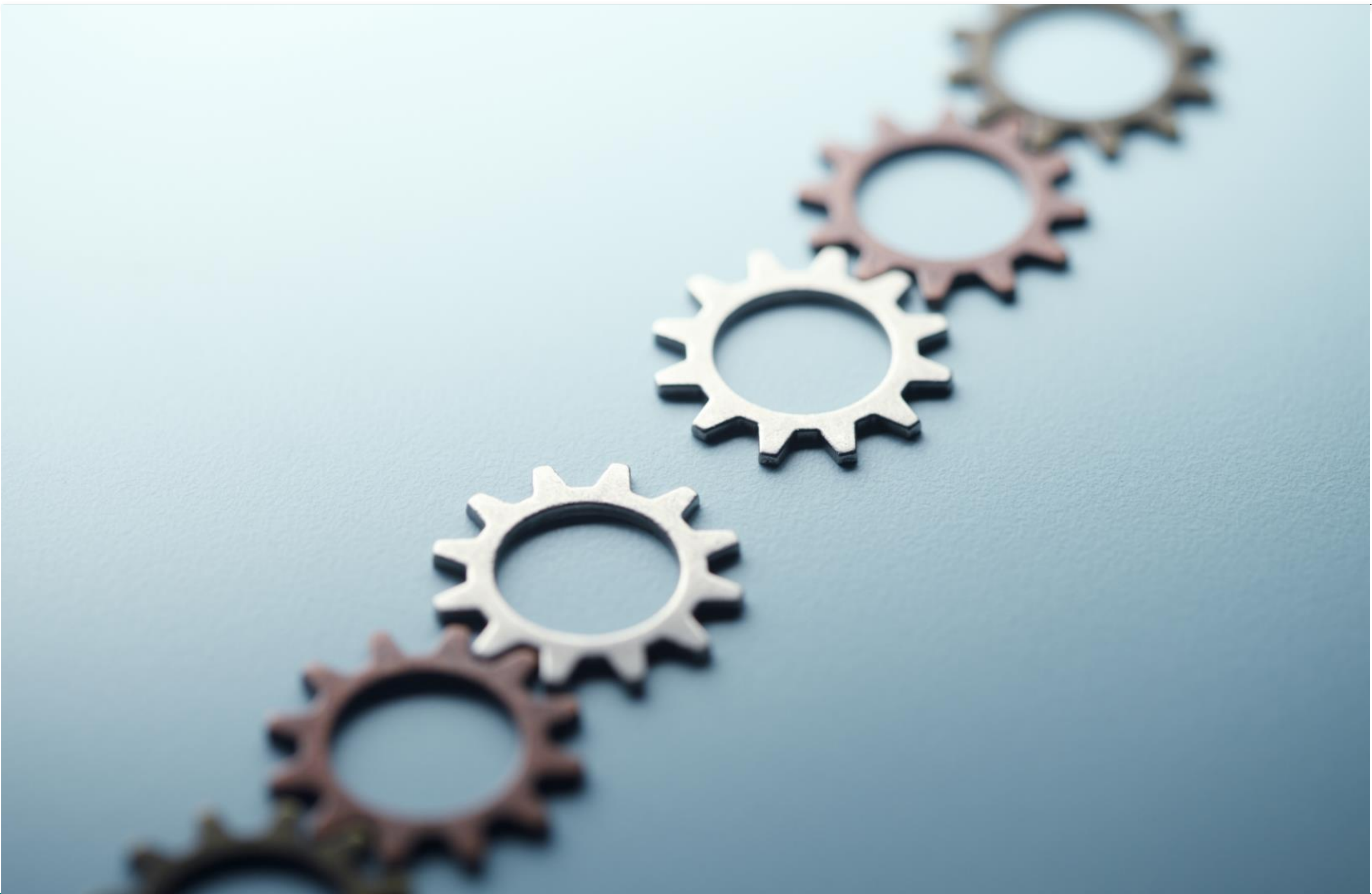
ETC CE Report 2025/5

Environmental impact of material's supply chain disruption

The cases of Aluminium and Lithium



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Executive Summary

The effects of recent geopolitical developments and events on raw material supply chains have led to new forms of instability and unpredictability in international relations. While economic and strategic considerations dominate the European agenda, the environmental implications of supply disruptions often receive less attention.

This report builds on a pilot study initiated in 2023, which developed an analytical framework to evaluate the environmental consequences of raw material supply chain disruptions and explore potential responses. The framework, which was initially applied to case studies on nickel and rare earth elements, has been further refined and implemented in this report to analyse aluminium and lithium—materials chosen based on specific criteria.

The study outlines three primary strategies to address supply chain disruptions:

1. Short-term (2024–2026): Establish trade relations with alternative suppliers.
2. Medium-term (2026–2030): Expand domestic recycling capacity to meet demand.
3. Long-term (2030–2040): Develop domestic capabilities for raw material extraction, processing, and refining.

The report analyses the EU trading countries to assess the environmental impact of supply disruptions. While main trading partners for bauxite are Guinea and Brazil, for lithium main trading partner are China and Chile.

The findings indicate that shifting aluminium supply to domestic EU sources and enhancing recycling capacity can significantly reduce environmental impacts—particularly in terms of global warming potential, energy use, and water ecotoxicity—when viewed through the lens of EU footprint.

For lithium, while short-term shifts to alternative suppliers are more complex, medium- and long-term measures, including increased recycling and expanded refining capacity within the EU, could prevent annual emissions of 0.5 to 1 million tonnes of CO_2-equivalent.

The report underscores the critical role of supply chain decisions, investment in recycling technologies, and domestic production in mitigating environmental impacts. However, while these measures may benefit the EU, the study acknowledges that they do not automatically translate into reduced global environmental effects.

This study provides a preliminary assessment of impacts, constrained by data limitations, resource availability, and strict assumptions. Future research should explore additional policy options, including demand reduction and material substitution, alongside detailed life cycle assessments of the entire value chain. These insights could significantly inform and improve policy-making processes.

1 Introduction

1.1 Background and context

The European Union's extensive reliance on global supply chains has exposed it to growing risks and uncertainties, particularly due to the increasingly contentious geopolitical landscape, along with unforeseen events such as the Covid-19 pandemic. The recent crisis and events such as the pandemic and the war in Ukraine, along with other natural and/or man-made crisis, have highlighted the significance of interruptions in supply chains of raw materials and showcased how this could trigger a complex set of economic, social and environmental impacts. These disruptions are particularly critical across critical raw materials[1] (CRM) supply chains and the broader clean tech industry, both of which are essential to Europe's future competitiveness and sustainability (EPRS, 2023).

Among various policy responses to such risks and vulnerabilities, the recent policy focus has shifted toward de-risking supply chains to enhance Europe's resilience and achieving greater autonomy. Key elements of such strategies include boosting domestic primary production, increasing the recycling capacity, leveraging trade tools, and fostering international cooperations. One key recent example is the Critical Raw Materials Act[2] (CRMA), which seeks to strengthen the EU's ability to produce, refine, and recycle CRMs necessary for green, digital, and defence technologies. While the Act sets domestic capacity benchmarks for critical raw materials by 2030, it acknowledges that domestic actions will never make the EU self-sufficient and therefore puts forward international strategy to diversify the EU's import. Similarly, the Net-Zero Industry Act[3] (NZIA) targets disruptions in clean technology supply chains by aiming to produce at least 40% of the EU's annual deployment needs domestically by 2030.

While these policies focus on enhancing supply chain resilience and strengthening economic security, there is growing recognition that actual and potential environmental impacts of the proposed strategies must also be considered. The CRMA, for example, has empowered the European Commission to establish rules for calculating and verifying the environmental footprint of CRMs. This step acknowledges the need to assess the ecological ramifications of supply chain strategies, especially as the EU strives to balance economic and geopolitical priorities with its green transition goals. Similarly, the NZIA aims for an annual CO_2 storage capacity of 50Mt by the same year to boost carbon capture and storage (CCS). To achieve these goals, the NZIA establishes a governance framework where member states identify and support key Net-Zero Strategic Projects (NZSPs) to drive implementation.

Despite ongoing efforts, further elaboration is needed to fully integrate environmental considerations into trade and supply chain decisions, ensuring that the pursuit of economic security does not undermine global sustainability goals and environmental and social agendas (Kosmol et al., 2023). The balance between maximizing supply chain resilience and minimizing environmental impacts should be taken into consideration policy making process. In this context, the particular objective of this study is to assess the environmental impacts of such policy-driven responses to supply chain disruptions and provide evidence-based insights that could be considered when deliberating potential responses by policy makers.

1.2 Objectives and scope

This report builds on a pilot study initiated in 2023 on the "Environmental Impact of Materials Supply Chain Disruptions." The primary objective is to establish and test an analytical framework for evaluating the environmental impacts of disruptions in raw material supply chains, look at alternative pathways and estimate the changes such pathways will entail when it comes to environmental footprint of Europe and

[1] CRMs are those that have high economic importance for the EU while associated with high supply risks.
[2] Critical Raw Materials Act: https://eur-lex.europa.eu/eli/reg/2024/1252/oj
[3] Net-Zero Industry Act: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ:L_202401735

globally. By analysing these scenarios, the study aims to provide policymakers with evidence-based insights to inform their decision-making on potential responses to supply chain challenges.

To achieve this, the study first develops a theoretical framework outlining possible responses to supply chain disruptions and their projected ex-ante environmental effects. This is followed by a practical methodology designed to analyse the complex environmental impacts of specific materials, identifying key variables that should be considered in such evaluations. Case studies are then used to apply and validate the methodology in real-world scenarios.

The case studies were selected based on criteria of relevance and feasibility, which have evolved since the study's inception in 2023. While the initial phase focused on nickel and rare earth elements (REE) (Specker et al., 2024), this report tests the framework's applicability to **aluminium (Al)** and **lithium (Li)**, reflecting a refined approach to assessing the potential impact of material-specific supply chain disruptions. The selection of these two materials was based on the following criteria:

- Import reliance of the EU on the extraction of the commodity (vulnerability of disruption for the EU)
- Critical or strategic importance of the commodity for the EU
- Environmental impact data availability (based on Ecoinvent)
- Literature data availability
- Trade data availability over time (for Europe)
- Trade data availability over time (globally)
- Domestic production of the commodity (active or in development)
- Recycling potential of the commodity (required time to establish large scale recycling in the EU)

Based on these criteria, aluminium was selected due to its status as a base metal critical to a wide range of products globally. In 2022, the EU used 13.5 million tonnes of aluminium (European Aluminium, 2022), the majority of which came from non-European sources. Additionally, aluminium benefits from a well-established recycling sector, further enhancing its relevance. In contrast, lithium was chosen to highlight a different dynamic. This critical metal, essential for lithium-ion batteries (LIBs), plays a pivotal role in the energy transition. The EU currently relies entirely on imports for its lithium supply, sourcing it from a diverse group of predominantly non-European countries. Further details about the selection of case studies, scenarios and the related analytical assumptions is provided in Sections 2.3 to 2.5.

2 A framework and methodology for mapping the expected effects

2.1 Framing environmental effects within market dynamics: An analytical framework

The environmental pressures of industrial materials are associated with their production (including mining, processing and refining), manufacturing into semi-finished/finished goods, trade, consumption-/use-phase and waste management (such as collection, treatment, disposal and recycling). Supply disruptions induce complex changes of these processes and of the associated environmental pressures across the material supply chain. Therefore, the analysis of expected changes in environmental pressure due to supply disruptions must be linked with the ex-ante changes it induces in production, trade, consumption and recycling as well as in material saving innovations and material substitution processes.

For a specific industrial material or metal for which an international market with many supplying countries exists, a supply disruption can induce changes for:

- Importing country and exporting countries (both old and new exporters);
- Transit countries (pure trade transit or phases of the value chain, e.g. semi-finished inputs).

The disruption can be quantity-related, quality-related and/or price-related, that is:

- Shock in prices that can dynamically trigger quantity disruption (e.g., non-viable raw materials costs).
- Raw material quality is only available at a lower ore grade or in more diluted secondary streams.
- Flow interruption that can dynamically trigger price increases or decreases.

