Simulation of the Environmental and Socio-economic Impact from the Lithium Industry within Producing Countries

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Abstract

Lithium, a lightweight metal, is used in various applications such as batteries, cell phones, ceramics, glass, and bipolar disorder medications. It's been brought to worldwide attention due to its high charge storage capacity in small places. However, concerns arise regarding the environmental and social impact of lithium extraction near mining communities. Issues include groundwater depletion, land destruction and community displacement. This study aims to develop a dynamic model using machine learning algorithms to measure the socio-economic and environmental impact of lithium mining projects. The proposed dynamic model reveals that, if keeping demand and production as of today, lithium mining will become an irresponsible practice by 2040. Hence, it is crucial to implement policies like battery recycling, reforestation initiatives by mining entities, and potential production limitations to ensure a sustainable lithium industry.

Keywords
Lithium, System Dynamics, Electric Vehicles, Environment, Machine Learning.

1. Introduction
Lithium has been used in different applications ranging from pharmaceutical products to the manufacture of air treatment systems. Recently there has been an increasing use from the commercial boom of lithium-ion batteries, which are used both in electronic items for personal use such as computers and telephones and in the electric vehicle market. It is precisely in this category where its main driver of demand lies. Although it is a market with relatively low penetration, its growth in recent years has been explosive and its annual sales are expected to grow in the order of an average compound annual rate of 27% towards the end of the decade (González and Cantallopts 2021).

On the other hand, it is worth noting the importance that lithium mining has obtained in recent years, thanks to this element various uses of it are derived; in which it stands out more for the creation of electric batteries, which have been one of the clean energy trends for the benefit of the environment. However, there has also been great uncertainty about the effects within mining communities; the exploitation of this mineral within the countries involved has been affected both positively and negatively.

It is thanks to this growth in demand by various industries, among which the automotive industry stands out for the use of lithium in the batteries used in electric cars, that the need to exploit lithium in increasing quantities, creation of new lithium mines and expansion of existing ones naturally follows. As it is a natural resource, it is pertinent to consider the impact that the practice of extracting it has on its environment.

From the economic point of view, the relevance that lithium production has gained globally can be directly linked to the price of this mineral per metric ton in recent years, the portal "Trading Economics" reports in its daily records of the price worldwide of this metal a significant growth, going from an average value of $ 19,000 dollars per metric ton in May 2017, to have a value of $83,000 dollars at the beginning of November 2022. This reflects the growing demand for this mineral having an almost exponential behavior and generating jobs of all kinds of nature around the world, it is reported that the 5 largest lithium mining companies in the world generate, today, more than 21,000 jobs worldwide meaning an industry of 7.42 billion dollars worldwide.

Today, the 10 countries with the largest lithium reserves in the world, according to the U.S. Geological Survey, are: In first place, Bolivia with 24.6% of world reserves, followed by Argentina with 22%. 6%, Chile with 11.2% (lead the Lithium Triangle), then the United States with 9.2%, Australia with 7.5%, China with 6% of world lithium reserves, Congo with 3.5%, Canada with 3.4%, Germany with 3.2% and finally Mexico with 2%.

As the exploitation of lithium is a field not deeply studied, this paper aims to understand the ecological impact based on its processes and the elements that participate within this exploitation, by using simulation techniques such as System Dynamics, so that allow us to determine important contributions and discoveries.

1.1 Objectives

General Objective

- Analyze the socioeconomic and environmental impact of the lithium industry through a dynamic analysis to study its future behavior with a margin of error of no more than 20%.

Specific Objectives

- Analyze the socioeconomic impact generated by the lithium industry in producing countries through statistical and dynamic analysis.
- Measure the environmental impact caused by the lithium industry in producing countries through statistical and dynamic analysis.
- Study different scenarios of the lithium industry and its economic and environmental impact in producing countries.

2. Literature Review

According to the literature review, it was found that the evolution of the lithium industry in recent years is an important topic to investigate because, as mentioned by several authors, including Jones et al. (2021), the demand for lithium products has grown by more than 124 thousand tons from 2015 to 2019. Among its main applications are the manufacture of glass, ceramics, lubricants, etc. So, the demand for these applications is related to economic drivers such as construction, industrial production, and the manufacture of aluminum and steel. However, the demand for lithium for industrial applications has been losing market share in recent years due to the significant increase in EVs and other lithium applications for batteries. Nevertheless, this does not mean that industrial demand for lithium has decreased, on the contrary, the CRU estimates that lithium demand has grown at a 2010-2019 CAGR of 4.3% to 135,365 LCE tons in 2019.

In addition, lithium allows the storage of energy derived from renewable energy, the use of lithium can lead to a considerable reduction in greenhouse gas emissions, however, lithium mining puts at risk the natural balance between freshwater and brackish water masses, thus creating a threat to the availability of water for ecosystems and human populations that inhabit the area (Heinrich Böll Stiftung 2020). It is for this reason that it has bought an important role in the debates on the energy transition and the growing need to reduce dependence on fossil fuels, in turn, this has caused different discussions and initiatives to be generated within the public, private, and academic sectors.

At present, with the research conducted so far, the possible effects on the environment of the exploitation of lithium in salt flats are unknown. The use of large amounts of fresh or brackish water, potentially used for agriculture and purification, makes several researchers wonder about these impacts (Flexer et al. 2018). Among the main effects of lithium mining can be mentioned the excessive use of drinking water, modifications in the fauna of the region, and contamination of napas, among others. According to Villalobos (2019), about 42 to 45 thousand liters of fresh or slightly brackish water are used for every 600 thousand liters of brine. The reservoirs of salt flats have margins of fresh and brackish water, so, being the same source, the extraction of brine often lowers the level of drinking water reserves (Del Barco and Foladori 2019). In addition, Handelsman (2018) adds that mining activity directly affects the way of life of the communities surrounding the lithium extraction territory, putting the interests of the mining sector in conflict with the ancestral customs of the native peoples.

Various measures that could be implemented to reduce the impacts that the industry could have on the environment or the community are not implemented since they usually are an extra cost that threatens the profits of the company producing this metal. How the lithium industry is advancing puts the maximization of corporate profit before the preservation of cultural diversity and respect for the history of Indigenous peoples (Handelsman 2018).

Finally, as mentioned by Marchegiani et al. (2019), few works explore the local impacts of lithium extraction, depending on the social and environmental sustainability of the projects. Considering the above, it can be noted that there is a notable lack of research that finds the factors that may benefit or, on the contrary, harm this industry.

Through the review of the literature, the key point of research is the "Lithium Triangle", a geographical area that has the most extensive and important lithium salt flats in the lithium mining industry in Latin America, and one of the most important worldwide. It is a shared land between Argentina, Chile, and Bolivia that has the largest lithium reserves in salt flats in the world, representing 58% of the world's lithium resources (Obaya 2021). These three countries have dedicated in the last two decades, a significant effort of investment of both national and international capital, technological applications, and strategies of new business models that have led each of these countries are expanding their productive links to technological sectors that had not been considered before. This phenomenon reaches international dimensions since the main companies interested in the exploitation of these resources are of foreign origin.

3. Methods

The methodology to be used is divided into three, firstly, it begins with scientific research in a qualitative way by developing the systematic and organized steps to give a logical structure. In Figure 1, a visual summary of the main steps used to carry out the research can be observed. The John Sterman's System Dynamics methodology will be carried out (see figure 1).

