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ARTÍCULO CIENTÍFICO

EXPLORING SUSTAINABLE DEVELOPMENT SCENARIOS USING COLLECTIVE INTELLIGENCE AND SYSTEM DYNAMICS MODELLING: THE LITHIUM EXPLOITATION CASE

EXPLORANDO ESCENARIOS DE DESARROLLO SOSTENIBLE UTILIZANDO INTELIGENCIA COLECTIVA Y MODELADO DE DINÁMICA DE SISTEMAS: EL CASO DE LA EXPLOTACIÓN DEL

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Resumen / Abstract

Lithium-ion batteries play a pivotal role in renewable energy, powering a multitude of rechargeable devices. The transition to renewable sources amplifies the demand for lithium, providing advantages for nations with reserves but also posing potential risks to soil and water resources. Previous research has predominantly concentrated on distinct dimensions like social acceptance, water sustainability, and economic development. Limited attention has been given to an integrated analysis encompassing both the holistic and individual aspects simultaneously. We applied collective intelligence experiments and the system dynamics methodology to uncover the dynamic complexity of this issue and to reveal the relationship between variables and their interactions as they unfold over time. Our research suggests that, although there is some room for sustainable utilization, the risks for stakeholders exhibit clear asymmetry. While economic gains appear stable across various scenarios, the local community's susceptibility becomes notably fragile due to excessive water exploitation.

Key Words: collective intelligence; genetic algorithms; Lithium exploitation; system dynamics; water sustainability.

Las baterías de ion de litio desempeñan un papel fundamental en la energía renovable, alimentando una multitud de dispositivos recargables. La transición a fuentes renovables potencia la demanda de litio, ofreciendo ventajas a las naciones con reservas, pero también planteando posibles riesgos para los recursos de suelo y agua. Investigaciones anteriores se han centrado principalmente en dimensiones específicas como la aceptación social, la sostenibilidad del agua y el desarrollo económico. Poco se ha desarrollado usando un análisis integrado que abarque tanto los aspectos holísticos como los individuales simultáneamente. Aplicamos experimentos de inteligencia colectiva y la metodología de dinámica de sistemas para desentrañar la complejidad dinámica de este problema y revelar la relación entre variables y sus interacciones a medida que se desarrollan con el tiempo. Nuestra investigación sugiere que, aunque hay cierto espacio para la utilización sostenible, los riesgos para las partes involucradas muestran una clara asimetría. Mientras que las ganancias económicas parecen estables en varios escenarios, la susceptibilidad de la comunidad local se vuelve notablemente frágil debido a la explotación excesiva del agua.

Palabras clave: algoritmos genéticos; explotación de Litio; inteligencia colectiva; sostenibilidad del agua.

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Introduction

The utilization of non-renewable energy sources gives rise to numerous ethical concerns. Human depletion of finite natural resources and the resultant global warming have adverse impacts on the functioning of ecosystems. As these ecosystem functions deteriorate, conventional production and consumption practices continue to steer the world towards an era where the biosphere's viability is uncertain, and its effects on life-sustaining systems are poorly understood. The transition from a fossil fuel-dependent economy to one based on sustainable energy sources has become an indispensable route to ensure the survival of the human species.

At the heart of the renewable energy paradigm, lithium stands as the crucial element for energy storage. Lithium plays a pivotal role as a primary resource for the construction of both existing lithium-ion and potential future generations of batteries.

The world's largest deposits of lithium lie in brines found underneath salt flats in the desert between Chile, Argentina, and Bolivia (Barandiarán, 2019). It is estimated that the three countries, together referred to as the "Lithium Triangle", account for almost 75% of the world's supply beneath their salt flats (Ahmad, 2020). Argentina appears to have advantages not only in terms of its natural conditions but also due to its regulatory environment, especially when compared to its neighboring countries in the region. This favorable regulatory climate makes it attractive for attracting investments focused on exploiting salt flats. Research carried out by the InterAmerican Development Bank concurs that Argentina holds the potential to emerge as the global leader in lithium carbonate production (López et al., 2019).

Unfortunately, although the extraction of lithium can yield significant advantages, it also presents a downside concerning environmental risks and the long-term well-being of local communities. According to Agusdinata et al. (2018), while there is a wealth of research on the exploitation of brine, there has been limited analysis of the actual mining's impact on local communities.

In Argentina, a political and social conflict has emerged pitting proponents of lithium exploitation against those who oppose it. Detractors, including primarily local indigenous communities and environmental experts, argue that the project has not obtained, neither the necessary level of social approval, nor the minimum environmental risk assessments. Meanwhile, supporters, which include certain local communities, policymakers, and companies, view it as an exceptional opportunity that should not be missed.

Although the nature of the conflict has been studied in detail, there has been a lack of focus on a comprehensive solution. This study aimed to address the question of to what extent lithium can be extracted without causing harm to the well-being of individuals or communities while still providing satisfactory economic incentives. We followed the system dynamics methodology, which aims to depict interactive relationships among components within a system and comprehend its evolution over time. Initially, we conducted an experiment with students utilizing a modified version of genetic algorithms, allowing us to unveil the systemic structure of the problem. Subsequently, we proceeded to construct a system dynamics model and conducted numerous simulations to quantify interactions, offering conceptual insights that would otherwise remain undiscovered.

Research background

Lithium

Lithium is an extremely lightweight and malleable metal, known for its high reactivity, which facilitates efficient energy transfer. These characteristics render lithium an ideal choice for crafting compact batteries (Minor Metals Trade Association [MMTA], s.f.). In a technical sense, an ion-lithium battery comprises three essential elements: a cathode, typically made of a metallic oxide like lithium cobalt oxide; an anode typically constructed from graphite; and an electrolyte consisting of lithium salts dissolved within organic solvents (Rodríguez et al., 2020).

Lithium deposits are of three main types: brines and related evaporites, pegmatites, and sedimentary rocks (Gruber et al., 2011). Brines are saline waters with high contents of dissolved salts. They can be

Table 1
World Lithium Resources and Reserves

Country	Resources (tons)	% World Resources	Reserves (tons)	% World Reserves
United States	12.000.000	12.2 %	1.000.000	3.8 %
Argentina	20.000.000	20.4 %	2.700.000	10.4 %
Australia	7.900.000	8.1 %	6.200.000	23.8 %
Brazil	730.000	0.7 %	250.000	1.0 %
Canada	2.900.000	3.0 %	930.000	3.6 %
Chile	11.000.000	11.2 %	9.300.000	35.8%
China	6.800.000	6.9 %	2.000.000	7.7 %
Portugal	270.000	0.3 %	60.000	0.2 %
Zimbabwe	690.000	0.7 %	310.000	1.2 %
Other Countries	35.710.000	36.4 %	330.000	1.3 %
World Total	**98.000.000**	**100.0 %**	**26.000.000**	**100.0 %**

Source: Own analysis based on U.S. Geological Survey (2023).

classified into continental, geothermal and oil field brines (Pistilli, 2023). Continental is the most common form of lithium-containing brine. Pegmatite deposits are large-grained intrusive igneous rocks originating from the solidification of magma deep within the Earth's crust. Within pegmatites, it is possible to find viable quantities of lithium and other elements (Gruber et al., 2011). Lithium is also present in various sedimentary rock formations, including clay and lacustrine evaporites. Within clay deposits, lithium is a component of clay minerals like smectite, requiring separation through processing methods (Gruber et al., 2011).

According to the U.S. Geological Survey (2023), there are approximately 98 million tons of identified lithium resources [1], whereas lithium reserves [2] account for 26 million ton (Table 1).

From the 35.7 million tons of world's lithium resources, Bolivia accounts for 31.6 % (21 million). According to Alvarez (2023), despite the potential of the Salar de Uyuni to place Bolivia prominently in the global lithium production landscape, strategic missteps and the complex technical challenges associated with extracting lithium from this unique terrain have hindered the country's ability to establish these resources as proven reserves, thereby assessing the feasibility of their exploitation. As a result, Bolivia is currently absent from the list of lithium reserves.

While the exact number of lithium deposits may vary among experts, it is estimated that both resources and reserves are concentrated in few deposits. According to the findings of Vikström et al.'s research (2013), the ten largest world deposits contain 65% of the known reserves and 70% of world lithium resources.

Social and environmental concerns in Argentina

According to León et al. (2020) the dynamics of lithium exploitation are reigniting discussions and tensions regarding the balance between the national, subnational, and local levels when it comes to sovereignty and

1. Resource is a concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible (U.S. Geological Survey, 2023, p. 195).
2. Reserve is the part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth (U.S. Geological Survey, 2023, p. 196).

the management of natural resources among South American countries. In some cases, certain parties have resorted to violence to safeguard their interests, particularly when they feel marginalized from participating in policymaking processes that directly influence them.

Over the past few years, lithium mining in Argentina has accelerated. While there haven't been any violent incidents to date, there are rising tensions between some local indigenous populations and the local administrations. According to Göbel (2013), locals have mixed feelings about lithium mining initiatives, which are characterized by a blend of indifference, uncertainty, and expectations. Although lithium extraction has an impact on all Indigenous communities, not all of them have the same reactions (Pragier, 2019). In accordance with Pragier's research, the initiation of lithium extraction projects within local communities has generated two kinds of responses, dependent or autonomous. These perspectives, in turn, have sparked calls for retribution and recognition. These are the cases of Olaroz salt flat (dependent and retribution) and Guayatayoc-Salinas Grandes (autonomous and recognition). Indigenous communities advocating for self-governance and recognition rights primarily emphasize the importance of obtaining Free, Prior, and Informed Consent (FPIC)[3] and upholding ancestral rights (Kachi Yupi, 2015). Ancestral rights go beyond being a mere assertion; they are intricately connected to age-old social dynamics. In this sense, Teves and Pasarin (2020) argue that salt in Northwestern Argentina should be seen as a valuable resource for trade and a symbolically significant element in fostering social connections between the Puna and the Quebrada regions. This holds historical and archaeological importance, as it occupies a pivotal role in the dynamic exchange within the Andean trade network.

