Review article

Concerns about lithium extraction: A review and application for Portugal[☆]

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ABSTRACT

The trend towards "clean" mobility is growing steadily, causing an exponential increase in lithium demand. Lithium reserves are therefore an important asset for the countries owning them, opening up opportunities for valuable economic activity. However, lithium mining is not free from social, environmental and health impacts and its extraction is far from being a consensual topic on the regions involved. This paper reviewed the main impacts of lithium exploitation and addressed, in particular, the case of Portugal, ranked as the country with the most promising lithium reserves in Europe. The analysis was based on an application of life-cycle assessment for the case of the Barroso-Alvão region in Northern Portugal. Albeit recognizing the limitations of the study given the scarcity of information, it is possible to envisage the importance of local impacts from lithium extraction specially related to Abiotic Resource Depletion, Ecological Toxicity Potential and Occupational Health Hazards. The conclusion of the study was that it was necessary to properly acknowledge the cultural and social characteristics of the region and account for the local communities' needs and expectations, together with the potential social and economic impacts, for the definition of fair and acceptable policies and pathways for the future.

1. Introduction

Lithium now plays an essential role in our economic system and is likely to do so in the future (Narins 2017; Vikström 2020; Andersson 2020). It is the key element in energy storage, responding to a highly rising trend of demand for several electronic devices and mostly Electric Vehicles (EVs). Some name it "new gold" (Tarascon 2010), "new oil" or "white gold" (Barandiarán 2019). The 2019 Nobel Prize in chemistry awarded to Goodenough, Whittingham and Yoshino for their work on developing lithium-ion (Li-ion) batteries clearly shows the relevance of this issue for modern society.

As owning lithium resources does not necessarily mean being able to convert them into useful reserves for the economic system, several opportunities and challenges apply to countries where lithium can be extracted. On the one hand, strong economic reasons exist to expand supply to meet growing market demand, leading to a situation of desirable extraction of this mineral in many locations. A country with lithium reserves can profit from the scarcity of the metal in the market and be more competitive and less dependant on external sources. On the other hand, exploring lithium deposits may bring about some environmental challenges, including problems in ecosystems, in surface and underground water and in human health. According to Epstein et al. (2011) each stage in the life-cycle of a metal (extraction, transport, processing, use, and final waste management) can create negative externalities that may affect health and the environment. In fact, we witness the growing emergence of social/environmental movements against mining, which creates the need to involve and inform all the stakeholders (Rodrigues et al., 2019) to seriously assess the consequences (positive and negative) of extracting lithium.

The context and potential as regards lithium deposits favour Portugal over other European countries (Amarante et al., 2011; Oliveira and Viegas 2011; Viegas et al., 2012; Machado Leite 2017), ranked as the biggest European potential producer, with the largest known European reserves (Carballo-Cruz and Cerejeira 2020). From an economic/political point of view, this represents an advantage in Portugal's economic strategic mosaic, increasing its global revenue and achieving not only the sectoral independence of a vital resource but also becoming one of its net exporters. That means Portugal may play an important role

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as a supplier for European companies that will have raw material "nearby", with evident savings in terms of transport costs and favourable supply deadlines.

The case of Portugal will be used in this research to afford a deeper insight into the potential effects of lithium extraction. We resort to the Environmental Protection Agency methodology for life-cycle assessment for batteries (EPA 2013), focusing on the extraction phase, as a reference study for some possible impacts occurring in the most prominent Portuguese lithium reserve (the Barroso-Alvão (B-A) region).

Although we are aware of the limits of our analysis, given the reduced availability of data and diffuse nature of studies, [1] this paper aims to contribute to the advancement of knowledge on the impacts of lithium extraction. Through a review of existing research and a new insight into the topic, we hope to offer some basis of reflection to support possible public and private measures suitable for bringing together economic and environmental interests. As Agusdinata et al. (2018, p.5) pointed out, there has been "a deficit of research contributions from lithium producing nations" since 1974, in particular Portugal. This being the case, we aim to contribute to this debate by presenting a preliminary analysis with regard to Portugal, as a lithium producer and a promising case for intensive extraction.

The study sought to answer the following specific research question: What are the main environmental and health impacts associated with lithium extraction? The exploratory nature of the research should be underlined, as we propose to investigate a still under-researched topic, though one which is highly relevant for industry, the scientific community, and society in general. The scientific contribution of the study is expected to go beyond the specific case of Portugal. This approach can then be applied to other countries/regions,particularly those contributing to the sustainable supply of raw materials, for instance as envisaged by the European Raw Materials Initiative. As a matter of fact, intensifying the share of European domestic sources of lithium for European battery manufacturers and the corresponding increase in the number of new mines in operation has been stressed as an imperative European goal (ETIP 2020).

This paper is divided into five main sections. The next section presents the research background addressing characteristics of lithium, the geographical location of the main deposits and the impacts related to their exploitation. The Portuguese case is introduced in Section 3. The description of the methodological approach used in the study is presented in Section 4. Section 5 discusses the main results. The final section concludes.

2. Research background

In terms of demand, lithium stands at the forefront of a large spectrum of essential uses in the economic system (Ebensperger et al., 2005) because of its special and numerous mechanical and physical properties. As regards supply, lithium is a finite natural resource, subject to provision restrictions and mainly located at some geographically diffuse sites (European Commission 2011).

2.1. Lithium

Under normal conditions of temperature and pressure, lithium is the lightest and least dense metal within the group of natural solid elements. In addition to being highly flammable, it possesses a high specific heat as well as high electrochemical potential (Martins 2011; Martins et al., 2011; Swain 2017). Due to its melting point and conservation of heating properties, lithium is used in metallurgy, in lubricating and in thickening greases (Hocking et al., 2016; Guberman 2017; Ober 2018). Thanks to its ability to maintain constant levels of humidity, both air handling and air conditioning systems use lithium chloride or lithium bromide (Hocking et al., 2016; Guberman 2017; Ober 2018). Other uses pertain to aircraft manufacturing, the military sector, pyrotechnics and the rocket propellants industry, non-linear optics, medicine, chemistry and pharmaceutics (Gruber et al., 2011; Swain 2017). Lithium is also appropriate for direct use in the ceramics industry, not only to lower the melting points but also to reduce the coefficient of thermal expansion and lower the viscosity, allowing the elimination of other toxic products (Ebensperger et al., 2005; Lima et al., 2011; Martins 2011; Oliveira and Viegas 2011; Machado Leite 2017). This is particularly important for a country such as Portugal, where the ceramics industry has dominated the use of lithium for many years (Oliveira and Viegas 2011; Viegas et al., 2012).

While the ceramics market, along with other traditional non-battery markets, requires steady and not very high levels of lithium (Amarante et al., 2011), the exponential growth trend of "clean" mobility and batteries has raised the total demand for the mineral (Ebensperger et al., 2005).