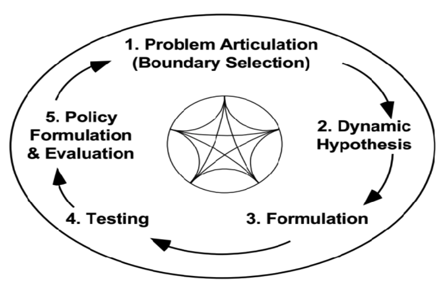

Figure 1. System Dynamics by John Sterman.

Applying the System Dynamics methodology consisted in defining the elements that would form part of the system to be built, once defined, the dynamic hypothesis was established together with the necessary cycles to demonstrate the behavior of the lithium industry in the producing countries and its feedback system; Once this stage was completed, the dynamic hypothesis was transformed into a dynamic simulation model that complied with the current characteristics. At the end of this stage, the tests of extreme conditions were carried out to validate the model, as well as the consistency of units and structures, this to eliminate errors within the model and thus be able to continue with the evaluation and formulation of model policies, where different scenarios and sensitivity tests that will yield the desired information.

Once the information of these variables was confirmed to come from official sources, it was all put into main databases to clean the data and ensure its quality by removing duplicates, ensuring it followed a chronological order, handling missing values and normalizing variables, by doing so the suitability of the data was ensured for subsequent analysis.

4. Dynamic Hypothesis

The dynamic hypothesis developed for the investigation of this paper is based on the mapping of the variables extracted from the literary and historical information. Then, the variables are connected to create the feedback structure that systematically expresses the current situation of the lithium industry. Figure 2 below explains each of the feedback loops obtained.

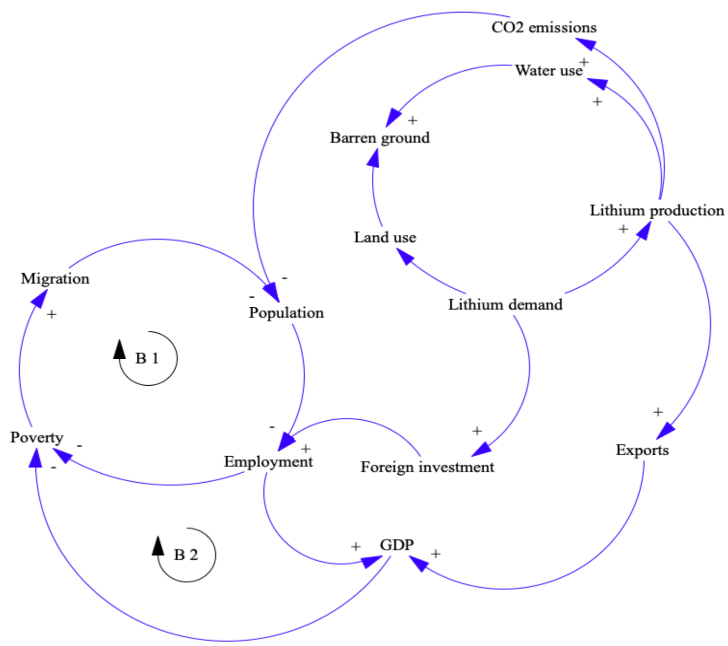

Figure 2. Dynamic hypothesis

From this hypothesis, the relationship between the variables can be recognized, and the structural analysis of the socioeconomic and environmental elements that are part of the effects of the lithium industry can be specified; Within this structure, the presence of two balance cycles can be recognized.

5. Stock and Flow Diagram

For the creation of the simulation model that is presented in figure 3, the dynamic hypothesis described in the previous section was used as a base.

The stock variables used within the model (differential equations) are:

- d(population)/dt = births(t) - deaths(t)
- d(employment)/dt = generation of jobs(t) - unemployed(t)
- d(migration)/dt = immigration(t) - emigration(t)
- d(lithium produced)/dt = production(t) - sales(t)
- d(water resources)/dt = water input(t) - unexploitable water(t)

Within the dynamic model, the five stock variables mentioned above are present, as well as the constants used, the auxiliary variables with the equation, the input and output flows, in addition to the constants used for the consistency of units that allow the correct functioning of the dynamic model. The other equations and the parameter values are described in depth in tables 1-7 in appendix A.

6. Validation

In this stage, the various tests that validate this model will be carried out. As a first check, the validation of the structure and units was carried out, where it is confirmed that the structure of the model is consistent with the descriptive knowledge. In addition, each of the equivalences and parameters within the model correspond to the real system, yielding logical behaviors. As the last validation tests, the extreme conditions test, the sensitivity analysis and scenarios on the dynamic model were applied. All tests were passed successfully.