There are ample justifications for environmental concerns. Lithium mining is established within the salt flats of a high-altitude semi-desert, which constitutes extremely delicate ecosystems (Göbel, 2013). Moreover, high-altitude wetlands' inherent ability to regulate the environment and aid in climate change mitigation and adaptation may be jeopardized by the extraction of lithium (Castillo Díaz, 2023). Hydrologically, salt flats in the Puna region are found within numerous closed basins characterized by internal (endorheic) drainage systems. These salars receive water input from sources such as summer rainfall, surface water runoff, and groundwater inflow.

Water scarcity strongly affect local communities. Communities near mining are most vulnerable to mining expansions, while distant residents experience long-lasting impacts due to lower compensation and delayed groundwater recovery (Liu & Agusdinata, 2021). Water usage in lithium facilities can exceed common consumption by several orders of magnitude. In the case of Salar de Atacama in Chile, water consumption from Lithium-mining was higher by two orders of magnitude compared to any other activity (Liu & Agusdinata, 2020). For the Olaroz salt flat, it is projected that its exploitation will result in a consumption during the production cycle that is five times the total consumption of the local departmental population (Arias Alvarado et al., 2022).

There is a massive number of experts that warn about the lack of understanding of the hydrological dynamics of the salt flats in the face of lithium exploitation (Barandiarán, 2019; Economic Commission for Latin America and the Caribbean [ECLAC], 2023; García et al., 2020; Holzbecher, 2005; Izquierdo & Julieta Carilla, 2017; Liu & Agusdinata, 2020; Liu & Agusdinata, 2021; Marchegiani et al., 2019; Mignaqui, 2019; Sticco et al., 2019; Vera et al., 2023). While new technologies to reduce water consumption and avoid brine evaporation are being developed (Nicolaci et al., 2023; Vera et al., 2023), there are other dangers outside just the freshwater reserves. According to Flexer et al. (2018), the emphasis on the chemistry of brine processing has led to a neglect of the analysis of the overall sustainability of the process. Holzbecher (2005) and Sticco et al. (2019) also consider the risk of eroding the freshwater-saltwater interface and urge to complete the necessary hydrogeological research to identify and map these interfaces.

Collective Intelligence and Genetic Algorithms

Succinctly speaking, collective intelligence (CI) refers to a group of individuals acting together in ways that seem intelligent (Massachusetts Institute of Technology, 2010). According to Por and Atlee (2000), CI is older than humankind itself and manifests its primal forms in the synergies and resilience of ecosystems. CI may take the

3. FPIC is a specific right granted to Indigenous Peoples recognized in the UN Declaration on the Rights of Indigenous Peoples (UNDRIP). https://www.fao.org/indigenous-peoples/our-pillars/fpic/en/

form of swarm intelligence, like bees (Pratt, 2010), or large numbers of people contributing to a single project (Maher et al., 2010). Yet, in essence, CI is grounded on the concept that large groups of cooperating individuals can produce higher-order intelligence innovations than working separately (Lykourentzou et al., 2011).

Johnson (2000) and Hong and Page (2004) established a strong case for the impact of diversity on CI results. Based on years of experimenting with groups, Johnson confirmed that group's ability responds to an individual ability plus a diversity factor. This factor is a group's property not attributable to individuals. On their side, Hong and Page revealed that groups with high cognitive diversity could outperform expert groups in problem solving. They argue that the different heuristics with which people process information and then make decisions more than compensate their lack of knowledge.

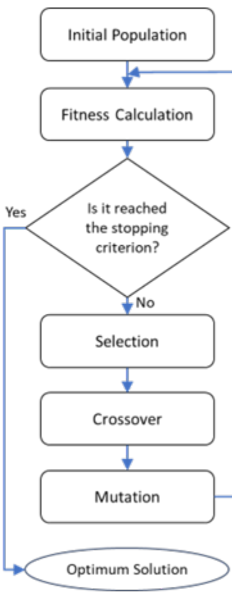
Genetic Algorithms (GAs) are metaheuristic algorithms inspired by biological evolutionary processes, emulating the principle of natural selection and the survival of the fittest (Katoch et al., 2020). Some GA standard applications include strategy planning, robot trajectory planning, Travelling Salesman Problem (TSP) and sequence scheduling, function optimizations, aircraft design and communication networks, machine learning–designing neural networks (Dahiya & Sangwan, 2018).

Standard use of GA starts with a specific population of "chromosomes", where each chromosome represents a potential solution to the given problem (see figure 1). The algorithm requires a fitness function to be optimized. The algorithm selects the top "fittest" from the population and then crosses over them to obtain offspring. Random mutation further affects the new offspring, who will become the new population. This heuristic is iteratively applied until specific conditions are met. Among various potential conditions, Alam et al. (2020), enumerate several cases to consider: the generated solution meeting minimum criteria, the expected population size being reached, the fulfillment of computational requirements like time and cost, or the discovery of the best fitness solutions.

Collective Intelligence experiments

Collective intelligence experiments can be classified by adapting the work of Maher et al. (2010) and Lykourentzou et al. (2011) (Figure 2). Maher et al. propose a group intelligence continuum, where higher degrees of collective intelligence correspond to increasing collaboration and synthesis. A synthesized

Figure 1
Basic Structure of a Genetic Algorithm (GA)



Source: extracted from Beg et al. (2011, p. 239).

Figure 2
Categorization of collective intelligence experiments

Output	Competitive	Collaborative
Additive	Painting the walls using only the most voted colors, without mixing them. (i.e Design Thinking ideation process)	Painting the walls using all contributed colors, without mixing them. (i.e each school division contributes by painting its own mural on a predefined wall)
Synthesized	Painting the walls using colours obtained by mixing the most voted colors. (i.e cocreation of the shared vision of an institutional program)	Painting the walls using a unique color palette obtained by mixing all contributed colors. (i.e Genetic Algorithm to integrate contradictory visions)

Group dynamic

Source: Own development based on Lykourentzou et al. (2011) and Maher et al. (2010).

final product of a CI experiment means that it is the result of a synergistic and creative combination of its constituents and is almost impossible to trace individual contributions. Conceptually, if A and B are the input of the participants, an additive (or combined) output would be A+B, whereas a synthesized output would result in AB. Lykourentzou et al. classify CI systems as passive and active, further categorizing the active interventions as competitive, collaborative, and hybrid.

Methodology

We designed a mixed methodology using a social experiment and the system dynamics methodology (figure 3).

According to Sterman (2000), the primary and crucial phase in modeling is articulating the problem. A model should be purposefully designed to address a specific problem rather than attempting to solve an entire system. The utilization of a genetic algorithm in the social experiment served as a tool to express the problem in systemic terms.

Figure 3
Methodological framework

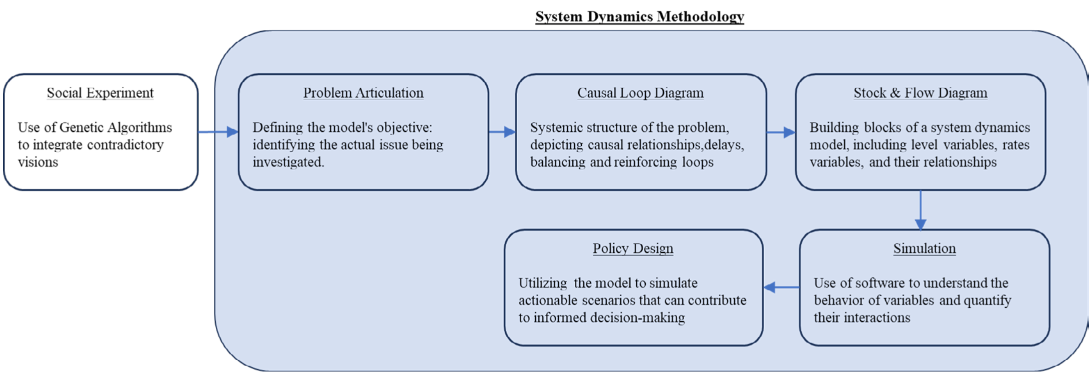


Table 2
Genetic Algorithm designed for the experiment with high school students

Standard GA	Experiment
Population of chromosomes	In favor and opposed statements taking the form of an assertion along with a rationale
Fitness function	Rationality
Crossover	Rationale with other rationale
Mutation	Verbs, adjectives, colors, position in the sentence
New population	New statements with compounded justifications
Stop Criteria	Repetitive final statements

Social Experiment

The experiment aimed to identify opportunities for sustainable lithium exploitation through a collaborative and synthesized effort. An adapted version of genetic algorithms (GA) was designed for the experiment. Thirty high school students divided in five groups took part in the experiment. Before the experiment, they were required to research on about the visions on the subject (See table 2).

