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Environmental and geo-strategic effects of raw materials supply supporting the energy transition and electric mobility: a focus on the "lithium triangle" in South America

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Electric vehicles (EVs) are breaking through, new incentives and new targets come to light to get the numbers that allow to reduce greenhouse gases over the next 30 years. On the current market, the automotive sector mainly make use of lithium-ion batteries (LIBs) as energy storage systems.

The paper examines the distribution of raw materials useful for the realization of LIBs. The availability of the world reserves of these elements is analyzed by presenting an index that highlights the risk of exhaustion of a resource based on economic trends, future objectives and recycling capabilities state-of-the-art. The focus is then on the South American "Lithium Triangle" where the metal is extracted through brine mining and where the environmental and social problems as the geostrategic aspects have been analyzed.

Keywords: *Li-ion batteries, lithium, resource, environment, geostrategy.*

1. Introduction

The world circulating fleet currently is about one billion and two hundred million cars, approximately there is one car on seven world inhabitants.

The Paris Agreement is a legally binding international treaty on climate change. It was adopted by 196 Parties at COP 21, on 12 December 2015 and entered into force on 4 November 2016.

Its goal, remarked by United Nations, is to limit global warming to well below 2 °C, preferably to 1.5 degrees Celsius, compared to pre-industrial levels. To achieve this long-term temperature goal, countries aim to reach global peaking of greenhouse gas emissions as soon as possible to achieve a climate neutral world by mid-century.

The increasing supply of lithium battery for automotive sector is given by the rising demand of technologies that must lead towards decarbonization and eco-sustainability.

Currently methodological challenges of emerging battery technologies, involving economic, ecologic, and social impacts, start to be analyzed and estimated in a prospective manner. All material, component, and cell developers as well as recyclers and other stakeholders need to work together in an interdisciplinary way, to reach shared visions of new battery systems (Edström *et al.*, 2020).

Reducing greenhouse effects could be achieved by the substitution of Internal Combustion Engine (ICE) transportation with new generation of Battery Electric Vehicles (BEVs) and Hybrid Electric Vehicles (HEVs). Nevertheless, the ecological transition called "Green Deal" by Europeans brings the enormous effort of exploiting a wide range of raw materials in order to achieve the transformation by maintaining the same economic standard. The huge amount of resources needed for the transition risks to danger those categories that are easily neglected by wholemeal transformations such as third country populations and environment.

Human right and social unbalance are easily disregarded and local biodiversity affection might lead to a complete ecosystem impoverishment.

Li-ion batteries strong suits provides high performance, energy efficiency to the vehicle during lifespan avoiding emission of carbon dioxide and particulate. However, the complex and long roadmap of raw materials supply, high energy consumption of battery production and low recycling capacity of many material involved make the future of LIBs very complex.

In particular, the tricky issue is made up by analyzing the world distribution and amount of raw materials necessary for the world objective of reducing greenhouse gases. In fact, according to the current circular economy of LIBs and data provided by some agencies, the near sharp increase of demand of raw materials from primary supply will be certain.

World economic and social balances will change toward the availability of these materials, the velocity of the process in order to achieve the transformation risks in generating many problems as not respect of local populations and environmental equilibrium.

Currently there are no raw material shortage problems but according to the declared objectives of the International Energy Agency, which takes up the Paris agreement, of replacing at least half of the world's car fleet with electric cars, there is a real possibility of running out of lithium and cobalt by 2050. In support of this thesis, the data relating to the low recycling percentages of some li-ion battery elements.

2. *Definitions*

The value chain of LIBs sector engages a high number of industries, starting from the mining industry to obtain the raw materials.

Specific range of raw materials provides relevant characteristics of the Li-ion battery such as specific energy and power, durability and safety. The specific energy of a lithium-ion battery depends on the type of cathode used and constituting anode materials as well as their nano and micro-structures (Zubi *et al.*, 2018).