The reason for looking at quantity and price together is that, in international commodity/energy markets, a temporary or stable supply/demand shock translates into price changes, and price changes translate into changes in supply and demand as a standard dynamic sequence of search for new equilibria (see Annex A).

If supply is the primary constraint, all extracted materials will ultimately be sold in the market, meaning that a shift to an alternative supplier does not reduce overall production but rather redirects consumption. For example, if the EU stops buying from one supplier, other countries will likely purchase what the EU no longer does. As a result, the global environmental footprint remains unchanged, even though the EU's footprint might decrease. This highlights the zero-sum nature of such shifts, where a change in demand flow does not necessarily reduce global environmental pressures but redistributes them geographically.

In this framework, the actual overall environmental effect of a supply disruption can critically depend on the type and the pace of reaction by the countries involved, which can range from the short-term (with limited reaction possibilities) to the long term (with large reaction possibilities), with the medium term in between.

The **short term (ca. 2 years)** is typically dominated by a limited elasticity of supply in both the world market of the material and domestically (primary and secondary supply) in the importing country, coupled with a limited elasticity of domestic demand (e.g., by substitution), and a limited possibility of deploying resource-saving innovations and demand-side changes in the same country. Although, in certain crisis situations or under specific political choices, such as those caused by the Russian aggression in Ukraine, the implementation of resource-saving measures can prove feasible within a short period of time, demonstrating that under pressure, significant adaptations can occur rapidly. Therefore:

- The immediate expected effects of a *quantity disruption* (e.g. flow interruptions due to pandemic, blocking of transport corridors, strikes, sanctions, etc.) without a reaction from an importing country are losses of value added and employment in both the importing and the exporting country. The reduction of production of the exporting country can generate a reduction of environmental pressures in both countries, provided all other variables and conditions do not change and there is no domino effect in other sectors. This is of course a theoretical example as in the reality a new equilibrium will possibly be found.

- If there is an increase in prices, the effects depend on the elasticity of demand to prices (see Annex A): if low, there can be increases in final good prices (up to inflation, if the material is economically important) in the importing country. In addition, it is relevant how the other suppliers in the world market can react to price increases by increasing supply (depending on supply elasticity to prices). The effects of the price increase can be, in any case, depressive on value added and employment in the importing country, as well as in the formerly exporting country, which however can benefit from higher prices on the still active export flows. As far as there is a reduction of activity (quantities), there are lower environmental pressures. Even though the elasticity of supply can be low in the short term, a possible new supplier could benefit from entering the market attracted by higher prices.

- The effects on value added and employment depend also on how the increasing costs of inputs are transmitted to final prices (pass-through) and how final demand can react (decrease). If the demand moves towards substitutes, the latter can benefit from an increase in production.

Consequently, the environmental effects depend on the elasticity of demand to prices (see Annex A): if it is high, price increases can reduce demand (industrial activity) and environmental pressures, but the cross-effects on substitutes must be considered. For example, as in many cases 1:1 substitution of materials is not possible, for calculating the environmental impacts, the exact amount of substitute materials used in a specific application should be taken into consideration. In this same case, the high prices might attract new suppliers in the world market, which can alleviate the price increase (but their elasticity of supply could be low in the short term).

The expected effects in the **medium term (2-6 years),** are dominated by a higher elasticity of supply in the world market (procurement shift is more possible) and possibly by domestic supply activation (primary production, if the country is endowed with the resource, or secondary through higher recycling and fuller circularity), together with a possible reduction of domestic demand via substitution and adoption of resource-saving innovations.

In the **long term (7-16 years)**, there is a higher possibility to put in place strategic reactions towards a permanent supply disruption for the material, up to achieving high self-sufficiency and re-shoring of those production phases that are subject to procurement risk. There is the possibility to adopt new industrial strategies to reshape the whole domestic value chain in which the material is used. There are also more possibilities to reduce domestic demand by fully deploying resource-saving innovations and demand-side shifts. Therefore:

- The importing country can achieve a full geographical shift of procurement, thus establishing and stabilizing the trade flows with new reliable suppliers; the new suppliers in the procurement portfolio of the importing country can gain value added and employment but can lose on the environmental pressure side if it opens new production capacities to supply the additional demand.

- The importing country can better implement measures to exploit and increase domestic supply potential (primary production and, especially, secondary raw materials), thus making steps towards self-sufficiency for the material.

- Self-sufficiency strategies of the importing country can cause increasing pressures on its domestic environment. Measures to mitigate these domestic environmental effects, as well as to respond to the NIMBY (Not In My Backyard) syndrome of households, communities and administrations (e.g. compensations), can be adopted. The higher the ambitions for self-sufficiency, the higher the concern, the stronger the measures must be to avoid domestic environment disruption, or failures of the strategy caused by oppositions. The net global balance of this transfer of environmental pressures to the importing country depends on whether these pressures are lower (country environmentally more efficient) or instead higher than those (now missing) of the former supplier country (given the quantities). This will also depend on various other factors, such as the quantity, type, and quality of domestically available reserves or resources. Depending on these factors, the economic feasibility and environmental impacts may be called into question. This scenario heavily depends on: i) the technical feasibility of recycling of the material; ii) the expected lifetime of those products embedding the material; iii) the alignment between the possible flow of recycled materials and future needs.

- The importing country can fully exploit the potential industrial and environmental benefits of secondary domestic supply within a circular economy paradigm, which can deliver a third dividend through increasing self-sufficiency and resource independence. For some materials, the increase in circularity can be the only real option in front of a permanent supply disruption. At the same time, the importing country can fully deploy resource savings innovations and new industrial policies, up to full adaptation of the domestic value chains in which the material is, directly or indirectly, relevant. Moving to a circular economy paradigm requires that the material stock has been largely built up in the buying country, so that sufficient amounts of secondary materials are available to satisfy economy-wide flows of materials demands, with all the limitations implied by the impossibility to have 100% recycling.

- A higher self-sufficiency can induce higher domestic prices along the value chain if domestic production costs (extraction, transformation. etc.) are higher than those of the imported material (at higher prices), and 'imported inflation' might be substituted for by domestically generated inflation. This cost can be seen as a cost of insurance against the riskiness of the international market, but measures must be taken to avoid a possible unfair distribution of this cost (as reflected in higher consumer prices).

The EU strategy pushed forward through the Critical Raw Materials Act (CRMA) has benchmarks designed for a 'long term' reaction, but possibly with an accelerated timing that envisages the 'medium term'. However, the degrees of strategic flexibility and feasibility that define the short-, medium- and long-term characterisation are within this theoretical framework (European Commission, 2024a).

2.2 Methodological approach: A practical framework

Based on the analytical framework explained above, this section introduces a range of variables that could be considered to analyse the environmental impacts of supply chain disruptions of a specific industrial raw material. The proposed approach has a distinct focus on environmental footprints (including also the upstream environmental implications of the material supply chain), mainly because the size of this project does not allow to fully capture the whole set of interactions among economic and social variables included in the analytical framework. At the general level, the potential variables relevant for such an analysis are as follows:

Type of materials: For this study, it is important to focus on a specific industrial material or metal for which an international market exists and the material market is not monopolistic, even though oligopolistic features may exist with single countries showing a dominant position (>60% of global capacity) across any of the supply chain stages (e.g., mining, processing, recycling). Furthermore, for a comprehensive analysis, the supply of the selected material in the form of co-products or by-products should be considered.

Countries involved: Based on existing trade data[4] the main importing country and exporting countries (both old and new exporters) should be identified. For a more comprehensive analysis, the main transit country (pure trade transit or phases of the value chain, e.g., semi-finished products) could be identified. This specific assessment will only focus on the extraction and processing stages.

Type of disruption: The disruptions could be temporary but significant in size or permanent, total (i.e., no flow) or partial (i.e., reduced flow), and must have in any case real or perceived consequences (e.g. higher risk) on the market. The framework does not differentiate the causes behind the supply chain disruptions, which could be due to either technical, economic, environmental, military or geopolitical reasons. They could also be triggered by natural disasters or pandemics.

Type of responses: This variable corresponds to the expected response from the importing country in different time frames. The potential responses include the search for alternative suppliers, increase in domestic capacity across relevant supply chain stages (e.g., mining, processing and recycling), substitution by other materials and technologies and reduction in demand. In the EU, the CRMA is pointing to mitigate risks from potential supply shortages of critical raw materials by diversifying EU import and reduce

[4] See the original trade analysis of the two case studies. A source of trade data for critical raw materials could be the recent report on "Study on the Critical Raw Materials for the EU" published by the EU Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs available here: https://op.europa.eu/en/publication-detail/-/publication/57318397-fdd4-11ed-a05c-01aa75ed71a1

strategic dependencies, and it tries to do that structurally and permanently (See Section 1.1 for more details about CRMA).

Type of environmental impacts: this includes environmental impacts for the importing country and for the rest of the World. Based on previous environmental assessment studies on raw materials supply chains (DIEH, 2010; Joint Research Centre et al., 2013), seven environmental impact categories could be considered for such an assessment

(i) Air pollution: This includes emissions of greenhouse gases (i.e., CO_2, CH_4, etc.) but also hazardous emissions (i.e., mercury, lead, nitrogen, sulphur, etc.). Emissions occur all along the value chain.
(ii) Water pollution and water scarcity: Water pollution mainly occurs when cyanide and sulphuric acids are used to separate targeted minerals from ores. Water scarcity can occur if freshwater is withdrawn from water bodies for mining operations thereby causing a lack of access to safe water supplies for local populations and ecosystems.
(iii) Biodiversity depletion: Mining processes can have a wide range of impacts on the fauna and the flora affecting their richness, their abundance, and diversity which leads to consequences on the soil and water quality. The level of impact on biodiversity could eventually lead to long-term damage to ecosystems.
(iv) Land use: Extraction of materials from the ground necessitates huge amounts of land, especially when done with open pits. Deforestation and general loss of above ground ecosystems lying there is to be accounted for in this category of impact.
(v) Soil pollution: Soil pollution generally occurs when leaching of the tailings/waste, when improper treatment of drainage water, and when high levels of dust.
(vi) Geological instability: Can create negative environmental impacts (e.g., habitat destruction, affect water balance, soil erosion, etc.) and can occur either in excavation sites, in mines, or with tailings storage.
(vii) Waste production: Waste rock and tailings are the common waste created in mining, processing and refining. Some of the tailings can be toxic, creating pollution as can be seen with soil pollution. Furthermore, tailings dam failures can lead to sever environmental damages and loss of life.

In addition, eight indicators, as defined by the German Environmental Agency on geological, technical and site-related environmental hazard potential of mining can be added for consideration in the assessment (German Environment Agency, 2020):

(i) Pre-conditions for acid mine drainage
(ii) Paragenesis with heavy metals
(iii) Paragenesis with radioactive substances
(iv) Mine type
(v) Use of auxiliary substances
(vi) Accident hazards due to floods, earthquakes, storms, landslides
(vii) Water Stress Index (WSI) and desert areas
(viii) Designated protected areas and AZE (Alliance for Zero Extinction) sites.

End-use of materials: An additional variable to be considered in the framework is the application or end-use of the materials analysed. This is key for the analysis of second-order effects. If, for instance, the materials are utilized in clean energy technologies, a disruption in the supply of those materials may have profound effects on the transition to renewable energy technologies. This could slow down the phase-out of highly polluting energy sources and the adoption of more sustainable renewable technologies. End-use type information is also relevant to determine possible material substitutes. This type of effect can only be considered if the end-use of materials is included in the framework.

Geographical distribution of the environmental impacts: This will depend on the combination of geographical redirection (which is dependent on raw material reserves and production capacity of the new supplying country), international procurement, activation of domestic supply, substitutability, and increase in circularity of the material (recycling, reuse, etc.). Other aspects such as the implication of co-products to mining are also highly interconnected with the geographical redirection of mining activities and distribution of environmental effects.

Timing of responses and effects: The precise identification of relevant timeframes, across short-, medium long-term, is dependent on the type of material analyses and its supply chain dynamics, and — to a certain extent — arbitrary. As explained in the previous sub-section, the buyers will have limited response possibilities in the short-term, moderate response possibilities in medium-term and larger response possibilities in long-term. The difference in global environmental effects in this case will depend on the technologies and regulatory framework in the new supplying countries compared with the previous supplying countries, as well as the technologies of the buying country if it activates domestic supply (primary and/or secondary).

