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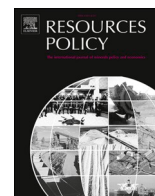
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Revising the ‘Economic importance’ dimension: The European framework for critical raw materials, completed and illustrated using lithium

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ABSTRACT

In demand since time immemorial, increasingly used as intermediate consumption and at the heart of energy and digital transitions, mineral substances are vital to the functioning of economies. While all are important, not all are strategic, and even less so, critical (as lithium). The European Union depends on them. Since 2010, the European Commission has produced statistics evaluating a broad and extensible set of criticality sub-indicators integrated in a two-dimensional matrix (Supply Risk, SR, and Economic Importance, EI) and a list of critical substances based on a combination of SR and EI, updated every 3 years. This article takes a closer look at one of these dimensions, namely the EI one. Our proposed dimension, "Economic effect, EE", integrates cost of using raw materials. Articulated in coherence with EI and assessed over the most recent period, it is compared with EI for lithium. EE suggests a systematically higher criticality than EI. Lithium stands out as 4% more critical. The dynamics of its criticality, on the other hand, is non-monotonic, enriching that of EI. The article also numerically illustrates the prospective use of SR, EI and EE. In addition, an up-to-date overview of lithium (markets, uses, production costs, supply, demand, prices, stocks and trade) has been provided, both for the EU and worldwide.

1. Introduction

The aim of studies on the concept of materials criticality is to identify substances of such economic (i.e., strategic) importance that a difficulty or shortage in their supply would disrupt the functioning of an economy and/or value chains to a greater or lesser degree.

The criticality approach involves the construction, assessment and dynamic analysis of one or more dimensions, each targeting a given issue (shortage risk, economic risk, environmental risk, social responsibility risk, etc.) and combined in a coherent manner. By quantifying these dimensions, criticality thresholds can be set. If these thresholds are exceeded, a substance is added to or removed from the list of substances deemed critical for the entity concerned, in this case the European Union (EU). The content of each dimension, i.e., the sub-indicators, makes it possible to situate the roles of the various factors explaining criticality.

In the EU, the Critical Raw Materials Act of 2023 has just set targets, including figures (for controlling volumes imported from third countries, as well as for extraction, refining and recycling) for regulating the supply of strategic and critical mineral materials.

Precise knowledge of the substances in question guides economic policy aimed at anticipating future supply tensions and overcoming dependence on foreign resources. Thus, mining policy will seek to encourage the supply of materials from the EU's subsoil rather than importing them, by promoting alliances. In the case of securing the supply of lithium – henceforth Li – and more generally on the value chain leading to electric batteries, we have, for example, the European Battery Alliance (EBA) launched since 2017 by the European Commission. Like mining policy, research and innovation policy, trade policy, recycling policy, the management of the energy and digital transition, but also trade negotiations, can rely on criticality work. The lists of critical materials for the EU, which have been in existence since the 2010s, also make it possible to identify countries or companies hindering trade in these materials. Among other things, the European commission uses these lists to negotiate against distortions in international trade and thus defend the competitiveness of European industry. The scale of analysis of the Commission's current criticality work – and of the main criticality frameworks – is currently macroeconomic and supra-national. This does not prevent stakeholders (public authorities, universities, national geological surveys, companies, etc.) from referring to

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them or drawing inspiration from them to adapt them to their activities (see [Blengini et al. \(2017\)](#), Section 7 for a survey of the interest of these lists for stakeholders). The dissemination of this framework, as *via* this article, will also enable it to be better appropriated.

Raw materials have always been used to produce goods and services. However, the general rise in living standards in the 21st century is ushering in economic, demographic, environmental and technological pressures, the pace of which is indeed the aspect that raises questions. All else being equal, the use of materials, in this case minerals, as intermediate inputs in value chain processes is an increasing function of these pressures.

To take the important but far from isolated case of the energy transition (without giving up growth), the investment required in low-carbon technologies calls for a higher material intensity,¹ i.e., a higher ratio between the quantity of raw materials used and installed energy capacity than for thermal technologies. Even if it is supposed to provide an environmental gain, this higher ratio is likely to shift fossil dependency towards mining dependency.² Public policies aimed at reducing or ending this dependence are likely to undermine the expected environmental gains. Moreover, mining resources are not more equitably distributed³ than fossil fuels and may be subject to international trade restrictions, showing that shifting dependency does not reduce supply risk.

The coronavirus pandemic of 2019–2020 and the Russian-Ukrainian armed conflict of 2022, which are still ongoing, have also recently brought a renewed awareness of the dependencies linked to the deepening of the division of production processes. Increasingly globalized value chains mean, for e.g., that the supply risk for a given material must always be considered at the level of the mining countries, but also

¹ Numerous studies corroborate this, as illustrated by the following examples. The [IEA \(2021\)](#) points out that a standard electric car that contributes to reducing GHG emissions requires 6 times more mineral materials than a conventional car with a petrol or diesel engine. In its projections to 2040, the IEA estimates a global demand multiplied by 3 for copper, 7 for rare earths, 21 for cobalt and up to 42 for Li. In a World Bank report, [Hund et al. \(2020\)](#), emphasized that, in the energy transition, the manufacture of solar panels, wind turbines and batteries will fuel tensions on mineral materials, even if uncertainties over the technologies that will be in use beyond 2030, or over the contribution of recycling, may more or less exacerbate these tensions. This report also confirms a World Bank precedent ([World Bank, 2017](#), p.17), which already pointed out that, in the field of decarbonized energy storage, for the production of Li-ion electric batteries alone, the requirements for aluminum, cobalt, iron, copper, Li, manganese and nickel to limit warming to below 2° Celsius by 2050, were all multiplied by more than 11 compared with their 2013 levels (however, the multiplier coefficient is 1 so demand for these substances would be stable, if warming were only to be contained below 4°). [Heffron \(2020\)](#) uses the term "super-criticality", suggesting that the energy transition amplifies the original criticality of mineral materials and is accompanied by higher constraints of societal responsibility, notably justice. Similarly, an article in *Nature* ([Ali et al., 2017](#), p. 367) highlighted the links between mineral resources and climate change because mining requires large amounts of energy, but also because "the world cannot tackle climate change without an adequate supply of mineral resources". Lastly, while not a panacea for the growing demand for primary mineral resources ([Labbé, 2020](#)), a higher recycling rate at the end of a product's life is a positive factor for the use of cleaner technologies incorporating mineral materials ([Fabre et al., 2020](#)).

² Given the constraints on mineral resources, technical progress, even within low-carbon technologies, could then focus more on becoming more mineral resource-efficient, where it previously consisted of switching from fossil fuels to minerals.

³ In the case of Li, which is the focus of this article, OECD calculations ([Kowalski and Legendre \(2023\)](#)) based on United States Geological Survey data (USGS) confirm this fact. The calculations show a concentration of Li-producing countries measured by a Herfindhal-Hirschman Index (HHI) rising from a high concentration of 57% on average over the 2012–2014 period to around 74% for 2017–2019, an increase in concentration of 17 percentage points. Australia, Chile and China lead the way.

increasingly in relation to the countries that refine these materials. For instance, 60% of Li is refined in China, and nearly 75% for rare earths. But we can go further down the Li value chain by examining the criticality of one of its uses, namely Li-ion batteries, or even further by looking just at which countries dominate production of the battery's anode or cathode ... In short, it's a question of applying the usual criticality method that we are going to see in this article, but applying it to more stages of the value chain. An economy can of course be independent in certain segments of the chain, but this independence is only partial, since the added value associated with this segment depends on the entire value chain.

As a corollary to this deepening trend, governments have a growing strategic interest in securing supplies of natural resources. For e.g, the European Commission's Critical Raw Material Act points out that, compared with 2023, the EU's demand for rare earths could increase sixfold over the next decade, and for Li by a factor of twelve.

The OECD ([Kowalski and Legendre, 2023](#)) reports that over the decade 2013–2023, Li production increased by 208%, a considerable figure, the highest of any metal, yet well below the demand projections mentioned above. USGS data show that by 2022, global Li demand and supply are growing strongly and are virtually equivalent.

The share of supply circulating in international trade, despite some fluctuations correlated with shocks to the global economy, has, according to our calculations in this article, been trending upwards since 2000. Our 3-year projections to 2025 confirm this trend. The historical presence of France, the growing penetration of China and even India in Africa over the last two decades, and the more recent penetration of Russia, can also be viewed from this angle of the geopolitics of materials. Although they are based on different logics, there are many examples of pressure having an impact on natural resources. It is the immediate macroeconomic consequences of these various pressures that this article seeks to capture.

It is within the most recent criticality framework developed by the European Commission ([EC, 2023](#)), which it complements, that this article proposes to address this issue.

The concept of criticality (and the criticality studies that evaluate it numerically and then analyze it) is the one with which the problem is approached in the economic and geological literature. This concept simultaneously reflects the situation of an entity (technology, company, country, group of countries, world) subject to a supply difficulty (supply risk) in a substance whose economic weight is estimated to be considerable (economic importance). In our view, the aim of work on criticality is to show where this entity stands in terms of its capacity and interdependencies to obtain substances that are necessary to its economic functioning – i.e., to the business model it has adopted or intends to adopt – and to be able to identify those for which it would be advisable to be vigilant, or even to change its mode of supply in the more or less short term. When this entity is a country or a group of countries, the criticality diagnosis is even more of a challenge for the public authorities, but also for the companies concerned.

In 2007, the US National Research Council ([US NRC, 2007](#)) presented a criticality assessment framework. At virtually the same time in Japan, [NEDO \(2009\)](#) proposed a framework of dimensions and sub-indicators designed to capture the importance of 39 substances to the Japanese economy. The term criticality was not yet used, but 14 of these 39 appeared to be critical in the usual sense of the term ([Hatayama and Tahara \(2014\)](#)). By 2010 and 2012, the European Commission and the British Geological Survey (BGS) were doing the same. Lists of more or less critical but also strategic substances aimed at identifying and assessing risks have resulted, while literature on the subject and political concerns are also growing.

Alongside these four frames of reference, other complementary works on criticality have emerged, particularly over the last 15–20

years. In summary, these works are distinguished by the substance or substances examined⁴ and the level of criticality analysis (world, group of countries, a single country, a company or a technology ...). They are based on a more or less significant combination of criticality factors for one or more given substances: level of reserves; level of resources; present and future supply and demand; existence of public and private stocks; concentration of the substance by country and sector; production cost and selling price of the substance; existence or non-existence of recycling; technical substitutability of the substance; geostrategic risk; socio-political governance indicators such as the World Bank's World-wide Governance Indicators (WGI); economic importance of the substance; question of substance transformation with criticality of the substance (upstream) versus criticality in the productive use of the substance (downstream); exploration budget per ton of substance produced; mining investment ... Environmental factors such as the impact on air, water or biodiversity pollution are also increasingly taken into account, including applications such as Life Cycle Assessments (LCA) designed to duplicate the criticality method for the value chain associated with a given substance ...

These factors, combined according to methods that may vary from the reference frameworks mentioned above, lead to the establishment of a specific and/or prospective, quantified and/or qualitative diagnosis for the entity concerned by tensions over the physical availability of a substance. Limiting ourselves to the last ten years, and apart from the works cited elsewhere in this article which is more specific to Li criticality for the EU, we mention articles dealing with criticality analysis (criticality works), bearing in mind that not all works dealing with critical substances (criticality works in the broad sense) are, strictly speaking, criticality analysis works. Strictly speaking, the following are examples of such articles: [Achzet and Helbig \(2013\)](#), [Graedel et al. \(2015\)](#), [Bach et al. \(2016\)](#), [Dewulf et al. \(2016\)](#), [Graedel and Reck \(2016\)](#), [Mancini et al. \(2016\)](#), [Bach et al. \(2017\)](#), [Brown \(2018\)](#), [Cimprich et al. \(2019\)](#), [Griffin et al. \(2019\)](#), [Andersson \(2020\)](#), [Arendt et al. \(2020\)](#), [Blagoeva et al. \(2020\)](#), [Bobba et al. \(2020\)](#), [Zhou et al. \(2020\)](#), [Galos et al. \(2021\)](#), [Helbig et al. \(2021\)](#), [Marinova et al. \(2023\)](#), [Polat et al. \(2023\)](#), [Nwaila et al. \(2024\)](#).

Summing up these works in broad strokes, and in addition to the characteristics mentioned above, we can say that some of these articles already address precise criticism on the EU criticality assessment while others are simply literature reviews or they introduce alternative methodologies which may be totally new, or more rarely, links with an existing methodology.

