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Risk-Economic Analysis of an Innovative Technology Project for Lithium and Boron Extraction from Oilfield Produced Water

Graduation Work presented to the Escola Politécnica – University of Sao Paulo for attaining the Bachelor's Degree in Production Engineering

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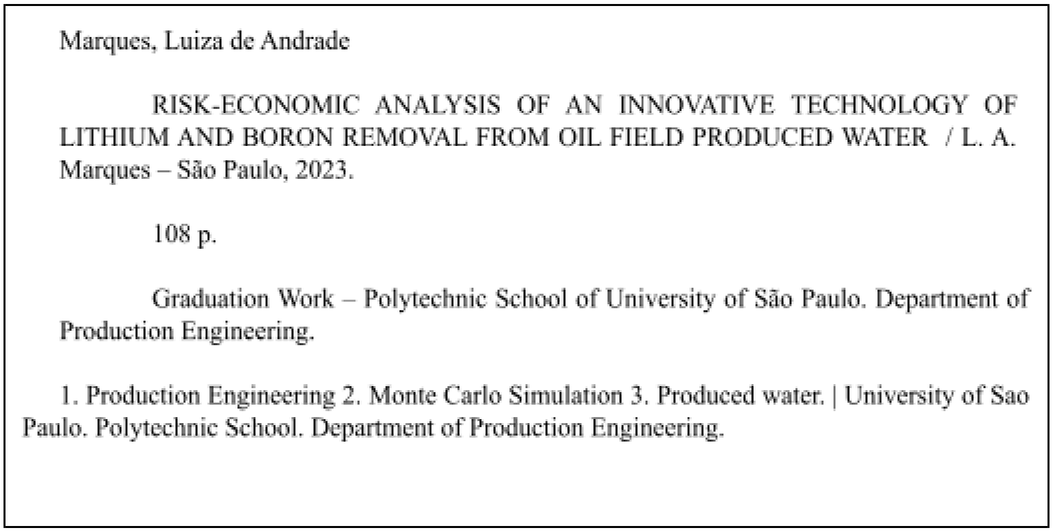

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To family and friends.

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ABSTRACT

Lithium is becoming an important raw material due to the expansion of the market of lithium-ion batteries, required for electric vehicles and for stationary energy storage. The current most common method of lithium extraction however is slow, inefficient and it has a strong environmental impact. In order to meet the demand associated with the accelerating growth of its consumption, high-efficiency methods for Li production are constantly being investigated. The biggest challenges, however, are developing both economically feasible and cleaner technologies that enable a sustainable future production of lithium.

When it comes to the treatment of produced water in oil extraction platforms, today there is not an economically feasible technology that meets the ambiental legislation regarding the lithium and boron disposal in nature. Thus an innovative technology system for produced water treatment is being designed for Boron and Lithium removal using membrane and electrochemical based processes, generating a new and green income source for the company, by selling the extracted products.

This thesis is focused on the risk-economic evaluation of the project, in order to analyze its economic feasibility. The costs associated with this system are being estimated for the project lifetime, based on the design specifications already known, plant parameters given by the company, online research and data available in the literature. Along with the costs, the project's risks were raised according to the system's technical, economical and environmental variables and related to different types of cash flow groups, in order to measure the economic impact of these risks on the project's NPV.

Key words: Produced water, Lithium, Boron, Monte Carlo, Cash flows, NPV, risk

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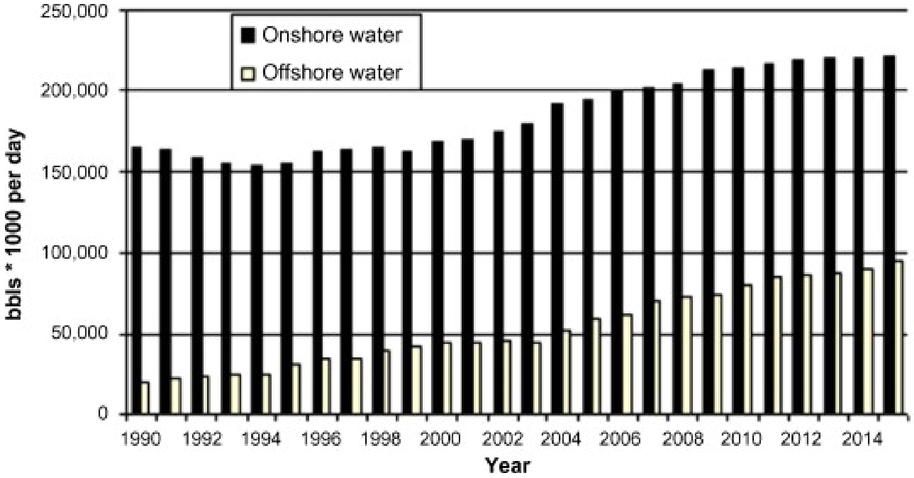
SUMMARY

PART I - Introduction

1.1. Oilfield Produced Water

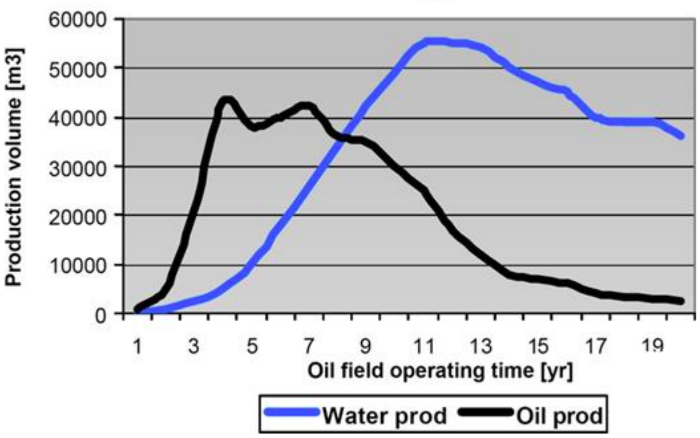
Produced water is a complex mixture of organic and inorganic compounds generated during oil and gas recovery operations as the largest by-product in volume, a ratio of around 3:1 water to oil (FAKHRU'L-RAZI et al., 2009). Globally, around 250 million barrels of water are produced daily from both oil and gas fields, in which more than 40% of it is discharged directly into the environment (IGUNNU; CHEN, 2014).



Graph 1 - Graph of the produced water production evolution

Source: (FAKHRU'L-RAZI et al., 2009)

The outcome and effect of years of produced water disposal has become a significant issue of environmental concern. The rate of oilfield produced water production increases as oilfield ages (figure 2), beside the fact that Petroleum is still a major source of energy and revenue for many countries today, with an estimated world daily consumption increase to 106.6 million barrels by 2030 (US Department of Energy, 2009). Thus legislations regarding this large discharge of waste stream into the environment have made produced water management a significant part of the oil and gas business, that are now facing the challenge of implementing a cost-effective technology for treating produced water to reduce contaminants for discharge and/or reuse (IGUNNU; CHEN, 2014).



Graph 2 - Oilfield produced water production profile

Source: (Nature Technology Group, 2010)

Produced water composition includes dissolved oil, grease, salts, anions and cations, heavy metals, radionuclides, treating chemicals, formation solids, dissolved gases, microorganisms, among others components, whose proportion depends on the geology formation and the age of oil well (IGUNNU; CHEN, 2014), as shown in table 1. Because produced water characteristics vary from one well to another, a unique technique cannot be recommended for achieving all environmental standards, recycling, and reuse requirements (FAKHRU'L-RAZI et al., 2009).

Parameter	**Value**
Density (kg/m3)	1,014 - 1,140
Conductivity (µS/cm)	4,200 - 58,600
Surface tension (dyn/cm)	43 - 78
pH	4.3 - 10
TOC (mg/l)	0 - 1,500
TSS (mg/l)	1.2 - 1,000
Total oil (IR; mg/l)	2 - 565

Table 1 - Composition of oilfield produced water

Source: (FAKHRU'L-RAZI et al., 2009)

Produced water is conventionally treated through different physical, chemical, and biological methods. Today the general practice in use for produced water treatment is gravity-based separation and discharge into the environment, which can pollute soil, surface water and underground water (FAKHRU'L-RAZI et al., 2009). Since the long-term effects of its disposal on the environment are not fully known, researchers are paying more attention to the consequences of dissolved organic components, heavy metals and production chemicals on living organisms (IGUNNU; CHEN, 2014).

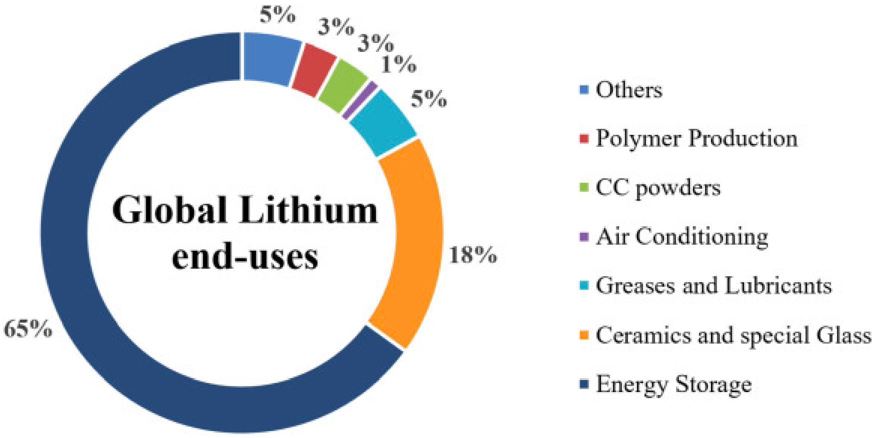
Regulations for discharging produced water into the sea can vary from country to country and are subject to specific regulations and environmental standards set by the respective regulatory authorities. A general legislation has been 40 ppm OIW (oil in water), while little attention was given to dissolved organics, heavy metals and production chemicals on living organisms, since their long-term effects on the environment are not fully documented and understood (IGUNNU; CHEN, 2014). Oil and gas companies operating in Malaysia are required to adhere to regulations, which typically include limits on oil and grease content, heavy metals, chemicals, and other contaminants in produced water before it can be discharged into the sea.

High levels of Boron in the water, for example, can lead to toxicity effects. These levels are not known yet for every living being, so the capability of technology to remove boron plays an important role in determining the regulated guideline value (LE TU, 2014). The existing removal technology was unable to reduce the boron level to 0.3 mg/L, the recommended boron level for drinking water. The maximum boron level in drinking water was set at 0.5 mg/L, by the WHO and European Union organization, and at 1 mg/L in the case of waste waters discarded to the environment. However, commonly used membrane desalination technologies are not efficient enough to fulfill these regulations (DYDO et al., 2005).

These environmental concerns as well as the prospect of beneficial uses, such as production of clean water and recovery of valuable metals from produced water with minimal or no negative impact on the environment, have driven research into the treatment of produced water, demonstrating its economical benefits. After all, although produced water is most often considered a waste, this stream has indeed a profit potential that the industry is beginning to consider.

1.2. The Lithium Market

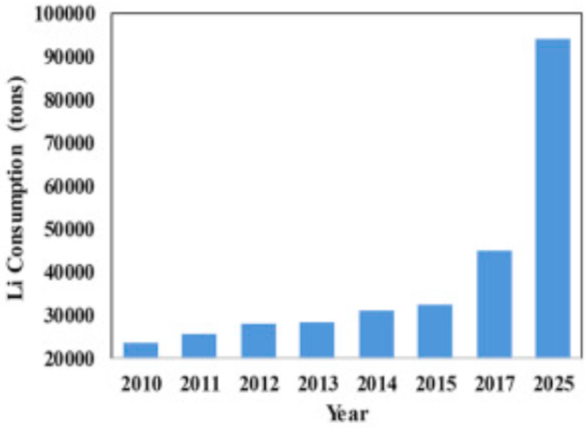
Lithium is becoming an important raw material due to the expansion of the Electrochemical energy storage market, required for electric vehicles, for stationary energy storage, among other segments. Lithium-ion batteries are able to provide uninterrupted power supply and load-shifting capability, given lithium's unique properties of light weight and high energy storage potential, making it highly likely to remain the material of choice in non-stationary batteries (British Lithium, 2023). The use of Lithium-ion batteries is expanding every day in various applications, from small cellular phones to large power generation systems. This industry is expected to account for almost 66% of the current Li production worldwide by 2025 (ZHAO et al., 2020).



Graph 3 - Distribution of global Li applications (2019)

Source: (ZAVAHIR et al., 2021)

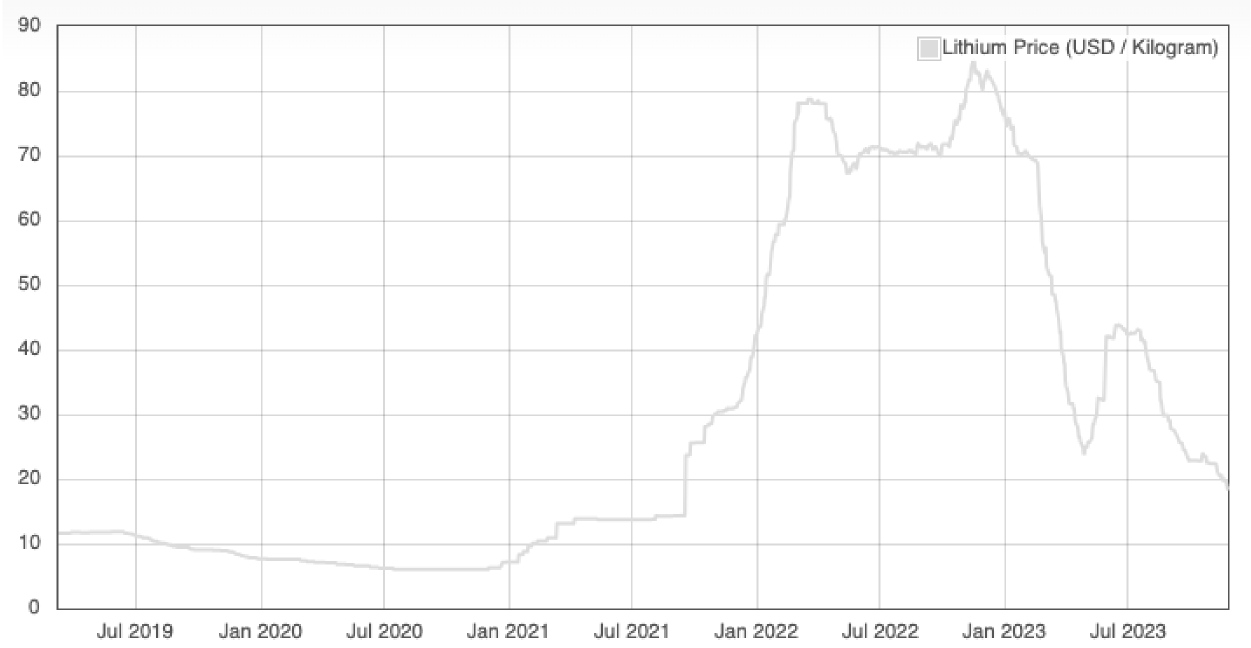
With the increased utilization of Li in various fields, the demand for accessible lithium is increasing (LIU; ZHAO; GHAHREMAN, 2019). The global consumption of the 25th most abundant metal on Earth during the period of 2010 to 2017 increased by approximately 6% annually and is projected to reach approximately 95,000 tons in 2025 (LIU; ZHAO; GHAHREMAN, 2019). According to the predictions, the current lithium global production capacity from brine of 120.5 Ktons/year will not be enough to cover the lithium market demand in the near future (PALAGONIA; BROGIOLI; LA MANTIA, 2020). Thus new projects have to be initiated to meet market needs and climate change goals.



Graph 4 - Global lithium production in the years from 2010 to 2025

Source: (CHOUBEY et al., 2017)

Pricing of lithium is currently following commodity style trends, with the price varying significantly depending on the supply-demand imbalance (British Lithium, 2023). Pricing of lithium carbonate has traded from $8 to $85 US dollars per kilogram over the past five years, as shown in figure 5, and is likely to increase with demand.



Graph 5 - Historical price of Lithium over the past 5 years

Source: (Daily Metal Price, 2023)

Today the main Lithium sources are salt lake brines, but also present in smaller concentrations in hard rocks, seawater, deep underground in geothermal brines and produced water coming from the oil extraction process. According to the US Geological Survey (USGS) of 2020, the total Li resource is about 80 million tons, with the majority of the Li resource concentrated in South America.