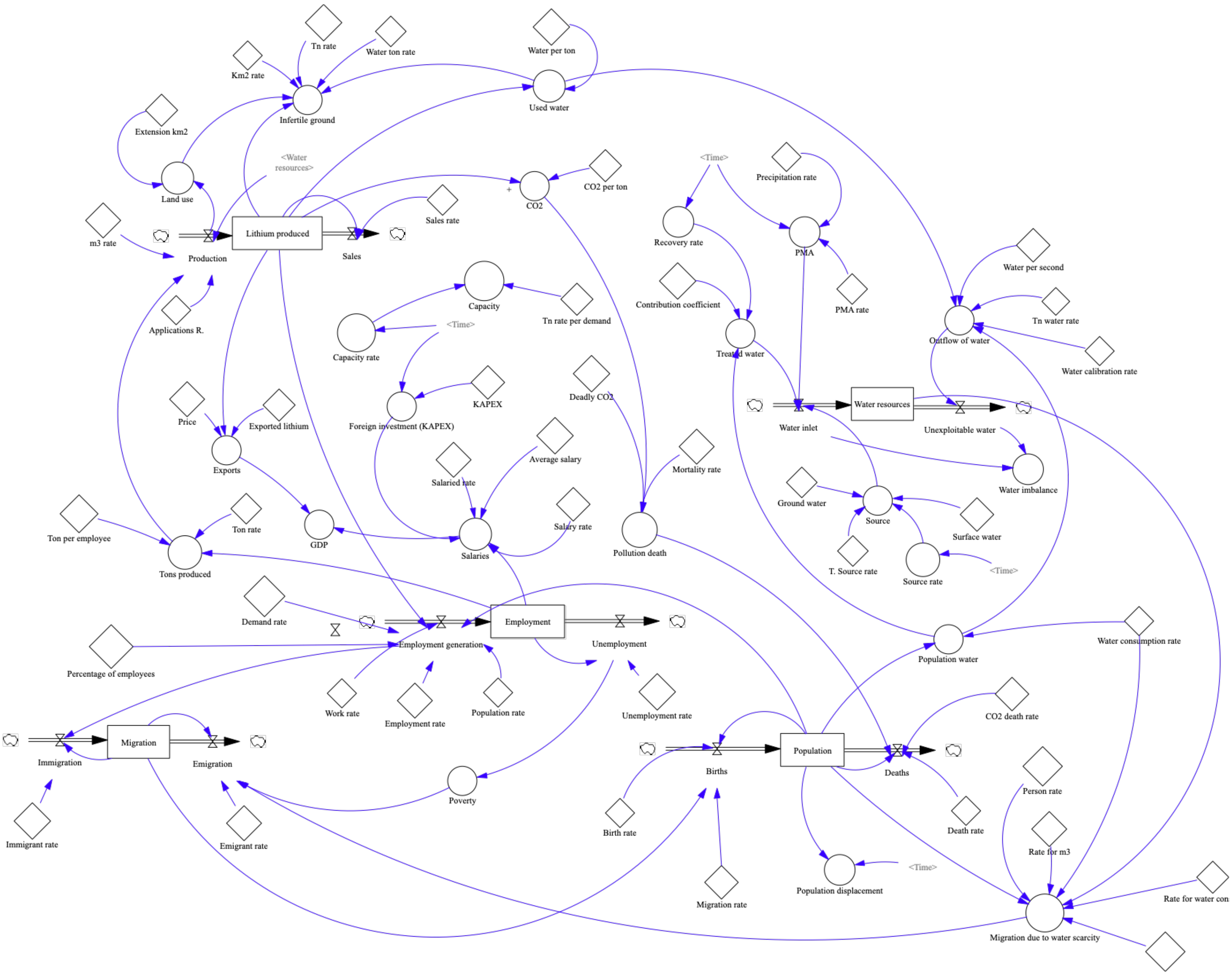

Figure 3. Dynamic Model

It should be mentioned that these multiple validation tests were applied to the three studied countries (Chile, Argentina, and Bolivia); yielding to very similar results between these countries.

8. Results and Discussion

8.1 Sensitivity analysis

Continuing with the sensitivity models, its main function is to evaluate the model against possible changes that can occur on its structure, thus identifying how sensitive the model is to uncertainty scenarios (Sterman 2000). For the development of the sensitivity models, changes were used within the parameters, with their respective values assigned to each country according to their base scenario. The results obtained by the country of Chile are presented in figure 4. It is worth mentioning that these same tests were carried out in the other two countries that make up the lithium triangle.

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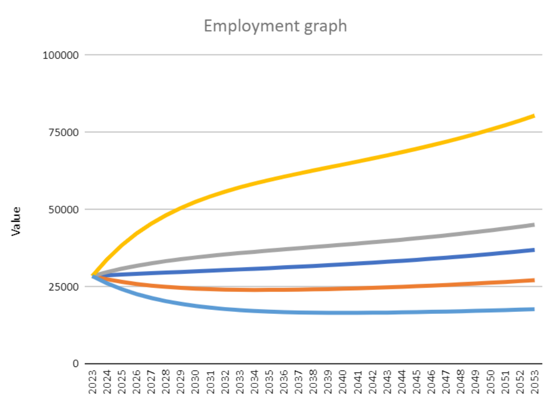
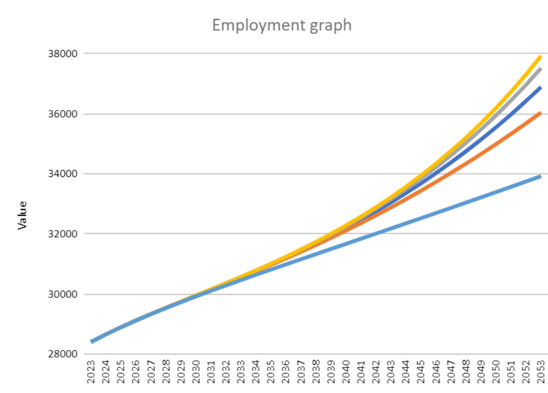
<tr><td>Demand rate</td><td>Emigration rate</td></tr>
<tr><td colspan="2">Employment</td></tr>
<tr><td>
</td><td>
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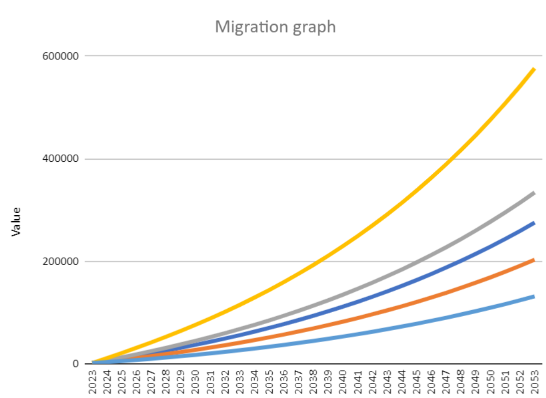
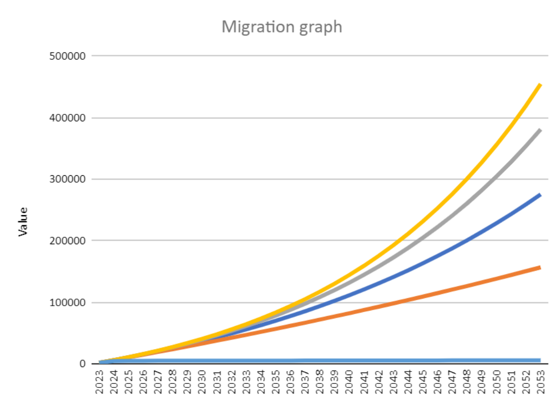
<tr><td>
</td><td>
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<tr><td colspan="2">Population</td></tr>
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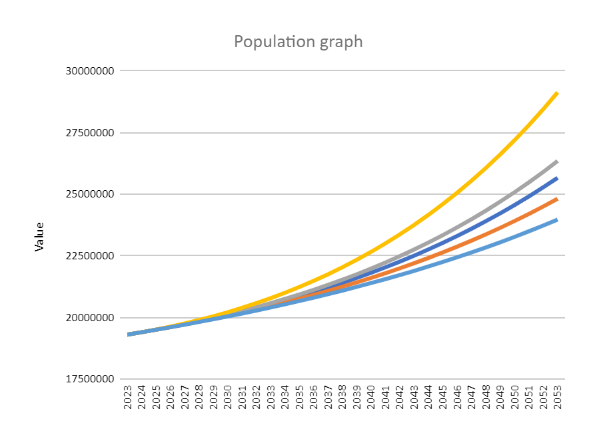
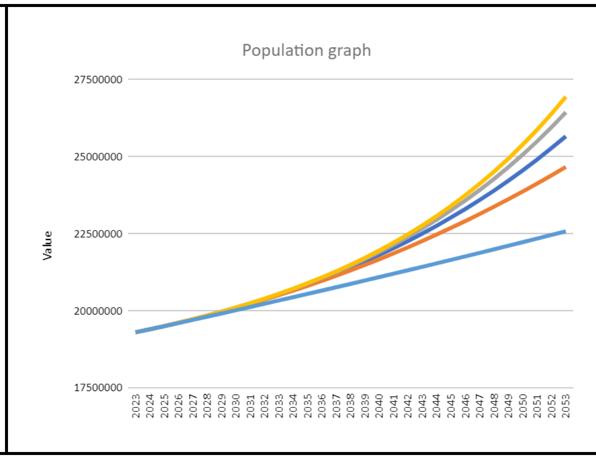
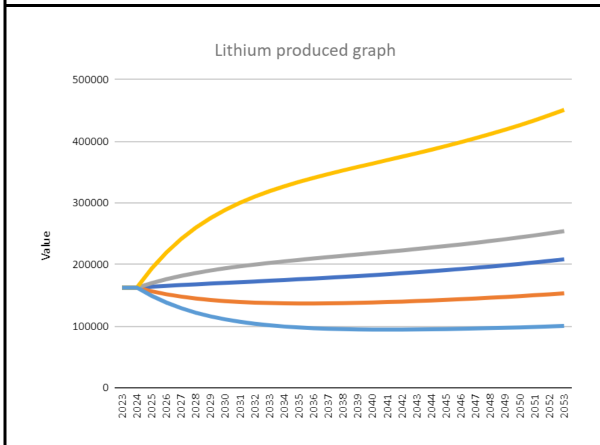
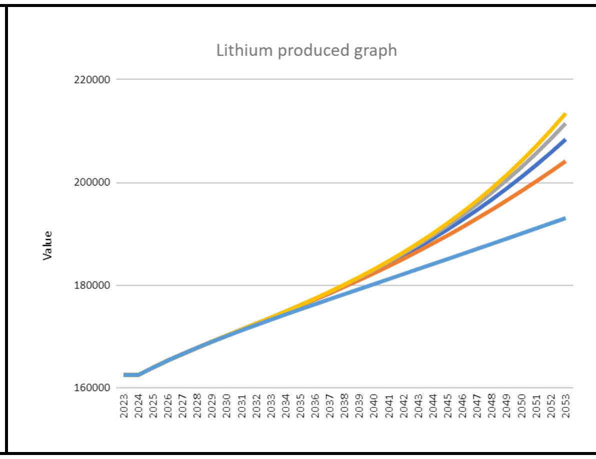