The aforementioned features makes the Li-ion batteries the most competitive on the market for the automotive sector. In particular the most used in this regard are the NMC ($LiNiMnCoO_2$) and the NCA ($LiNiCoAlO_2$) types, that differ in active cathode compounds (Bobba, Mathieux and Blengini, 2019).

The most important elements implied for battery cells units can be reassumed in seven essential components: Nickel, Cobalt, Manganese, Lithium, Aluminum, Graphite and Copper (Mayyas, Steward and Mann, 2019).

Lithium is a primary constituent in rechargeable LIBs for mobile devices and electric vehicles, and is used in the cathode and some electrolyte materials. Lithium has the lowest reduction potential of any element, giving it the highest possible cell potential. It also is the third lightest element and has one of the smallest ionic radii of any single charged ion. These properties ensure that lithium will continue to play a critical role in batteries.

Figure 1 shows the distribution of most important LIBs raw materials by disassembling the

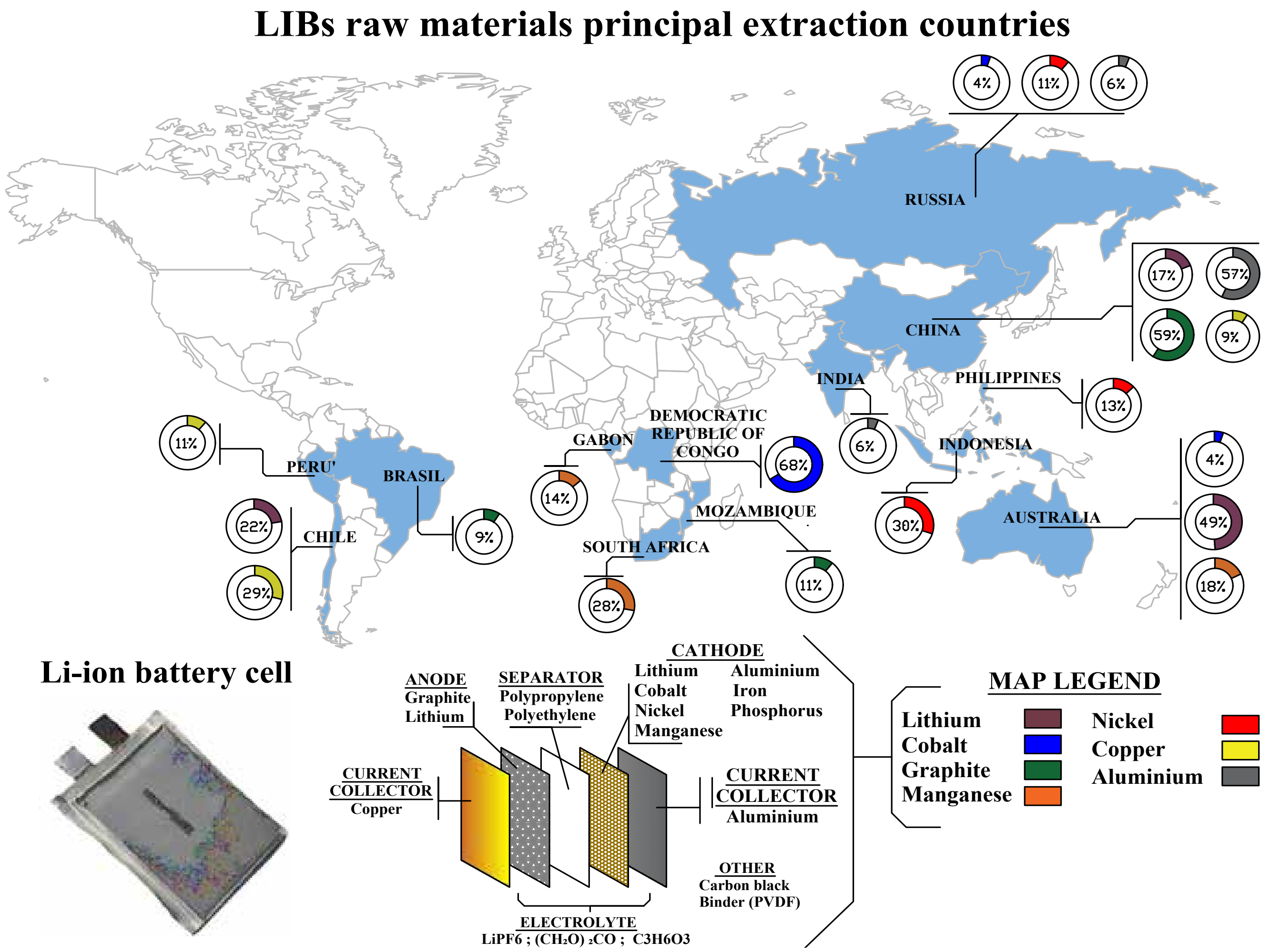


Fig. 1 – Li-ion battery cell representation and composition; LIBs cell principal raw materials and their main extracting countries worldwide during 2020 according to U.S. Geological Survey (2021).

battery cell components (Gaines, Richa and Spangenberger, 2018) and deploying them on the geographical representation according to extraction information provided by U.S. Geological Survey (2021).

During the year 2020, Lithium, Cobalt and Graphite were included by the European Commission in the list of "Critical Raw Material", that is, within the list of chemical elements that are essential for the functioning and integrity of a wide range of industrial ecosystems and which, at the same time, have very limited reserves and are found in a small number of areas in the world (Keersemaker, 2020).

The assessment of the "criticality" of a raw material would depend basically on two factors, economic importance and supply risks. Criticality is a concept that changes over time according to market conditions, technological evolution and internal political factors, changing the geopolitical framework in supplier countries.

It's important to underline the conceptual and methodological frame of resource potential exploitation. The economic and technical conditions of a given period in a given country permit or not the mining activity of a mineral resource that become a reserve, which is an exploitable resource (U.S. Bureau of Mines and U.S. Geological Survey, 1980).