Li source	**Li concentration [mg/L]**	**Ref**
Salt lake brines	100 - 3,800	(ZAVAHIR et al., 2021), (GARRET 2004)
Geothermal brines	10 - 20	(ZAVAHIR et al., 2021)
Seawater	0.17	(FLEXER; BASPINEIRO; GALLI, 2018)
Produced water	3 - 150	(IGUNNU; CHEN, 2014), (EPA, 2016)

Table 2 - Li concentration values by source type

Source: Elaborated by the author

The cost of extracting Li from brine is US$ 2–3 per kg and from hard rocks is estimated to be US$ 6–8 kg−1. The alternative of extracting Li from seawater is considered a major challenge due to the complicated technical procedures, high capital costs, and the low concentration of Li, all of which make it economically impractical (ZAVAHIR et al., 2021).

The current most common method of lithium extraction is slow, inefficient and it has a strong environmental impact. Thus in order to meet the demand associated with the accelerating growth of its consumption, high-efficiency methods for Li production are constantly being investigated. The biggest challenges, however, are developing both economically feasible and cleaner technologies that enable a sustainable future production of lithium.

PART II - Literature review

2.1. Produced water management

The objectives of produced water treatment management include meeting discharge regulations and water quality requirements for different potential uses. In order to meet up with these objectives and environmental concerns, operators have applied many standalone and combined physical, biological and chemical treatment processes for produced water management (IGUNNU; CHEN, 2014).

The selection of the produced water treatment structure is often a challenging problem that is steered by the overall treatment objective. The options can differ in their inherent facility requirements, capital costs, operating expense and waste streams. All these factors can be important to the oil and gas operator, when it comes to produced water management alternatives (ARTHUR et al., 2005).

Injection is based on injecting the produced water into the same formation from which the oil is produced or handling it to another formation. Discharge is another alternative, requiring treatment of produced water to meet onshore or offshore discharge regulations. Reusing the water is also a possibility, whether in the oil and gas operations or for consumption in other beneficial uses, such as irrigation or drinking water, after the specific treatments for quality requirements (ARTHUR et al., 2005).

The produced water treatment process is based on the de-oiling (removal of dispersed oil and grease), desalination, removal of suspended particles and sand, soluble organics, dissolved gases, radioactive materials and on the disinfection and softening, to remove excess water hardness (ARTHUR et al., 2005).

Chen and Igunnu (2012) reviewed the major produced water treatment technologies advantages and disadvantages, as well as their application in future management. According to their analysis, current thermal produced water treatment technologies are mature and more attractive in treating highly contaminated water, but the energy consumption is high compared to other technologies, so it may not be relevant in future management unless significant reductions are made in energy costs.

MPPE (Macro-porous polymer extraction) technology is a fairly new produced water treatment technology, with a good potential to achieve a zero pollutant discharge and a significant reduction in energy consumption compared with thermal technologies. However, it has a relatively high cost of unit as a major disadvantage to compete in the future management of produced water.

Membrane technologies are pointed as some of the finest for produced water treatment today, but membrane fouling and secondary waste generation are an impediment for them to compete well in the future management of produced water, unless significant progress is made to reduce the high costs of rigorous pre-treatment, fouling, and regular backwashing.

Membrane filtration technologies selectively separate a fluid from its components, depending on the pore ratings of its microporous films. There are four established membrane separation processes: microfiltration (MF) that separates suspended particles, ultrafiltration (UF) that separates macromolecules, reverse osmosis (RO) separates dissolved and ionic components and nanofiltration (NF) is selective for multivalent ions, used for water softening and removal of metals from wastewater.

Bench-scale studies have shown the potential of RO membranes to successfully treat oil and gas produced water, with appropriate pre-treatment technology (XU; DREWES, 2006). Mondal and Wickramasinghe (2008) studied the effectiveness of NF membranes for the treatment of oilfield produced water. Results showed NF as a poor technology for produced water treatment and is inappropriate as a standalone technology. Its energy requirement is less than what is required in RO systems, but both require extensive pre-treatment to prevent fouling of membrane. Water recovery from NF is about 75% to 90%, while RO depends on the configuration, SWRO is between 30% and 60%, and BWRO between 60% and 85%.

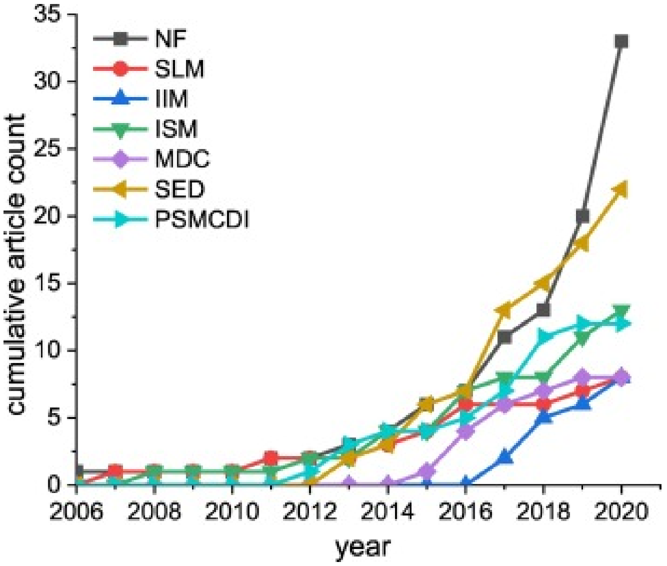
Finally, Chen and Igunnu (2012) reports that although electrochemistry is not a popular method and has only been tested for produced water treatment on laboratory scale, it has a great potential to be the future technology for the management of produced water, as a cost-effective green technology with zero pollutant discharge. The choice of the best technology, however, changes from one case to another, once is based on the produced water chemistry, cost-effectiveness, space availability, reuse, discharge and byproducts plans. Indeed, to optimize produced water treatment, two or more technologies may be combined or employed in a hybrid system.

2.2. Lithium recovery technologies

Today there are different types of Lithium recovery technologies in the literature, such as soda evaporation process, solvent extraction, chemical precipitation, membrane based process and electrochemical techniques.

Commercial-scale Li production is carried out by soda evaporation process, which uses solar evaporation in order to concentrate the brine, followed by a chemical process until final purification of LiCl. Since the sun is a freely available resource, this process has a low cost, but it is very slow, taking up to 2-3 years depending on the weather and producing large amounts of chemical waste . Solvent extraction and chemical precipitation add different reagents in the brine solution and can leave huge volumes of sludge to dispose, which therefore is less environmentally friendly (ZAVAHIR et al., 2021).

The membrane based processes are the most known in the market, with different studies in the literature, as shown in figure 6. They are promising in sustainability aspects, because they have a low footprint, yet they suffer from membrane fouling, thus high operational costs, beside the fact that the best performing membrane systems exhibited up to 85% separation of Li+ over Mg2+ (ZAVAHIR et al., 2021).



Graph 6 - Number of published papers for membrane-based techniques.

Source: (ZAVAHIR et al., 2021)

In the last decade, however, it was proposed the electrochemical ion separation process, which exhibits outstanding performance in terms of Li recovery and sustainability. This promising technique is based on the “electrochemical ion pumping” concept, consisting in the intercalation of lithium cations from the solution into a lithium selective material. The main advantage compared to the conventional ones is that it does not require the use of chemicals, but the application of current as the driving force of lithium capturing and release.

Electrochemical ion-separation processes have emerged as a promising and effective methodology for lithium capture, exhibiting outstanding performance in terms of Li recovery capacities, tunability, cyclic efficiency, reversibility, and selectivity. Overall, there are three main categories of ELiCs according to their basis of separation: electrodialysis (ED) is an electro membrane-based process, capacitive deionization (CDI) is membrane enhanced battery-based and electrochemically switchable ion exchange (ESIX) as a battery-based (ZAVAHIR et al., 2021).

Electrochemical lithium capturing systems (ELiCSs) approach was first reported in the early 1990s by Kanoh and his team, when they designed a system that used λ-MnO2 as the working electrode and Pt wire as the counter electrode to capture Li ions from a solution of mixed cations. Two decades later, Pt was substituted by silver as the counter electrode, consuming less energy. This approach was known as the electrochemical ion-pumping system (EIPS), which is battery based (ZAVAHIR et al., 2021). The λ-MnO2/Ag system with two consecutive recovery processes was able to produce a concentration of Li in the recovery solution of 190 mM with 99% purity (KIM et al., 2019).

Membrane-enhanced battery-based ELiCSs have a similar configuration to the battery-based ones, but include both membranes and electrodes to achieve Li capturing. An electric potential between the two electrodes, where an anion exchange membrane (AEM) divides the cell into two compartments. Li is captured from the brine reservoir by the cathode, while it is released into the recovery solution at the anode. Traditional capacitive deionization (CDI) is known for its extensive and effective use in low saline desalination applications (ZAVAHIR et al., 2021).

The ED system for Li recovery is a membrane-based technology, based on a series of anion and cation exchange membranes between two electrodes. When the potential is applied to those electrodes, Li selectively migrates through the cation exchange membranes toward concentrating compartments. In order to obtain a high concentration of Li in the final product, it is important to keep the volume of the recovered solution as low as possible (JOO et al., 2020).

Palagonia et al. (2020) proposed a reactor design aimed to capture lithium from brines with concentration of LiCl down to 1 mM, in order to increase the variety of the potential lithium sources. By using LMO and NiHCF as lithium-capturing and lithium-excluding electrodes respectively, with a flow-through configuration and optimized working parameters, they were able to extract more than 90% of the lithium present in the source solution. According to the article, his technology represents a sound response to the increase in lithium demand envisaged in the next future, opening the way to the industrial realization of the lithium recovery from diluted brines and thus to the exploitation of lithium sources that were untapped so far.

The majority of the studies concerning these electrochemical processes are still in laboratory scale, remaining substantial room for enhancement and prospective research, such as in the selection of materials for increasing the lithium selectivity, the concentration of the recovery solution and its purity, and on investigation the reaction efficiency (PALAGONIA; BROGIOLI; LA MANTIA, 2020).

2.3. Economic-risk evaluation of TI projects

Innovation is essential for companies to form long-term competitive advantages. The use of appropriate tools for determining financial and economic feasibility of implementing an innovation and related activities is necessary, allowing the decision maker to assess whether this innovation is justified in respect of implementation funds. This requires improvement and grounded updating of traditional approaches to financial and economic evaluation of the planned innovation and related activities (MATH; BRUSEVA, 2015).

Project evaluation aims to determine the extent to which the adoption of new or advanced technologies and products will enhance the company's competitive edge. Achieving this goal of innovation requires investment and the evaluation of projects from a financial and economic perspective. Assessing innovation projects should encompass the entire potential of new technologies and products to benefit the company over an extended period, beyond a singular annual assessment.

There are different methods for making the economic assessment of a project, such as the Net present value (NPV), Internal rate of return (IRR), Benefit-Cost Ratio (B/C ratio), Payback period (PVP), Profitability Index (IP), among others. The most practical one is the NPV (MATH; BRUSEVA, 2015), which determines whether the sum of the discounted net cash income over the duration of the economic life of the project exceeds the amount of discounted costs, as following, where r is the discount rate and Ci the cash flows over the n years:

$$NPV = -C_0 + \frac{C_1}{(1+r)^1} + \frac{C_2}{(1+r)^2} + \dots\dots\dots\dots + \frac{C_n}{(1+r)^n} \qquad (1)$$

The IRR is the rate that produces a zero value for the NPV, while the B/C ratio is the ratio between discounted economic benefits and costs. The NPV should be greater than zero for the project to be desirable from an economic standpoint, while the IRR should be greater than the social discount rate (DJUKIC et al., 2016).

Miorando et al. (2014) proposed an economic-probabilistic model for risk analysis for technological innovation projects. The risks are identified, financially quantified and treated as probability distributions. Each risk is analyzed according to its potential to impact cash flows and its probability of occurrence. The result is an economic-probabilistic analysis of the expected return of the project.

The model is built based on a risk structure and a cash flow structure which are then merged into one. Risks can be grouped into categories that describe the main dimensions of an IT project, such as the ones on the table below. The cash flows are usually divided into the following groups: Benefits, Financial Costs, Infrastructure, licensing and equipment, Manpower, Training & Education, Third-party services, Consumables, Travel expenses, Others.

Risk Category	**Risk Factor**
Costs	Budget conformity Financial exposition Estimates and contingencies
Benefits	Benefit clarity Benefit reliability Benefit validation Benefit achievement plan Benefit measurement Benefit metrics and targets Benefit capture process
Skills and experience	IT skills Business skills Project Management skills
Size and complexity	Project size Project complexity Dependence on other projects Dependence on individuals Dependence on suppliers

Architecture and performance	Architecture alignment Safety Critical performance point
Schedule	Development time Development termination
Scope clarity	Future state clarity Results clarity Area focus clarity
Organizational support	Business areas involvement Support from areas impacted by the change Sponsor disposition Sponsors Resource source commitment Computational operations support Top management involvement
Change impact	Change extension Change competences
Business environment	Adaptive capability regarding business changes Business environment sensibility Changes in customer needs
Technological maturity	IT maturity IT sofistication
Risk management	Guidelines planning Quality assurance Decision-making

Table 3 - Main risks associated with IT projects

Source: (MIORANDO; RIBEIRO; CORTIMIGLIA, 2014)

In summary, the model consists in the following steps:

1. Building the risk structure: identify the categories of risks and the risk factors associated to each of them;
2. Identifying the cash flow structure;
3. Integration of the risk categories with the cash flow groups;
4. Data collection;
5. Estimation of the cash flows: calculate the NPV of each group and then the total project's NPV;
6. Risks evaluation: estimate the economic impact of each risk factor, as well as its probability of occurrence in the best and worst case scenarios;
7. Generate a probability distribution for the economic impact that translates the risk associated with each factor, using the mean value of each interval and its respective probability;
8. Calculate the risk-adjusted NPV for each cash flow group by adding the deterministic value for the group, indicated in the cash flow, and the probability distribution of the risk factor impacting the group, by stochastic simulation: 10,000 iterations for each simulation using the Monte Carlo sampling technique;
9. Calculate the risk-adjusted NPV of the project by aggregating the probability distributions for each cash flow group through another stochastic simulation;
10. Prioritization of risk factors: identify the primary risk factors (bigger impact on the CFs), which offer the main threats and the best opportunities to evaluate alternative development options that aim to increase returns and reduce risks.

A zero NPV suggests that investors receive back the exact capital invested along with an interest equivalent to the discount rate. A negative NPV indicates that the investment doesn't generate ample returns to cover opportunity costs. Positive NPV values label investment projects as exceeding average profitability expectations. The discount rate substantially impacts the NPV, serving as an indicator for opportunity cost (ARNOLD; YILDIZ, 2015).

2.4. Monte Carlo simulation

Monte Carlo simulation is a popular modeling technique used to predict the probability of different outcomes of an uncertain variable. Using probability distributions enables a more realistic way of describing uncertainty in variables of a risk analysis. Therefore, this simulation method is largely used in many fields, such as engineering, investing and business, once it allows more accurate forecasting and, ultimately, better decision-making under uncertainty, by measuring and assessing risks in different predictions.

MCS is based on assigning multiple random values to an uncertain variable to achieve many results, a range of possible outcome values. The core idea is to simulate a system or process multiple times, each time using randomly generated inputs or variables within their defined ranges (KROESE et al., 2014). This data on possible results builds a distribution, with which it is possible to calculate the probabilities of different outcomes, as well as perform a wide range of additional analyses. This process can be summed up in four main steps:

1. Define a domain of possible inputs;
2. Sample values at random from the input probability distributions;
3. Make many iterations with each set of samples and record the resulting outcomes;
4. Aggregate the results.

Monte Carlo simulation results provide a much more comprehensive view of what may happen and how likely it is to happen, considered an important tool for risk management in project assessment.

For a correct application of the MCS the input variables need to be considered uncorrelated. if interdependencies between two input quantities exist, standardizing one input variable by the other can be used to decouple them. In addition, determining the probability density functions for the random input parameters is a crucial step of MCS application. If it is not already known and there's a lack of suitable data, a first analysis is carried out based upon literature, reference cases and expert interviews revealing variation ranges of the input quantities of interest. These input values are discussed in a workshop with the stakeholders involved in the project in order to determine plausible worst case, base case, and best case estimates. (ARNOLD; YILDIZ, 2015).