Economic perspective: Supply disruptions can be originated by geopolitical and geo-economic changes as well as changes internal to the markets, like price changes, that can be understood by economic analysis. The whole theoretical framework presented above is rooted in the economic analysis of markets in an open economy. In addition, the assessment of the two case studies will incorporate a concise economic evaluation, specifically focusing on international trade in quantities, values and prices. Economic analysis is also behind the assessment of 'preferable' exporting countries for the EU though Multi-Criteria Analysis (MCA). This addition will provide a comprehensive economic viewpoint within the assessment framework.

2.3 An abridged framework for this study

In the current study, the analytical framework explained in Section 2.1 has been streamlined to facilitate the assessment of environmental impact of two selected raw materials, aluminium and lithium under conditions of limited information. To align with the scope of this research, the analysis focuses on three-time frames (short, medium and long term) and considers a single potential response or scenario for each time frame. This approach excludes the consideration of secondary effects that might arise from any potential response, assuming that all other variables remain constant. A detailed explanation of this customized approach is outlined in Table 1 below.

Table 1. Short-, medium- and long-term scenarios considered in this study

Short term (2 years, 2024-2026) In the short term, the possible EU (importing country) reactions can be limited. If there are alternative supplying countries, the supply chain can shift, and the environmental pressures will most probably shift to the new exporting countries. The difference in global environmental effects in this case will depend on the technologies and regulatory framework in the new exporting countries compared with the previous exporting countries.	
Key response	Establishment of trade relations with alternative exporters
Key environmental impacts dependent on:	The difference in environmental impacts in this case will depend on the technologies, energy mix, quality of the deposits, and regulatory framework in the new exporting countries compared with the previous exporting countries.
Potential scenarios for Europe	If there is a disruption in the supply of the raw material (here: aluminium or lithium) and demand in the importing country stays

	fixed, can demand be met through supply from alternative countries in Europe and/or globally[5]?
	If demand can be fully satisfied by an alternative exporter, what is the relative environmental performance of supply from the 'old exporter' vs. the 'new exporter'?
	If demand can only be partially satisfied by alternative exporters, what is the effect of the quantity disruption of the buyer country? (This scenario allows to consider second-order effects, see definition above in "end-use material section 2.2")
Medium-term (2-6 years, 2026-2030) The medium-term time frame is characterized by moderate response possibilities. In case of a permanent supply chain disruption, demand can be satisfied by alternative exporting countries, and an increase in domestic recycling. The overall environmental effects would depend mostly on the availability of a secondary value chain which is in turn dependent on policies, and on the maturity of the domestic recycling industry (EEA, 2022), and the actual amounts of the raw materials available from recycling flows now and in the medium-term future (until ca. 2030)[6]. For this scenario, it should also be considered the growth in the raw material demand.	
Key response	Growth in domestic capacity for recycling to satisfy demand in addition to establishing trade relations with alternative suppliers (of primary and secondary materials)
Key environmental impacts dependent on:	Share of demand that can be satisfied via recycling rather than primary mining
	Relative environmental impact of recycling versus primary mining of the raw material
Potential scenarios for Europe	What share of internal demand can be met through domestic recycling?
	What is the relative environmental impact of recycling vs. primary extraction?
	Is it expected that alternative (primary and secondary) suppliers will enter the market and/or increase their supplying capacity?
	Are there any materials that could substitute the disrupted commodity in key industrial products and uses?
Long term (6 – 16 years, 2030 - 2040)	

[5] The selection of the alternative supplier is made using a multi-criteria framework as discussed in the next section.

[6] Note that depending on the material under investigations and the expected future demands, the availability of the secondary raw material from recycling can vary significantly. Especially for growth markets and products with long lifetimes, the amounts of the material that can be supplied from secondary sources might be limited.

In the longer term, the importing country can decide to design and implement more radical strategies of self-sufficiency of domestic supply with the development of fully integrated domestic primary (e.g., mineral extraction and refining) value chains. The overall environmental effects would depend mostly on the availability of a secondary value chain which is in turn dependent on policies and on the maturity of the domestic recycling industry (EEA, 2022) , and the actual amounts of the raw materials available from recycling flows now and in the medium-term future (until ca. 2040). The two response options of the short term and medium-term—alternative suppliers and increase in domestic capacity for recycling—are still valid for this scenario.	
Key response	Growth in domestic capacity for primary extraction, processing and refining to satisfy demand
Key environmental impacts dependent on:	Share of demand that can be satisfied via domestic extraction and processing
	Share of demand that can be satisfied via domestic recycling
	Relative environmental impact of domestic mining, processing and refining
Potential scenarios for Europe	What share of internal demand can be met through domestic extraction, processing and refining?
	What is the relative environmental impact of domestic vs. foreign extraction, processing and refining?
	Is it expected that alternative (primary and secondary) suppliers will enter the market and/or increase their supplying capacity?
	Are there any materials, technologies, or life-style changes that could substitute the disrupted commodity in key industrial products and uses.

2.4 Trade analysis and 'preferable' supplying countries

2.4.1 Trade analysis

Within the above framework, trade analysis plays a pivotal role for assessing the overall environmental impact of supply disruption. For the two target materials (aluminium, Section 3, and lithium, Section 4) the analysis of EU trade will be carried out at different levels of the value chain. Trade codes considered are reported in Annex B.

The focus will be on direct trade because from official trade data it is not possible to track indirect trade, that is the inputs of materials embodied in the flow of processed, fabricated and recycling-related products directly exported to the EU. It can be further noted that the level of aggregation of data (trading code) matters because it can hide a certain degree of substitutability among specific products within a trading code. The unit values at import into the EU (the ratio of total values to total quantities) are examined as price indicators. There can be a number of limitations in using this indicator. For example, in international trade statistics, import is recorded at CIF values (Cost, insurance and freight) and freight can be very different and variable across countries and years. However, unit values can be an indicator of real prices paid by importers (and received by exporters) and then can provide a more specific information with respect to, for example, indexes of international commodity prices. Also, even considering separately different stages of the value chain does not allow to fully disentangle the role played by true import price changes for each product code and partner from compositional changes in terms of products and partners. This also explains the different contribution of partners in terms of quantity and value of products imported in the EU.

Trade analysis by value-chain stages will cover the last decade (2014-2024) and can provide useful information on different grounds. First of all, it can reveal how stable or unstable has been the structure of trade in terms of countries and stages of the value chain, what changes of trade structure have occurred, and how these changes might have been influenced or not by prices (unit value), especially in the recent years of booming international commodity prices. However, the study doesn't include an analysis of demand (import) response to prices, which would require econometric analysis of complete markets models (see Annex A for a discussion on demand elasticities to prices). Trade analysis can reveal, in particular, the persistency, or not, of key supplier countries over time, and then it can suggest how much the import flows may be flexible in terms of shifting the procurement portfolio or if they are rigid and not sensitive to changes in relevant variables. This can be relevant also for the analysis of the most reliable procurement country mix (change) carried out with the Multi-Criteria Analysis (see section 2.4.2).

To evaluate trends and composition of import of aluminium and lithium the list of relevant trade codes (by CN8) identified by the Joint Research Centre (Georgitzikis, 2023) were considered. For a selection of raw materials, the list includes detailed products and commodity codes for different stages of the value chain (extraction, processing, fabrication and recycling). The list of relevant trade codes for lithium and aluminium are reported in two tables in the Annex C.[7] Bilateral trade data were collected from the COMEXT Eurostat database for the period 2014-2023. Both monetary values (in nominal euros) and quantities (in weight) were considered. Monthly data were aggregated at the yearly level to get rid of seasonality.

For both lithium and aluminium, trends in imports in monetary and physical terms as well as the average price of imported products and commodities, computed as the ratio between value and quantity were considered. Also, the trends in the main trade partners over the same period were evaluated.

To evaluate the extent to which trade barriers could represent a major constraint to strategies aimed at changing the composition of trade partners, the magnitude of tariff barriers for the import of aluminium and lithium were considered. If tariff barriers were high, that would entail a degree of freedom for the EU to mitigate sudden price spikes in key trade partners by making import from these (or other) countries cheaper by simply reducing tariffs. Data on tariffs were collected from the WTO Tariff Download Facility. A main limitation of the data is that information is reported at a more aggregated product level (6-digit HS instead of 8-digit as trade flows), leading to possible biases. The analysis of tariff can be found in Annex K.

2.4.2 Reliable supplying countries: a Multi-Criteria Analysis

As highlighted in the short-term scenario above, shifting to an alternative country is considered one of the major response possibilities to mitigate the effects of a supply disruption. In order to properly assess the environmental implications of such a shift, alternative supplying countries have to be preliminarily selected, for both commodities. This selection was based on a Multi-criteria Analysis with the following methodology (see the excel tool in the Annex H):

[1] **Selection of relevant assessment criteria**
Five performance criteria were chosen to rank countries from "best" alternative supplier to "least good" alternative supplier of the commodity. Those performance criteria were selected because of their relevancy in highlighting target countries that can ensure a stable supply of the commodities to Europe and with a reduced impact on the environment. The five performance criteria are:

[7] For lithium, the focus was given to trade codes relating to processing, as trade codes for extraction and recycling were introduced just in 2023. To illustrate, trade codes in processing represent, in 2023, 93% of the value of lithium imports in the EU and 75% of the weight of lithium imports in the EU.

- Country’s reserves endowment of the commodity, as known in 2024. The higher the reserves of the commodity, the higher the ranking of the country. For instance, a country with low reserves will be of lower interest as a possible alternative supplier of the commodity than a country with higher reserves.
- Country’s mining production of the commodity, as established in 2022. The country ranks best when it has a developed mining production capacity. For instance, a country with no mining capacity cannot be considered.
- Country’s membership to the European Union, as established in 2024. A preference is given to EU member states, which will get a better ranking than non-EU countries.
- Country’s membership to the European Economic Area, the European Free Trade Association and to Schengen Area, as established in 2024. A preference is given to EFTA and Schengen area member states, which will get a better ranking than non-EFTA and non-Schengen countries.
- Country’s scores for the Worldwide Governance Indicators (WGI), as established in 2022. The indicators used in the WGI are “Voice & Accountability”; “Political Stability and Absence of Violence/Terrorism”; “Government Effectiveness”; “Regulatory Quality”; “Rule of Law”; “Control of Corruption”. The higher the score of the country for the WGI indicators, the better the ranking of the country as an alternative option.

[2] **Attribution of a score**
The second step consisted in attributing a score for each country and criteria. This was done in the form of a matrix which can be found in Annex H. In the first place, the values for the different performance criteria were given and for “yes” or “no” criteria the binary approach was used (0=no and 1=yes). In a second place, those numbers were ranked from best to worst with 0 (or “no”) being the worst value and 100 (or “yes”) being the best.

[3] **Weighing the criteria**
Because the criteria do not all prevail in the same way, weights had to be given, depending on the importance of the criteria. Following the Analytical Hierarchy Process methodology, each criterion was given an importance in comparison to the other criteria. The importance and weights given to each criterion can be found in Annex I.

[4] **Final ranking and results**
This process gives us a final grade for each country, based on the criteria and the weighing system. Countries were thus ranked from “best” alternative country to “least good” alternative country. Giving an illustration of this multi-criteria assessment, we show that there are alternative countries where a shift in supply could result in an environmental gain.

The results of the multi-criteria decision analysis conducted for this report are:
For aluminium, the best supplying countries are: (1) Greece (score 58/100); (2) Australia (score 46/100); (3) Guinea (score 36/100).
For lithium, the best supplying countries are: (1) Portugal (score 62/100); (2) Australia (score 49/100); (3) Chile (score 41/100).

2.5 Analytical assumptions and limitations

The assessment is based on the best information available at a certain point in time. This of course brings assumptions and limitations to the assessment as a consequence.