Most of resources ore grades are currently calculated with sophisticated mathematical models, on the basis of established knowledge of the geology of a territory. However a raw material reserve may also step back to a resource, according to the industrial and economical trend, for example if the mineral demand decreases driven by the reduction in sales of a product.

According to U.S. Geological Survey (2021), lithium reserves have progressively risen up during years due to the increasing interest in technological field and consequently in market shares values.

Furthermore, the importance resource primary supply for a given application is based on the recycling capacity, reusage and life-time, in few words the material life cycle.

Among the battery materials, technologies for recycling lithium are currently available in the EU, even though not yet at industrial scale. Now a day lithium recovered by spent batteries results to bel less than 1% (Bobba *et al.*, 2020).

It is also important to understand the longevity of the technological application, the pros and cons of extending the useful life of the product by giving it a second use (Bobba *et al.*, 2018).

So said, it is relevant to assess scenarios based on indexes and assumption in order to understand the feasibility of a resource exploitation from environmental and economic point of view as illustrated by some authors (Rosenau-Tornow *et al.*, 2009).

3. Resources and environment challenges

From 2013 to 2019 the total amount of electric vehicle BEV (Battery Electric Vehicles) and PHEV (Plug-in Hybrid Electric Vehicle) increased from 400.000 units up to 7.200.000 units according to statistics of International Energy Agency (Glob. EV Outlook, 2020).

Generally, within 10 years Sustainable Development Scenario (SDS) aims to reach almost 250 million EV and in 20 years have 600 million electric cars in circulation around the world, to be able to contain the average warming of the planet below two degrees established by Paris climate agreement (Glob. EV Outlook, 2018) (Global EV Outlook, 2020).

Table 1 shows the rise of demand of some basic raw material used in EV LIBs according to International Energy Agency (IEA) statistics.

IEA calculated approximately the increasing supply in order to fulfil Sustainable Development Scenario or Stated Policies Scenario (STEPS) according to current agreements.

New policies and research are working hard on the potential improvement of materials recycling and reuse share, otherwise, with the increasing demand, it would mean to push strongly on primary supply for batteries basics elements procurement.

