation.

According to Sclove (2010), technology assessment "is a practice intended to enhance societal understanding of the broad implications of science and technology". It is a systematic attempt to comprehensibly foresee the consequences of the introduction of a particular technology. One of the purposes of technology assessment is to clarify the circumstances when technology can dynamically influence subsequent socio-technological developments (Sclove, 2010).

Technology assessment is a multi-team process that involves investigation at many levels where assessment and selection criteria are chosen so that they could be associated with indicators that enable to measure the performance of alternatives assessed against each criterion (Ibáñez-Forés et al., 2014). If a product's life-cycle is considered, technology assessment can be divided into three levels: level 1, direct effects during production; level 2, effects in the usage phase; and level 3, long-term effects through changes in social structures and behaviors (Lang-Koetz et al., 2010).

Countless methods have been created for the different stages of multi-criteria decision-making for technology selection (Ibáñez-Forés et al., 2014). It is recommended to leave the choice of selection criteria in the hands of expert decision-makers, who must do it based on his/her opinions. However, some objective methods for criteria selection can be used to reinforce the decision maker's choice (Ibáñez-Forés et al., 2014). In the case of HOQ, the selection criteria are based on customers' demands.

Other assessment techniques, like life-cycle assessment, require plenty of information to be analyzed and a lot of resources to examine input data as it is often based on information of variable quality, which affects the robustness of the outcome (Zhou et al., 2014). Risk assessment systematizes knowledge and uncertainties about phenomena, processes, activities and systems to be analyzed, however, risk cannot be defined through pre-defined limits and criteria (Aven, 2011). These and other assessment techniques drift us away from this work's goal.

Technology assessment has evolved through various stages with shifts in perspectives, focuses, and approaches. A wide range of methodologies has been utilized in technology assessment, ranging from analytical techniques to integrated impact analysis approaches. The methodologies and approaches used include: structural modeling and system dynamics analysis; impact analysis; scenario analysis; risk assessment; decision analysis; environmental concerns and integrated technology assessment; emerging technologies analysis; cost-benefit analysis methods; measures for technology; road mapping; scenarios and the Delphi method; surveying, information monitoring and new technology assessment; mathematical, and other synthesis methods (Tran and Daim, 2008). However, there are no universal tools or methods that can be applied in all technology assessment studies. Technology assessment is a rapidly changing area in which new issues and challenges continuously arise, and the development of new methodologies and approaches is required to meet new demands of the field (Tran and Daim, 2008).

2.2. Quality function deployment

The purpose of quality function deployment is to ensure that consumers' needs are properly interpreted and adequately transformed into technical specifications. Quality function deployment is used throughout the development of new products or services, also in improving the product development process itself. Quality function deployment as a methodology allows early identification of risk areas and opportunities for improvement. All this is achieved because quality function deployment is a systematic method to find out the connection between the alternatives and their impacts (Akao and Mazur, 2003; Chan and Wu, 2002).

Quality function deployment has redefined quality control in manufacturing by shifting it towards development and design and providing a communication tool for designers. Engineers are leaders in new product development working together with marketing and production staff (Akao and Mazur, 2003).

Quality function deployment main drivers are: improvement of the quality of design and providing manufacturing and field staff with planned quality control before the initial production run (Chan and Wu, 2002). The decision-making process is based on charts, tables and descriptive matrices with interrelationships, weight factors, comparative data and algorithms (Zhou and Schoenung, 2007).

2.3. House of Quality

The purpose of applying HOQ is to guarantee that the design or improvement of the product meets customers' demands. The underlying principle of HOQ is to establish a relationship between the manufacturing functions and these demands (Hauser and Clausing, 1988), which leads to more fluent communication among customers, engineers and managers, and better manufacturing decision making. Fig. 1 shows different components of an HOQ matrix, which are defined below.

a) Customer attributes and relevant importance: Important features for designers are not always the same as for customers. In addition to taking account of the different preferences, HOQ measures the relative importance of the attributes to the customers. Thus, market research plays an important role in indicating required actions.
b) Engineering characteristics: In this section, the product is described in terms that are measurable, and the engineering characteristics should be directly affected by customer perceptions. Study of the engineering characteristics should indicate how to apply the change requires by customers.
c) Correlation matrix: The correlation matrix shows the interaction between the engineering characteristics. The strength of the correlation is given by symbols indicating positive or negative interaction when other features remain unchanged.
d) Competitive assessment: Comparison with competing technologies can identify opportunities for improvement.
e) Deployment matrix: The body of HOQ, deployment matrix, should reflect how each engineering feature affects each customer attribute. Symbols or numbers are used to indicate the strength of the relationship.
f) Target values: The target values present priorities and goals for product design or improvement. They summarize basic data representing the customers' opinion and can help indicate strategic opportunities.

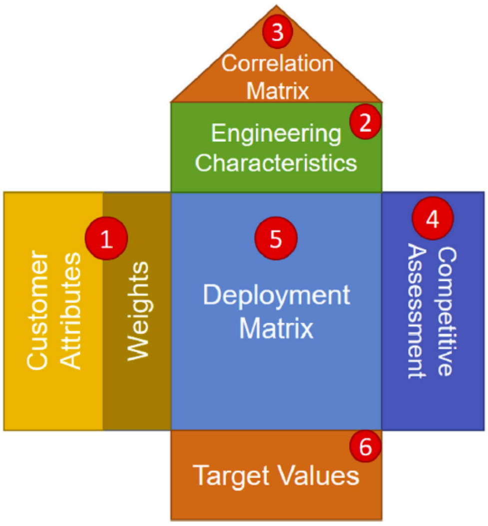

Fig. 1. House of quality matrix, adapted from Lin and Pekkarinen (2011).

In the case at hand, the aim of applying an HOQ matrix is to analyze which technology is the most adequate for a particular case, starting from collecting data on clients' demand for water quality (*e.g.* odor, turbidity, color, taste etc.) and translating it into technical water characteristics (*e.g.*: hardness, pH, chlorine, total organic carbon, etc.) (Zaitsev and Dror, 2013). The use of HOQ allows identifying the aspects of technology which need to be modified by customer's preferences. It allows achieving competitive advantage over analogical technologies by better addressing market requirements. The application of HOQ shows which aspects of the assessed technology should be improved, based on customers' demands and/or the performance of competing technologies, giving the first approach to improve a design or an operative seawater pretreatment process. The HOQ enables finding a new application for the technology, according to customers' requirements and the technical possibility of scaling up. DAF technology can be applied to perform functions other than algae elimination from the system. For example, DAF can be used for algae recovery aiming at its cultivation due to low-pressure separation of the algae (in comparison with filtration) in the flotation tank provided by the buoyancy force of bubbles acting over the particles reducing the cell lysis potential (Voutchkov, 2010; Zhu and Bates, 2012). Also, algae can be injected into the DAF system to treat waste (heavy metals biosorption), or even for biofuel production of the overflow (Hilten et al., 2010; Rattanapan et al., 2011).

2.4. Water treatment

Currently the technologies available for seawater desalination are multi-effect distillation (or multi-effect evaporation), multi-stage flash distillation (Altaher et al., 2012; Mastouri et al., 2011), vapor compression distillation, and membranes processes, such as reverse osmosis, nanofiltration, and electrodialysis (Fritzmann et al., 2007). RO is commonly used for water desalination because it has lower operational costs than water distillation, mainly due to its lower energy consumption. However, a sporadic problem in RO desalination is the presence of large quantities of microscopic algae (algal blooms). Such algal blooms are caused by physicochemical variation in natural water bodies and may lead to major operational problems in RO desalination plants, affecting water quality and, in the case of water for human consumption, causing health problems to the population. Blooms can range from a dilute suspension of cells to dense accumulations that can change the water color (Villacorte et al., 2015). Water pretreatment to treat feedwater removing some contaminants and control microbial growth on the membrane is a commonly implemented solution to this problem (WHO, 2007). Reduction of the organic load in early stages of the desalination process can also decrease the nutrient loading on the biofilm of the RO membranes.

2.5. Water pretreatment

Pretreatment processes improve the quality of aw feed water, thus ensuring the performance of the process. Pretreatment usually involves physicochemical processes that remove suspended solids, oil, and grease (Mastouri et al., 2011; WHO, 2007). In RO processes a suitable pretreatment is essential to run an optimum performance (Galloway and Mahoney, 2004). Seawater pretreatment purpose is to remove particles, debris, microorganisms, suspended solids and silt from intake water before RO treatment (Voutchkov, 2010). Water pretreatment in seawater RO plants must control membrane fouling and scaling, plugging, biofouling, chemical oxidation, chemical reduction, and effects caused by oil, aquatic organisms, and heavy metals (Kim et al., 2011; Mastouri et al., 2011; WHO, 2007).

There are a number of different technologies to pretreat water and reduce the organic load present in seawater during algal blooms, and several studies indicate that over 99% removal of algae can be achieved. However, algal species may produce organic compounds that can pass through pretreatment processes, and these compounds are the direct or indirect cause of biofouling in RO membranes (Villacorte et al., 2015). The specific technology and level of treatment required are determined by local demands, i.e. quality of intake water, output water requirements, and other factors. The following technologies are described to develop a technology assessment for water pretreatment.

2.5.1. Sedimentation

A sedimentation process is usually used when the feedwater presents a daily average turbidity over 30 NTU or spikes over 50 NTU for a period of over 1 h and operations for seawater pretreatment are typically designed to produce settled water with <2 NTU by feeding the system with an appropriate dosage of coagulant and flocculate. For water with turbidity over 100 NTU, sedimentation basin design can comprise lamella plate modules combined with fine granular media to enhance solid removal (Voutchkov, 2010).

2.5.2. Dissolved air flotation

DAF is a clarification process in which coagulant is added to the feedwater prior to a flocculation step, and flocs are removed by injecting the feedwater with saturated water (a mixture of pretreated water with dissolved air under pressure) followed by its release into a tank, producing microbubbles (10–100 μm) that separate the flocs from the clarified water. DAF is considered an alternative process for water pretreatment due to its efficiency in treating reservoir water supplies with low turbidity that contain algae, natural color or natural organic matter (Zhu and Bates, 2012). DAF water pretreatment has been effectively optimized, resulting in better coagulation, decreased flocculation tank size and increased hydraulic loading rates (Edzwald, 2010). The flotation system reduces the concentration of algae, preventing rapid clogging of the media filter and resultant reduced capacity and breakthrough (Villacorte et al., 2015). The DAF high-rate clarification process, compared with sedimentation and ultrafiltration systems, provides small footprint, ease of operation, and protects RO membranes against total organic carbon, harmful algal blooms and oil, with reduced sludge volume (Zhu and Bates, 2012).

2.5.3. Granular media filtration

Granular media filtration takes the form of a single or dual stage granular media filtration with sand or anthracite. Filtration processes can be operated in gravity or pressure configurations. For operation with feedwater of high organic load or turbidity, full-scale in-line coagulation might be necessary before granular media filtration. The product water quality can exhibit considerable fluctuations over time, i.e. algae removal efficiency is in a range of 48–90% (Villacorte et al., 2015).

2.5.4. Ultrafiltration

Ultrafiltration membranes can be operated in pressure or vacuum-driven systems. Ultrafiltration as a pretreatment presents some advantages over its competitors, like a lower footprint, constant high permeate quality, higher retention of large molecular weight organics, lower overall chemical consumption, full automatic operation, superior permeate quality (Di Profio et al., 2011; Galloway and Mahoney, 2004; Xu et al., 2012). As ultrafiltration membranes are usually more effective at removing particulate and colloidal matter than granular media filtration, lower biofouling of RO membranes can be expected when using ultrafiltration for water pretreatment. Optimized coagulation can be applied to ultrafiltration systems to attain higher efficiency, and using ceramic membranes (Dramas and Croué, 2013; Kim et al., 2008) a higher permeate flux is produced (Xu et al., 2010). However, inappropriate coagulation may lead to deterioration in long-term ultrafiltration operations because unreacted iron species can foul ultrafiltration membranes by adsorbing on the membrane surfaces and pores (Villacorte et al., 2015). The use of ceramic ultrafiltration membranes, like zirconium dioxide, may provide consistent permeate quality and low fouling potential at high permeate fluxes (Xu et al., 2010). Di Profio et al. (2011) have proven the feasibility of submerge ultrafiltration hollow fiber in an integrated membrane desalination systems to reduce energy consumption and natural organic matter during seawater pretreatment. Nevertheless, it should be noted that operation of a driving vacuum system over 0.4–0.6 bar may produce disruption in algal cell walls, releasing intracellular substances (Voutchkov, 2010) and thus making the separation process more challenging.

3. Case study

The analysis of water pretreatment technologies shows that none of them has exhibited superior performance for all operational conditions, meaning selection of a specific technology must be made on a case-by-case basis. Therefore, it is important to prioritize the most relevant variables involved in water treatment, such as geographical factors, input water quality, output water quality, temperature, pathogens, ions, organic matter, and so on. Heavy metals content, the chemical solubilities (*e.g.* calcium carbonate, strontium sulfate, calcium sulfate, calcium difluoride, barium sulfate, magnesium hydroxide), turbidity, alkalinity, pH, silica, boron and bromide content, and total dissolved solids are the parameters that influence the pretreatment behavior the most. Pretreatment residuals should be monitored for turbidity/suspended solids, coagulant chemicals, residual disinfectants, and pH (WHO, 2007).

3.1. House of Quality

The analysis of subject-specific literature on seawater pretreatment technologies demonstrates that they are selected for vastly differing conditions, making a comparison of system characteristics difficult. However, the assumption must be made that all analyzed technologies were selected because they were the most suitable for particular contexts, operational conditions, investment cost, operational cost, the most effective, easy to operate, and so on. Therefore, when comparing a specific variable in the HOQ analysis we are not interested in how the technology works; our main preoccupation is that a variable attains a certain value as a result of the application of a given pretreatment technology, and the improvement of DAF as water pretreatment technology is mandatory to achieve results better than the competitors under required conditions.

The HOQ matrix is composed, as mention in sub-chapter 2.3, of sections called "customers' attributes and relevance importance", "engineering characteristics", "deployment matrix", "competitive assessment", "correlation matrix", and "target values".

The section "relevance importance" is represented by the weights of customer attributes. They were obtained by counting the papers given in the site Web of Knowledge (www.webofknowledge.com, 2016) and addressing the issue of water treatment, where the specific attributes were mentioned. The scores for the section "relevance importance" are given in Table 1. The results correspond to the number of publications where each customer attribute is mentioned.

The engineering characteristics must be measurable and operational in order to satisfy the customer needs (Yang et al., 2015). For the case studied in this paper, the pretreatment system design is governed by the source of the feed water, water composition and the nature of the potentially polluting materials (Sutzkover-Gutman and Hasson, 2010).

The section "correlation matrix" shows the degree of correlation between engineering characteristics and customer attributes, where the symbols denote a strong (■), medium (▲), and weak (●) relationship.

The "competitive assessment" was obtained using the results presented in the studies on water treatment given in sub-chapter 3.1.1. Table 2 shows references analyzed for the evaluation for each technology.

The "correlation matrix" is the triangular roof of HOQ, where the symbols denote a positive (✚) or negative (▬) relationship.

The customers' attributes and target values are described in the sub-chapters below.

3.1.1. *Customers' attributes*

The HOQ matrix is built based on customer needs treated as initial input information. These needs can be ascertained by qualitative research, for example, using interviews and/or focus groups (Yang et al., 2015). In this study, customer attributes were obtained from bibliographic research of the four pretreatment technologies considered by searching for characteristics that were prominently mentioned in the literature. The analysis was performed considering the principal challenge, problems, advantages and disadvantages presented in previous studies.

Specific issues to consider in seawater pretreatment technologies assessment are desalination process requirements, such as water conveyance to the treatment plant, intake pretreatment, disposal of brine, and process maintenance. Also, it must be remembered that the cost of pumping from seawater intake depends on geographical location, altitude, and distance from water source (Shannon et al., 2008). Conventional treatment methods may address problems with quality and supply. These methods are chemical, energy- and operationally intensive, they involve substantial capital cost, engineering expertise, and infrastructure (Shannon et al., 2008). Better water management, improved efficiencies, and conservation are vital for moderating demands and improving availability (Shannon et al., 2008).

Table 1
Relevance importance results for each customer attribute.

	Results
Footprint	125
Operational Life	57
Operational Flexibility	10
Operational Cost	284
Energy consumption	653
Alga Removal	584
Water Clearness (Turbidity)	1515
Fouling	2235
Water Quality Change	749

3.1.1.1. Footprint. The footprint is a site design parameter that is restricted by the topography and/or proximity of populated areas, which influences many other pretreatment parameters (Sutzkover-Gutman and Hasson, 2010). Conventional pretreatment processes, like dual-media filtration, sedimentation or air flotation, often lead to a high plant footprint due to low filtration velocities and the use of coagulants, requiring collection and treatment of the backwater waters (Remize et al., 2009). DAF structures have a smaller footprint than sedimentation systems (Ross et al., 2003; Voutchkov, 2010). Membrane filtration meets water quality objectives with a smaller footprint than conventional water treatment technologies (Kim et al., 2008). Additionally, low-pressure membrane filtration provides high efficacy in producing high quality of water with a small footprint and at relatively low cost (Huang et al., 2009). Membrane pretreatment ultrafiltration has a smaller footprint (Kimura et al., 2004; Kurniawan et al., 2006; Xu et al., 2012), than granular media filtration (Sutzkover-Gutman and Hasson, 2010).

3.1.1.2. Operational life. The life of ultrafiltration cartridges varies between 5 and 8 years depending on the dissolved solids concentration (Gupta et al., 2012). Concrete structures for gravity filters have a useful life of 50–100 years and steel structures used with pressure filters have a lifespan up to 25 years. In seawater desalination, the internal surface of pressure filters has a rubber coating that needs to be replaced every 5–10 years and examined periodically (Voutchkov, 2010). Frequent chemical cleaning of ultrafiltration systems can shorten the membrane unit's service life (Heng et al., 2008; Kimura et al., 2004) and disposal of chemical reagents, which can be toxic, brings other problems (Kimura et al., 2004). Sometimes, additional pretreatment may be needed to obtain the ultrafiltration membrane life indicated by the supplier, due to membrane fouling and lack of previous data from suppliers, which may reduce the projected membrane life and increase membrane replacement costs (Voutchkov, 2010).

3.1.1.3. Operational flexibility. Water pretreatment systems should be able to adapt to meet subsequent process requirements. DAF offers advantages such as better quality of treated water, greater flexibility of the plant, shorter startup time, and easier sludge handling (Zabel, 1985). During membrane pretreatment, oil contamination and oil spills are difficult problems, which can often be removed by DAF (Greenlee et al., 2009; Mastouri et al., 2011). Ultrafiltration provides a fully automatic operation (Xu et al., 2012), its modules have got backwash and can operate in near dead-end modes, which gives them higher operational flexibility (Greenlee et al., 2009). Waters with heavy algae blooms are difficult to treat by sedimentation, the treatment of low-turbidity, soft, highly colored waters produce very light flocs that settle very slowly, challenging to operate at low surface loadings, and costly flocculation aids are needed to increase settling rates (Zabel, 1985). Granular media filtration can be sensitive to feed water changes, changing the permeate quality due to algal blooms and oil contamination (Greenlee et al., 2009).

3.1.1.4. Operational cost. DAF requires additional equipment associated with air saturation, diffusion, and recirculation of a portion of the treated flow and, therefore, DAF construction costs are typically comparable to conventional sedimentation basins (Voutchkov,

Table 2
Competitive assessment references.

	Sedimentation	DAF	Granular media filtration	Ultrafiltration
Footprint	(Ross et al., 2003; Voutchkov, 2010; Zhu and Bates, 2012)	(Ross et al., 2003; Voutchkov, 2010; Zhu and Bates, 2012)	(Remize et al., 2009; Sutzkover-Gutman and Hasson, 2010)	(Di Profio et al., 2011; Galloway and Mahoney, 2004; Huang et al., 2009; Kim et al., 2008; Kimura et al., 2004; Kurniawan et al., 2006; Remize et al., 2009; Sutzkover-Gutman and Hasson, 2010; Xu et al., 2012; Zhu and Bates, 2012)
Operational Life	(Voutchkov, 2010)			(Gupta et al., 2012; Heng et al., 2008; Kimura et al., 2004; Voutchkov, 2010)
Operational Flexibility	(Zabel, 1985; Zhu and Bates, 2012)	(Greenlee et al., 2009; Mastouri et al., 2011; Zabel, 1985; Zhu and Bates, 2012)	(Greenlee et al., 2009)	(Di Profio et al., 2011; Greenlee et al., 2009; Xu et al., 2012; Zhu and Bates, 2012)
Operational Cost	(Gupta et al., 2012; Voutchkov, 2010)	(Adlan et al., 2011; Féris and Rubio, 1999; Gupta et al., 2012; Voutchkov, 2010)	(Gupta et al., 2012; Remize et al., 2009)	(Fritzmann et al., 2007; Galloway and Mahoney, 2004; Gupta et al., 2012; Kurniawan et al., 2006; Remize et al., 2009)
Energy Consumption	(Plappally, 2012)	(Féris and Rubio, 1999; Plappally, 2012)	(Plappally, 2012)	(Fritzmann et al., 2007)
Alga Removal	(Henderson et al., 2008; Liang et al., 2008; Villacorte et al., 2015)	(Henderson et al., 2008; Kim et al., 2011; Rubio et al., 2002; Villacorte et al., 2015; Voutchkov, 2010)	(Henderson et al., 2008; Villacorte et al., 2015; Voutchkov, 2010)	(Castaing et al., 2010; Huang et al., 2009; Liang et al., 2008; Villacorte et al., 2015; Zhang et al., 2011)
Water Clearness	(Bourgeois et al., 2004)	(Altaher et al., 2012; Bensadok et al., 2007)		(Xu et al., 2010)
Fouling	(Moon et al., 2009; Nguyen et al., 2012; Zhu and Bates, 2012)	(Geraldes et al., 2008; Voutchkov, 2010; Zhu and Bates, 2012)	(Voutchkov, 2010)	(Dramas and Croué, 2013; Huang et al., 2009; Kim et al., 2008; Kurniawan et al., 2006; Malaeb and Ayoub, 2011; Xu et al., 2010; Xu et al., 2012; Zhu and Bates, 2012)
Water Quality Change	(Yan et al., 2006)	(Bunker et al., 1995; Edzwald, 1995; Yan et al., 2006)		(Di Profio et al., 2011; Galloway and Mahoney, 2004; Her et al., 2004; Xu et al., 2010; Xu et al., 2012; Zhang et al., 2011)

2010). Although water saturation accounts for ~50% of DAF operational energy cost (Feris and Rubio, 1999), DAF treatment offers low capital investment, low operational cost and high separation efficiency (Adlan et al., 2011). Ultrafiltration systems equipment is generally more expensive than conventional pretreatment systems (Galloway and Mahoney, 2004). Ultrafiltration implies high operational cost compared to DAF for physicochemical treatments for inorganic effluent (Kurniawan et al., 2006), however, the out-turn cost of ultrafiltration technologies is competitive with conventional seawater pretreatment processes (Remize et al., 2009). Sedimentation and granular media filtration operational costs are 0.005–0.01 U\$/m^3 permeate, for DAF it is 0.005–0.025 U\$/m^3 permeate and for ultrafiltration it is 0.015–0.4 U\$/m^3 permeate (Gupta et al., 2012).