The general assumptions are as follows:

- This research did not enable the researchers to further develop primary data and had to rely on data from previous research. The whole assessment is based on the assumption that the collected data represents a realistic state of knowledge.
- While a variety of responses exists in case of supply chain disruption (as explained in the analytical framework in section 2.1, the study has focused on three key scenarios: (i) for the short-term scenario that, in case of disruption, alternative countries are available for the EU to completely or partially shift its supply; (ii) for the medium-term scenario, that the technology will continue to develop and make recycling of lithium and aluminium more accessible and with a reduced energy demand; (iii) and for long-term scenario, that technology and investments enable the EU to increase its mining/refining capacities. In each timeframe and for each potential response it is assumed that all other variables and effects, including the demand in the buyer country (in this case Europe) remain fixed and the 'second order effects' are excluded from the scope of analysis.
- The focus of this study is on the 'environmental' impacts of supply chain disruptions. An assumption made is that environmental impacts can be meaningfully studied independently, even though a more comprehensive and realistic evaluation of disruptions would consider the 'economic and social' impacts as well, which are not specifically addressed in this report due to their complexity and limited information.

The primary limitations of this study stem from the availability and accuracy of data for conducting a study of this nature. The principal limitations can be outlined as follows:

Data availability limitations

- For most of the calculations in this study, the aggregated environmental impacts of the exporting countries (initial trading country vs. new trading country) or sectors (primary extraction/refining vs. recycling) are compared. However, a proper assessment of environmental impacts related to these processes would require detailed knowledge of the actual locations of extraction, processing, production, and recycling sites, which is not available.
- This study faces challenges in comparing data due to the absence of standardized and transparent information regarding mineral reserves, resources, production, and processing. The availability of consistent and reliable data is crucial for accurate assessments, but the fragmented and inconsistent nature of existing information limits the ability to draw comprehensive and precise conclusions. This lack of standardized datasets represents an important data availability limitation for the study.
- The data on bilateral trade flows is widely available by narrowly defined product groups. However, the availability of country or site-specific trade data for each specific product category can be challenging.
- The medium-term assessment for lithium relies on Life Cycle Assessment (LCA) data from a recycling company developing hydrometallurgical battery recycling, but the details of the LCA study remain undisclosed. As the recovery of lithium from end-of-life batteries is still evolving, there is significant uncertainty regarding the environmental impacts of recycling in the future. This lack of transparency and the dynamic nature of the recycling process contribute to a notable data availability limitation in this study.

Environmental assessment limitations

- The environmental assessment in this study focuses on production-related impacts from the perspective of the EU, utilizing Life Cycle Assessment (LCA) to evaluate cradle-to-factory-gate environmental impacts for supplying a unit of material. The system boundary is defined within an attributional LCA framework. While this approach enables comparison between the environmental impacts of the current supply chain and those of potential new suppliers or production routes (e.g., increased use of recycled material), it is limited by the scope and assumptions of the LCA. Specifically, the assessment calculates environmental benefits or trade-offs based on differences between the old and new production systems, which may not fully capture dynamic or indirect effects beyond the defined system boundary. This limitation highlights the constrained ability of the study to account for broader or long-term environmental implications.

- Due to the global nature of the impacts assessed, the environmental benefits are defined at the EU level and do not account for the potential that other countries may fill the gap created by the EU shifting its supply. This limitation means that the analysis may overlook the broader environmental consequences of such shifts, including potential increases in environmental impacts in other regions that could offset the benefits observed within the EU. Therefore, the assessment may not fully capture the global environmental dynamics and trade-offs involved in these supply chain changes.

Material selection limitations

- This report focuses specifically on lithium chemicals for battery usage, such as lithium carbonate (Li_2CO_3) and lithium hydroxide (LiOH), as the battery market is currently the most significant end use for lithium and is experiencing rapid growth. Additionally, available information on environmental impacts is predominantly centred around battery-grade lithium chemicals. This material selection limitation means that the study may not fully account for the environmental impacts of lithium used in other applications or for non-battery-grade lithium chemicals, potentially overlooking other important sources and uses of lithium.

3 Case study 1: Aluminium potential supply disruptions and environmental impacts

3.1 Aluminium supply chain

Aluminium properties and applications are reported in Annex C. The primary aluminium production is one of the most energy and CO_2 intensive industrial processes, with some estimates showing that more than 60% of the sector's emissions come from the production of electricity from extraction to production (IAI, 2021). The methods for extracting aluminium from its ore consist of two primary stages, the extraction and refining bauxite aluminium minerals to smelter grade alumina (Al_2O_3) via the so-called Bayer process and the reduction of alumina to aluminium via the Hall-Héroult smelting process. The entire aluminium production chain is displayed in Figure 1.

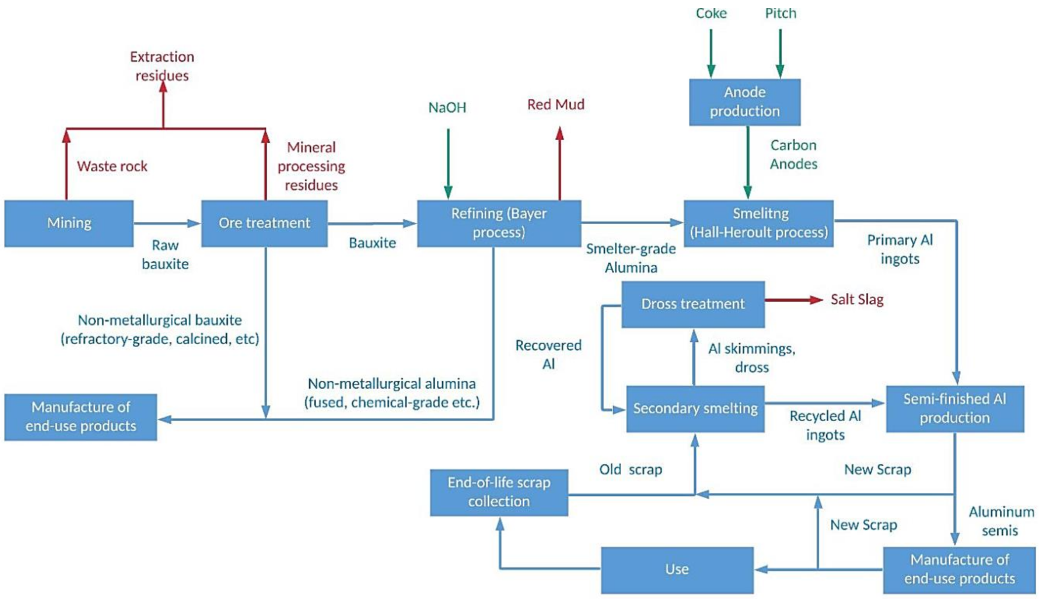


Figure 1. Simplified flow chart for the entire production of aluminium, with waste streams represented by the red arrows (Georgitikis et al., 2021).

The Bayer process uses a progressive stepwise extraction method starting from crushed bauxite ore. Aluminium bearing minerals are dissolved in caustic solution of sodium hydroxide (NaOH) and at a temperature between 140 and 280 C. At this phase the majority of the aluminium bearing phases have been dissolved to form an alkaline solution of sodium aluminate that then undergoes a series of filtration and purification steps, to remove all insoluble iron and other metal oxides and other phases (European Aluminium, 2018; Georgitikis et al., 2021), including those containing rare earth elements (REE) (Balomenos et al., 2011). This residue is known as "red mud" and is a highly alkaline waste product. Aluminium hydroxide ($Al(OH)_3$) is then precipitated from the dissolved solution and is subsequentially calcinated high temperature (~1,100 C) to drive off impurities, converting the aluminium hydroxide ($Al(OH)_3$) to alumina (Al_2O_3). The result is a highly pure fine-grained white powder (European Aluminium, 2018; Georgitikis et al., 2021). It has been estimated that in Europe per tonne of alumina, about 2.2 tonnes of bauxite are utilized (European Aluminium, 2018).

Alumina must thereafter undergo an electrolytic reduction step, called the Hall-Héroult process, to convert it to metallic aluminium. This is the most energy-intensive stage, as it requires a large amount of electricity. Aluminium metal is produced by passing an electric current though a series of baths containing a liquid mixture of alumina, aluminium fluoride and compound called cryolite (Na_3AlF_6) at a temperature of between 960 – 980 C. The current then converts alumina into its components, oxygen and molten aluminium. The dense metallic aluminium sinks to the bottom of the baths where it can be collected (IAI, 2023; Balomenos et al., 2011). Following refining, the aluminium undergoes casting into ingots, involving heating to temperatures up to 750 C, or alloyed with other elements such as magnesium, silicon or manganese to add corrosion resistance, strength or other useful properties. Other semi-fabrication steps at this stage also include rolling and extrusion. Rolling consists of heating the aluminium to a temperature of about 525 C while passing it through a hot and then cool rolling mill, forming the aluminium into thin sheets for eventual end product design. Extrusion process consists of heating and then forcing the aluminium into a steel die to the desired size for transport and further product design (IAI, 2023). In terms of recycling, the process of refining secondary aluminium, from recycling of scrap coming from either the manufacturing of aluminium containing finished products or from post-consumer waste, consists of collection, sorting, pre-treatment, remelting or refining process (European Aluminium, 2018; Georgitikis et al., 2021).

3.2 Overview of global and European supplying countries

The historical global production of bauxite has seen a marked increase for decades. As is displayed in Figure 2a, since the year 2000, the global output of bauxite ore has strongly increased, with an average annual growth rate of over 5%. In 2021, the total output reached more than 380 million tonnes of bauxite ore (Joint Research Centre, 2024). The world's main primary aluminium producing countries in terms of extraction and mining of bauxite ore are mostly constrained geologically to the sub- to tropical areas where these vast bauxite deposits are found. A map showing the global bauxite mine locations is displayed in Figure 3.

Almost 85% of the world's bauxite is coming from five countries: Australia (27.2%), Guinea (23%), China (18%), Brazil (9.5%), and Indonesia (6.8%), with the remaining coming mostly from India, Russia, Jamaica, Saudi Arabia, Kazakhstan, and Vietnam (USGS, 2024a). More than 20 countries are currently active in mining substantial quantities of bauxite for the global market (USGS, 2024a).

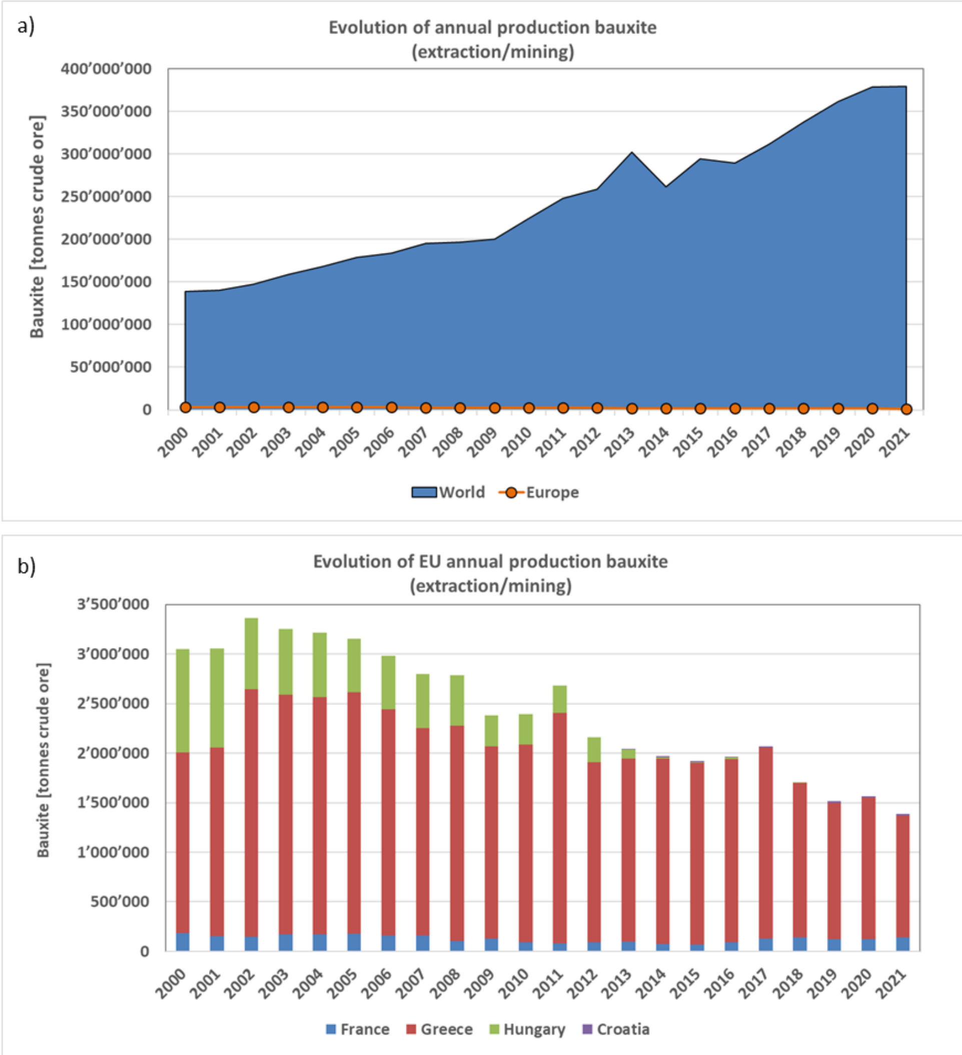


Figure 2. Annual a.) global and b.) European production for bauxite (extraction and mining) in the 21st century. Production reported in tonnes of crude ore. Note: change in y-scale between a) and b) shows that European extraction is a small share of the global total. Source: Joint Research Centre, 2024.