Students incorporated both supportive and opposing viewpoints regarding lithium exploitation. Each statement consisted of an assertion along with a rationale. For instance, one might state, "Lithium extraction benefits the country by creating jobs", while another might argue, "The lithium industry is detrimental to the nation due to soil destruction". Then they crossed over the rationale, i.e., "creating jobs due to soil destruction". Then the participants introduced random mutations, such as exchanging positions in the sentence and introducing colors, verbs, and adjectives. For example, "Creating jobs may destroy the soil". These new statements became the offspring. Participants expanded upon as many statements as possible. Subsequently, they selected only those that made logical sense (fitness function). Next, they combined the statements from each group with those of other groups. This process was repeated until the entire group collectively generated several statements, typically ranging from 10 to 15. (See figure 4)

Figure 4
Heuristic of the proposed Genetic Algorithm to integrate contradictory visions

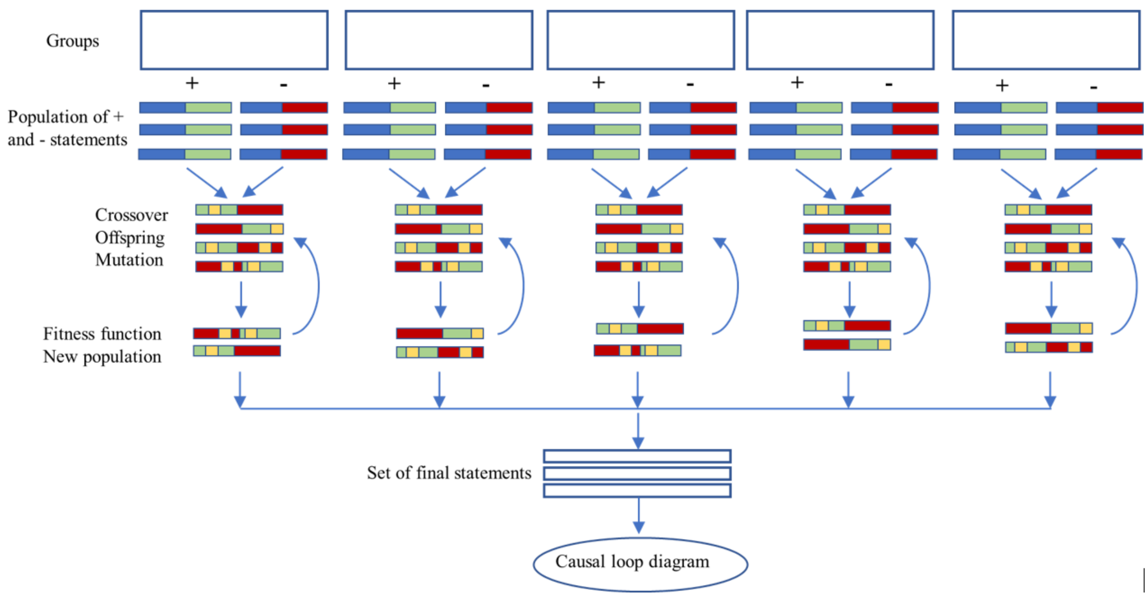


Figure 5
Set of final statements after several loops of crossing-over

1. Lithium is a non-renewable material that will eventually disappear because of industrial exploitation
2. Production of lithium batteries may stop global warming but it depletes lithum reserves
3. The government has incentives to promote lithum exploitation because it generate significant exports and taxes
4. While lithium is non-renewable, it generates jobs
5. Local communities may have incentives to accept lithium exploitation because it generates local jobs
6. Lithium companies can earn significant profits because of the high demand of lithium batteries
7. Lithium exploitation creates political conflict with local communities because it uses significant amounts of water
8. While lithium exploitaton generates jobs, it destroys the ecosystems
9. Lithium generates conflict with local communities because exploitation interferes with local lifestyle

- ***Experiment results***

While creating the population, the students covered much of the state-of-the-art about lithium exploitation. However, after several loops of crossing over rationales and introducing random mutations, a singular emergent phenomenon arose from this experiment: the selected final statements perfectly described the dynamic structure of the problem, composed by feedback loops, causal relationships, and trade-offs (positive and negative causal relationships at the same time). Conflicting perspectives were replaced by a systemic structure that could be modelled and simulated. The final statements and the causal-loop diagram are shown in figures 5 and 6 respectively.

Figure 6
Causal loop diagram of lithium exploitation

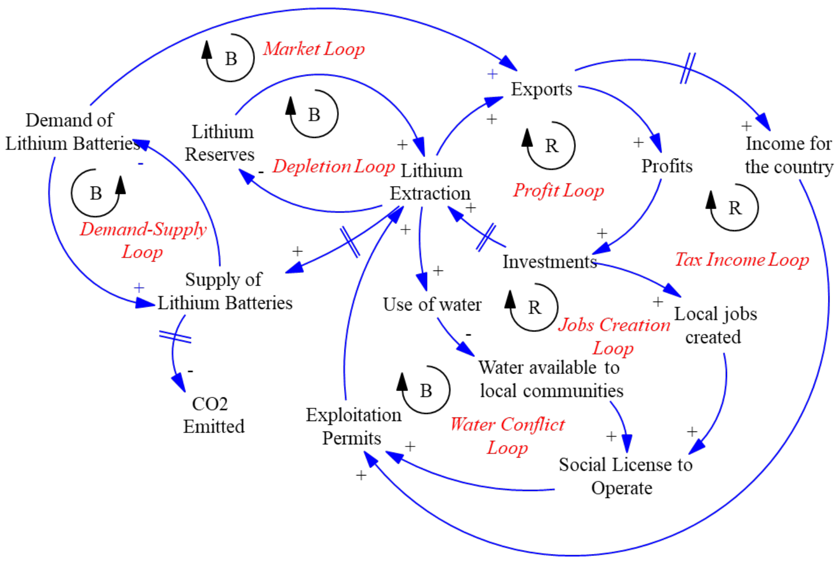
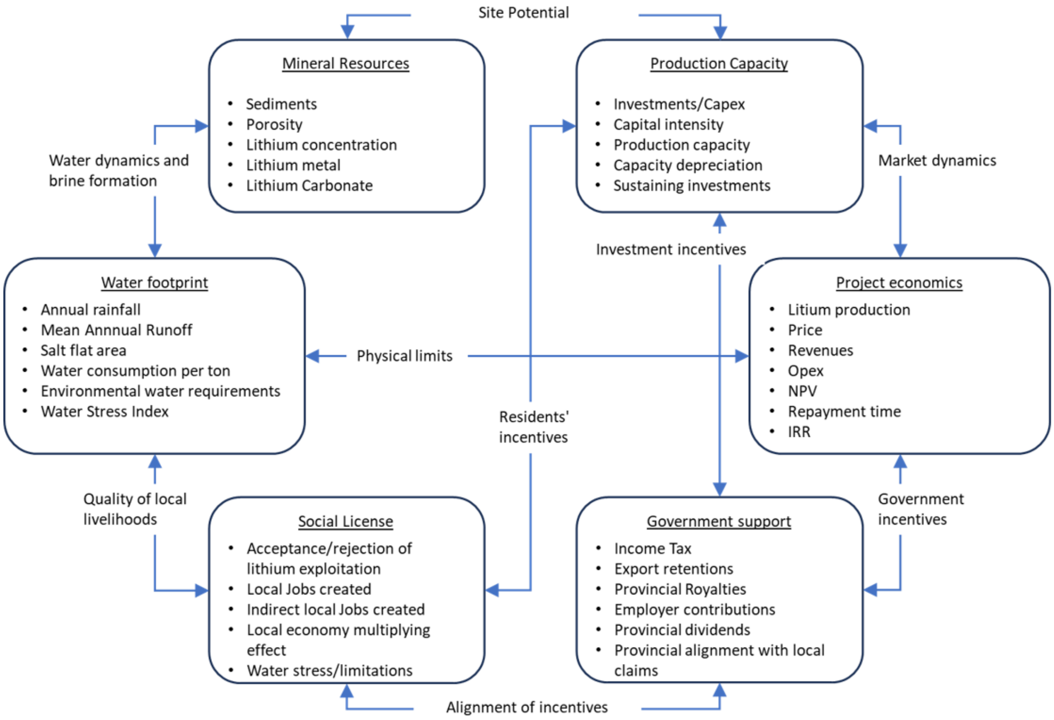


Figure 7
Subsystem diagram for modeling the lithium sustainable exploitation



Stock & Flow Diagram of The Royalties, Taxes, and Export Retentions Subsystem

System Dynamics Model

- ### *Model Subsystems*

Given their intrinsic interconnectedness within the model, it is more convenient for explanatory purposes to present the variables in subsystems (See Figure 7)

In the figure 7, Arrows denote the existence of causal links between the different variables or components of each group. The model will be transformed into a stock-and-flow diagram and then simulated using Powersim Studio 10 Professional simulation software.

- ### *Model Stock & Flow Diagram*

The causal loop diagram enhances conceptual comprehension and might be viewed as a qualitative model (Liu et al., 2019). Incorporating quantitative modeling through stock-and-flow models, enriched by simulation capabilities, aids in assessing the effects of various scenarios and lends a sense of realism to the systemic structure of the system.

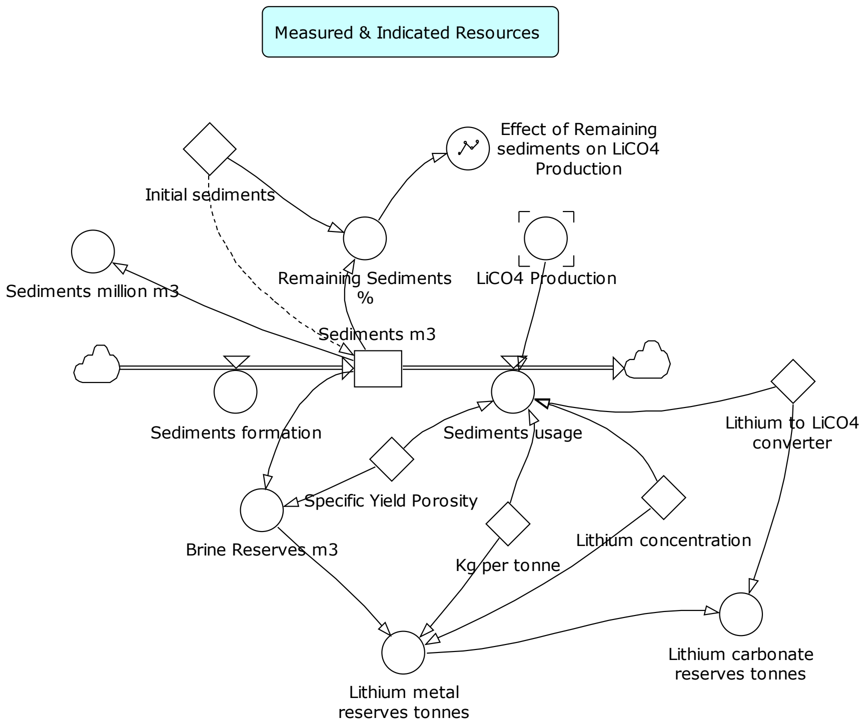
The suggested lithium extraction model is theoretical, although it draws on reported information from the Olaroz and Cauchari-Olaroz projects (Worley Parsons, 2011; Hydrominex Geoscience, 2022; Burga et al., 2019; Houston & Gunn, 2011). Lithium production is based on brine evaporation ponds.

The time horizon for the simulation is established at 40 years for the base case and extended to 50 years in cases where production cannot meet its maximum potential.