The pretreatment system must be designed to minimize chemical consumption and optimize life-cycle costs (Galloway and Mahoney, 2004). Cost of chemicals in conventional pretreatment processes is reported to be in the range of 4.8–5.7% of total operation and maintenance costs (0.03 \$/m^3 permeate). Energy consumption in pretreatment is typically 1.04 kWh/m^3 permeate, representing 20.2% of the total energy consumption of the reverse osmosis section of the plant (Fritzmann et al., 2007).

3.1.1.5. Energy consumption. The RO desalination stage can consume 1.9–5 kWh/m^3 of water produced (Shannon et al., 2008; Shaffer et al., 2012) for seawater RO plants with capacities of 1000 to 5400 m^3/d (Fritzmann et al., 2007), where seawater pretreatment can consume 0.2–0.416 kWh/m^3 of produced water (Fritzmann et al., 2007; Shaffer et al., 2012).

Energy consumed during sedimentation is in the range 5x10^{-4}–1x10^{-3} kW h/m^3 (Plappally, 2012). Energy consumption associated with utilization of polymers for coagulation is reported as ranging between 0.4 and 0.7 kWh/m^3 (Plappally, 2012). DAF energy consumption during the process is in the range 9.5x10^{-3}–35.5x10^{-3} kW h/m^3. Energy consumed by gravity filters is found to be in the range of 0.005–0.014kWh/m^3 (Plappally, 2012).

3.1.1.6. Alga removal. Rapid algae growth can create problems in all water reservoirs by elevating values over the limits for suspended solids and pH. Algae growing may change fouling characteristics on membrane surface depending on species, nutrients, seasons and so on (Huang et al., 2009). Furthermore, discharge of algae-laden effluents can release associated toxins to surface and ground waters (Rubio et al., 2002). If algae are not gently removed by granular media filtration or DAF prior to membrane systems, cell rupture may accelerate membrane fouling (Voutchkov, 2010). DAF has demonstrated an effective algae removal performance (Kim et al., 2011), DAF can also reduce algal concentration, preventing media filters from lower capacity, rapid clogging, and breakthrough (Villacorte et al., 2015). In case of granular media filters technology cannot maintain production capacity at high algal cell concentrations, and product water may highly vary over time (Villacorte et al., 2015).

Pretreatment sedimentation can remove algae cells and 75% algae removal has been observed in experimental work (Liang et al., 2008), nevertheless conventional sedimentation basins are not recommended to generate water with algal content (Villacorte et al., 2015). Results obtained with filtration showed the elimination of more than 99%, 87% and 98% of microalgae, total suspended solid and turbidity, respectively (Castaing et al., 2010). Membrane filtration technology offers complete removal of algal cells and is less affected by raw water quality changes (Zhang et al., 2011). Henderson et al. (2008) suggested that coagulation is the key process for algae removal in pretreatment systems, however, for algae-rich reservoir treatment, coagulation applied to ultrafiltration system could not satisfy the requirements to the extent it did for the treatment of other water containers (Liang et al., 2008). Algal blooms can damage inside-out ultrafiltration membranes by accumulating through the length of the membrane capillary, at the capillary entrance and at its dead-end (Villacorte et al., 2015).

3.1.1.7. Water clearness (turbidity). Turbidity is affected by seasonal changes, weather, and ships traffic (Galloway and Mahoney, 2004). Turbidity removal achieved with DAF is high compared to the rejection standard (5 NTU) although turbidity can be reduced by about 99% (Bensadok et al., 2007), reducing water turbidity below 1 NTU (Altaher et al., 2012). On the other hand, the use of sedimentation allows reducing the turbidity up to 94% compared to control tests when it is applied to residual waste water treatment with high-density solids (Bourgeois et al., 2004). In ultrafiltration, ceramic membrane exhibits turbidity removal efficiency over 97% (Xu et al., 2010).

3.1.1.8. Fouling. Membrane fouling results from interactions between dissolved and suspended solutes in the feed and membrane surface. The degree of membrane fouling during operation will affect the frequency of cleaning and hence the process cost (Mondal and Wickramasinghe, 2008). Membrane fouling is a major problem in membrane filtration processes, and it is a major factor in determining their practical application in water and wastewater treatment and desalination regarding technology and economics. Fouling due to organic and inorganic components and microorganisms may occur simultaneously (Nguyen et al., 2012).

Fouling may have several adverse effects on membrane systems, such as membrane flux decline due to the formation of a low permeability film on the membrane surface, increased differential pressure and feed pressure needed to maintain the same production rate, membrane degradation caused by acidic by-products concentrated on the membrane surface, increased salt passage through the membrane, and reduced quality of the product water due to the accumulation of dissolved ions in the film at the membrane surface (Dramas and Croué, 2013; Nguyen et al., 2012). Hence the most challenging problem affecting ultrafiltration performance is membrane fouling (Xu et al., 2012). The use of coagulants with DAF can improve the efficacy by reducing fouling (Geraldes et al., 2008), and high rate DAF prevent RO membranes against total organic carbon, harmful algal blooms and oil, with lower sludge volume (Zhu and Bates, 2012). However, it is recommended that coagulant pretreatment is optimized for membrane fouling by controlling the residual coagulant and establishing a proper cleaning protocol, which has been applied also for sedimentation (Moon et al., 2009; Nguyen et al., 2012).

Scaling is caused by high levels of calcium, silica, phosphate, carbonate, and other ions. It decreases productivity and deteriorates permeate quality (Malaeb and Ayoub, 2011). Inorganic scale causes membrane fouling not only on the membrane surface but also deep within the membrane pores. Dissolved aluminum and silica precipitate in the membrane, creating aluminum silicate scale (Moon et al., 2009). Scale layer formation becomes critical when the product of the concentration of the soluble components exceeds the solubility limit. Scaling is controlled by injecting antiscalants, lowering the pH, and reducing the recovery rate (Malaeb and Ayoub, 2011). Disadvantages of antiscalants include their high cost, increased brine volumes and the fact that excess dosages may promote scaling.

Granular media filtration and removal of particles larger than membrane pore sizes can reduce surface fouling and extend the filtration cycle. However, due to differences between the surface composition of media filters and polymeric membranes, aquatic materials that adhere to membrane surfaces may pass through media prefilters and cause irreversible membrane fouling (Huang et al., 2009).

Ultrafiltration is prone to membrane fouling (Kurniawan et al., 2006), but fouling is significantly reduced after prefiltration (Huang et al., 2009). The decrease in ultrafiltration efficiency caused by membrane fouling has prevented a wider application in wastewater treatment (Kurniawan et al., 2006). Yet, colloidal fouling can be effectively controlled through ultrafiltration (Malaeb and Ayoub, 2011). Turbidity levels above 0.1 mg/L are indicative of a high potential for fouling, and spikes above 50 NTU for more than 1 h require sedimentation or DAF treatment before filtration (Voutchkov, 2010).

3.1.1.9. Water quality changes. Pretreatment processes are rather complex due to large volumes of waste generated during operation, the sensitivity of membranes and low tolerance to system disturbances (*e.g.* intake water quality variations, temperature changes, filter plugging) (Xu et al., 2008). The effects of algal blooms include water quality changes such as pH increase and an increase in disinfection by-product formation potential (Her et al., 2004). One alternative is to combine different pretreatments with coagulation, but coagulation behavior changes seasonally with water quality (Yan et al., 2006). Coagulant dosage and coagulation pH is critical, due to short residence time in the flotation plant, and changes in raw water quality must be monitored closely to maintain optimum coagulation conditions (Edzwald, 1995), where the correct coagulant selection, flocculation time and flocculation mixing intensity are capable to improve the process (Bunker et al., 1995). Measurements of sedimentation and flotation have been made showing that the effectiveness of coagulants differs greatly, due to seasonal changes (Yan et al., 2006); for example, flotation with alum works well under summer conditions, but presents high residual turbidity for lower water temperatures (4–6 °C) (Edzwald, 1995). Membrane filtration technology, on the other hand, provides a superior permeate quality (Xu et al., 2012), less affected by raw water quality changes (Zhang et al., 2011), providing a consistent water quality (Galloway and Mahoney, 2004), however fouling consequences must be considered (Her et al., 2004).

3.1.2. Target values

In a water pretreatment process, goals for removal of various potential fouling contaminants are partly defined by characteristics or performance of the membrane, by the needs of downstream treatment processes, and membrane manufacturers (Sutzkover-Gutman and Hasson, 2010). However, these values may change for each particular location and season.

Fig. 2 presents a HOQ matrix based on the characteristics required for seawater pretreatment with high variability of input water quality due to algal bloom in warm seasons and microscopic organisms in cold seasons. Algal bloom can be harmful (toxic) if output water is required for drinking purposes, and microscopic organisms can be a threat to reverse osmosis membranes and cause system problems.

Engineering characteristics can be optimized to reduce the chemical dosage, operational costs and chemical excess that can be harmful to subsequent processes, especially those involving RO membranes.

4. Discussion

In technology assessment studies decision makers' judgments play a crucial role in different stages of the process (Ibáñez-Forés et al., 2014). Therefore, it is recommended that decisions be made by a multidisciplinary team composed of experts (Ibáñez-Forés et al., 2014). For the case of HOQ, the decision-making process is supported by straightforward specification of customers' demands and technical support given by the manufactures. It results in the identification of suggested changes to the analyzed technology.

By analyzing information from the HOQ matrix for DAF and comparing it with water pretreatment competitors: ultrafiltration, sedimentation, and granular media filtration, we have come to the following observations: DAF performance is acceptable with respect to characteristics considered important by the customers, i.e., fouling and water clearness (turbidity). Thus, there is no need to improve DAF for these characteristics.

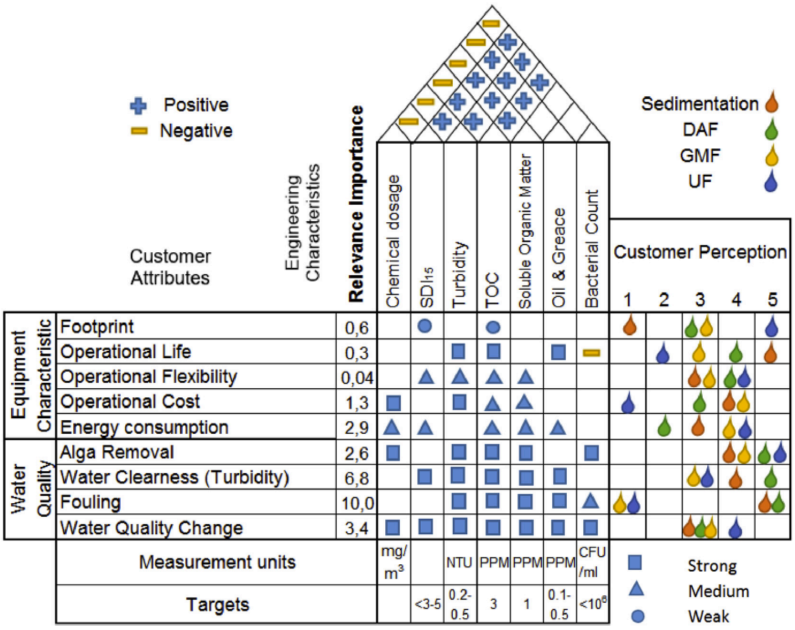

Fig. 2. House of quality matrix for water pretreatment technology.

However, fouling poses a big challenge for all pretreatment technologies, because any excess of coagulants or flocculants added to the system to improve the process may cause scaling on RO membranes, and poorly pretreated water may contain biological matter, from algae to their interstitial tissue, all of which cause biofouling.

Water turbidity can be increased by pretreatment coagulant, such as ferric salts, after pretreatment process. This rise in turbidity represents an extra challenge because it is necessary to implement a solution to struggle with this problem.

When it comes to the second group of the most important customer attributes, namely, water quality change and energy consumption, DAF technology requires an improvement to meet customers' demands. The challenge presented by the change in water quality is the variability in coagulant dosage to meet optimum operational conditions. Input water quality changes can be managed by characterizing water parameters, studying seawater cycles over the day and over the seasons, confronting the specific problem presented currently and preventing its consequences. Higher energy consumption of DAF systems is caused by water saturation with air that occurs at high pressures (4–6 atm). Efforts are being made to change microbubbles generating mechanisms (Sadatomi et al., 2012; Terasaka et al., 2011), which can be helpful to reduce energy consumption in DAF systems.

For the least relevant customer attributes: alga removal, operational cost, footprint, operational life and operational flexibility, DAF pretreatment is less effective than competing technologies, and there is some room for improvement, although development is not as urgent as for the second group of customer attributes. The problem of alga removal can be handled by learning about their behavior and managing them without producing disruptions to the cells, by knowing which coagulant we should use and the relationship between coagulant concentration and alga concentration. DAF operational cost can be minimized by reducing the two main cost drivers, changing the mechanisms to generate microbubbles, which consume most of the energy, and optimizing the coagulation-flocculation systems, reducing the chemical costs. Footprint can be reduced by operating in-line coagulation systems (Huang et al., 2009), changing the saturator equipment for a microbubble generator to dissolved air into water (Sadatomi et al., 2012; Terasaka et al., 2011), rearrange the pretreatment system, flotation tank can be placed above the filter in a vertical arrangement (Edzwald, 2010), and increasing hydraulic loading rates of DAF cell (high rate DAF) (Edzwald, 2007). DAF operational life cannot compete with a concrete structure, but reducing the secondary process equipment, as mentioned above, and leaving the flotation tank as the main structure, which can be built from resistant plastics to prevent corrosion, will reduce maintenance cost and develop a longer life of the system. Finally, DAF operational flexibility can be improved by managing the input water quality, finding out its composition, to develop a chemical program that immediately adds correct coagulants and/or flocculants, and the dosage needed.

Other considerations may include the improvement of the pretreatment process, such as: well intakes of seawater RO plant that provide a water treatment system similar to multiple pretreatment process using open ocean intakes (Rachman et al., 2014); a combined effect of water treatment technologies can lead to an optimized system which can reduce RO process problems such as fouling, scaling, and their respective consequences. Improving science and technology of water purification can help provide cost-effective and robust solutions (Shannon et al., 2008).

5. Conclusions

Demand for large amounts of high quality water requires a more comprehensive analysis of how water treatment processes are managed, looking for new sources or improved treatment methods while testing new technologies or improvements to the existing technologies are expensive and time-consuming. Technology assessment covers all the key areas involved in the analysis to provide an unbiased decision-making process.

Technology assessment using HOQ identifies these aspects of technology that need to be improved, as demonstrated by the case study. DAF as a seawater pretreatment system for RO desalination, allows taking decisions based on a comparison of different pretreatment systems that have already been tested for different operational conditions, but with the purpose of minimizing operational challenges in downstream processes. HOQ matrix has been used to evaluate different processes, which deploy different operating mechanisms but their input and output water is comparable, which allows assessing competing technologies. The HOQ matrix provides an objective evaluation tool for managers. It is based on customers' demands and technical availability, allowing technology improvement to be guided by the satisfaction of customers' needs (qualitative) transformed into engineering characteristics (quantitative), to deploy a planning matrix to achieve the design quality required and specific elements of the manufacturing process, without assessing the technologies as traditionally HOQ was used. HOQ provides a comparative analysis of DAF as a pretreatment system with similar technologies, that other assessment tools are not available to achieve, so far, showing the specific characteristics that must be improved to develop the chosen technology, giving the direction in which this technology must evolve and allowing HOQ matrix to reflect flexibility through its evaluation expanding its application. This paper presents a new approach to technological assessment using HOQ matrix, an extended methodology for decision makers to improve their technologies given customers' demands.

Analysis of water pretreatment technologies shows that no single technology performs significantly better with respect of all customer attributes, and the technology must be selected on a case-by-case basis depending on a specific application. As we have already mentioned, there are many opportunities to improve DAF as a seawater pretreatment technology: by identifying input water parameters to overcome water quality changes, replacing the method of microbubble generation to minimize energy consumption, develop an optimized chemical program to improve algal removal, rearrange DAF system layout to reduce the footprint, operational life can be improved by replacing the structural material of the main system and reducing secondary equipment to minimize maintenance, and finally, operational flexibility can be managed through developing an optimized treatment plan where the input water quality is directly related with coagulant type and dosage and type of treatment needed, including a bypass of the pretreatment to be used when necessary. Additional improvement opportunities are found in contamination retention and recovery of valuable components from brine, without intensive chemical treatment, and an additional step of decontamination.

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Decision-support framework for the environmental assessment of water treatment systems

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ABSTRACT

Environmental assessments require the development and analysis of a large amount of data. Decision-makers must manage considerable amounts of information just to obtain a viable set of alternatives. The environmental assessment proposed in this study is a decision-support framework that facilitates obtaining results that endorse the decision-making process.

This study aims to provide a fast and straightforward analysis of the influence of energy consumption in water treatment systems (energy-for-water) and its impact onto the environment, considering water quality requirements, water distribution systems, and how different energy combination setups affect these variables. The framework was applied to countries on the seashore experiencing water scarcity distress and world average greenhouse gas emissions regimes as examples, but it can also be applied to other types of systems.

Energy-for-water greenhouse gas emissions can be decreased through the awareness-related measures reflected in the selection of energy sources, changing water desalination process, optimizing water intake, choosing water reuse, and using untreated seawater in industrial processes. Countries with the highest greenhouse gas emissions continue obtaining electricity from coal. Likewise, greenhouse gas emissions are lower in countries using nuclear energy as a source of electricity. However, the reliance on nuclear energy often depends on stakeholder approval.

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1. Introduction

Arid and semi-arid regions experience serious water supply deficiencies, and water infrastructure development is the primary challenge in these areas (Banihabib et al., 2017). In Chile, mining operations are located at high altitudes and in hyper-arid regions where the amount of mineral resources exceeds water demand for processing. Water availability and cost are critical factors for economic and environmental feasibility of new projects and for the expansion of existing mines (Oyarzún and Oyarzún, 2011). Seawater is currently used in mining operations without desalination (Cu, Co, Zn, Mn, Ni, Mo, Pb, Au, U, and iodine extraction), so the process must be adapted to new conditions involving possible interaction of dissolved elements with minerals, chemical agents, and equipment, also the relationship between desalinated water production and the use of fossil fuel causes economic, social, and environmental problems (Cisternas and Gálvez, 2018).

High energy consumption of water treatment processes is the reason why operational costs are significant. Improvements in energy efficiency have been the focus to reduce carbon footprint and greenhouse gas (GHG) emissions (Feliciano et al., 2014; Plappally and Lienhard, 2012). Energy is needed for construction, maintenance, treatment, monitoring, and pumping, which are the most energy demanding activities, including supply, use, and disposal of fresh water, wastewater, and recycled water (Plappally and Lienhard, 2012; Rothausen and Conway, 2011). Energy demand of water transfer systems is highly dependent on the density, topography, and the location of raw water extraction and wastewater release (Loubet et al., 2014; Rothausen and Conway, 2011).

Unsustainable use of fossil fuels can be reduced; some approaches include wastewater treatment and water reuse, reduction in water consumption (water efficient technologies, infrastructure

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and piping network improvements, and public awareness), and implementation of renewable energy (Mezher et al., 2011). The use of non-traditional water sources involves many implementation challenges including its energy-intensive requirements. Demand for energy in the water sector has increased because of the growing water demand, which has created the need for integrated water and energy management to identify energy saving opportunities (Rothausen and Conway, 2011).

Climate policy has focused on climate change mitigation through the reduction of GHG emissions. Similarly, there is a need to adapt to climate variability (Bhullar, 2013). Climate change is a global occurrence with regional economic, political, and physical impacts and implications. Adaptation to climate change depends on regional and local geographic and economic diversity to assess the effect at a specific level (Bhullar, 2013).

Assessment tools that measure the ecological status, environmental degradation, and depletion of natural resources are essential for long-term natural resources' management (Al-Kalbani et al., 2016). Different approaches have been adopted to evaluate engineering systems, each of them has got its advantages and unique features. Quantitative and qualitative methods are applied to evaluate technical, economic, environmental, and social performance of water and sanitation supply chain options that include mathematical optimization, multi-criteria decision analysis, specific net present value, and statistical analysis (Balfaqih et al., 2017), these methods have not quantified the influence of energy on water systems, yet.

Some life cycle assessments (LCA) (Fang et al., 2016; Gibon et al., 2015; Santoyo-Castelazo and Azapagic, 2014; Svanström et al., 2014) propose handling the measurement from different points of view. Santoyo-Castelazo and Azapagic (2014) frameworks include scenario analysis, LCA, life cycle costing, social sustainability assessment, and multicriteria decision analysis to assess and identify the most sustainable energy option, as well as develop a decision-support framework for a sustainable integrated evaluation of energy systems considering environmental, economic, and social aspects. Svanström and coworkers (2014) introduced an iterative assessment approach with a life cycle perspective that considers technical, economic, and environmental aspects, which refine and converge different performance aspects, especially when dealing with large complex systems. The modeling framework proposed by Gibon et al. (2015) is an integrated hybrid LCA with a focus on the environmental and economic model with integrated scenarios of climate change mitigation measures used to evaluate various technologies. Fang and coworkers LCA (2016) was used in the early research and development phase of a new wastewater process to identify the environmental trade-off of current technologies as a decision-support tool.

Some approaches select information before making an assessment, adding an extra step to the analysis to minimize the amount of data. Statistical approach based on K-means clustering was applied to manage environmental energy data to evaluate energy from renewable sources (Di Piazza et al., 2011). The assessment framework proposed by Cominola et al. (2015) automatically selects the most valuable information using a quantitative metric to operationally and economically assess water system performance.

Other frameworks propose optimization solution for scheduling environmental water flow management alternatives under changing environmental availability conditions. These frameworks are a multi-objective optimization approach for long-term planning, where forecasting is sustained by artificial neural network (ANN) models and schedules updated on an annual basis (Szemis et al., 2014). Mathematical and conceptual models used by Haasnoot et al. (2011) describe natural environment and a socio-economic system but uncertainty limits their capacity to understand and predict future conditions.

Individual tools have several limitations when it comes to boundary conditions, spatial specifications, interventions, and types of impact (Chen et al., 2012). However, integrated tools add on complexities and problems to the modeling or analyzing all accumulative and interactive environmental effects (Chen et al., 2012) and call for a substantial amount of effort to meet methodological requirements (Svanström et al., 2014). The frameworks require extensive data and information to be examined, and some authors suggest increasing the number of variables to enhance the effectiveness of their framework (Cominola et al., 2015). Besides, a higher number of indicators does not necessarily lead to a better average result, due to difficulties in weighing the indicators and deciding about their relative importance (Strezov et al., 2017). Access to data is crucial for determining the definition of system boundaries, sometimes disregarding variables when data outside of the public domain have a significant impact on the result.