2.5. Economics in chemical engineering projects

The investment costs for a chemical industry project depend on many factors including the plant capacity, installation site, system technology, feed water composition, among others. It is divided into direct and indirect capital costs. Direct capital costs refer to costs associated with the land purchase, plant construction, purchasing process equipment, and installation charges. Indirect capital costs refer to interest during construction, project management, overhead, supervision, working capital and contingency (PARK et al., 1997). Total indirect capital cost is estimated as 10% of total direct capital cost (TAVAKKOLI et al., 2017). However, estimating the direct capital costs of an innovative project is challenging because of the lack of specifications known at an early stage, available only after the detailed engineering design.

Tavakkoli et al.(2017) proposes a Techno-economic assessment (TEA) for evaluating the economic feasibility of a desalination plant by membrane distillation for treatment of high salinity shale gas produced water. and appointed the following investment cost composition:

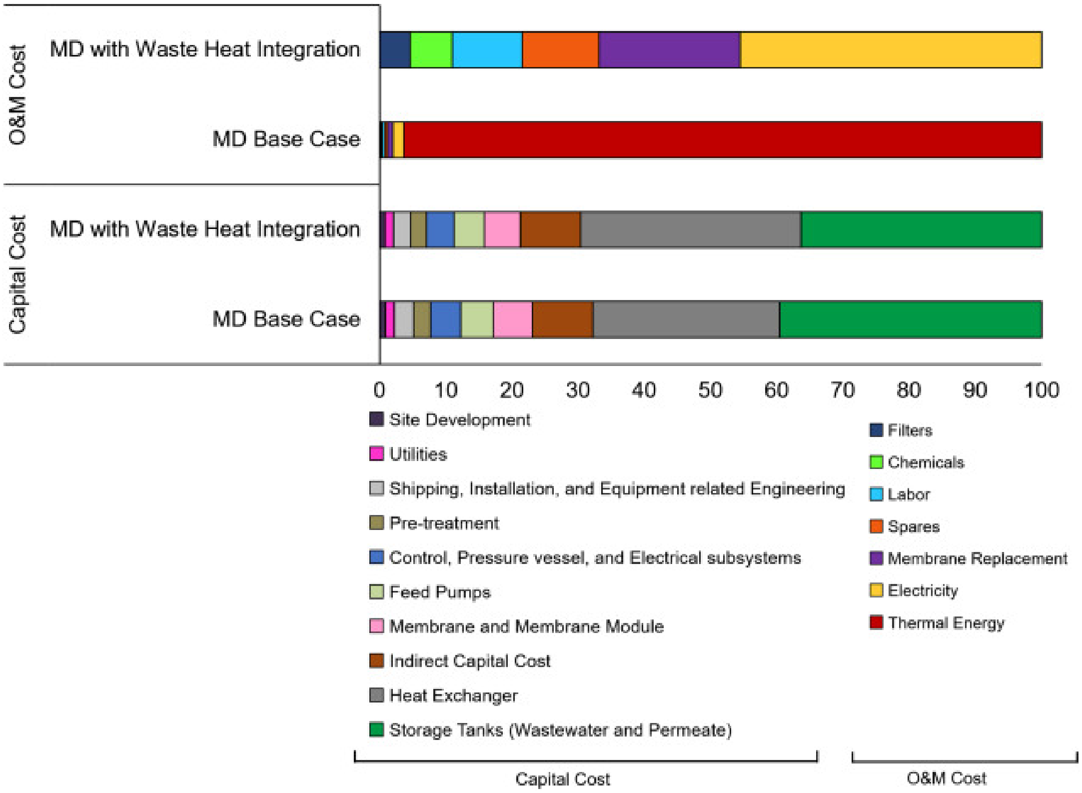


Figure 1 - Fractional contribution of capital and O&M costs by various cost elements for base case and MD

Source: (TAVAKKOLI et al., 2017)

A capital cost estimate is presented as a range of potential costs rather than a specific figure. Effective cost estimators strive to comprehend and honestly acknowledge the details and variables that remain uncertain. Those responsible for creating estimates should effectively communicate the project's associated risks, the spectrum of potential outcomes, and, notably, how these elements interconnect. The extent of scope definition significantly influences cost uncertainty. As the scope definition becomes more detailed, estimate precision also increases. Since the 1990s, nearly every prominent CPI (Chemical and Process Industries) owner company has adopted a phase-gate project system, aligning closely with the phases outlined by the Association for the Advancement of Cost Engineering (AACE) International (ChemEng, 2020).

AACE has delineated five levels of cost detail, contingent upon the project stage, available information, and uncertainties, as shown in table 4:

AACE class	**Key deliverable status**	**Expected accuracy**

Class 5 – Order of Magnitude	Block flow agreed by stakeholders	within ±50-100%
Class 4 – Preliminary	Process flow diagrams issued for design	within ±30-50%
Class 3 – Definitive	Process and instrumentation diagrams issued for design	within ±10-15%
Class 2 – Detailed	All specifications and datasheets complete	within ±5-10%
Class 1 – As Bid	Most or all engineering and design work complete	within ±5-10%

Table 4 - AACE cost detail classification

Source: (ChemEng, 2020)

Towler and Sinnot (2006) proposed different investment cost projection methodologies depending on the project's stage. There are different methods in the literature about estimating investment costs for different projects. Analyzing historical data from previous plants with similar technology is the quickest way to make an order of magnitude estimate of the capital cost implied. Different articles use cost databases to find the correlation between the capital cost of plants and their capacity. The normal capacity/cost correlation used in engineering practice is the well-known power law rule, represented by the equation below:

$$C_2 = C_1\left(\frac{S_2}{S_1}\right)^n \qquad (2)$$

Where C2 is the capital cost of the plant with capacity S2 and C1 the capital cost of the plant with capacity S1. The exponent n is typically assumed as 0,6 for the chemical industry, known as the "six-tenths rule".[1] This law can be used to calculate the capital cost of a new plant (of known capacity) based on the known capital cost of an existing plant, with an accuracy of typically 30-50%.

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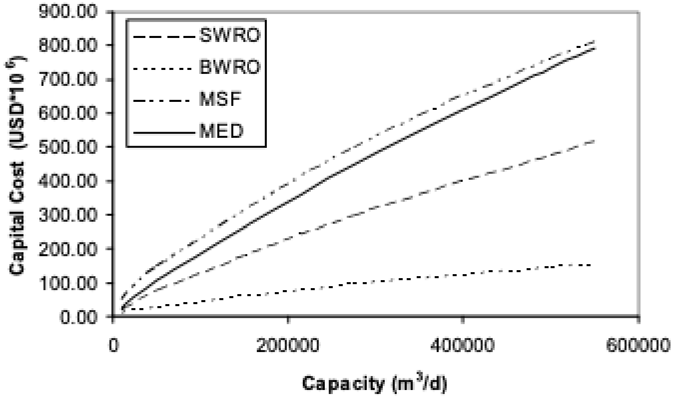
[1] CHEMICAL ENGINEERING DESIGN. Principles, Practice and Economics of Plant and Process Design (GAVIN TOWLER, RAY SINNOTT)



Graph 7 - Capital Cost vs Capacity of membrane bases systems

Source: (TAVAKKOLI et al., 2017)

Another approach is the Factorial Method of Cost Estimation. Capital cost projection is often based on an estimate of the purchase cost of the major equipment items required for the process. However, in addition to the purchase price of the equipment, fixed capital investment include many other costs associated with building a chemical plant, such as delivery and installation of equipment, preparation of land for construction, salaries of contractors and construction workers, contingency charges, among others.

These other costs, in turn, can be estimated as factors of the equipment costs, known as the Factorial Method. The accuracy of this type of estimate depends on what stage the design has reached at the time estimated and on the reliability of the data available on equipment costs.

A quick estimation was proposed by Lang (1948), in which the capital cost would be the sum of the main equipment, multiplied by an installation factor that varies according to the type of plant. The equation is given by the following:

$$C = F\left(\sum C_e\right) \qquad (3)$$

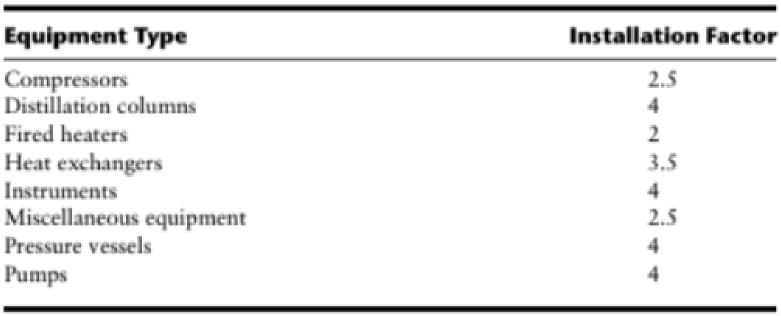
With F derived from historical cost data for similar processes, assuming the following values:

F = 3.1 for solids processing plant;

F = 4.74 for fluids processing plant;

F = 3.63 for mixed fluids-solids processing plant.

Hand (1958) later proposed using different factors for different types of equipment, in order to obtain better results.

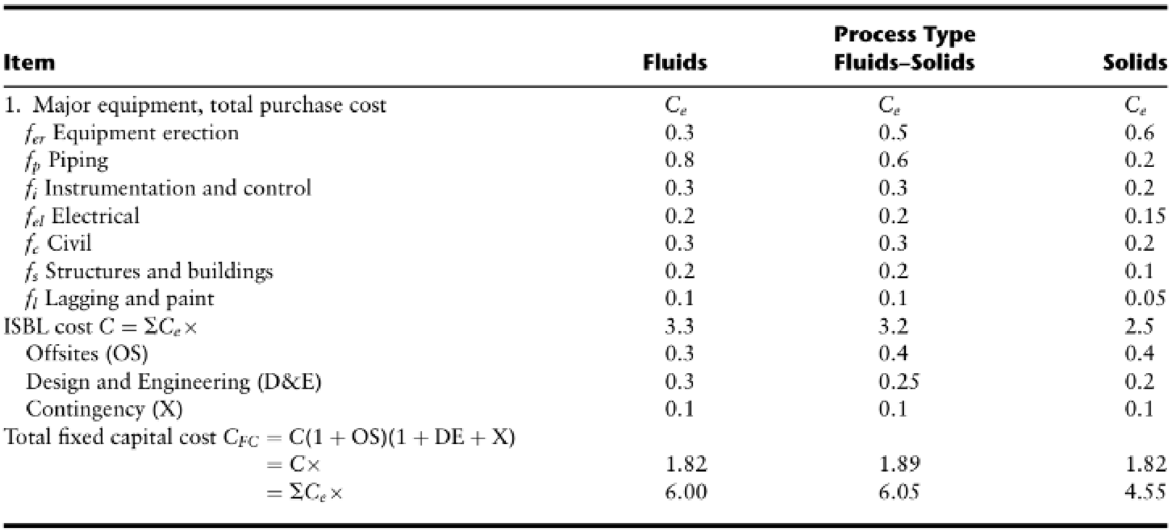


Equipment Type	Installation Factor
Compressors	2.5
Distillation columns	4
Fired heaters	2
Heat exchangers	3.5
Instruments	4
Miscellaneous equipment	2.5
Pressure vessels	4
Pumps	4

Table 5 - Hand installation factors

Source: (TOWLER; SINNOTT, 2021)

More detailed factors were later on published in the literature, breaking the additional costs into ISBL (Inside Battery Limits), Offsite or OSBL (Outside Battery Limits), engineering and contingency costs. ISBL refers to the cost of procuring and installing the equipments. OSBL is associated with off-site developments that require the plant to run. Engineering cost is related to designing equipments and structures. Finally, contingency costs to deal with unexpected charges. Typical factors for these components of the capital cost are given by the table 6:



Item	Fluids	Process Type Fluids–Solids	Solids
1. Major equipment, total purchase cost	C_e	C_e	C_e
f_{er} Equipment erection	0.3	0.5	0.6
f_p Piping	0.8	0.6	0.2
f_i Instrumentation and control	0.3	0.3	0.2
f_{el} Electrical	0.2	0.2	0.15
f_c Civil	0.3	0.3	0.2
f_s Structures and buildings	0.2	0.2	0.1
f_l Lagging and paint	0.1	0.1	0.05
ISBL cost $C = \Sigma C_e \times$	3.3	3.2	2.5
Offsites (OS)	0.3	0.4	0.4
Design and Engineering (D&E)	0.3	0.25	0.2
Contingency (X)	0.1	0.1	0.1
Total fixed capital cost $C_{FC} = C(1 + OS)(1 + DE + X)$			
$= C\times$	1.82	1.89	1.82
$= \Sigma C_e \times$	6.00	6.05	4.55

Table 6 - Capital cost factorial method

Source: (TOWLER; SINNOTT, 2021)

PART III - Overview of the extraction process

3.1. System's design

The extraction system of the project was designed based on both the potential of treating the produced water for an environmentally correct disposal into the sea and, at the same time, extracting the Lithium in order to sell it. The design consists of 3 main systems: the pretreatment by Reverse Osmosis, the Boron extraction system by Nanofiltration and the Lithium extraction system by Electrochemical process.

The process begins with the inflow of the produced water that is pumped into the first storage tank. It then passes through the reverse osmosis pretreatment system, which separates the permeate and the concentrate. These fluids are stored in two separated tanks before being pumped into the Boron and Lithium removal systems. Finally, the final products are stored in different tanks and the remaining fluids are disposed. These processes are illustrated below in the flowchart of the project (figure 2).

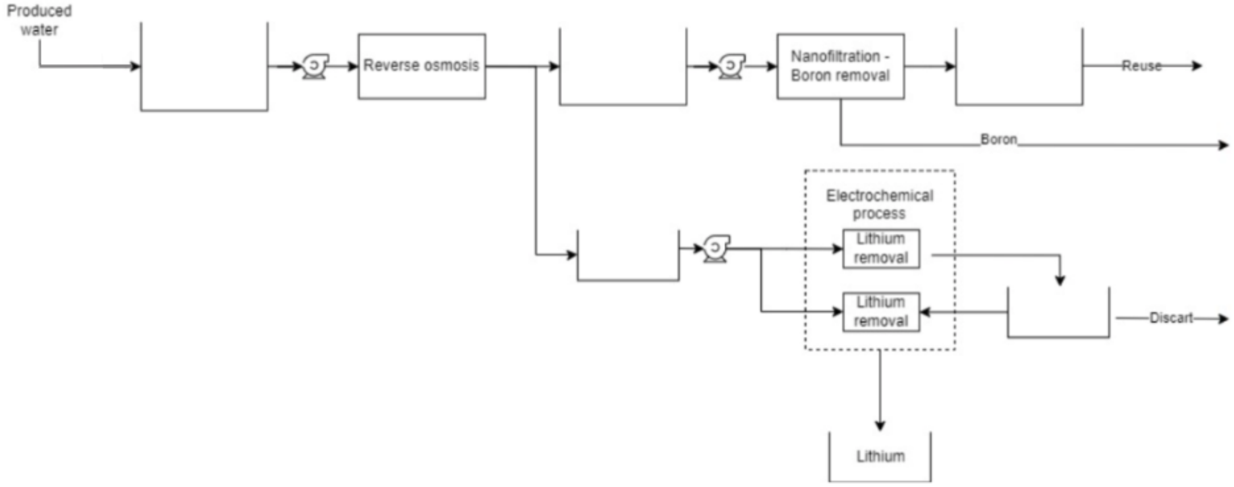


Figure 2 - System's fluxogram design

Source: Elaborated by the author

3.1. Reverse osmosis

Reverse osmosis is a membrane based technology widely used as a pre-treatment process, due to its capacity of removing a large range of contaminants, including dissolved salts, heavy metals, bacteria, and other impurities as small as 0.0001 µm. Below is a simplified diagram illustrating the RO process (figure 3), in which the feed water is separated into two flows: the permeate and the concentrate. The permeate is the fluid that passes through the membrane, carrying a smaller concentration of dissolved solids and contaminants. The concentrate corresponds to the portion of the inflow which does not pass through the membrane and so carries higher concentration.