Table 3
Variables of Mineral Resources and Reserves

Variable	Selected Number	Source
Brine Reserves	400 million m3	Calculated based on following variables
Porosity specific yield	4%	(Hydrominex Geoscience, 2022, p. 16)
Lithium Concentration	718 mg Li/L	(Hydrominex Geoscience, 2022, p. 16)
Lithium Metal	287.200 tonnes (simulated)	Calculated based on LCE multiplier 5.32
Lithium Carbonate	1.525 million tonnes (simulated)	(Burga et al., 2019, p.20)

Figure 8
Measured and Indicated Resources Stock & Flow Diagram



- ***Stock & Flow Diagram of The Mineral Resources and Reserves Subsystem***

All geological variables, including sediments reserves, porosity, lithium metal concentration and lithium carbonate reserves are based on geological research by Worley Parsons (2011), Burga et al. (2019) and Hydrominex Geoscience (2022).(See Table 3 and Figure 8)

- ***Stock & Flow Diagram of The Investments and Production Capacity Subsystem (See Table 4 and Figure 9***

Table 4
Variables of Investments and Production Capacity

Variable	Selected Number	Source
Investments/Capex	560 USD million	(Burga et al., 2019, p.17)
Capital Intensity	13.500 USD/ton	(Hydrominex Geoscience, 2022, p. 17)
Production Capacity	40.000 tons/year	(Burga et al., 2019, p.21)
Plant depreciation time	40 years	(Allkem, 2023, p. 87)
Sustaining Investments	13.5 USD million/year	Own estimation, based on requirements to maintain operating capacity

Figure 9
Investments & Production Capacity Stock & Flow Diagram

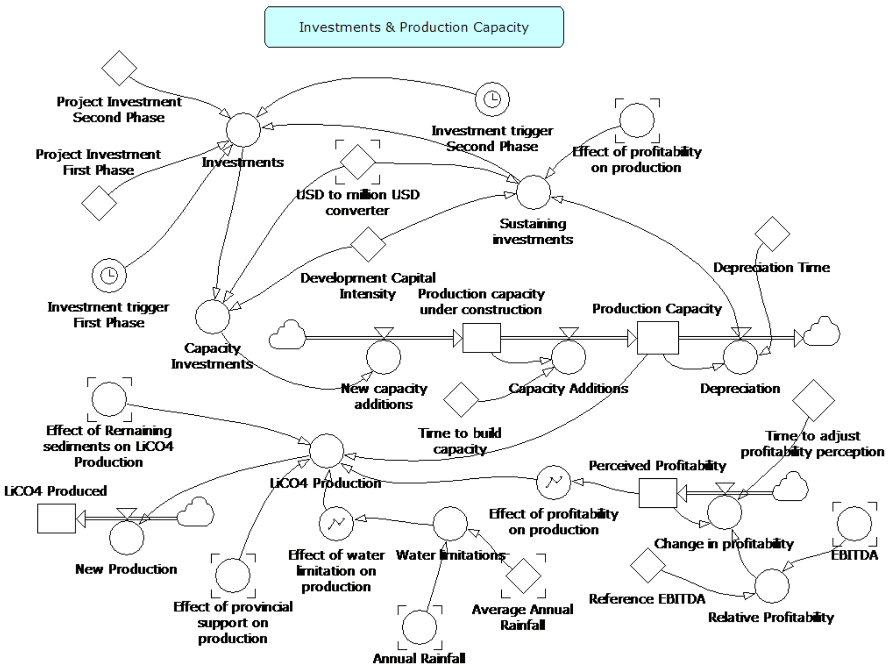


Table 5
Categorization of environmental water scarcity

WSI (proportion)	Degrees of Environmental Water Scarcity of River Basins
WSI>1	Overexploited (current water use is tapping into EWR)
0.6 ≤ WSI ≤ 1	Heavily exploited (0 to 40% of the utilizable water is still available in a basin before EWR conflict with other uses)
0.3 ≤ WSI < 0.6	Moderately exploited (40% to 70% of the utilizable water is still available in a basin before EWR conflict with other uses)
WSI < 0.3	Slightly exploited

Source: Extracted from Smakhtin et al. (2004, p. 10).

- ***Stock & Flow Diagram of The Water Footprint Subsystem***

The projected water footprint draws from the research conducted by Smakhtin et al. (2004), Mignaqui (2019), and Arias Alvarado et al. (2022). According to the findings of Arias Alvarado et al., the water footprint for lithium carbonate (Li2CO3) is calculated at 584.1 m^3 per ton, with freshwater accounting for 8% of this total, equivalent to 46.73 m^3 per ton. Smakhtin et al. (p.9) measure water scarcity by creating the Water Stress Indicator or WSI as follows:

$$WSI = \frac{Withdrawals}{MAR - EWR} \qquad (1)$$

In the equation, MAR corresponds to Mean Annual Runoff and EWR to Environmental Water Requirements. Smakhtin et al. (2004) proposes a range between 20% to 50% of MAR as EWR, or water requirements for ecosystem services. Mignaqui (2019) recommends a 25% for the Puna, the number selected for the simulation. On the other side, MAR is calculated based on Mignaqui (p.48):

$$MAR = 5\% * \text{Average Yearly Rainfall} * \text{Area of the Salt Flat Basin} \qquad (2)$$

Annual Rainfall in the Olaroz basin is approximately 50 mm (Burga et al., 2019, p. 289). 5% refers to the percentage of rainfall that transforms into surface runoff. According to Smakhtin et al. (2004), the value of WSI determines the degree of water as can be see in table 5, table 6 and figure 10:

- ***Stock & Flow Diagram of The Social License Subsystem***

Social License is quantified as a continuous variable within a range of 0 to 1, where a value of 1 indicates

Figure 10
Water Footprint Stock & Flow Diagram.

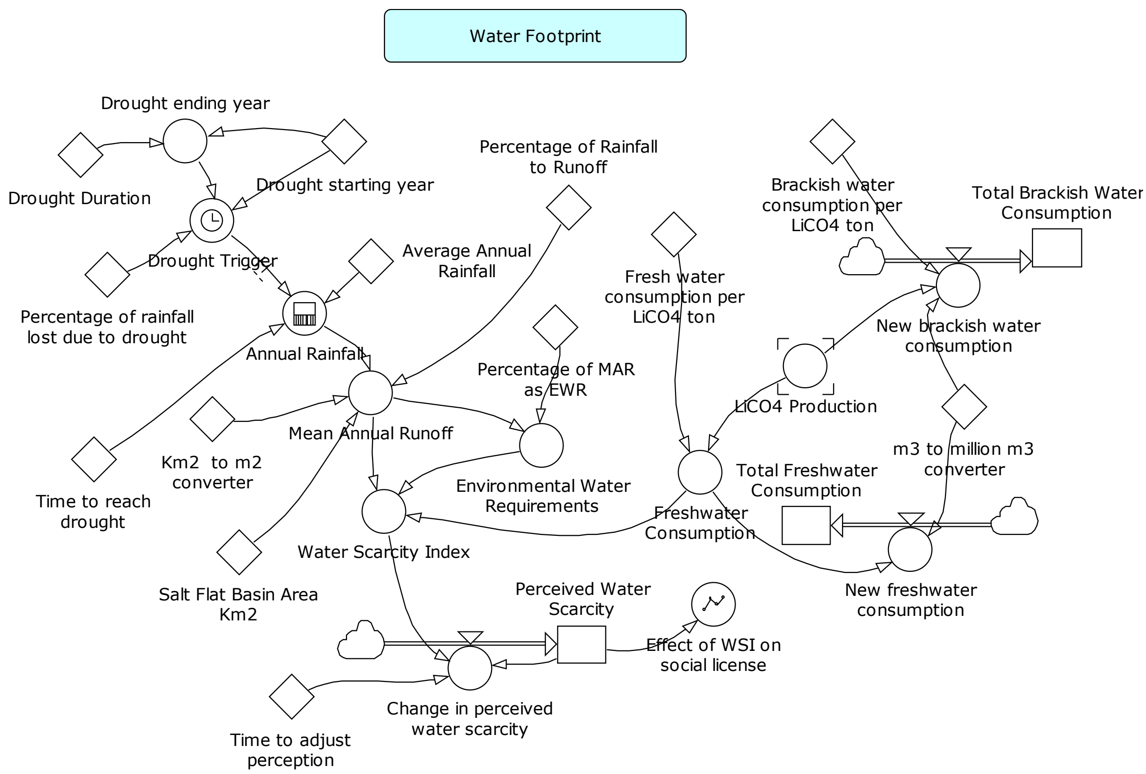


Table 6
Variables of Water Footprint

Variable	Selected Number	Source
Basin Area	1500 Km2	An area slightly bigger than the largest alluvial fan in the Olaroz basin, Archibarca (Houston & Gunn, 2011, p. 48)
Annual rainfall	50 mm	(Burga et al., 2019, p. 21)
Mean Annual Runoff	Based on formula	(Mignaqui, 2019, p. 48)
Water Consumption	50 m3/ton of LiCO4	Adapted from Arias Alvarado et al. (2022, p. 229)
Environmental Water Requirements	25% of MAR	(Mignaqui, 2019, p. 48)
Water Stress Index	Based on formula	(Smakhtin et al., 2004, p. 9)

complete acceptance by residents and 0 indicates total rejection (see Table 7 and figure 11) . An intermediate value, for instance, 0.65, signifies an average support level of 65%. A higher WSI reduces social license, while employment enhances social license, especially if it has a multiplying effect on local economy. Direct employment is expected to be around 780 (Secretaría de Minería, s.f.; Minera Exar, 2022), whereas Indirect employment has a multiplier of 4,5 (Minera Exar, 2022). Local population is estimated to be 4000 and the starting Social License is estimated to be 0,4.