The increased stress on natural resources highlights the need to improve our understanding of these resources through the use of data to ensure equitable and safe access to natural resources for humans and the environment (Chini and Stillwell, 2018). The inclusion of water-energy nexus principles into modeling frameworks enables more understanding and better decision-making (Chini and Stillwell, 2018). The complexity can be reduced by dividing the analysis of the water-energy nexus into two components: energy-for-water and water-for-energy (Chini and Stillwell, 2018). By choosing to work with only one component, energy-for-water, we can manage more variables and better analyze the system in question and its interactions. This framework is applied to the energy-for-water component with the aim to manage fewer data, and to ease the generation of alternatives from which decision-makers can endorse they rule.

Based on a simplified decision-support framework, we can environmentally assess seawater treatment and distribution system for different water quality requirements, topography scenarios, and energy mixes. Our goal was to estimate GHG emissions and their environmental consequences for every location to compare the same scenario for every country. Evaluations are performed using literature data, such as those from the techno-economic assessment completed by Tavakkoli and coworkers (2017), with the purpose of calculating the impact of the system while demonstrating the unbreakable bond between water treatment and energy demand.

2. Materials and methods

Water treatment process and distribution are involved in a complex and dynamic system including climate, biological, hydrological, physical, and human interactions (Blanc et al., 2014), meaning water management must overcome significant challenges, including stricter water quality standards, increased water demand, and adaptation to climate change. Simultaneously, GHG emissions must be reduced, and a sustainable management framework must be provided for water resource treatment and transportation (Rothausen and Conway, 2011).

Water supply and demand depend on factors such as population growth, increasing urbanization, intergovernmental relations, political and policy choices, social factors, technological growth, and climate uncertainties (Plappally and Lienhard, 2012). By assessing water treatment processes, performance measures and metrics allow for the continuous improvement of water supply chain and can be used to report the current situation, with a better understanding of the past, while helping to identify future goals (Balfaqih et al., 2017).

The decision-support framework is based on the definition of the preliminary design of a treatment unit (Svanström et al., 2014). It stipulates that the initial plan of a treatment unit includes the development of a flow sheet for mass balance calculation, quantitative characterization of water and sludge streams, and data collection (Svanström et al., 2014). The framework can be applied as a strategy when environmental and ecological impacts are not to any market price mechanism. So, to be quantified, the non-market value of natural resources can be assessed for decision-making purposes (Chang et al., 2012). Sometimes it is not possible to show returns from environmental investments in the short term; however, if required by the regulations, an investment may be necessary for operational continuity or to avoid negative consequences (Salomaa and Watkins, 2011).

2.1. Scenario definition

To define a system we need to delimitate borders, develop a scenario, collect data, and assess its performance. System boundaries delimitation is essential, especially when considering assessments outside of the water industry. Water treatment chain can be divided into several stages: water supply, water treatment, residential end-use, wastewater treatment, and agriculture end-use. The basic hydrologic cycle of water engineering systems can be separated into potable water production, distribution, and consumption, and wastewater collection, treatment, disposal, and reuse (Xu et al., 2001). Each stage can be affected by geographic location, water availability, local climate, culture and customs, and economic status (Plappally and Lienhard, 2012).

The scenario used for this assessment is presented in the flowsheet in Fig. 1. All the systems are analyzed under different energy arrangements, presented for countries with water scarcity problems. As a comparison, we use GHG emissions in grams of carbon dioxide equivalent. Fig. 1a provides a graphic overview of System A boundaries intended for municipal water use, following wastewater treatment and disposal. Treatment A involves several alternatives of seawater desalination through multi-effect distillation (MED), multistage distillation (MSF), reverse osmosis (RO), brackish RO, and electrodialysis, along with their energy consumption. For all the treatment processes analyzed for System A (Fig. 1a) we assumed the same chemical consumption and the same wastewater rejection per cubic meter of seawater treated.

Fig. 1b provides a graphic overview of System B boundaries, intended for municipal use, with the same treatment process alternatives as in System A: MED, MSF, RO, Brackish RO, and electrodialysis, but with the addition of posterior wastewater recycle, where water is planned to be used for irrigation purposes. For all the treatment processes in System B (Fig. 1b), we also considered the same chemical consumption and the same wastewater rejection per cubic meter of seawater treated. Finally, Fig. 1 c provides a graphic overview of System C boundaries, where seawater is non-desalinated, without treatment (WT), intended for the industrial purpose. After it is used, water recirculates through industrial processes.

There are two types of common, obvious errors: systematic errors or biases that decrease the accuracy of the estimates and random errors that reduce the precision of the forecast. The lack of accuracy and precision may lead to uncertain estimates, but we can deal with precision errors by increasing the number of samples, whereas bias can be reduced by monitoring and reporting (Bellassen and Stephan, 2015). However, when analyzing complex systems, we need to reduce the number of samples to ensure that calculation is manageable. In this study to decrease the bias, calculations were completed under best, worst, and average case scenarios, with data supplied by peer review articles, the World Bank (The World Bank, 2017) and Organization for Economic Cooperation and Development (OECD) data ("Waste water treatment - Water - OECD iLibrary," 2017).

To represent best, worst, and average case scenarios, we considered different distances (horizontal and vertical) from which seawater must be pumped to be treated and distributed, as shown in Fig. 2. The best-case scenario considers the shortest distance, vertically and horizontally, from seawater extraction site to the treatment plant and towards end-user location. The worst-case scenario involves the longest distance from the extraction zone to the treatment plant, and afterward to the end-use zone. The average-case scenario represents the in-between situation of the other two cases. Cases considering vertical and horizontal distance represent different topographies in the analyzed countries and different water distribution paths from extraction to end-user location. Also, we assessed different types of water demand with three water treatment flows: low, medium, and high. Data used to define all scenarios were taken from literature as shown in Table 1.

2.2. Case study

The framework was applied to a selected number of countries experiencing water scarcity as listed by Mekonnen and Hoekstra (2016) or countries located in regions with water problems and with access to the coastline. The group of selected countries included: Argentina, Australia, Algeria, Bahrain, Bangladesh, Chile, China, Arab Republic of Egypt, India, Indonesia, Israel, Iran, Iraq, Italy, Kingdom of Jordan, Kuwait, Lebanon, Libya, Malaysia, Mexico, Morocco, Nigeria, Oman, Pakistan, Portugal, Saudi Arabia, South Africa, Sudan, Syrian Arab Republic, Spain, Tunisia, Republic of Turkey, United Arab Emirates, United States of America, and Yemen. We also used average world GHG emissions. Data included Finland to show that not only renewable energy but also nuclear energy generation, as used by Spain, can decrease GHG emissions. The results for all these countries are provided in the Supplementary Information section.

3. Data collection and water characteristics

Data collected for the systems covered by our study are summarized in Table 1. Variables considered for each modeling situation are shown in bold in Table 1. The data were obtained from peer review articles (Cong et al., 2009; Jamaly et al., 2014; Kesieme et al., 2013; Macedonio and Drioli, 2017; Petry et al., 2007; Plappally and Lienhard, 2012; Racoviceanu et al., 2007; Stokes and Horvath, 2009; Tavakkoli et al., 2017). For calculation, we chose the best, worst, and average scenario for every low, medium, and high water treatment flow.

For quantitative characterization, water and sludge were assumed the same for all cases in our study to facilitate the comparison of results.

3.1. Balance calculation

3.1.1. Mass balance

Environmental impacts of a flow can be calculated using a simple mass balance of all associated inputs, outputs, and storage (Chen et al., 2012). For each system, we calculated the mass balance of water flow based on the cubic meters of seawater treated with data from Table 1, using the feed seawater in bold for each type of treatment, obtaining the results in cubic meter per day.

3.1.2. Energy consumption balance

The energy balance was based on the mass balance with data from Table 1. The feed seawater data were used for calculations across the system, with three types of water demand: low, high,

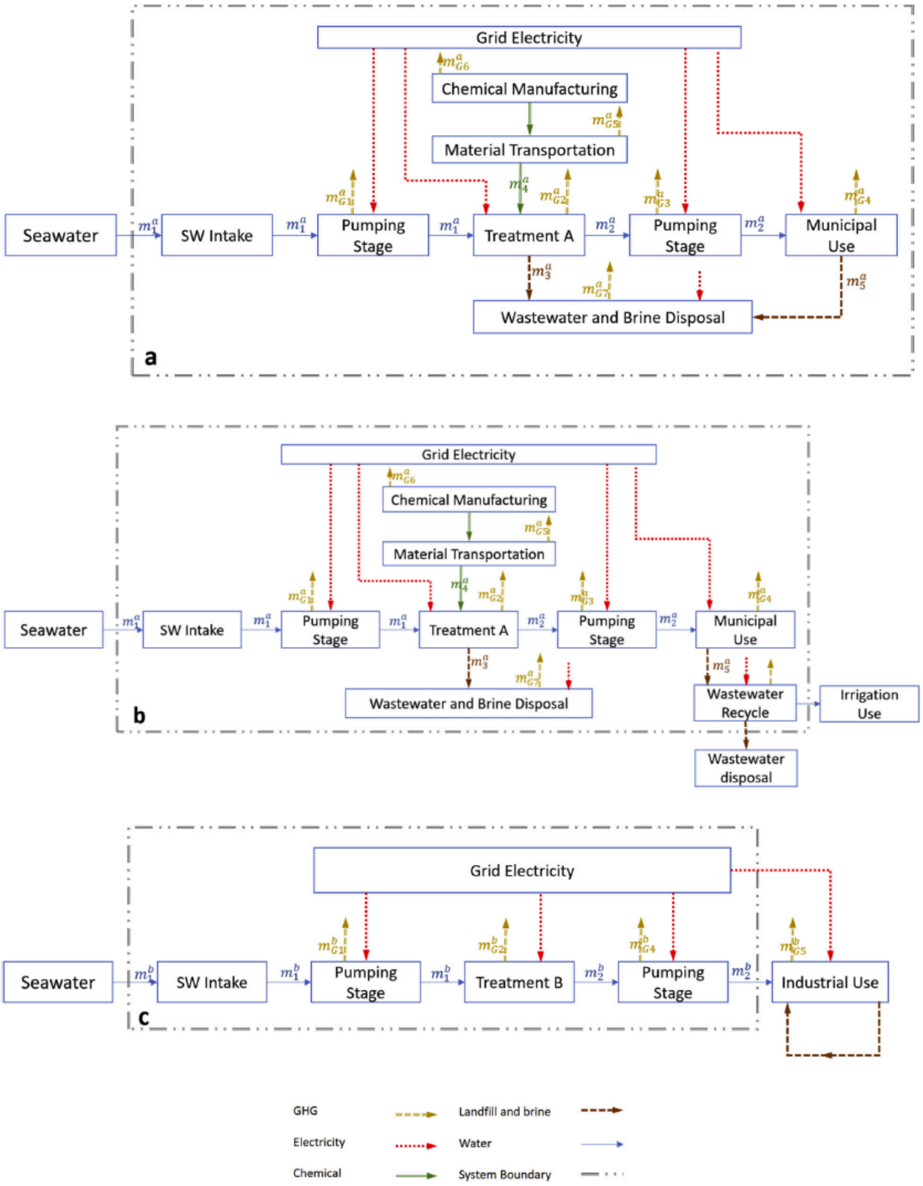

Fig. 1. Graphic overview of the boundaries of a. System A intended for municipal water use, b. System B with wastewater recycling, c. System C proposed for the industrial purpose.

and medium. Calculations were completed for each type of treatment, and results obtained are presented in kilowatt-hour per day.

- Seawater intake stage: horizontal distance data and energy consumption were calculated for the three scenarios: best, worst, and average.

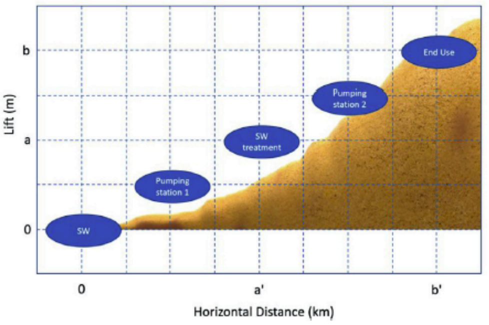

Fig. 2. Vertical and horizontal distance for seawater (SW) treatment and distribution throughout the use and treatment journey.

- Pumping station 1 stage: the data used were applied to a primary theoretical physical relationship presented (Rothausen and Conway, 2011):

$$Energy\ Consumption\ [\mathrm{kWh}] = \frac{9.8\left[\frac{\mathrm{m}}{\mathrm{s}^{-2}}\right] \times \mathrm{d}[\mathrm{m}] \times \rho\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right] \times \mathrm{Q}\left[\frac{\mathrm{m}^3}{\mathrm{day}}\right]}{3.6 \times 10^6 \times \eta[\%]}$$

where d is the vertical distance, ρ is the density of seawater 1025 (kg/m^3), Q is the volumetric flow of seawater, and η is the efficiency. The variables considered for each scenario were distance and efficiency, calculated for the three types of water demand.

- Seawater treatment stage: each type of treatment with its energy consumption was calculated. Also, in this stage, we added the energy consumption of chemical manufacturing and transportation based on the amount of seawater treated. This stage was omitted for System C.
- Pumping station 2 stage: this is the second half of calculations for Systems A and B based on the quantity and quality of treated water. However, calculations remain the same for System C. Horizontal energy consumption was calculated for three scenarios with variables in distance and energy consumption. The latter was supplemented with energy consumed for vertical transportation, calculated in relationship to water density of 1000 (kg/m^3) and the same variables.
- Municipal use (end-use) stage: energy consumption was calculated based on average work (Plappally and Lienhard, 2012), due to its high variability. This stage was not calculated for System C.
- Wastewater treatment stage: this stage was calculated for System A, assuming no losses to the system.
- Wastewater recycling stage: this stage was calculated for System B, assuming no losses to the system, and the product water is intended for irrigation.
- The last step consists of adding up all energy consumed in each system and then calculating the GHG emission per country based on the type and amount of generated energy. To evaluate GHG emissions, we used data from Table 2, where A corresponds to the data from Amponsah et al. (2014) and B corresponds to Racoviceanu et al. (2007).

4. Results

The framework was applied to the world average as a case study, though calculations and results for all selected countries are presented in the Supporting Information section. The results are shown to illustrate the methodology and provide an understanding of the results obtained. Fig. 3 depicts the countries covered by the analysis of average GHG emissions, and in Fig. 4 we compare these emissions with the world average.

Fig. 5 demonstrates the mix of energy sources used for each

Table 1
Input values obtained from literature that were applied in the framework.

	Values used in the application of the framework are shown in bold and subscript numbers: $_1$best case, $_2$average case, and $_3$worst case.								
Seawater Intake	Feed Seawater (m^3/day)	**1,893**$^{a}_{1}$	24,000^{b}	37,450^{b}	45,360^{c}	**90,000**$^{d}_{2}$	**432,000**$^{e}_{3}$		
	Horizontal distance (km)	**1**$^{f}_{1}$	3.2^{f}	4.8^{f}	125^{f}	170^{c}	**236**$^{g}_{2}$	400^{f}	**1,100**$^{f}_{3}$
	Energy Consumption (kWh/m^3 km)	0.002$^{h}_{1}$	0.005$^{h}_{2}$	0.007$^{h}_{3}$					
Pumping Station 1	Vertical Distance (m)	10$_1$	648$^{g}_{2}$	3,200$^{c}_{3}$					
	Efficiency (%)	**40$_3$**	50	60	**70$_2$**	80	**90$_1$**		
Seawater Treatment	Treatment Type	MED	MSF	RO	Brackish RO	Electro-Dialysis	Without treatment		
	Recovery (%)	50^{e}	50^{e}	50^{e}	50^{e}	50^{e}	100		
	Energy Consumption (kWh/m^3)	1.79^{h}	3.84^{h}	5.02^{h}	1.63^{h}	1.25^{h}	0		
Chemical Manufacturing	Energy Consumption (kWh/m^3)	0.039^{i}							
Chemical Transportation	Energy Consumption (kWh/m^3)	0.008^{i}							
Pumping Station 2	Water treated (m^3/day)	**946.5$_1$**	12,000	18,725	22,680	**45,000$_2$**	**216,000$_3$**		
	Horizontal distance (km)	**1**$^{f}_{1}$	3.2^{f}	4.8^{f}	125^{f}	170^{c}	**236**$^{g}_{2}$	400^{f}	**1,100**$^{f}_{3}$
	Energy Consumption (kWh/m^3)	0.002$^{h}_{1}$	0.005$^{h}_{2}$	0.007$^{h}_{3}$					
	Vertical Distance (m)	10$_1$	648$^{g}_{2}$	3,200$^{c}_{3}$					
	Efficiency (%)	**40$_3$**	50	60	**70$_2$**	80	**90$_1$**		
End-Use	Energy Consumption (kWh/m^3)	66.57^{*h}							
Wastewater Treatment	Energy Consumption (kWh/m^3)	0.20$^{i}_{1}$	0.30$^{i}_{2}$	0.42$^{i}_{3}$					
Wastewater Recycling	Energy Consumption (kWh/m^3)	0.33$^{i}_{1}$	0.91$^{i}_{2}$	1.86$^{i}_{3}$					

[a] Tavakkoli et al. (2017).
[b] Kesieme et al. (2013).
[c] Petry et al. (2007).
[d] Jamaly et al. (2014).
[e] Macedonio and Drioli (2017).
[f] Stokes and Horvath (2009).
[g] Cong et al. (2009).
[h] Plappally and Lienhard (2012).
[i] Racoviceanu et al. (2007); and.
*calculated based on data from Plappally and Lienhard (2012).

Table 2
GHG emission data for energy generation in gCO_2eq/kWh. Information from A corresponds to the data from Amponsah and coworkers (2014) and B corresponds to Racoviceanu and coworkers (2007).

Renewables		Hydro	38.5^{A}
Wind	64.5^{A}	Coal	1031^{B}
Geothermal	44.5^{A}	Oil	792^{B}
Photovoltaic	154.5^{A}	Natural Gas	397^{B}
Solar Thermal	90^{A}	Nuclear	14^{B}
Prom Renewable	88.4	Biofuels and Waste	332^{A}

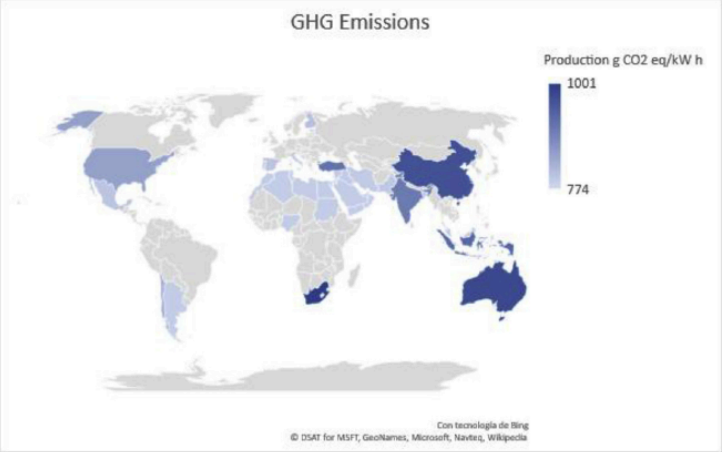

Fig. 3. Map of GHG emissions in analyzed countries based on the production of gCO_2 equivalent per kWh; data calculated based on IEA – Report (IEA, 2011).

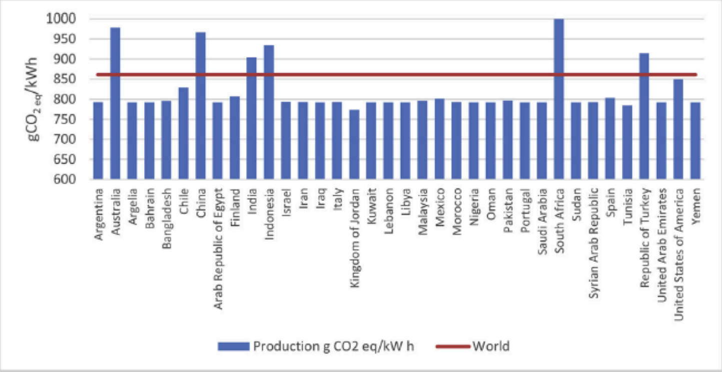

Fig. 4. GHG emission comparison with the world average based on the data from IEA – Report (IEA, 2011).

selected country, which includes: coal, crude oil, natural gas, nuclear, hydro, renewable sources (geothermal, solar, wind, and others), biofuel, and waste (OECD, 2018). Fig. 5 presents GHG emissions in ascending order, from the lowest releasing country in the analyzed sample, Kingdom of Jordan, to the biggest emitter, South Africa.

Fig. 6 displays energy consumption in different seawater desalination processes analyzed in this work. Table 3 shows calculations for the three analyzed scenarios: low consumption (1893 m^3/day), medium consumption (90,000 m^3/day), and high consumption (432,000 m^3/day) of treated water.

Fig. 7 is a graphic representation of GHG emissions for three

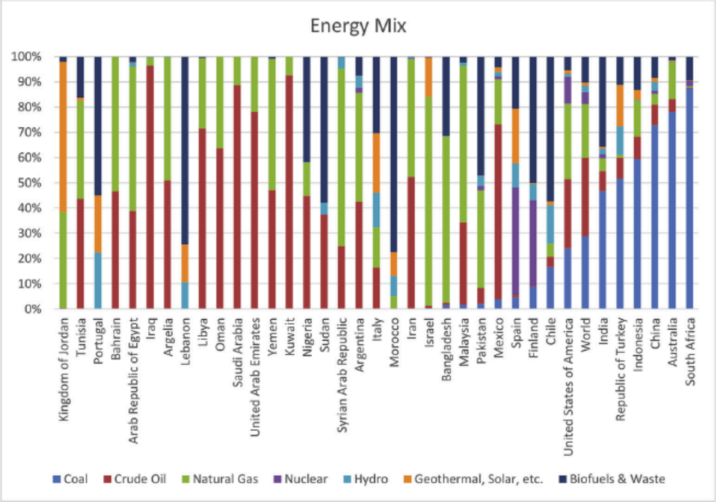

Fig. 5. Diversity of energy mix generation based on previously reported data (IEA, 2011).