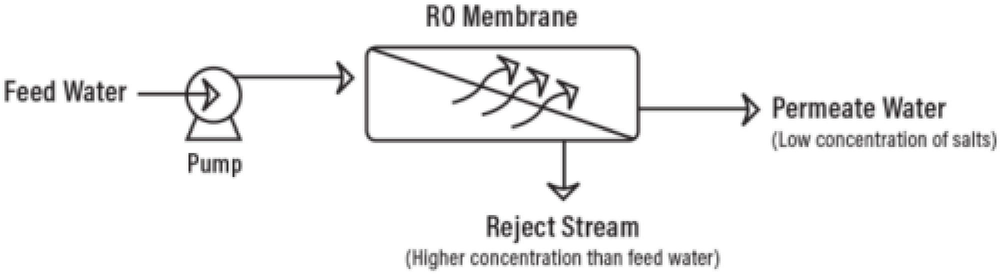


Figure 3 - The RO process

Source: (PuretecWater, 2023)

There are different metrics that calculates the performance of the RO system and so influences the projection of the project's cash flows:

- The concentration of salt that will end up in the permeate depends on the membrane's rejection rate, which is typically between 75% to 100% and it is given by the following equation:

$$Salt\ rejection\ \% = \frac{TDS\ \ of\ feed\ water - TDS\ of\ permeate\ water}{TDS\ of\ feed\ water} \times 100 \tag{4}$$

- The salt passage is the inverse of the salt rejection, representing the amount of salts that are passing through the RO system, given by the following equation:

$$Salt\ passage\ \% = (1 - Salt\ rejection\ \%) \tag{5}$$

- The volume of permeate water depends on the permeate share of the membrane and the system's design, given by the following equation:

$$Recovery\ \% = \frac{Permeate\ flow\ rate}{Feed\ flow\ rate} \times 100 \qquad (6)$$

3.2. Nanofiltration

Nanofiltration (NF) is a pressure driven membrane liquid-separation technology. Unlike RO, which has high rejection of virtually all dissolved solutes, NF provides high rejection of multivalent ions and low rejection of monovalent ions (TheEngineersPerspectives, 2023). It is a robust technology for water softening and metals removal and is designed to remove contaminants as small as 0.001 µm.

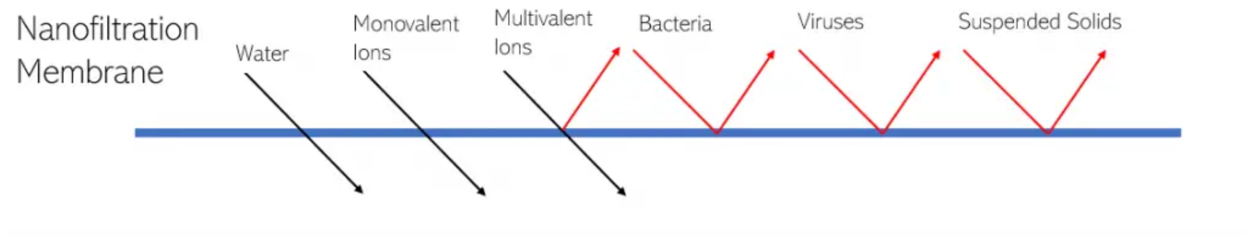
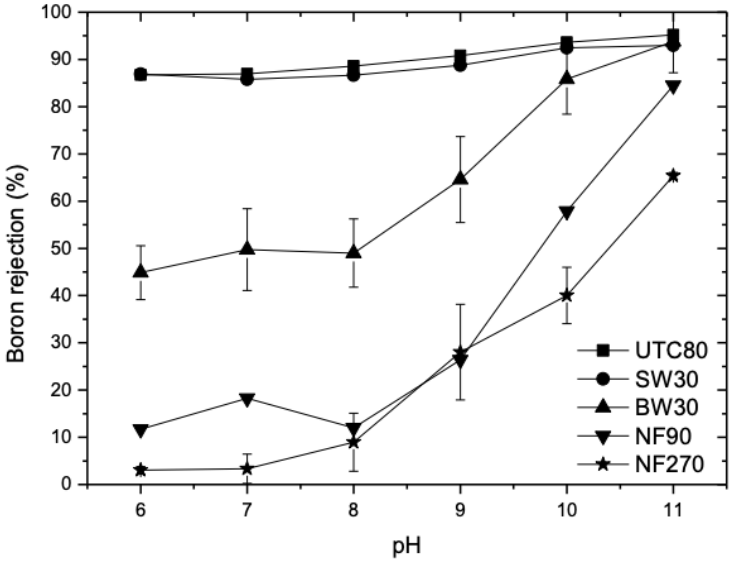


Figure 4 - The NF process

Source: (PuretecWater, 2023)

The factor that impacts boron removal the most by NF membranes is the PH of feedwater. Studies indicate that higher PH solution improves boron rejection overall, as shown in the graph 8. The boron element might be efficiently removed on reverse osmosis/nanofiltration membranes only at a shifted pH, close to 11, reaching up to 90% under certain operational conditions. Additionally, a two or three stage RO/NF system, operated under alkaline conditions should be considered to remove boron efficiently.



Graph 8 - Influence of pH in the Boron rejection

Source: (Palagonia et al., 2017)

Operating pressure of the system also affects the nanofiltration process and usually higher pressure increases the boron rejection. On the other hand, high feedwater temperature decreases the boron rejection.

A single-pass process, with only one membrane module, operates usually at a recovery between 40% - 50%. However, the Boron concentration in the permeate with this configuration (see figure below) is above the regulated limit for some applications. Thus multi-pass configuration for NF is mostly required.

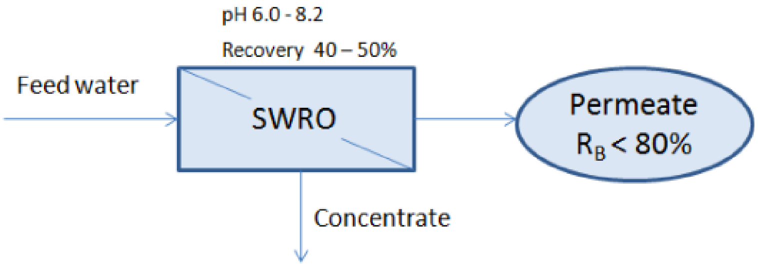


Figure 5 - RO single-pass configuration

Source: (TU, 2014)

The permeate boron concentration is considered the most important factor in the process' analysis, since the NF permeate is supposed to be discarded directly to the environment. The performance parameters are the same as the ones described before in the Nanofiltration section.

3.3. Electrochemical process

An electrochemical process is based on the application of an electric potential gradient as the driving force of ion transportation, in which cations and anions migrate through the respective ion exchange membrane towards the corresponding electrode, as shown in figure 6. The separation then occurs with the transport of cations to the negatively charged cathode, while the anions migrate toward the positively charged anode, demineralizing the feed solution.

Ion exchange membranes are porous membranes that have a charge, with the property of only allowing cations or anions to pass through. As an advantage, these processes have a higher rate of elimination and a greater concentration factor than the pressure driven membrane separation (KURUMATANI and KITAURA, 2007). It is an important separation method today, used for removal of charged components from solutions such as for producing potable water.

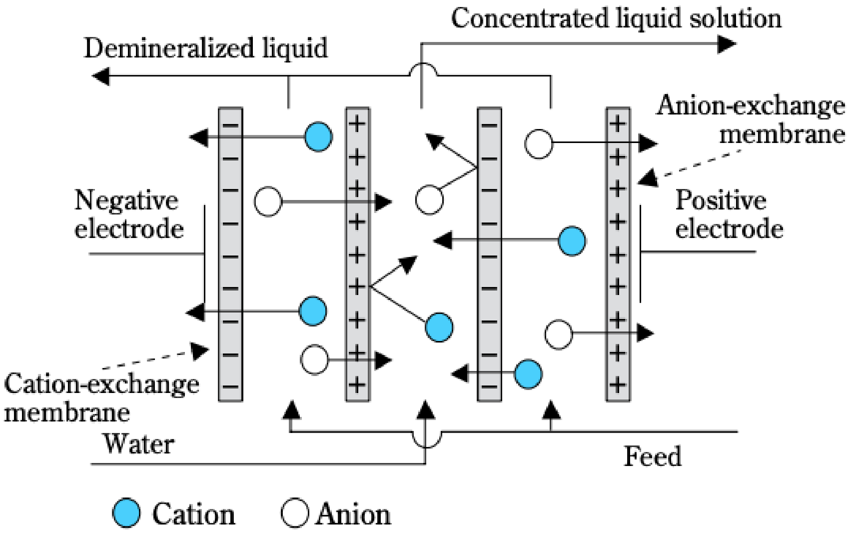


Figure 6 - The EQ process

Source: (KURUMATANI and KITAURA, 2007)

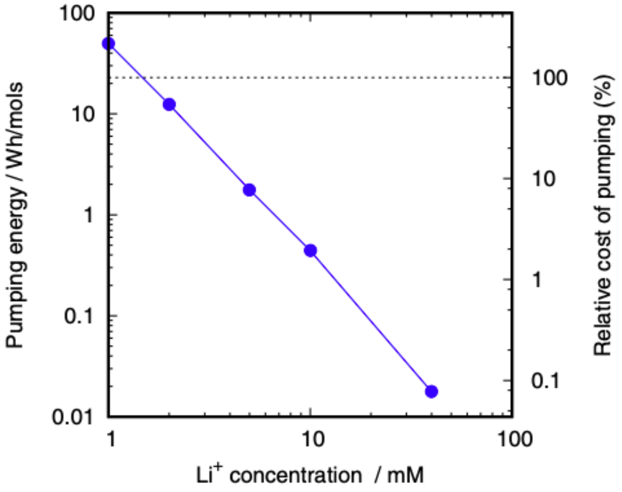
The development of a monovalent ion exchange membrane, which separates monovalent ions from divalent ions, is extremely important for the application of ED to extract lithium from salt-lake brine or seawater.

Electrochemical ion-separation processes have emerged as a promising and effective methodology for lithium capture, exhibiting outstanding performance in terms of Li recovery capacities, tunability, cyclic efficiency, reversibility, and selectivity. Overall, there are three main categories of ELiCs according to their basis of separation: electrodialysis (ED) is an electro membrane-based process, capacitive deionization (CDI) is membrane enhanced battery-based and electrochemically switchable ion exchange (ESIX) as a battery-based.

ESIX is simple, rapid, easy to operate, and shows low energy consumption with high selectivity. It isolates Li from the coexisting ions in the source solution and concentrates it in the release solution. Li is captured and subsequently released by applying potentials in the range of 0.2 to 1.2 V and then reversing the potential. The recovery of Li or any other elements from a very low concentration solution can be overcome by having a higher electrode surface area with a stack of smaller electrode pairs of working and counter electrodes arranged in an array, rather than a single electrode with a larger area. In order to obtain a high concentration of Li in the final product, it is important to keep the volume of the recovered solution as low as possible. Studies indicate that λ-MnO2/Pt system was effective for recovery of Li at concentrations higher than 10 mM, while it was completely ineffective at concentrations below 0.1 mM.

Palagonia et al. (2020) indicated that the captured lithium increases linearly with the flow rate, up to a saturation value, which depends on the current applied. The flow rate at which saturation takes place decreases by decreasing the current. Palagonia et al. (2017) observed that a saturation molar flux exists, whose value is weakly dependent on the concentration of lithium and equal to 5-6 μmol/min.

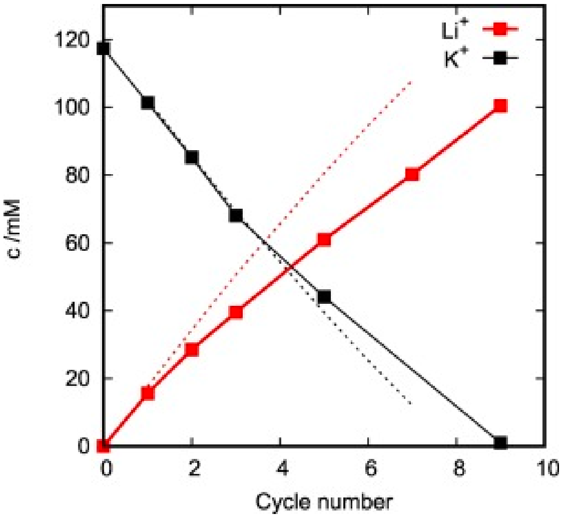
According to the graph below, using a source solution with a low concentration of lithium chloride makes the process less economically convenient. The pumping energy depends on the lithium brine concentration, as it roughly decreases with the square of the brine concentration value (PALAGONIA et al., 2017).



Graph 9 - Pumping energy vs Li concentration for EQ process

Source: (Palagonia et al., 2017)

It is important to notice that the source solution is changed every cycle, while the same recovery solution is used for consecutive cycles, so that its concentration progressively increases. Thus the bigger the number of cycles, highest the final concentration of Li in the recovery solution, as stated in the graph 10.



Graph 10 - Number of cycles vs Li concentration for EQ process

Source: (Palagonia et al., 2017)

The performance of ELiCs is assessed by different parameters such as the Li recovery ratio, separation coefficient of Li toward co-existing ions in the feed solution and the separation efficiency:

- The percentage of Li recovered is found by the difference of initial and final concentrations of Li+ in the concentrate chamber compared to the initial volume and concentration of Li+ in dilute chamber as shown in equation x: determines the amount of Li+ recovered from the source solution per unit mass of the electrode material

$$R_{Li+}\% = \frac{V_c(C^f_{Li,c} - C^0_{Li,c})}{V_d(C^0_{Li,d})} \times 100 \qquad (7)$$

- The separation factor of Li toward the co-existing ions represents the enhancement of Li concentration by recovery process, as well as a comparison of Li purity in the recovery and in source solution, shown in equation 8, where C_{Li} is the molar concentration of Li in the recovery solution and C_M represents the molar concentration of coexisting cations (e.g., Na+, K+, Mg2+ or Ca2+) in the source solution.

$$Separation\ Factor_{Li} = \frac{(C_{Li}/C_M)_{Recovery}}{(C_{Li}/C_M)_0} \qquad (8)$$

- The separation efficiency refers to the difference of initial and final concentration of Li+ with respect to the initial concentration of Li+ in the dilute chamber, as shown in equation 9:

$$Separation\ efficiency_{Li+}\% = \frac{(C^0_{Li,d} - C^f_{Li,d})}{C^0_{Li,d}} \times 100 \qquad (9)$$

PART IV - Methodology

4.1. Economic assessment structure

The net present value (NPV) was chosen as a major comprehensive measure of financial feasibility assessment of the project since it is the most practical method used. The project's NPV is defined by the following equation, in which $y_{NPV,0}$ is the NPV related to $\tau = 0$, $CF_{tot,\tau}$ is the total cash flows in period τ, i_D is the discount rate (opportunity cost) and T the number of years of the project's lifetime.

$$y_{\mathrm{NPV},0}(T, i_{\mathrm{D}}) = \sum_{\tau=1}^{T} \mathrm{CF}_{\mathrm{tot},\tau}(1 + i_{\mathrm{D}})^{-\tau} \qquad (10)$$

The cashflow structure of the project was divided into nine groups: Revenue, Investment cost, Material cost, Operation and maintenance cost, Energy cost, Transportation cost, Technology decommissioning cost/reuse cost, Labor cost and Depreciation cost. For each group, an estimation of the income or cost has to be made per year to finally find the resulting NPV of the project. These estimations are based on the literature review, market data and expertise of the professionals involved in the project.

Cash flow groups \ years	**NPV**	**0**	**1**	**2**	**3**	**4**	**5**	**…**	**n**
Revenue									
Investment cost									
Energy cost									
Transport cost									
Depreciation cost									
Materials cost									
Operation and maintenance cost									
Technology decommissioning /reuse cost									
Labor cost									
Project NPV									

Table 7 - NPV structure assessment

Source: Elaborated by the author

4.2. Risk assessment structure

A network was built by connecting the different variables used in technological risk assessment, based on peer-reviewed publications on the energy sector, mainly related to technical, environmental and economic risks. The resulting variables defined were divided into technical parameters variables (predefined variables), fluid parameter variables (related to the produced water quality), system variables (design parameters), consequence variables (derivative from the other parameters), economic variables and environmental variables, that are external parameters.