As mentioned above, a third dimension (in addition to SR and EI, there is an environmental dimension and sometimes social aspects) is appearing in some works. Some call for greater harmonization between criticality methodologies, or question the techniques used to aggregate the indicators used in the criticality calculation. Some works take into account the inclusion of the criticality in LCA not only for raw material but products or processes including raw materials. There is also some work arguing for the construction of criticality indicators that are more pedagogical than the current formulas, which are sometimes difficult to quantify and therefore less useful for economic policy decisions.

However, the vast majority of the criticality studies cited above remain retrospective (although more regularly updated, as in the case of the EC studies). A few works, however, allow us to conceptualize criticality calculations in a more forward-looking way.

[Frenzel et al. \(2017\)](#) recall the importance of criticality work for the management of raw materials policy, but find it perfectible. In particular and in the wake of [Gloeser et al. \(2015\)](#) the authors share the observation

⁴ Criticality works can be applied to the concept of resources in the broadest sense of the term: resources are divided into three categories: Energy resources (e.g: oil, coal, and natural gas ...); Metallic resources (e.g: gold, silver, lead, lithium, copper, tin, nickel, zinc, niobium, rare earths elements ...) and Non-metallic resources (e.g: bauxite, phosphate ...).

that these works do not adhere to modeling in line with risk theory even though this is precisely what they seek to measure and manage. In the "Supply risk" dimension, the authors propose replacing this term with "Disruption probability, DP" and modeling it as a risk (we would have used "Supply risk" or "Disruption risk" to retain the term risk).

As a result of this modeling, the other dimension, i.e., EI, also becomes stochastic. This modelling, which calculates criticality for a substance as the product of a probability of its supply disruption and the cost that this disruption would constitute for the economy, is visible in their equation (5), whereas equation (6) temporally delimits the criticality calculation (which the EC nevertheless does). It should be pointed out, however, that while the authors include both dimensions (SR or DP and EI), the contents, i.e. the sub-indicators included in these two dimensions, are not the same as those of the EC. The authors also point out that the quantification of their models nevertheless requires multidisciplinary knowledge (geoscientists, mining and mineral process engineers, materials scientists, metallurgists, and economists ...).

The introduction of this probabilistic, future-oriented aspect cannot be easily implemented, but it could be an avenue of research, for example, by trying to integrate it into current EC work (while also maintaining consistency with the EC framework). We have nevertheless shown, in an admittedly non-probabilistic way, how the current EC framework can be used for forward-looking criticality (See Section 6.2 for example)

Since 2010, [EC \(2023\)](#) has been developing a framework with two dimensions of criticality for mineral raw materials, which is widely used in the literature and updated or improved every 3 years. These are the Supply Risk (SR) and Economic Importance (EI) dimensions. At the outset of this article, we will go into detail on these two dimensions, which include parameters that should be retained in their current form, and others that should be revised. The contribution of this article lies precisely in the enrichment of EI.

The thinking behind this article is that the [EC \(2023\)](#) framework can be completed by incorporating the role of variables that are at the forefront when it comes to examining supply tensions. Indeed, variables such as substance price and stockpiling behavior are not currently taken into account. Even if we must insist on their relevance, these variables are the ones that best reflect the economic pressures exerted on the supply of a substance. As such, they should be included among the sub-indicators for assessing the degree of criticality. Our thesis is that they should all be taken into consideration in the design and construction of criticality dimensions. However, it is important to proceed in an articulated manner with existing dimensions.

To this end, this contribution focuses on one of the two criticality dimensions used by the European Commission, namely EI, seeking to transform it into an Economic Effect (EE) dimension. In fact, in its current form, EI does not consider the use/acquisition value of raw materials.

EE is a useful complement to EI, considerably enriching its statistical measurement and economic interpretation. The numerical illustration of its calculation is pedagogically carried out using the example of Li for the EU.

Several sources agree on scenarios of sharply rising demand and price for Li, moreover, in a context of energy and digital transition, even though Europe's physical autonomy is currently close to nil. This illustration can be replicated for other substances and regions of the world.

As secondary contributions, the article also discusses the issue of indicator normalization as applied to criticality dimensions, and above all shows how to pedagogically implement a forward-looking capability to the criticality dimensions mentioned, which are currently static. It also provides a European and global overview of Li.

The document is organized as follows. Section 2 provides an up-to-date statistical and economic overview of Li (markets, uses, production costs, supply, demand, prices, trade, storage possibilities). This has been proposed at both EU and global levels, generally from 2016 to 2022. Sections 3 and 4 are devoted to the European Commission's SR

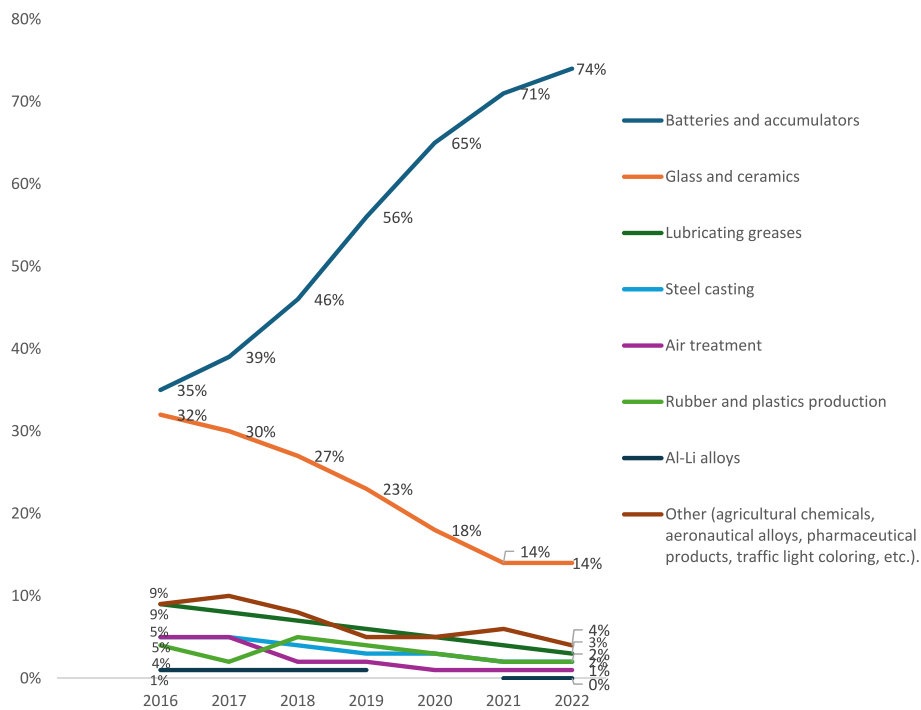


Fig. 1. Overview of lithium's industrial uses worldwide between 2016 and 2022. Source: Compiled and edited by the author from Jaskula (2023), USGS.

and EI dimensions respectively. Detailed comments, a numerical application of their calculation between 2016 and 2020 and a numerical application illustrating their prospective use are successively presented. In Section 5, the problematic of our EE dimension is exposed but also its calculation and normalization. We illustrate too the dynamics of criticality with EE and its comparison with that of EI. In Section 6, we show, step by step, the statistical procedure for calculating EE for Li in the EU over the period 2016–2020, as well as its prospective numerical illustration. We recall the main contributions in Conclusion (Section 7).

2. Lithium: an overview

This section successively provides information on the substance under review and its market, uses, production costs, supply, demand and world prices, as well as its international trade.

2.1. Overview: lithium and its market

Li is the third element in Mendeleev's periodic table. It is an alkali metal like sodium and potassium. It's the lightest of all metals, and with a specific gravity of 0.54, it's almost twice as light as water. It's a soft, silvery-white metal that can be cut with a knife, for instance, and is not very abundant in the earth's crust (20 parts per million [ppm] like niobium, three times less than copper but twice as much as lead). The oceans contain around 0.18 mg/l, a concentration that is economically unviable. Due to its high reactivity (flammable in the presence of oxygen), it is not available as a native metal, but can be produced by electrolysis of a mixture of potassium chloride and Li chloride (Brown, 2016). Its high electrochemical potential justifies its use in Li-ion batteries. Depending on the sector, Li is used in the form of minerals (spodumene, petalite, lepidolite, etc.), Li carbonate (Li_2CO_3), hydroxide (LiOH), lithium metal (Li), chloride (LiCl), niobate (LiNbO_3), nitrate (LiNO_3), butyllithium ($\text{C}_4\text{H}_9\text{Li}$) ...

The Li market, by compounds consumed, can be segmented into three compartments.

- The various types of Li-bearing mineralization (spodumene, lepidolite, petalite, amblygonite, jadarite, zinnwaldite) are purchased by

the glass and ceramics industry and in continuous casting, without prior conversion to a Li compound. The cost of extracting and producing Li depends on the mineralogical form used. Gloaguen et al. (2018) point out that it also varies depending on whether or not co-products such as tantalum, tin or tungsten are considered. Minerals with low Li contents, such as lepidolite or zinnwaldite, may nevertheless be of interest in high criticality regimes. What's more, this interest exists precisely because the EU's production potential lies in these less conventional deposits, as Demeusy et al. (2023) report in their work on the example of the Beauvoir site at Echassières (Allier), itself at the heart of lithium production projects in France.

- Base Li compounds, including Li carbonate which can be produced from rocks – generally giving a carbonate with a higher degree of purity, compatible with the needs of electric vehicle batteries⁵ – or brines, but also from the two elements that follow, Li hydroxide (which can be produced from rocks or Li carbonate, and whose use in new-generation⁶ electric battery cathodes is set to grow according to Roskill (2021)) and Li oxide. We also have Li chloride (which can be produced directly from brines, Li carbonate or Li hydroxide), lithium metal (which can be obtained by high-temperature electrolytic mixing of Li and potassium chlorides);

⁵ A standard 50 kWh electric battery requires around 40 kg of Li carbonate (Gielen and Lyons, 2022).

⁶ In Li-ion batteries, marketed since the early 1990s, the storage and circulation of energy, once the battery is charged, is ensured via the electrolyte, by the constant movement of lithium ions from the positive electrode (cathode, made up of oxides such as Lithium manganese oxide (LiMn_2O_4) or lithiated metal phosphates such as iron phosphate (FeLiO_4P)) to the negative (anode, made up of lithiated titanium oxide or, more generally, graphite). A great deal of research is underway, in connection with the electric vehicle market, but more generally in energy storage, to find safe materials with a high power-to-weight ratio and lower self-discharge. For instance, for research into improved cathode performance using tungsten oxide, see Baazizi et al. (2023). The chemical composition of these battery materials, beyond the cathode alone, will obviously have repercussions on each type of lithium compound used, its quantity and its price.

- Other compounds with finer chemistry and high purity, produced from the preceding Li compounds. These include Li bromide (LiBr), Li aluminate (LiAlO₂), Li nitrate (LiNO₃), Li nitride (LiN₃), Li phosphate (Li₃PO₄), Li borohydride (LiBH₄), Li acetate (LiC₂H₃O₂·2H₂O), lithium-manganese oxide (LiMn₂O₄), butyllithium (C₄H₉Li) ...

2.2. Lithium applications

The first category seen in 2.1 is mainly used in glass, ceramics and glass-ceramics industries. The other two categories, notably carbonate, hydroxide and chloride, are used in batteries (electric vehicles, cell phones, computers.), steel continuous casting, aluminum smelting, air treatment, synthetic rubbers – as in the tire industry and thermoplastics such as pipes and household utensils – chemicals for the agricultural sector, aeronautics with aluminum-lithium alloys, pharmaceutical sector ... and even for the red coloring of traffic lights with Li chloride.

These industrial applications of Li vary from year to year and from country to country. From a global perspective, Li uses in 2011 (for a more detailed look at uses within each industry, see. [Labbé and Daw, 2012](#)) concerned the glass, ceramics and glass-ceramics industry (30%), batteries and Li cells (22%, but as shown in [Fig. 1](#), growing strongly in line with the penetration rate of electric, hybrid or plug-in vehicles in the automotive market), lubricating greases (11%), air treatment (4%), continuous casting (4%), rubber and thermoplastics (3%), pharmaceuticals and fine chemicals (2%), aluminum metallurgy (2%), aluminum-lithium alloys (0.4%) and, for just over 21%, electronics, construction, water treatment, dyeing, pyrotechnics and thermonuclear fusion.