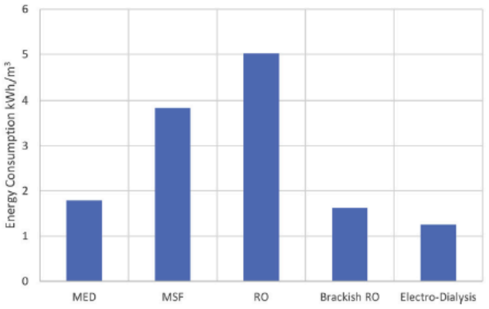

Fig. 6. Energy consumption for different types of seawater desalination treatment complete the analysis, we left some variables unchanged to show more relevant results.

types of water demand. We selected countries with the highest and lowest release from our study sample and compared them with the world average emissions. Fig. 7 displays the results corresponding to the world average, South Africa, and The Kingdom of Jordan GHG emissions. First, the GHG emissions from the treatment of wastewater from residential end-users and its disposal (System A, correspond to the first five technologies on the graph). Second, the GHG emissions from wastewater recycling from residential end-users to irrigation applications (System B, correspond to the second five technologies on the graph). Finally, the GHG emissions from untreated seawater intended for industrial use (System C, corresponding to the last group of columns). The results consider energy consumed by pumping seawater at different distances and heights.

5. Discussion

Systems engineering strategy frameworks are sufficiently flexible to support a broad range of applications and contribute to an organization's sustained competitive advantage (Smartt and Ferreira, 2012). The challenge is that engineers and technical managers must consider the technological system as part of a larger whole (Svanström et al., 2014). However, larger technological systems have countless opportunities for isolating subsystems to enable comprehension and analysis (Bartolomei et al., 2012). Inability to carefully understand the subsystem can lead to only

Table 3
Energy consumption for analyzed seawater treatment processes.

Energy Consumption for Treatment (kWh/day)			Seawater Consumption (m³/day)		
Type of Treatment	Recovery (%)	Energy Consumption (kWh/m³)	1893	90,000	432,000
MED	50	1.79	3388	161,100	773,280
MSF	50	3.84	7269	345,600	1,658,880
RO	50	5.02	9503	451,800	2,168,640
Brackish RO	50	1.63	3076	146,250	702,000
Electro-Dialysis	50	1.25	2366	112,500	540,000
Without treatment	100	0.00	0	0	0
	Water out (m³/day)	50%	947	45,000	216,000
		100%	1893	90,000	432,000

Fig. 7. Comparison of GHG emissions between countries with the highest, lowest and world average releases for different water demand. More details about the calculations and results can be found in the Supplementary Material.

partial, or even distorted, picture of the system behavior, which argues in favor of our decision to consider only the energy-for-water component of the water-energy nexus in this analysis. We chose to study the energy-for-water component to facilitate the aim of generating a framework that is simple and fast in providing results for the endorsement of the decision-making process.

Analyzing individual sectors without considering their interaction with each other can lead to misinterpretation of impacts and therefore to poor decisions (Harrison et al., 2016). Water and energy are inseparably associated because water is a crucial component in energy production and vice versa. Energy is needed for supplying, treating, and using water. In all cases analyzed by Loubet and coworkers (2014), electricity contributed to the majority of impacts in water treatment, and particularly in desalination processes, where energy requirements are higher than in conventional water treatment processes. However, analyzing the components of the water-energy nexus is a challenging endeavor. For this reason, we only examined the energy-for-water component to facilitate obtaining results more quickly.

Energy consumption also depends on the specific technology applied at each stage of the water cycle and on the water source (Plappally and Lienhard, 2012). Water treatment technologies have been introduced to improve water quality, with technological developments that provide options for design or advances in previous water treatment processes (Ramírez et al., 2017). The type of technology selected depends on other variables, such as the analysis of technologies influencing the energy-for-water GHG emissions as was compared as Treatment A types in systems A and B (see Fig. 1). However, the selection of water treatment technology should consider GHG emissions. RO is the most frequently used water treatment technology, but it produces the biggest GHG emissions (see Fig. 6), which gives us three options: to select a technology with lower GHG emissions, to improve the current technology to consume less energy, or to opt for a lower GHG emission source of energy.

When analyzing the energy mix for providing electricity in Figs. 4 and 5, the alternatives for reducing GHG emissions include opting for renewable sources of energy and/or nuclear energy. This is shown in the results obtained in the analysis of the energy mix for countries like Spain and Finland and supported by the results obtained by Santoyo-Castelazo and Azapagic (2014), where energy sources, such as nuclear power release less GHG emissions than renewable energy (see Table 2). Countries with lower GHG emissions do not use coal as energy source (see Fig. 5, from the Kingdom of Jordan to Israel). Moreover, countries with the highest GHG emissions are those with coal as a principal source of energy (see Fig. 5, from India to South Africa), nearly 50% and over. However, public approval is vital for the implementation and operation of any water treatment system. Factors influencing public acceptance are disgust, perception of risk, sources of water for recycling, specifically for the intended use of recycled water, trust in authorities, knowledge, attitudes toward the environment, environmental justice, cost, and socio-demographic factors.

The analysis of different scenarios of seawater desalination processes for several countries facing water scarcity problems showed that a diverse energy mix has got an essential impact on GHG emissions. The location of the water source and end-users produce the most prominent environmental effects if we only consider energy-related emissions. These metrics provide opportunities to develop and understand the impact of topology on energy consumption to deliver water for industrial, irrigation, and municipal purposes. Seawater treatment and distribution system efficiency must be improved (Cisternas and Gálvez, 2018). Mining operations that are located at high altitudes entail increased costs of using seawater, either with, without, or with partial desalination, due to transport costs. The supply chain in the analyzed scenarios differs with respect to the selected technology, which influences economic and environmental performance. Therefore, a generic supply chain is not sufficient in the framework for informed decision-making (Ribeiro et al., 2016).

Countries located in non-arid regions can experience water supply deficiencies. Singapore's strategy involves local catchment water and desalinated water in addition to water imported from Malaysia (Bhullar, 2013). Desalination expands domestic water supply sources, as the geographic location does not require much energy, due to the highest point being located 165 m above sea level, and the entire population lives less than 100 km from the coast (Bhullar, 2013).

Stakeholders must be provided with all alternatives to select and implement the best-case scenario for the market, especially when, as is the case here, all the countries included in this study present a variety of geographic challenges and a diversity of user locations. Water utilities should assess their management strategy to ensure a high level of service, safe and reliable drinking water, and appropriate network performance, which requires a suitable long-term balance between cost, performance, and risk at the strategic and operational levels (Feliciano et al., 2014). Public perception and acceptance are critical to the implementation of any energy technology (Santoyo-Castelazo and Azapagic, 2014). Government policies and stakeholders' approval depend on the location as well as on specific political, social, and economic circumstances (Svanström et al., 2014) that vary across all the analyzed countries. An integrated management strategy should be adopted to allow sustainable development of the industry for all stakeholders (Oyarzún and Oyarzún, 2011).

Water desalination sustainability involves improved human health, environment, and fresh water for domestic, industrial, and agricultural use (Balfaqih et al., 2017). Other alternatives, such as complete reuse of wastewater, can be competitive options in the market due to the increasing demands on environmental policy, changes in public attitude, and water technologies advancement (Xu et al., 2001). Also, the selection of these alternatives can lead to non-conventional water sources becoming an alternative for other areas that are not facing severe water scarcity problems. Desalinated water could be an economically competitive option, producing a less negative impact on the environment. Water desalination, however, is a management and technical solution that is not self-sufficient; the price and availability of energy determine the future price and availability of water. Desalination is costly, energy-intensive and leaves a huge ecological footprint (Bhullar, 2013).

In Northern Chile, conventional water sources are scarce, affecting water reservoirs that provide flow for water springs and Andean wetland ecosystems. These ecosystems are essential for the pastoral activities of Aymara native communities and natural habitats of the local population of flamingos and other wild species (Oyarzún and Oyarzún, 2011). Sustainable water management is complicated and the concern over water scarcity is growing (Loubet et al., 2014). Sustainable water management should include conservation, recycling, and desalination (Mezher et al., 2011). Urban water systems are elaborate and embrace many aspects that often require separate management. Integrated urban water management is a general approach that requires quantitative tools to assess environmental impacts and involves water sources, water use sectors, water services, and water management scales (Loubet et al., 2014). The end-use water consumption can vary significantly from one person to another, as shown by Plappally and Lienhard (2012), therefore end users' unpredictable behavior is a non-reliable tendency. The environmental regulatory system quality and stringency are related to national wealth (Salomaa and Watkins, 2011). To develop a sustainable water management strategy involves the identification of vulnerable and adaptation possibilities, and compelling analysis under possible futures must be completed (Haasnoot et al., 2011).

Limitations of this decision-making framework for the environmental assessment of water treatment processes and distribution systems come from its concept of a simplified framework, which makes assessments of more complex systems that involve, e.g., different types of energy sources in different parts of the system, a really daunting task in practice. Also, a great challenge will be to consider the water-for-energy component of Water-Energy nexus, redefine the analyzed system or insert more variables and interactions into the mix.

6. Conclusions

A decision-support framework was proposed and developed in this study to analyze the energy-for-water component of the water-energy nexus. This framework was applied to water treatment and water distribution systems and their impact on the environment. This work aimed to show the lasting relationship between water and energy, analyzing the energy-for-water component against GHG emissions and its variability throughout water systems.

It is essential to assess the energy mix diversity given the effects of water treatment and consumption on the environment so that stakeholders could make better decisions, and improve the overall consumer awareness. Water and energy are inseparably associated given the energy required for the processes of supplying, treating, and using water. Electricity is responsible for the most significant part of the impacts of water treatment, particularly in desalination processes, where energy requirements are higher than in conventional water treatment processes. The location of water source and of the final consumer cannot be changed, however, improvements in the selection of technology, energy source, and the promotion of water reuse, water recycling, and non-treated water for industrial processes can be improved to help lower GHG emissions from water treatment processes and water distribution systems.

The different water process systems analyzed for several countries facing water scarcity problems showed that a diverse energy mix is the main factor affecting GHG emissions. The locations of the water source and end-users have the most significant impact on the environment if solely energy-related GHG emissions are considered. To lower GHG emissions, one of the options is to opt for a different source of energy having in mind that nuclear power generation produces the lowest GHG emissions, even lower than renewable energies. However, to develop new projects or to improve the existing ones it is vital to consider stakeholders' opinions, to start or continue such operations.

Water sustainability alternatives can also be applied to zones not experiencing severe water scarcity. Water desalination, water reuse, and wastewater treatment can be competitive options for the market due to the increasing demands of environmental policy, changes in public attitude, and advancements in water technologies. Public perception and approval are critical for the implementation of any water treatment project, especially when water is intended for drinking purposes.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.03.319.

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Publication III

Araya, N., Ramírez, Y., Cisternas, L.A. and Kraslawski, A.

Feasibility of re-processing mine tailings to obtain critical raw materials using real options analysis

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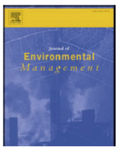

Research article

Feasibility of re-processing mine tailings to obtain critical raw materials using real options analysis

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ABSTRACT

The re-processing of mine tailings to obtain critical raw materials (CRMs) could reduce the mining of new deposits as well as ensure the profitable use of the waste materials. Though, it requires large scale industrial installations and the development of specialized technologies to obtain CRMs. New investment in mining activities is an operation, engaging for considerable financial resources involved. The scale of such an endeavor makes a new mining activity a high-risk operation due to several uncertainties present. Therefore, there is an acute need to use new tools to assess the risk associated with the planning and development of new mining activities.

This study introduces a framework to evaluate the economic risk related to the re-processing of mine tailings to obtain CRMs. The framework, based on real options analysis (ROA), and sensitivity and uncertainty analysis, was applied to analyze the profitability of using mine tailings as a source of CRMs in the Chilean mining industry. The novelty of this approach consists in enabling the investment decision making including the uncertainties related to a novel investment mining project.

Results: show that tailing storage facilities in Chile have some stocks of CRMs, like scandium, whose extraction could be profitable. For the data used, the results of uncertainty and sensitivity analyses show that capital expenditure has a more significant influence than the other variables. Therefore, for the case of mine tailings re-processing, it is essential to develop processes and technologies that enable lower capital expenses.

1. Introduction

Mine tailings are waste obtained after the processing of some minerals to acquire one or more elements of interest. They are composed of a mixture of heavy metals, water, sand, and fine-grained solid material, and generally are deposited in ponds without further treatment (Babel et al., 2016; Santibañez et al., 2012; L. Wang et al., 2017). The annual amount of mine tailings generated by the mining industry exceeds 10 billion tons (Adiansyah et al., 2015) and is expected to be growing because of the increasing production forecast by 2035 the volume of tailings will double (CESCO, 2019). Due to higher demand for mineral products and lower grades of ore as a result of which more materials will have to be processed in more energy-intensive processes (Wang et al., 2014). Particularly, Chile has already 10,565 million tons of mine tailings and an approved capacity of 23,935 million tons, from which 99% belongs to mines of copper-gold-silver-molybdenum resources (SERNAGEOMIN, 2020).

Mine tailings deposits may contain many valuable elements as has been shown in several studies (Alcalde et al., 2018; Andersson et al., 2018; Figueiredo et al., 2018; Khalil et al., 2019; Khorasanipour and Jafari, 2017; Macías-Macías et al., 2019; Markovaara-Koivisto et al., 2018; Medas et al., 2013; Wen et al., 2019). In the particular case of Chilean copper mine tailings, 0.82% are metals, non-metals, and metalloids, 0.01% rare earth elements, and the rest major rock-forming elements (SERNAGEOMIN, 2017). Nowadays, mine tailings are increasingly often seen as a potential source of raw materials, and secondary sources are attracting more and more attention due to the benefits of a circular economy approach (Jeswiet, 2017; Kinnunen and Kaksonen, 2019).

Currently, extracting raw materials and metals from ore bodies of declining ore grade means potentially bigger mine size generating more waste, overburden to the environment, higher consumption of energy,

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water, and auxiliary materials which overall produce severe environmental consequences and larger political risks (de Koning et al., 2018; Mudd, 2010; Northey et al., 2016; Žibret et al., 2020). Furthermore, by 2050 the overall demand for metals will rise by a factor of 3–4 (de Koning et al., 2018). When a mine has exhausted its resources whose extraction is economically viable, an alternative is to close it and then reopen when the market and technology conditions enable a profitable re-processing of tailings (Northey et al., 2016). The long-term supply of metals highly depends on actual and expected prices, cumulative availability curve, and new mining technologies (de Koning et al., 2018; Gordon et al., 2007; Tilton and Lagos, 2007; Yaksic and Tilton, 2009). Additionally, the development of new high-tech technologies might lead to disruptive demand change (Tukker, 2014); meanwhile, it may take ten years or more to open new mines and adjust production (de Koning et al., 2018).

There is a group of materials that is drawing considerable attention, recently. They are called critical raw materials (CRMs) and are fundamental to the manufacturing of a broad range of equipment essential in digital technologies, low-carbon systems, and sustainable mobility (David and Koch, 2019; Mathieux et al., 2017; X. Wang et al., 2017). According to the European Commission, critical raw materials possess two common characteristics: they have high economic importance to the European Union and their supply is associated with high risk (European Commission, 2017). Supply risk results from the concentration of primary supply in the countries, considered as risky due to their governance performance and trade aspects (European Commission, 2017). The recent list made by the European Commission contains 30 raw materials or groups of raw materials that are identified as critical (European Commission, 2020).

Mine tailings contain several CRMs, even if their content is low, the volumes of mine tailings are big enough to consider re-processing (Binnemans et al., 2015; Careddu et al., 2018). Several studies analyze the geochemical content of mine tailings to demonstrate that they contain CRMs and point out that tailings could be re-processed in the future (Ceniceros-Gómez et al., 2018; Dino et al., 2018; Markovaara-Koivisto et al., 2018; Moran-Palacios et al., 2019; Tunsu et al., 2019).

This study aims to propose a framework to assess the feasibility of re-processing mine tailings to obtain CRMs considering the uncertainties involved. The presented methodology is illustrated by the set of unique data applicable to Chilean mine tailings. The proposed approach consists of applying the Discounted Cash Flow (DCF) method alongside Real Options Analysis (ROA) as well as uncertainty and sensitivity analysis. It could be applied to other mine tailings deposits for which geochemical data are available. For example, the contents of CRMs in mine tailings have been already measured in some deposits in Finland, Sweden, Portugal, Indonesia, and Mexico (Ceniceros-Gómez et al., 2018; Hällström et al., 2018; Markovaara-Koivisto et al., 2018; Peelman et al., 2018; Szamałek et al., 2013; Tunsu et al., 2019).

The research questions that this study seeks to answer are:

- Is it economically feasible to invest in a project developed around the idea of re-processing mine tailings to obtain critical raw materials?
- How can real options analysis improve the decision to invest in a project using mine tailings as a source of critical raw materials?
- How can the net present value variables influence real options performance?

Sustainable development components involved in mine tailings management strategy should include energy, water, technology, environmental impact, cost (Adiansyah et al., 2015), and policy. The valorization of mine tailings appears a critical component to achieving a circular economy model in the mining industry, which needs to improve its processes to minimize the environmental impacts of mining waste (Lèbre et al., 2017; Tayebi-Khorami et al., 2019). The valorization of tailings is still in the early stages, but it is expected to improve in the future (Kinnunen and Kaksonen, 2019). Economic tools are crucial to analyze the use of secondary sources (Alwaeli, 2011a). The proposed approach consists of applying the Discounted Cash Flow (DCF) method alongside Real Options Analysis (ROA) as well as uncertainty and sensitivity analysis.

The novel contribution of this article consists of considering ROA and sensitivity and uncertainty analysis to give flexibility to the economic assessment of mine tailings re-processing, acknowledging the uncertainties involved. Net present value (NPV, which is a metric to assess the feasibility of a project, is calculated using the DCF method as a starting point, and next using ROA, different outcomes for an investment project are estimated (Arnold, 2014; Brandão et al., 2005; Kodukula and Papudesu, 2006; Trigeorgis, 1996). The viability of mining investments depends on variables that have high uncertainty as to the market prices of metals. In the case of re-processing mine tailings, technology developments and business model development are still needed. To study the influence of several variables on NPV outcome, Monte Carlo simulation is used to perform sensitivity and uncertainty analysis.

2. Methodology

The profitability analysis of mine tailings processing requires the identification of geochemical characteristics of the tailings deposit, also named tailings storage facility (TSF). Mineral characteristics and concentration of elements that are present in the TSF along with the mass of tailings accumulated in the deposit allow estimating the quantity of each CRM (Araya et al., 2020; Markovaara-Koivisto et al., 2018; Moran-Palacios et al., 2019).

In the economic analysis, the in-situ value is estimated by multiplying the total mass of a specific CRM by its price. Total mass is calculated based on the average concentration and mass in a TSF (Araya et al., 2020; Markovaara-Koivisto et al., 2018). DCF method is used to estimate the NPV of a project for extracting one or more CRMs from one of the TSF analyzed. Criteria used to choose which CRM could be extracted include concentration, total mass, and price. In some cases, finding such data, as well as get access to data for estimating the capital expenses (CAPEX) and the operating expenses (OPEX) for each CRM is rather difficult.

Subsequently, an overview of technologies suitable for re-processing mine waste stored in a TSF to extract the CRMs is needed. If these technologies are still not applicable on an industrial scale, then, technologies used to process primary ores to obtain such CRM are considered, the same goes for economic inputs such as CAPEX, OPEX, and production. When dealing with mine waste, some consideration needs to be given to aspects, such as a lower grade of elements contained in it (Araya et al., 2020; Binnemans et al., 2015; Falagán et al., 2017). Mine tailings are already in the form of a paste or slurry, so there are no mining costs, which usually represent 43% of operating costs in a mine (Curry et al., 2014).

ROA is applied using the NPV obtained with the DCF method using the method of risk-neutral probabilities presented in. The binomial tree analysis is used to apply ROA. A binomial tree is built by using the method of risk-neutral probabilities presented by Kodukula and Papudesu (2006); this methodology involves adjusting the risk of the cash flows across the lattice with risk-neutral probabilities and discounting them at a risk-free rate (Kodukula and Papudesu, 2006). Sensitivity and uncertainty analyses are used to assess the effect of uncertainties on net present value. Monte Carlo simulation is used to perform uncertainty analysis and the Sobol' indices are calculated to perform global sensitivity analysis.

2.1. Project valuation tools

Investments in the mining sector are capital intensive and mostly irrevocable with a limited economic life span. Their economic viability depends on the uncertain world market price and on how project risks emerge (Guj and Chandra, 2019). The project value is determined by the commodity market and flexibility inherent in the metal mining system to respond to uncertainties (Savolainen et al., 2017). The available future metal prices can be used as certain in the project valuation process, where their maturity is maximum between two to five years (Savolainen, 2016).

Traditional valuation tools, such as the DCF method, are static methods that do not consider the uncertainty of the variables used to estimate the profitability of an investment (Arnold, 2014; Brandão et al., 2005; Kodukula and Papudesu, 2006; Trigeorgis, 1996). The project valuation techniques that ignore the real option nature of the project are widely used in the mining industry, e.g., net present value, internal rate of return, and static DCF (Savolainen, 2016). DCF method treats future cash flows as deterministic values. Methods to include uncertainty in the result of NPV are: increasing the discount rate, applying sensitivity analysis, comparing pessimistic and optimistic cash flows, or to use scenario planning to estimate expected cash flows (Gaspars-Wieloch, 2019).

There are many approaches to analyze cost-intensive investments under the conditions of uncertainty (Cristóbal et al., 2013). One of the methods gaining popularity is real options as it is being applied in different fields (Insley, 2002; Nelson et al., 2013; Regan et al., 2015; Schatzki, 2003; Slade, 2001). Real options are a right, not an obligation, to undertake business initiatives connected with tangible assets (Kodukula and Papudesu, 2006; Wang and Neufville, 2005). Real options acknowledge managerial flexibility and readiness to adjust investment projects due to future uncertainty and the changing environment, involving possible managerial options that can reshape a project and adapt it to changing conditions to maintain or enhance its profitability (Trigeorgis, 1993). Real options for a project exploit the flexibility of sequential investment with flexible strategies and the capability to delay decisions in an engineering system to react to an uncertain outcome; where the changes depend on exogenous and endogenous uncertainties, so it is hard to make credible value estimates (Guj and Chandra, 2019). Common attributes of real options valuation design include identification of sources of uncertainty, available real options recognition, modeling of uncertain variables, and real option valuation (Kozlova, 2017). Methods used to evaluate real options are decision trees, Monte Carlo simulations, and the Black-Scholes model (Arnold, 2014; Collan, 2011; Kodukula and Papudesu, 2006).

ROA is used in metal mining to assess mining investments due to the growing market uncertainty and project complexity of new investments. The real options valuation method aims to protect and increase the economic return from a project (Savolainen, 2016) and is applied predominantly in investment project valuation (Kozlova, 2017).

2.2. Discounted Cash Flow (DCF) method

DCF method is based on the calculation of NPV of a project over its entire life cycle accounting for the investment and the free cash flows throughout its whole life (Kodukula and Papudesu, 2006).

$$\begin{aligned} Project\ NPV = PV\ of\ free\ cash\ flows\ in\ production\ phase \\ -PV\ of\ investments\ costs \end{aligned} \tag{1}$$

According to the DCF method, if the project *NPV* is greater than zero, it means that the project revenues are greater than the costs of the project, so it is financially attractive (Arnold, 2014; Kodukula and Papudesu, 2006).