In contrast, over that same time span, European extraction of bauxite saw a steady decline, by an average of over 3% per year (see Figure 2b). European bauxite output has been dominated by extraction from Greece. In terms of its contribution to the global market, the European Union extracts only about 0.4% of the global bauxite supply, with the majority coming mostly from Greece, at an average (2016-2020) of about 1, 628 thousand tonnes (kt) a year, with minor supplies coming from France (about 115 kt), Croatia (12 kt), and Hungary (4 kt; average from 2016-2018; no reported output after 2018) (Joint Research Centre, 2024; SCRREEN Project, 2020a). However, recent acquisitions and investments are currently being made in the Greece mining sector to secure fully integrated bauxite mining, alumina and primary aluminium production in Europe (The National Herald, 2024; Metlen Energy & Metals, 2024). Furthermore, the largest aluminium mining company in Greece has aspirations for green and sustainable aluminium production, with commitments that by 2030, its primary aluminium refinery and smelter will be using only renewable energy sources for its operations (Metlen Energy & Metals, 2021).

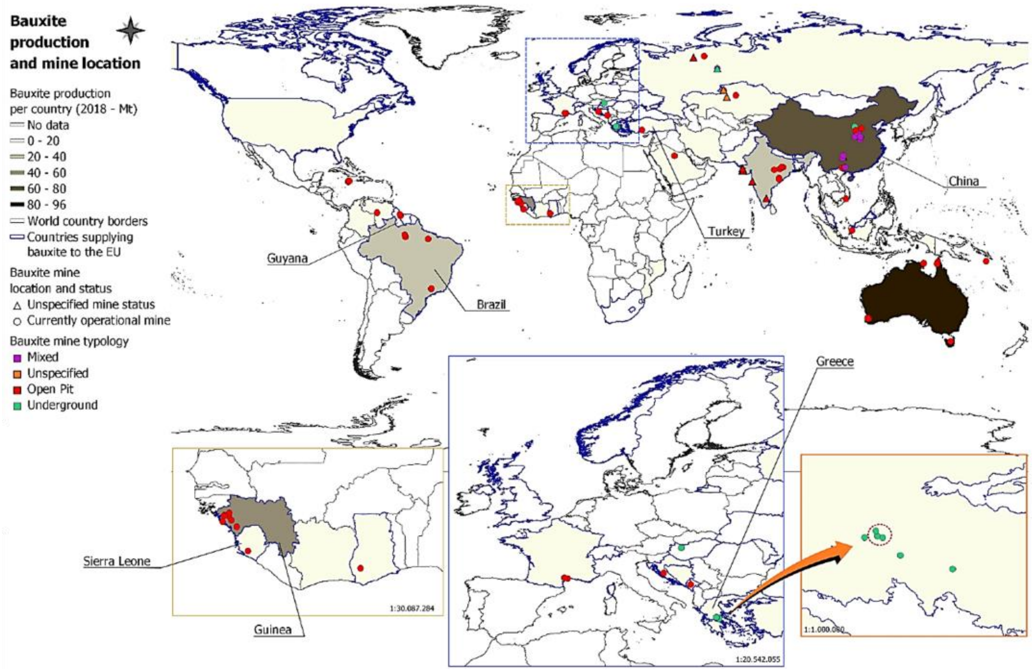


Figure 3. Global bauxite mine locations modified after (Georgitikis et al., 2021). Country shading displays bauxite production for the year 2018 (in Mt), point colour represents mine extraction type and shape of point represents operational status of mine (as of 2021).

As of 2023, it has been estimated that the world's bauxite resources are between 55 and 75 billion tons, with the majority of that found in Africa and Oceania followed by South America, the Caribbean and Asia (USGS, 2024a). Figure 4 the largest known bauxite reserves are in Guinea, with an estimated 7.4 billion tonnes of ore remaining, while Australia reserves are estimated at over 3.5 billion tonnes (USGS, 2024a). The EU also has reserves of bauxite ore, but in much smaller estimated volumes than elsewhere. In fact, no country in the EU even ranks in the top 10 countries in terms of estimated reserves (Figure 4). What reserves are present are deposits found in France (exact estimated reserves unknown), Greece with estimated reserves of 250 million tonnes, Romania with estimated reserves of 2.5 million tonnes and Italy at a small estimate of reserves of 1 million tonnes (SCRREEN Project, 2020a).

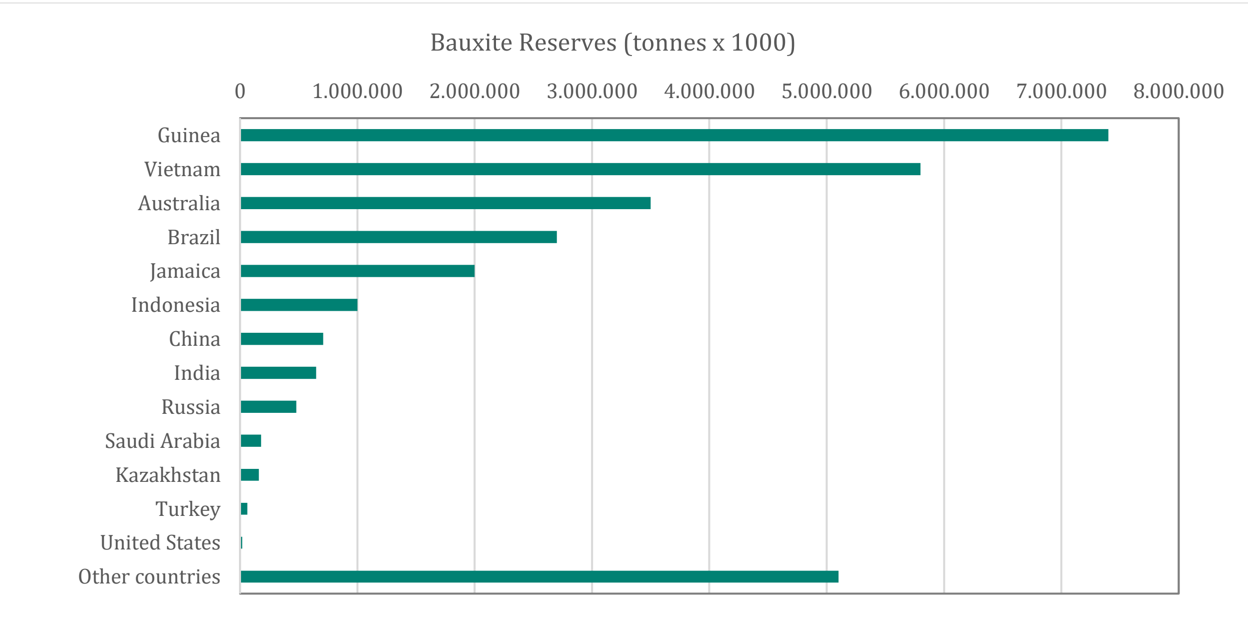


Figure 4. Global bauxite reserves in million tons (Mt) listed by country. Source: USGS, 2024a.

Just as the demand for bauxite extraction has grown over the last decade, so has the production of both alumina and primary aluminium. The global production of alumina since 2000 has seen an average increase of about 5% per year, with alumina production reaching over 140 million tonnes in 2021. The five largest alumina producing countries in 2021 were China (55.1%), Australia (14.7%), Brazil (7.9%), India (5.2%) and the European Union (4.4%). For the year 2021, alumina refinery annual capacity in the EU from the largest producers were Ireland (1'878 thousand tonnes(kt)), Spain (1'536 kt), Germany (1'050 kt), Greece (720 kt, France (500 kt) and Romania (498 kt) (Joint Research Centre, 2024).

Similarly, primary aluminium saw a similar rate of increase and production reached over million tonnes Al in that same year (Joint Research Centre, 2024). If these data are also broken down by country, the top producers of primary aluminium are China (56.9%), India (5.9%), Russia (5.8%), Canada (4.6%), and the United Arab Emirates (3.8%). The EU ranked 6th with 2.9% of the global primary aluminium production in 2021. It is important to note that in that same year, the majority of countries active in the extraction and processing value chain did not possess the capability to be self-sufficient by having both in-country extraction, and alumina and primary aluminium processing activities. This is displayed in Figure 5 with the countries of origin for the largest producers in 2021 (Joint Research Centre, 2024). For the year 2021, primary aluminium capacity in the EU from the largest producers were Norway (1'419 kt), Iceland (729 kt), Germany (509 kt), France (430 kt), Romania (293 kt), Spain (190 kt), Greece (169 kt), Slovakia (163 kt), Sweden (124 kt), and the Netherlands (49 kt) (Joint Research Centre, 2024; Idoine et al., 2024).

It is well known that the production process generates the majority of the environmental impacts. In China, the electricity used to power the aluminium industry relies heavily on coal-fired powerplants. Some recent estimates found that in Chinese production, approximately 15.9 tonnes CO_2 are emitted per tonne of aluminium produced, with the majority being produced during the Hall-Héroult process followed by that of alumina production (Peng et al., 2022). This value is similar to the global average of 16.1 tonnes CO_2 per tonne of aluminium (European Aluminium, 2024a)

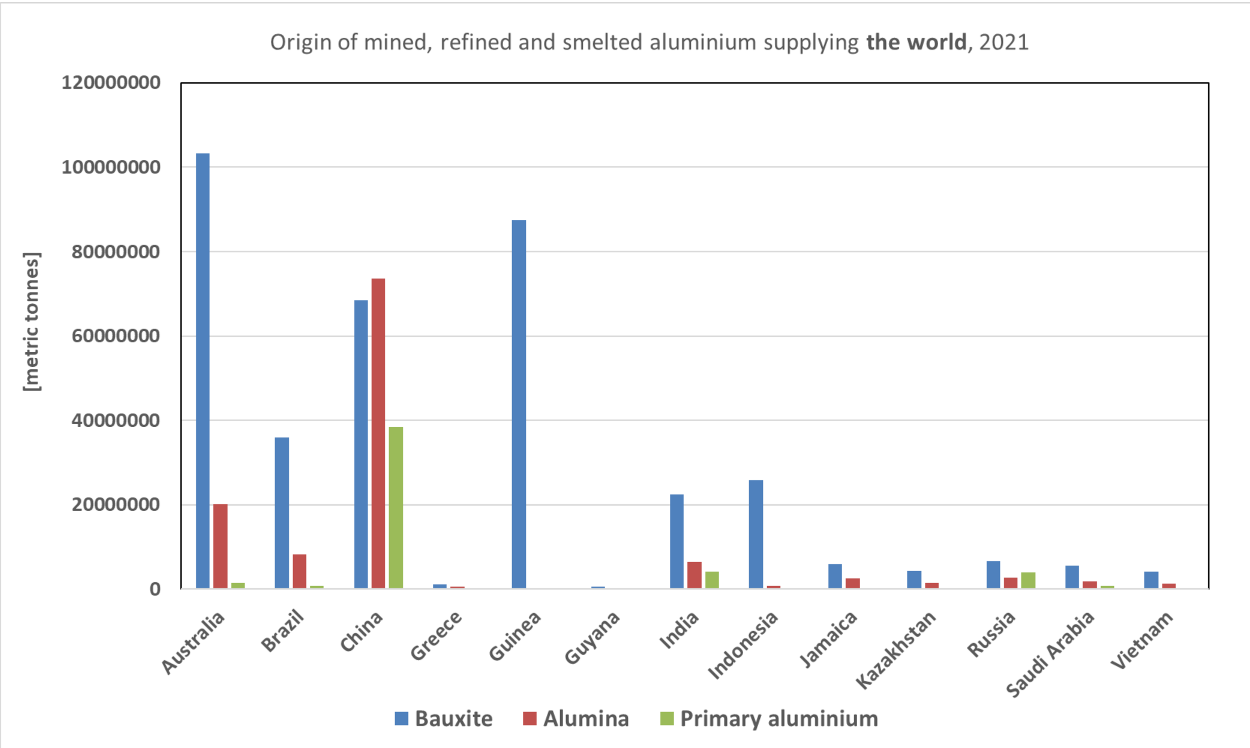


Figure 5. Countries of origin for the largest bauxite extraction, alumina and primary aluminium production and respective production (tonnes) supplying the world in 2021 (Joint Research Centre, 2024)