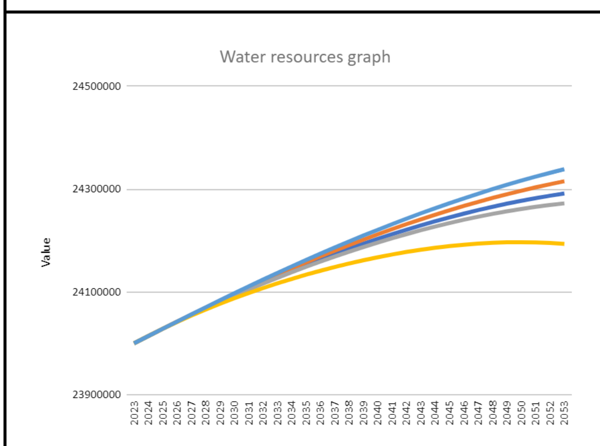


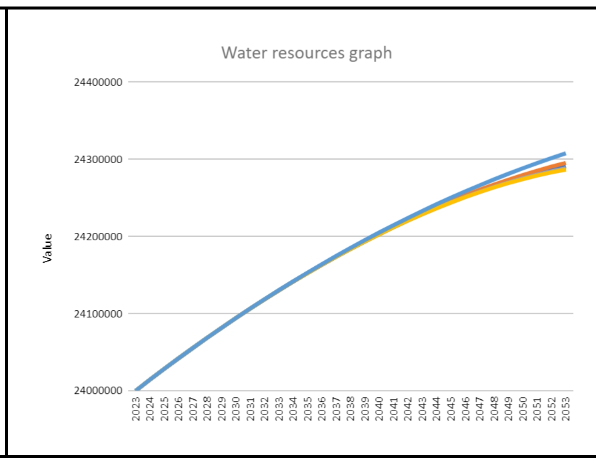
Lithium produced





Water resources





CO_2

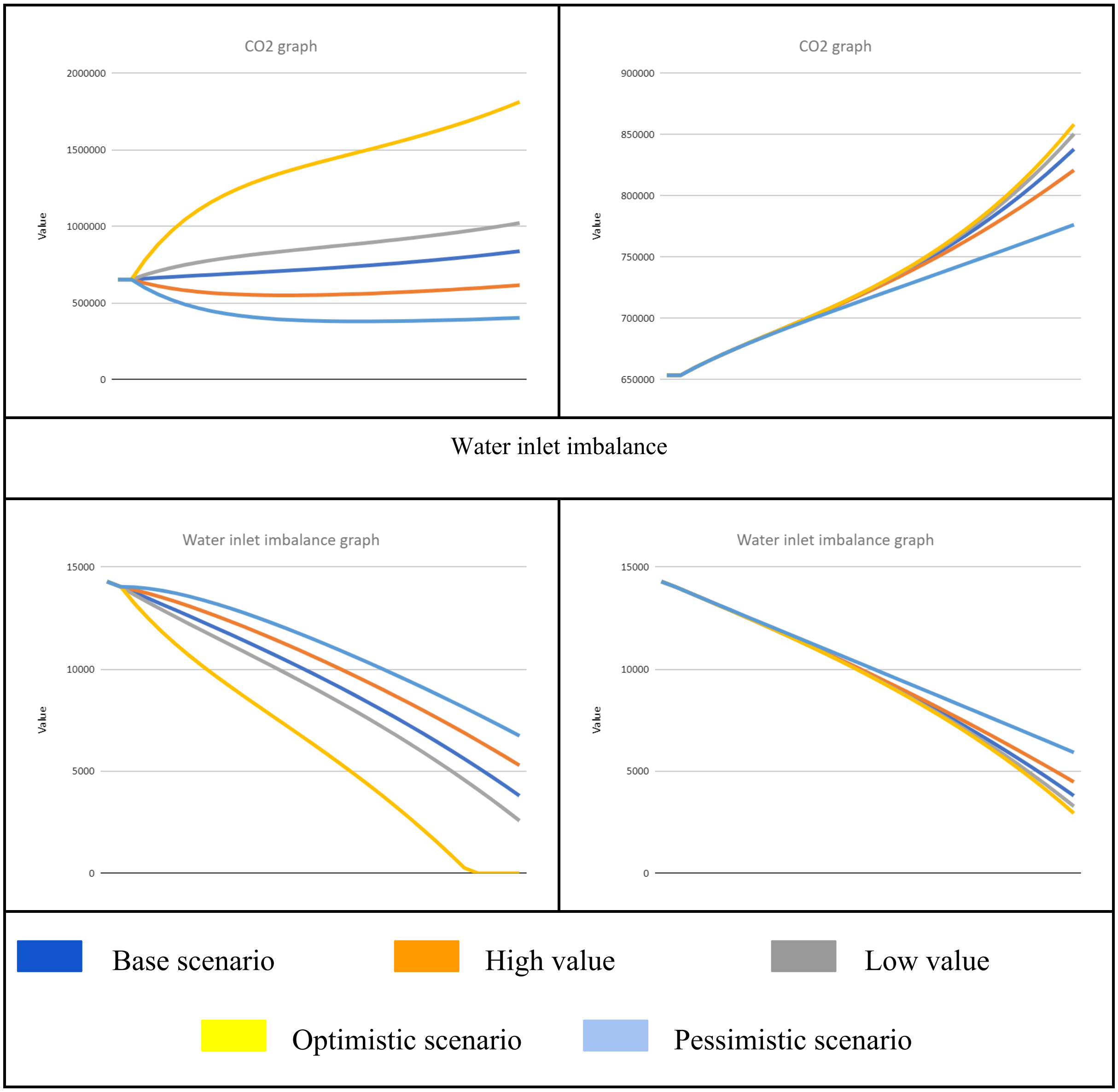


Figure 4. Results of sensitivity analysis, Chile.