Present value *(PV)* is the estimation of costs and net revenues of the development production phase. These are the free cash flows over the entire life cycle of the project (Kodukula and Papudesu, 2006).

$$PV = \frac{FV}{(1+r)^n} \tag{2}$$

Where *FV* is the future value, *r* is the discount rate per time period, and *n* is the number of the time period.

To estimate the NPV of a project, CAPEX and OPEX of a project with similar characteristics in terms of ore grade and production capacity are used. CAPEX may include treatment equipment, water intake structure, site preparation, concentrate discharge system, auxiliary equipment, piping, and valves (Bhojwani et al., 2019). OPEX includes labor, energy cost, chemicals, maintenance, spare parts, as well as indirect cost (Bhojwani et al., 2019).

The following equation was employed to estimate NPV and PV of a project based on the use of mine tailings:

$$\begin{aligned} cash\ flow = \left(price \cdot production - OPEX \cdot production - \frac{CAPEX}{n}\right) \cdot (1 - taxes) \\ + \frac{CAPEX}{n} \end{aligned} \tag{3}$$

$$Annuity = 1 - \frac{1}{\frac{(1+R)^n}{R}} \tag{4}$$

$$PV = cash\ flow \cdot annuity \tag{5}$$

$$NPV = PV - CAPEX \tag{6}$$

Where n is the time of the project development, and r is the discount rate or interest rate. The equations formulated replace calculating cash flows for every year of the project and then adding them up to calculate the PV.

2.3. Sensitivity and uncertainty analysis

A project is based on many inputs that are uncertain, such as production costs, price of materials and equipment, and sales volume. The analysis and modeling of uncertainty enhance the ability to make appropriate decisions. The need to analyze uncertainties comes from the awareness that data abundance does not necessarily provide certitude, and sometimes can lead to errors in the decision-making process (Attoh-Okine and Ayyub, 2005). Due to uncertainty, there is no project without risk, and the uncertainty could be caused by different factors, e. g. lack of information or data (Munier, 2014).

Sensitivity analysis examines the response or reaction of an output variable, such as the NPV to the variations of input variables, such as price or sales volume, etc. (Munier, 2014). Sensitivity analysis methods explore and quantify the impact of possible errors in the input data on predicted model outputs (Loucks and van Beek, 2005). Sensitivity analysis is used in a broad spectrum of disciplines to study how various sources of uncertainty in a model contribute to the model's overall uncertainty. On the other hand, uncertainty analysis assesses the impact of ambiguous values of parameters on the final results (Cacuci, 2003). Sensitivity analysis may be performed together with uncertainty analysis to ensure the quality of the model and the transparency of the decision-making process (Borgonovo, 2017).

Monte Carlo simulation methods are tools widely used to perform sensitivity and uncertainty analysis (Attoh-Okine and Ayyub, 2005). Monte Carlo simulation can be used for risk analysis by modeling the probability of the different outcomes of a process; it can be used as a valuation tool for projects (Arnold, 2014; Collan, 2011; Kodukula and Papudesu, 2006). Monte Carlo simulation randomly generates values of the uncertain variables within a certain range to simulate the potential outcomes (Kodukula and Papudesu, 2006; Mun, 2002). Sensitivity and uncertainty analysis can be used as a complementary tool to the DCF method and ROA to study the effect of the inputs on NPV (De Reyck et al., 2008; Gaspars-Wieloch, 2019; Kodukula and Papudesu, 2006; Pivorienė, 2017).

2.4. Real Options Analysis (ROA)

A ROA or real options valuation (ROV) is performed alongside the DCF method; ROA is applied using PV of free cash flows and NPV of a project calculated with DCF method as a basis to estimate different outcomes (Kodukula and Papudesu, 2006). Traditional options used in ROA are the option to defer or the option to wait to invest in a project, expand a project, and an option to choose between projects (Kodukula and Papudesu, 2006).

In this study, a binomial tree is used, which is a decision tree. The binomial model can be solved using risk-neutral probabilities or market-replicating portfolios, both have the same theoretical framework leading to the same solutions but with different mathematical approaches (Kodukula and Papudesu, 2006). The inputs required to build a binomial tree and calculate the option value are the risk-free rate *(r)*, the value of the underlying asset (S_0) which is the PV of the expected free cash flows based on the DFC method, the cost of exercising the option *(X)* which is the investment required, the life of the option *(T)*, the volatility factor (σ) which is a measure of the variability of the underlying asset during its lifetime, and the time frame chosen for the calculations (δt) (Kodukula and Papudesu, 2006). In Fig. 1, a generic binomial tree of 2 steps is shown.

The up *(u)* and down *(d)* factors are functions of the volatility of the underlying asset, and they are described as follows:

$$u = \exp\left(\sigma\sqrt{\delta t}\right) \tag{7}$$

$$d = \frac{1}{u} \tag{8}$$

The risk-neutral probability is a mathematical intermediate that allows for discounting the cash flows using a risk-free interest rate. The risk-neutral probability *(p)* is defined as follows:

$$p = \frac{\exp(r\delta t) - d}{u - d} \tag{9}$$

The option to wait also called the option to defer should be included in every project. A company may prefer to wait before it invests in a project with either negative or marginal NPV when it is highly uncertain that the project will achieve a high NPV in the future (Kodukula and Papudesu, 2006). An example is a delay in mining a deposit until the market conditions are favorable.

3. Case study

Chile has a large mining industry (Cisternas and Gálvez, 2014; Jane, 2003); mining represents 9.8% of the gross domestic product, and copper mining is responsible for 8.9% (COCHILCO, 2019). Chile has a rich territory endowed with porphyric deposits in terms of copper and molybdenum (Oyarzún and Oyarzún, 2011). In 2018, Chile produced 5, 872 million fine copper tons equivalent to 28.3% of global production, which made it the No. 1 world producer of copper (SERNAGEOMIN, 2019a). The country is also the second world producer of molybdenum, a copper by-product, with 60,248 tons representing 20.4% of the world's production.

The production of copper in Chile is concentrated mainly in the northern and central parts of the country, where 40% of the worldwide reserves of copper are found (SERNAGEOMIN, 2019a). Copper can be found in sulfide ores and oxides. Sulfide ores are the primary source of copper. Copper is obtained from sulfide ores by flotation to concentrate copper; mine tailings are the waste of flotation.

In Chile, there are 740 tailing storage facilities. Most of them come from copper mining, and all are registered in a national cadaster kept by The National Service of Geology and Mining - SERNAGEOMIN, out of which geochemical characteristics of 634 tailing deposits are available online, 56 chemical elements have been analyzed, including 25 CRMs. The content of silicon dioxide is also analyzed because silicon metal is a CRM that can be obtained from silicon dioxide (SERNAGEOMIN, 2019b).

The Antofagasta Region is located in the Atacama Desert in northern Chile, and it holds the largest tailings deposits in the country, including the biggest one with a capacity of 4,500 million tons (SERNAGEOMIN, 2020). This study is focused on active tailing deposits, i.e., those currently used until they reach the legally allowed capacity. These tailing deposits are Laguna Seca, Talabre, Esperanza, Sierra Gorda, and Mantos Blancos; the location of these mine tailings deposits is shown in Fig. 2. The capacity of the active mine tailings analyzed in this study is presented in Table 1. In the supplementary material, the detailed geochemical characterization of the analyzed deposits is included.

4. Results

Despite low concentrations of CRMs found in mine tailings, these appear as possible sources of CRMs due to their availability in larger volumes and the ease with which they can be treated on-site using the geochemical analysis provided by SERNAGEOMIN, which shows the average concentration of 56 chemical elements present in tailing facilities (SERNAGEOMIN, 2019b). The total mass of each CRM contained in the TSF was calculated using its average concentration and the mass of the tailing facility. The in-situ values were calculated using current

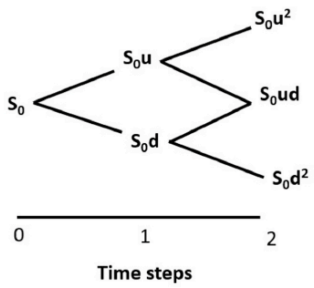

Fig. 1. Generic recombining binomial tree (source: adapted from Kodukula and Papudesu, 2006).

Fig. 2. Active TSF located in the Antofagasta Region, source: (SERNAGEOMIN, 2020).

Table 1
Allowed capacity in active tailings storage facilities in Antofagasta Region, source:(SERNAGEOMIN, 2020).

Tailing storage facility (TSF)	10^6 t (until April 23, 2019)	10^6 t (allowed capacity)
Laguna Seca	1,302.24	4,500
Talabre	1,792.72	2,103.95
Sierra Gorda	142.80	1,350
Esperanza	240.50	750
Mantos Blancos	130.71	138.2

prices, in some cases when it was not possible to find the price of the CRM as metal, the price of the oxide was used, so these are estimates based on the available data provided by the United States Geological Survey in their report about commodities released in 2019 (U.S. Geological Survey, 2019), the prices that were not available in this report were taken from websites providing metal prices (Metal Prices, 2019; Statista, 2019). The average concentration, total mass, and price of each CRM of Esperanza TSF appear in Table 2 as an example. The same calculations for the other four TSF analyzed can be found in Supplementary Material. In Table 2, it is also presented the price of the mischmetal, which is an alloy of rare earth elements, usually 50% cerium and 25% lanthanum with smaller amounts of neodymium and praseodymium (Sciencedirect, 2020).

The profitability of using mine tailings as a source of CRMs is analyzed using a ROA to produce a CRM using the examined TSF. The ROA is illustrated using the option to wait if the investment is not an attractive option according to the results of the DFC method. Reasons to wait to invest include situations when capital cost and/or operating costs are too high, and the prices of CRMs are not high enough to obtain a positive NPV for the project.

The example used to illustrate this analysis is the production of scandium metal. Scandium was chosen as a CRM to be extracted from mine tailings out of Table 2 due to its elevated price and the quantity present in the TSF, as well as the availability of data about CAPEX and OPEX for a similar project of scandium production. Scandium is not reported to be recovered from mine tailings; it is produced mainly from primary resources and the principal source for scandium is metal imports from China (U.S. Geological Survey, 2019), from REE, and iron ore processing in Bayan Obo, China (European Commission, 2017). Hydrometallurgy processes have been suggested to recover scandium from secondary sources.

Table 2
Concentration, mass, and in-situ values of critical raw materials in the Esperanza tailing storage facility.

Critical raw materials	Average concentration (mg/kg)	Mass (t)	Price (USD $/t)	CRM in-situ value (10^6 USD$)
Vanadium	160	120,000	30,865	3,704
Cobalt	11	8,250	72,753	600
Niobium	21	15,750	21,000	331
Barium	185	138,750	180	25
Hafnium	3.88	2,910	775,000	2,255
Silicon	224,632	168,474,330	3,042	512,563
Yttrium[a]	49	36,750	36,000	1,323
Scandium[a]	26	19,500	5,420,000	105,690
Lanthanum[a]	15.96	11,970	2,000	24
Cerium[a]	32.32	24,240	4,830	117
Praseodymium[a]	4.31	3,233	92,400	299
Neodymium[a]	17.46	13,095	51,000	668
Samarium[a]	3.65	2,738	14,850	41
Europium[a]	1.06	795	56,000	45
Gadolinium[a]	3.43	2,573	22,330	57
Terbium[a]	0.49	368	647,500	238
Dysprosium[a]	2.87	2,153	280,700	604
Holmium[a]	0.55	413	38,000	16
Erbium[a]	1.71	1,283	140,000	180
Thulium[a]	0.26	195	not available	0
Ytterbium[a]	1.6	1,200	not available	0
Lutetium[a]	0.23	173	1,258,000	217
Mischmetal[a]	85.9	63,630	20,300	1,292

[a] Rare earth elements.

4.1. Discounted Cash Flow method and Net Present Value

The data for the production of scandium from primary resources were used to estimate PV and NPV (Investorintel, 2014). The following considerations were made to adapt the data from the original report to the case of mine tailings: the concentration of scandium in the tailing deposits is ten times lower than in the primary resource, hence it was considered that CAPEX and OPEX would be ten times higher. However mining and comminution costs are not considered since there is no need to incur these costs when dealing with mine tailings, in the case of the OPEX, 43% is discounted from the original values since that percentage corresponds to mining and comminution processes (Curry et al., 2014). To have a realistic and profitable process, lower production volume was considered. Moreover, an 80% process efficiency was assumed. The input parameters are listed in Table 3, and they correspond to the adapted parameters from the project that was used as a reference.

The DCF method using a risk-adjusted discount rate for five years showed that the PV for the project is 195 million USD, an NPV -138 million, for an investment of 333 million USD. If the DCF method is screened for a longer period, e.g., ten years, it shows a higher value of PV and NPV, 244 million USD, and −89 million USD, respectively. It is essential to point out that traditional mining projects, planned for 15 or 20 years, are used for calculating NPV because they are long-term investment projects, but in the case of a project based on mine tailings and CRMs it is more reasonable to use a shorter period.

4.2. Uncertainty and sensitivity analysis of NPV

To study the effect of uncertainties of input variables and their distribution on NPV results and their sensitivity. Sensitivity and uncertainty analyses were performed using Monte Carlo simulation in RStudio. NPV was modeled using equations (6)–(9), which is a function of the inputs used to calculate the NPV; in this analysis, taxes, and depreciation were included. The inputs ranged between a minimum and maximum value, considering a range ±20%, the following values for each output were considered: price 4.4–6.6 million USD/ton, CAPEX 268–402million USD/ton, OPEX 4400–6600 USD/ton, discount rate 0.08–0.12, production 6.4–9.6 ton, and the number of years of the project was constant since NPV is highly sensitive to changes in the period of investment. The analysis was made for an investment of five and ten years. Fifty thousand simulations were run.

Summary of results shows, for an investment of 5 years, a minimum value of −229.03 and maximum value of −32.5 for NPV and a mean and median that are almost equal, - 137.33 and −137.47, respectively.

To perform global sensitivity analysis, the function of R-studio Soboljansen implements the Monte Carlo estimation of Sobol' indices with independent inputs. Fig. 3 shows the main and total effects of the

Table 3
Input parameters for the Discounted Cash Flow method.

Input parameters	Value	Unit
Capital expenses	333	million USD
Operating expenses	5,700	USD/t
Price of scandium metal	5.42	million USD/t
Ore grade	26	ppm
Production	8	Ton/year
Discount rate/interest rate	0.1	
Period	5 &10	years
Taxes rate	0.35	

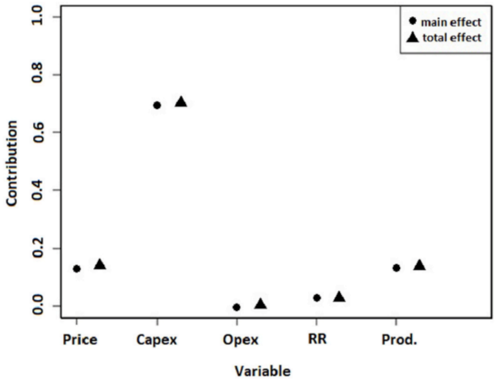

Fig. 3. Sobol'-Jansen indexes for 5-years investment scandium project.

inputs. It can be seen that the main effect and the total effect of each variable are very close which indicates that there are no significant interactions between them. A boxplot was used to confirm the results obtained by the estimation of the Sobol indices. It allows to visualize the minimum, lower quartile, median, upper quartile, and a maximum of a data set (Spitzer et al., 2014). The boxplots as a visualization method enable to represent the characteristics that might not be visible otherwise, and they are a straightforward and informative method of data interpretation (Sun and Genton, 2011). The boxplot is presented in the supplementary material. It can be seen, using the boxplot and the Sobol indices, that CAPEX in this investment has the most significant impact on NPV.

4.3. ROA using the binomial tree method

ROA is performed using a binomial decision tree methodology presented by Kodukula and Papudesu (2006), for an investment of five years and an investment of ten years. The input parameters and option parameters are shown in Table 4.

For the two cases, five years and ten years, option parameters are the same. Next, the development of a decision tree for an investment of five years is explained; the procedure is the same for both cases. With the option parameters, the binomial tree is built by calculating asset values and options values over the life cycle of the option; asset values are obtained after multiplying S_0 to u and d raised to the power indicated in each node. Those are the numbers on top of every node of the binomial tree. For example, in node S_0u^5, the expected asset value is 874 million USD.

Option values are the bottom numbers in the tree. The option to wait expires at the end of the binomial tree, so a decision cannot be made after the time that the decision tree takes. Option values at year five are calculated as the expected asset value of each node minus the cost of exercising the option, which corresponds to the investment. So, for example, in node S_0u^5, the expected asset value is 874 million USD, the investment is 333 million USD, then the net asset value is 541 million USD. The decision in node S_0u^5 would be to invest.

Table 4
Input and option parameters for ROA.

Input parameters		Unit
S_0 (5 years)	195	million USD
S_0 (10 years)	244	million USD
T (time to expiration)	5/10	years
X	333	million USD
σ (volatility)	30	%
r (risk-free rate)	5	%
Δt (time step)	1	
Option parameters		
u (up factor)	1.35	
d (down factor)	0.74	
P (risk-neutral probability)	0.51	

If the option value is negative, then the option value is equal to zero, because a real option is a choice, not an obligation. The option to invest is exercised at nodes where the option value is not zero.

Option values are the numbers below each node, and they are calculated with backward induction. Fig. 4 shows the binomial tree for five years, and the binomial tree for ten years' investment is included in the supplementary material. Each node represents value maximization to invest in that point or to wait until the next period; at every node, there is an option to either invest in the project or the option to wait until the next period, until the option expires, the net asset value, in this case, represents the NPV. Since the option is evaluated at five-year intervals, in node S_0u^5, see Fig. 4 the decision is to invest in this point, and the option value is 541 million USD, but in year five, there are also nodes where the option value is zero. In node $S_0u^3d^2$, the expected asset value is 263 million, for an investment of 333 million, the net asset value is −70 million. Hence, the option value at this point is zero, so the decision in this node would be not to invest.

Next on the intermediate nodes, the expected asset value for keeping the option open is the discounted weighted average of potential future option values using the risk-neutral probability that value, e.g., at node S_0u^4 is:

$$p(S_0u^5) + (1-p)(S_0u^4d) \cdot exp(-r\delta t) \tag{10}$$

In this node, if the option is exercised the payoff would be 647 million, resulting in a net asset value of 314 million, by investing 333 million, since the net asset value obtained by keeping the option open is higher, 330 million, then the option to invest is not exercised. In some intermediate nodes, the expected asset value is lower than the

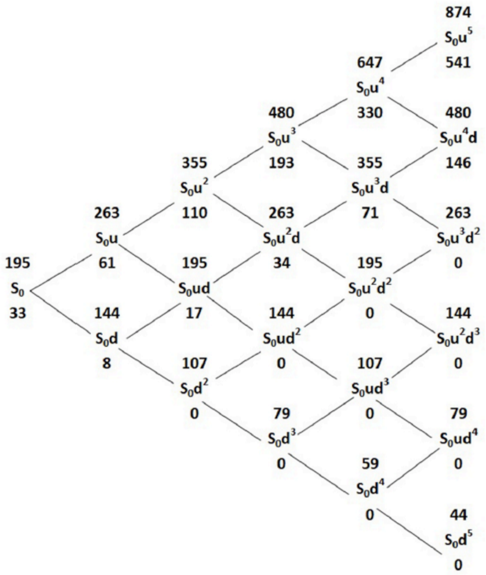

Fig. 4. Binomial tree for the option to wait for five years to invest in the scandium project.

investment, which results in a net loss, then the decision at that node is to wait, which means that the option value is $0. The option valuation binomial tree is completed until year 0.

In each node, the upper numbers represent the expected future values of the underlying asset during the option life cycle as it evolves according to its cone of uncertainty, see Fig. 4. For example, in year 2, the project is estimated to produce a total payoff between 107 and 355 million USD, at the end of year five, the payoff is between 44 and 874 million. The bottom numbers represent option values on the maximization of investing in that point or applying the option to wait until the next period. The option expires in the fifth year because it is framed in such a way that it considers competitive forces and uncertainty in the market.

Based strictly on DCF results, the payoff of the project will be 195 million USD, resulting in a negative NPV of −38 million USD, this negative outcome means that an investment is not attractive. If the decision is based exclusively on the NPV result, then the decision would be not to invest. Real options analysis provides an additional value of 33 million USD, considering a net present value of −138 million USD, the added value with real options analysis is 171 million USD. The same analysis was made for a 10-year investment as shown in the supplementary material, if the same investment is screened to 10 years, NPV based on the DCF method is −89 million, ROA analysis gives an added value of 105 million.

5. Discussion

Waste valorization is a crucial component that the mining industry must do to shift from a linear economy to a circular economy (Khaldoun et al., 2016; Kinnunen and Kaksonen, 2019). There are different approaches to mine tailings valorization, e.g., the simplest and traditional one is to recover water or to decrease water usage in the tailing stage. Other strategies consist of recovering metals from mine tailings or using mine tailings as a construction material (Ahmari and Zhang, 2012; Lam et al., 2020b).

The cyclic nature of the supply and demand for specific metals whose production is extremely concentrated in geographic terms and controlled, and where society cannot solely rely on ore mining (Kirchherr et al., 2017) makes sticking to circular economy principles, such as effective recycling and processing of secondary sources, a must (Tunsu et al., 2019). Mine tailings are now seen as a potential source of several metals and minerals (Binnemans et al., 2015; Tunsu et al., 2019). The valorization of mine tailings is at an early stage of research; there is a lack of technology that would enable transferring knowledge from the laboratory scale to an industrial level (Kinnunen and Kaksonen, 2019).

Economic gains from the recovery of CRMs come with the added benefits of reducing the volume of mine waste. Additional benefits can be achieved if, as a result of the processing of mine tailings, these can be chemically and physically stabilized, reducing the costs of mine closure by decreasing environmental impact and health consequences. A significant advantage is to recover water for mining reuse from mine tailings while reducing its reliance on seawater (Cisternas and Gálvez, 2018; Ramírez et al., 2017). Another essential factor is decreasing energy consumption and greenhouse gas emissions involved in pumping seawater to high altitudes for hyperarid locations, where mining companies are located (Araya et al., 2018; Ramírez et al., 2019). It is also essential to notice that obtaining CRMs from mine tailings reduces the processing of comminution stages (Falagán et al., 2017), minimizing energy consumption and greenhouse gas emissions. Notably, greenhouse gas emissions can vary for every CRM, e.g., in the case of phosphorus the greenhouse gas emissions rise gradually in the mining phase and increase exponentially in the recycling stage (Rahimpour Golroudbary et al., 2019b); in the case of niobium, mining represents 21% of greenhouse gas emissions, 72% are generated in the production stage and recycling from scrap accounts for only 7% (Rahimpour Golroudbary et al., 2019c); on the other hand, recycling of lithium from lithium-ion batteries generates greenhouse gas emissions by 16–20% higher than its primary production (Rahimpour Golroudbary et al., 2019a).