[Fig. 1](#) shows how these annual uses have evolved between 2016 and 2022.

2.3. Lithium production costs

It may be useful to distinguish between the costs of producing Li and the costs of acquiring/using Li used in our EE dimension, the latter costs being simply assimilated to Li prices. The former can be assimilated to a production cost. Between these two costs, there is a margin of varying size. However, this margin is not necessarily greater when one or other of these costs is lower. [Gielen and Lyons \(2022\)](#), for example, report that the margin on Li production from brine was higher than that on Li rock, even though the cost price of Li from brine is higher. The study comes from [S&P Global Market Intelligence \(2019\)](#) and covered 11 producers of Li from mineralizations (average cost: \$2540/ton carbonate) and 9 from brines (\$5580/ton carbonate). These are averages, although production costs vary widely from \$1000/ton to \$12,000/ton.

Generally speaking, production costs obviously depend on the source of Li (brines, rocks, rock types, etc.), but also on the production location. Production costs can be explained by the cost of labor, capital, energy, water, transport, reagents used in downstream processing such as sodium carbonate (much higher in the case of Li obtained from brines) and royalties (e.g., royalties per ton of Li carbonate) paid to public authorities.

2.4. Lithium supply, demand and world prices

Based on USGS data and estimates by [Daw and Namur \(2014\)](#), who approximated the "confidential" production of the United States, global Li production over 2010–2014 averaged 33,500 tons. Over 2016–2021, it will average 65,150 tons, according again to the USGS, but this time excluding US production. USGS records a production of 130,000 tons and very probably more, around an additional 3%, if US production had been disclosed.

According to [Roskill \(2009, 2013\)](#), global consumption was 21,300 tons in 2008 and 26,600 tons in 2011. According to USGS (2013), it was 28,300 tons in 2012 and 30,000 tons in 2013. In a projection of future

demand based on data from [Roskill \(2009\)](#), [Labbé and Daw \(2012\)](#) estimated demand for 2015–2016 at 32,500 tons and 37,000 tons under medium and high assumptions respectively. The USGS ([Jaskula, 2023](#)) reports a demand of 36,700 tons, close to the forecast made 4–5 years earlier. Still according to the USGS, between 2016 and 2021, world demand for Li will be 57,750 tons, slightly below average world production, although it should be noted that the gap between production and demand is decreasing over this period. For 2022 USGS estimates a demand of 134,000 tons, even higher than the supply, even if the latter does not consider US supply. In terms of projections, [Roskill \(2021\)](#) estimates demand of 188,000 tons for 2027, exceeding supply by 18% on average until 2030.

Between 2016 and 2022, according to our calculations from [Table 1](#), global Li production stands at 606,260 tons, or an average of 86,609 tons per year. Over the same period, demand was 480,500 tons, or an average of 68,643 tons per year. Li stocks have been built up every year, amounting to 125,760 tons over the period under review, i.e., an average of 17,966 tons per year. These stocks are probably a little higher. Indeed, the positive US production is not included in the production figures reported here or [Daw and Namur \(2014\)](#) then [Daw \(2017\)](#), show that between 2000 and 2014, US production accounted for 3.1% of world production. Assuming that this weight remains at least the same, world production would be around 625,000 tons and stocks 144,500, i.e., 18,740 tons more (144,500 - 125,760).

Australian and Chilean production are clearly the biggest contributors, with 51.76% and 25.34% of global production from 2016 to 2022 respectively. They are followed respectively by China (12.1%), Argentina (6.97%), Brazil (1.39%), Zimbabwe (1%), Portugal (0.78%) and Canada (0.51%). Much smaller quantities are produced in Germany, France, Finland, Mali, Namibia, the Czech Republic and Serbia, all of which account for less than 0.2% of Li production over the period under review.

Prices are set by direct contract negotiations between primary producers and processors or users. These prices may be spot prices or reflect forward contracts of various maturities, sometimes including clauses opening up the possibility of price revisions. In addition to storage, forward contracts can be entered into to ensure the availability of Li at agreed hedging prices, which are therefore not or only partially subject to the greater or lesser variability of spot prices. The prices on the China market are obtained as an average of the spot price at the beginning of the year and the spot price at or near the end of the same year. \$/€ exchange rates are applied to spot and forward prices. However, prices for Li-bearing minerals not listed here, are increasingly being published. The spot price for a ton of spodumene, to take just on example, is given at €2570 for 2022.

2.5. International lithium trade

International trade in Li mainly involves Li carbonate, Li oxide, Li hydroxide and, to a much lesser extent, Li chloride. Li, in mineral form is mainly traded in categories such as spodumene, lepidolite and petalite ... but statistical nomenclatures tracking their movements are not yet available. Despite this, it is estimated that the Li contained in the volumes traded in these mineralized forms is not negligible in relation to overall Li volumes.

As mentioned in the Introduction, Li production is highly concentrated in a few countries. Its international trade, apprehended by the Herfindahl-Hirschman Index-HHI on exports was the most concentrated among critical materials between 2017 and 2019. Imports are much less concentrated. In order to preserve resources, or with the aim of reserving these resources for their downstream domestic industrial users, public authorities can restrict their trade. Restrictions can take various forms (export taxes, export licenses, export quotas and embargoes, etc.).

For trading partners, this can be a critical factor in terms of price and quantity (lower quantities combined with higher prices). According to the OECD ([Kowalski and Legendre \(2023\)](#)), between 2017 and 2019,

however, the impact of trade restrictions⁷ on exports in the case of Li represented less than 3% of the value of these exports, which is considered relatively low compared with the impact on other substances. Compared with other substances, Li trade, measured by the value of global exports, was the most dynamic between 2007–2009 and 2017–2019.

The value of global Li exports increased by a factor of 4.35.

In Fig. 2, we present Li's international trade volumes over the period 2000 to 2022.

This extends the volumes presented in Daw and Namur (2014) from 2000 to 2014. The rule of construction is based on the equality, at world level, between total exports and total imports in volume. If world exports are 100 tons, then world imports are also 100 tons.

As a consequence of this mechanical equality,⁸ any differences between exports and imports are corrected by selecting the higher volume. For e.g., if exports are 100 tons and imports 97 tons, the figure used is 100 tons.

The issue of harmonizing data on world trade in goods in general and mineral substances in particular is fundamental, if only because it lies at the heart of criticality calculations. Our solution of taking the highest figure may work, but it remains dependent on the statistical sources used. Harmonization of statistical data is obviously the best solution, but is not easy to implement. Initiatives do exist, however. At an institutional level, Fortanier and Sarrazin (2016) point out that « organizing bilateral asymmetry that talks between the reporting agencies of different countries is the best method to resolve these asymmetries,

respectively.

3. Supply risk (SR): The European Commission's approach

The most recent revised version applied by EC (2023) is methodologically described in Blengini et al. (2017).

We reproduce it here without any change in notation and, where appropriate, propose a personal reading.

The statistics used to calculate the indicators concern the period 2016–2020. Our reading will consist in i) commenting in detail on the SR dimension and discussing each factor influencing this supply risk ii) proposing a numerical application of SR in the case of Li for the EU and iii) finally showing how it is possible to project in a simple way the impact of the variation of a given factor on the supply risk of Li for the EU.

3.1. Detailed commentary on SR

EC (2023) indicates that supply risk is in fact the upper value of SR, depending on whether this risk is assessed at the extraction (or mining) or refining stage. SR may well then be different depending on which stage of the value chain (Chapman et al. (2013) it is applied to. Here, only two stages are considered.

$$SR = \left[(HHI_{WGL,t})_{GS} * \frac{IR}{2} + (HHI_{WGL,t})_{EUS} \left(1 - \frac{IR}{2} \right) \right] (1 - EoL_{RIR}) * SI_{SR} \quad (1)$$

$$SR = \text{Argmax} [SR_{Mining}; SR_{Refining}] = \begin{cases} SR_{Mining} = \left[(HHI_{WGL,t})_{GS} * \frac{IR}{2} + (HHI_{WGL,t})_{EUS} \left(1 - \frac{IR}{2} \right) \right] (1 - EoL_{RIR}) * SI_{SR} \\ SR_{Refining} = \left[(HHI_{WGL,t})_{GS} * \frac{IR}{2} + (HHI_{WGL,t})_{EUS} \left(1 - \frac{IR}{2} \right) \right] (1 - EoL_{RIR}) * SI_{SR} \end{cases} \quad (2)$$

being the only way of achieving completely reliable results and the total resolution of any asymmetries for individual trade flows ». When there are differences in exports and imports between two countries, Tercero Espinoza and Soulier (2016) take an average of the two discrepant records. Bremer et al. (2024, see in particular their Section « Data Harmonization ») propose to correct any disparities between data by applying the weighted average of a simple « reliability score ». The country with the highest confidence score will have a higher weighting in the international trade figure for a given mineral substance.

Trade involves Li carbonate, Li oxide and Li hydroxide, which we convert into Li content. However, as there is no key to determine the share between hydroxide and oxide, an average conversion rate between the Li hydroxide-oxide group and lithium metal is used, i.e., one unit of Li for 2.8 units of the LiOH-Li2O group. With these two precisions, we have connected the data from 2015 to 2022 to those from 2000 to 2014 in a coherent manner.

Fig. 2 shows the evolution of Li tonnages traded over almost a quarter of a century. The approximation by a polynomial function of order 3 is the best fit in the sense of R², as trade has experienced some fluctuations linked to international crises over the period examined. Based on this approximation, the forecast trends in world Li trade for 2023, 2024 and 2025 are 108,967, 125,075 and 142,922 tons of Li

SR ∈ [0; 10] is the increasingly severe risk in the vicinity of 10. The supply risk threshold at which a substance is listed as critical is currently 1. When, for the same substance, SR is assessed at different stages of the value chain, it is the highest value of this figure that is conventionally used to decide whether or not to list the substance as critical.

Although this threshold is practical and consistent between successive versions of the Commission's criticality reports, it is not a scientific exercise (Schrijvers et al. (2020)). This remark also appears briefly in Frenzel et al. (2017, see their Section 3.4). It is currently based on the opinions of scientific and industrial experts, a list of whom is made public and available for consultation in Appendix 13 of EC (2023). However, the process by which a given threshold value is chosen is not publicly detailed.⁹

Observation of the SR formula shows that the calculation data used (Global supply, GS with more reliable production data, or European supply, EUS with trade data with the EU considered by the European Commission to be less reliable) will depend on IR (Import reliance, see below). The lower the IR, the less dependent the EU, and the greater the weight of EUS data in the SR calculation. Only when IR = 1, is the

⁷ Among the countries with a significant weight in Li's international trade, Argentina has the highest trade restrictions in relation to the monetary value of its exports.

⁸ The degree of openness to world trade, usually calculated as [(Exports + Imports)/2], is equal to Exports or Imports, since Exports = Imports when viewed from a global perspective.

⁹ For information, we can observe from the successive versions of the European Commission's criticality reports of 2011, 2014, 2017, 2020 and 2023, that the expert opinions seem to consider that the threshold value for passing to criticality (1) is lower for the risk of supply than for that relating to the economic importance (2.8) of the substance. A substance is critical when the calculation of the supply risk and economic importance dimensions respectively results in values at least equal to the pair (1; 2.8).

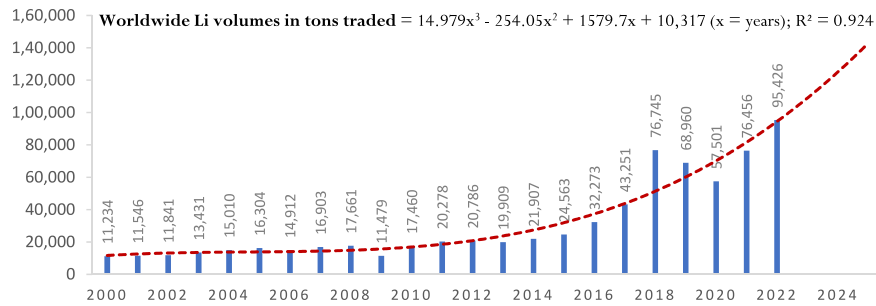
Table 1

Overview of global lithium supply, demand and prices between 2016 and 2022.