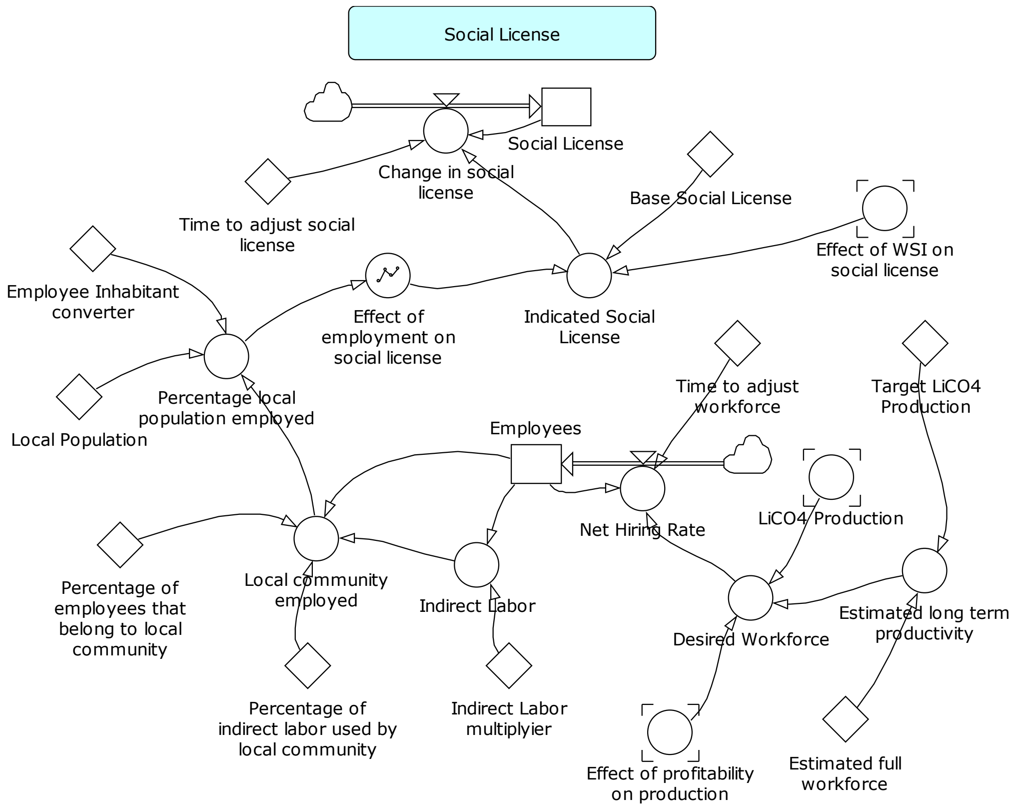
- ***Stock & Flow Diagram of The Project Economics Subsystem***

Lithium exploitation projects have internal rates of return (IRR) that range from 24% to 60%, and payback periods from 1, 5 to 5 years (Ibarra-Gutiérrez et al., 2021). Olaroz expansion project estimates a Lithium Carbonate price of USD 14.000 per tonne (Hydrominex Geoscience, 2022). Lithium prices are very unlikely to drop since project pipeline is insufficient to meet future demand (S&P Global Market Intelligence, 2022). Different studies of Olaroz and Cauchari-Olaroz projects placed estimated IRR somewhere between 30% to 40%, a payback period of 2,5 to 5 years and a NPV @8% between USD 2,5 to 3,0 billion (Burga et al., 2019;

Table 7
Variables of Social License

Variable	Selected Number	Source
Direct jobs created	780	(Secretaría de Minería, s.f.)
Local economy multiplier effect	4,5	(Minera Exar, 2022, p. 40)
Indirect jobs created	3500	Based on Minera Exar (2022, p. 40)
Local population	4000	Population of department of Susques
% of employees that belong to local communities	64%	(Minera Exar, 2022, p. 81)
Initial Social License	0.4	Own estimation based on reported media

Figure 11
Social License Stock & Flow Diagram.



Hydrominex Geoscience, 2022). The model recreates these numbers as a validation test (See Table 8 and figure 12)

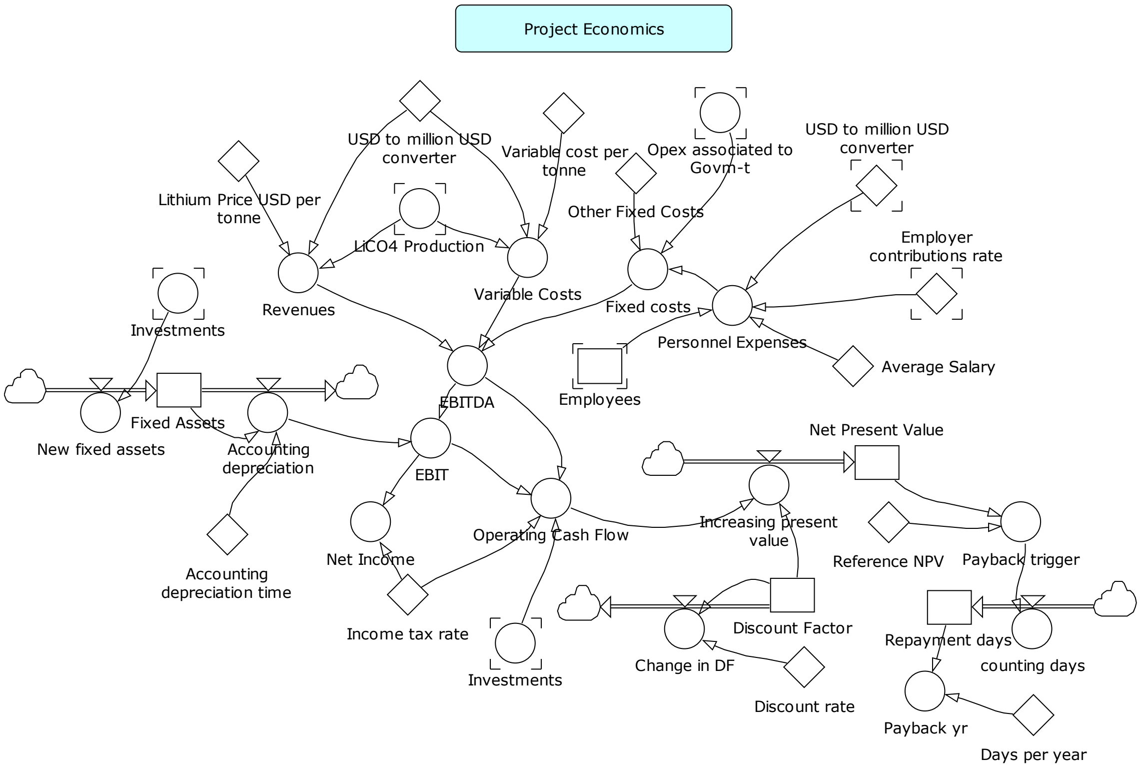
- ***Stock & Flow Diagram of The Royalties, Taxes, and Export Retentions Subsystem***

Mining activity in Argentina, including prospecting and exploration, is primarily governed by the National Constitution. Following that, the Mining Code, Article 75, Clause 12, comes into effect. Lastly, the Mining Investment Law (Law No. 24.196/93, amended by Law No. 25.429/01), applies. According to these references, provincial royalties are expected to be around 2,3% (Worley Parsons, 2011, p. xv) and export retentions of 4,5% (Freytes et al., 2022). It is

Table 8
Variables of Project Economics

Variable	Selected Number (Base Case)	Source
Lithium production	Max 40.000 tons/year	Nominal production, modulated by constraints based on simulation scenario
LiCO4 price	14.000 USD/ton	(Burga et al., 2019, p.21) (Hydrominex Geoscience, 2022)
Revenues	560 USD million/year	(Burga et al., 2019, p.21)
Opex	3.576 USD/ton	(Burga et al., 2019, p.19)
Net Present Value	2.1 USD billion (simulated)	Based on simulation. Depends on scenario
IRR	36.4% (simulated)	Based on simulation. Depends on scenario

Figure 12
Project Economics Stock & Flow Diagram



expected both a higher federal and provincial support with higher income (See table 9 and Figure 13)

Discussion

Base Case

The base case simulation depicts the expected behavior of the system. In a 40-year simulation, the project extracts and refines almost 1,5 million tons of lithium carbonate. The project yields an IRR of 36,4% and a NPV of 2,1 billion USD. Payback time is 5,21 years. Due to employment opportunities, social license increases from 0,4 to a maximum of 0,64, a 1,73-multiplying effect. (See figure 14)

Table 9
Variables of royalties, taxes, and export retentions

Variable	Selected Number	Source
Federal government export retentions	4,5% of FOB exports	(Freytes et al., 2022, p. 31)
Federal government income tax	35% of taxable income	(Freytes et al., 2022, p. 31)
Employer contributions	21.8% of gross salary	Calculated based on Minera Exar (2022, p. 73)
Provincial royalties	3% of pithead value or 2.32% of revenues	Based on Freytes et al. (2022, p. 31) and Worley Parsons (2011, p. xv)
Provincial shareholding position	8.5% of Sales de Jujuy SA	(Allkem, 2023, p. 22)