The results show that tailing storage facilities of copper mines in Chile contain significant quantities of CRMs and, depending on the price, some of them could be extracted. Therefore, the early evaluation of the project's profitability and feasibility to recover CRMs from mine tailings help in finding alternatives, and considering the flexibility given by real options, even to postpone the investment until the technology development allows to re-process the tailings. Additionally, it represents a secondary source of CRMs, decreasing the dependence on reserve extraction (El Wali et al., 2019).

The analysis made on the in-situ value of TSFs of active tailings of northern Chile shows that they contain considerable quantities of several critical metals such as REEs, vanadium, cobalt, silicon metal and scandium. The advantages of mine tailings re-processing include the recovery of desirable metals in one location, ensuring land reclamation, reduction of landfill areas, diminishing the concentration of harmful compounds, and no need to open new mines (Binnemans et al., 2013; Farjana et al., 2019; Ganguli and Cook, 2018).

Since mine tailings have been already part-processed, by comminution, the costs, both CAPEX and OPEX, of extracting metals from tailings could be attractive in comparison to the development of a new project, based on primary ores (Falagán et al., 2017). Moreover, the use of secondary sources could help mitigate the depletion of natural resources (Alwaeli, 2011a). For the data used, the result of the DCF method is a negative outcome of the NPV which suggests that the investment should not be considered at the moment. The results of the sensitivity and uncertainty analysis show that CAPEX has a greater influence than the other studied variables. Therefore, it is justified to develop processes and technologies that enable lower capital expenses. If time is a variable in an investment project, then time and CAPEX are both variables with greater influence. It can also happen that the cost of secondary materials is lower, but the cost of processing is higher because of additional treatments or due to lower capacity (Alwaeli, 2011b).

ROA brings in additional value, so decision-makers can explore alternatives while waiting to invest or decide to abandon a project. While waiting for the uncertainty to clear off, to re-estimate the project payoff (Arnold, 2014; Kodukula and Papudesu, 2006). If the payoff continues to be unfavorable, the decision may be to keep waiting; otherwise, if the conditions to invest in scandium production from mine tailings are favorable with a high expected payoff, the decision would be to invest. ROA calculations are a supplement to traditional valuation methods such as DCF based NPV (Brandão and Dyer, 2005; Kodukula and Papudesu, 2006).

ROA is usually framed in shorter periods than the ones used for long term investments (Kodukula and Papudesu, 2006), in this study five and ten-year time horizons were used to frame the project; for both periods, NPV is negative, but if the uncertainty clears out, the project may be feasible. Framing the investment in a longer period, such as ten years, but not as long as twenty years, allows decision-makers to wait to invest in a project when investment can be regained.

The methodology presented in this study was validated using copper tailings of northern Chile as a case study. The geochemical content of tailings may vary from one geographical area to another depending on the type of mineral deposits. In consequence, the content of the valuable elements will be different depending on the mine tailing analyzed. The geochemical results of mine tailings analysis are essential to perform profitability analysis of their re-processing.

On the limitations of the study, it considers only the economic aspect of valorization of the project to obtain CRMs from mine tailings. However, it should be mentioned that the valorization of tailings may be profitable in most cases if environmental, social and safety factors are considered, e.g. chemical and physical stabilization, land reclamation, social license to operate. As was previously stated by Kinnunen and Kaksonen (2019) technology development is still much needed to add value to mine tailings. Therefore, a multidisciplinary approach is imperative to develop projects based on re-processing mine tailings. Future research should include the assessment of the environmental impact of the re-processing of mine tailings, as they can contain heavy metals that could be scattered during the process. Some tailings deposits in Chile need urgent intervention due to the presence of one or more heavy metals (Lam et al., 2020a). Because, at the moment, the economic assessment does not justify the recovery of CRMs, a comprehensive solution to the problem of tailings should be applied. The valorization of tailings could include not only recovering of valuable elements, but also carbon capture from tailings, as it has been suggested in some studies (Azadi et al., 2019; Li et al., 2018), and use of tailings as construction material (Lam et al., 2020b; Solismaa et al., 2018).

6. Conclusions

Mine tailings need to be adequately stored; otherwise, they can lead to massive catastrophes that can affect human settlements and the ecosystem inflicting irreparable damage. Proper mine tailings management includes their chemical and physical stabilization; however, resource recovery can also add profitability to the last stage of mine closure. Moreover, the re-processing of wastes contributes to limiting the number of new mining projects based on virgin resources, which usually have a considerable environmental impact. The assessment of the economic potential of wastes is a crucial activity facilitating the implementation of the circular economy principles.

The mine tailings deposits have usually lower concentrations of CRMs than ore mines. However, the mine tailings are an attractive alternative for exploitation as they are stored in deposits with large volumes and hence, having a considerable potential for the production of CRMs. The additional factor is the fact that tailings have been already pre-processed, e.g. in comminution processes. The case study features Chilean copper mine tailings, to analyze the ones with significant volume among the 740 tailing storage facilities present in the country. Mine tailings deposits that are currently active were analyzed, using geochemical content information provided by The National Service of Geology and Mining (SERNAGEOMIN). These deposits contain important quantities of rare earths elements, cobalt, vanadium, silicon, and barium. Therefore, these copper mine tailings could have substantial economic potential as secondary sources to obtain CRMs. It is well-known that some CRMs are more economically attractive than others, due to their high market price. Therefore, the demand, supply risk and economic importance of each CRM should be considered when analyzing the profitability of mine tailings re-processing.

In this study, a novel approach to assess the profitability of mine tailings to obtain CRM is introduced. A framework that includes ROA, sensitivity and uncertainty analysis is proposed, which allows for adding flexibility, contrary to traditional valuations tools. DCF and ROA were applied to analyze the feasibility of producing scandium by re-processing the tailing deposits featured in the case study. Additionally, sensitivity and uncertainty analysis was performed to study the influence of the price of the commodity, CAPEX, OPEX, and discount rate. These evaluations were used as a complement to the DCF and they include Monte Carlo simulation of the NPV and the representation of the results as boxplot and Sobol' indices.

The DCF method showed a negative NPV for investments of 5 and 10 years. The results of the sensitivity and uncertainty analysis indicate that CAPEX has a greater influence on NPV. ROA adds flexibility and the possibility, as an alternative, to choose to wait until the uncertainty is reduced. Based on the calculations, it is concluded that using a real options approach to analyze an investment for the production of CRMs from mine tailings is a useful instrument, considering the high uncertainties in the market and the development of process technology.

To summarize, the main conclusions of this study are following:

- One can state that the analyzed mine tailings have substantial economic potential to be re-processed to obtain some CRMs. The assessment is based on the quantity and actual price of specific critical materials.
- The basic evaluation tool used, DCF, gives a negative value to the investment based on re-processing of tailings to obtain scandium.
- Sensitivity and uncertainty analysis show that CAPEX and time to invest, either to invest in year 0 or to wait to invest until year 10, have more impact on the outcome of the NPV than OPEX, price, and production volume. Therefore, one can conclude that technology development is much needed to improve processes and technologies of mine tailings re-processing to recover valuable elements.
- Based on the calculations, it is concluded that using a real options approach to analyze an investment for the production of CRMs from mine tailings is a useful alternative, considering the uncertainties in the market and the development of process technology.

The novelty of this article relies on including risk and uncertainty in the evaluation of re-processing of mine tailings projects. The proposed approach enables flexible assessment of investment decisions. When traditional methods, such as the DCF method, indicate that a project is not economically attractive, a ROA reevaluates the project by considering options such as wait until the project is economically feasible. The option of waiting is an interesting alternative in the case of resource valorization of mine tailings. It is due to the lack of technological development and economic business models for treating mine tailings as a source of CRMs. Therefore, more research on these aspects is still needed.

Mine tailings as a secondary source for obtaining valuable elements is still a novel option that needs to be developed on an industrial scale. Therefore, there are many opportunities for improvement that may eventually lead to the successful valorization of mining waste. A multidisciplinary approach is essential to secure the success of re-processing of mine tailings to obtain CRMs.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2021.112060.

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Publication IV

Araya, N., Ramírez, Y., Cisternas, L. A., and Kraslawski, A.

Use of real options to enhance water-energy nexus in mine tailings management

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Use of real options to enhance water-energy nexus in mine tailings management

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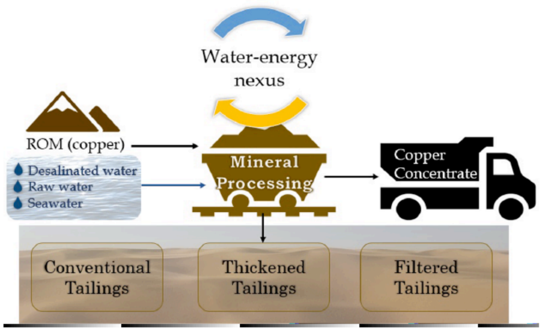
HIGHLIGHTS

- Water-energy nexus in mine tailings and water management is evaluated.
- Real options approach for choosing alternatives of tailings and water management.
- Cost of water transport to the mine is the biggest cost component.
- Thickened tailings are less energy-intensive than conventional ones.
- Energy has high influence in water reuse and recycling for mining sustainability.

GRAPHICAL ABSTRACT



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ABSTRACT

The tailing storage facility is the largest water sink in most mines. An incorrect management of water content in mine tailings can become a threat to their stability, and consequently, their environmental safety. Also, water reuse and recycling are plausible options to mining companies for reasons pertaining to water scarcity. Dewatering technologies for tailings, desalination and water transport are energy intensive. Proper handling of mine tailings and water supply management can considerably improve the water-energy nexus. This article evaluates the water-energy nexus in copper mining companies using a water reduction model focused on mine tailing facilities and water supply to the mine site to find the trade-offs between water and energy. The originality of this work consists in the application of a real options approach, enabling to increase the flexibility of decision-making thanks to quantitative analysis. This approach deploys the Monte Carlo simulation to perform sensitivity and

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uncertainty analysis to evaluate every cost component of water management strategy. Results show that if seawater is the primary source of raw water to the mining plant, water transport represents the largest cost due to the use of energy. So, improving the reuse of water by using dewatering technologies will improve the water-energy nexus, by improving energy consumption. Even though the costs of these technologies are elevated because they are energy-intensive, reduction of water use requirements in the mine will reduce the cost of its treatment and transport.

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1. Introduction

Water and energy are essential for the well-being of society. Mining is both water and energy-intensive in its processes. In Chile, the mining industry represents between 2 and 4.5% of the national water demand [1]. Nevertheless, if mines are located in places suffering from water scarcity, water use can impact the local supply. Besides, mining is a particular case due to the following characteristics: high revenues, excess discharge of water, social and environmental performance, water efficiency, and alternative energy sources [2]. Water consumption by the mining industry has increased. In Chile, the copper mining industry consumed 17.35 m^3/s of water in 2018 [3], 13.36 m^3/s of raw water, and 3.99 m^3/s of seawater; back, in 2012 the sector consumed 13.4 m^3/s of water. The decrease in ore grades is one reason why the mining industry has increased its water and energy consumption.

The biggest water sink in a mineral processing plant is the tailing facility [4]. Mine tailings are waste obtained after mineral ore processing to obtain element(s) of interest. They are a mixture of ground rocks with process effluents generated in the processing plant. Their composition depends on the nature of the rock being mined and the recovery process. Mine tailings disposal methods include cross valley or hillside dams, raised embankments/impoundments, dry-stacking of thickened tailings on land, backfilling into abandoned open-pit mines or underground mines, and direct disposal into rivers, lakes, and the ocean (ocean surface and submarine tailings disposal) [5].

Production in lower grade ore mines will be growing, generating larger amounts of mine tailings and, by extension, pressing for the development of a comprehensive framework for mine tailings management [6] that would include adequate water and energy sustainable management. Significant water savings can be achieved by reducing the available wet and open water area, which can be done by carefully managing the placement of the tailings [7,8].

Mining operations are both energy and water-intensive. If all the water supply relies on seawater, water must be treated and transported to the mine site, which leads to high energy consumption. Considering that the biggest water sink on the mine site is the tailings facility, water from tailings can be recovered to diminish the dependence on freshwater sources. Dewatering technologies, such as thickened tailings, paste tailings, and filtered tailings, allow water recovery from the tailings facility. However, they are more expensive than conventional tailing disposal because they are energy-intensive. Though, from the security perspective, reducing water content in mine tailings will improve their stability, lessen future environmental disasters, and lower the storage volume.

1.1. *Article's aim*

Mining exerts a local impact on water resources. If mining companies are located in an area suffering from water scarcity, water needs to be transported over long distances, and in some cases, to high altitudes above sea level. Proper mine tailings management can optimize the use of water, as well as the use of energy. This article aims to evaluate the water-energy nexus (WEN) in copper mining plants, focusing on tailings facilities to find out about the trade-offs between water and energy and propose a framework for sustainable mine tailings management.

This article aims to answer the following research questions:

- What is the relationship between water and energy in the copper mining industry for different tailing disposal methods?
- How can WEN be improved by using a real options approach?
- In which scenarios can WEN be improved?

A novel approach consisting in the use of real options is introduced to study the relationship between water supply and dewatering technologies and the economic output of every option. A real options approach (ROA) consists in offering the choices that company management can take in order to expand, change or delate investments based on economic, technical, or market conditions. In this study, ROA is used to reduce the risk of mining investments thanks to quantitative analysis of responses to unexpected market developments. The existing methods of managerial evaluation allow optimizing the decisions under the known level of available capital resources and existing investment alternatives. The technique used in this work provides for considering the financial value and the role of timing of decisions. It permits for better assessment of uncertainty and, in consequence, often identifies it as a source of additional value.

1.2. *Water-energy nexus in mining*

Saving water and energy has become one of the most important premises of global sustainable development. Nowadays, water and energy are interdependent and mutually reinforcing factors. Research has been conducted to explore the interlinks between water and energy, known as WEN [9,10]. WEN is the relationship between water used to produce energy, electricity and fuel sources, and energy consumed in the process of water purification, extraction, cooling, treatment, disposal, etc. Considering WEN in the planning, design, and operation of a water supply system ensures its sustainability, conserves energy and minimizes related greenhouse gas (GHG) emissions [11], which is imperative in mining since it is an carbon intensive sector [12]. This study focuses on the interlink between energy and water at a regional level where energy is used to produce, clean, treat, and distribute water in mineral processing plants.

Water and energy flows are interconnected with different links, and the nexus between them can be of different nature. WEN can be found in production, transportation, and consumption. The heart of the nexus may have several dimensions such as environmental, economic, technological, and social [13]. Various issues need to be addressed, such as water and energy allocation, capacity extension, planning for power plants, and environmental impacts, to manage the WEN [14]. Despite the interdependencies between water and energy flows, policies that consider them are rarely integrated [15].

Tsolas and coauthors introduced a network perspective that considers the interactions between energy and water within a generalized WEN by providing a method to design and optimize WEN using graph theory-based network representation and a novel WEN diagram. This approach considered the interactions between water and energy simultaneously, and it was noted that depending on the objective, the results could be significantly different [16]. As water and energy have an essential role in economic development, a network-based framework for the risk of scarcity of both water and energy, and the nexus between them was developed by Liu and coauthors [17].

Mining operations are both water and energy-intensive, and water demand has increased due to the decrease of grade in new ores [18].

According to Pimentel-Hunt [19] factors such as lower grade, greater haulage, distance, and technological change have made copper mining more energy-intensive. Nguyen and coworkers [20] presented a protocol to recognize water-energy synergy and trade-off potentials in water management in mining processes. They concluded that most water management options in mining have trade-off potentials, and few options will have synergy between water and energy.

1.3. Chilean political energy strategy and GHG emissions contexts

As a small country, Chile releases 0.3% of the global GHG emissions, with a high potential to increase its current energy capacity 70 times as the country enjoys the highest solar radiation on Earth and strong and constant winds [21]. In 2019 Chile produced 81,195 GWh, where 32.6 % came from coal, 3.7% from oil, 18.6% form natural gas, 5.4% from biofuels, 25.7% from hydro, 5.9% from wind, 7.8% from solar PV, and 0.2% from geothermal sources [22]. In 2018 32.3 gCO_2/MJ was the carbon intensity of energy consumption by industry where the industry consumed 60.4% of the energy, 1.6% of energy was consumed by transport, 18.4% went for residential purposes, 16.2% was consumed by the commercial sector, 0.2% by fishing, and 3.3% by agriculture and forestry [22].

In September 2015, Chile undertook to reduce its CO_2 emissions per unit of GDP by 30% by 2030 compared to the level reached in 2007. This goal is conditional on obtaining financial support from the international community. The country commits to increasing its reduction of CO_2 emissions per unit of GDP by 2030 until reaching a reduction between 35% and 45% compared to the level reached in 2007, considering, at the same time, future economic growth that will allow it to implement the appropriate measures to achieve this commitment [23]. The difficulties that emerged over time have produced changes to the priorities of the country's policy. The crisis that affected the electricity sector due to the drought and rationing in 1999, as well as the Argentine natural gas crisis from 2005, put the security of energy supplies at the top of the policy agenda under strict conditions of economic efficiency and acting in line with the sustainable development of the country [23]. For the development of the methodology for the elaboration of the Energy Policy, *Energía 2050*, the Ministry of Energy decided to adhere to international practices in this field presented, among others, in the New Zealand Energy Development Strategy, the Energy Policy 2005–2030 of Uruguay, the process German Energy Policy, and Australia' s Green Paper and White Paper [23].

The World Energy Council develops the Trilemma index to rank countries on their ability to provide sustainable energy by ensuring energy security, energy equality (accessibility and affordability), and environmental sustainability. In 2020 Chile ranked 37th among 108 countries [24]. Chile has made significant efforts to diversify its energy mix and reduce dependence on hydro and fossil fuels by incorporating power generation from renewable sources into the system, predominantly from wind and solar sources. It has been a solution for mitigating risks associated with importing other types of fuels from neighboring countries [24].

The Chilean national government launched its clean hydrogen strategy in November 2020, which is crucial for Chile to reach carbon neutrality by 2050 [25]. The abundant renewable energy allows the country for having the cheapest clean hydrogen production, enabling the supply of products and services developed with zero GHG emissions and the exports of clean hydrogen, clean ammonia, methanol, and synthetic fuels [21].

As indicated in the Roadmap 2050 document, the country's gross hydroelectric potential corresponds to approximately 16 GW. Energy policy for 2050 offers the opportunity to address hydroelectric development in the country, incorporating sustainability and social and environmental protection. This policy promotes the advantages that this energy source represents for the country, especially the advantages related to energy independence, flexibility, adjustment capacity, and additional services it provides to the electricity system, favoring the incorporation of other renewable sources. Added to all of this are the contributions that hydroelectricity can make to reduce greenhouse gases [23]. Nuclear power energy has not been included as a short-term option. It requires studies in critical aspects, such as long-term economic viability under different legal and market conditions and the legal and institutional adjustments required. These studies must be coordinated and commissioned by the Chilean Nuclear Energy Commission and conducted by competent national organizations.

Chile's energy policy has changed dynamically in recent years. In response to the developments in domestic and international environment, deep institutional and policy reforms and significant infrastructure projects have been carried out. The national energy policy 2050 was adopted in 2015, following an exceptionally inclusive public consultation. The electricity sector, in particular, has developed fast [22]. Chile is a world-class destination for solar and wind energy developers. New legislation supports investment in generating capacity across the electricity sector. The prominent role of the state in energy mix planning has helped to boost project development, especially in electricity transmission. Additionally, Chile has a single interconnected national electricity system [22].

Chile's PV growth is expected to fast-track after 2022. As part of the Covid-19 economic recovery efforts, the government has accelerated the environmental approvals of 55 solar projects. Furthermore, Chile has recently launched a Casa Solar program that supports the development of distributed PV projects by allowing community groups to obtain solar panels at lower prices and receive state co-financing. Chile is well on track to meet its 2025 target of 20% electricity from non-conventional renewable sources [26]. One of the latest example to embrace the zero emission generation of energy is the commissioning of Chile's Cerro Dominador plant with 110 MW and 17.5 h of molten salt storage, the largest in Latin America [27], allowed to carry out the Likana project in Chile, which the Cerro Dominador group acquired in 2019. The group plans to offer a 450 MW concentrated solar capacity project in a power auction in Chile in 2021 [26].

1.4. Water management in mining

As a notoriously water-intensive activity, the mining industry often infringes other forms of water use, and the negative impacts occur at a local level [28]. Mining consumes large amounts of water to process mineral ore. Water is pumped and sometimes treated to be used along the process [29]. To separate the non-valuable minerals from the ore, wet processes, such as flotation, which uses large quantities of water, are often used; 70% of the freshwater used in copper mining in Chile is used in the concentration plant where the flotation process takes place [30]. Nowadays, modern mines reuse or recycle water. In Chilean copper mining, the average total recirculation of water is 74% [30].

As mine sites are usually located in arid zones suffering from water scarcity, their water demand can be fulfilled with a combination of different sources of water, such as groundwater, seawater, freshwater, and recycled water. Transporting seawater to the mine sites is cost-intensive due to the costs of desalination, treatment, and transport of water [31], which involves pumping it over long distances to mine sites located up to 4000 m above the sea level [32], demanding for a large amount of energy [33]. Increasing water recovery in the mine site has a significant effect on reducing the cost of supplying water to the mine [34].

The use of desalinated seawater has increased due to the overexploitation of water resources in hyper-arid, arid, and semi-arid places where mine plants are usually located [35]. Desalination is still perceived as an expensive and environmentally damaging solution [36]. However, the adverse effects of desalination can be mitigated by carbon-neutrality achieved by using renewable energy. Environmental issues associated with brine disposal can be managed, at a local scale, by an appropriate design of outfalls minimizing its impact through dilution

[36]. Desalination costs have declined over the past decades, thanks to increased plant capacity, higher permeation rates, and improvement of membrane materials [37]. However, achieving further cost reductions is quite challenging despite the continuous enhancements in membrane and energy recovery technologies [38]. Between 1977 and 2015, the capital costs of seawater desalination plants decreased with a learning rate of about 15% [39], which means the capital cost is reduced by 15% when the cumulative capacity has increased twice.

The cost of water treatment can be associated with GHG emissions as energy consumption and CO_2 emissions per unit of water, often referred to as energy and carbon intensity [40]. There is a gap in studies assessing energy use and GHG emissions in the water sector partially due to the absence of clearly defined boundaries [41]. Therefore, some studies strategical define their boundaries to assess GHG emissions' water treatment due to its intrinsic relationship with the energy generation mix [33].

Due to water scarcity in arid and semi-arid regions, there is growing interest in non-conventional water resources as a new alternative [42]. Partial desalination has been proposed to reduce cost, instead of desalination using the reverse osmosis process, as a treatment for seawater to remove only the elements that cause problems in industrial processes [35]. Some mining plants are currently using seawater that is partially desalinated or not treated at all. However, we need to bear in mind that these options may cause operational problems [43].