System parameters	**Technical**	influx feed water (m3/h) Operating hours per year (h/year) Temperature (°C) Lifetime (year) Water pH Minimun water treated share
	Design	n of RO stages n of RO membrane modules RO module flow (m3/h) RO membrane permeate share (%) Li rejection RO membrane (%) Bo rejection RO membrane (%) n of NF stages n of NF membrane modules NF Material surface area (m2) NF membrane permeate share (%) Bo rejection NF membrane (%) Li separation efficiency EQ (%) Pump efficiency (%) Pumping pressure (atm) EQ energy consumption

		Moles of electrons reacting to produce a mole of product
		Magnitude of electric charge per mole of electrons (10^4 C/mol)
		Current efficiency (%)
		Cell operating voltage (V)
	Consequence parameters	Lithium output rate (kg/m3)
		Boron concentration in disposed water (g/L)
		Energy consumption (kWh/m3)
External Parameters	**Fluid parameter**	Lithium concentration in produced water
		Boron concentration in produced water
	Environmental	Environmental legislative penalty
		Limit of Boron in disposed water
	Economical	Lithium price
		Electrical energy price
		Wages
		Product and by-product market
		Price of RO membrane module
		Price of NF membrane module
		Price of EQ cell
		Price of tank
		Price of pump
		Minimum attractive rate of return

Table 8 - Risk assessment structure

Source: Elaborated by the author

Each of these parameters influences the cash flows of the project and thus the uncertainty concerning its value represents a risk for the project performance and economical viability. The system's technical parameters however, were treated as fixed predefined variables given by the company, describing the operating conditions of the plant for the project's execution, as stated in the table below:

Technical parameters	**Value**	**Unit**
influx feed water	1,496.31	m^3/h
Operating hours per year	8,200	h/year
Temperature	25	(°C)
Lifetime	20	years

Water pH	7.5	
Minimum water treated share	80	%

Table 9 - Predefined variables

Source: Elaborated by the author

The other parameters, on the other hand, can vary from a small (more certain) to large range (very uncertain), depending on the amount of information already available in the project's design specification. Moreover, some of the input variables provoke a slight variation in the output parameters while others vary the output more abruptly. Before applying the Monte Carlo Simulation (MCS) technique, it's advisable to conduct a sensitivity analysis on the deterministic model to prioritize model input variables based on their influence (ARNOLD; YILDIZ, 2015).

For the design parameters, once the total capacity of the plant in terms of feed flow is already given, some of the design requirements considering 100% operating rate can be derived from it, such as the number of stages, equipment and material required for building the plant. Those parameters should not vary in the analysis, otherwise the capacity of the plant varies too. Other design parameters, however, such as the EQ process efficiency, the RO and NF rejection rate and energy consumption are very uncertain yet at this level of the project, affecting the cash flows and causing risks for the NPV projection. Their values thus vary from a possible range found in the literature and on previous similar projects and studies.

The consequence parameters, as the name suggests, depend on other parameters, so it will not be the primary source of the risks related to the project. The external parameters do affect the cash flows projection, however it is not possible to control them, their values are given by the economical, legal and environmental forces and they also vary between a more likely interval known based on historical data and researches.

There are 9 input variables that were selected as the primary sources of risks, impacting the other variables and, consequently, the cash flows of the project. They are all independent parameters, whose range of possible values is known and considered uniform for this analysis. The risks related to each of these variables are presented in table 10.

Risk	Risk Category	Input parameters	min	max
Variation of this parameters impacts directly the NPV	External risk	C,Li in the feed water (mg/L)	40	400
		Lithium price (US dollars)	13	85
	Technology risk	EQ Lithium separation efficiency (%)	70	90
		RO Lithium Rejection rate (%)	95	99
		O & M cost (% of investment cost)	10	30
		Pump Efficiency (%)	70	90
Variation of this parameters impacts directly the Boron removal	External risk	C,Bo in the feed wate (mg/L)	40	700
	Technology risk	RO Boron Rejection Rate	70	90
		NF Boron Rejection Rate	95	99

Table 10 - Risk parameters

Source: Elaborated by the author

4.3. Data collection

In order to proceed with the risk-economic analysis of the project, data concerning the risk variables and cash flow projections need to be collected from different sources. Once it is an innovative technology system, historical data is not always available in the literature. However, similar lithium and boron extraction systems for produced water or desalinization with membrane and electrode based technologies are a good basis of comparison. Data provided by the company was also used for the analysis, as well as expert judgment from different people involved in the project so far.

4.4. Cash flows projection

For the cash flow projection, the calculation of each cost and the revenue were made repeatedly, changing the parameters values according to the specified range in which they probably are as uniform variables. Monte Carlo Simulations were carried out with 1,000 sample runs each with Microsoft EXCEL, in order to find the probability distribution of each cash flow group and then of the project's NPV. In this section, it will be described how each cash flow group was estimated, based on different methodologies and approaches.

4.4.1. Investment Cost

Once the project already has a relevant quantity of design specifications, a more accurate capital cost estimation can be performed in the early stage by using the Factorial Method, instead of the "six-tenths rule" (both presented in topic 2.5 of this thesis), which gives only an order of magnitude of the cost. Thus the following steps are necessary to estimate the total investment cost:

a. List and size major equipment items;
b. Estimate the purchased cost of the major equipment items;
c. Calculate the fixed capital investment using the factors given in table 6;
d. Estimate the working capital as a percentage of 10 to 20% of the fixed investment;
e. Calculate the total investment cost of the project, by adding the fixed and working capital costs.

Major equipment items (a)

The extraction system of the project consists of 3 main systems: the pretreatment by Reverse Osmosis, the Boron extraction system by Nanofiltration and the Lithium extraction system by Electrochemical process, as shown in figure 7.

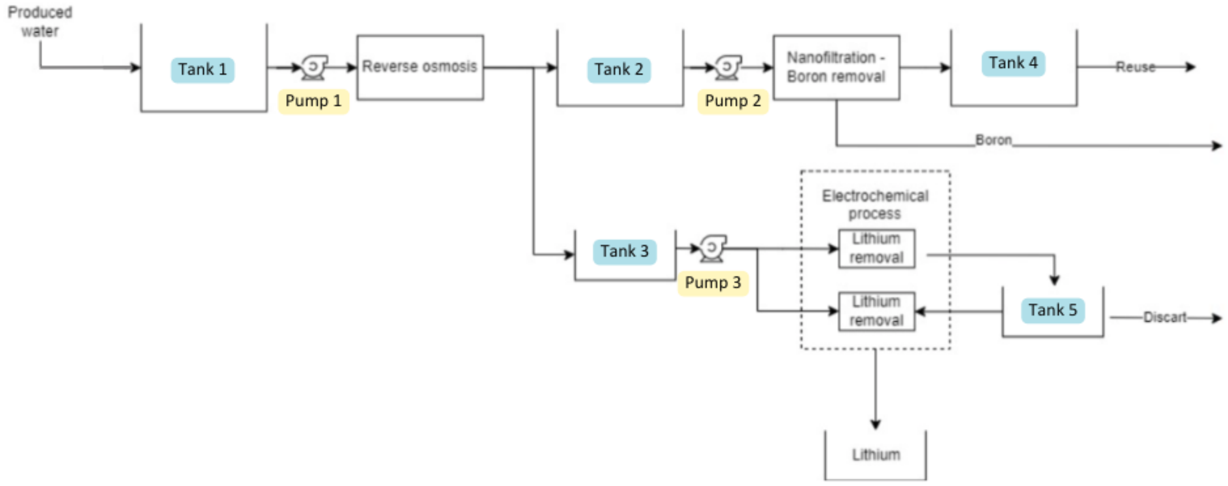


Figure 7 - Fluxogram of the system's design

Source: Elaborated by the author

For the RO and NF processes, the major equipments necessary are the high-pressure pump and the membrane modules. For the EQ process, the main equipments are the peristaltic pump to inject the solution into the electrochemical cell, which is composed of the electrode, counter-electrode, power supply, electrolyte solution, among other elements that, in the current stage of the project, are not defined yet. Thus for the EQ process, a specific model proposed by Stinn and Anllanore (2020) was used in order to estimate its implied capital cost, based on the operating conditions.

Estimating the purchased cost of equipments (b)

The costs of the major equipments were estimated based on online research and different methodologies found in the literature. For the RO system, the main capital investment is based on the number of membrane modules necessary to filter the feed water, generating 80% of permeate and 20% of concentrate. The module found has a capacity of 3.6m³/h and a permeate share of 15% for a cost of approximately 400$ dollars (Dupont, 2023). The table below shows the number of modules and stages necessary to filter the produced water and reach 80% of feedwater recovery as permeate.

Stage	Inflow (m³)	Permeate (m³)	Concentrate (m³)	Number of modules	Modules costs (USD)
1	1496	224	1,272	415.6	166,256.48
2	1272	191	1,081	353.3	141,318.01
3	1081	162	919	300.3	120,120.31
4	919	138	781	255.3	102,102.26
5	781	117	664	217.0	86,786.92
6	664	100	564	184.4	73,768.88
7	564	85	480	156.8	62,703.55
8	480	72	408	133.2	53,298.02
9	408	61	347	113.3	45,303.32
10	347	52	295	96.3	38,507.82
Total		1,202	295	2,225.4	890,165.57

Table 11 - Reverse osmosis system cost

Source: Elaborated by the author

Around 10 stages and 2.226 modules are necessary for the system, which results in 890.400,00 USD dollars in membrane investment.

For the NF system, four different types of modules were proposed by the design team of the project, each with a 35 m² area to support a 3.6m³/h flow. The prices for each of these modules, as well as its composition, are stated in the table below:

Description	**Quantity**	**Cost US**	**Reference**
ZIF-8 (commercial)		**677.39**	
Membrane module	1.00	400.00	DuPont
Polyethyleneimine	0.11 g/m²	4.41	SigmaAldrich
ZIF-8 (Bazolite Z1200)	0.11 g/m²	260.73	SigmaAldrich
Methanol	10.00 ml/m²	12.25	SigmaAldrich
ZIF-8 (home made)		**435.25**	
Membrane module	1.00	400.00	DuPont
Polyethyleneimine	0.11 g/m²	4.41	SigmaAldrich
2-metilimidazole	0.74 g/m²	8.82	SigmaAldrich
Zn(NO3)2.6H2O	0.37 g/m²	2.22	SigmaAldrich
Methanol	16.16 ml/m²	19.80	SigmaAldrich
ZIF-67		**440.92**	
Membrane module	1.00	400.00	DuPont
Polyethyleneimine	0.11 g/m²	4.41	SigmaAldrich
2-metilimidazole	0.74 g/m²	8.82	SigmaAldrich
Co(NO3)2.6H2O	0.37 g/m²	7.89	SigmaAldrich
Methanol	16.16 ml/m²	19.80	SigmaAldrich
Grafeno		**602.51**	
Membrane module	1.00	400.00	DuPont
Polyethyleneimine	0.11 g/m²	4.41	SigmaAldrich
2-metilimidazole	0.74 g/m²	8.82	SigmaAldrich
Co(NO3)2.6H2O	0.37 g/m²	7.89	SigmaAldrich
Methanol	16.16 ml/m²	19.80	SigmaAldrich
Reduced graphene oxide	0.03 g/m²	161.58	SigmaAldrich

Average	**539.02**

Table 12 - Nanofiltration modules cost

Source: Elaborated by the author

In order to obtain a total of 80% permeate share and a permeate with very small Boron concentration, it was chosen a multi-passage configuration for the NF process, in which the permeate passes through the membrane filtration 3 times. In the first step there are 20 stages (i.e., the concentrate is redirected 20 times into another membrane module), in the second step, there are 15 stages and in the third, more 15 stages, resulting in a final 20% share concentrate and 80% share permeate. Each step is presented on the following tables:

Stage	Inflow (m³)	Permeate (m³)	Concentrate (m³)	Number of modules
1	1202	180	1,021	334
2	1021	153	868	284
3	868	130	738	241
4	738	111	627	205
5	627	94	533	174
6	533	80	453	148
7	453	68	385	126
8	385	58	327	107
9	327	49	278	91
10	278	42	237	77
11	237	35	201	66
12	201	30	171	56
13	171	26	145	47
14	145	22	124	40
15	124	19	105	34
16	105	16	89	29
17	89	13	76	25
18	76	11	64	21
19	64	10	55	18
20	55	8	47	15
Total		**1,155**	**47**	**2,139**

Table 13 - Step 1 of the NF process

Source: Elaborated by the author

Stage	Inflow (m³)	Permeate (m³)	Concentrate (m³)	Number of modules
1	1155	173	982	321
2	982	147	835	273
3	835	125	709	232
4	709	106	603	197
5	603	90	513	167
6	513	77	436	142
7	436	65	370	121
8	370	56	315	103
9	315	47	268	87
10	268	40	227	74
11	227	34	193	63
12	193	29	164	54
13	164	25	140	46
14	140	21	119	39
15	119	18	101	33
Total		**1,054**	**101**	1,952

Table 14 - Step 2 of the NF process

Source: Elaborated by the author

Stage	Inflow (m³)	Permeate (m³)	Concentrate (m³)	Number of modules
1	1054	158	896	293
2	896	134	762	249
3	762	114	647	212
4	647	97	550	180
5	550	83	468	153
6	468	70	398	130
7	398	60	338	110
8	338	51	287	94
9	287	43	244	80
10	244	37	208	68
11	208	31	176	58

12	176	26	150	49
13	150	22	127	42
14	127	19	108	35
15	108	16	92	30
Total		**962**	**92**	**1,782**

Table 15 - Step 3 of the NF process

Source: Elaborated by the author

Each membrane module has a permeate share of 15% for each module and in total around 5,874 membrane modules are needed for the NF process, resulting in the following total cost for each of these four membranes:

Description	Quantity	Cost
ZIF-8 (commercial)	5,874	\$3,978,979
ZIF-8 (home made)	5,874	\$2,556,666
ZIF-67	5,874	\$2,589,989
Grafeno	5,874	\$3,539,124
Average cost		**\$3,166,189**

Table 16 - Total NF material cost by membrane type

Source: Elaborated by the author

For the EQ process, the capital cost calculation was based on the model proposed by Stinn and Anllanore (2020), that described the direct capital cost of the electrolysis process by considering relevant operating parameters divided in three main categories: front end processing (F), electrolysis and product handling (E) and rectifier (R). The total capital investment cost for an electrochemical process (C) is then described by the following equation:

$$C = F + E + R \tag{11}$$

The front-end processing capital cost (F) is based on the installed capacity (P) in tonnes and the electrolysis temperature (T) in °C, as the following equation:

$$F = \frac{51010}{1+e^{-0.003823*(T-631)}} P^{0.8} \tag{12}$$

The capital cost associated with the electrolytic and metal recovery process (E) depends on the number of electrolysers required, which is a function of the total installed production rate (p) in kg/s, product molar mass (M) in kg/mol, current density (j) in A/m2, number of electrons per mole of product (z), current efficiency (ε) and electrode or cathode area (A) in m2, where *f* is the magnitude of electric charge per mole of electrons in C/mol.

$$F = \frac{5634000}{1+e^{-0.007813*(T-349)}} \left(\frac{pzf}{jA\varepsilon M}\right)^{0.9} \qquad (13)$$

Finally, the capital cost of the rectifier (R) that is considered a function of installed power capacity (Q) in MW and cell operating voltage (V) in volts, where N is the number of rectifier lines:

$$R = 750000QV^{0.15}N^{0.5} \qquad (14)$$

The resulting scaling law is then proposed for the overall capital cost estimates for the electrochemical process in 2018 US dollars:

$$C = \frac{51010}{1+e^{-0.003823*(T-631)}}P^{0.8} + \frac{5634000}{1+e^{-0.007813*(T-349)}} \left(\frac{pzf}{jA\varepsilon M}\right)^{0.9} + 750000QV^{0.15}N^{0.5} \qquad (15)$$

For the current project, the following input parameters of the model described were used as an estimate, in order to find the total capital cost of the EQ process:

	Parameter	**Unit**	**Value**
P	Installed yearly production capacity	[tonnes/year]	121 - 3,926
p	Total installed production rate	[kg/s]	0.004 - 0,133
z	Moles of electrons reacting to produce a mole of product	[moles]	1
F	Magnitude of electric charge per mole of electrons	[10^4 C/mol]	9.65
j	Current density	[A/m²]	9 ; 1.8
A	Electrode (for metals, cathode) area	[m²]	30 ; 60
e	Current efficiency		0.90
M	Electrolysis product molar mass	[kg/mol]	0.006941
Q	Installed power capacity	[MW]	0.04 - 0.47
V	Cell operating voltage	[V]	0.96
N	Number of rectifier lines		1 ; 2

T	Temperature	[°C]	25.00

Table 17 - Input parameters for the EQ capital cost model

Source: Elaborated by the author

The installed yearly production capacity and rate varies according to the different parameters, such as the feed water flux, the concentration of Lithium in it, the efficiency of the system to extract Lithium and the operating hours. Once the concentration and the efficiency of the systems are considered variables in this analysis, the installed capacity and rate also varies between the range indicated in the table above. The total installed power capacity of the EQ process also varies due to the same reason.

These costs refer to the total installed cost of the EQ facility, in 2018 US dollars. In order to translate them for today values, it was used the price index for the chemical industry CEPCI (Chemical Engineering Plant Cost Index):

$$Cost\ in\ year\ A\ =\ Cost\ in\ year\ B\ \times \frac{Cost\ index\ in\ year\ A}{Cost\ index\ in\ year\ B} \qquad (16)$$

The CEPCI in 2018 was of 603 and in 2022 of 810 (ChemicalEngineering, 2023), resulting in a correction factor of 1,34 and an updated EQ capital cost ranging from 348,297 - 6,750,957 US dollars, with an average of 2,340,952 USD dollars.