Figure 13
Royalties, taxes, and export retentions Stock & Flow Diagram

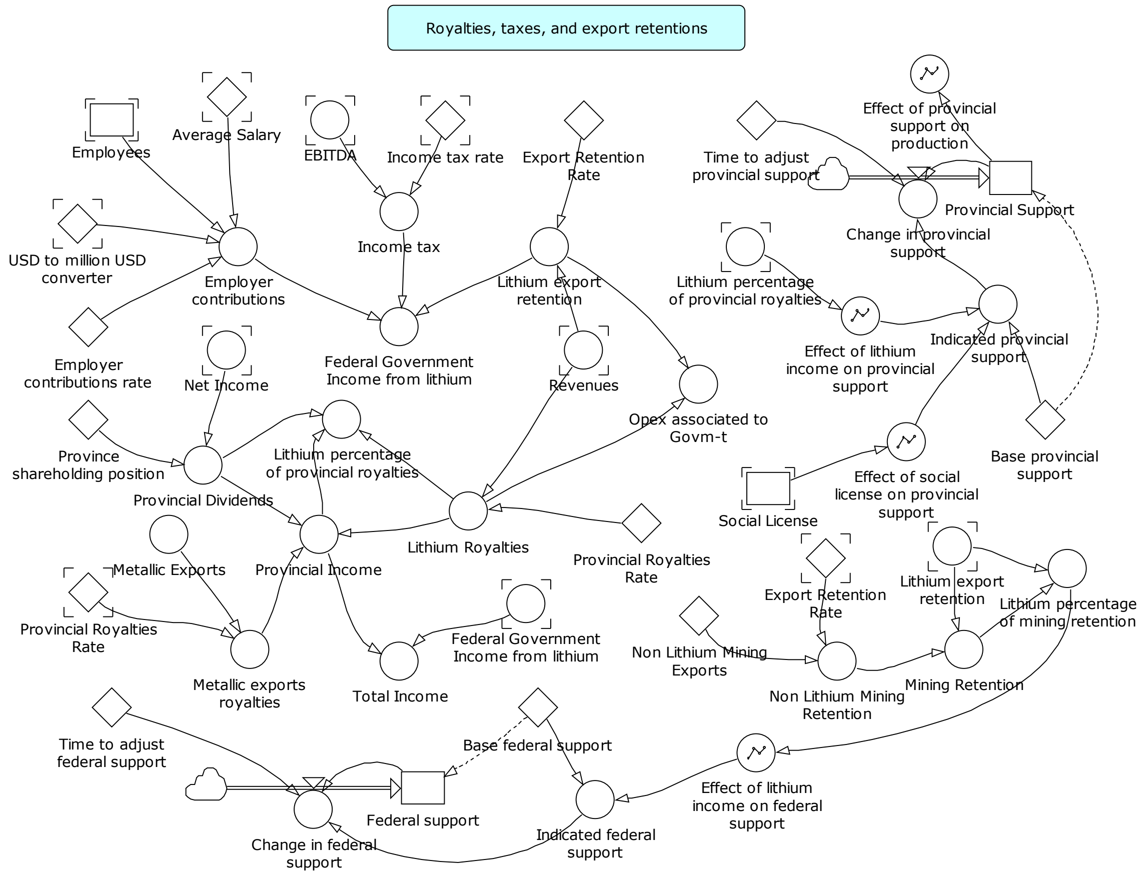


Figure 14
Main indicators of the Base Case simulation

Production Statistics

LiCO4 Produced	1.469.906 tons
Total Freshwater Consumption	73 millionM3
Total Brackish Water Consumption	790 millionM3
Remaining Sediments %	3,80 %

Project Economics

Net Present Value	2.016 millionUSD
Internal Rate of Return	36,4 %/yr
Repayment days	1.901 da
Payback yr	5,21 yr

Social Benefits

Max number of direct employees	780 Employees
Max number of indirect labor	3.508 Employees
Max % of local population employed	25,6 %
Present Value of Salaries	117 millionUSD
Base Social License	0,40
Min Social License	0,31
Max Social License	0,64
Max effect of employment on SL	1,73
Min effect of employment on SL	0,66
Min effect of WSI on SL	0,93

Economic Benefits for the State

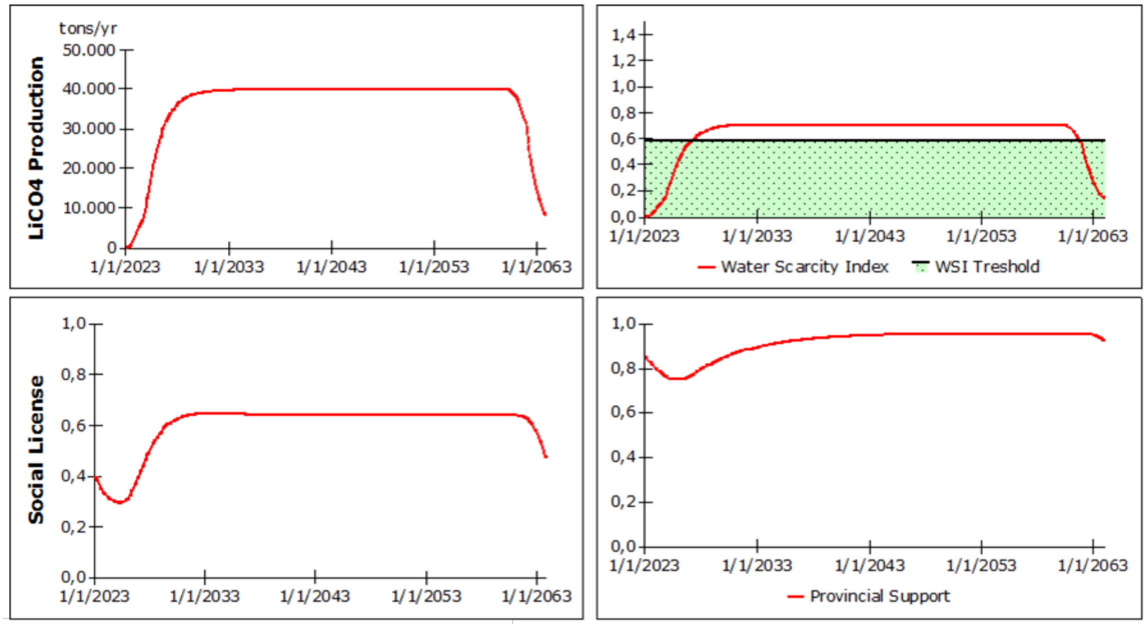
Present Value of Federal Income	1.620 millionUSD
Present Value of Provincial Income	373 millionUSD
Max Annual Federal Income	172 millionUSD/yr
Max Annual Provincial Income	40 millionUSD/yr
Max Provincial Support	0,95
Min Provincial Support	0,75

Water Stress

% of days with WSI Slightly Exploited	8,8 %
% of days with WSI Moderately Exploited	7,5 %
% of days with WSI Heavily Exploited	83,7 %
% of days with WSI Overexploited	0,0 %
Max Water Stress Index	0,71
Min Water Stress Index	0,16

Source: System Dynamics Model.

Figure 15
Behavior of key variables of the Base Case simulation with 50 m3/ton water consumption



Source: System Dynamics Model.

It's worth noting that the current total value of state economic benefits, which includes both federal and provincial contributions, stands at approximately 2.0 billion USD, a figure remarkably close to the project's Net Present Value (NPV). With a salt flat surface o 1,5 Km^2 and an annual rainfall of 50 mm, the WSI slightly exceeds the threshold value of 0,6, yet remains most of the time in the heavily exploited range. The social license is sustained at a relatively high level, primarily attributed to job opportunities and positive externalities among the community. The benefits of job opportunities outweigh potential challenges related to water stress. The support from the province remains robust. The simulation depicts significant potential water stress with substantial social and federal benefits (See figure 15)

Figure 16
Main indicators of the 80 m3/ton water consumption scenario

Control Panel

Production Statistics

LiCO4 Produced	1.469.900 tons
Total Freshwater Consumption	118 millionM3
Total Brackish Water Consumption	790 millionM3
Remaining Sediments %	3,80 %

Economic Benefits for the State

Present Value of Federal Income	1.620 millionUSD
Present Value of Provincial Income	373 millionUSD
Max Annual Federal Income	172 millionUSD/yr
Max Annual Provincial Income	40 millionUSD/yr
Max Provincial Support	0,88
Min Provincial Support	0,28

Project Economics

Net Present Value	2.016 millionUSD
Internal Rate of Return	36,4 %/yr
Repayment days	1.901 da
Payback yr	5,21 yr

Water Stress

% of days with WSI Slightly Exploited	6,1 %
% of days with WSI Moderately Exploited	4,2 %
% of days with WSI Heavily Exploited	7,4 %
% of days with WSI Overexploited	**82,4 %**
Max Water Stress Index	1,14
Min Water Stress Index	0,20

Social Benefits

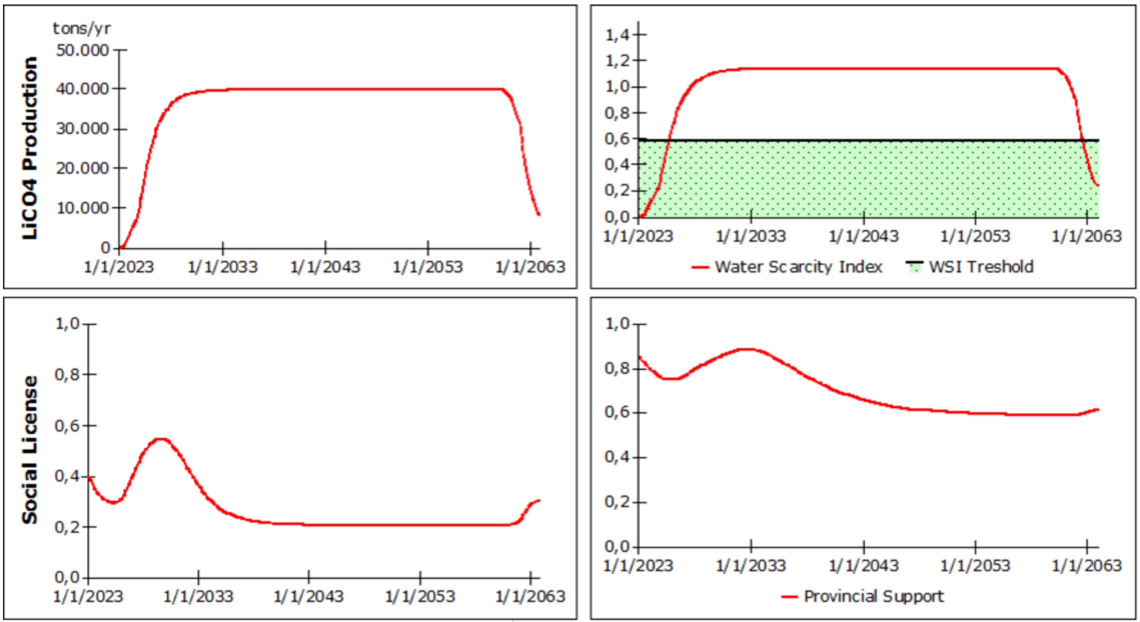
Max number of direct employees	780 Employees
Max number of indirect labor	3.508 Employees
Max % of local population employed	25,6 %
Present Value of Salaries	117 millionUSD
Base Social License	0,40
Min Social License	0,12
Max Social License	0,47
Max effect of employment on SL	1,73
Min effect of employment on SL	0,66
Min effect of WSI on SL	0,17

Alternative Scenarios

There is a potential scenario where water consumption is considerably higher, for example, at 80 m^3 per ton. In such a situation, the outcomes can vary significantly.(See figure 16, 17 and 18)

In such a scenario (see figure 17), the project essentially pushes water stress to its extreme, well into overexploitation territory, while the project's economic aspects remain unchanged. Consequently, social acceptance drops because of water scarcity. Under the influence of provincial revenue, the local government moderately reduces its support but still aims to maintain lithium production at the current rate since

Figure 17
Behavior of key variables and water stress simulating with 80 m3/ton water consumption



Source: System Dynamics Model.