When analyzing each one of the graphs with their respective change of values within the parameters, it can be observed that all the variables have undergone changes, therefore, we can say that the dynamic model presents sensitivity in its entirety; specifically, for the case of Chile, its different scenarios show changes compared to its baseline scenario. To conclude the validation stage of the model, it was verified that all the variables had the correct units and that they were coherent when relating to each other.

The best scenario for Chile, Argentina and Bolivia is the base scenario, that is, to continue and maintain the pace of production that is currently in place, neither more nor less, but we know that this is not possible due to the growing demand in the world for this element (lithium). Taking this relationship between demand and the effects of lithium production into account, the worst scenario that could arise would be the optimistic scenario, presenting the highest values of production and employment, accompanied by the highest CO_2 emissions, as well as the reduction of water resources. However, there are alternatives that help us maintain socioeconomic benefits without major impacts on the environment; these alternatives can be seen developed in the following section.

8.3 Policy evaluation

In this stage, the specifications of the scenarios and the future conditions that could improve the negative consequences of the lithium exploitation are evaluated. Considering the structure of the system, policies are incorporated in the model, looking for creating synergy between them and compensation responses.

Recycling policy: currently, one of the largest applications for which lithium is required is for the manufacture of automobile batteries due to the importance it entails for the environment, however lithium batteries become highly polluting waste, therefore recycling them should be the main destination. Currently, within the lithium triangle, current recycling initiatives have not allowed this process to be carried out in a way that could lead to a significant reduction in pollution and a well-developed recycling cycle (Derichebourg 2020). This policy suggests that, although it is not possible to take advantage of 100% of the materials used to create a lithium battery, at least 58% can be used, as mentioned by in Obaya and Céspedes (2021), to reduce the extraction and production of lithium directly from the mines and thus considerably reduce the pollution that this industry generates. Figure 5 shows the integration of the policy within the dynamic model. The parameter values, and equations that feed this module are found in appendix A in tables 8-11.

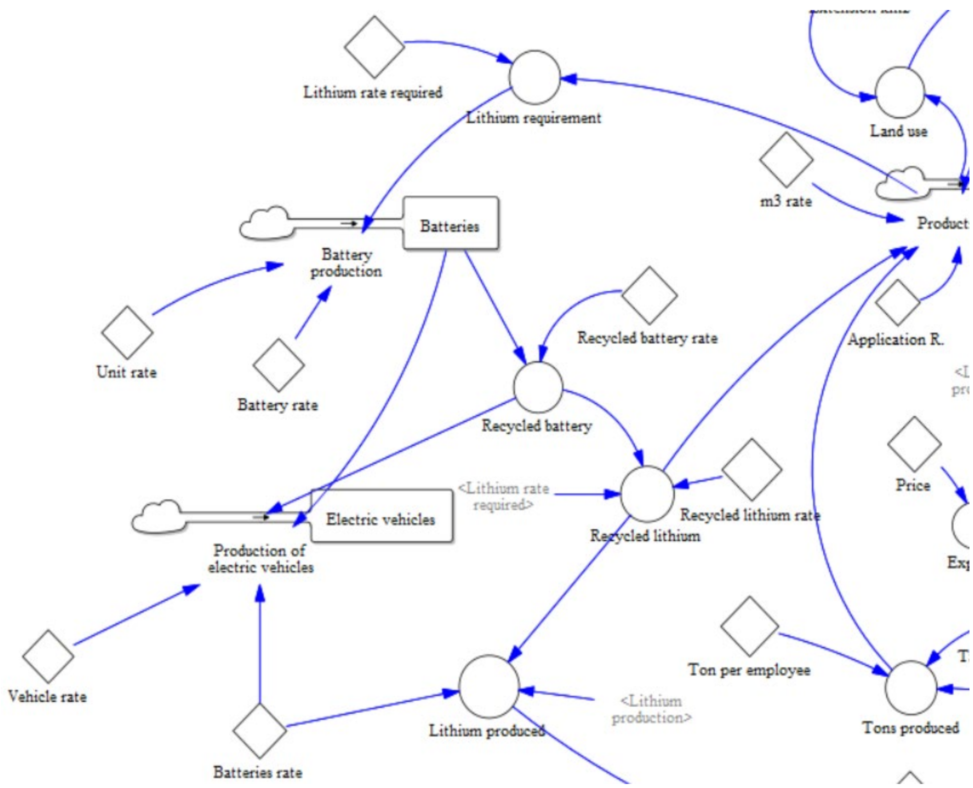


Figure 5. Recycling policy

Reforestation policy: Trees help to maintain the environmental balance, and the lack of these can cause an increase in global temperature, thus causing droughts in different regions. Trees can inhale, on average, between 10 and 30 kg of CO_2 per year (Aquae Fundación 2016). In addition to this, another benefit they provide is that they can help to maintain river flows and increase rainfall forecasts. According to Aquae foundation (2022). This policy intends that the companies in charge of lithium production are committed to the reforestation of their territory to mitigate the CO_2 emissions caused by this industry as well as the recovery of rivers and flows. Also, companies can become socially responsible with the environment. Figure 6 shows the integration of the policy within the dynamic model. The parameter values and equations that feed this module are found in appendix A in tables 12-15.

Pollution policy: carbon dioxide is one of the main responsible for 63% of climate change, which is why reducing these emissions is one of the most important responses to curb climate change. The benefits of mitigating CO_2

emissions are the prevention of negative impacts such as soil degradation or water pollution (Gobierno de México 2020). That is why this policy intends for companies to stop the increase in lithium production when they have exceeded a level of CO_2 emissions declared as not dangerous for the environment and for people; however, this policy does not intend for companies to stop produce but do it responsibly. Once production has reached the level of emissions considered non-harmful, production should remain constant. Figure 7 shows the integration of the policy within the dynamic model. The parameter values and equations that feed this module are found in appendix A in tables 16-17.

Figure 8 shows the results of the simulations of the implemented policies.