The cost of tanks and pumps were based on the methodology proposed by Towler and Sinnot (2021), using the equation 17, in which the values of the coefficients a, b and exponent n are given based on historical data correlation and S refers to the size of the tank:

$$C_{eq} = a\ +\ b\ \times S^{n} \qquad (17)$$

Tank 1 supports one hour storage of the feed water, resulting in a 1,496 m³ size tank. Tank 2 stores the permeate generated after the RO process, also 1 hour capacity, resulting in a 1,202 m³ tank. Tank 3 stores the concentrate generated after the RO process, with 2 hours storage capacity, resulting in a 589 m³ size. Tank 4 stores the final treated water after the NF process, with an 1 hour capacity, resulting in 965 m³ size. Tank 5 stores the feed solution generated after the EQ process, also with 1 hour capacity, resulting in a 295 m³ size tank. The estimated costs of the tanks using equation 17 are stated in table below:

Tanks	**Size (m³)**	**a**	**b**	**n**	**a + b x S^n**
Tank 1	1,496	53000	2400	0.6	245,852
Tank 2	1,202	53000	2400	0.6	222,081
Tank 3	589	53000	2400	0.6	163,244
Tank 4	965	53000	2400	0.6	201,240
Tank 5	295	53000	2400	0.6	125,734
Total					**958,150**

Table 18 - Tank pricing

Source: Elaborated by the author

For the high-pressure pump costs, the equation depends not on the size, but on the feed water flow (F) through the pumps, as per below:

$$C_{eq} = a + b \times F^{n} \qquad (18)$$

The feed water flux in pump 1 is a given parameter by the company of 1.496,31 m³/h, equivalent to 515.64 L/s. The flow in pump 2 is the permeate generated by the RO system, which is 80% of the system's feed water, after the 10 membrane stages, resulting in 1.201,72 m³/h (or 333,81 L/s). Lastly the flow in pump 3 is the concentrate generated after the RO, which is the 20% rejected to the EQ process, resulting in 294,58 m³/h (or 81,83 L/s).

Pumps	**Flow (L/s)**	**a**	**b**	**n**	**a + b x F^n**
Pump 1	415.64	3300	48	1.2	69,935
Pump 2	333.81	3300	48	1.2	54,520
Pump 3	81.83	3300	48	1.2	12,778
Total					**137,234**

Table 19 - Pump pricing

Source: Elaborated by the author

These costs found are on US Gulf Coast Basis prices of 2006. In order to translate them for today values, it was used the index price shown in equation 16, with CEPCI in 2006 of 499 and in 2022 of 810 (ChemichalEngineering, 2022), resulting in a correction factor of 1,62 and an updated cost of tanks and pumps of 1,778,079 US dollars.

Calculate the fixed capital using the factorial method ©

Following the factorial method detailed in Towler (2006), as shown in table 6, the factors that are more related with the project are the ones of fluids, concerning equipment erection, piping, instrumentation and control and electrical, as ISBL costs. The factors civil, structures and buildings and lagging and paint were not considered, once the system will be built in an already existing plant. Furthermore, the total fixed capital cost is presented by:

$$FC\ Cost = C_{eq} \times (1 + f_{ISBL}) \times (1 + f_{OSBL}) \times (1 + f_{Design\ and\ engineering} + f_{Contigency})$$

$$FC\ Cost = C_{eq} \times (1 + 1.6) + (1 + 0.3) + (1 + 0.4)$$

$$FC\ Cost = C_{eq} \times 4.732 \qquad (19)$$

In which,

$$f_{ISBL} = f_{equipment\ erection} + f_{piping} + f_{instrumentation\ and\ control} + f_{electrical} = 0.3 + 0.8 + 0.3 + 0.2 = 1.6$$

$$f_{OSBL} = 0.3$$

$$f_{Design\ and\ engineering} = 0.3$$

$$f_{Contigency} = 0.1$$

Once the EQ capital cost found using the model proposed by Stinn and Anllanore (2020) already considers the installation cost of the facility, it will not be considered in this step of the calculation. So the costs of equipments that have to be corrected by the fixed capital cost factor of 4.732 (equation 19) are the costs of tanks, pumps and the membrane modules for the RO and NF processes, as shown below:

Description	Average equipment cost [US$]	Average FC cost [US$]
Pumps	222,765	1,054,122

Tanks	1,555,314	7,359,746
RO membrane modules	892,400	4,222,837
NF membrane modules	3,277,258	15,507,986
EQ cell		2,337,775
Total		**30,482,465**

Table 20 - Fixed capital costs

Source: Elaborated by the author

Estimating the working capital cost (d)

Working capital is the money needed in addition to the fixed capital cost, so the system can start running. It typically includes cash on hand to pay the initial cost of production of the plant, varying from 10% to 20% of the total fixed capital cost, as stated by Towler (2006). An average of 15% was considered for the current analysis, as below:

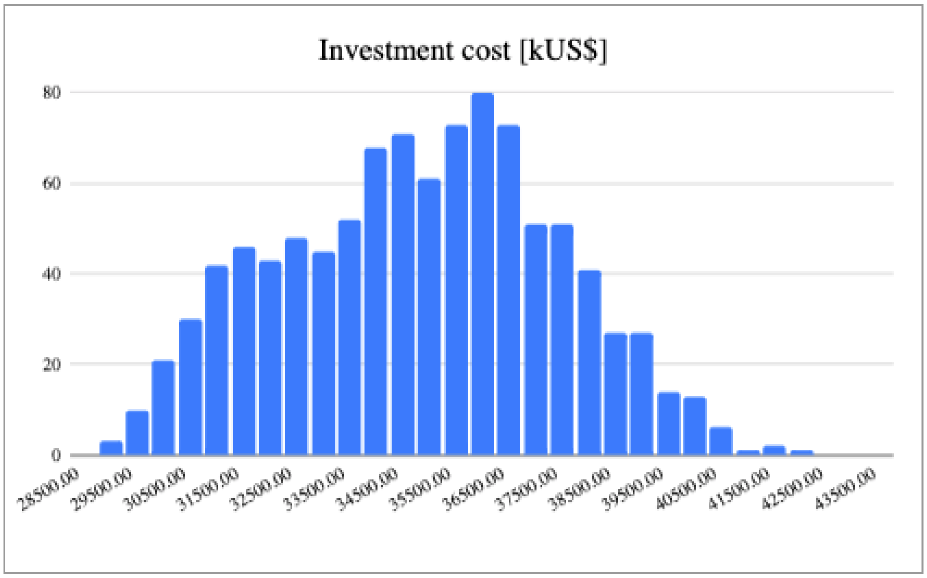
$$Working\ capital\ = 15\% \times\ FC\ Cost \qquad (20)$$

Total investment cost (e)

The total investment cost is then the sum of the total fixed capital cost and the working capital cost, as below:

$$Investment\ cost\ = (FC\ cost +\ Working\ capital\ cost) = 1,15\ \times FC\ cost \qquad (21)$$

After 1.000 iterations with the parameters listed before, the resulting distribution of the investment cost is shown below:



avg	35,057
sd	2,576
1% value	29,920
99% value	40,359

Graph 11 - Distribution of the investment cost

Source: Elaborated by the author

4.4.2. Revenue Estimation

The revenue of the project is based on selling the lithium extracted from the produced water, measured by the volume of sold product times its market price. The volume of sold product was considered the total volume of extracted product, as if there would always be market demand. The volume of extracted products depends on many factors such as the inflow supported by the system, the concentration of Lithium in the source solution and on the performance of the technology on recovering Lithium from the produced water.

$$Revenue\,[US\$] = volume_{Li}\,[kg] \times price_{Li}\,[US\$/kg] \tag{22}$$

In order to find the total amount of Lithium recovered from the system it is first necessary to find the Lithium output from the RO process and then the Lithium output from the EQ process. For the RO, the total amount of Lithium recovered in the concentrate depends on the rejection rate of the membrane (i.e. how much of the salt that passes through the system is rejected into the concentrate flow, not passing through the membrane to the permeate) and also on the number of stages (i.e. how many times the concentrate flow passes through the RO membrane). The RO Lithium rejection rate ranges from 95 - 99%, according to the company's specification. As stated on table 11, the number of stages necessary in the system to result in a 20% concentrate and 80% permeate is 10, so the total amount of Lithium recovered in the final concentrate volume is given by the following equation:

$$Li_{concentrate} = (Li_{feed\ water} \times membrane\ rejection\ rate)^{10} \tag{23}$$

The total amount of Lithium in the source solution depends on the concentration of Lithium in the feed water and on the influx of the system. The feed flow is a system's capacity parameter, given by the company as 1,496.31 m^3/h. The Li concentration in the produced water varies according to different geological factors. According to an analysis given by the company, the range from which the concentration can vary is between 40 - 400g/m^3. The total amount of Lithium in the feed water is thus given by:

$$Li_{feed\ water} = (Li\ concentration_{feed\ water} \times inflow_{feed\ water}) \tag{24}$$

After the RO process, the concentrate flows to the EQ process, where the Lithium is separated from the rest of the salts present in the concentrate solution. EQ Lithium separation efficiency ranges from 33-99% (table 20). The total amount of Lithium in the EQ recovery solution thus is expressed as below:

$$Li_{recovery\ solution} = (Li_{concentrate} \times Li\ separation\ efficiency_{EQ}) \tag{25}$$

Grouping the equations x, x and x it is possible to find the final amount of Lithium recovered by the system as:

$$Li_{recovery\ solution} = (((Li\ concentration_{feed\ water} \times inflow_{feed\ water}) \times membrane\ rejection\ rate)^{10} \times Li\ separation\ efficiency_{EQ}) \tag{26}$$

Finally, the Revenue per year of each product was estimated by the resulting formula:

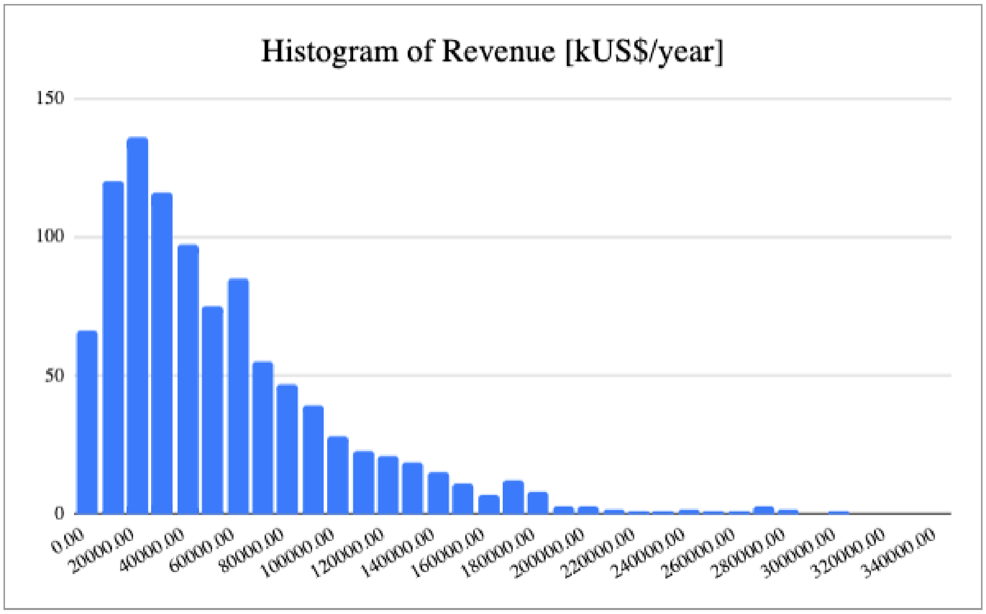
$$Yearly\ revenue = (Li_{recovery\ solution} \times price_{Li} \times operating\ hours\ per\ year \times stream\ factor) \tag{27}$$

After the 1,000 iterations using the variable values stated in table x as uniform, the following distribution was found for the yearly revenue:

Parameter	**Unit**	**Value**	**Reference**
Feed water flow	[m^3/h]	1,496	Given by the company
Feed water Li concentration	[g/m^3]	3 - 400	Given by the company
RO Li rejection rate	[%]	95 - 99	(DuPont, 2023)
EQ Li separation efficiency	[%]	33 - 99	(LI et al., 2019), (ZAVAHIR et al., 2021); (BATTISTEL et al., 2020)
Li price	[US$/kg]	13 - 85	(Bloomberg, 2023)
Operating hours	[h/year]	8200	Company

Table 21 - Input parameters for the revenue estimation

Source: Elaborated by the author



avg	59,615
sd	48,467
1% value	4,195
99% value	230,375

Graph 11 - Distribution of the revenue

Source: Elaborated by the author

4.4.3. Other costs

Energy cost

The energy cost of the system is based mainly on the pumps' energy consumption and on the electrochemical process, which also consumes electric power. In total there are three pumps in the system: one for the RO process (1), other for the NF process (2) and the last one for the EQ process (3). For pumps 1 and 2, the energy consumption was calculated based on the pump power found by the following equation:

$$Power\ [W] = \frac{Pressure\ [Pa] \times Flow\ [m3/s]}{Efficiency\ [\%]} \tag{28}$$

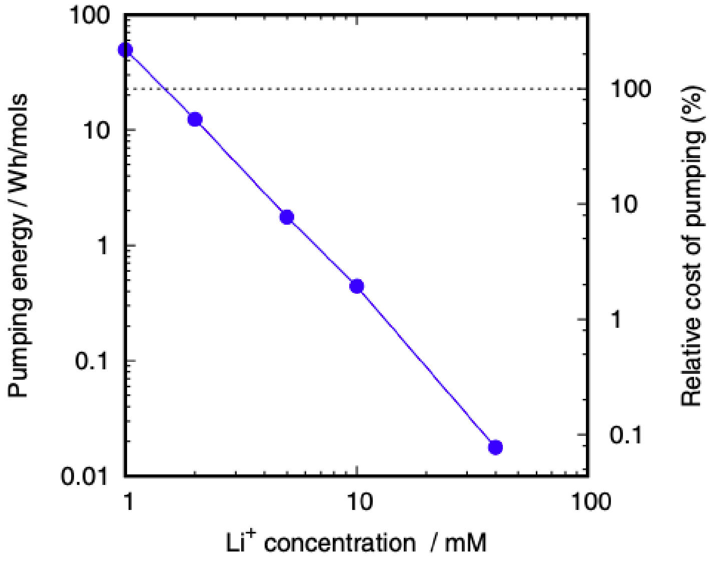
The feed water flow as well as the working pressure values for pumps 1 and 2 were pre defined as given system parameters and the pump efficiency was considered an uniform variable ranging from 70% to 90%.

Parameters	unit	Pump 1	Pump 2	Reference
Feed water flow	[m³/h]	1,496	1,202	Company
Pump pressure	[atm]	55	41	
Pump efficiency	[%]	70 - 90	70 - 90	

Table 22 - Input parameters for the energy consumption estimation

Source: Elaborated by the author

For pump 3 and the electrochemical process, the energy consumption used in the analysis was the ones found in previous studies. Palagonia et al (2017) evaluated the energy required to pump the liquid through the electrodes, which depends on the lithium brine concentration. They found that using a source solution with a low concentration of lithium chloride makes the process less economically convenient, as the energy consumption roughly decreases with the square of the brine concentration value. As stated in the graph 12, the cost of pumping is sustainable for concentrations of lithium in the source solution down to 2 mM, corresponding to 50% of the Lithium price.



Graph 12 - EQ pumping energy consumption vs Li concentration

Source: Elaborated by the author

Palagonia et al. (2020) also performed a preliminary economic analysis stating that the process is still favorable even at a concentration as low as 1 mM of LiCl, in which the cost of energy corresponds to around 30% of the Lithium price. Moreover, pumping costs can be further reduced by applying lower current and optimizing the porous structure of the electrode to decrease the hydraulic resistance of the cell.

After the RO process, the concentration of Lithium in the feed solution goes from 40-400 g/m³ up to 122-1.913g/m³ in the concentrate, which is the EQ source solution. Once the molar mass of the lithium is 6,94 g/mol, the initial Li concentration in the EQ process ranges from 17 mM to 275 mM. According to the graph, the pumping energy consumption then ranges between 0.1 and 0.01 Wh/mols for this Li concentration, with an approximation of:

$$Energy\ consumption_{Pumping}\ [Wh/mol] = 0,10611 + (-\ 0,00035) \times Concentration_{Li}\ [mM] \qquad (29)$$

In addition, electrical energy must be spent for moving Li+ from the less concentrated source solution to the more concentrated recovery solution. However, as stated by La Mantia et al (2020), this energy consumption of the electrochemical process is negligible when compared to the pumping cost. Nine cycles were performed one after the other; with 1.35 L of source solution and the release was to the same recovery solution of 5 mL, increasing the concentration progressively. The total energy consumption found was 6.1Wh/mol.