World	2016	2017	2018	2019	2020	2021	2022
Li supply (tons) (excluding USA supply)	38,000	68,500	94,900	86,100	82,580	106,880	129,300 ^e
Li demand (tons)	36,700	39,700	49,100	56,000	70,000	95,000	134,000 ^e
Prices (spot based) per ton Li carbonate China (€)	5556	16,667	16,957	14,732	7683	5885	15,514
Prices (future based) per ton Li carbonate USA (€)	8145	12,536	14,017	9786	6911	12,333	34,579
Prices (spot based) per ton Li hydroxide China (€)	nd	nd	nd	nd	9553	6549	16,822
Prices (spot based) per ton Li metal (€)	nd	nd	nd	nd	82,114	68,142	81,308
Exchange rates \$/€	1.06	1.2	1.15	1.12	1.23	1.13	1.07

Notes: e = estimation for 2022.

Source: Author's compilation from Jaskula (2023), USGS and European Central Bank (extracted by Eurostat, 2023) for exchange rates.

**Fig. 2.** Overview of global lithium trade from 2000 to 2022. Source: Daw and Namur (2014): 2000 to 2015; Author: 2015 to 2022 from UN Comtrade Database (2023); Author: projections for 2023 (108,967 tons), 2024 (125,075) and 2025 (142,922).

weight given to GS and EUS data identical ($\frac{1}{2}$ and $\frac{1}{2}$). When $IR = 0$, the formula indicates that only the risk arising from international trade counts. In the case of the EU¹⁰, $IR = 0$ can refer to 2 configurations. It can mean that the EU produces but does not participate in world trade, and the supply risk is the risk associated with EU member countries supplying the EU. It may mean that the EU produces the substance, but its exports are identical to its imports, a textbook case, in which the SR formula indicates an influence coming solely from the countries (including the EU) supplying the EU, using only EUS international trade data. In the latter configuration, an even more special case, where all trade is intra-EU, would correspond to a lower SR, due to the risks associated with the EU's trading partners, which are theoretically lower.

The formulas of SR_{Mining} and $SR_{Refining}$ are indeed identical, but the list of countries concerned (GS is for global supply; EUS is only for european suppliers) by the extraction stage of a substance is not necessarily the same as that of countries concerned by the refining stage, which can generate different results between SR_{Mining} and $SR_{Refining}$.

The SR used will therefore be the higher value between SR_{Mining} and $SR_{Refining}$.

$HHI_{WGI} = \sum_c s_c^2 * WGI_c$ is the Herfindhal-Hirschman Index (used as a proxy for country concentration) with s_c the share of country c 's production in world production for the assessment of global supply risk (GS) or the share of country c 's production in total production destined for the EU (EUS); WGI is the scaled Worldwide Governance Indicators (used as a proxy for country governance). WGI (2022) provides data from public and private sources between 1996 and 2021 on perceptions of

¹⁰ Let us note that if, instead of the EU, we reasoned in the case of a single country, SR would then depend neither on world production data, nor on international trade. This is because $HHI_{WGI,t}$ would be equal to 0 (a country not trading with itself!) and SR would consistently be minimal, i.e., zero.

governance.¹¹ The latter is itself broken down into 6 dimensions that are widely used in economic literature in general. They are not specific to the natural resources sector, and even less so to the mineral sector. We simply recall them here: Voice and Accountability (VA); Political Stability and Absence of Violence/Terrorism (PSAV); Government Effectiveness (GE); Regulatory Quality (RQ); Rule of Law (RL); Control of Corruption (CC).

The perception variables originally vary over the range $[-2.5; 2.5]$. The closer the country is to 2.5, the better the indicator. If these variables need to be normalized, for e.g., to an interval $[0,10]$ which would be compatible with the SR interval, we can use the following renormalization formula. In the case of RL, for instance, the formula is:

$$RL = (10 - [(2.5 + RL_{original}) * 2]) \quad (3)$$

Consequently, a country with economic governance perceived as perfect in terms of this sub-indicator ($RL_{original} = 2.5$) is left with an indicator $RL = 0$. We can use a same renormalization for the 5 other perception sub-indicators.

The European Commission (Blengini et al., 2017; EC, 2023) considers that VA, PSAV and RL are the most relevant for criticality assessment. An average of these 3 values for each country producing and/or exporting a given substance can constitute a proxy of WGI_c . An average of the 6 is also possible, but may be redundant as the variables may be very strongly statistically correlated.

t is the trade adjustment of WGI , i.e., a trade variable representing exports taxes, exports quotas and other exports prohibitions imposed by some supplying countries to secure raw material domestic supply or to support processing companies and is used to adjust the HHI_{WGI} to $HHI_{WGI,t}$ in this manner: $(HHI_{WGI,t})_{GS \text{ or } EUS} = \sum_c s_c^2 * WGI_c * t_c$ where t_c is

¹¹ WGI (2022): « Governance consists of the traditions and institutions by which authority in a country is exercised. This includes the process by which governments are selected, monitored and replaced; the capacity of the government to effectively formulate and implement sound policies; and the respect of citizens and the State for the institutions that govern economic and social interactions among them.»

the value of the trade-related variable of country for the substance considered and which appears in concrete terms as a growth factor. The higher this factor, the higher SR is *ceteris paribus*. In the case of Li, intra-European trade reduces supply risk. Portugal's t is 0.8, while Argentina's is 1.1. For all substances and all countries combined, the values retained in EC (2023) range from 0.8 to 1.5. However, values are highly

$$EoL - RIR = \frac{\text{Input of secondary material (only from old scrap)}}{\text{Input of primary material} + \text{Input of secondary material (new and old scrap)}} \quad (4)$$

concentrated between 0.8 and 1.1. It should be noted here that the data available for this variable relate to a country's trade as a whole, i.e., all database codes for traded goods combined, and in the best case to trade in extractive industry products, and not to trade in the substance of interest in question. Put another way, t is not specific to Li and even less so to Li carbonate or Li hydroxide.

IR stands for Import Reliance i.e., the following ratio:

$$\left[\frac{(\text{Imports} - \text{Exports})}{\text{Domestic production} + \text{Imports} - \text{Exports}} \right]$$

$IR \in [0; 1]$ and 3 special situations may arise if the country is affected by the substance:

- i) the country is a producer but does not participate in international trade, or participates with exports exactly equal to imports, a textbook case, $IR = 0$;
- ii) the country is a net exporter of the substance ($\text{Imports} - \text{Exports} < 0$), $IR < 0$ and in this case, the EC, by convention, reduces IR to 0;
- iii) the country does not produce the substance itself, $IR = 1$.

$EoL - RIR \in [0; 1]$ is the End-of-Life Recycling Input Rate i.e., the percentage of overall demand that can be satisfied through secondary material. A high recycling rate helps to reduce the risk in the supply of a substance. For Li, this rate is close to 0 according to the data reported by the European Commission (EC, 2020 p.41 and EC, 2023 p.48). As in the case of the substitution indicator mentioned below, calculation formulas can sometimes be developed faster than the availability and quality of the data needed to calculate them. Estimates of the EU EoL-RIR are not available for all raw materials (Tercero Espinoza, 2023). In our opinion, the very maintenance of these formulas does not appear to be assured at present, and so their numerical replicability is not yet assured. For the moment, the formulas come chronologically from UNEP (2011) and BIO by Deloitte's Study on data for a Raw Material System Analysis-MSA project (2015).

As Tercero Espinoza (2021) points out, there is no perfect alignment of definitions, the objective assigned to recycling (criticality, circular economy, etc.) and the geographical coverage of this indicator between the EU and the rest of the world. Nevertheless, to give readers an idea of how EoL-RIR is calculated and bearing in mind that this calculation is global and should ideally converge with EU data (Talens Peiro et al.

(2018) present regionalized versions of the EoL-RIR and readers will find further developments and examples of how to calculate this indicator), we reproduce the UNEP (2011) formula, which is often used to measure the contribution of old scrap (the quantity of the substance contained in a product at the end of its life cycle, i.e., after final consumption¹² of the product) to the total volume of the substance:

SI_{SR} is the Substitution Index (in Supply risk) i.e., a sub-indicator theoretically ranging from 0 (perfect substitutability and therefore maximum reduction in supply risk via this channel) to 1 (no substitutability and therefore no reduction in supply risk). In practice, in EC (2023), for all substances combined (87 examined), SI_{SR} ranged from 0.59 to 1, and was 0.94 for Li.

This sub-indicator within the overall supply of a substance is itself dependent on a number of parameters. Indeed, the formula used by the Commission (Blengini et al., 2017, p.19) to calculate the degree of substitution in the supply of a substance i is:

$$SI_{SR} = \sum_i \left[(SP_i * SCR_i * SCo_i)^{1/3} * \sum_a (subshare_{i,a} * share_a) \right] \quad (5)$$

These parameters reflect expert opinions and practical conventions for numerically determining the following 5 factors: Substitute Production (SP): Is the substitute material produced and available in greater or lesser quantities than the substance to be replaced? Substitute criticality (SCR): Is the substitute material itself critical according to the EU list? Substitute co-production (SCo): Is it supplied as a co-product only, which would make its supply itself risky? Finally, this sub-indicator takes into account the industrial application concerned by the substance (Share) and the degree to which it would be eco-technically (cost/performance/feasibility) replaced (Sub-share).

The first 3 factors range from 0.7 in the favorable case (substitute available in sufficient quantity, itself non-critical and not co-produced), thus allowing a reduction in SR, to 1 in the unfavorable case, thus not reducing SR. We can therefore note the asymmetrical role of these 3 factors: at best, they reduce criticality by 30% by convention, but at worst, SR is not affected.

To illustrate how the above 5 factors can be considered, let's suppose, for the sake of argument, that we manage to demonstrate, with a patent to back it up,¹³ that we can replace Li (critical) with sodium (supposed available in sufficient quantities, non-critical and not co-produced) as a component of Li-ion batteries. Let's also assume that the share (Share) of Li consumption in batteries is 50% (this is an example, but the share should match the reality found in Table 3, i.e.

¹² When it comes to secondary or recycled resources, a practical classification distinguishes between old and new resources. Old or downstream resources are those used outside the production process itself, i.e., after final use (vehicles, batteries, end-of-life households or office equipment, etc.). New or upstream resources are substances generated during the product manufacturing process, i.e., before final use. They appear, for instance, when molten copper is cast into shapes (wafers, ingots, wire rod, etc.), when these shapes are converted into semi-finished products (strips and sheets, rods, tubes, wires, etc.) and also when these semi-finished products are used for intermediate consumption in electrical, electronic or construction products.

¹³ The cost of the more abundant sodium is much lower, but the size of the compatible battery could be inadequate, posing a potential feasibility problem and deterring substitution.

Table 2

Data required to calculate SR (threshold value: 1) for the EU in 2023 - Processing stage - Data source: European suppliers.

EU supplier countries (Sc in %)	Chile (79%)	Switzerland (7%)	Argentina (6%)	United States (5%)	China (1%)	Others (3%)
WGI (1–10)	3.08	1.49	5.11	2.68	5.68	Not relevant
t (growth factor)	1	1	1.1	1	1	Not relevant
IR (in %, common to all countries)	1					
EoL _{RIR} (in %, common)	0					
SI _{SR} (0–1, common)	0.94					

Note: "Common" means that the sub-indicator refers to global supply and not by country.

Source: Author from EC (2023).

Table 3

Data required to calculate EI (threshold value: 2.8) for Li in the EU in 2023.

NACE Rev.2 economic sectors	C20	C21	C22	C23	C23	C24	C25	C27
Lithium's industrial applications	Lubricating greases	Pharma-ceutical products	Rubber and plastics production	Glass and ceramics	Cement production	Steel casting	Al-Li alloys	Batteries and accumulators
Q _s (millions €)	132,361	101,943	86,487	64,990	64,990	64,561	163,568	89,422
A _s (in %)	25%	4%	4%	50%	5%	5%	2%	5%
SI _{EI} (0–1, common)	0.91							

Note: C20: « Manufacture of chemicals and chemical products »; C21: « Manufacture of basic pharmaceutical products and pharmaceutical preparations »; C22: « Manufacture of rubber and plastic products »; C23: « Manufacture of other nonmetallic mineral products »; C24: « Manufacture of basic metals »; C25: « Manufacture of fabricated metal products, except machinery and equipment »; C27: « Manufacture of electrical equipment ».

Source: Author from EC (2023).

C27 called "Batteries and accumulators", which is 5%) of total Li consumption in the EU.

In this hypothetical example, if sodium can replace 25% (Sub-share) of Li in this sector, then the 3 factors mentioned above will apply to 12.5% (0.5*0.25, i.e., Share*Sub-share). Numerically, for $a = \text{batteries and accumulators}$, we have: $((0.7*0.7*0.7)^{1/3}) * 0.125 = 0.1$.