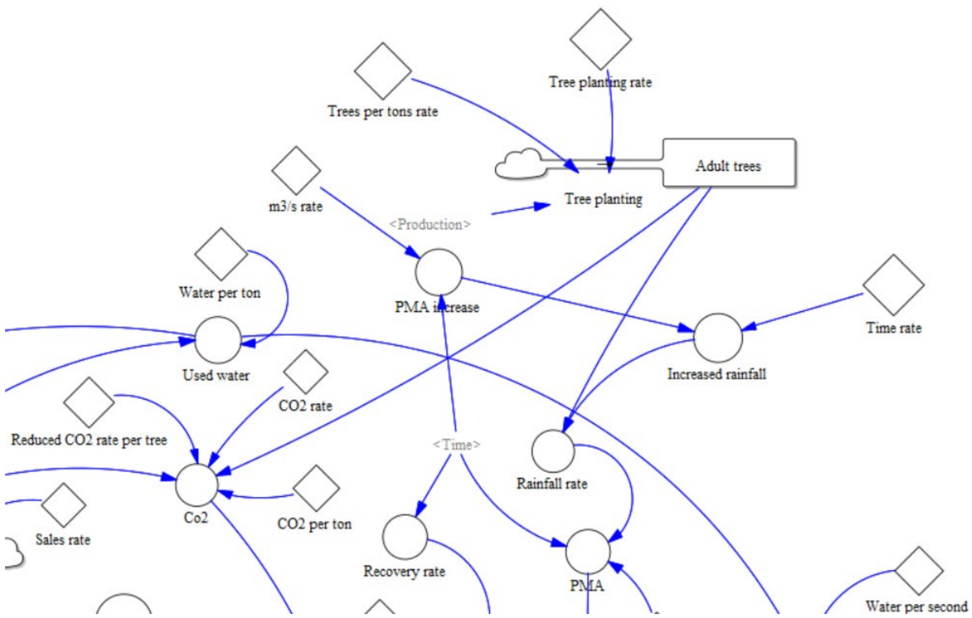


Figure 6. Reforestation policy

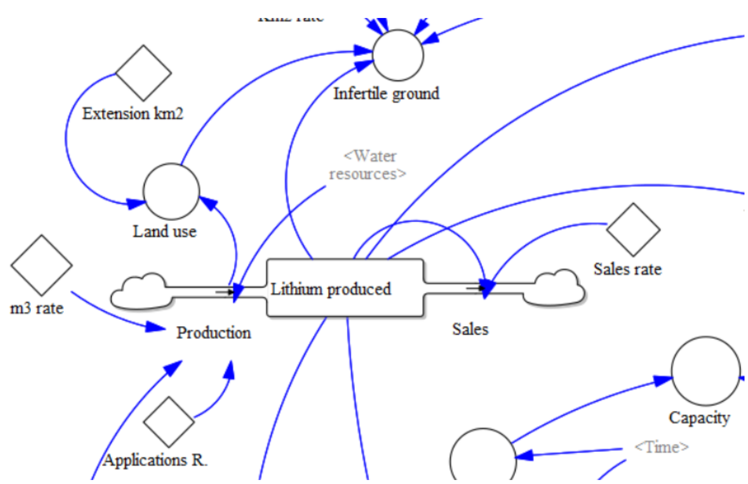


Figure 7. Pollution policy

Reserved scenarios	Neutral scenarios	Optimistic scenarios

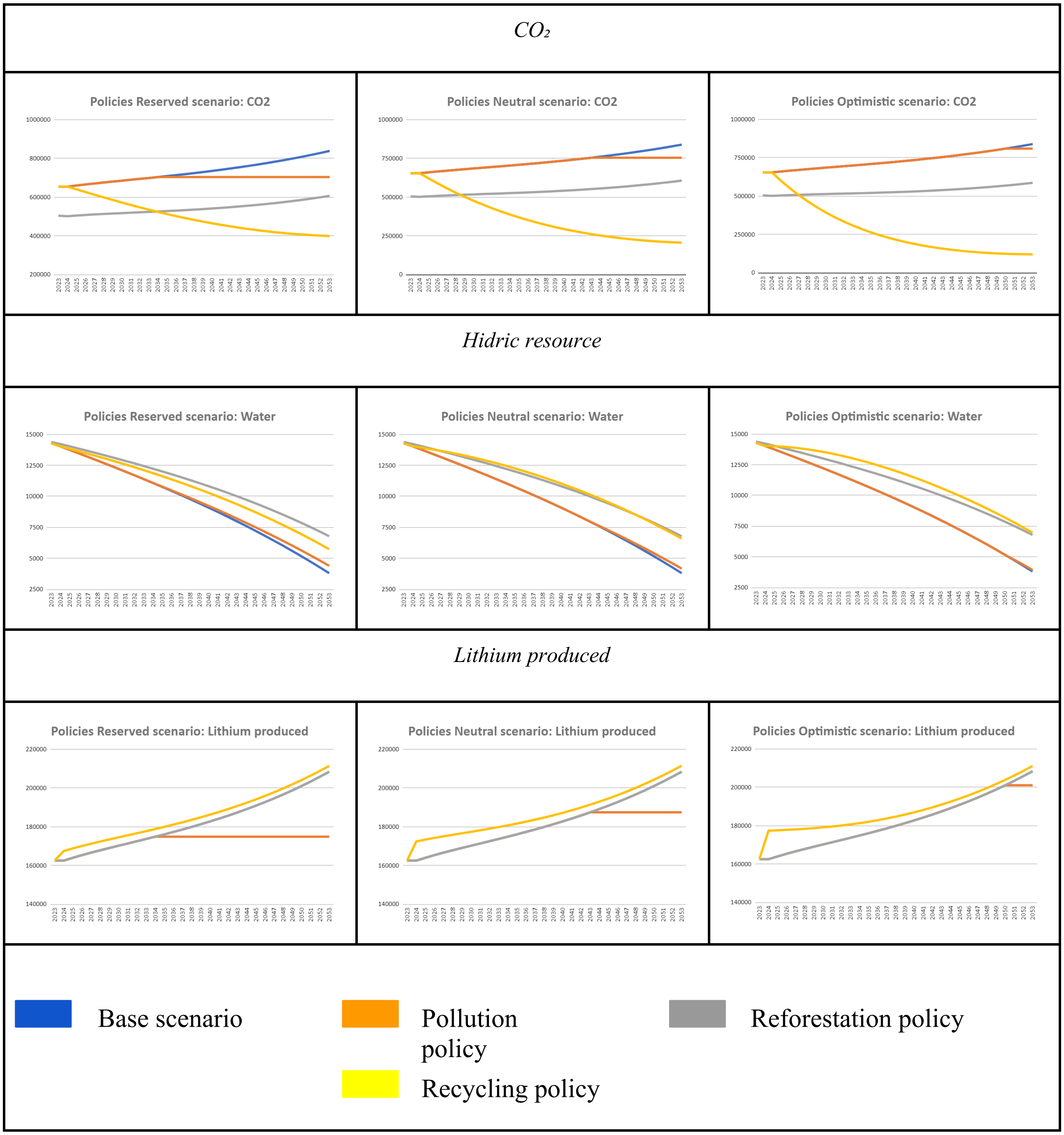


Figure 8. Policy results, Chile.

The policy that leads to the best results while maintaining socioeconomic benefits and at the same time manages to mitigate the environmental effects caused by lithium production is the recycling policy. This policy maintains the lowest levels of CO_2, high production and the water resource presents a delay of its consumption in comparison with the other policies. It should be noted that the policy that obtained the worst results was the pollution policy, since it fails to greatly reduce the negative effects on the environment and does not allow the growth of production.

8. Conclusion

It can be concluded that the best policy that brings the greatest benefit both for the reduction of CO_2 emissions and care of water resources is the battery recycling policy in the three scenarios described, in addition to the fact that this policy does not affect the amount of lithium produced; so there would not be a negative impact on the industry. As a result, it would be a good option for the producing companies to dedicate efforts to start recycling these batteries as part of their industrial activity.

On the other hand, the reforestation policy also presents a notable reduction in terms of CO_2 emissions and recovery of aquifers; however, it is a more long-term option, since the desired effects will not be reflected immediately. Finally, the pollution policy presents a moderate reduction in emissions, as well as recovery of the water resource, however, even though it is the policy that has the least impact, it could be the least expensive policy to adopt by companies.

Finally, the beginning of these regulations means allowing the industry to continue extracting this metal for international demand, leading also to a positive contribution to the GDP of the country where it is practiced; nevertheless, the negative environmental impact derived from the lithium exploitation does not worth its economic benefit. Additionally, it appears that by 2040 the lithium industry might be considered a harmful practice for the environment. In the case of ignoring regulations and possible policies in lithium production, its negative impact on society and environment can be accelerated.