Figure 18
Main indicators of the 80 m3/ton water consumption scenario and production modulated by provincial authorities due to water stress

Control Panel

Production Statistics

LiCO4 Produced	1.252.192 tons
Total Freshwater Consumption	100 millionM3
Total Brackish Water Consumption	673 millionM3
Remaining Sediments %	18,05 %

Economic Benefits for the State

Present Value of Federal Income	1.403 millionUSD
Present Value of Provincial Income	328 millionUSD
Max Annual Federal Income	170 millionUSD/yr
Max Annual Provincial Income	38 millionUSD/yr
Max Provincial Support	0,88
Min Provincial Support	0,54

Project Economics

Net Present Value	1.678 millionUSD
Internal Rate of Return	34,2 %/yr
Repayment days	1.972 da
Payback yr	5,40 yr

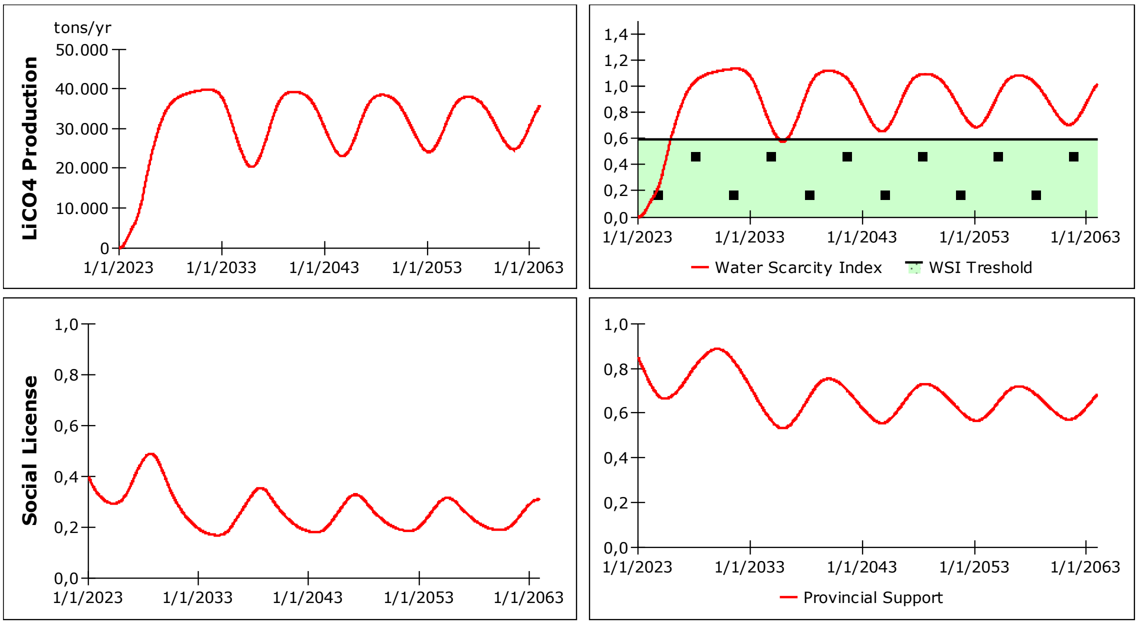
Water Stress

% of days with WSI Slightly Exploited	5,1 %
% of days with WSI Moderately Exploited	4,2 %
% of days with WSI Heavily Exploited	51,1 %
% of days with WSI Overexploited	39,7 %
Max Water Stress Index	1,12
Min Water Stress Index	0,19

Social Benefits

Max number of direct employees	766 Employees
Max number of indirect labor	3.447 Employees
Max % of local population employed	25,2 %
Present Value of Salaries	102 millionUSD
Base Social License	0,40
Min Social License	0,18
Max Social License	0,46
Max effect of employment on SL	1,72
Min effect of employment on SL	0,66
Min effect of WSI on SL	0,23

Figure 19
Behavior of key variables of the simulation with 80 m3/ton water consumption and production modulated by provincial authorities due to water stress



authorities do not employ water stress as a means to regulate production.

If provincial authorities decide to limit production as WSI surpasses the danger threshold, the system behaves seeking an equilibrium goal (figures 18 and 19).

(See figure 19) The model depicts an oscillating behavior (cycles of 12-year period) due to the balancing loop to correct water stress with the presence of significant delays to adjust both expectations and production. Economically, the project repays almost in the same period that the base case. NPV reaches 1,68 billion USD and IRR results in 34,2%. After a 40-year simulation, there are many years left of production since remaining sediments reach 18 %. The water stress diminishes significantly, yet the project remains a

Figure 20
Key indicators for the scenario with a water consumption of 50 m3/ton and a 50% reduction in annual rainfall, imposing a physical limitation on production

Control Panel

Production Statistics

LiCO4 Produced	898.694 tons
Total Freshwater Consumption	45 millionM3
Total Brackish Water Consumption	483 millionM3
Remaining Sediments %	41,18 %

Economic Benefits for the State

Present Value of Federal Income	934 millionUSD
Present Value of Provincial Income	231 millionUSD
Max Annual Federal Income	108 millionUSD/yr
Max Annual Provincial Income	25 millionUSD/yr
Max Provincial Support	0,85
Min Provincial Support	0,63

Project Economics

Net Present Value	943 millionUSD
Internal Rate of Return	22,2 %/yr
Repayment days	2.840 da
Payback yr	7,78 yr

Water Stress

% of days with WSI Slightly Exploited	5,9 %
% of days with WSI Moderately Exploited	4,1 %
% of days with WSI Heavily Exploited	90,0 %
% of days with WSI Overexploited	0,0 %
Max Water Stress Index	0,91
Min Water Stress Index	0,17

Social Benefits

Max number of direct employees	497 Employees
Max number of indirect labor	2.234 Employees
Max % of local population employed	16,3 %
Present Value of Salaries	69 millionUSD
Base Social License	0,40
Min Social License	0,23
Max Social License	0,40
Max effect of employment on SL	1,29
Min effect of employment on SL	0,65
Min effect of WSI on SL	0,42

significant portion of the simulation in the heavily exploited region. Social license and provincial support follow the oscillating behavior yet indicating that both stakeholders still receive significant benefits.

In all previous scenarios, it is assumed that LiCO4 production remains viable even in conditions of high-water stress. The subsequent scenario illustrates a situation where annual rainfall decreases by 50%, imposing a physical constraint on LiCO4 production (see figure 20).

(See figure 21) In this situation, all stakeholders experience reduced benefits. The NPV stands at 0.95 billion USD. Although the IRR exceeds 22%, more than 40% of sediments are still available for exploitation. Despite provincial and physical constraints, the project maintains a positive NPV, and water stress remains predominantly in heavily exploited region.

Figure 21
Behavior of key variables for the scenario with a water consumption of 50 m3/ton and a 50% reduction in annual rainfall, imposing a physical limitation on production

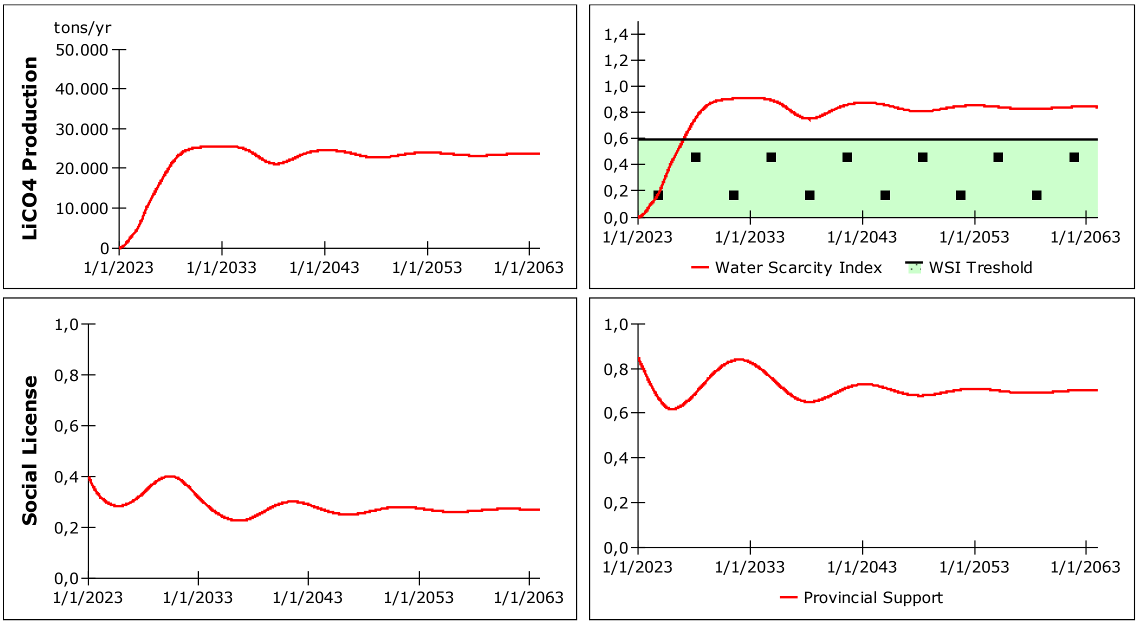


Figure 22
Main indicators of the simulation with 50 m3/ton water consumption scenario and a maximum production policy based on a threshold WSI of 0,6