Then, following the same approach as for sodium in Li-ion batteries, we need to find the application(s) concerned by the remaining 50%, and if there are substitutes (like sodium), what their degree is (25% in the example).

We sum 0.1 with results for other applications a and substitutes i to obtain SI_{SR}.

3.2. Numerical application and prospective use of SR in the case of Li for the EU

First, we propose an illustration of SR calculation in the case of Li for the EU. The European Commission uses data averaged over the previous 5 years, so the criticality results cover a five-year period.

For e.g., EC (2023) calculates supply risk based on average data over 2016–2020. EC (2020) calculations are based on the 2012–2016 period, and so on. For each of the 2 phases retained in the value chain (Mining and Refining or, equivalently, Extracting and Processing) and for each of the supply levels (GS or EUS), the calculation remains constrained by reliable data availability. In the event of a constraint, SR will have to be calculated on a piecemeal basis, e.g., based solely on the Processing phase from EU supplies, or Extracting from worldwide supplies, etc.

Based on these data from Table 2, the SR calculation is a simple numerical application of the following formula¹⁴:

$$SR = [(HHI_{WGI,t})_{EUS}] * IR * (1 - EoL_{RIR}) * SI_{SR} = \left[\sum_c (s_c^2 * WGI_c * t_c)_{EUS} \right] * IR * (1 - EoL_{RIR}) * SI_{SR} = 1.84 \quad (6)$$

¹⁴ Calculation details are: $1.84 = [0.79^2 * 3.08 + 0.07^2 * 1.49 + 0.06^2 * 5.11 * 1.1 + 0.05^2 * 2.68 + 0.01^2 * 5.68] * 1 * 0.94$.

First of all, it should be noted that the SR for Processing has not been calculated on the basis of an average of global supply¹⁵ and EU-specific supply, in accordance with the original SR formula. This implies that the term $(HHI_{WGI,t})_{GS}$ does not appear in this original calculation formula for Li, and that import dependence IR is therefore not weighted but applied in full to the supply specifically intended for the EU. Furthermore, only the Processing phase is used, in principle due to a lack of reliable data on Extracting supply specifically for the EU. If the EU-specific Extracting offer had been used, the same calculation as above would have had to be carried out, and the highest SR value would have been retained. In the event, for e.g., $SR_{Extracting} < SR_{Processing} = 1.84$, then 1.84 would be assumed for the supply risk borne by the EU for Li. In the opposite case, $SR = SR_{Extracting}$.

With regard to the result found, the supply risk reported by the EC (2023, Appendix 4, Tle 15) is 1.9. In both cases (1.84 and 1.9), the criticality threshold value (1) is exceeded. The discrepancy, which is not significant, can nevertheless be explained by the list of countries, which only includes the main suppliers. As indicated in the last column, 3% of Li Processing's supply comes from countries that are much more marginal, but not listed. It should also be noted that only Argentina's supply presents a commercial risk, with a multiplier coefficient of 1.1, which increases the criticality of Li via SR.

Finally, we can see that Chile's role in supply risk for the EU is crucial, since it exceeds 100% of SR $[(0.79^2 * 3.08) / 1.84]$, or precisely 104.5%. This is the substitutability index that brings SR down to 1.84.

To provide a more forward-looking view, we show below that SR and the formulas that will follow in the article, can be used to examine the impact of a variation in a factor acting on supply risk. Readers can, of course, choose the impact they wish. Let us take, for e.g., the impact on SR of a deterioration in Chile's governance rating WGI_{Chile} .

A deterioration of 1 point increases supply risk, taking SR from 1.84 to 2.43. This differential (0.59) is simply obtained by the partial derivative of SR, all else being equal (i.e., holding other factors constant):

$$\frac{\partial SR}{\partial WGI_{Chile}} = s_{Chile}^2 * IR * (1 - EoL_{RIR}) * SI_{SR} = 0.79^2 * 1 * 0.94 = 0.59 \quad (7)$$

¹⁵ According to European Commission (2023, Appendix 1), the main Li Processing countries are: China (56%) Chile (32%) Argentina (11%).

4. Economic importance (EI) risk according to European Commission

As in Section 3, we will first comment in detail on the EI formula and examine each factor influencing EI.

Next, we will calculate the EI dimension in the case of Li for the EU in 2023 and, finally, show how to simply project the impact of variation in a given factor on EI for EU Li.

4.1. Comprehensive discussion on EI

We present in turn each of the EI sub-indicators that we will be working on later in this article. The original notations of EC (2023) have been retained for ease of identification. EI is presented as follows:

$$EI = \sum_s (A_s * Q_s) * SI_{EI} \quad (8)$$

In this formula, EI stands for Economic Importance. $EI \in [0; 10]$ is the risk that is considered to be increasingly high as it approaches 10. However, unlike SR, the calibration of the formula does not result in a value belonging to this interval because of the values of the sub-indicators that make it up. Normalization is then necessary to ensure that: $EI \in [0; 10]$. The economic importance risk threshold at which a substance is listed as critical is currently 2.8. As mentioned for SR, this threshold for EI, although practical, is not a scientific exercise (Schrijvers et al. (2020)). Here too, it is the result of opinions expressed by scientists and industrialists, a list of which is publicly available and can be consulted in Appendix 13 of EC (2023) for the most recent version. A_s is the share of demand of a substance in NACE-Rev.2 sector (Statistical nomenclature of economic activities of the European Community) and Q_s is the NACE Rev.2, 2-digit level sector's value added (VA). We are therefore first interested in the economic contribution of a substance ($A_s * Q_s$).

Until 2014, the approach used was to assess the importance to the EU of a substance in terms of its contribution to the added value of 17 mega manufacturing sectors (building materials, real estate, electronics and information and communication technology, road transport, maritime transport, air transport, food, pharmaceuticals, etc.).

Based on NACE-Rev.2, these mega-sectors were loosely defined as "a collection of related NACE-Rev.2 sectors" and accounted for almost 90% of EU value added.

For each of the 17 mega-sectors, the economic importance (in Euros) of the substance s is equal to the product of the percentage of its total consumption by this mega-sector (A_s) and its added value (Q_s).

The spirit of this technique is similar to that of calculating apparent productivity from a production function. Consequently, the quantities of the other factors contributing to mega-sector value added are assumed to be constant. Although it is not really apparent productivity, since the latter is calculated at the margin and not globally, this technique can nonetheless be used as a proxy for economic contribution ($A_s * Q_s$) of a substance. However, it does not mean that this contribution measures the true contribution of this substance. The term that seems more appropriate to us is the involvement or the role (and not the contribution) of a substance in added value.

By way of example, this technique means that if 10% of the global tonnage of Li consumed is used in a mega-sector with an added value of 10 billion Euros, then the sectoral economic importance of Li would be evaluated at one billion Euros. We'll need to do the same to find the added value associated with 90% of the global tonnage of Li in order to determine, by summation, the overall economic importance of Li in the

relevant GDP (European, French ...). This summation for the 17 mega-sectors (or less, if the substance is not used everywhere) results in a non-scaled value of ($A_s * Q_s$) ¹⁶ which is finally converted on a scale ranging from 0 (no importance) to 10 (very high). This conversion is performed by dividing the non-scaled value of ($A_s * Q_s$) for a substance by the highest non-scaled value of EI (or, equivalently, by the sum of all EIs) among all the substances considered.

Since 2017, while the principles for calculating a substance's contribution to added value have been renewed by the Commission, one improvement has been a desire to better match the assignment between the quantity used of a substance and the added value it contributes to achieving. This involves abandoning the mega-sector concept and moving towards a more refined NACE Rev.2 codification. For Li, Blengini et al. (2017) point out that its use, for e.g., in electric batteries, was attached to the "Electronics" mega-sector. The latter is a broad and less precise grouping, as it may concern several Nomenclature Divisions. Today, in NACE Rev.2, this same use is attached to Section C "Manufacturing" sector, Division 27/27.2 entitled "Manufacture of electrical equipment/Manufactures of batteries and accumulators".

In practice, ¹⁷ beyond the previous example, each use of a substance is identified at a level of subdivision 3–4 of NACE Rev.2 or the Statistical Classification of products by activity (CPA). The various subdivisions are then grouped together to form a 2-level subdivision. PRODCOM (Eurostat), which covers Section C of NACE Rev.2, then provides added value statistics for EU companies. This new methodology for assigning uses to the substance of interest is expected to result in a more accurate calculation of ($A_s * Q_s$) and therefore a more accurate contribution (implication) to the economic importance of this substance, and ultimately to its criticality.

Despite these advances, this technique remains an approximation, which is why we would have preferred the terms "implication" or "role". On other hand, given the current state of knowledge, the EC technique seems to be the most satisfactory. Although it remains an approximation for calculating a substance's contribution to value added, it is internally consistent because it is applied identically to all substances. This at least makes it possible to compare contributions, and thus degrees of criticality, in a coherent way while waiting to move from « role » to contribution.

SI_{EI} is a new parameter that does not appear in versions prior to EC (2020a and 2023). The formula used by the European Commission (Blengini et al., 2017) to calculate the degree of substitution of a given substance i in an industrial application a is as follows:

$$SI_{EI} = \sum_i \sum_a SCP_{i,a} * (subshare_{i,a} * share_a) \quad (9)$$

SI_{EI} is the Substitution Index (in Economic importance) i.e., a sub-indicator theoretically ranging from 0 (perfect substitutability and therefore maximum reduction of EI via this channel) to 1 (no substitutability and therefore no reduction of EI). In practice, in EC (2023), for all substances combined (87 examined), SI_{EI} ranged from 0.59 to 1. For Li, it was 0.91.

Whereas the SI_{SR} substitution index was concerned with characteristics such as availability, criticality or feasibility of substitution, SI_{EI} measures the cost and productive performance aspects of the substitute for a given industrial application. This degree of substitution – which is

¹⁶ Normalization more specifically concerns EI and not ($A_s * Q_s$). Therefore, following the formula for EI, we multiply ($A_s * Q_s$) by SI_{EI} , the index we present immediately below.

¹⁷ NACE Rev.2, CPA and PRODCOM are linked by equivalences, making it possible to match the classifications of these nomenclatures with the PRODCOM statistical database.

Table 4
Substance criticality changes according to the EE dimension.

Production effect (PE)	Production cost effect (PCE)	Economic effect (EE)	Substance criticality
Increasing	Increasing	Increasing	Increasing
Increasing	Decreasing	Increasing if PE > PCE Decreasing if PE < PCE	Increasing or decreasing (unchanged if PE = PCE)
Decreasing	Increasing	Increasing if PE < PCE Decreasing if PE > PCE	Increasing or decreasing (unchanged if PE = PCE)
Decreasing	Decreasing	Decreasing	Decreasing

Note: The case where PE is constant and PCE is increasing or decreasing, the case where PCE is constant and PE is increasing or decreasing, and the case where PE and PCE are constants, could have been added to this Table, but would bring no new insights to the analysis.

Source: Author.

Table 5
EU lithium production, imports and exports.

EU (in metric tons)	2016	2017	2018	2019	2020	2021	2022	Average (2016–2020)
Lepidolite (0.019 Li content)	40,758 (774.4)	52,741 (1002.1)	76,818 (1459.5)	59,912 (1138.3)	23,185 (440.5)	18,533 (352.1)	na	nr
Lithium		538	535	417	161	129	na	nr
Total production (1)	774.4	1540.1	1994.5	1555.3	601.5	481.1	na	1293.2
Li oxide and hydroxide (0.357 Li content)	3181.3 (1135.7)	4268.4 (1523.8)	4811.1 (1717.5)	4983.4 (1779.1)	5,201.7 (1857)	4594.3 (1640.2)	6110.4 (2181.4)	nr
Li carbonate (0.188 Li content)	16,321 (3068.3)	12,682.1 (2384.3)	15,575.7 (2928.3)	14,771.5 (2777.1)	16,576.9 (3116.5)	17,919.5 (3368.9)	16,366 (3076.8)	nr
Total imports (2)	4204	3908	4645.7	4556.2	4973.5	5009.1	5261.2	4457.5
Li oxide and hydroxide (0.357 Li content)	na	803.9 (287)	380.7 (135.9)	802.3 (286.4)	1093 (390.2)	2319.3 (828)	3598.1 (1284.5)	nr
Li carbonate (0.188 Li content)	na	5575.1 (1048.1)	5642.6 (1060.8)	7824.5 (1471)	13,227.7 (2486.8)	9463.4 (1779.1)	8456.8 (1589.9)	nr
Total exports (3)	na	1335.1	1196.7	1757.4	3579.8	2607.1	2874.4	1967.1
Consumption and inventory variations (4)	na	4113	5444	4354	1995	2883	na	3977

Note: na = not available; nr = not relevant.