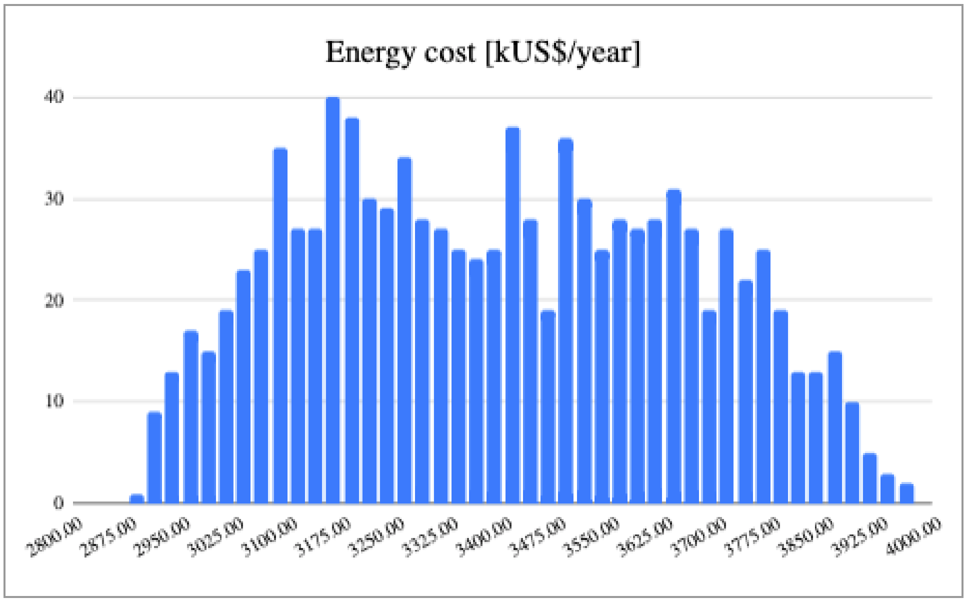
After 1,000 iterations with the parameters listed above, the following average energy consumptions were found:

Description	**Average energy consumption [kWh/m3]**
Pump 1	1.95
Pump 2	1.45
Pump 3	0.01
EQ process	0.74
Total	**4.15**

Table 23 - Average energy consumption of the system

Source: Elaborated by the author

Considering the electricity price for businesses in Malaysia of 0.128 US$/kWh, as of March 2023 (Global Petrol Prices, 2023), and operating hours of 8,200 per year, the total annual energy cost distribution has the following distribution:



avg	3,393
sd	261
1% value	2,928
99% value	3,900

Graph 13 - Energy cost distribution

Source: Elaborated by the author

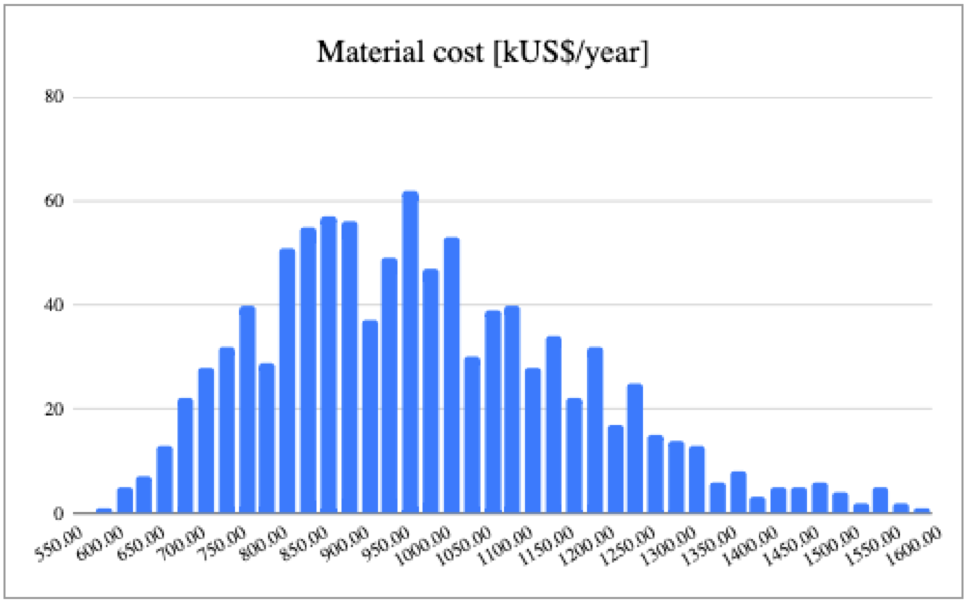
Material cost Estimation

The material cost refers to the membrane and electrode replacement necessity. In different articles, this cost is considered as 10% to 20% of the total investment cost in material for the system technology used (TAVAKKOLI et al., 2017). Using an average of 15%, after 1.000 iterations with the parameters listed previously, the following average material cost were found:

Description	Average material cost [kUS$/year]
RO	133.86
NF	144.87
EQ	280.03
Total	**558.76**

Table 24 - Average material cost

Source: Elaborated by the author



avg	977
sd	192
1% value	648
99% value	1,499

Graph 14 - Distribution of the material cost

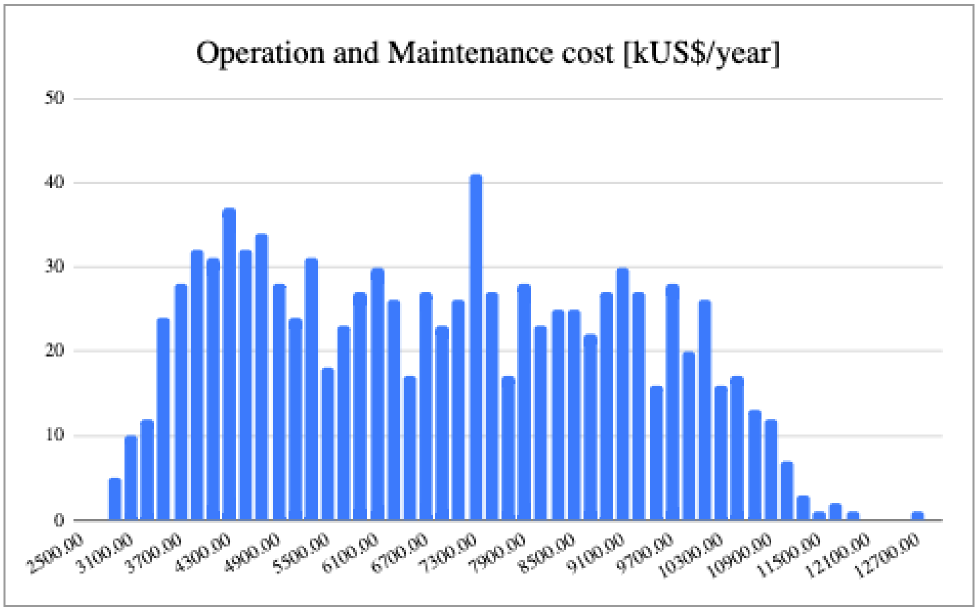
Source: Elaborated by the author

Operation and Maintenance cost

The operation and maintenance costs in this project refers to additional costs necessary to run the process such as pretreatment, spares and disposal. Produced water needs to be pretreated before entering the separation system, which typically requires chemical addition. The cost of chemicals available in the literature for MD plants is \$0.018/m3. Cost of spares refers to the cost of replacing parts needed to maintain the system operating including pumps, valves, and miscellaneous parts (cost of replacing membrane, membrane modules and electrodes is not included in this category, but in the material cost). The representative cost of spares for MD plants is assumed to be \$0.033/m3 (TAVAKKOLI et al., 2017).

Concentrate disposal is normally considered to be a major issue in the engineering design of any desalination facility (AHMED et al., 2001). Disposal costs are dependent upon the volume and chemistry of produced water as also size and location of the operation (FAKHRU'L-RAZI et al., 2009). For a typical water desalination plant, the cost of brine disposal incurs an additional 15% of the total investment cost (GLUECKSTERN; PRIEL, 1997).

In other articles, it is also common to find the approximation of maintenance cost as 10% of the capital cost (CHA-UMPONG et al., 2021). In order to make sure the maintenance cost globles all these factors, a uniform range of 10 to 30% of total investment cost was considered for this analysis, resulting in the following distribution:



avg	6,967
sd	2,240
1% value	3,200
99% value	11,269

Graph 15 - Distribution of the O&M cost

Source: Elaborated by the author

Transportation cost

The oil and gas industry usually uses different types of transportation modes, such as barges, tankers, pipelines, trucks, and railroads, to transport the extracted materials to the refineries. Most of the oil moves through pipelines for at least part of the route, to another carrier or directly to a refinery. Petroleum products then travel from the refinery to market by tank truck, railroad tank car, or pipeline (DOWNY, 2009). The cost of transportation varies by mode. Pipelines remain the cheapest and most utilized way to transport oil (Forbes, 2016). Trucking is the final mode, beside more flexible, is used over shorter distances given the higher cost.

The transportation cost depends on the distance of produced water and final products travel and it's given by the following equation. This cost was not considered in the economic analysis of the project once the company already has a transport modal operating for the oil production and the project's system would be implemented into the already existing structure.

Labor cost

The labor cost is mainly composed by the cost of operators that work in the plant, but also other general expenses related to manufacturing, such as taxes, insurance and other administrative expenses (VERRET et al., 2012). In order to estimate the cost of operators, it's first necessary to estimate the number of operators needed in the plant to ensure it runs smoothly. Alkhayat and Gerrard (1984) created a correlation between this number of operators and the number of processes in the plant based on data from major chemical companies. This correlation is given by:

$$n\ of\ operators = (6.29 + 31.7P^2 + 0.23N_{np})^{0.5} \times \frac{\#\ of\ total\ shifts\ in\ a\ year}{\#\ of\ shifts\ per\ operator} \qquad (29)$$

Where P is the number of processes handling solids and N_{np} the processes not involving solids. On average, an operator works 5 shifts per week and 49 weeks per year, which results in 245 shifts per year. Considering the plant works 3200 hours a year and one shift is 8 hours, the total number of shifts in a year is 400.

The operating system described in figure 2 has 2 processes involving handling solids, the transportation of boron and lithium, so P = 2. The processes handling fluids are the reverse osmosis, nanofiltration, electrochemical process and the disposal of the permeate solution, so N_{np} = 4. The resulting number of operators necessary then is given by:

$$n\ of\ operators = (6.29 + 31.7 \times 2^2 + 0.23 \times 4)^{0.5} \times \frac{400}{245} = 47 \qquad (29)$$

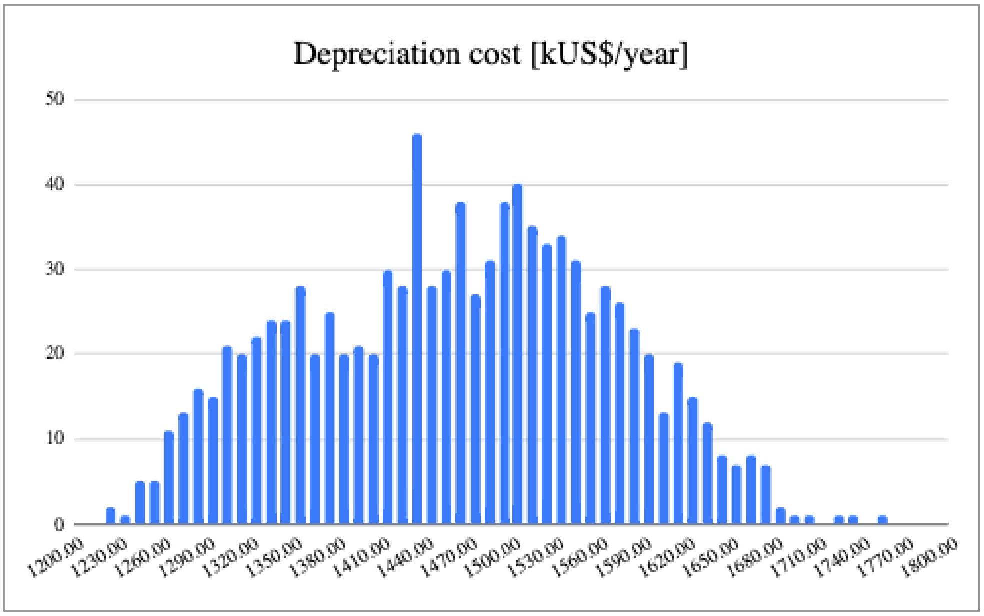
The average salary of a manufacturing employee in Malaysia is around 750 USD dollars a month, according to Take-profit.org data from June 2023. So the total annual labor cost estimation is given by:

$$Labor\ cost = 47 \times 750 \times 12 = 423,000 \text{ US\$/year} \qquad (29)$$

Depreciation cost

The depreciation cost was considered linear throughout the 20 years of the system's lifetime, with a residual value of 15%, given as:

$$Depreciation\ cost = \frac{CAPEX \times (1 - residual\ rate)}{Life\ time} \tag{30}$$



avg	1,462
sd	105
1% value	1,253
99% value	1,675

Graph 16 - Distribution of the depreciation cost

Source: Elaborated by the author

Technology decommissioning cost

The decommissioning costs refers to the expenses associated with dismantling, removing, and replacing outdated, inefficient, or no longer used equipments. These costs however were excluded based on the assumption decommissioned equipment would be repurposed where possible (PRYCE; KAPELAN; MEMON, 2022).

PART V - Results

5.1. NPV of the project

The NPV of the project was calculated considering the life time of the system of 20 years and a discount rate that would be the minimum attractive rate of return (MARR) of 10% per year, with a risk premium of 7% in relation to the current basic rate set by Malaysia's central bank of 3% (Bank Negara Malaysia, 2023). Considering the average cost found for each cash flow group in the previous section, the result presented in the table x shows a positive NPV average of the project of around 360.5 MM US$.

Cash flows [kUS$]			**years**				
Description	**Annual avg**	**NPV**	**0**	**1**	**2**	**3**	**... 20**
Revenue	59,680	508,094		54,255	49,323	44,839	8,869
Investment cost	-35,061	-35,061	-35,061				
Energy cost	-3,394	-28,892		-3,085	-2,805	-2,550	-504
Materials cost	-977	-8,315		-888	-807	-734	-145
Operation and maintenance cost	-6,963	-59,277		-6,330	-5,754	-5,231	-1,035
Labor cost	-423	-3,601		-385	-350	-318	-63
Depreciation cost	-1,462	-12,449		-1,329	-1,208	-1,099	-217
Project NPV		**360,500**	**-35,061**	**42,239**	**38,399**	**34,908**	**6,904**

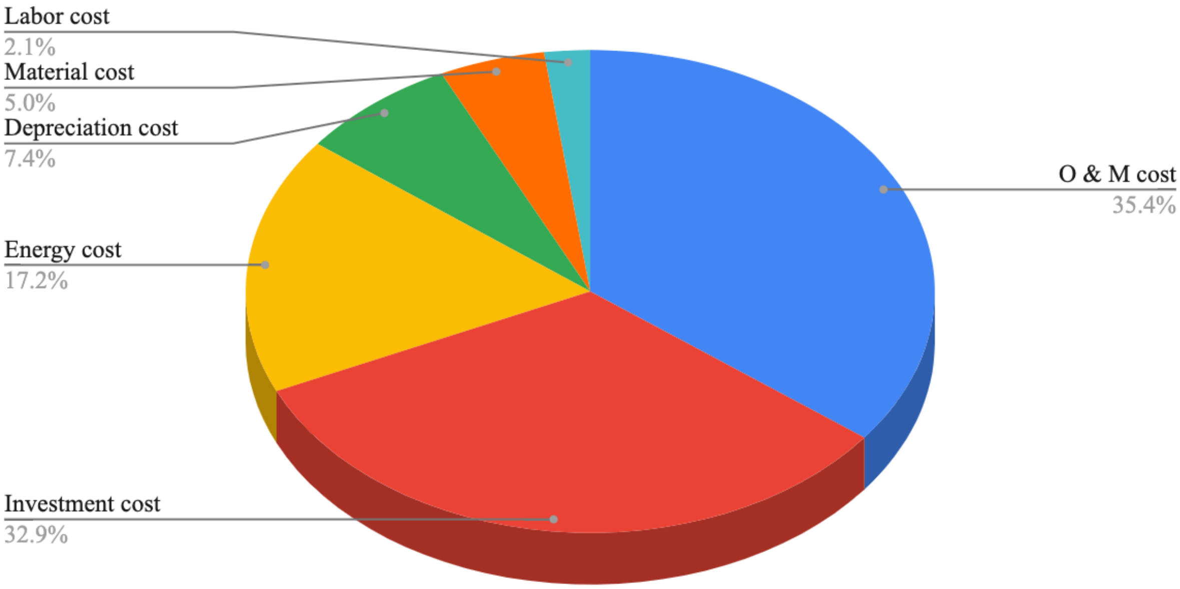
Table 25 - Average NPV of the project

Source: Elaborated by the author

When comparing the impact of each type of cost on the NPV (figure x), it is possible to see that operational and maintenance costs are the biggest ones, due to the necessity of pre-treating the produced water before it enters the system in order to avoid membrane fouling and also meeting better quality fluid characteristics. In addition, this cash flow group also includes the disposal cost of the concentrate generated in the NF process and on the EQ process. This concentrate has to be properly treated and disposed according to the regulatory requirements.