For example, some authors sta-

Tab. 1 – Annual demand projection for active cathode raw material to make batteries for electric vehicles according to IEA (Notes: kt = kilotonnes; y = year; STEPS = Stated Policies Scenario; SDS Sustainable Development Scenario) ('Global EV Outlook 2020', 2020).

	Lithium	Cobalt	Manganese	Nickel
2019 material demand for EV Li-ion batteries	17 kt/y	19 kt/y	22 kt/y	65 kt/y
2019 material demand for EV Li-ion batteries respect to total annual extraction	20 %	13 %	0,1 %	2 %
2030 material demand for EV Li-ion batteries (STEPS)	190 kt/y	180 kt/y	177 kt/y	925 kt/y
2030 material demand for EV Li-ion batteries respect to extraction of 2019 (STEPS)	221 %	125 %	1 %	35 %
2030 material demand for EV Li-ion batteries (SDS)	370 kt/y	375 kt/y	370 kt/y	1920 kt/y
2030 material demand for EV Li-ion batteries respect to extraction of 2019 (SDS)	430 %	260 %	2 %	74 %

ted that lithium annually recycled is less than 1% (Bobba *et al.*, 2020), translating this information into primary supply, that would mean to extract annually around 365 kilotonnes of lithium by 2030. The upward trend to fulfil the objective of 2040 of more than twice of EV respect 2030 is easily translated into almost 900 kt/year extracted just for electro-mobility.

Many challenges come to surface just watching the aforementioned scenarios imposed by supranational institution and agencies such as: availability of raw materials to fulfil the objectives, the environmental burden for resource supply and the shifting interest on countries that own huge storage of LIBs basic elements as South America.

3.1. Availabilities of raw materials

Based on data collected (U.S. Geological Survey, 2021), global reserves of raw materials were estimated during 2021, including the basic materials for the construction of lithium batteries.

The Figure 2 shows the countries that possess most of the resources. It is noted that there is an unbalance toward few countries of the globe in Oceania, Africa and South America continents, in few words toward the southern hemisphere.

With the purpose of estimate the depletion risk of a specific resource according to its present and future exploitation, it is presented a new index that it is defined by the given formula (1):

$$ERR_t = \frac{\int_{t2}^{t1} E\,dt}{R_m(\Delta t)} \qquad (1)$$

Where *ERR* = Extraction Reserve Ratio: is a variable index in time that help to understand current availability of material and the warning state about the potential extinction of it; *E* = Extraction: raw material extracted from a time t_1 to a time t_2; R_m = mean reserve estimated: average amount of raw material economically exploitable assessed during the same interval $\Delta t = t_2 - t_1$.

Values of ERR range from 0 to 1, and can also be expressed in percentage *ERR*(%), when *ERR* is equal to 1 it means that a defined temporal windows the reserve has been completely consumed.