The EU has a smaller but significant capacity for processing alumina and refining aluminium. According to the European Aluminium, a member-based industry organization, Europe has over 600 processing plants across continental Europe, ranging from raw materials, processing and semi-fabrication. This also includes a considerable number of world class aluminium recycling facilities. As is displayed in Figure 10, there are approximately 8 alumina- and 27 primary aluminium production facilities, with significantly more recycling facilities (European Aluminium, 2024a). Given this, Europe is still struggling to meet the demand of aluminium and is increasingly relying on aluminium imports. This is deemed by European Aluminium to be due to unfair trade arrangements and the energy crisis caused by the war in Ukraine (European Aluminium, 2024a).

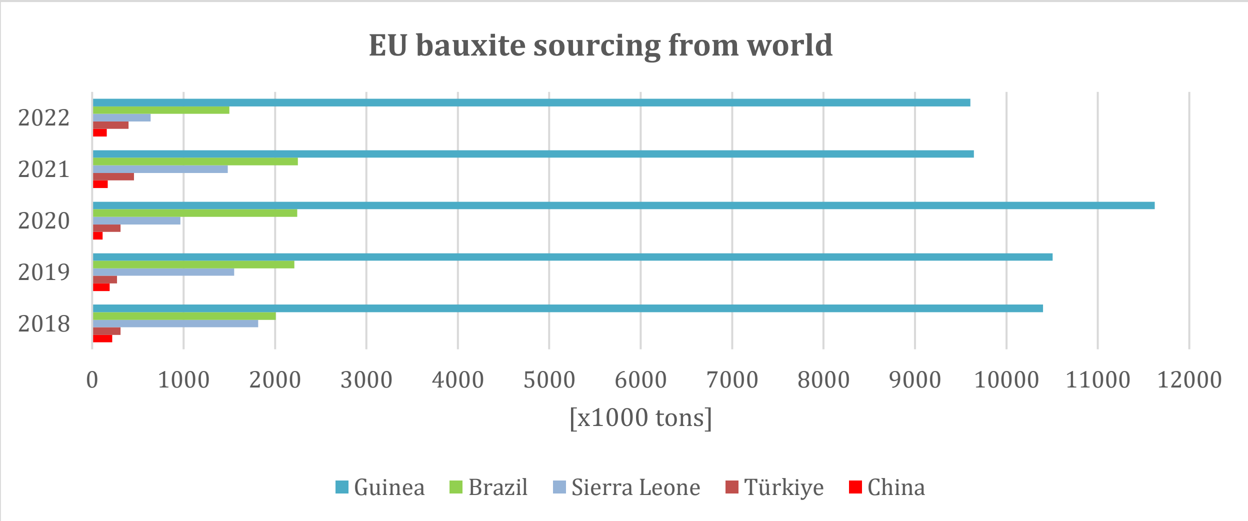


Figure 6. Countries from which the EU sources bauxite. Source: Joint Research Centre, 2024

Currently the EU's supply of bauxite ore (extracted raw material) is largely dominated by Guinea (Figure 6). Although Guinea represents close to 70% of the EU's supply in bauxite, other countries such as Brazil (10% of total supply) or Greece (8% of total supply), represent an important source for the EU. The supply of domestic bauxite that is utilized by the EU is shown in Figure 7. As can be seen, this is a small percentage as compared to other non-EU countries.

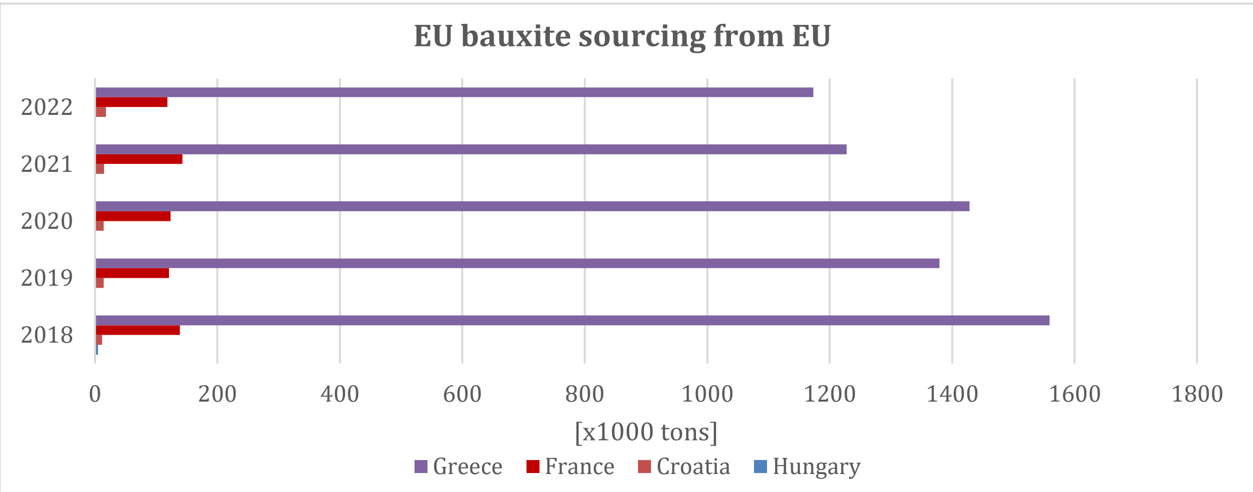


Figure 7. Amount of domestic bauxite the EU utilizes, by year, Source: Joint Research Centre, 2024

The primary aluminium (after smelting process) that is supplied to the EU comes from a very diverse source of countries, worldwide and in the EU. The most important source comes from Russia which accounts for 13% of the supply, followed by Mozambique (13%), India (11%), Iceland (9%) and France (9%). Figure 8 and Figure 9 show the supplying countries (non-EU countries and EU countries) of refined aluminium for the EU. In 2022, EU countries supplied 30% of the total primary aluminium supplied to the EU. This number reaches close to 40% when including Iceland. Although there is a very high diversity of supplying countries, this shows that the EU remains strongly dependant on countries outside of Europe for its supply in primary aluminium.

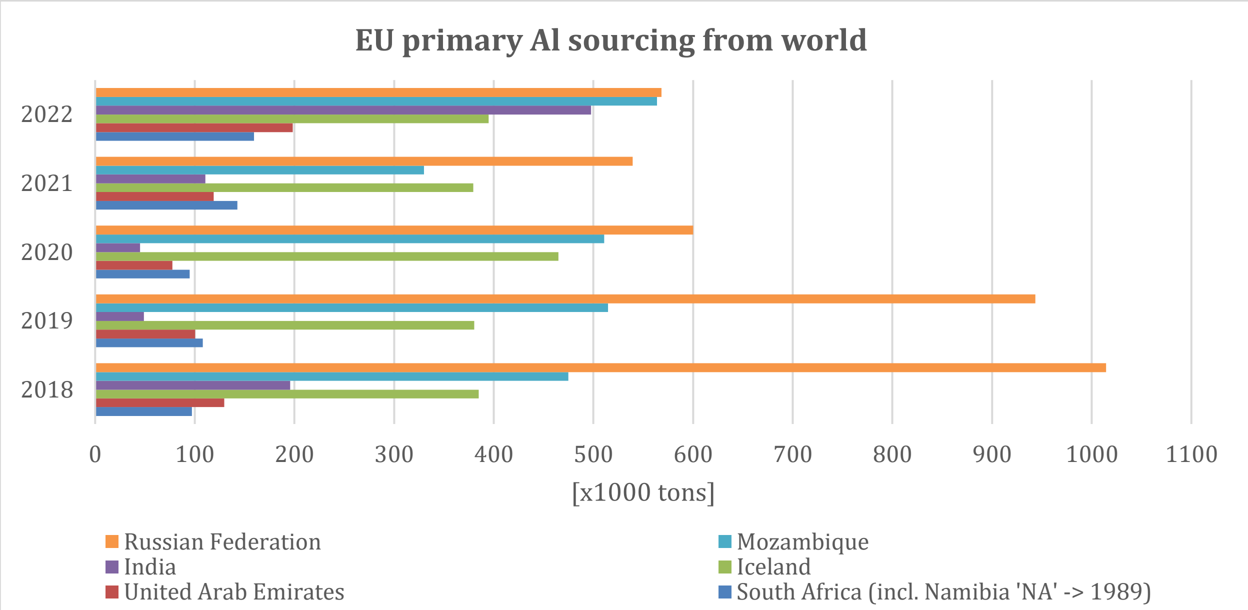


Figure 8. Non-EU Countries supplying the EU with refined aluminium. Source: Joint Research Centre, 2024.

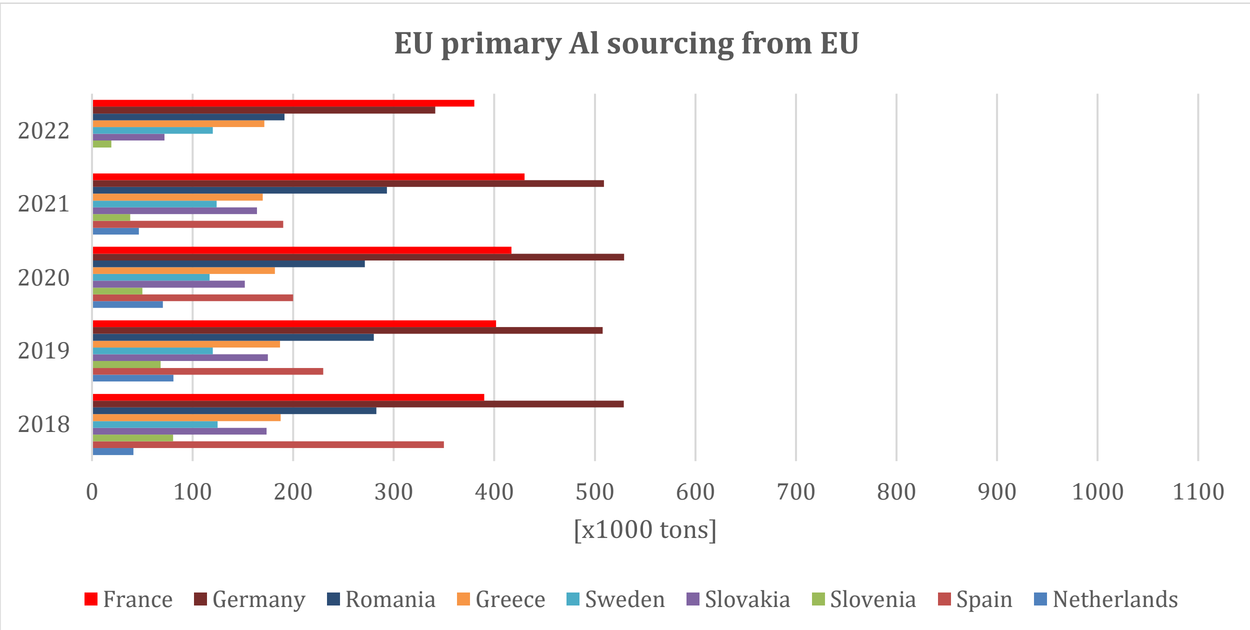


Figure 9. Non-EU Countries supplying the EU with refined aluminium. Source: Joint Research Centre, 2024.