Although it has been stated by some authors that lithium exists in abundance (Gruber et al., 2011; Reuter 2016; Narins 2017) with sufficient geographic dispersion and a wide variety of forms, quality and logistic supply restrictions have created an important uncertainty about its future. For instance, the biggest resources of lithium in the world are located in one country (Bolivia), which is no one of the biggest lithium producers, and suffers, amongst other things, from low quality/purity salt flats (Narins 2017). Social and political issues can also be pointed out (Narins 2017), leading to visible risks in the metal's supply (Vikström 2020). Actually, no country is completely self-sufficient in terms of critical raw materials (Veraart et al., 2020), such as lithium, causing concerns of dependency, particularly in the transition to renewables technology. Some recognize that lithium has been seen as one of the most critical mineral bottlenecks in this evolution (Siljković et al., 2017; Bazilian 2018).

The dispersion in the geographic distribution of critical metals increases concerns about possible future shortages (Vikström 2020). Thus, in the next section we revisit the geographic distribution of lithium, according to its deposits, resources and reserves.

2.1.1. Lithium deposits

Generally speaking, mineral deposits can be classified as resources, "the geologically assured quantity that is available for exploitation", and reserves, "the quantity that is exploitable with current technical and socioeconomic conditions" (Vikström et al., 2013, p. 253). While resources have little importance for real supply, their conversion into economically recoverable reserves makes them suitable for production and for use by society (Vikström et al., 2013). However, very few resources can be qualified as recoverable reserves, which strengthens their economic scarcity.

In the mining life-cycle several phases may be considered: exploration, evaluation, exploitation, processing and mine closure with environmental remediation (Revuelta 2017). If the exploration phase results in the discovery of a mineral deposit of economic interest, it may pass to the exploitation phase, where the most relevant step for our study, extraction, takes place.

Lithium deposits are of three main types: i) brine, a basin with a water solution enriched in salts of lithium; ii) hard-rock, also known as

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[1] Specific local data and empirical studies are very scarce. Moreover, information is often classified. As Ebensperger et al. (2005, p. 230) recognize "Many of the smaller mineral sectors are dominated by few producers, who apparently possess high levels of market power. Extensive information about them is not widely available in the public domain." Also Simoes and Amorim (2020, p. 2) state: "In June 2019, Li's price development was announced (…). However, the 4 major players opposed this initiative by announcing that they would not participate in the definition of this price benchmark, i.e., they would not inform the markets about volumes and prices transacted by them."

pegmatite[2]; and iii) sedimentary rock (Gruber et al., 2011; Martins 2011). The most common and often easiest and least costly extraction method is lithium exploitation from brines (i). This kind of mining process involves huge extensions of brines to obtain an economically feasible result. Extraction as well as the consequent treatment of lithium are very long processes and are thus inadequate to meet any short-term increase in demand (Grosjean et al., 2012). Flexer et al. (2018) see this metal extraction as chemical intensive and responsible for large amounts of waste. Moreover, this process is normally translated into poorer results in terms of the amount of the final concentration of lithium.

In contrast, obtaining lithium from pegmatites (ii) requires geological surveys and drilling, whereby relatively large quantities of ore must be processed to reach expressive lithium contents (Prior et al., 2013), which demands high energy intensive processes (Ebensperger et al., 2005; Viegas et al., 2012; BGS 2016; Jiang et al., 2020). Moreover, high transport costs, as well as relatively small dimensions of deposits prevent production from benefiting from economies of scale and raise costs (Ebensperger et al., 2005). Thus, extracting lithium from rock is much more complex and generally more expensive than extracting it from brines (Flexer et al., 2018; Bell 2020; Bowell et al., 2020). Still, it may lead to better results and pay off, if the higher metal concentration (Bell 2020) offsets the disadvantages. In brines, the concentration of lithium ranges from 0.001% to 0.14%, while in pegmatites, representing a much smaller magnitude in the potential supply of lithium, it varies between 0.59% and 1.6% (Gruber et al., 2011). Even though pegmatite deposits are smaller, they "will remain of interest because of their wider geographic distribution and consequently lesser susceptibility to supply disruptions and their more lithium-dominant compositions, which might allow more flexible response to market changes" (Kesler et al., 2012, p. 55).

Brine resources (i) can be found in the “Lithium Triangle” of Bolivia (21 Million Tones (Mt), salar de Uyuni, unexplored), Argentina (17 Mt, salar del Hombre Muerto), and Chile (9 Mt, salar de Atacama). This area, submitted to geostrategic and geo-economic bottlenecks (Grosjean et al., 2012), represents about 30% of global production of lithium, and approximately 60% and 70% of total world reserves and resources respectively.[3] Therefore, this group of countries is located in one of the most promising geographical areas regarding both current economically feasible extraction and potentially profitable exploitation of lithium in the future. Other important brine deposits are located in the U.S.A and China (Hocking et al., 2016).

Pegmatites (ii) can be found in Australia, Brazil, China, some African countries and some European countries: “hard rock mine projects exist in Austria, Portugal, Serbia and Finland, with a collective planned capacity of 11 000 t Lithium Carbonate Equivalent (LCE), corresponding to about 8% of the estimated 2027 world demand” (ETIP 2020, p. 46). Finally, lithium in sedimentary rocks (iii) prevails in the U.S.A and Serbia (Gruber et al., 2011; Martins 2011; Martins et al., 2011; Swain 2017). Therefore the global geographical distribution of lithium deposit types is quite diffuse. Fig. 1 presents a comprehensive picture of lithium production, reserves and resources around the world in 2019.

In 2019 the nine countries with the biggest reserves were (in descending order) Chile, Australia, Argentina, China, the U.S.A, Canada, Zimbabwe, Brazil and Portugal. In terms of production, the picture slightly varies with Australia, Chile, China, Argentina, the U.S.A, Zimbabwe, Portugal, Brazil and Canada being the main producers, listed in decreasing order of importance (U.S. Geological Survey 2020).

2.1.2. *Impacts*

In general, mineral extraction has both positive and negative impacts, not only from a technical-geological-environmental point of view, such as direct effects on ecosystem services (Tost et al., 2020), but also from a socio-economic perspective. However, the impacts of lithium mining have been rarely addressed in the literature. Agusdinata et al. (2018) followed a bibliometric analysis related to lithium mining and impacts, remarking that studies are scarce, especially from countries producing lithium, representing about 2% of total publications. Liu et al. (2019) diagnosed that the lack of investigation is mainly because sites are in distant locations and data is not available.

Furthermore, the great majority of studies focus on the effects of lithium mining from brines, in particular on the triangle of lithium. However, the specific features of brine extraction are not necessarily comparable to hard-rock extraction, the main aim of the present study. A review of some of the most important impacts of lithium mining follows, and major topics are summarized in Table 1. In this table, possible differences between brines and pegmatites are portrayed, based on studies surveyed and a generalization of known cases (similar to the reasoning presented for example in BGS (2016)). Particular differences of specific situations may not follow this general qualitative pattern, which should be seen as a pilot attempt of comparison.