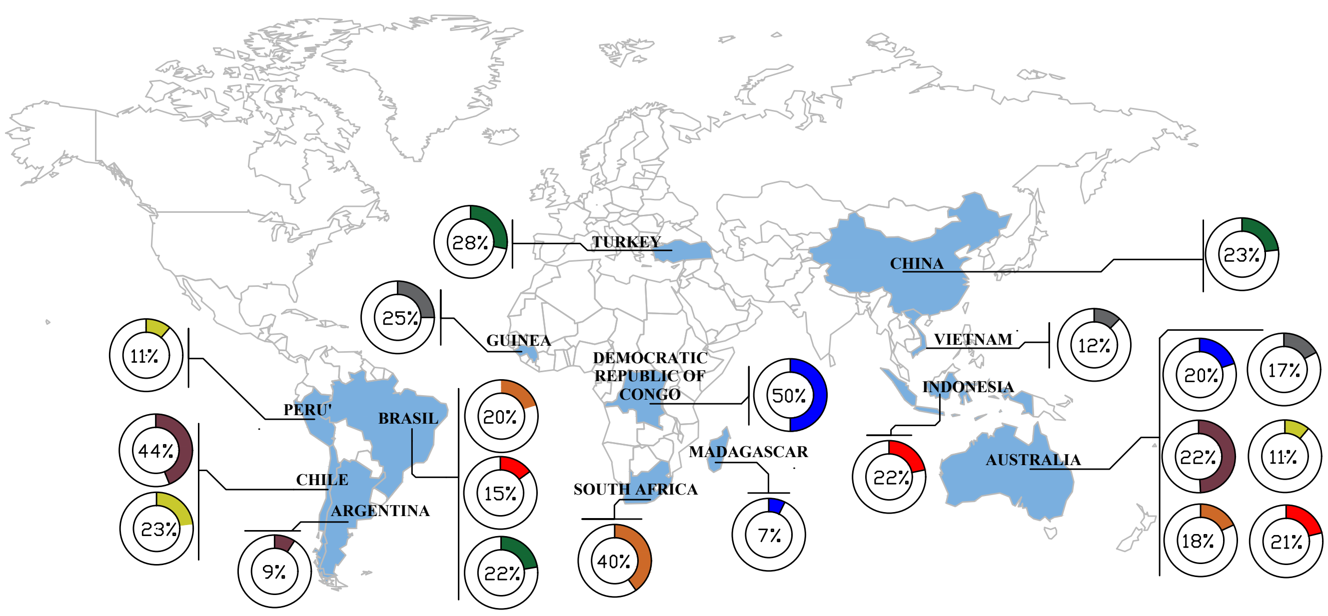
This index can be facilitated considering the extraction activity related to a year time step as shown by formula (2):

$$ERR_{2020} = \frac{E_{2020}}{R_{2020}} \qquad (2)$$

In Figure 2 are represented the *ERR* of 2020 year of some raw materials involved in LIBs.

It's worth to notice that the Extraction Reserves Ratio is current-

Li-ion batteries raw materials reserves



	Lithium	Cobalt	Manganese	Graphite	Nickel	Bauxite	Copper
$R_{m\,2020}$ (kilotonnes)	21.000	7.100	1.300.000	320.000	94.000	30.000.000	870.000
E_{2020} (kilotonnes)	82	140	18.500	1.100	2.500	371.000	25.000
$ERR(\%)_{2020}$	0,4	2,0	1,4	0,3	2,7	1,2	2,9

MAP LEGEND

Lithium	🟫	Nickel	🟥
Cobalt	🟦	Copper	🟨
Graphite	🟩	Bauxite	⬛
Manganese	🟧		

Fig. 2 – Li-ion battery cell principal raw material reserve percentually calculated during 2020 according to U.S. Geological Survey (2021). Below: total reserves estimated during 2020, global extraction in 2020 and ERR(%) index of the same year.

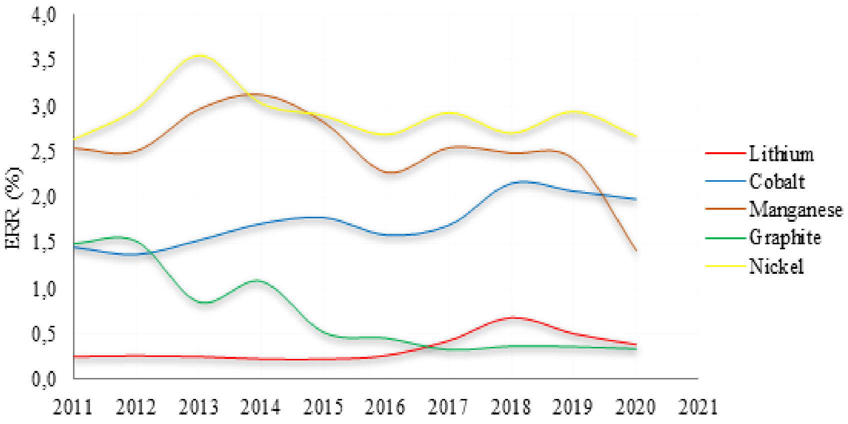


Fig. 3 – ERR[%] variation from 2011 to 2020 of some LIBs raw material with annual time step Δt; (U.S. Geological Survey, 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021).

ly very low for every material.