Europe's aluminium production process emits a significantly lower quantities of CO_2, at 6.8 CO_2 per kg of aluminium produced (European Aluminium, 2024a). Low carbon emissions aluminium production exists in the European value chain. For example, Norway and Iceland are the EU's largest primary aluminium producing countries (Figure 10). These processing plants reportedly all utilize renewable energy for electricity production, greatly reducing the European and global CO_2 emissions from aluminium processing (Saevarsdottir et al., 2020).

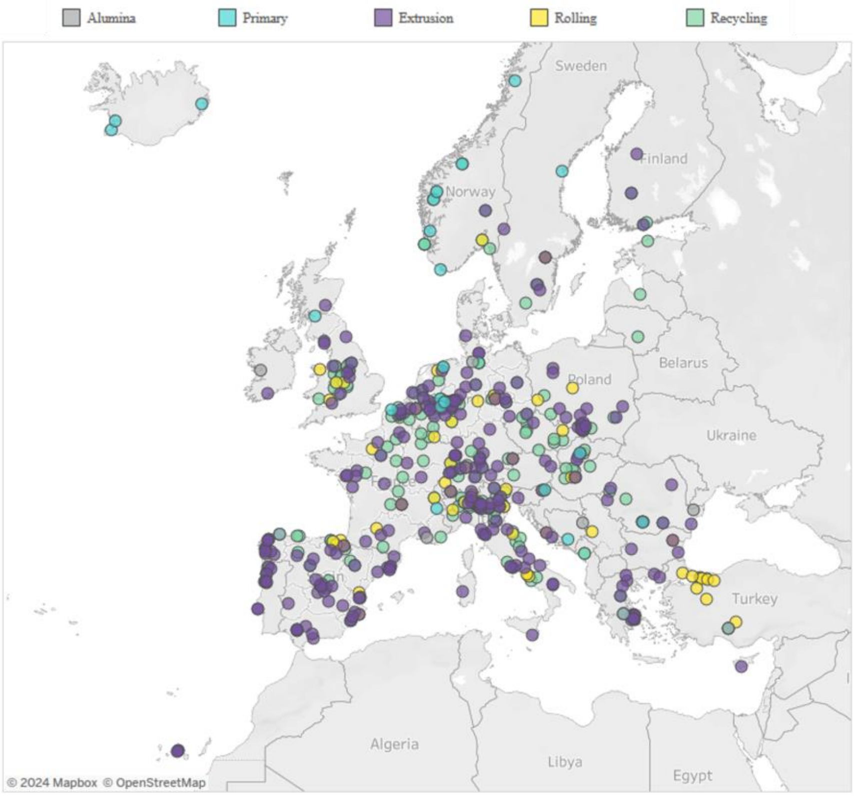


Figure 10. Map of Europe showing the approximate locations and type of aluminium processing facility (European Aluminium, 2024a).

As shown in Figure 11, the demand for aluminium is expected to significantly increase. The EU recently recognized the importance of the metal to the green energy transition by including it on the most recent critical raw materials list. This decision was reportedly not just a reflection of the criticality of aluminium but also on Europe's increasingly uncertain situation with its aluminium supply (Home, 2023). A report in 2022 found that by just the end of this decade, the aluminium sector will need to produce an additional 33 Mt to meet this anticipated demand (European Aluminium, 2019). The report also found that the demand will be coming from mostly the transportation sector, with the increasing need from of electric vehicle (eV) mobility of 55% by 2050 (see Figure 11a). Other research estimates have derived similar percentages in demand increases by the transportation sector (Billy and Müller, 2023). Another report found that an important growing sector where aluminium will be in high demand is in energy technologies (see Figure 11b), specifically a growing demand coming from the solar sector (Hund et al., 2020). The authors determined that aluminium demand from solar PVs is 119% greater than the 2 degrees warming baseline scenario (Hund et al., 2020).

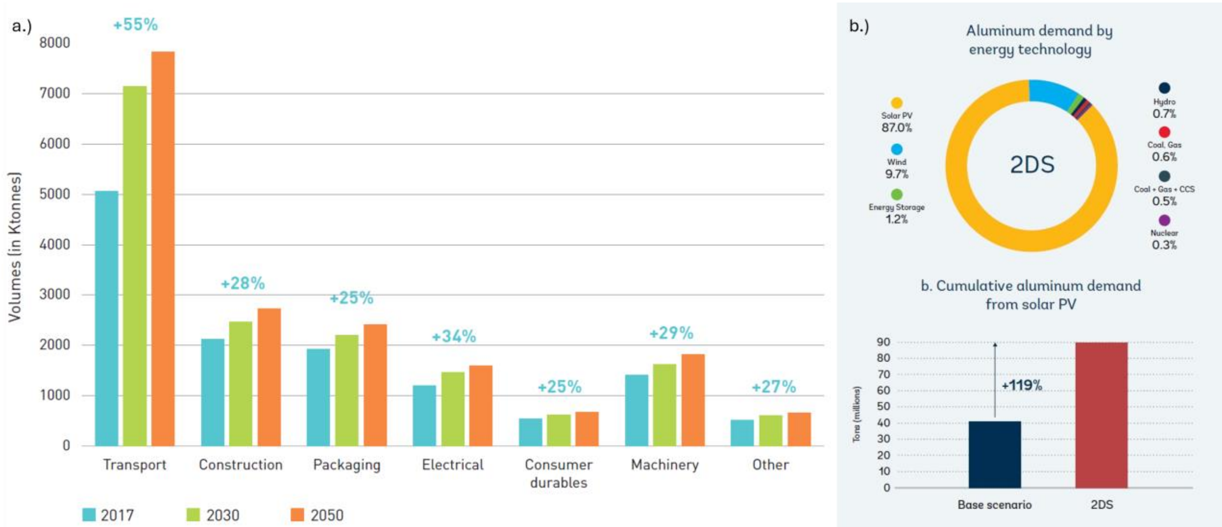


Figure 11. a.) Aluminium demand in 2017 and forecasts for 2030 and 2050 by sector on the European market (European Aluminium, 2019) and b.) Aluminium demand in various energy technology sectors (Hund et al., 2020).

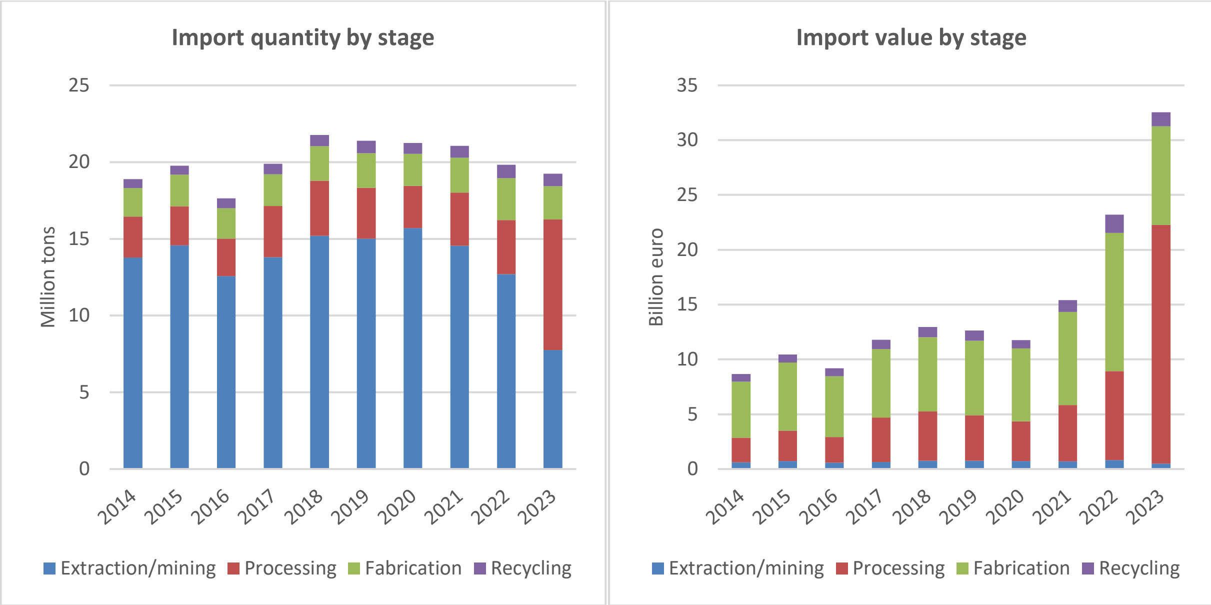
Recycling will play an important role in alleviating some of the demand of importing primary aluminium into Europe. Currently, Europe has one of the highest aluminium recycling rates of any material and a recent report showed that recycling of aluminium beverage cans in 2021 reached a record level of 76% in the EU block (Metal Packaging Europe and European Aluminium, 2024). Indeed, it has been estimated that by 2020 for European demand, there will an equal share of aluminium coming from recycling as from primary sources, provided that there continues to be policies supporting recycling (European Aluminium, 2019). Such policies like the EU Critical Raw Materials Act, with its benchmark stating that by 2030, at least 25% of annual consumption of critical raw materials must come from recycling sources, will help to ensure Europe stays on its recycling targets (European Commission, 2024b).

3.3 EU trade structure and dynamics

The value chain of aluminium includes a variety of product codes at the different stages (see Annex B). Therefore, this section first provides an overall picture for aggregate aluminium trade of the EU in the whole value chain and then looks at changing trends in trade for major stages (extraction, processing, fabrication, recycling)[8].

The changing role of these stages within the total trade over the last decade is illustrated in Figure 12. Products of aluminium at the extraction stage dominated import of the EU between 2014 and 2022, but in 2023 the products at the processing stage gained the dominant share in quantities. It is too early to say whether this can be a structural change in trade composition, or it is specific to the market conditions of that year. The dominant share of the processing stage gained in total import value in both 2022 and even more 2023 also depends on the higher prices (higher value added) of processed products (see Annex D).

[8] Detailed definitions for the stages and the relevant trade codes can be found in Georgitzikis, 2023, and Annex B of this report.



Notes: product codes of the CN8 classifications are reported in Annex B. Totals do not take into account of heterogeneous aluminium content across different product codes.

Figure 12. EU import of aluminium products by stage. Source: ETC-CE elaboration on COMEXT Eurostat data.