Regarding socio-economic impacts, the most quoted advantage for a country or region possessing lithium is an increase in income (Agusdinata et al., 2018; Rodrigues et al., 2019; Carballo-Cruz and Cerejeira 2020). In addition, the creation of jobs and youth employment in different technological and industrial sectors accompanied by an increase in workers’ incomes and improvement of the region’s development can be expected (Valle and Holmes 2013; Rodrigues et al., 2019). For instance, in Chile, mining activities resulted in an in-flow of a long-distance workforce and encouraged local economic growth (Liu and Agusdinata 2020). Thus direct and indirect employment is expected to increase in relation to mining activities, as well as in their supporting industries (Carballo-Cruz and Cerejeira 2020). This fact helps to reverse trends of desertification in different extents, depending on each particular situation . For instance, in Portugal, the extraction of lithium pegmatites is supposed to boost the economic situation of rural areas (Simoes and Amorim 2020).

The global world dependency on lithium positions its producer countries strategically as important players in this field. Given internal and foreign demand for the mineral, countries possessing lithium may become independent producers, avoiding importations and even emerging as net exporters. Because of their magnitude and their extraction characteristics, this effect is expected to be more visible in countries possessing big brine reserves. The EU, with member countries mainly possessing pegmatites, is specifically focusing on the promotion of mining productions inside the European space to decrease external dependence. Lists of Critical Raw Materials are being released, designated for key sectors with risks of supply and lack of substitutes (European Commission 2014). This aims to ensure a sustainable supply in global markets, with no distortions, promoting the supply of raw materials within the EU, reducing consumption of materials coming from outside Europe and promoting recycling practices (Blengini et al., 2017; European Commission 2017; ETIP 2020). In 2020, lithium was added to this list, foreseeing an internal rise in demand for EV batteries and energy storage 18 and 60 times higher for 2030 and 2050 respectively, within a 100% import reliance (European Commission 2020).

While some economic activities are fostered, others may be at risk. First, lithium extraction can endanger ecotourism (Valle and Holmes 2013). For instance, the Food and Agriculture Organization (FAO 2020) states that the environmental and social characteristics of the B-A region in Portugal represent “a fundamental asset, also in terms of the ability to promote tourism, especially in its rural and nature modes, which play an increasingly important role in the region’s activities”.

In addition, local agro-pastoral activities may be affected by environmental degradation (Babidge 2013). For instance, Valle and Holmes

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[2] Only 0.1% of granitic pegmatites are rich in rare metals. From that short fraction, an even smaller part constitutes lithium-rich pegmatites. Globally, the most important lithium mineral in pegmatites is spodumene (Kesler et al, 2012). In this text, we will use "pegmatites" and "hard-rock" interchangeably as representative words for "lithium pegmatites".

[3] Own calculations with data from U.S. Geological Survey (2020).

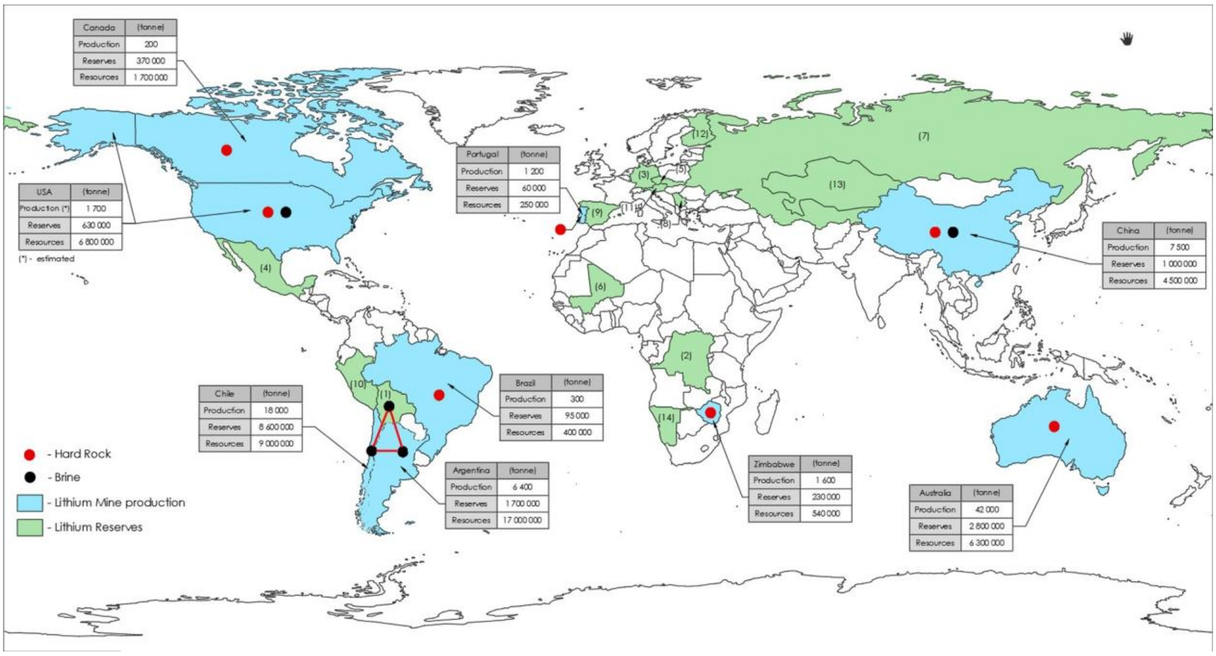

Fig. 1. Lithium deposits around the world by deposit type. *Source:* Own elaboration based on data from Hocking et al. (2016) and U.S. Geological Survey (2020). Countries with considerable lithium resources (not classified as significant producers) are here listed in decreasing order of known amounts: (1) Bolivia, (2) Congo, (3) Germany, (4) Mexico, (5) Czechia, (6) Mali, (7) Russia, (8) Serbia, (9) Spain, (10) Peru, (11) Austria, (12) Finland, (13) Kazakhstan, (14) Namibia.

Table 1
Summary of main socio-economic, environmental and human health expected impacts.

	BRINE	PEGMATITE
	SOCIO-ECONOMIC IMPACTS	
Increased global economic revenues	þ þ þ	
Growth of local economy and job creation, counteracting desertification	þ þ/ þ þ þ	
External independence of lithium supply and eventual exporting possibilities	þ þ	þ
Effects on ecotourism	¡/ ¡ ¡	
Local agro-pastoral activities	¡	¡ ¡
Local population migrations	¡ ¡?	
Contestation of mining activities	¡/ ¡ ¡	
	ENVIRONMENTAL IMPACTS	
Diminishing quantity and quality of surface and underground water resources	— ¡ ¡	¡
Wastewater generation	¡ ¡ ¡	¡
Fauna, flora, ecosystems degradation	¡/ ¡ ¡	
Visual impacts/ changes in the landscape	¡	¡ ¡
	EFFECTS ON HUMAN HEALTH	
Impacts on air quality	¡	¡ ¡
Effects on human health	¡	

þ þ þexpected positive and very significant impact; þ þexpected positive and significant impact; þexpected positive and not significant impact; ¡ ¡ ¡expected negative and very significant impact; ¡ ¡expected negative and significant impact; ¡expected negative and not significant impact; **?** unknown impact.
Source: Own elaboration.