Nevertheless, taking into account lithium demand scenario, recycling and reserve current state, and longer evaluation timespan (Δt = 10, 20 years), lithium *ERR*(%) could easily reach 10% by 2030 and 45% by 2040.

Research effort may help in transforming lithium resources into new reserves by improve the economic and technological feasibility for this critical material exploitation in order to reduce *ERR*(%) time by time.

Figure 3 shows how ERR of LIBs principal elements had varied during last 10 years according to the raw material market condition and reserve knowledge due to historical moment.

3.2. *Lithium resources*

Owing to continuing exploration, identified lithium resources have increased substantially worldwide and the total amount reaches 86 million tons. Although lithium is well distributed on the crust, its resources are coming mostly from continental brines, geothermal brines, hectorite, oilfield brines, and pegmatites.

Lithium resources are mainly placed in Bolivia, 21 million tons; Argentina, 19.3 million tons; Chile, 9.6 million tons; United States 7.9; Australia, 6.4 million tons; China, 5.1 million tons, according to USGS data (U.S. Geological Survey, 2021).

The higher exploitability of resources in South America salt brines due to less energetic burdensome, softer soil surface impact and lower CO_2 emission respect to hard rock extraction, move the attention on three principle countries: Chile, Bolivia and Argentina (Grosjean *et al.*, 2012).

Here are located most of the continental brines in the world, where lithium rich solution is pumped up from groundwater to the plant where lithium increase percentage step by step through evaporation ponds till is ready to be refined into lithium carbonate (Liu, Agusdinata and Myint, 2019).

Chile and Argentina processed most of their mined lithium from brine. While Australia led in raw lithium production, it did not process its lithium ore, instead exporting most of it to China, where it underwent beneficiation and refining into lithium carbonate.

Currently Bolivia is not one of the most extracting site in the world, nevertheless hydrogeological features of this country makes it the perfect target for lithium gathering. In particular, Salar de Uyuni for its characteristics stores huge amounts of lithium, not exploited yet.

3.3. *Environmental impact of lithium extraction activity in South America*

Worldwide lithium brines are

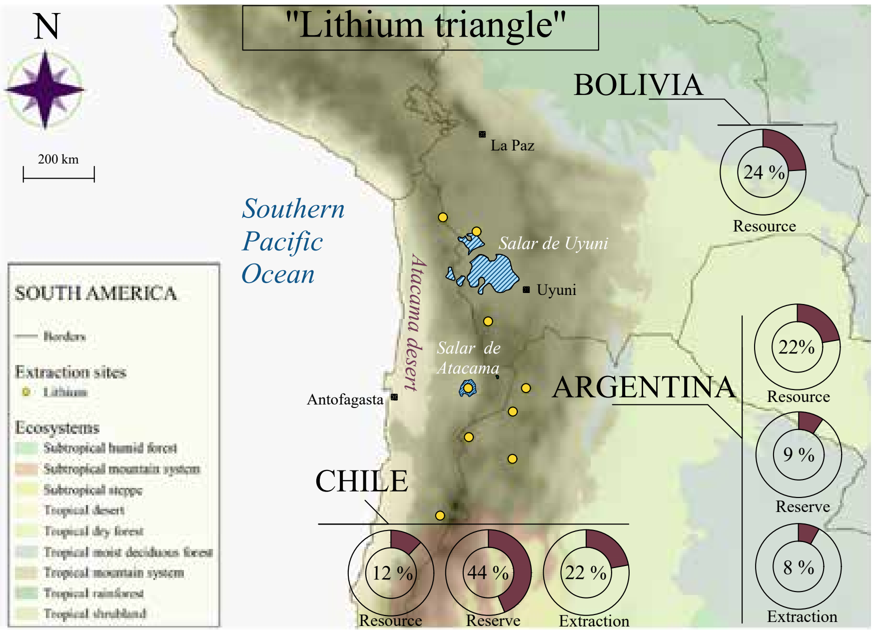


Fig. 4 – Global percentages of lithium resources, reserves and 2020 extraction amounts inside the "Lithium Triangle" assessed by U.S. Geological Survey (2021).

mostly concentrated in a small region of South America (Grosjean *et al.*, 2012) often referred to as the “Lithium Triangle” extended between the Salar de Uyuni and the Salar de Atacama, where about 60% of the world’s lithium is found (U.S. Geological Survey, 2021).