Source: Author's calculations based on BGS (2023) and UN Comtrade Database (2023).

calculated using the same approach as for SI_{SR} ¹⁸ – corresponds more closely to the (micro)economic definition of technical substitution, although here it is based on expert opinion rather than calculation. Each of the two aspects is subdivided into 3 levels (e.g., technical performance of the substitute that is inferior, identical or superior to the substance under consideration, in this case Li). If, for e.g., the substitute offers a similar productive performance but does not cost much more, then this substitute mitigates less (it is at 0.9) the economic importance than if it cost the same or less (it would then be at 0.8). The degree of substitution chosen then appears as an average degree, representative of the various degrees estimated in the different industrial uses of the substance.

4.2. Numerical application, prospective use and normalization of EI for Li in the EU

First, we propose an illustration of the numerical calculation of EI in the case of Li for UE. Here too, the European Commission uses average data over the previous 5 years, and so does our calculation.

Based on these data, the EI calculation is a simple application of the following formula¹⁹:

$$EI \text{ (non-scaled)} = \sum_s (A_s * Q_s) * SI_{EI} = \text{€ million } 79,481.68 \quad (10)$$

¹⁸ This formula is practically the same as that of SI_{SR} seen above, with the difference that it contains only one (and not 3) substitutability parameters, and that this parameter is specific to the industrial application associated with the substance under review, hence the index a associated with SCP.

¹⁹ Calculation details are: $EI \text{ (non-scaled)} = (0.25 * 132,361 + 0.04 * 101,943 + 0.04 * 86,487 + 0.5 * 64,990 + 0.05 * 64,990 + 0.05 * 64,561 + 0.02 * 163,568 + 0.05 * 89,422) * 0.91$.

$$EI = (0.25 * 132,361 + 0.04 * 101,943 + 0.04 * 86,487 + 0.5 * 64,990 + 0.05 * 64,990 + 0.05 * 64,561 + 0.02 * 163,568 + 0.05 * 89,422) * 0.91$$

We now turn to the normalization of the previous result. In order to obtain a scale that is comparable with SR, i.e., from 0 to 10, the European Commission normalizes the results obtained for EI. To do this, it relates these results to the highest VA among NACE Rev.2 sectors, then multiplies the ratio obtained by 10. The sector with the highest VA in the 2023 breakdown is C28: "Manufacture of machinery and equipment n.e.c (not elsewhere classified)". The result is:

$$EI \text{ (scaled)} = \left(\frac{79,481.68}{204,200} \right) * 10 = 3.89 \quad (11)$$

The economic importance of Li reported by the EC (2023, Appendix 4, Tle 15) is 3.9. This is above the criticality threshold value (2.8). For 2020, for e.g., the economic importance of Li was 3.1.

The rise to 3.9, illustrating increasing criticality, can be explained by a distortion in the distribution of industrial uses, with Li appearing more in those uses with relatively higher VA growth between 2020 and 2023. This is especially the case for lubricating greases in Sector C20, and for batteries and electric accumulators in Sector C27. This deformation is sufficiently significant to compensate for the slight improvement in the economic substitutability index, which was 0.93 in 2020, and thus ultimately increase Li's criticality for the EU.

In forward-looking terms now, in general terms, the non-normalized EI formula can be used to examine the impact of a variation in any factor acting on normalized EI. For e.g., the impact of VA growth in the bat-

teries and accumulators sector in the EU $\left(Q_{\text{Batteries and accumulators}} \right)$ of €1

obviously has no impact on economic risk, leaving EI at its initial value of 3.89. This result is highly intuitive, since €1 represents nothing compared with the VA of batteries and accumulators, which stands at almost €90 billion.

This neutral impact is calculated by the partial derivative of EI (non-normalized), all else being equal (i.e., other factors assumed constant):

$$\frac{\partial EI (\text{non-scaled})}{\partial Q \text{ Batteries and accumulators}} = A \text{ Batteries and accumulators} * SI_{EI} = 0.05 * 0.91 = 0.05 \quad (12)$$

$$EI (\text{scaled}) = \left(\frac{79,481.68 + 0.05}{204,200} \right) * 10 = 3.89 \quad (13)$$

We could of course calculate the impact of larger, more realistic variations, which would obviously have a greater impact on the EI criticality dimension. For e.g., a variation of €10,000, which is still relatively small, already results in an increase in criticality from 3.89 to 3.92, i.e., an increase of 0.77%, using same calculation method as above.

In another possible scenario, an increase of, say, one percentage point in the share of Li tonnage used in batteries and electric accumulators (Sector C27) at the expense of, say, glass and ceramics (Sector C23) – which would mechanically lose one percentage point²⁰ – has a considerable impact on the criticality of Li for the EU: It leads to a 28% increase in its perceived criticality via EI. This is due to the VA differential, which is around 25 billion higher for batteries and accumulators.

$$\begin{aligned} \frac{\partial EI (\text{scaled})}{\partial Q \text{ Batteries and accumulators}} &= \frac{\partial EI (\text{non-scaled})}{\partial A \text{ Batteries and accumulators}} + \frac{\partial EI (\text{non-scaled})}{\partial A \text{ Glass and ceramics}} \\ \frac{\partial EI (\text{non-scaled})}{\partial A \text{ Batteries and accumulators}} &= Q \text{ Batteries and accumulators} * SI_{EI} = 89,422 * 0.91 = € 81,374 - \left(\frac{\partial EI (\text{non-scaled})}{\partial A \text{ Glass and ceramics}} \right) = - \left(Q \text{ Glass and ceramics} * SI_{EI} \right) \\ &= -(64,990 * 0.91) = -€ 59,140 \end{aligned} \quad (14)$$

$$EI (\text{scaled}) = \left(\frac{79,481.68 + \left(\frac{\partial EI (\text{scaled})}{\partial Q \text{ Batteries and accumulators}} \right)}{204,200} \right) * 10 = \left(\frac{79,481.68 + (81,374 - 59,140)}{204,200} \right) * 10 = 4.98 \quad (15)$$

²⁰ The loss of this percentage point could obviously have been distributed over as many sectors as desired. Distribution between several sectors, although capable of affecting the criticality result, would lengthen the calculations without much interest. Keeping to a symmetrical loss simplifies the presentation. At the same time, it should be emphasized that the *ceteris paribus* reasoning behind the calculation of EI partial derivative remains valid, subject, however, to the imperative compensation of the shares, their total having to remain 100% by definition.

5. Economic effect (EE): the proposed approach

The issues underlying this dimension are discussed first; secondly, EE is presented in greater detail, and the enrichment it offers in relation to EI and its dynamics are explained; thirdly, we show i) the instructions that will be useful for calculating EE in the next section ii) how to normalize the result obtained in coherence with SR and EI and finally iii) how to project in a simple way the impact of a given factor variation on EE for the Li of the UE.

5.1. The need for EI to be transformed

The approach we propose takes as its starting point the economic importance dimension of a substance, i.e., EI.

We show why and how EI can be transformed into an economic effect dimension (EE).

We highlight two effects. We will distinguish between the "production effect" identified in EI and the "production cost effect" with which we complete it in EE.

Indeed, in its current form, EI only gives a role to the physical quantities of the substance used in the production process – and this via A_s . These quantities appear as a percentage affecting the VA produced in each application sector considered. The quantities themselves, in tons, do not appear as such. This is not a problem, since what we are looking for approximates the apparent productivity of the substance in each sector where it is used. This is what we call the "production effect".

On the other hand, not including these used quantities as such in the EI formula prevents us from knowing their use or acquisition value. And yet, this valuation, which requires the price of the substance and introduces the variation in inventories, allows for a more realistic analysis of the physical tensions (quantities consumed, variation in inventories) as well as the nominal tensions (use or acquisition price; use or acqui-

sition value of the substance, i.e., the product of its price and the quantity consumed) involved in the supply of materials.

The EI dimension, therefore, does not consider the use or acquisition value of raw materials, and consequently the weight they represent in the VA of the user sectors. As a result, and as mentioned above, variables such as substance price and stockpiling behavior can address this more realistic concern. If anything, these two variables best reflect the pressures on a substance's supply. EI would benefit from including them alongside the sub-indicators for assessing the degree of criticality.

EE thus transforms and usefully completes EI by integrating the

dimension relating to the cost of using or acquiring a substance. This "production cost effect" completes EI, as we now show in detail.

5.2. The economic effect dimension (EE)

5.2.1. Description of EE formula

The EE dimension (not yet scaled) is written as follows:

$$EE(\text{non-scaled}) = \left(\underbrace{\sum_s (A_s * Q_s)}_{\text{Production effect (PE)}} + \underbrace{\bar{P}_s * (C_s + \Delta S_s)}_{\text{Production cost effect (PCE)}} \right) * SI_{EI} \quad (16)$$

\bar{P}_s is the average price of using/acquiring a substance s (here $s = Li$). This price in € can vary according to whether the substance is produced locally, here in the EU, or otherwise according to the place of origin of its acquisition, to whether or not co-products such as tantalum, tin or tungsten are considered but also according to the marketed forms of the substance, i.e., either the basic Li compounds²¹ such as: Li carbonate, hydroxide, oxide, chloride ... or Li minerals such as: Spodumene, lepidolite, petalite ... or even the finer chemical Li compounds such as Li bromide, butyllithium or nitrate ... C_s is the consumption of the substance in question, and ΔS_s the change in its inventory over an interest period. C_s and ΔS_s are expressed in tons. The term on the right (PCE) therefore measures the value of the cost of use/acquisition, or simply the production cost effect associated with the use/acquisition of the substance.

These costs and their variations influence criticality's degree. They should therefore be considered, as EE does here.

When EI (product of the left-hand term of EE and SI_{EI}) increases or decreases, EE also increases or decreases, all else being equal. The increase in EI meant, for a given SI_{EI} , an increase in $(A_s * Q_s)$ and illustrated higher production from the substance or, what amounts to the same thing, a higher economic contribution from this substance.

It is true that when EI increases, criticality increases. However, when EI increases and, at the same time, the cost of using/acquiring a substance (product of the term on the right-hand side of EE and of SI_{EI}) decreases for instance, the result relating to the evolution of the degree of criticality is no longer as immediate as with EI.

5.2.2. Illustrated description of criticality dynamics with EE and comparison with EI

The economic contribution of a substance is indeed increased and increases its criticality, but at the same time the cost of this substance is lower. It is the calculation of EE that makes it possible to establish the result in terms of criticality at a given date or period. In dynamic terms, between two dates, Table 4 illustrates the typology of situations between the 2 effects with regard to the criticality of a given substance.

This typology of criticality behavior according to the evolution of the 2 effects illustrates the enrichment that the proposed dimension brings to the analysis. Only the first and last configurations (unshaded areas) are compatible with EI. They therefore implicitly assume that PCE is also increasing or decreasing when PE is. However, even this compatibility remains only qualitative, i.e., relating to the direction and not the

²¹ Quantities of Li produced, consumed or exchanged are not always presented in the same unit. It is useful here to recall some conversion factors between lithium metal (Li) and other chemical forms containing Li. Thus, from Labbé and Daw (2012) we have: 1 unit (kg, ton) of Li = 5.32 units of Li carbonate; 1 Li = 2.15 Li oxide; 1 Li = 3.45 Li hydroxide; 1 Li = 6.11 Li chloride; 1 Li = 26.8 spodumene or 1 Li = 52.08 lepidolite ... To get the lithium content (Li content), we obviously just need to take the inverse of these figures. So, in one unit of lepidolite, there is approximately 0.019 Li contained, i.e., 1/52.08.

magnitude of variation.

Indeed, both in the compatible configurations and in the two other configurations *à fortiori*, criticality does require a calculation between examination periods. The result of this calculation, in the last column, can just as easily be an increase, a decrease or a constancy in the degree of criticality. These variations, whatever their direction, are not of the same magnitude depending on whether we are calculating EI (i.e., PE) or EE (i.e., PE and PCE).