Control Panel

Production Statistics

LiCO4 Produced	1.217.539 tons
Total Freshwater Consumption	61 millionM3
Total Brackish Water Consumption	654 millionM3
Remaining Sediments %	20,31 %

Project Economics

Net Present Value	1.324 millionUSD
Internal Rate of Return	23,6 %/yr
Repayment days	2.872 da
Payback yr	7,87 yr

Social Benefits

Max number of direct employees	652 Employees
Max number of indirect labor	2.932 Employees
Max % of local population employed	21,4 %
Present Value of Salaries	86 millionUSD
Base Social License	0,40
Min Social License	0,28
Max Social License	0,58
Max effect of employment on SL	1,58
Min effect of employment on SL	0,63
Min effect of WSI on SL	0,91

Economic Benefits for the State

Present Value of Federal Income	1.177 millionUSD
Present Value of Provincial Income	282 millionUSD
Max Annual Federal Income	143 millionUSD/yr
Max Annual Provincial Income	34 millionUSD/yr
Max Provincial Support	0,95
Min Provincial Support	0,60

Water Stress

% of days with WSI Slightly Exploited	10,1 %
% of days with WSI Moderately Exploited	89,9 %
% of days with WSI Heavily Exploited	0,0 %
% of days with WSI Overexploited	**0,0 %**
Max Water Stress Index	0,59
Min Water Stress Index	0,08

Policy Design

There is still the possibility of exploiting lithium without stressing the water availability. It's possibly to produce at the rate that drives WSI to the 0,6 value. That would be the maximum production rate. Using the equations (1) and (2), it is possible to calculate the maximum production as follows: *Maximum Production=5%*Average Yearly Rainfall* Area of the Salt Flat Basin*0,75*WSI/water_consumption_per_ton* (3). (See figure 22 and 23)

Figure 23
Behavior of main variables of the simulation with 50 m3/ton water consumption scenario and a maximum production policy based on a threshold WSI of 0,6

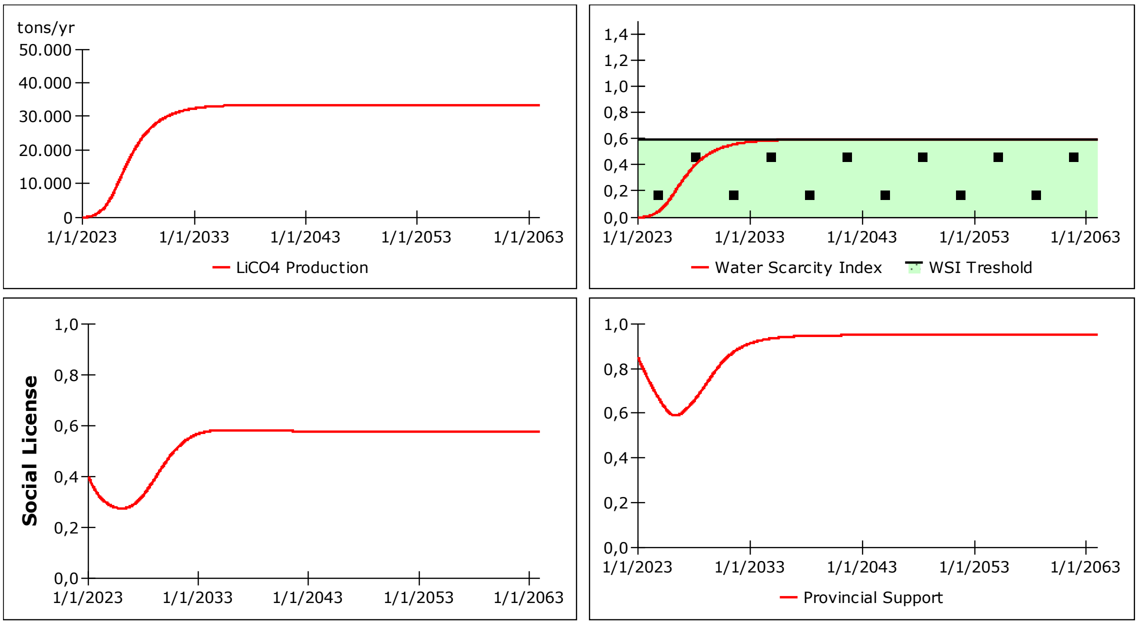


Figure 24
Main indicators of the simulation with 80 m3/ton water consumption scenario and a maximum production policy based on a threshold WSI of 0,6

Control Panel

Production Statistics

LiCO4 Produced	959.426 tons
Total Freshwater Consumption	77 millionM3
Total Brackish Water Consumption	516 millionM3
Remaining Sediments %	37,21 %

Economic Benefits for the State

Present Value of Federal Income	764 millionUSD
Present Value of Provincial Income	197 millionUSD
Max Annual Federal Income	85 millionUSD/yr
Max Annual Provincial Income	22 millionUSD/yr
Max Provincial Support	0,87
Min Provincial Support	0,60

Project Economics

Net Present Value	673 millionUSD
Internal Rate of Return	17,5 %/yr
Repayment days	3.654 da
Payback yr	10,01 yr

Water Stress

% of days with WSI Slightly Exploited	6,6 %
% of days with WSI Moderately Exploited	93,4 %
% of days with WSI Heavily Exploited	0,0 %
% of days with WSI Overexploited	**0,0 %**
Max Water Stress Index	0,58
Min Water Stress Index	0,10

Social Benefits

Max number of direct employees	396 Employees
Max number of indirect labor	1.780 Employees
Max % of local population employed	13,0 %
Present Value of Salaries	58 millionUSD
Base Social License	0,40
Min Social License	0,28
Max Social License	0,40
Max effect of employment on SL	1,07
Min effect of employment on SL	0,63
Min effect of WSI on SL	0,92

The simulation spanning 40 years indicates the feasibility of lithium carbonate (LiCO4) exploitation without causing undue strain on water availability, maintaining a positive Net Present Value (NPV) of 1.32 billion USD and a positive Internal Rate of Return (IRR) of 23.6%. Although the social impact is slightly lower than the base case, it remains significant. The project still possesses several years of production potential, offering opportunities to enhance profitability. Throughout the project's duration, the Water Stress Index (WSI) consistently remains within the moderately exploited range. Repeating the same process for the 80 m3/ton scenario, NPV reaches 0,67 billion USD and IRR remains positive at 17,5% (see figure 24).

In all scenarios with a production cap, both social acceptance and government support remain strong. Table 10 presents a sensitivity analysis by varying WSI thresholds under the 80 m^3/ton scenario. In every case, the Net Present Value (NPV) is positive, and water withdrawals stay below the overexploitation range.

Model validation

The model's validation process adhered to the criteria set out by Barlas (1996) and Sterman (2000). Structural assessments, including unit consistency checks, sensitivity analyses, and evaluations under extreme conditions, were conducted, revealing the model's robustness. With more than 230 variables encompassing diverse units such as operational, technical, financial, and motivational, the model demonstrates coherent interactions. It accurately replicates the anticipated operational and financial performance of a real-world case, drawing from comprehensive technical data as a reference. Sensitivity analyses exhibit consistent patterns and unveil unexpected insights. The incorporation of provincial support into the lithium production loop results in oscillatory behavior, while capping production diminishes the project's financial resilience, though the impact remains limited. If lithium price drops significantly and operating profitability falls below zero, production will eventually stop. Social support highlights the tension between employment opportunities and water stress, indicating a degree of tolerance and a clear threshold for rejection. Boundary and extreme condition tests consistently affirm model behavior. Following Sterman (2000) guidelines about coherence of physical laws, if rainfall reaches zero, production becomes unfeasible. When remaining sediments approach to zero, no more production is feasible. In cases of drought, if production continues without interruption, social approval eventually diminishes to zero, paralleled by a decline in provincial support.

Conclusion

According to our simulations, lithium extraction in the Puna region entails uneven risks for the involved parties. While the model indicates consistent project profitability and financial returns across all simulated scenarios, significant water stress is evident in all cases except for those relying on a WSI of 0.6 for production. In the face

Table 10
Sensitivity analysis based on varying WSI thresholds under the 80 m3/ton scenario

WSI Threshold	NPV billion	IRR %	Repayment Yrs.	% of time in heavily exploited range	% of time in overexploited range
0,65	0,79	18,7	**9,37**	81,6	0
0,70	0,90	19,8	**8,93**	85,1	0
0,75	1,00	20,7	**8,59**	86,6	0
0,80	1,10	21,6	**8,33**	87,3	0
0,85	1,20	22,4	**8,13**	87,8	0

Source: System Dynamics model.

of production limitations based on water scarcity, the expected IRR reaches 24%, almost the same IRR as the preliminary economic assessment (Burga et al., 2019, p. xvi). The simulation also indicates that achieving both profitability and sustainable lithium exploitation is possible through a gradual production increase, contingent upon considerations of water stress.

Both the federal and provincial governments accumulate substantial economic benefits. In aggregate, the present value of these benefits is nearly equivalent to the net present value (NPV) of the company. Proportionally, the federal government retains just over 80% of all government benefits. Simultaneously, lithium exploitation provides residents with employment opportunities and has a noteworthy positive impact on the local economy. Nevertheless, the model indicates the presence of a short-term tolerance threshold, primarily attributed to complexities related to water stress. It suggests that increased salaries and improved livelihoods may not sufficiently compensate for the depletion of water resources needed to sustain ecosystem services, particularly in cases of overexploitation. Under such circumstances, the advancement of lithium mining can only occur if both the government and companies choose to overlook the concerns of the residents.

The model adopts the concept of water stress due to the absence of specific studies on the hydrological dynamics of the region where the saline is located. With this precise information, it is possible to directly model the physical dynamics of water reserves and the risks associated with their exploitation. Despite the model's validation based on experts' generally accepted criteria, historical corroboration was not entirely possible. Certain historic information such as project economics and operating data have been successfully recreated. However, other variables could have not been validated due to incomplete or complete lack of information. The combined efforts of researchers and the data gathered during this study reveal that local communities are not a homogenous group. They comprise both local residents and indigenous native communities, some of whom endorse lithium exploitation, while others are opposed to it. Future research should focus on exploring into the intricate dynamics that intertwine these communities.

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