Several efforts to quantify water and energy in mining processes have been undertaken to reduce the consumption of these resources or improve the efficiency of mining processes. A mine water reduction model was introduced by Gunson and coauthors [1] to improve the mine water system performance in a copper mine plant by comparing scenarios of water reduction with the base scenario that does not consider water savings. Scenarios include tailings dewatering technologies, and water conservation options. Afterward, Aitken and coauthors [44] applied a cost-benefit analysis to the options analyzed by Gunson et al. [1], finding out that elevation is in some cases low, under 1600 m, thickened tailings with the use of raw water is the most effective solution. In comparison, for heights exceeding 1600 m, the most effective solution is the use of filtered tailings. An approach to minimize the energy consumption of water mine processes is called the mine water network design method, developed by Gunson et al. [45]. This strategy describes all water sources and water consumers to put together energy requirement matrices and use linear programming to minimize energy consumption.

1.5. Mine tailings management

The purpose of the mine tailing management approach is to protect humans and the environment from risks associated with mine tailings. Mine tailings management is crucial in mining operations because of the irreversible impacts of mine tailings [6]. Mine tailings storage leaves a significant environmental, temporal, and space footprint, and for its physical and chemical stability, we need to strive to decrease acid mine drainage risk [6]. As tailings contain a multitude of various contaminants, the integrity of these impoundments is a significant issue of global environmental concern [46]. One of the environmental issues related to mine tailings is acid mine drainage [47] which occurs due to the content of sulfide minerals in mine tailings when they are in contact with oxygen and water [48].

Inadequate storage of mine tailings may lead to catastrophic consequences. Errors made in the storage and management of mine tailings are the largest source of severe effects experienced globally by the public [49]. Water has a significant role to play in determining tailing's behavior. Therefore, water recovery from tailings impoundments is a common strategy to reuse water and reduce tailings dam risks, especially in places with water scarcity [50]. In the case of coal mining, the trade-offs between water and energy in mine tailings include both the pumping of tailings and the technology used for dewatering tailings [51]. Most mines still use the conventional method for tailings disposal, consisting in transporting mine tailings slurry through pipes to a tailing storage facility or a tailing dam. A typical tailing storage facility includes a dam, a beach produced by the discharge of tailings slurry, and fine sand to silt and clay slimes farthest from the dam in a layer sufficiently impermeable to maintain an overlying pond [52]. This method requires a high percentage of water, approximately 70%, but it is chosen because it is cost-effective [6]. Thickened tailings (TT) and filtered tailings (FT) reduce the water content of tailings but are considered energy-intensive, hence more expensive. Nevertheless, the implementation of these technologies would reduce the costs of mine closure [53,54]. Various studies indicate that emerging technologies, such as TT and FT, represent a breakthrough in the mining industry as they rely much more heavily on recycled water and reduce freshwater consumption [55]. Other benefits of TT and FT, compared to conventional tailing disposal, are a lower footprint, reduced potential of acid mine drainage, reduced risk of potential dam failure, and higher reagent recovery [56].

Pumping tailings to the storage facility is also energy-intensive; it depends on the solid content since the tailing slurry can only be pumped until a certain percentage of solids. Rheology analyses are needed to determine if the tailings can be transported. The yield stress is a parameter that indicates the point at which a material begins to deform plastically. Tailings with high solid content (65 and 70% mass solids) have very high yield stress which means they are difficult to pump. Higher mass solids need to be transported by other means, such as using a filter press [51].

1.6. Real options approach

The costs of putting technology in place can be broken down into capital expenditure (CAPEX) and operational expenditure (OPEX), which depend mainly on the pump type, energy consumption, and the chemicals used [6]. A new mining project is based on many uncertain inputs, such as production costs, price of materials, and supplies. The analysis and modeling of uncertainty enhance the ability to make appropriate decisions [57]. Water management strategies, such as the use of desalinated seawater, include costs associated with water treatment and its transport. Desalinated water must be transported over long distances to the mine sites as they are usually located far away from the coast. ROA can evaluate each cost component of different water management strategies to then analyze the WEN of the proposed methods.

In the project valuation field, a real option is a right, not an obligation, to take any action on an underlying nonfinancial asset, referred to as a real asset [58]. That action can consist of, for example, abandoning or expanding a project or even deferring a decision for some time. Such actions cannot be considered in the traditional discounted cash flow method due to its static nature with a one-off decision-making process. In contrast, ROA considers the strategic management options that may arise for specific projects and the flexibility in exercising or abandoning these options [59]. Real options have been used recently in different fields to assess investments surrounded by uncertainty to provide the flexibility that traditional valuation methods cannot offer. Applications of ROA can be found in several mining investment studies [60]. ROA can be used to model the profitability of new metal mining investments [61], forecasting uncertainties in mining projects [62], and reduce the uncertainty due to commodity price, as well as to give operational flexibility [63].

There are applications of ROA in research related to the energy sector. ROA was used to analyze the uncertainty of CO_2 sequestration in depleted shale-gas [64]. A methodological approach that integrated ROA into multicriteria analysis was developed to assess energy firms [65]. A real options model using system dynamics was built to optimize financial subsidies for renewable energy technologies [66]. The photovoltaic power generation under carbon market linkage has been analyzed with ROA to consider uncertainties such as investment costs, electricity prices, carbon prices, and subsidy payments [67]. ROA was

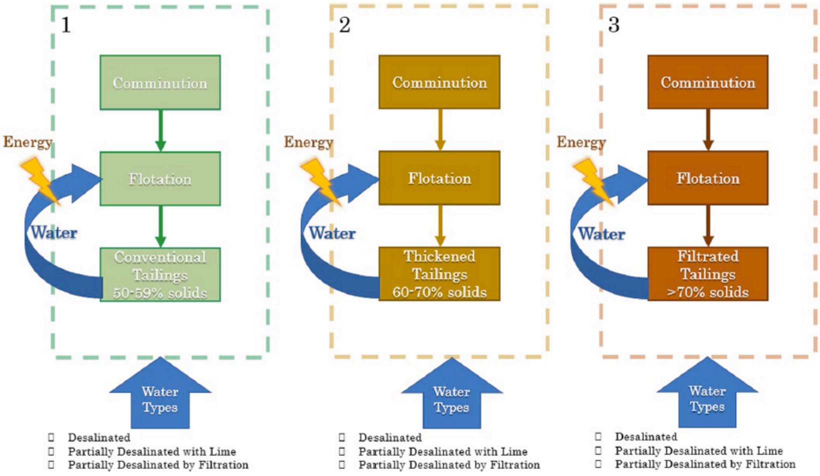

Fig. 1. Simplified scheme of every option of tailings management and water treatment considered in the study.

used to analyze the impacts of government subsidy on the investment decision of full-chain carbon capture utilization and storage projects [68]. ROA was used to analyze the economic feasibility of waste-to-energy projects; this approach considers options such as waiting and the optimal timing of switching technologies [69]. A model that aims to enhance the flexibility in gas-fired power plants with an approach of real options helped assess the future profitability of power plants and support the decision-making process regarding the operation of power plants [70].

ROA supplements traditional tools used to assess investment projects [58]. In this article, ROA is used to assess the uncertainties inherent in the costs of implementing different options and analyzed scenarios. Monte Carlo is applied to perform an uncertainty analysis and the estimation of Sobol' indices is used to perform global sensitivity analysis.

Sensitivity analysis and uncertainty analysis are often used together to ensure the quality of the model and the transparency of the decision-making processes [71]. Sensitivity analysis examines the response of an output variable to variations of input variables [72]. It explores and quantifies the impact of possible errors in the input data in predicted model outputs [73]. Instead, uncertainty analysis assesses the effect of ambiguous values of parameters on the output results [74]. Sensitivity and uncertainty analyses can be used as complementary to valuation tools to study the impact of inputs in investment projects.

Monte Carlo simulation is widely used to perform uncertainty and sensitivity analyses [75], and is a method that consists of a thousand possible scenarios and can be used as a valuation tool to calculate the net present value of a project for each scenario and analyze probability distribution of the net present value result [58], it can also be used for risk analysis by modelling the probability of different outcomes of the process. This simulation approach is relatively simple, each random variable in a process is sampled several times to represent the underlying probabilistic characteristics [75]. It can also be complemented with other statistical tools to study the probability distribution of a function according to different parameters.

2. Methodology

2.1. Water reduction model

Strategies pursued to reduce the amount of water used in a mineral processing plant deploy the water reduction model introduced by Gunson et al. [1] to estimate the raw water requirement for the mine site. These strategies are technologies for dewatering tailings and options for water supply to a large mine plant that produces fine copper. They include technologies such as traditional disposal of tailings, in which tailings contain 35% of solids and the rest is water; TT and FT are considered to reduce water content in tailings. Due to the scarcity of groundwater or water from lakes, mine sites can be supplied only from the sea. A combination of water supply is also considered since some treatment procedures for seawater give water of a higher quality that might be required for processes like flotation. In contrast, lower quality water can be used in other processes. The higher quality water corresponds to seawater desalinated using the reverse osmosis process, and the lower quality corresponds to seawater that is partially desalinated using filtration or precipitation with lime.

2.2. Real options approach

A ROA approach is used to assess the cost of each option by analyzing every cost component, which includes the costs of the technologies used for water and tailings management. The annual cost of each strategy is calculated considering a 20-year project life. The uncertainties in the cost of CAPEX and OPEX are considered in all the options assessed as these costs are subject to change. OPEX includes the cost of electricity and materials for operating different technologies. CAPEX and OPEX have uncertainties connected to the price of electricity and water for the implemented technologies. The price of copper is also an uncertainty considered in the revenues of the process. The system is shown in Fig. 1, which illustrates its boundaries.

2.3. Uncertainty and sensibility analysis using Monte Carlo

The application of ROA consists in applying Monte Carlo simulation to perform uncertainty analysis and calculate the Sobol' indices as a global sensitivity analysis. Sobol' indices or Sobol' method is a variance-based sensitivity analysis, a form of global sensitivity analysis [76]. The analysis is completed using RStudio, an open-source software. The function of the annual cost is analyzed; its components are the CAPEX and OPEX of the different technologies included in each strategy, such as tailings dewatering technology, water treatment of water supplied to the

Table 1
Major parameters of the mineral processing plant described in the case study.

Parameters	Mine site
Feed (tpd)	405,712
Grade (%)	0.86
Process water requirement (m^3/d)	567,151
Water recycled (m^3/d)	106,274
Recycled water (%)	0.187
Raw water requirement (m^3/d)	473,288

mine, and the transport of water from the water treatment plant located on the coast to the mine site.

2.4. Energy consumption and GHG emissions

Energy consumption of each dewatering technology for tailings is calculated and compared to the water reclaimed by each technology, additionally water supply and treatment for water management is calculated. Energy consumption involved in pumping the water from the water treatment plant to the mine site can be estimated from a basic theoretical physical relationship represented by Equation (1) [41]:

$$Energy\ consumption(kW\ h) = \frac{9.8\left(\frac{m}{s^2}\right)*lift(m)*mass(kg)}{3.6*10^6*efficiency(\%)} \quad (1)$$

GHG emissions are calculated to determine the environmental impact of the different sources of energy deployed in the generation of electricity used by the technologies involved in tailings disposal, water treatment, and water transport To calculate the GHG emissions, the CO_2 equivalent emissions were determined for different percentage share of energy sources; the energy mix can be powered by different sources like coal, oil, hydroelectrical, natural gas, Photo Voltaic, wind, biofuel, geothermal, nuclear, among others. CO_2 emissions vary within a certain range for every energy source; hence three cases of CO_2 emissions were used, minimum, median, and maximum. Therefore, CO_2 equivalent emissions were estimated for every option under study. The data were obtained using secondary sources from the International Energy Agency [22] and the World Nuclear Association [77], and the calculation is presented in the Appendix A.

In general terms, the methodology can be described by the following stages:

- Determination of the boundaries of the studied system. It includes the selection of the dewatering technologies, types of water, size of mine, project lifespan, energy mix, among others.
- Modelling the amount of water used in the system under study using a water reduction model.
- Calculating CAPEX and OPEX for different options.
- Application of a ROA approach, implementation of sensitivity and uncertainty analysis for every option.
- Calculating energy consumption and GHG emissions for the options assessed.

3. Case study

Chile's Geochemical and mineralogical characteristics have made mining one of the main economic activities in the country. Chile is the leading world producer of copper, whose production in 2018 reached 5872 K tons of copper, which corresponds to 28.3% of the world's production [78]. Furthermore, Chile is the second world producer of molybdenum, with 60,248 tons produced in 2018 [78]; molybdenum is a by-product of copper mining. Most of these mining activities have developed in the Atacama Desert, the driest non-polar desert on earth, and it extends all over the northern parts of Chile.

The Atacama Desert is an area where demand for water has been growing due to the water scarcity that this area suffers from. Desalination is seen as the best option to meet the water demand. Hence, the Chilean government has proposed new policies to promote desalination processes in different sectors; moreover, Chile has got the largest desalination system in South America [43].

Methods used in Chile to store mine tailings are conventional tailings stored in tailing dams, TT, FT, and paste tailings [79], being tailing dams, the most common type of tailing storage facility in the country. By 2015, approximately 70% of tailing storage facilities were dams constructed using cyclone sand tailings, 7% by earth fill or rock fill, and 3%, by FT, paste, or TT, for the remaining 20%, no information is available [80].

The developed framework was applied to a case study of a large mine plant. It resembles an actual open pit mine operation in the Antofagasta Region, an area located in the Atacama Desert, Northern Chile, that hosts several mining operations of the copper industry. The mine site uses water supplied from a water treatment plant located on the coast. In this study, we assumed that the demand for water represented by the mine must be fulfilled with seawater since freshwater is not available due to the water scarcity in the nearby areas.

At the mine site, copper is recovered by flotation, which is the separation process that generates mine tailings. The water reduction model was used to calculate the raw water requirement for each scenario, including tailings dewatering technologies. The mine site covered by the study has the same feed and grade as the Escondida mine, which is the world's largest copper mine, located in the Antofagasta Region. Data on the main water streams of Escondida Mine were obtained from reports of the company [81]. Escondida mine produced 906.8 ktpa of payable copper in 2019 [82]. Copper price of 2.60 US$/lb is considered, which is the price of copper in 2019 used in the BHP report [82]. Table 1 includes the main values of parameters of the case study used to estimate different outcomes with the water reduction model.

Process water requirement refers to the water flow used in the mineral processing plant. Raw water requirement refers to the water flow input, which is equal to water losses in the process, which can also be called consumption water or withdrawal. Recycled water refers to the water used in the process and can be recycled to be used again. Mine process operations are considered a black box, as shown in the different figures. The different dewatering scenarios lead to different water content in tailings which implies a reduction in the raw water requirement of the mine site. The surplus water, i.e., the overflow water of tailings that will not be used inside the mine plant, is available for other uses outside the plant.

4. Results

Water management strategies within the framework are applied to different scenarios to analyze the impact of each alternative. When scenario 1 is a base case, no water-saving approach is used because tailings go through a traditional tailing dewatering method and disposal. Scenario 2 considers the strategy of TT technology to enhance the dewatering of tailings. Scenario 3 uses filtering tailings as a dewatering technology for tailings disposal. CAPEX and OPEX of tailings dewatering technologies were obtained by scaling the equipment costs stated in the Ajax Project Report [83]. The costs of equipment were scaled using the 0.6 rule [84]. For the feed considered, the costs of conventional tailings disposal are: CAPEX of 669 M US$ and OPEX of 369 M US$; for TT, CAPEX is 678 M US$ and OPEX is 396 M US$; and FT has a CAPEX of 1,326 M US$ and OPEX of 1,290 M US$. The same report was used to estimate energy consumption of each tailings management technology, however, the numbers were adapted to the case study presented here.

Mining companies can take seawater from the coast and transfer it to their locations, subjecting it to different treatment processes dictated by their specific requirements. In this case study, water treatment options include seawater partially desalinated with filtration, seawater precipitated with lime, and desalinated water with reverse osmosis, as

Table 2
Raw water requirement for dewatering tailings technologies and the base case of conventional tailing disposal.

Technology	Raw water requirement (m^3/d)
Conventional tailing disposal	473,288
Thickened tailings	406,436
Filtered tailings	313,046

Table 3
Cost of implementing different scenarios and options for tailings dewatering and water supply management.

Scenario and option	Annual cost (M US$/ year)	Total cost (M US$)
Conventional tailings + option 1	629	12,578
Conventional tailings + option 2	660	13,200
Conventional tailings + option 3	853	17,069
TT + option 1	549	10,984
TT + option 2	576	11,518
TT + option 3	742	14,841
FT + option 1	512	10,249
FT + option 2	533	10,660
FT + option 3	661	13,220
FT + 50% option 1 + 50% option 3	587	11,733
FT + 50% option 2 + 50% option 3	597	11,940

Table 4
Values of the variables used for sensitivity and uncertainty analyses.

Variables	Value	Value × 0.9	Value × 1.1	Value × 0.8	Value × 1.2
CAPEX filtered tailings (MUS$)	442	398	486	354	530
OPEX filtered tailings (MUS$)	430	387	473	344	516
CAPEX thickened tailings (MUS$)	226	203	249	181	271
OPEX thickened tailings (MUS$)	132	119	145	106	158
CAPEX conventional tailing disposal (MUS$)	223	201	245	178	268
OPEX conventional tailing disposal (MUS$)	123	111	135	98	148
CAPEX water treatment – filtration (US$/$m^3$)	0.230	0.207	0.253	0.184	0.276
OPEX water treatment – filtration (US$/$m^3$)	0.070	0.063	0.077	0.056	0.084
CAPEX water treatment - precipitation with lime (US$/$m^3$)	0.350	0.315	0.385	0.280	0.420
OPEX water treatment - precipitation with lime (US$/$m^3$)	0.130	0.117	0.143	0.104	0.156
Cost water treatment - reverse osmosis (US$/$m^3$)	1.600	1.440	1.760	1.280	1.920
Cost water transport - supply system (US$/$m^3$)	3.040	2.736	3.344	2.432	3.648

considered by Aitken et al. [44]; these options replace the raw water requirement of the mine site. Additionally, a combination of water supply sources was considered since some operations require water of higher quality, which is relatively expensive. Therefore, water supply options consist of 50% of water desalinated with reverse osmosis process, and 50% of filtered seawater or 50% of seawater desalinated with reverse osmosis and 50% of seawater precipitated with lime are also considered. Water desalinated with reverse osmosis is designated as having higher quality, while filtered seawater and seawater precipitated with lime is of lower quality.

The annualized cost, which included both capital and operating expenses, of using seawater partially desalinated with filtration, which is option 1, and using seawater precipitated with lime, option 2, were taken from Aitken et al. [44]. The costs of filtration can be broken down into CAPEX (0.23 US$/$m^3$) and OPEX (0.07 US$/m^3), and for precipitation with lime, 0.35 US$/$m^3$ for CAPEX and 0.13 US$/$m^3$ for OPEX.

For option 3, in which seawater desalinated with reverse osmosis is used, the annualized cost of a reverse osmosis plant was taken from Herrera-León et al. [31] and it amounts to 1.6 US$/$m^3$. The cost of the water supply system, i.e., pipelines and the pumping system to carry the water from the coast up to the mine sites, was calculated from the model validation performed by Herrera-León et al. [31] and it amounts to 3.04 US$/$m^3$.

Each scenario of tailings dewatering technology can be combined with water supply options 1, 2, and 3. These options are meant to meet the plant's water requirement with seawater treated using different methods described in the options above. For the mine site, calculations were made for the three scenarios combined with each option of water supply. The results are presented in Table 2. FT has been found out to be the most effective technology for tailings dewatering because it dramatically reduced the raw water requirement from 473,288 m^3/d to 313,046 m^3/d, which is a 33.86% reduction of the water requirement. In the case of TT, the water requirement is reduced to 406,436 m^3/d, which is 14.14% less.

Table 3 contains the costs for each combination of scenarios and options. The most economical water supply system for a mine is using filtered seawater, followed by a solution using water precipitated with lime. However, water quality for these two options is low, which is why we considered a combination of 50–50% of water desalinated with reverse osmosis, and filtered seawater and 50–50% of water desalinated with reverse osmosis and seawater precipitated with lime, more detailed results are included in the Appendix A.

On the other hand, CAPEX and OPEX for TT and FT are higher than conventional tailings dewatering technologies. Still, since the raw water requirement for these technologies is considerably lower, the annualized costs are lower.

Assuming annual production of 906.8 ktpa of payable copper at a price of 2.6 US$/lb, the revenue would be 5,239 M US$/y, investment in tailings management, and water supply represents between 9.77% and 16.28% of annual costs of mine site operation for a 20-year project life.

Equation (2) represents the cost of water and tailings management. This equation was modelled in RStudio using Monte Carlo simulation and the estimation of the Soboĺ indices.

$$Annual\ \ cost = CAPEX_d + OPEX_d + CAPEX_w + OPEX_w + COST_{RO} + COST_t \tag{2}$$

where $CAPEX_d$ and $OPEX_d$ are the annual costs of dewatering technologies; $CAPEX_w$ and $OPEX_w$ are the annual costs of water treatment, be it filtration or precipitation with lime, $COST_{RO}$ is the annual cost of reverse osmosis, and $COST_t$ is the annual cost of the transport of water from the water treatment plant to the mine site. In the case of filtered tailings and water supply that consists of 50% of water representing higher quality, which is desalinated with reverse osmosis, and 50% of water representing lower quality, which is filtered seawater, the annual cost is 587 M U$/year.

Sensitivity and uncertainty analyses were performed as ROA for the implementation of water management options. The Monte Carlo simulation models the probability of different outcomes from the options assessed. Fifty thousand simulations were run. To carry out these analyses, we assumed the value of variables that ranged between a minimum and maximum considering a range of ±10% and ±20%, these values are presented in Table 4. The investment was planned for 20 years, which is a usual timeframe for a project of this magnitude. The results considering TT and conventional tailing disposal are included in the Appendix B.

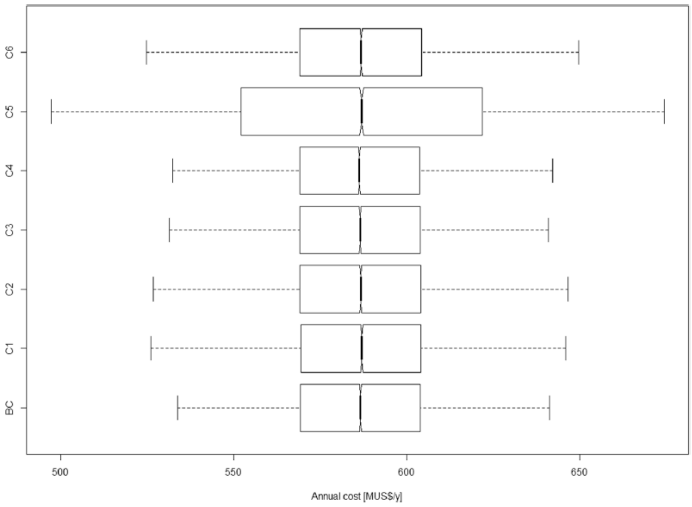

Fig. 2. Boxplot of the annual costs of implementing filtered tailings technology and water supply of 50% of higher quality and 50% of lower quality water. BC represents the base case, C1 $CAPEX_d$ ± 20%, C2 $OPEX_d$ ± 20%, C3 $CAPEX_W$ filtered seawater ± 20%, C4 $OPEX_W$ filtered seawater ± 20%, C5 $COST_T$ ± 20%, and C6 $COST_{RO}$ ± 20%.