Brines can be described as highly saline solutions, were total dissolved solids (mineral salts) show much higher values than in sea water, usually averaging 170 – 330 *g/L*. Brines can either be accessible directly from the surface, or deep under large saline expanses (salt lakes or salars) in very dry regions that allow salts to persist. The lithium content in mineable brines ranges from 0.01 to 0.2% (Vikström, Davidsson and Höök, 2013).

Currently, the brine lithium extracting plant own by SQM and Albemarle in Atacama Desert, Northern Chile, is the biggest in the world visible in Figure 5 (Bustos-Gallardo, Bridge and Prieto, 2021).

Atacama Desert presents extremely arid climate and unique topography produce the saline groundwater containing 0.15% lithium that serves as the major water source for lithium extraction. The Atacama Desert’s exceptional topography and environmental features produce a combination of physical conditions conductive to the formation of brine and its low-cost exploitation.

Generally, the saline groundwater containing lithium is pumped through a cascade of ponds where impurities are precipitated by solar evaporation, wind, and chemical additives. After that, the concentrated brine is transported back to the recovery plant in Antofagasta for future purification and processing. The extraction is chemical intensive, extremely slow, and delivers large volumes of waste. This technology is heavily dependent on the geological structure of the deposits, brine chemical composition and both climate and weather conditions (Flexer, Baspineiro and Galli, 2018).

The Atacama Salt Flat is the third largest salt flat in the world (around 3000 km^2), providing crucial ecosystem services to local communities and diverse flora and fauna species. Geographically, the salt flat is an intramontane endorheic basin (i.e. an alluvium-filled valley within mountainous ranges with a closed drainage system) bound by high mountains to each side. Unlike

Fig. 5 – Satellite photo of SQM and Albemarle lithium mining plant. There are also visible on the background the national reserves of Los Flamengos and of Eduardo Avaroa, https://earth.google.com/web/@-23.47349143,-68.28063101,2312.0573539a,74769.52040311d,35y,63.09470794h,64.98950307t,0r (accessed April 15, 2021).

other salt flats, the topography is of a high level of roughness and seldom covered by shallow water due to the rapid evaporation process. Biodiversity of the region is spread on the territory according to some zones and protected areas such as Los Flamencos National Reserve, permanent lagoons which support diverse biodiversity serving as an important nesting center for flamingos and some areas mostly covered by barren soil and salt crests providing habitats to diverse species.

Recently this area of around 7000 km^2 were monitored by satellite sensing in order to observe the effects induced by the mining area increasing activity (20 km^2 to 80 km^2) on surrounding environment. 20 years of monitoring with LandSAT satellite images and spectroradiometer have brought to surface several changes on all the area monitored such as:

- Soil moisture decreasing
- Land surface temperature increasing
- Vegetation depletion.

Negative outcomes of extracting activity identified by the aforementioned indexes are recognized as aquifer running out that lead to hydraulic unbalance and ecosystem wormed up and impoverished (Liu *et al.*, 2019).

In South America, lithium deposits are often located in desert areas, so the extraction process would create a severe water shortage. Although the water in the plant tends to be recovered, the large amount needed and the difficult environmental context of the South American salt flats makes the problem almost unsolvable (Lithium National Commission, 2010).