(2013) underline fears from quinoa producers in Bolivia's mining areas. Because generally the soils from pegmatites fields have more potential for agro-pastoral activities than territories where brines exist, this impact may be higher in pegmatites regions.

Moreover, the local population is induced to migrate, in particular abandoning ancestral sites (Agusdinata et al., 2018) near brines. Furthermore, the increasing consciousness about environmental issues may lead to social contestation related to lithium mining (Liu and Agusdinata 2020). One reason is a noticeable contradiction that "resource extraction often occurs on indigenous lands and benefits least those who experience its negative impacts" (Babidge and Bolados 2018, p. 171). In Portugal, in a different context, the fears for negative consequences, especially environmental ones, have been driving assemblies and demonstrations headed by various civil and environmental groups (Simoes and Amorim 2020). The social impact tends to be bigger or smaller according to different social dynamics. To counteract social contestation and population dissatisfaction, activities related to corporate responsibility of lithium producers have been advocated (Carballo-Cruz and Cerejeira 2020), as shown by the increasing number of diversified initiatives with the local communities, as is the case in Chile (Babidge 2013; Babidge and Bolados 2018; Liu and Agusdinata 2020). The need to engage local population is also stressed, for instance by Valle and Holmes (2013) and Rodrigues et al. (2019).

As regards impacts on the environment, some authors recognize significant consequences derived from lithium mining (Wanger 2011; BGS 2016; Agusdinata et al., 2018; Kaunda 2020). In the first place, impacts on quantity and quality of surface and underground water resources have often been addressed (Wanger 2011; Agusdinata et al., 2018; IEA 2019; Liu et al., 2019; Liu and Agusdinata 2020). The exploitation of lithium is water intensive, especially in brine deposits, leading to water shortages (Kaunda 2020; Vikströ¨m 2020). Valle and Holmes (2013) state that sizeable quantities of toxic chemicals used in Bolivian mining may cause pollution of water, air and soil. In a study based on an Australian case, Prior et al. (2013) note that large amounts of wastewater are released, while the discharge of chemical substances leads to water pollution. Furthermore, Wanger (2011) and Flexer et al. (2018) acknowledge that freshwater may be affected by the mining activities in Bolivia and Argentina. However, Rodrigues et al. (2019) found no evidence of effects on water and soil quality from a pegmatite lithium mine in Portugal. Yet, in a similar case, Visa Consultores (2018) acknowledge that pegmatite mining leads to fragmentation of rocky materials, releasing immobilized elements into the water. Also the addition of chemicals for the extraction process may affect its quality. Hence, some quality degradation of freshwater and groundwater, as well as wastewater release, are envisaged.

Damaging effects on fauna and flora are expected as lithium mining activities evolve (Agusdinata et al., 2018; Flexer et al., 2018). Liu et al. (2019) found evidence in Chile of declining local vegetation cover, higher temperatures and drier soils. With substantial requests for water for mining in brines, several agricultural activities and pastures may be abandoned, exacerbating the extinction of fauna and flora, thus resulting in damages to ecosystems and communities (Kaunda 2020). Regarding pegmatites, in smaller areas than brines, the effects are very dependant on the biodiversity dynamics from the extraction area.

Visual impacts, resulting from changes in the landscape, even if later mitigated, may be highlighted (Partid´ario and Pinho 2000; Visa Consultores 2018; IEA 2019). Because of its complex procedures, this effect is generally more perceivable in hard-rock extraction. Moreover, impacts on air quality, in particular atmospheric dispersion of particulate matter, prevail in open-pit pegmatites mining (Partid´ario and Pinho 2000; Rodrigues et al., 2019).

The above mentioned characteristics may affect human health (Wanger 2011). According to Agusdinata et al. (2018) lithium supply mainly comes from developing regions (such as the triangle of lithium), potentially less demanding on academic research than the more developed lithium-consumer countries. In fact, social and human health impacts from mining on local communities have not been much explored in the literature. We approach this social impact topic later, especially contemplating pegmatites in the B-A region.

Although we recognize the importance of assessing both positive and negative socio-economic impacts, we will concentrate our analysis on environmental and health impacts, focusing on their potential relevance in the Portuguese case.

3. Application to Barroso-Alva˜o

Portugal is ranked in 7th and 9th places in terms of world lithium production and reserves, respectively (U.S. Geological Survey 2020), and 1st in Europe, representing more than 1% of world production (Gourcerol et al., 2019). It is the biggest potential lithium producer in Europe transforming it into an appealing object of research. However, very few Portuguese studies have been published related to diverse lithium aspects (Agusdinata et al., 2018). On the contrary, in recent years, the relevance of lithium for Portugal has been strongly emphasized, by the Government, with various measures and legislation,[4] accompanying manifested interests from big players in the area of lithium extraction in Portugal.

Lithium pegmatites in Portugal[5] are associated with differentiated granitic magmas, mainly located in the central and northern regions. This mineralization was traditionally intended to feed the ceramics and painting industries but as is to be expected, lithium is now being directed to supply growing electric battery markets (Lima et al., 2011; Oliveira and Viegas 2011; Viegas et al., 2012).

The extraction phase in open-pit mines includes steps such as drilling and blasting of hard-rock, excavation and transport, a process of removing the ore, in order for it to be processed (Revuelta, 2017). For the purposes of this study, the lithium ore processing occurs after the extraction phase, and thus lies outside the scope of the present paper. This applies to one of the largest Portuguese lithium reserves, located in Northern Portugal in the region of Barroso-Alva˜o (B-A) (Fig. 2). In this area, an amount of 14 Mt of lithium, more concretely 10.3 Mt of exploitable lithium ore, was identified, with an average content of 1% of Li_2O (GTL 2017; Oliveira et al., 2018). The concentrations range between 0.9% to 3% (Amarante et al., 2000). This is considered a very promising concentration for exploitation and production, from an economic point of view, given such a high content of lithium in such a small area. In the B-A region this higher concentration, together with the high purity of the metal and political stability of the country, paint a very interesting case for extraction (Narins 2017). Nevertheless, this possible supply may entail negative effects for the country/region possessing noteworthy socio-environmental features.