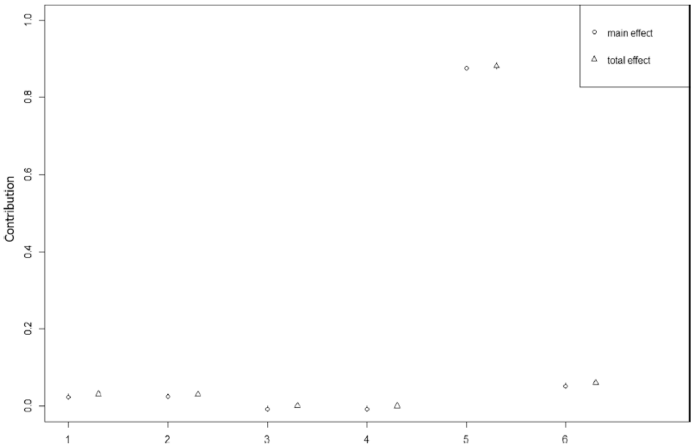

Fig. 3. Sobol' indices of the annual costs of implementing filtered tailings and water supply of 50% of higher quality water and 50% of lower quality water. Where 1 $CAPEX_d$ 2 $OPEX_d$,3 $CAPEX_W$ filtered seawater, 4 $OPEX_W$ filtered seawater, 5 $COST_{T,}$ and 6 $COST_{RO}$.

The summary of results delivered by RStudio, considering the option of using filtered tailings and a combination of 50% desalinated water and 50% partially desalinated water of lower quality obtained by filtration, shows a minimum value of 531.7 M US$/y and a maximum value of 640.1 M US$/y, mean of 586.6 M US$/y and median that equals 586.6 M US$/y. Boxplots represent the summary and the primary data; they visualize the minimum, lower quartile, median, upper quartile, and maximum data set [85]. They are a straightforward and informative method of data interpretation [86]. A boxplot is presented in Fig. 2 to visualize the characteristics of data used to calculate the annual cost. BC stands for the base case using a ±10% variation for each input. For the rest of the boxplots, the uncertainty of one input was expanded to ±20%, leaving the rest of the inputs in the previously settled ±10% range.

With Monte Carlo simulation, global sensitivity analysis is performed by estimating the Sobol' indices with independent inputs. Fig. 3 shows the main and total effects of the inputs of the annual costs of implementing filtered tailings and water supply, combining 50% of higher quality water and 50% of lower quality water obtained using the Soboljansen function of RStudio. This method decomposes the model output variance into fractions that can be attributed to each input.

Table 5
Energy consumption and CO_2 emissions of dewatering technologies and a base scenario of using reverse osmosis.

	Conventional tailing disposal	Thickened tailings	Filtered tailings
Energy consumption dewatering technology (kW h/d)	708,593	474,314	1,169,755
Energy consumption water supply (kW h/d)	4,380,540	3,761,792	2,897,418
Energy consumption water treatment (RO) (kW h/d)	1,467,192	1,259,952	970,444
Energy consumption dewatering technology + water supply + treatment (RO) (kW h/d)	6,556,326	5,496,058	5,037,616
CO_2 emissions (gCO_2 eq/d) × 10^9 median	2.683	2.249	2.061
CO_2 emissions (gCO_2 eq/d) x10^9 min	2.277	1.909	1.750
CO_2 max (gCO_2 eq/d) x10^9 max	6.940	5.818	5.333

Therefore, in the case of using filtered tailings method and water supply combining 50% of higher quality and 50% of lower quality water, the main contribution to the variance, 0.84, is due to the cost of transporting the water from the water treatment plant located on the coast to the mine site. If the main effect and the total effect of each input are close to each other, then there are no significant interactions between them.

Results of uncertainty and sensitivity analyses for the rest of the options show similar results that the cost of the water supply system exerts the bigger impact on the cost of investment in implementing a dewatering technology and having a water supply system that combines seawater with desalination or other treatment method leading to partial desalination. Results of the other options assessed are included in the Appendix B. In the case of traditional tailing disposal and TT, the differences between the contribution of each input are more noticeable. Because the cost of traditional tailing disposal is lower than FT and since the raw water requirement is much higher when using traditional tailing disposal, the costs of the water supply system and water treatment are increased.

The WEN can be divided into energy for producing water and water for producing energy. In this study, the energy component needed to produce water is examined since it is part of the energy used in water treatment, water transport, and tailings dewatering technology. Improving energy efficiency will reduce GHG emissions. Energy consumption for each dewatering technology, TT and FT, and for the base case of conventional tailings disposal was estimated to assess the energy component of each strategy proposed. It was then compared to the amount of energy consumed in pumping the water from the water treatment plant to the mine site. Table 5 presents energy consumption and CO_2 emissions of each technology. FT consumes 1,169,755 kW h/d, which represents 65% more energy than conventional tailing disposal. TT consumes less energy than conventional tailing disposal, showing a reduction of 33.063%. Energy consumption associated with water supply was estimated in each case as the energy consumption of pumping the water from the water treatment plant located on the coast to the mine site. Considering the transport of water to the mine site and the technology chosen to deal with tailings, using FT represents a 20% reduction in energy consumption compared to the conventional tailings disposal method. In the case of TT, a decrease of 17% of energy consumption is achieved compared to the conventional tailings disposal method.

In Table 2, we can see that the raw water requirement of the mine site is different depending on how tailings are handled. FT is energy-intensive; however, the raw water requirement of the mine site is minimized; hence the cost of transporting water to the mine site is lower, so is energy consumption, which can be seen in Table 5. Total energy consumption considers each option of tailings management and energy consumed in transport as there is a trade-off between them. As to reverse osmosis, it is known that it is energy-intensive and costly compared to other treatment methods. Data concerning energy consumption of precipitation with lime and filtration treatment were not found in literature, hence we considered a scenario where water supply relies only on reverse osmosis, using for energy consumption a value of 3.1 kW h/m^3 obtained from literature [87]. Data from the International Energy Agency were used to calculate CO_2 emissions [88]. These data contain CO_2 emissions per energy source for Chile's energy mix and are included in the Appendix A. A minimum, median, and maximum value of 374.34, 409.2, and 1058.56 g CO_2 eq/kWh respectively were used to estimate the CO_2 emissions of the water supply system and tailings disposal technologies. The GHG emissions were determined for the Chilean energy mix. This scenario conforms to different sources of energy 32.6% coal, 25.7 hydroelectrical, 18.6% natural gas, 7.8% Photo Voltaic, 5.9% wind, 5.4% biofuel, 3.7% oil, and 0.2% geothermal [22].

5. Discussion

There is a trade-off between water and energy in choosing the tailings dewatering technology. Even though dewatering technologies, such as FT and TT, are more expensive than conventional tailings disposal, in terms of both CAPEX and OPEX, they reduce the raw water requirement of the mine. These technologies decrease the cost of water treatment and water transport to the mine site and, ultimately, reduce the overall cost of the mine site operation. Furthermore, the use of FT and TT technologies, by removing additional water from the mine tailings, improves the stability of deposit, diminishes the risk of acid mine drainage, and reduces the deposit site volume as a mining liability.

Suppose mine plants use seawater and are located far away from the coast; having TT or FT could be more economically viable than conventional tailings disposal due to the costs involved in transporting water to high altitudes. The costs of technologies to manage tailings are directly related to the energy they consume. FT is highly energy-intensive, but the final product is tailings with the lowest percentage of water, meaning that the raw water requirement of the mining plant decreases more considerably than when using conventional tailings disposal. Additionally to the dewatering technologies as a strategy to save water in the mining plant, it has been demonstrated that the use of road dust suppressant products is a cost-effective solution to save water [89].

Chile is a developing country that is highly dependent on coal [88]. However, this is a struggle that several developing and under-developed countries have faced [90]. For developing countries, economic growth raises energy consumption [91]. Hence, Chile should adopt energy-efficient technologies and use renewable energy sources to achieve sustainable development with lower CO_2 emissions [90]. Additionally, Chile as a seismic region, cannot rely on the safe use of nuclear energy as a source for its energy mix.

In areas suffering from water scarcity, seawater is the primary source of water for mining sites. There are insufficient water resources in the North of Chile to cover environmental, domestic, and industrial requirements [92]. In this study, we assumed that the whole water supply relies on seawater and that continental water is not available due to the water scarcity situation that most areas where mines are located suffer. This assumption is based on the Chilean legal context, where every new mineral process plant should be operated by seawater only. In the future, 70% of the desalination capacity in Chile will meet the demand of the mining industry [43].

In cases where the mine site is located far away from the coast, water needs to be pumped over long distances up to the mine site. Water transport is one of the main cost components of water supply, having a bigger impact than water treatment. Reverse osmosis is the leading technology applied to desalinate seawater, and it is still quite expensive as a way of fulfilling the total requirements of a mine site. However, some mining processes do not require high-quality water produced with reverse osmosis [35]. Other technologies applied in this study are filtration and precipitation with lime, in which water quality is inferior but still satisfactory for some processes.

Additionally, the combination of water was considered since relying only on the supply of seawater through a filtration process can be unrealistic since some operations in the mine site require high-quality water, such as the one obtained with reverse osmosis. Currently, some mine sites use a combination of water that includes recycled water, freshwater, and desalinated water. Water transportation and treatment are energy-intensive processes that generate a large amount of GHG and threaten the competitiveness of the copper price by increasing the production cost in mines geographically located in water scarcity places [18].

Using ROA allowed us to study every cost component of the combinations analyzed to better assess the uncertainty inherent in each component. Results of sensitivity and uncertainty analyses indicate that water transport to mine sites located far away from the coast contributes more to the overall uncertainty of the applied model, despite implementing tailings dewatering technologies, such as thickened tailings and filtered tailings, that reduce the water requirement of the plant. In the near future, seawater will be the primary water source for mining due to the scarcity of freshwater sources. Therefore, reducing the water requirement by maximizing the recycling and reuse of water inside the mine is essential.

Waste reduction is crucial for achieving a circular economy. Circular economy principles include reducing and, whenever possible, reusing waste generated by the industry. The potential utility of tailings is enormous since secondary sources are nowadays increasingly more often viewed as sources of minerals and metals for production due to the declining grades in primary ore bodies and the negative impact of mining on the environment. A geophysical study of the Aijala tailings ponds, a combination of Cu, Pb-Zb, and Ni-Cu tailings, showed that the concentration of elements did not change significantly between samples taken in 1982 and 2016 [93]. One may suppose that in arid regions, where acid drainage has a lower chance to occur, the composition of tailings may not change significantly over time. Therefore, the resource estimation of mine tailings performed now will not change in the future. Dewatering technologies will allow storing mine tailings so that they facilitate re-processing them to obtain certain metals or recycle tailings to use them as construction material or ceramics in the near future. Chilean mine tailings contain quantities of critical raw materials such as rare earth elements, whose recovery could be feasible in the future [94], ROA can also be applied in this case. Mine tailings also have the potential for the sequestration of CO_2 via ex-situ mineral carbonation, which could be a way to reduce CO2 emissions from power plants [95].

6. Conclusions

Continental water sources in areas of mine sites are usually scarce or semi-scarce; therefore, part of the water demand must be satisfied by desalinated or partially desalinated seawater. The transport of water from the coast to the mine sites is expensive, and its cost can be 3–4 times higher than that of water treatment. The mining industry has made efforts to reduce the freshwater requirement by recycling several water streams in the process; in copper mining, the average percentage of recycled water is close to 70%. However, the mining industry must reduce water consumption as mine plants are usually located in places suffering from water scarcity. Additionally, this sector in Chile must gradually switch to seawater to comply with the law.

The water reduction model was used to estimate the water requirement of different options and scenarios to reduce the water requirements applied to a case study that consists of a large mine company using the data of an actual mine site. Three dewatering technologies for tailings were considered: traditional tailing disposal, thickened tailings, and filtered tailings. To ensure water supply to the mine site, we examined using seawater treated in different ways and representing different quality. Seawater that is filtered or precipitated with lime is a low-quality resource. Higher quality water can be obtained when desalination is performed using reverse osmosis, but its cost is more than three times higher than that of other technologies; hence a combination of water seems more reasonable to fulfill the mine site requirements.

The novelty of this study consisted of assessing the economic output of various options to supply water and treat mine tailings by applying an approach based on real options. It allows the identification and transparent presentation of existing investments and management options. The method used gives the flexibility to choose between different water management options, as it includes combinations of different water treatments for the water supply to the mine. Investments in mining are characterized by great uncertainty due to the nature of markets and the complexity of new projects. A real options approach enables to assess the uncertainty of every cost component and evaluates each option to make a decision. Real options methods allow for the analysis of consequences of delaying or speeding up managerial decisions and could contribute to the reduction of financial and operational risks.

Uncertainty and sensitivity analyses were carried out for the results of the water reduction model to investigate the uncertainties about costs of the different options of dewatering technologies for tailings management and water supply. These analyses were implemented using Monte Carlo simulations as a real options approach to study the influence of the uncertainties of the inputs on the overall cost of the system.

The following main conclusions can be drawn:

- Results indicate that water transport costs are one of the biggest cost components; hence, efforts to reduce the water requirements are crucial. Since most water can be found in tailings, investing in dewatering technologies is vital to reduce the water requirement of the mine.
- Mine tailings disposed using the traditional disposal method contain approximately 70% of water. It makes the tailing facility the biggest water sink in the mine site. As water is a scarce resource, efforts to reduce water content in tailings are crucial in lowering the demand for water in the mine sites.
- The water-energy nexus is a major component of the total cost for different options of water supply management systems in mines, including water used by the tailing dewatering technologies. On the other hand, energy is needed to transport water, to desalinate or partially desalinate seawater, and in technologies used to recover water from the mine tailings.
- Switching from conventional tailings disposal to thickened tailings or filtered tailings solutions would reduce the water requirement of the mine site. Still, it would increase the amounts of energy needed because these technologies are energy-intensive. However, if the water requirement is reduced, as the results show, the cost of water treatment and transport is reduced, and less energy is required in these processes, which are also energy-intensive.
- The amount of seawater used in the mining industry has been rising, and it is expected that the seawater demand will increase, intensifying the demand for energy. Therefore, to reduce greenhouse gas emissions is mandatory to use low emitting sources of energy.

CRediT authorship contribution statement

Natalia Araya: Conceptualization, Methodology, Investigation, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **Yendery Ramírez:** Conceptualization, Methodology, Investigation, Writing – original draft, Visualization. **Luis A. Cisternas:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **Andrzej Kraslawski:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of Competing Interest

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

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Appendix A

See Tables A1 and A2.

Appendix B

Sensitivity and uncertainty analysis figures

See Figs. B1-B4.

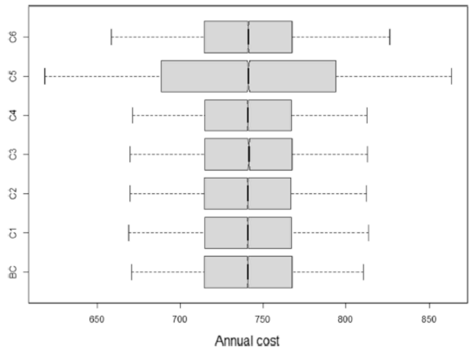

Fig. B1. Boxplot of the annual costs of implementing conventional tailing disposal technology and water supply of 50% of water quality 1 and 50% of water quality 2. BC represents the base case, C1 $CAPEX_d$ ± 20%, C2 $OPEX_d$ ± 20%, C3 $CAPEX_W$ filtered seawater ± 20%, C4 $OPEX_W$ filtered seawater ± 20%, C5 $COST_T$ ± 20%, and C6 $COST_{RO}$ ± 20%.

Table A1
Summary of costs of each dewatering technology and water treatment option.

	Dewatering technology cost		Dewatering technology water flow (m^3/d)	Water treatment and supply technology [†]			Water treatment and supply costs	Water treatment and supply costs (20 years)
Dewatering technology [§]	CAPEX $M	OPEX $M	Raw water requirement	1	2	3	$M/y	$M
1	669	369	473,288	x			577	11,540
1	669	369	473,288		x		608	12,162
1	669	369	473,288			x	802	16,031
2	678	396	406,436	x			495	9,910
2	678	396	406,436		x		522	10,444
2	678	396	406,436			x	688	13,767
3	1,326	1,290	313,046	x			382	7,633
3	1,326	1,290	313,046		x		402	8,044
3	1,326	1,290	313,046			x	530	10,604
3	1,326	1,290	313,046	50%		50%	456	9,116
3	1,326	1,290	313,046		50%	50%	467	9,320

[§] Dewatering technologies: 1 Conventional tailings disposal; 2 Thickened tailings; 3 Filtered tailings.

[†] Water treatment and supply: 1 Water partially desalinated with filtration and supply until the mine site; 2 Water partially desalinated using precipitation with lime and supply until the mine site; 3 Water desalinated with reverse osmosis and supply until the mine site.

Table A2
Chile's electric matrix, source: IEA Electricity Information 2020.

Energy source – 2019	GWh	%	gCO_{2eq}	$gCO_{2\ min}$	$gCO_{2\ max}$
Coal	26,494	32.6	$2.1725 \times 10^{+13}$	$1.960 \times 10^{+13}$	$2.411 \times 10^{+13}$
Oil	3,033	3.7	$2.2232 \times 10^{+12}$	$1.6591 \times 10^{+12}$	$2.8359 \times 10^{+12}$
Natural gas	15,128	18.6	$7.4127 \times 10^{+12}$	$6.2025 \times 10^{+12}$	$9.8332 \times 10^{+12}$
Nuclear	0	0	0	0	0
Hydro	20,874	25.7	$5.0098 \times 10^{+11}$	$2.0874 \times 10^{+10}$	$4.5923 \times 10^{+13}$
Biofuels	4,351	5.4	$1.0007 \times 10^{+12}$	$5.6563 \times 10^{+11}$	$1.8274 \times 10^{+12}$
Wind	4,809	5.9	$5.2899 \times 10^{+10}$	$3.3663 \times 10^{+10}$	$2.693 \times 10^{+11}$
Geothermal	202	0.2	$7.6760 \times 10^{+9}$	$1.2120 \times 10^{+9}$	$1.5958 \times 10^{+10}$
PV	6,304	7.8	$3.0259 \times 10^{+11}$	$1.1347 \times 10^{+11}$	$1.1347 \times 10^{+12}$
Total	81,195	100	$3.3226 \times 10^{+13}$	$2.8202 \times 10^{+13}$	$8.5949 \times 10^{+13}$

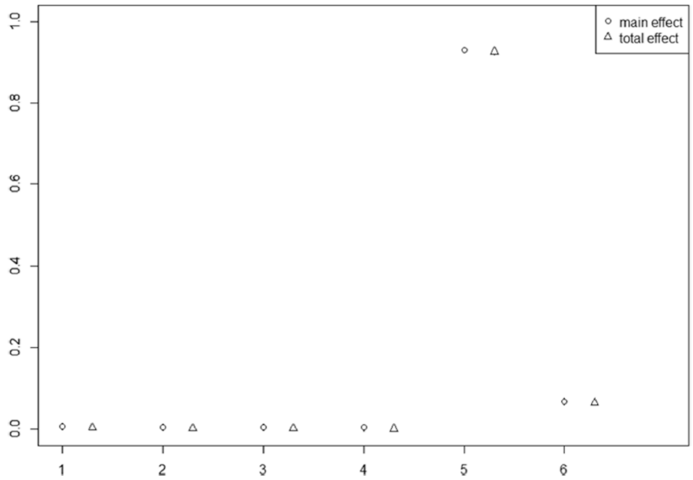

Fig. B2. Sobol' indices of the annual costs of implementing conventional tailing disposal and water supply of 50% of water quality 1 and 50% of water quality 2. Where 1 $CAPEX_d$ 2 $OPEX_d$,3 $CAPEX_W$ filtered seawater, 4 $OPEX_W$ filtered seawater, 5 $COST_T$, and 6 $COST_{RO}$.

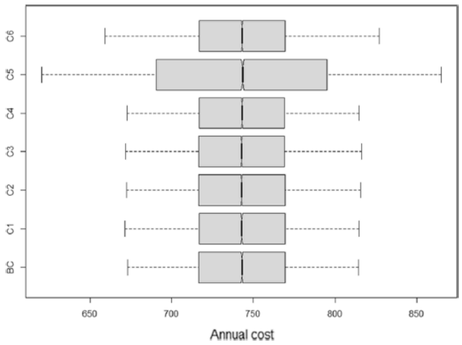

Fig. B3. Boxplot of the annual costs of implementing thickened tailings technology and water supply of 50% of water quality 1 and 50% of water quality 2. BC represents the base case, C1 $CAPEX_d$ ± 20%, C2 $OPEX_d$ ± 20%, C3 $CAPEX_W$ filtered seawater ± 20%, C4 $OPEX_W$ filtered seawater ± 20%, C5 $COST_T$ ± 20%, and C6 $COST_{RO}$ ± 20%.

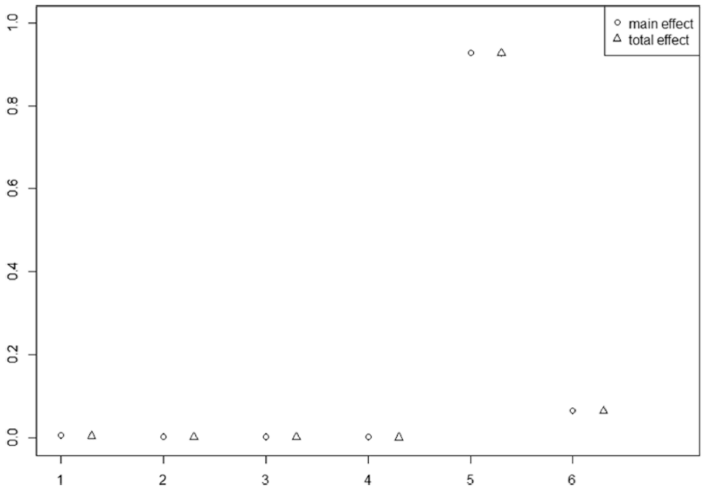

Fig. B4. Sobol' indices of the annual costs of implementing thickened tailings and water supply of 50% of water quality 1 and 50% of water quality 2. Where 1 $CAPEX_d$ 2 $OPEX_d$,3 $CAPEX_W$ filtered seawater, 4 $OPEX_W$ filtered seawater, 5 $COST_T$, and 6 $COST_{RO}$.

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