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Biographies

Carlos D. López is an IB graduate, Business Management Engineer and certified ISO 9001 auditor with work experience in data science and consulting along some of the largest Mexican companies within the financial and construction industries. He has led different groups such as his major's student council as vice-president in 2019 and an "Odyssey of the Mind" team back in 2010 and 2011 as an international contestant. His interest in research since a young age has brought him to develop a passion for acquiring new knowledge in relevant world topics. His interests include business management, clean energies, data science, consulting, history, and philosophy, combining different thinking methods with a passion for public speaking to achieve large goals.

Fernanda Reyes Is a student in Business Management Engineering at the Universidad de Monterrey. She has work experience as a Regulatory Assistant for the Team SISOPA Monterrey group specialized in the hydrocarbons industry; also performed her professional practices within the company FRISA Forjados with the implementation of a dashboard of machine failures within the maintenance area and has also taught digital image manipulation and design courses. She has participated in various leadership courses and entrepreneurship promoters, as well as in student groups within her academic studies. Her research interests include modeling, marketing, simulation, applying dynamic systems and data analysis.

Constanza J. Martínez University student about to graduate from the Engineering career in Business Management from the University of Monterrey, Mexico in 2018 and 2023, respectively. She has completed professional internships at Grupo SCANDA, a project focused on the control of databases for customer segmentation, as well as professional practices within Meritor Mexican Holdings for the development of preventive maintenance. She has also participated in student groups as well as the UNICO union of Coahuilenses. As work experience, she has been an administrative assistant at MYSE, a group specialized in maintenance and supply of traveling cranes. Her research interests include system dynamics, simulation models as well as the implementation of machine learning algorithms.

José D. Morcillo received the Electronic Engineer degree, and the M.Sc. degree in industrial automation from the National University of Colombia, Manizales, in 2010 and 2012, respectively. He got his Ph.D degree in Computer Science from National University of Colombia, Medellín, in 2018. He also worked as a postdoctoral researcher at the National University of Colombia, Manizales, in 2020. In 2010, he joined the Perception and Intelligent Control Group, and in 2014, joined the Systems and Informatics Group, working in different I + D projects. Currently, he is working as a full-time professor at University of Monterrey, Mexico, in the Engineering and Technologies Department. His research interests include modeling, simulation and control of power electronics and electricity markets, applying the theory of dynamical systems, system dynamics and data analytics/machine learning.

Appendix A : TABLE-1

Constants	*Values*			*Units*	*Autors*
	Chile	***Argentina***	***Bolivia***		
Extension Km2	25	25	25	km2/Tn	Mohr, Steve H., Gavin M. Mudd, and Damien Giurco.
Water per ton	2000	2000	2000	m3	Departamento de Ingeniería Química y Procesos Minerales de la Universidad de Antofagasta
CO_2 per ton	4.022	6.65	3	kg	InvestChile, El Mercurio
Contribution coefficient	0.75	0.58	0.62	1/yr	Ortiz Muñoz Pablo, OECD
Precipitation rate	1.129e-11	1.87e-11	2.12e-11	m3/s	ClimateData, Banco Mundial de datos, SQM
Water per second	3.1536e+07	3.1536e+07	3.1536e+07	s	Calibración
Water calibration rate	280	100	350	Dmnl	Calibración
Ground water	15499.6	22880	7581	m3/s	Ortiz Muñoz Pablo,OECD, Fuentes Claros Ebeliz
Surface water	13745	3120	17689	m3/s	Istúriz Diego, Bertoni Juan Carlos y Del Valle María, Fuentes Claros Ebeliz
Water consumption rate	2.198e-06	2.083e-06	1.435e-06	m3/hab/s	Superintendencia de Servicios Sanitarios, Tolcachier Alberto, Control Social de Agua Potable y Saneamiento
Death rate	7/1000	9/1000	9.3/1000	1/yr	Banco Mundial, Expansión
Birth rate	12/1000	14/1000	2.5/1000	1/yr	Banco Mundial, Expansión
Unemployment rate	0.173	0.062	0.058	1/yr	INDEC, INE
Employment rate	0.182	0.15	0.06	1/yr	SONAMI, Minería Chile, KPMG, INE
Demand rate	1	1	1	Dmnl	Base de datos maestra
Sales rate	1	1	1	1/yr	Base de datos maestra
Emigrant rate	0.034	0.0237	0.0777	1/yr	Expansión
Immigrant rate	0.075	0.0503	0.0137	1/yr	Expansión

TABLE-2:

Variable	*Equations*	*Units*
Land use	Extension km2*Production	km2/yr
Infertile ground	(((Lithium produced*Tn rate)*((Water ton rate*Tn rate*Used water)))*Km2 rate)-Land use	km2/yr
Used water	Lithium produced*Water per ton	m3*Tn
CO_2	CO_2 per ton*Lithium produced	kg*Tn
Capacity rate	0.01*(Time-2022)	yr
PMA	Precipitation rate*((Time-(2023-1))*PMA rate)	m3/s
Treated water	((Population water*Contribution coefficient)*Recovery rate)	m3/s
Outflow of water	((Used water/Water per second)*Tn water rate*Water calibration rate)+(Population water*Water calibration rate)	m3/s
Source	(Ground water+(Ground water*(Source rate*"T. Source rate"))+(Surface water+(Surface water*(Source rate*"T. Source rate")))	m3/s
Source rate	-0.007*(Time-2022)	yr
Population water	(Population*Water consumption rate)	m3/s
Tons produced	((Employment*Ton per employee))*Ton rate	1/yr
Exports	(Lithium produced*Exported lithium)*Price	USD
GDP	Exports+Salaries	USD
Foreign investment (KAPEX)	KAPEX*(Time-2022)	USD*yr
Pollution death	(CO_2/Deadly CO_2)*Mortality rate	hab
Water imbalance	IF THEN ELSE(Water inlet-Unexploitable water>=0, Water inlet-Unexploitable water, 0)	m3/s

TABLE 3:

Variable	*Equation*	*Constants**			*Units*
		Chile	***Argentina***	***Bolivia***	
Capacity	((Capacity rate+1)****C***)*Tn rate per demand	210000	37500	45000	Tn
Poverty	Unemployment****C***	0.17	0.406	0.363	hab/yr
Salaries	((Average salary*Employment)* Salaried rate)+(("Foreign investment (KAPEX)"****C***)*Salary rate)	0.4	0.65	0.55	USD

TABLE 4:

Input flow		
Flow	*Equation*	*Units*
Employment generation	IF THEN ELSE((Lithium produced*Population rate*Work rate)>0,(Employment rate*(Population*Percentage of employees)*Demand rate),0)	hab/yr
Immigration	((Immigrant rate*Migration)+Employment generation)	hab/yr
Production	IF THEN ELSE(Water resources*m3 rate>=2000, Tons produced*"Applications R.", 0)	Tn/yr
Water inlet	Treated water+Source+PMA	m3/s
Births	(Birth rate*Population)+Migration*Migration rate	hab/yr

TABLE 5:

Output flow		
Flow	*Equation*	*Units*
Unemployment	Unemployment rate*Employment	hab/yr
Emigration	(Emigrant rate*Migration)+Poverty+Migration due to water scarcity	hab/yr
Sales	(Lithium produced*Sales rate)	Tn/yr
Unexploitable water	Outflow of water	m3/s
Deaths	(Death rate*Population)+(Pollution death*CO_2 death rate)	hab/yr

Table 6.