B-A is located in the north of the Vila Real district, incorporating part of the Barroso and Alv˜ao mountains. The surrounding area is largely forested, combined with fields devoted to agriculture and livestock activities, some farms and three small population hubs, at a distance of between 200 and 750 metres from the site of the planned open-pit mine (Visa Consultores 2018). A large dam (*Albufeira do Alto Rabaga˜o)* is also located in the region which is an area restricted by special Forestry Regime. The economic activities related to agriculture, forestry and grazing are still predominant and contribute significantly to household economies. The region of Barroso has been classified as the only Globally Important Agricultural Heritage System in Portugal by the United Nations since 2018, one of a total of seven in Europe and Central Asia (FAO 2020). The importance of several local plants and animal species, agro diversity and varied cultures, value systems and social organizations were recognized for this region, where "a number of very significant and relatively intact environmental areas are still found" (FAO 2020). Among other serious fauna concerns, nesting zones of critically endangered bird species are located in the area (Visa Consultores 2018). B-A forms part of the territory of the Iberian Wolf (*Canis lupus signatus*), one of several endangered species, classified in the Red Book of Vertebrates in Portugal (Cabral et al., 2005). Therefore, this location, mainly from the bio and agro-forestry-pastoral standpoint, poses important challenges when we speak about extracting lithium, in terms of environmental and biodiversity protection as well as impacts on health.

4. Methodological approach

Fig. 3 presents an overview of the research method used in this study. The main research interest of the paper is related to the assessment of the environmental and health impacts of exploiting lithium reserves on a large scale, in particular to satisfy the growing demand for EV batteries. The research was developed in four main steps: (1) contextualization of the study; (2) brief characterization of the specific application; (3) life-cycle assessment (LCA) and (4) conclusions.

Firstly, the formulation of the research question was established based on the main purpose of the study. Secondly, potentially relevant research studies were reviewed to demonstrate the scientific relevance of the topic and support the fundamentals of the study. The literature background addressed three main topics (an overview of lithium, the geographical dispersion of the deposits and main impacts of its extraction), bringing into play a new insight from the particular perspective of pegmatites. Then the region of B-A in Portugal was selected as a central point of interest.

Thirdly, we adapted the already existing LCA for EV batteries (EPA 2013), concentrating on the extraction phase for the evaluation of the potential impacts associated with lithium extraction in Portugal. Since EPA (2013) has mainly a quantitative focus and assesses different elements included in battery production, we extended it by including a

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[4] In 2016 the "Working Group on Lithium" (GTL) was created to analyze various aspects related to its new strategic opportunities (Gabinete do Secret´ario de Estado da Energia, 2016). In 2018, faced with requests for assignment of lithium prospection and extraction from national and foreign investors, more legislation was released, where the potential of lithium, not only as regards macroeconomic variables but also regarding economic development for more impoverished areas in the country, was reinforced. The "initial phase of the chain", regarding the geological knowledge, of the minerals, supported by the reports of GTL, was underlined (Resoluça˜o do Conselho de Ministros, 2018). On 31st December 2020 the Portuguese Parliament, in the State Budget, assigned revenues from the Environment Fund for the strategic environmental evaluation of lithium mining, including the analysis of the externalities, seen as "real costs" inherent in mining for populations and State (Assembleia da República, 2020).

[5] In the case of our application area, two types of lithium minerals prevail: spodumene and petalite are the most common lithium minerals in Portuguese pegmatites and are expected to supplant the production of the other sorts of minerals (Lima et al. 2010; Lima et al. 2011).

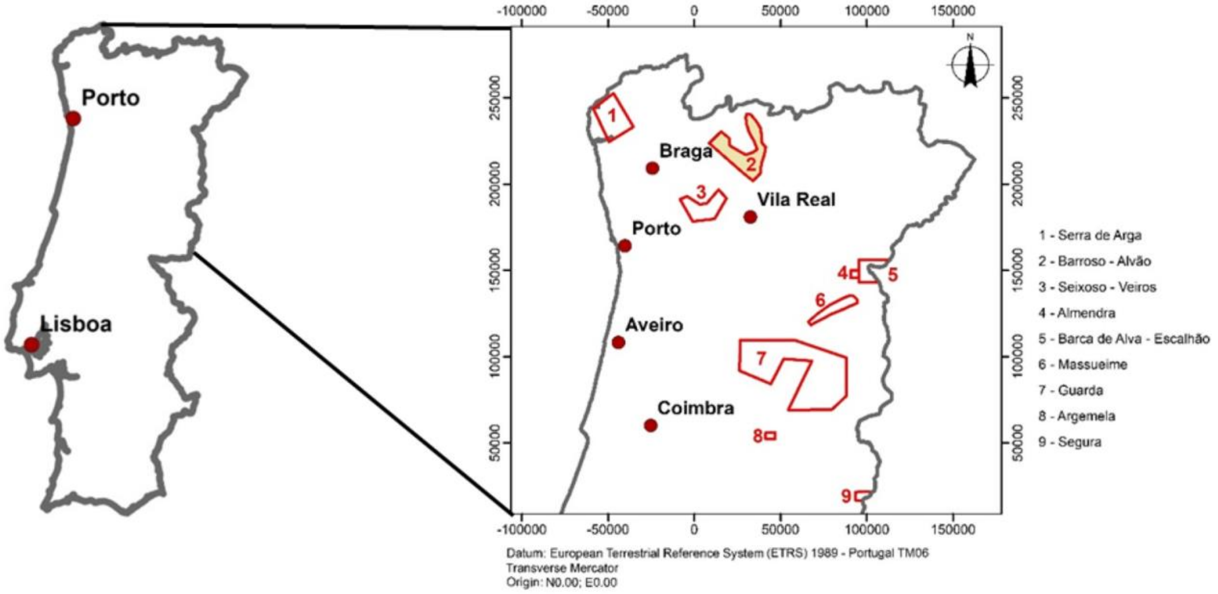

Fig. 2. Lithium in Portugal – locations identified. *Source*: Own elaboration, based on GTL (2017).

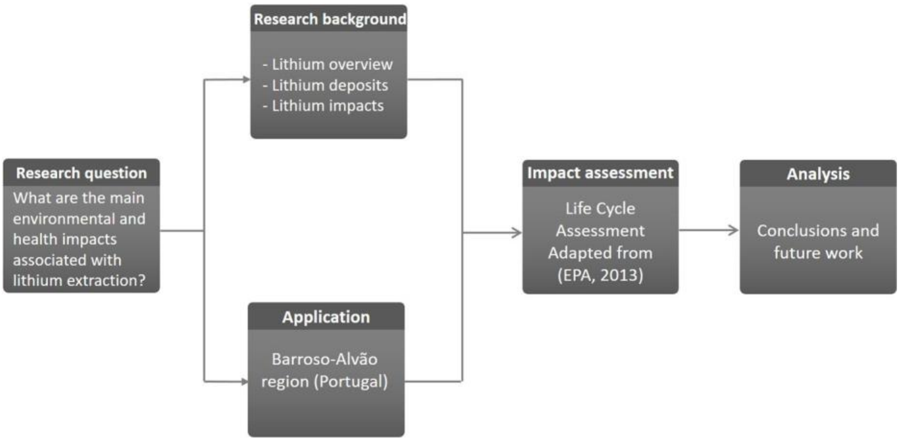

Fig. 3. Methodological approach. *Source*: Own elaboration.

qualitative scale, addressing the specific case of lithium for the region under analysis. Finally, exploratory analysis was undertaken to provide implications from the research, leading to avenues for further research.