4. Geopolitics of LIBs

The issue of energy transition in the automotive sector and battery production is not only technological. The geopolitical aspects are relevant if it is considered the relations between the Europe, United States, Russia and China and the geographical division of the world, high-income countries (benefiting from the technology), and low-income countries but depositaries of the raw materials needed for that technology. This highly concentrated, and often disruptive, production raises concerns about security of supply.

To this must be added the dynamism and farsightedness of China which, although is already rich in deposits of raw materials necessary for LIBs production, is adopting policies aimed at acquire mineral resources of other producer countries.

4.1. Geopolitics of lithium in South America

What makes South West geostrategic is that most of the reserves and resources of lithium are located in a very narrow area between Chile, Argentina and Bolivia. This confirms the assumptions that indicate that the southern cone of Latin America could take advantage of its supremacy in the market, especially when Bolivia, which currently does not yet participate in production and its resources are not valued as reserves, will also join as an exporting country and enter into negotiations with Australia (world leader in lithium production).

Taking into account that each salt flat is different in its characteristics and chemical composition, the technology applied to obtain lithium carbonate is specific for every salt flat. In this regard, Bolivia is investigating its own ways to extract lithium in a profitable and efficient way, given that it is technically more difficult than in neighboring countries due to the significant presence of magnesium and by the precipitations that delay the concentration by evaporation (Javier and Equiza Fernández, 2019).

Although research on the socio-environmental impacts of lithium extraction at local level has been very limited (Agusdinata *et al.*, 2018), lithium represents the element on which the entire ecological transition should rest. While extractive sector generate same positive impacts at the local level (e.g. jobs and fiscal resources) the problems represented by the significant environmental impact (eg: ecosystem degradation, landscape damage and water scarcity) that derive from its extraction represent a big-challenge for the real sustainability of the energy transition to the electric not only for the local communities but also at a global scale.

5. Discussion

The market condition of LIBs and the new trend toward electro-mobility has pushed many country to fulfil their own economic interest by increase the home extracting activity and binding new agreements with other countries in order to exploit precious resources. For example, China has presented a very dynamic behavior in this concern, by accumulating out of border raw materials through trade agreements.

Within “Lithium Triangle” water collection for the metal enrichment process has outcome into hydrogeological unbalance and a spread of polluting chemicals.

Atacama Salt Flats consequences given by extracting brine activity is just a warning bell to what can induce the tenfold of extraction activity in South America.

Hence, the peninsular continent ecosystem may meet a huge hydrogeological and climatic modification and the high ecological impact risk increases with the unproper management of water resources with the sharp increase of lithium demand on the market.

Downscaling LIBs cell on world map gave the orientation of where are the storages of our globe aimed for a precise common tool used worldwide by citizens. This makes us focus attention on the local aspects of the extraction areas targeted by the technological and industrial progress itself.

This zooming criteria has shown how LIBs, which are aimed for energy transition, can affect the local scale environment in term of habitat impoverishment and social challenges.

Furthermore, focusing on just the abundance of the resource, as shown by ERR index, distracts from the issues and environmental consequence of the extracting activity. In fact, although the resource and reserve of lithium may increase over time due to the strengthen in research and increasing demand, the intense exploitation of the resource disregarding the local environment balance lead inevitably to an ecological wreck.

6. Conclusion

If on the one hand, Li-ion batteries represents the element on which the entire ecological transition should rest, on the other hand, the expectation could be frustrated by the significant environmental impact that would derive from its extraction as mining activities have been responsible for ecosystem degradation and landscape damage.

Analyzing several technologies is clearly visible that their social and technological bond with exhaustible resources, persistent reliance on growth, short-term planning horizons, could be causes of instability, overproduction and ultimately collapse. Thus lithium-ion batteries seems to belong to this category for many aspects, nevertheless the usage of lithium with less demand expectation and the proper management of resources can be translated to a powerful key element in optic of energetic transition.

The economically efficient and environmentally sustainable recovery of lithium by exhausted batteries therefore represents an indispensable work horizon in the scientific, technological and industrial fields in order to guarantee an acceptable time dimension to the ecological transition in progress. Both in terms of global environmental sustainability and in terms of international supply security.

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