Level variables					
Variable	*Equation*	*Initial value*			*Units*
		Chile	***Argentina***	***Bolivia***	
Lithium produced	(IF THEN ELSE(Lithium produced<=0, 0, Production-Sales))	162477	31770	600	Tn
Employment	IF THEN ELSE(Employment<=0, 0, Employment generation- Unemployment)	28400	37764	15105	hab
Migration	Immigration-Emigration	1642	2344	-4666	hab
Water resources	IF THEN ELSE(Water resources<=0, 0, Water inlet-Unexploitable water)	2.4e+07	2.4e+07	2.4e+07	yr*m3/s
Population	IF THEN ELSE(Population<=0, 0, Births-Deaths)	19300000	45808747	12079472	hab

Table 7.

Parameters	Base scenario	Low value	High value
Unemployment Rate / Chile	0.173	0.09	0.2
Unemployment Rate / Argentina	0.062	0.03	0.10
Unemployment Rate / Bolivia	0.058	0.025	0.10
Optimistic Scenario Unemployment Rate (used in the three countries)	0.005		
Pessimistic Scenario Unemployment Rate (used in the three countries)	0.450		
Poverty Rate / Chile	0.17	0.09	0.25
Poverty Rate / Argentina	0.406	0.2	0.75
Poverty Rate / Bolivia	0.363	0.15	0.70
Optimistic Scenario Poverty Rate (used in the three countries)	0.005		
Pessimistic Scenario Poverty Rate (used in the three countries)	0.950		
Demand rate (used in all three countries)	100%	75%	120%
Optimistic Scenario Demand rate (used in all three countries)	200%		
Pessimistic Scenario Demand rate (used in all three countries)	50%		
Emigration rate / Chile	0.034	0.015	0.070
Emigration rate / Argentina	0.037	0.015	0.070
Emigration rate / Bolivia	0.0777	0.035	0.140
Optimistic scenario Emigration rate (used in the three countries)	0.005		

Table 8. Recycling policy

Constants					
Constants	*Values*			*Units*	*Authors*
	Chile	***Argentina***	***Bolivia***		
Lithium rate required	0.24	0.16	0.16	Dmnl	BloombergNEF
Unit rate	1	1	1	Batteries	Consistencia de unidades
Battery rate	0.011	0.011	0.011	Tn	Departamento de energía Estados Unidos
Recycled battery rate	0.58	0.58	0.58	1/yr	Pagliaro y Meneguzzo
Recycled lithium rate	0.01	0.01	0.01	Tn/Batteries	Politica Escenario reservado
	0.02	0.02	0.02		Politica Escenario deseado
	0.03	0.03	0.03		Politica Escenario optimista
Batteries rate	1	1	1	1/yr	Consistencia de unidades
Vehicle rate	1	1	1	EV'S/Batteries	Consistencia de unidades

Table 9:

Auxiliary variables (with equation)		
Variable	*Equation*	*Units*
Lithium requirement	IF THEN ELSE(Production>=0,Production*Lithium rate required,0)	Tn/yr
Recycled battery	Batteries*Recycled battery rate	Batteries/yr
Recycled lithium	(Recycled battery*Lithium rate required)*Recycled lithium rate	Tn/yr
Lithium produced	Recycled lithium+(Production lithium*Batteries rate)	Tn/yr

Table 10:

Input flow		
Flow	*Equation*	*Units*
Battery production	(Lithium requirement/Battery rate)*Unit rate	Batteries/yr
Production of electric vehicles	(Recycled battery+(Batteries*Batteries rate))*Vehicle rate	EV'S/yr
Production	IF THEN ELSE(Water resources*m3 rate>=2000, (Tons produced*"Applications R.")-Recycled lithium, 0)	Tn/yr
Employment generation	IF THEN ELSE((Lithium produced*Population rate*Work rate)>0,(Employment rate*(Population*Percentage of employees)*Demand rate),0)	hab/yr

Table 11.

Level variables					
Variable	*Equation*	*Initial value*			*Units*
		Chile	***Argentina***	***Bolivia***	
Batteries	Battery production	0	0	0	Batteries
Electric vehicles	Production of electric vehicles	6.6e+06	6.6e+06	6.6e+06	EV'S

Table 12. Reforestation policy

Constants					
Constants	*Values*			*Units*	*Authors*
	Chile	***Argentina***	***Bolivia***		
Tree planting rate	4000	800	15	1/Trees	Política Escenario reservado
	2000	400	7		Política Escenario deseado
	1600	300	6		Política Escenario optimista
Trees per tons rate	1	1	1	1/Tn	Consistencia de unidades
m3/s rate	0.5	0.5	0.5	m3/s	Tasa de calibración
Time rate	1	1	1	1/yr	Consistencia de unidades
Reduced CO_2 rate per tree	30	30	30	kg/Trees	Aquae fundación
CO_2 rate	1	1	1	Tn	Consistencia de unidades

Table 13.

Auxiliary variables (with equation)		
Variable	*Equation*	*Units*
PMA increase	"m3/s rate"*((Time-2022)/5)	m3/s*yr
Increased rainfall	IF THEN ELSE(PMA increase*Time rate<1.3,PMA increase*Time rate, 1.3)	m3/s
Source	IF THEN ELSE(Adult trees>1, (Ground water+(Ground water*(Source rate*"T. Source rate"))+Surface water, (Ground water+(Ground water*(Source rate*"T. Source rate"))+(Surface water+(Surface water*(Source rate*"T. Source rate"))))	m3/s
Rainfall rate	IF THEN ELSE(Adult trees>1, (((356.2*Increased rainfall)/1e+06)/3.1536e+07), ((356.2/1e+06)/3.1536e+07))	m3/s
PMA	Rainfall rate*((Time-2022)*PMA rate)	m3/s
CO_2	IF THEN ELSE((CO_2 per ton*Lithium produced)>((Reduced CO_2 rate per tree*Adult trees)*CO_2 rate), (CO_2 per ton*Lithium produced)-((Reduced CO_2 rate per tree*Adult trees)*CO_2 rate), 0)	kg*Tn

Table 14.

Input flow		
Flow	*Equation*	*Units*
Tree planting	IF THEN ELSE(Tree planting rate<=0, 0, (Production*Trees per tons rate)/Tree planting rate)	Trees/yr

Table 15

Level variables					
Variable	*Equation*	*Initial value*			*Units*
		Chile	***Argentina***	***Bolivia***	
Adult trees	Tree planting	5000	5000	5000	Trees

Table 16. Pollution policy

Input flow		
Flow	*Equation*	*Units*
Production	IF THEN ELSE(Water resources*m3 rate>=2000:AND:CO_2<=CO_2 allowed, Tons produced*"Applications R.", Capacity)	Tn/yr

Table 17.

	CO_2 allowed	**Capacity**	**CO_2 allowed**	**Capacity**	**CO_2 allowed**	**Capacity**
Contamination rate / Chile	750000	187366	700000	174816	800000	201019
Contamination rate / Argentina	450000	68161.2	350000	54070.7	550000	54070.7
Contamination rate / Bolivia	1800	600	1806.21	602.071	10,000	700