4.1. *The EPA methodology*

To make a first assessment of the potential effects for the environment and human health in the B-A region, we resorted to the methodology of the life-cycle of EVs led by EPA (2013) as a guiding reference. This EPA study was the first LCA elaborated one, which had as a basis data collected directly from suppliers, manufacturers and recyclers, mainly addressing lithium brine extracted from saline lakes in Chile.

The LCA is an analytical tool used to assess and evaluate environmental and health impacts on each stage of a product, activity, or process life-cycle (Domènech et al., 2002; Almeida et al., 2010; EPA 2013; Curran et al., 2016; Özkan et al., 2016; Mellino et al., 2017; Brondani et al., 2019). In other words, this tool appraises the impacts from materials extraction and processing, manufacturing and product design, transport, distribution, and use, up to final disposition/recycling. It can be used as a sort of instrument, helping in the political decision-making process and guiding the environmental performance as to the choice of the least impactful existing options (SAIC and Curran 2006; Hossain et al., 2007; Rostkowski et al., 2012; Curran et al., 2016). LCA "is a kind of 'bottom-to-top' method, which includes the process 'from start to finish' of the product. It is generally recognized as a quantitative and qualitative analysis tool of environmental impact caused by life cycle of product at the international level" (Liang et al., 2017, p. 285).

Nevertheless, implementing LCA is a task that requires valid and solid data regarding impact quantification that is not always available or easy to collect (Levasseur et al., 2010; Basbagill et al., 2013). It is therefore important to understand that the "hidden costs" could very well raise the real cost of a product if they were all taken into account (Fava 2002). As a matter of fact, each stage in the life-cycle of a mineral/concentrate carries unquestionable risks to the environment and the population, independent of the material. Therefore, accounting for these externalities may affect prices and make recycling and second uses viable (Epstein et al., 2011).

As regards the specific case of lithium for Li-ion batteries, uncertainties play an important role in the metal's extraction, use, and disposal, making the application of a tool such as the LCA crucial (Stamp et al., 2012; Hawkins et al., 2013). On the one hand, these uncertainties relate specifically to the initial phase of the analysis, since the diversity of natural occurrences of lithium deposits is high, although they also relate to the final phase, since lithium is an element with high demand but still limited production. Thus, the LCA is an operational tool for investigating the consequences of the production of lithium batteries and EVs (Reuter 2016; Peters et al., 2017). However, there are very few studies using LCA to analyse the environmental performance of EVs powered by Li-ion batteries, for they mainly address the energy benefits and costs, while the remaining impacts are overlooked (Mellino et al., 2017). EPA (2013) applies this methodology to Li-ion batteries used in EVs. "The LCA methodology is structured along a framework with four main steps: goal and scope definition, inventory [LCI], impact assessment [LCIA] and interpretation" (Ligthart et al., 2010, p. 746).

Environmental impacts are evaluated for the following life-cycle stages: i) materials extraction, ii) materials processing, including the processing of resources and transport of processed materials to manufacturing sites, iii) product and components manufacture, iv) product use, and v) final disposition (EPA 2013). Several impact sub-categories were focused on and analysed for each life-cycle stage, from which we selected the most suitable ones for the application, categorizing them as environmental and human health aspects (Fig. 4).

Integrating the categories into two different groups (environmental or health) does not mean that each of them has a boundary-limit effect on the attributed influence area, but that the category is seen as more appropriate for being considered as such. Moreover Jiang et al. (2020) analyse similar categories to assess environmental and health impacts from lithium production, using rock-based compared to brine-based technology. They conclude that impacts from the first are much larger than those from the second, because rock-based technology requires "a considerable amount of fossil fuel and chemicals to melt the rock", while the second "just needs solar energy to evaporate water". They centre their analysis on lithium production "including calcining, roasting, leaching, purification, carbonation, drying, air compression, and auxiliary system".

Our analysis will concentrate directly on the extraction phase, particularly on the possible local impacts in B-A.

5. Analysis

Every stage of the life-cycle of Li-ion batteries has positive and negative impacts on the economy and environment. However, the extraction phase stands up as the one that will have the most effect on a country that possesses lithium mines but does not produce batteries, such as Portugal.

This LCA stage is precisely the one that is least addressed in the literature, perhaps because the environmental and health effects of the different life phases of Li-Ion batteries point to the use (Notter et al., 2010) and final disposal as the most damaging ones.[6] Besides, "environmental impact evaluation tools, such as life-cycle assessment, prevalent in other engineering disciplines are significantly limited in mining due to a lack of adequately defined quantifiable impact categories (…) and functional units" (Kaunda 2020, p. 241–242). Last but not least, the scarce literature on the subject focuses mainly on extraction from brines. Notter et al. (2010), for instance, develop a pioneer application of LCA to EVs, restricting results from lithium extraction to the brine context, and admitting that different impacts may occur if lithium was taken from pegmatites.

We argue that the extraction stage embracing lithium from hard-rock (pegmatites) must be more closely scrutinized, since it constitutes the most common source in some areas, as European countries. Therefore an exploratory analysis of this issue is presented below. We support our study on some assumptions, resorting to an application and adaptation of EPA (2013), seen here as a reference for our case. Furthermore, some studies on impact assessments performed for the B-A region are used to support our reasoning.

Finally, we face another major challenge. Since the quantitative values obtained by EPA (2013) relate to the extraction phase of minerals for EV batteries, comprising not only lithium, the effects related to lithium have to be carefully reassessed as Portugal extracts lithium, but not all the other necessary minerals for battery production. This specific lithium analysis was based on a qualitative approach for the B-A extracting conditions.

For a first assessment, we compiled several evaluations made by EPA (2013) for the different impact categories, for a base-case battery (assuming the average value for three different battery chemistries) and the corresponding percentage of effects from the materials extraction phase in relation to the total life-cycle of the battery. Table 2 summarizes the results collected for the extraction phase. Some of the categories considered here may be somehow connected to the environmental and health impacts listed in Table 1. However, impacts in Table 1 are generic and broad, while in Table 2 we have specific impacts, following different criteria and scale.

Because the units of each item in Table 2 are different, we cannot make direct comparisons between the absolute values, but we can assess the relative importance of the extraction phase for each variable. Furthermore, the EPA (2013) values are based on information computed for the case of lithium brine extracted from saline lakes in Chile. Given the scarcity of information, we will assume that the relative importance of the impacts across each life-cycle stage for the case of hard-rock in Portugal will relate to these EPA (2013) values. Some expected differences are mentioned in the following paragraphs and in Table 2. Some illations for the case of B-A will be attempted.