The investment cost is the second biggest cost in the NPV result, in a way that the cash flows generated by the operation of the project over time outweigh the initial investment cost when discounted back to the present value. Essentially, the revenue generated from the operation over the project's lifespan are substantial enough, exceeding the initial investment, resulting in a positive NPV for operating costs.

Energy consumption is the third biggest cost in the NPV analysis, representing the electrical energy necessary to power the pumps of the system and also the EQ process, whose energy consumption is still a delicate parameter, varying sharply according to the concentration of Lithium in the feed water and still not an exhaustive experiments and researches investigating this point, representing then a potential risk of the project.



Graph 17 - Proportion of the total costs on the NPV

Source: Elaborated by the author

For the worst case scenario, using the minimum revenue value found in the distribution and the biggest cost values found, the NPV of the project would be as below:

Cash flows [kUS$]			years					
Description	**Min**	**NPV**	**0**	**1**	**2**	**3**	**...**	**20**

Revenue	2,010	17,112		1,827	1,661	1,510		299
Investment cost	-42,497	-42,497	-42,497					
Energy cost	-3,969	-33,788		-3,608	-3,280	-2,982		-590
Materials cost	-1,585	-13,492		-1,441	-1,310	-1,191		-236
Operation and maintenance cost	-12,749	-108,540		-11,590	-10,536	-9,579		-1,895
Labor cost	-423	-3,601		-385	-350	-318		-63
Depreciation cost	-1,756	-14,951		-1,597	-1,451	-1,319		-261
Project NPV (worst case scenario)		**-199,756**	**-42,497**	**-16,792**	**-15,266**	**-13,878**		**-2,746**

Table 26 - Worst case scenario on the NPV

Source: Elaborated by the author

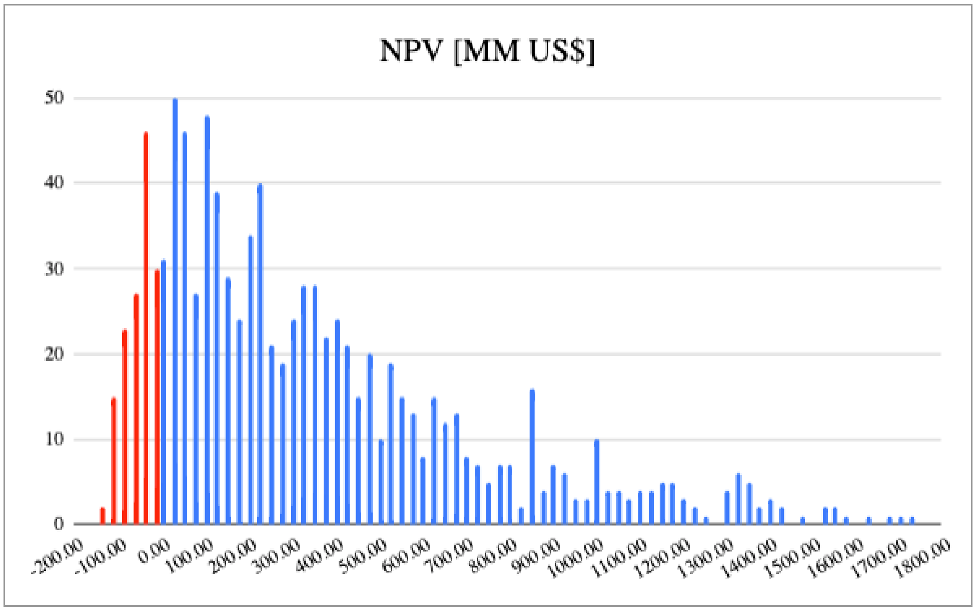
For the best case scenario, using the maximum revenue value found in the distribution and the minimum cost values found, the NPV of the project would be as below:

Cash flows [kUS$]			**years**					
Description	**Max**	**NPV**	**0**	**1**	**2**	**3**	**...**	**20**
Revenue	307,720	2,619,798		279,746	254,314	231,195		45,741
Investment cost	-29,208	-29,208	-29,208					
Energy cost	-2,896	-24,658		-2,633	-2,394	-2,176		-431
Materials cost	-590	-5,020		-536	-487	-443		-88
Operation and maintenance cost	-2,921	-24,866		-2,655	-2,414	-2,194		-434
Labor cost	-423	-3,601		-385	-350	-318		-63
Depreciation cost	-1,227	-10,447		-1,116	-1,014	-922		-182
Project NPV (best case scenario)		**2,521,998**	**-29,208**	**272,422**	**247,656**	**225,142**		**44,543**

Table 27 - Best case scenario on the NPV

Source: Elaborated by the author

The determination of risk-adjusted net present value for the project was carried out by summing up the probability distributions for the cash flow groups. Graph 18 presents the probability distribution for the project NPV.



avg	361
sd	409
1% value	-106
99% value	1,749

NPV > 0	85.7%
NPV < 0	14.3%

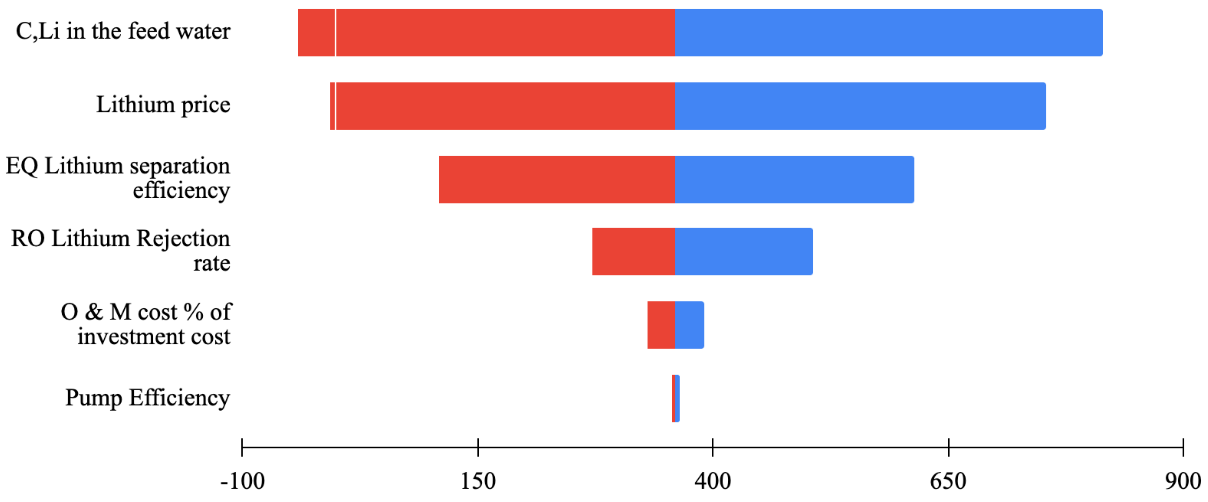
Graph 18 - Project's NPV distribution

Source: Elaborated by the author

Graph 18 also shows that the NPV standard deviation is 409 MM US$ and the probable values for a 99% confidence interval vary from -106 to 1,749MM US$. However, the probability for a positive NPV for the project is 85.7%, which suggests that, although on average the project is attractive, it offers a reasonable economic risk of 14.3% of negative NPV.

5.2. Sensitivity analysis

In order to better understand which of the risk parameters affects the NPV the most, a sensitivity analysis was taken in place. For a sensitivity analysis of a deterministic model, a single input parameter is varied systematically within a predefined range of values $[x_{i,min}; x_{i,max}]$ (ARNOLD; YILDIZ, 2015). All the other input variables are kept constant with their base-case value, as in the average scenario shown before in table 10. The related deviations of the model-output variable of interest (the project's NPV) from its base-case value are recorded in order to better understand its impact on the evaluation, resulting in the following impact on the NPV (Graph 19):



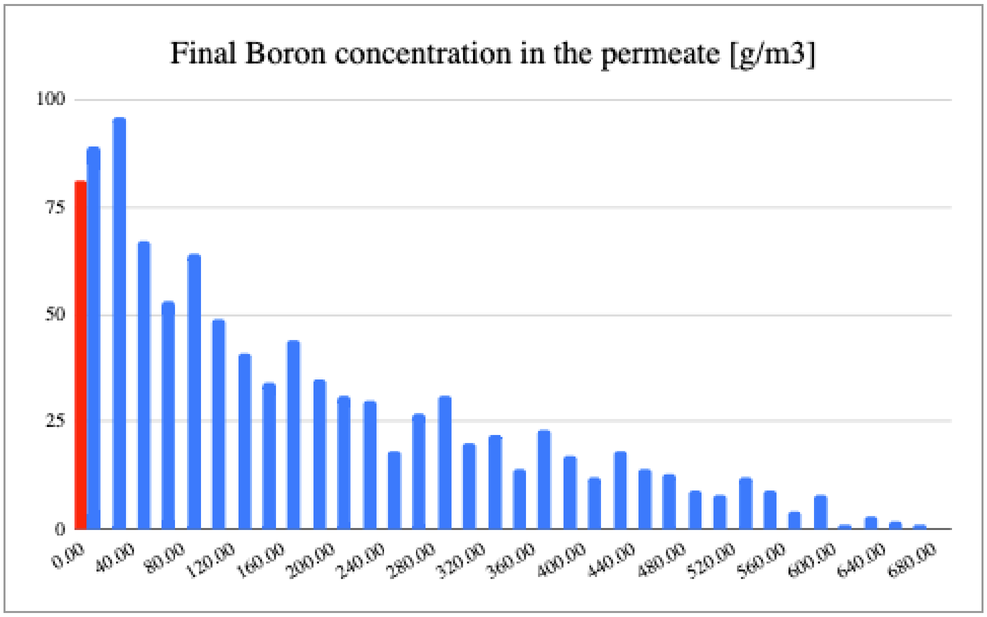
Graph 19 - sensitivity analysis of the NPV

Source: Elaborated by the author

From graph 19, it is possible to see that two parameters have the biggest impact on the NPV, when compared to the others: the concentration of Lithium in the feed water and the Lithium price. Indeed, the majority of the cash flows depend on these two variables in a relation of, the bigger their value, the more attractive the NPV of the project. In the sequence it appears the separation efficiency of Lithium in the EQ process, followed by the Lithium RO rejection rate, both important factors for the extraction of Lithium from the feed water and thus essentially affecting the Li production rate.

5.3. Boron removal

After the completion of the RO process, with a Boron rejection rate ranging from 85%-90%, followed by a multi-passage configuration NF process, with a rejection rate ranging from 85%-99%, the results of concentration of Boron in the permeate flow are as follows:



avg	171
sd	159
1% value	1
99% value	594

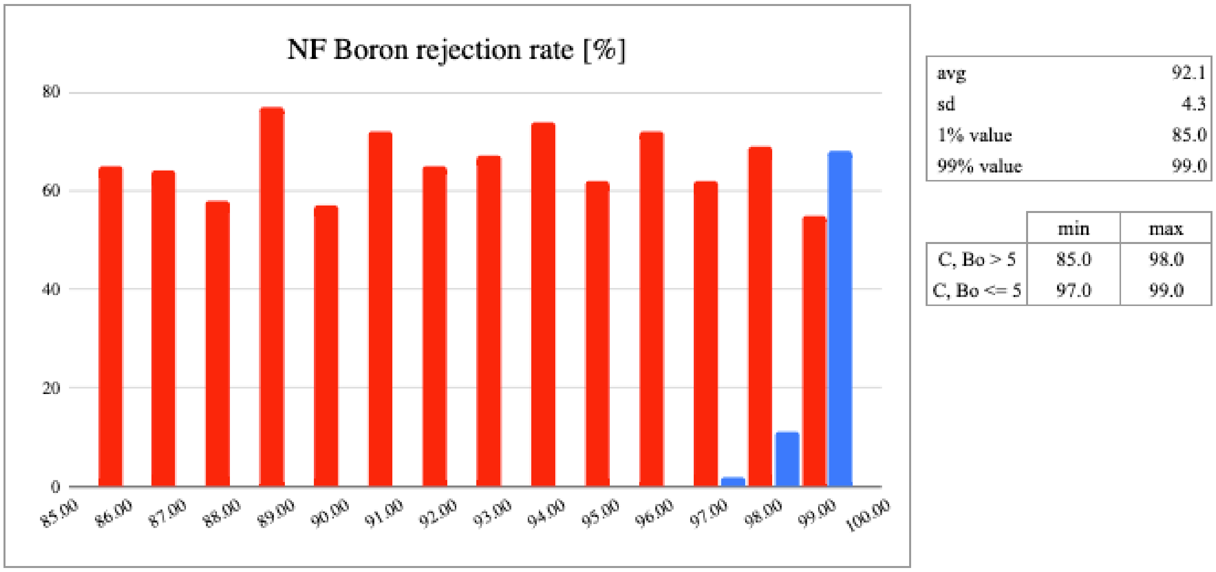
C, Bo > 5	91.9%
C, Bo <= 5	8.1%

Graph 20 - Final Boron concentration distribution

Source: Elaborated by the author

The results indicate an average of 171 mg/L of Boron in the final permeate flow, which is very above the limit of efficiency of 1 mg/L limit determined by the California Regional Water Quality Control Board, as the Waste Discharge Requirements General Order. When compared to seawater boron concentration of around 5 mg/L, there is only 8,1% of probability of achieving this or smaller level of concentration in the permeate. Thus the system presents a significant risk in not succeeding the boron removal goal.

In graph 21, it is possible to see that only when the boron rejection rate is bigger than 97% that the final concentration of boron is equal or less than 5 mg/L. However, there are still cases when the rejection rate is close to 98% and still, the final concentration of boron is above 5 mg/L. This probably happens when the concentration of boron in the source solution is very high, close to the 700 mg/L upper limit.



avg	92.1
sd	4.3
1% value	85.0
99% value	99.0

	min	max
C, Bo > 5	85.0	98.0
C, Bo <= 5	97.0	99.0

Graph 21 - NF boron rejection rate distribution

Source: Elaborated by the author

PART VI - Conclusion

The approach presented by this work analyzes the financial risk for investors by subjecting the NPV of the project to Monte Carlo simulations. Data collection was performed so that the project's cash flow is carried out, as well as the NPV calculation. After that, the MCS input and output parameters are selected to find the project's NPV probability distribution and likelihood to be positive and attractive for investors. MCS provides significant methodological benefits compared to standard NPV estimation, once it allows simultaneous variation of multiple uncertain input parameters in project financial assessments, acknowledging the inherent uncertainty in forecasts. By running the model and discussing the results, this study shows an attractive result with almost 86% probability of positive NPV.

A sensitivity analysis is carried out, by measuring the individual impact of each risk parameters on the project's NPV. The results reveal that the concentration of Lithium in the feed water and the Lithium price are the parameters with the biggest impact on the total NPV, followed by the EQ Li separation efficiency and the NF Li rejection rate.

Finally, this study evaluated the system performance in removing the Boron from the produced water. From the conditions yet imposed, the system does not succeed in achieving the limit of 5 mg/L, remaining room for alternative membrane configuration options and improvement of the source solution characteristics before entering the membrane filtration system, such as adding chemicals to increase its pH.

For future discussions, with more information and data available about the system variables, a more specific probability distribution can be attributed for the model, in order to achieve even more accurate results and facilitate the analysis of incremental design changes and its overall impact on the project's economical-risk assessment.

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