To illustrate numerically what's going on in the last column of Tables 4 and it's best to have the scaled formulas for EI and EE clearly in mind, and to calculate each between two dates, e.g., 2020 and 2024. Readers will be able to do this using any data with the scaled formulas for EI (Section 4.2) and EE (Section 5.2).

Nevertheless, it is possible to show how this works in a simplified and concrete way here by first recalling the EE formula written synthetically for the purposes of our illustration here. The terms PE and PCE are the variables in Table 4. When we speak of PCE, we're referring to the normalized product $\mu PCE * SI_{EI}$. Reasoning with this product or with PCE makes no difference to the illustration below, but the presentation is simpler with PCE alone, since Table 4 refers to PCE.

$$EE(\text{scaled}) = \left(\frac{(PE + \mu PCE) * SI_{EI} * 10}{Q_s^{Max}} \right) \quad (17)$$

We start with EE and the example of Line 2 in Table 4.

To do this, let us express normalized EE in figures using the data available between 2 periods (2020 and 2024), so that only PE and PCE, referred to in Table 4, appear in the EE formula. In 2020, by directly replacing the data available in the formula, EE is the ratio: [(PE (€79,482 million) + PCE (€3347 million)]/204,200 million)*10. Calculating this ratio gives Li a criticality level of 4.056.

Line 2 considers a situation where PE is increasing and PCE decreasing. Assuming an increase in the importance of Li in the EU from €79,482 million to €90,000 million by 2024, the new PE value becomes €90,000 million. If, over the same period, the costs of using this Li fall from €3347 million to €2500 million, the new PCE value becomes €2500 million. This €10,518 million increase in PE combined with the €837 million decrease in PCE is consistent with the situation described in Line 2 and leads to a scaled EE equal to: ((79,482 + 10,518 + 3347 - 837)/(204,200))*10, which results in a criticality level of 4.53, well above 4.056.

The third column of Table 4 clearly shows that if PE is increasing and PCE decreasing, then EE is increasing and so is the degree of criticality, as shown in the last column. The growth in criticality degree is precisely 11.7%.

Other trends between 2020 and 2024 can of course be chosen by readers.

As indicated in the title of this subsection, to compare with the dynamics of EE, we are now also able to reason in the same way, but with EI. EI does not include PCE. In 2020, normalized EI is the ratio: (PE (€79,482 million)/€204,200 million)*10, which results in a criticality level of 3.89, as found by the European Commission in 2020. With the same evolution as for EE, EI scaled becomes equal to: ((79,482 + 10,518)/204,200)*10, i.e., a criticality level of 4.41. The increase in criticality here is 13.37%, which is much higher than the 11.7%, and is explained by the fact that Li utilization costs are not taken into account in the EI formula.²²

²² Equivalently, we can read these two dynamics as follows: if we had started with a criticality level of 3.89 (that of EI), the progression of this level, which is less with EE, would have brought it to 4.35, which is smaller than 4.41. The dynamics of the degree of criticality are therefore well cushioned by the costs of using the substance.

Table 6
EU lithium demand prices.

EU (in €)	2016	2017	2018	2019	2020	2021	2022
Import values (Li oxide and hydroxide)	34,723,846	37,818, 838	33,841,151	36,800, 545	22,885, 201	30,643, 819	162,070, 179
Import prices (Li oxide et hydroxide)	30,575	24,794	19,704	20,685	12,324	18,683	74,296
Import values (Li carbonate)	106,115,835	108,557,526	181,716,406	147,862,791	117,214,013	115,106,267	319,095,120
Import prices (Li carbonate)	34,585	45,530	62,055	53,244	37,611	34,167	103,710
Import average prices	33,502	37,445	46,398	40,530	28,168	29,097	91,514
Export values (Li oxide and hydroxide)	na	11,316,090	7,164,710	8,419,094	5,929,124	15,618,529	35,274,869
Export prices (Li oxide and hydroxide)	na	39,429	52,720	29,396	15,195	18,863	27,462
Export values (Li carbonate)	na	46,570,337	56,642,563	62,903,215	43,929,729	59,245,327	277,076,590
Export prices (Li carbonate)	na	44,433	53,396	42,762	17,665	33,301	174,273
Export average prices	na	43,357	53,319	40,584	17,396	28,716	108,867
(Y + X)/(Y + X + M)	na	42.39%	40.72%	42.11%	45.67%	38.14%	na
EU average Li demand prices	na	39,951.1	49,216.2	40,552.7	23,248.4	28,951.7	na
Exchange rates \$/€	1.06	1.2	1.15	1.12	1.23	1.13	1.07

Source: Author's calculations based on BGS (2023) and European Central Bank (extracted by Eurostat, 2023) for exchange rates.

5.3. The EE dimension: instructions for calculation, normalization and prospective use

The calculation of EI had shown how to determine PE numerically. To establish EE numerically, we now need to show how to calculate PCE.

$$PCE = \bar{P}_s * (C_s + \Delta S_s) \quad (18)$$

Data on the consumption²³ of a substance are not always available, and even less so for changes in its stocks.

When relevant data are unavailable, we use the ex-post macro-accounting « supply-demand » identity applied to a substance for each period studied, to determine the quantity ($C_s + \Delta S_s$). The latter, which assumes that production and international trade data are reliable, is usually presented as follows (in bold, the 2 aggregates to be determined):

$$\underbrace{\text{Production } (Y_s) + \text{Imports } (M_s)}_{\text{Supply}} = \underbrace{\text{Consumption } (C_s) + \text{Inventory changes } (\Delta S_s) + \text{Exports } (X_s)}_{\text{Demand}} \quad (19)$$

It follows from the above that: $C_s + \Delta S_s = Y_s + M_s - X_s$

\bar{P}_s is the average use/acquisition price of a substance s (here, $s = Li$). It has already been presented in Section 5.2, and we will come back to it when calculating it in Section 6.1. It should be added that, in the absence of data on EU Li production prices, we approximate these prices by those of EU Li exports. This approximation is acceptable, for lack of anything better at present. Besides Li, this identity can obviously be used for other substances.

With regard to normalization, which allows us to have the same criticality scale as the SR dimension, i.e., from 0 to 10, we have adapted²⁴ the technique used by the European Commission when normalizing EI. The latter relates the result obtained for EI to the highest VA (noted Q_s^{Max}) among all the NACE Rev.2 sectors selected, then multiplies the ratio by 10. In the EC report (2023), $Q_s^{Max} = \text{€}204,200,000,000$ and corresponds to the sector's VA:

²³ Estimates of average annual consumption in the EU can be obtained, for example, from EC (2020b). Unfortunately, however, the Li data factsheet was not included among the substance data sheets examined in this publication.

²⁴ The adaptation is more in the spirit than in the calculation to be carried out. The adaptation is more in the spirit, because the European Commission normalization technique implicitly assumes that the criticality calculation is a comparative calculation between all substances, which is what normalization means. The numerical implementation of this normalization, on the other hand, follows a technique that is specific to our article, and which manifests itself in the appearance of new normalization terms (cf. EE scaled formula). However, the aim is for EE to maintain the criticality range of the EI dimension from 0 to 10, and therefore also of SR.

C28: « Manufacture of machinery and equipment n.e.c (not elsewhere classified) ». Q_s^{Max} therefore, corresponds to the maximum ($100\% * Q_s^{Max} = Q_s^{Max}$) that a substance can contribute to EU production.

In scaled EE, the production cost of the substance under examination present in the numerator will also be added to the denominator, together with the maximum production Q_s^{Max} . The substitutability index is considered as with the normalization of the European Commission for EI.

In addition, since we give equal weight²⁵ to PE and PCE in their influence on EE, we need to introduce a normalization factor into the normalized formula μ to correct the differences in orders of magnitude between PE and PCE. This factor must be such that the ratio normalized to 10 between Q_s^{Max} and PE (see, μ formula above) is applied to PCE (see, EE scaled formula below). PE being a principle of a higher order of magnitude²⁶ than PCE, μ will multiply PCE. In our numerical example, this factor is equal to:

$$\mu = \frac{Q_s^{Max}}{\sum_s (A_s * Q_s) * SI_{EI}} * 10 = \left(\frac{204,200}{79,481.68} \right) * 10 = 25.69 \quad (20)$$

Finally, the scaled EE dimension can be written as:

$$EE(\text{scaled}) = \left(\frac{\left(\underbrace{\sum_s (A_s * Q_s)}_{\text{Production effect (PE)}} + \mu \underbrace{(\bar{P}_s * (C_s + \Delta S_s))}_{\text{Production cost effect (PCE)}} \right) * SI_{EI}}{Q_s^{Max}} \right) * 10 \quad (21)$$

²⁵ We need to give equal weight to the effect of PE and PCE. We know that the cost of the substance is much lower – not to say disproportionate – to the VA it helps generate. PE is therefore much higher than PCE, so we need to normalize, otherwise we would be creating an unnecessary inconsistency with the EU's calculations, and one that wouldn't be justified. Furthermore, we see no economic reason why the quantities used should be weighted more heavily than the costs of using these quantities. Generally speaking, for future works, there is nothing to prevent us from modifying this weighting and therefore modifying our μ but, once again, we will have to justify it.

²⁶ The cost of the substance is much lower – not to say disproportionate – to the VA it helps generate. Furthermore, the cost of using a substance cannot exceed the maximum value added of all the substances considered. Thus, the comparative aspect of the criticality calculation in the scaled EI is retained in the scaled EE.

This formula can be written more simply as:

$$EE(\text{scaled}) = \left(\frac{(PE + \mu PCE) * SI_{EI,s} * 10}{Q_s^{Max}} \right) \quad (22)$$

with bold characters indicating new normalization terms compared to EI and $Q_s^{Max} > \bar{P}_s * (C_s + \Delta S_s)$ which is the condition for the existence of the normalization factor μ defined as above.

EE (scaled) formula therefore says something new – while remaining very consistent with the European Commission's normalized EI. Its message can be read this way: when a substance s contributes significantly to the wealth of the EU, and therefore for which the ratio $\left(\frac{\sum_s (A_s * Q_s) * SI_{EI}}{Q_s^{Max}} \right)$ is high, the production cost effect (or cost-of-use effect)

would be less preponderant in calculating the degree of criticality, since the normalization factor μ would in this case be lower. For instance, if iron or lithium contribute a lot in terms of VA to the EU economy, then their cost of use will contribute to raising the degree of criticality, but less than gallium, which (let's assume) contributes less to EU VA. In summary, the cost of use therefore always increases criticality, but to a lesser extent when the substance's contribution to the economy is greater. This message of EE (scaled), is consistent with economic theory: a worker's salary weighs less on a company when that worker is more productive.

Finally, as was done for SR and EI non-scaled, the EE non-scaled formula can also be used to examine the impact of a variation in a factor acting on Li criticality. For e.g., we can look at the impact of a marginal variation in the average price of Li demanded in the EU, all else remaining equal. We then partially derive the non-scaled EE:

$$\frac{\partial EE(\text{non-scaled})}{\partial \bar{P}_s} = (C_s + \Delta S_s) * SI_{EI} \quad (23)$$

The value obtained is then transferred to EE (scaled) to obtain the impact of a given variation in the average price of Li on the indicator measuring the economic effect (EE) and therefore on the criticality of Li.

Some of the values needed to calculate this impact are not yet known at this stage. These include \bar{P}_s and $(C_s + \Delta S_s)$. We now need to estimate them numerically.

6. Numerical application of EE calculation for Li in the EU (2016–2020)

In this section, we show in detail the procedure for calibrating EE before measuring the desired impact on Li criticality, which has just been mentioned. For all practical purposes, the data presented below can go as far back as 2021 or 2022, although only the period 2016–2020 is necessary to link EE with EI calculated by EC (2023), which therefore concerns this five-year period.

6.1. EE assessment

Table 5 shows in detail the calculation leading to the consumption aggregate and changes in inventories ($C_{Li} + \Delta S_{Li}$) following the instructions in Section 5.3. The average price of Li (\bar{P}_{Li}) is shown in Table 6.

Production data are not sufficiently refined, in the sense that we do not have information on the various forms of Li sources, the sum of which corresponds to the quantity of Li produced. Thus, apart from the role of lepidolite in EU production, statistical references do not provide information on the content of the rest of total Li production. Consumption and stock variations are, as announced, obtained from the supply-demand accounting identity seen in Section 5.3 (cf. also formula last line of Table 5). We are interested in the average figure for this aggregate from 2016 to 2020, i.e., 3977 tons of Li.