According to EPA (2013), as regards general effects, Product Use (iv) and Materials Extraction (i) are the phases that dominate environmental and health impacts. Abiotic Resource Depletion (ARD), Global Warming Potential (GWP) and Acidification Potential (AP) (more related to environmental effects) as well as Photochemical Oxidation Potential (POP) and Human Toxicity Potential (HTP) (more connected with human health), have more than 80% weighting in the use phase.

As the extraction phase is the one that will take place in Portugal, we will concentrate on understanding its major impacts. Although values in Table 2 help to envisage the expected effects of the extensive extraction of lithium in B-A, it must be recalled that the EPA study is about the LCA of batteries, and so the extraction effects are not located in a restricted area because several minerals are needed.

There is no doubt, however, that a part of these effects takes place in the extraction of lithium itself. Given this, we resorted to additional qualitative analysis based on an ordinal scale of the expected importance of the impact of lithium extraction. This qualitative analysis is presented in the two last lines of Table 2. Taking as reference the value obtained by EPA, i.e., the weight in the total LCA of Li-ion batteries, we typify an impact of different order on brines and pegmatites. In this last case, we especially resort to available information and concrete characteristics of the B-A region, where the extraction of lithium is expected to take place.

The ARD (1) effect, representing less than 10% weight in the whole chain, may be justified both by the mining of lithium and by the need to obtain other components for the production of batteries, as well as by the use of chemicals. "The per-unit mass impact is directly related to the rate of resource depletion, and indirectly related to the abundance of the material" (EPA 2013, p. 68). Although this is considered quite relevant, EPA (2013) recognizes that a lack of accuracy may exist. Furthermore, data are based on the Chilean case, which may be insufficient to extrapolate to other cases. Nonetheless, supported by this quantitative result, we offer a qualitative interpretation for our case. The impact is foreseen as small in brines, but it can be more significant as regards pegmatites, because the resource depletion is higher, due to the smaller quantity of exploitable lithium.

A major issue exists regarding the main value attributed to environmental impact categories such as GWP (2), AP (3), ODP (Ozone Depletion Potential) (4) and ETP (Ecological Toxicity Potential) (5), in

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[6] Viana et al. (2020), for instance, found evidence, on the Portuguese coast of potential toxic effects in aquatic systems caused by the anthropogenic use of lithium.

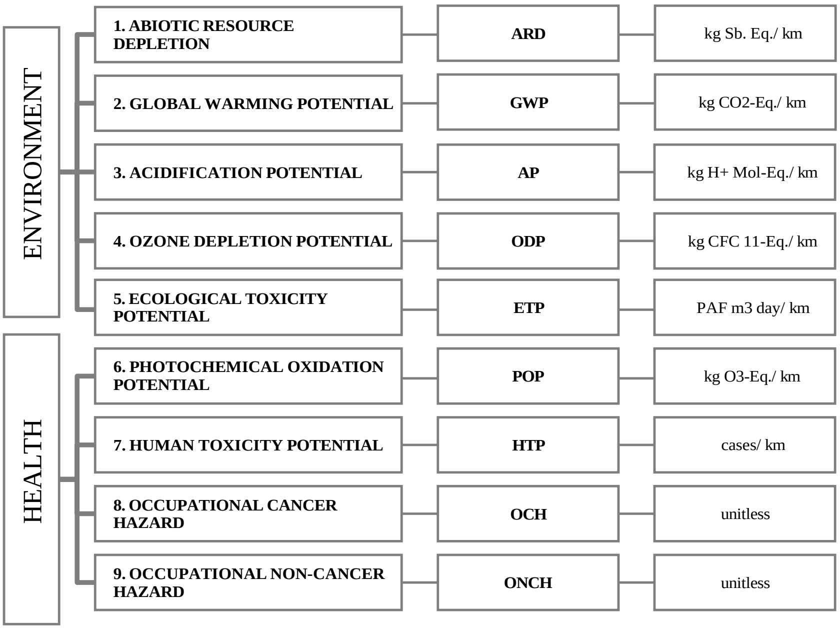

Fig. 4. Impact categories considered in the study for each stage of the LCA of a Li-ion battery. *Source*: Own elaboration, based on SAIC and Curran 2006; EPA 2013.

Table 2
Impact categories for the materials' extraction phase.

		ENVIRONMENT					HEALTH			
		1. ARD kg Sb-Eq	2. GWP kg CO2-Eq.	3. AP kg *H*+Mol-Eq.	4. ODP CFC 11-Eq	5. ETP PAF m3 day	6. POP kg O3-Eq	7. HTP cases	8. OCH (unitless)	9. ONCH (unitless)
Quantitative absolute and relative estimates obtained from EPA (2013)										
Extraction Phase (EPA 2013)	Absolute values	9.01 E-05	1.57 E-02	7.97E-03	5.62E-10	1.63E-03	7.57E-04	2.58E-13	1.37E-01	1.16E+00
	Weight in the total LCA	9.2%	10.7%	12.5%	46.2%	94.3%	8.5%	8.2%	69.8%	92.4%
Qualitative estimates by lithium deposit types										
- Extraction from Brines		¡	¡	¡? ¡ ¡ ¡	¡ ¡			¡	¡ ¡	¡ ¡
- Extraction from Pegmatites		¡ ¡ ¡	¡ ¡	¡ ¡? ¡ ¡	¡			¡	¡ ¡	¡ ¡

— ¡ ¡expected negative and very significant impact; ¡ ¡expected negative and significant impact; ¡expected negative and not significant impact; **?** unknown impact.
Source: Own elaboration. Quantitative results based on EPA (2013).

the extraction phase. The negative effects are not essentially the result of pegmatite lithium extraction, the most important causes being related to extraction of other chemical elements, such as aluminium and nickel (EPA 2013). Resorting to LCA of EV batteries, Liang et al. (2017) concluded that the extraction phase has low effects on greenhouse-gas emissions, compared to other stages such as the use phase. Additionally, the values for GWP (2) should be looked at with close attention as they depend on the carbon intensity processes used. For instance, countries such as Chile expressed concern about high fossil fuel dependency of the grid and the high prices (Vikstro¨m 2020). Concerning lithium pegmatites, the need for electricity in the extraction phase is not so high, because this phase mainly involves the use of mechanical equipment, using fossil fuels. Therefore, even in the case of a relatively low carbon grid such as in Portugal, the GWP can still play a not insubstantial role in the material extraction phase. Nevertheless, this negative effect has been considered quite small for the pegmatites of B-A (Visa Consultores 2018).

For the production of the different components of the battery, the AP effect (3), albeit small, plays a role. Although the intensive use of water in brines contributes to AP, the extraction of lithium from pegmatites can also be seen as relevant, because more chemicals are expected to be used in this kind of extraction.

As for ozone depletion (4), the materials extraction for battery production makes a substantial contribution, yet this is not mainly due to lithium mining, but to other components, such as aluminium. Precisely because the dominant materials responsible for these effects are not lithium, we assign an unknown impact on our qualitative scale and assume no difference in ODP, by producing a battery using lithium from brine or pegmatite.

Regarding ETP (5) in particular, we can expect a significant negative result, derived from the potentially affected fraction of species (PAF) over time per volume of freshwater compartment (m^3) i.e. concentrations of toxic substances in water over the tolerable limit for aquatic organisms. The effect is mainly due to the necessity of the battery to embody other elements than lithium, such as iron. Accordingly, we foresee a smaller effect from the extraction of lithium in brines and pegmatites than other components needed for the battery (in total about 90%, as predicted by EPA for all materials in the extraction phase). Still, in line with their salt areas characteristics, a higher magnitude in brines is envisaged.

As for human health, again POP (6) is associated with the use of chemical processes to extract some metals other than lithium. Albeit small, this effect may be present especially in brines, as a result of the synthesis processes of lithium salts (EPA, 2013). Additionally, HTP (7) i. e. the potential toxicity of air emissions released into the environment for the general public, emanating especially from aluminium production, is expected to be small in the extraction phase. Regarding the effects from lithium extraction itself, these are even smaller, because in most cases, lithium mines are located a long way from high population concentrations.

Finally, OCH (8) and ONCH (9) (Occupation Cancer and Non-Cancer Hazard) refer to the potential harm caused to workers likely to be exposed to cancer-causing or non-cancer causing (but also harmful) chemicals, dust, radiation, and certain industrial processes. This cause-effect relation is especially difficult to assess and leads to large uncertainties. "Cancer impacts are primarily attributable to the materials and extraction needed for the cathode, especially the lithium brine" (EPA 2013, p. 89). "EPA's Structure Activity Team estimated that soluble lithium salts like lithium chloride and lithium carbonate (…) would have good absorption from the lung and GI tract" (EPA 2013, p. 89). Different morbidity causes may occur, regarding lithium pegmatites in the extraction phase. As a consequence of emissions of fine dust, especially particulate matter (PM), occupation and non-occupational diseases may occur. Short-distance movements of PM_{10} are the most likely air pollutant affecting human health (Visa Consultores 2018).

To sum up, for the main impact categories analysed, and according to the LCA of Li-ion batteries, we expect the major prejudicial effects of the extraction phase to derive from other minerals, such as aluminium and cobalt, for instance, which are beyond the scope of this study. Nonetheless, we argue that lithium impacts are non-negligible especially from a local communities perspective, affecting human health, environmental conditions, and ways of live.

Thus, lithium extraction in the B-A region may help to develop and promote the region in an innovative local microeconomic way, to supply energetic and strategic raw materials to the national, European and global markets. However, it is also important to underline that local communities concerns, such as is the case with this region should be taken into account both from a health and social organization perspective (Visa Consultores 2018; Carballo-Cruz and Cerejeira 2020).

6. Conclusions and further research

The very recent developments regarding the potentiality for lithium extraction in Portugal were the challenge for this study. The process of exploring and extracting lithium to produce EV batteries has taken its first steps, and will undoubtedly have positive and negative effects not only on the Portuguese economic framework, but also on its local communities and ecosystems. Whether the opportunities are able to overcome all the threats is the key question, whose answer remains to be seen. It is therefore important to take into account all the pros and cons and to act accordingly, i.e. cautiously and mindfully. In particular, it is crucial to assess whether, by supplying foreign countries with lithium to supposedly power EVs, Portugal will thus be impacting its own ecosystem.

There is a dearth of studies focusing on the impacts of the pegmatites extraction phase as a stand-alone phase in relation to local communities, collective health and environment, which is why this study focuses on the EPA methodology, as a tool for evaluating these specific effects for Portugal. An application of several impact categories proposed by EPA leads to some considerations, pointing to the importance of looking at aspects that may affect the B-A region. Apart from the abiotic resource depletion, the ecological toxicity potential and occupational health hazards should be emphasized. This may help in the decision phase for the strategy of mining, to determine what measures should be taken and what policies should be followed. Moreover, the cultural and social characteristics of the B-A region should not be overlooked or devalued. We argue there is a need to focus not only on the global advantages but also on local characteristics to avoid the common sustainability argument surrounding EVs (and lithium batteries), which mainly addresses the climate argument from a global perspective. This is a major aspect to be taken into account in the extraction phase, and it substantiates an important dichotomy for sustainability and low carbon policies: the tradeoff between the global benefits (e.g. reduced greenhouse gas emissions) and the negative impacts frequently borne by local communities. This argument is increasingly linked to the idea of energy justice and the need to explore the extent to which low-carbon transition can negatively impact on communities at opposite ends of the supply chain (Sovacool et al., 2020). This shows the importance of proceeding with LCA studies to properly quantify these impacts and openly sharing this information with the population, to ensure mutual respect and a collaborative environment that should not only facilitate the process but would also contribute to mitigating damaging impacts.

Although we recognize the limitations of the research, given the scarcity of information, lack of academic studies and data, and albeit having as reference a methodology developed for different sources of lithium deposits, we believe that this example can provide relevant contributions to the potential impacts of lithium mining activities and therefore promote related scientific development. Thus, this research has resulted in two main contributions: (1) it has provided new insights into the lithium effects on environmental and human health, considering in particular the extraction from pegmatites such as the region under study, and (2) it has explored the possibility of adapting an existing LCA for impact evaluation, consequently creating opportunities for further examination of different regions and contexts. We recognize, with ETIP (2020, p.30), that "Tools and methodologies to perform environmental and social life-cycle analysis (LCA and S-LCA) to quantify sustainability performance of batteries must be further developed from a holistic perspective".

Moreover, this study addresses a real situation and thus can generate new knowledge that may be useful in similar situations and even facilitate the understanding of the complex process of mining impact assessment. It can also open some avenues for further research, including the need for the development of a well-tailored methodology for the assessment of the social, economic and environmental impacts of lithium exploitation. Forthcoming research must go beyond overall country indicators and recognize the necessity to account for local communities' needs, expectations and potential impacts. The analysis of the possible co-existence of mining with current activities, potential negative effects or synergies and the proposals for possible routes and pathways going forward are important fields for further research.

Following Jiang et al. (2020), who provide "the first life-cycle inventory for mass-produced rock-based lithium" focusing on onsite processing, we support the claim, that more primary data of upstream processes are needed. Future research should follow this line and improve LCA analysis with a focus on the impacts of extraction itself, as in the case of local extraction in B-A. This study should be seen as a preliminary stage leading to future developments and precise calculations, when holding the appropriate data. Policy implications based on these results are very relevant for decision making as regards the best way forward for the country and its people and in particular for the regions directly affected by mining development.

Declaration of Competing Interest

None

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