Although the metal compartments of stock exchanges such as the

London Metal Exchange – LME, or the Shanghai Metal Market – SMM,²⁷ which specialize in the pricing of non-ferrous metals such as Li, publish prices for Li concentrates (such as spodumene or petalite), the reference prices are for carbonate, oxide and hydroxide.

In addition, for the sake of consistency with the statistical source of Li production in Tables 5 and i.e., BGS (2023), we use the values for international trade in carbonate, oxide and hydroxide published by this source (i.e., no trade in lepidolite). As these values are in kilograms of Li in \$, we simply convert them into tons in € at official exchange rates. Prices and average export and import prices are in €/ton.

Our average Li price is the average of the prices for Li carbonate, hydroxide and oxide, which are both the most widely traded categories and for which data is most readily available.

Below, we provide details of the calculations made for the 4 types of price shown in Table 6. These are the price of imports or exports of each type of Li, the average price of imports or exports of Li, the average annual price of Li demanded in the EU and the average price of Li over the period 2016–2020.

The price of Li imports and exports: this is simply the ratio between the value of Li imports or exports and the quantities imported or exported, as shown in Table 5. So, for e.g., the 2019 price of Li carbonate imports is the ratio of the value of Li imports (€147,862,791) to Li imported (2777.1 tons, see Table 5), i.e., €53,244/ton.

The average price of Li imports by the EU in 2016, for instance, is, without decimals, €33,507 with an exchange rate of €1 = \$1.06. This average price is obtained as the mean of the import prices of each type, weighted by the tonnages of the various types (Li oxide, hydroxide and carbonate) shown in Table 5. Thus: $(1135.7/4204) * 30,575 + (1 - (1135.7/4204)) * 34,585$ gives a price of €33,502. The calculation is exactly the same for Li exports.

The average price of Li demanded annually in the EU will depend on two elements: i) the structure of this demand between exports X and production Y on the one hand, and imports M on the other ii) the average price of X and Y on the one hand (approximated by the average price of exports) and the average price of M on the other.

The calculation of the average price of Li's annual demand by the EU is therefore a weighted mean of average export prices and average import prices, according to the structure of this demand between domestic production and exports (Y and X) on the one hand, and imports (M) on the other. The data needed to calculate this structure, i.e., the ratio: $(Y + X)/(Y + X + M)$, can be found in Table 5. By way of example, the average price of Li demanded in the EU in 2020 is obtained as follows: $17,396 * 0.4567 + 28,168 * 0.5433$, i.e. €23,248.4/ton of Li content.

Finally, the average Li price demanded in the EU over the interval 2016 and 2020, i.e., €36,492.1/ton, is the average of the annual average Li prices from 2017 to 2020, since the 2016 data is unavailable.

The average Li demand in the EU between 2016 and 2020, i.e., 3977 tons seen in Tables 5 and is also the average annual Li demand between 2017 and 2020, since the 2016 data is unavailable.

We now have all the data we need to calculate the scaled EE indicator:

$$EE(\text{scaled}) = \left(\frac{\left(\frac{\sum_s (A_s * Q_s) + \mu (\bar{P}_s * (C_s + \Delta S_s))}{Q_s^{Max}} \right) * SI_{EI}}{Q_s^{Max}} * 10 \right) \quad (24)$$

$$= \left(\frac{(87,342.51 + 25.69 (0.036 * 3,977)) * 0.91}{204,200} \right) * 10$$

$$= \frac{828,287.45}{204,200} = 4.05$$

As a reminder, the economic importance of Li carried forward by the

²⁷ Depending on the degree of purity of lepidolite, whose Li oxide (Li₂O) content ranges from 1.5% to 2.5%, SMM (2023) indicates that it is worth, on average, between \$721 and \$1030 per ton.

EC (2023, Appendix 4, Table 15) was 3.9. Taking into account the production cost effect (PCE) in addition to the production effect (PE) therefore leads to an amplification of more than 4% of the economic risk of Li for the EU over the same period examined (2016–2020). This result illustrates that, in static terms, as in this numerical illustration, normalized EE is always higher than normalized EI. This is easily verified by observing the numerators of normalized EI and normalized EE. It simply means that taking into account the cost of using a substance mechanically increases its degree of criticality.

EI therefore systematically reduces the degree of criticality (by 4% in this example). In dynamic terms, i.e., by comparing the criticality calculated with EI and that with EE over time, the trajectory will depend on the comparative behavior of PE and PCE (see Section 5.2, Table 4). This trajectory is non-linear, since movements in the numerator include both the economic contribution of the substance to the economy (which is what EI was already doing) and the cost of using that substance (which is what EE is doing).

6.2. Prospective use of EE

As with SR and EI, it is possible here, for instance, to determine the impact of a variation in the average price of Li demanded in the EU on the EE dimension. To do this, we partially derive the non-scaled EE dimension:

$$\frac{\partial EE(\text{non-scaled})}{\partial \bar{P}_{Li}} = (C_{Li} + \Delta S_{Li}) * SI_{EI} = 3,977 * 0.91 = 3,619.07 \quad (25)$$

This means that when the average price of Li in the EU rises by €1, EE increases by €3619.07. When the same price increases by €1,000, EE increases by €3,619,070.

Following these 2 examples of impacts, normalized EE is now respectively:

$$\begin{aligned} EE(\text{scaled}) &= \left(\frac{(87,342.51 + 25.69(0.0365 * 3,977)) * 0.91}{204,200} \right) * 10 \\ &= \frac{828,752.32}{204,200} * 10 = 4.06 \end{aligned} \quad (26)$$

We specify that, as the average price of Li has risen by €1, it now stands at €36,493.1, or €0.0365 million, since the monetary values in the formula are all expressed in millions of Euros. It is expected that an increase of only €1 in the average price of Li will have virtually no impact on our indicator. This means that, given the characteristic economic conditions for Li in the EU (current average Li price, quantity demanded, production effect and production cost effect), a variation of €1 has virtually no effect on the criticality partially²⁸ captured by EE. Consequently, it does not create any additional deviation from EI. This result is intuitive, since if \bar{P}_s tends towards 0, PCE tends towards 0 and EI is equal to EE.

If we now consider the example of a €1000 increase in the average price of Li, we have:

$$\begin{aligned} EE(\text{scaled}) &= \left(\frac{(87,342.51 + 25.69(0.0375 * 3,977)) * 0.91}{204,200} \right) * 10 \\ &= \frac{829,682.06}{204,200} = 4.063 \end{aligned} \quad (27)$$

The EE calculation produces a different criticality result from that of the European Commission. In dynamic terms, a rise in prices therefore amplifies the economic risk, which is increasingly greater than that given by the EI dimension. Price fluctuations can be radically greater than the €1 and €1000 examples, as illustrated by the difference in the average price of Li exports rising from €28,716 in 2021 to €108,867 in

2022, or that of Li imports rising from 29,097 to 91,514 between these two dates (cf. Table 6).

The case of price variations has been used as an illustration. It is also obviously conceivable, using the same approach, to examine the impact on criticality perceived *via* EE, of variations in the quantities of Li requested by the EU, or of the modification of a term in the PE or the PE as a whole (i.e., $\sum_s (A_s * Q_s)$) or of a term in PCE or PCE as a whole (i.e., $\bar{P}_s * (C_s + \Delta S_s)$) or the substitution index SI_{EI} .

7. Conclusion

At the heart of the debate on mineral resources and their criticality, and in line with the most recent work of the European Commission, this contribution takes the EU's lithium requirements as an illustration. The EU has been active on these issues for a dozen years and, in addition to its own works, has probably stimulated numerous national initiatives and raised awareness of its criticality lists among many public and private stakeholders, to give just one example. A constant pillars of its studies since the late 2000s, the supply risk (SR) and economic importance (EI) dimensions are widely used in the literature, and their combination makes it possible to draw up these lists and update them every three years. However, there is room for improvement in these core dimensions. Rather than extend the literature criticality frameworks with a new criticality method/technique, in the wake of the overwhelming majority of works, the option of this contribution has been to deepen an existing framework.

Thus, the contribution of this article has been, on the one hand, to enrich the EU dimension of Economic Importance (EI) by considering the cost of using substances, leading to an Economic Effect (EE) dimension, and, on the other hand, to articulate it in coherence with the EU normalization technique, which greatly facilitates the comparison between EI and EE. To this end, it was necessary to integrate the costs incurred by the use of a substance, whether through European production or imports. Based on this idea, crucial parameters for reflecting raw materials tensions appear in the proposed new dimension (prices, consumption, international trade, stocks). We have named this dimension EE to signify that it is intended to measure economic effects, encompassing the cost to the EU of using/acquiring a substance, and not just its economic importance. EE was articulated coherently with EI, calculated over the same period as the Commission, and this coherence was continued by normalization in line with that of EI (and SR). This article has therefore suggested moving from the combination (SR, EI) to (SR, EE) for assessing the criticality of mineral substances.

The lesson gained from the new dimension is that it enriches both the statics and the trajectories of the indicator measuring criticality. In static terms, EE is more favorable to raising the criticality level. For the period 2016–2020, Li's criticality is therefore confirmed as EI, but its intensity is 4% higher than that given by EI. In terms of trajectories over time, as illustrated in Section 5.2.2, the calculation of several criticalities with EI is to be compared with the calculation of several criticalities with EE. While statically EE is higher than EI, the dynamics of a substance's cost of use produces richer non-monotonic criticality trajectories (higher or lower) than with EI.

EE (scaled) formula also brings another message – while remaining very consistent with the European Commission's normalized EI. As shown in Section 5.3, the cost of use therefore always increases the criticality of a substance, but to a lesser extent when the substance's contribution to the economy is greater. This message is consistent with economic theory: a worker's salary for e.g., weighs less on a company when that worker is more productive.

We conclude by mentioning three other lessons from this article:

Criticality studies, even if they are intended to alert us to current tensions, are for the moment static, i.e., at best contemporary or retrospective. For each of the three dimensions examined, we have demonstrated and numerically illustrated their prospective use. In

²⁸ Partially, because SR must not be forgotten when assessing the substance's overall criticality.

addition, the procedure can be implemented on software in order to routinize its replicability on substances and geographical areas other than the EU.

An updated statistical and economic overview of Li (markets, uses, production costs, supply, demand, prices, possible existence of stocks and trade) has been proposed for EU, but also on world scale, from 2016 to 2022.

Finally, the conclusions of a European Commission consultation in 2016 (cf. Blengini et al., 2017) on its criticality work, from some sixty public and private stakeholders, highlighted the following two findings: "improve the definitions of the indicators used in the Commission's work" and "improve and refine the components of SR and EI for more reliable and transparent calculations". By proposing, on the one hand, a reading of the existing dimensions in line with the original, but also a personalized one, and, on the other, by delving deeper into the content of EI, this article has, along the way, provided the beginnings of a response to these two conclusions.

Data availability Statement

I confirm that all data generated or analysed during this study are publicly available. All other data necessary for the final calculations or econometric simulations ... will be transmitted upon request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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Révision de la dimension 'Importance économique' : le cadre européen de criticité des matières premières minérales, complété et illustré au travers du lithium'

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Sollicitées depuis la nuit des temps, de plus en plus utilisées comme consommations intermédiaires et au cœur des transitions énergétique et numérique, les substances minérales sont vitales pour le fonctionnement des économies. Si toutes sont importantes, toutes ne sont pas stratégiques, et encore moins critiques (comme le lithium). L'Union européenne en dépend. Depuis 2010, la Commission européenne produit des statistiques évaluant un ensemble large et extensible de sous-indicateurs de criticité intégrés dans une matrice bidimensionnelle (risque d'approvisionnement, RS, et importance économique, IE) et une liste de substances critiques basée sur une combinaison de RS et d'IE, mise à jour tous les 3 ans. Cet article examine de plus près l'une de ces dimensions, à savoir celle de l'IE. La dimension que nous proposons, « Effet économique, EE », intègre le coût d'utilisation des matières premières. Articulée en cohérence avec l'IE et évaluée sur la période la plus récente, elle est comparée à l'IE pour le lithium. L'EE suggère une criticité systématiquement plus élevée que l'IE. Le lithium se distingue par une criticité supérieure de 4 %. La dynamique de sa criticité, en revanche, est non-monotone, enrichissant celle de l'IE. L'article illustre également numériquement l'utilisation prospective de SR, EI et EE. En outre, un aperçu actualisé du lithium (marchés, utilisations, coûts de production, offre, demande, prix, stocks et commerce) a été fourni, tant pour l'UE que pour le monde.