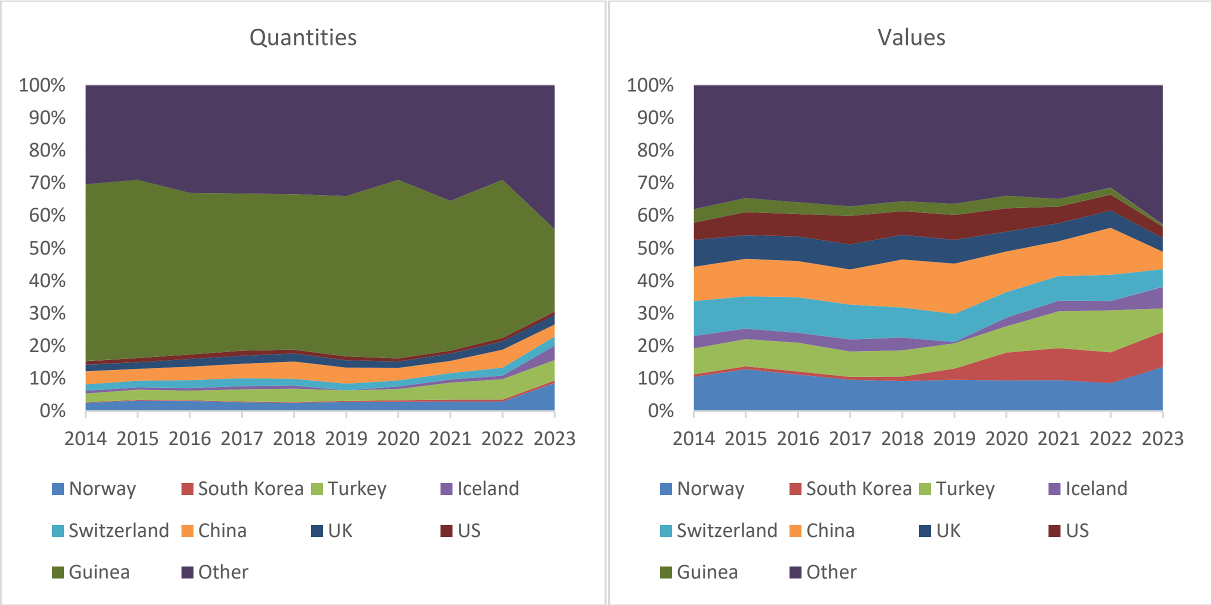
While the quantities of import oscillated along an overall stable trend in the last decade, prices (unit values of import) started to increase from 2020, in a way that in 2022 and 2023 the cost of aluminium import into the EU increased significantly, up to doubling with respect to 2021. From Figure 12 it can also be noted that a high jump in unit values of import may have had a role in the decrease of imported quantities of aluminium especially in 2023. This limited evidence is not sufficient to claim that there is a certain degree of demand (import) elasticity to prices for aluminium.

As part of this analysis, the ratio of average prices from 2021–2023 to those from 2014–2020 was calculated for aluminium (see Annex E for more details). The results indicate that the ratio decreases with the level of processing of the product (product codes) in a very regular way. This suggest that the early stages of production suffered the major jumps of prices at import in the EU between 2021 and 2023.

In terms of major trade partners for all product codes, Figure 13 shows that Guinea is the dominating supplier in quantities of the EU, followed China, Turkey and, more recently, Norway. In recent years, the share of Guinea is decreasing, and it is not fully compensated by growth of the other three main suppliers. This may depend on the shift towards products in the processing stage as Guinea is a major supplier in the extraction phase (as explained in section 3.2).[9]

It is interesting to look at the monetary value of import in Figure 13, as the ranking changes substantially compared to quantities. Turkey, China, Norway and Switzerland dominate the scene, even though the role played by China declined markedly recently, while Guinea's share is very small [9]. Also, South Korea recently emerged as a very important partner for sourcing aluminium products. This picture may be explained by composition effects and the progressive shift of EU aluminium import towards more processed products, which implies a recombination of suppliers and higher unit values at import.

[9] The case of Guinea is paradigmatic: it represents the main single supplier of aluminium products in terms of quantities but it just account for a very small share of the value of EU import of aluminium products. As it is shown in Figure 39, Guinea is responsible for more than half of both quantity and value of EU import in the aluminium extraction phase, where unitary prices (per kg) are much lower than in later stages.



Notes: product codes of the CN8 classifications are reported in Annex B. Totals do not take into account of heterogeneous aluminium content across different product codes.

Figure 13. Main trade partners for aluminium (all value chain stages). (Source: ETC-CE elaboration on COMEXT Eurostat data).

The trends in the aggregate aluminium trade can be better understood by looking at trade at the different stages of the value chain. The results are commented here while figures are reported in Annex D.

At the extraction stage, the EU import (in value) remained stable until 2020, and then decreased significantly (again, in value) even as prices increased. The dominant supplier in quantities in 2023 was Guinea followed by Brazil, and the same countries dominate imports in value (Figure 40 in Annex D).

At the processing stage, there is an increasing trend of import in quantities, although with oscillations, with a sharp increase in quantities, prices and then in total import value in 2023. The dominating supplier in quantities in 2023 is Norway, while Jamaica, one of the main suppliers until 2020, almost disappeared in 2023. In terms of total value, the dominant suppliers in 2023 were Norway and South Korea, that substituted for the US and Japan in the last few years, with a sharp increase of their share. It is clear that the import mix of the EU for processing product codes include countries with large export to the EU at low prices (like Jamaica) and suppliers that export relatively small quantities at very high prices. This combination can be the result of composition effects within the stage processing depicted by the product codes.

In the fabrication stage, import quantities and values were stable in the last decade, with a spike in both quantities and prices (and, consequently, values) in year 2022. Import in quantities and values is dominated by three countries: Turkey, Switzerland and China.

In the case of recycling product codes (waste) there has been a good increase in quantities with a substantial growth in prices between 2020 and 2022. The dominating suppliers are, with large oscillations, the UK, Switzerland and Turkey.

All in all, it seems that the EU has moved its trade structure towards the processing stage, possibly substituting for import of fabricated products through domestic supply. It increased also the import of recycling related products for feeding its domestic aluminium recycling industry

3.4 Environmental impacts of aluminium production

Aluminium production is a significant industrial activity with substantial environmental impacts, particularly when it comes to greenhouse gas (GHG) emissions, energy consumption and mining waste management. As highlighted in section 3.1, the production process includes multiple stages: bauxite mining, alumina refining and aluminium smelting and each stage contributes differently to the overall environmental burden.

Electricity consumption and Greenhouse Gas Emissions

One of the most critical environmental issues in aluminium production is its high electricity consumption, particularly during smelting process, where it significantly contributes to environmental emissions (Farjana et al., 2019). The electrolysis process in aluminium smelting is the most emission-intensive step of aluminium production, with a requirement of approximately 15 MWh per tonne of metal produced. This stage therefore accounts for 61% of the total GHG emissions in the aluminium sector (Georgitikis et al., 2021).

The Bayer process (explained in section 3.1 above), used for refining of bauxite into alumina, also contributes significantly to GHG emissions, generating 19% of the total emissions for the aluminium industry. Bauxite mining, however, has a relatively minor role in GHG emissions compared to refining and smelting (Georgitikis et al., 2021).

Renewable Energy and Process Heat Reduction

In light of the above statements, switching to lower carbon emitting energy sources, such as photovoltaic and nuclear power, can significantly mitigate the environmental impacts of aluminium production (Farjana et al., 2019). In Europe, for instance hydropower is the primary electricity source for aluminium smelters (80% of the total electricity used in aluminium smelting) (Figure 14). However, in China, 88% of the electricity used for aluminium smelting comes from coal, and globally, this figure stands at 60% for coal (Georgitikis et al., 2021). Thus, the origin of the aluminium smelting can greatly reduce carbon footprint of aluminium production.

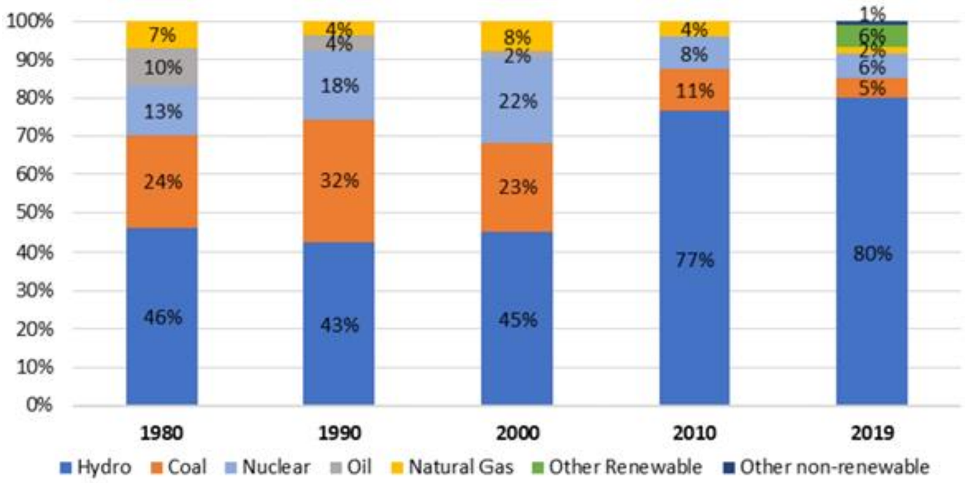


Figure 14. Evolution of the energy mix used in primary aluminium smelting in Europe. Source: Georgitikis et al., 2021.

Additionally, reducing process heat consumption in the Bayer process is crucial for lowering the environmental burden. The Bayer process is energy-intensive and optimising this process can lead to significant environmental benefits (Farjana et al., 2019).

Environmental impact of bauxite mining

Bauxite mining, although less impacting compared to the other steps of the value chain, still represents a step with notable environmental impacts. Bauxite deposits are typically stratified, horizontal, and shallow, requiring large areas of land to be dug up, often near nature-protected and tropical forest areas. This extensive land use impacts biodiversity and local communities (SCRREEN Project, 2020a).

Environmental impact of processing

Processing of bauxite ore also generates significant amounts of red mud, a byproduct of the Bayer process. The production of 1 tonne of alumina generates between 1 and 1.5 tonnes of red mud, which is considered hazardous due to its alkalinity (pH 10-13) and potential for environmental contamination (Liu and Naidu, 2014).

Life cycle assessment of the aluminium value chain

Based on a life cycle assessment study from (Luthin et al., 2021), which compares the impact of aluminium production in three different countries (Germany, China and Norway), it is clear that the main environmental impacts (for global warming potential (GWP), acidification potential (AP) and photochemical oxidant creation potential (POCP)) arise during the electrolysis part. Mining of bauxite and ingot casting only contribute marginally to the environmental impact categories. The results show that the electricity mix of the country can significantly impact the overall environmental impact meaning this is where lies the biggest potential of reduction of environmental burden from the industry. Indeed, countries with a sustainable electrolysis electricity mix (like Norway which has 96% electricity production from hydropower) has a much lower environmental impact than countries like China or Germany (which respectively have 69% and 42% electricity production from coal). Figure 15 to Figure 17 below show the different results for each environmental impact category, between different countries.

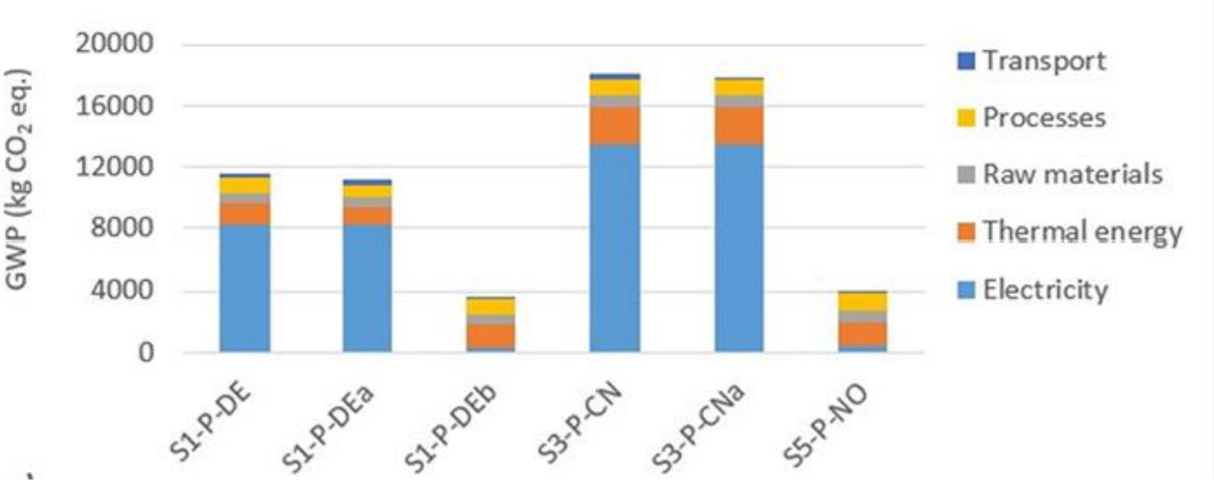


Figure 15. Impact of primary aluminium production on GWP (kgCO_2-Eq). S1PDE (Germany with the current electricity mix used for electrolysis); S1PDEa (Germany with no import of alumina from Jamaica); S1PDEb (Germany with a scenario where 100% wind power energy is used for the electrolysis); S3PCN (China with the current electricity mix used for electrolysis). Source: Luthin et al. (2021).

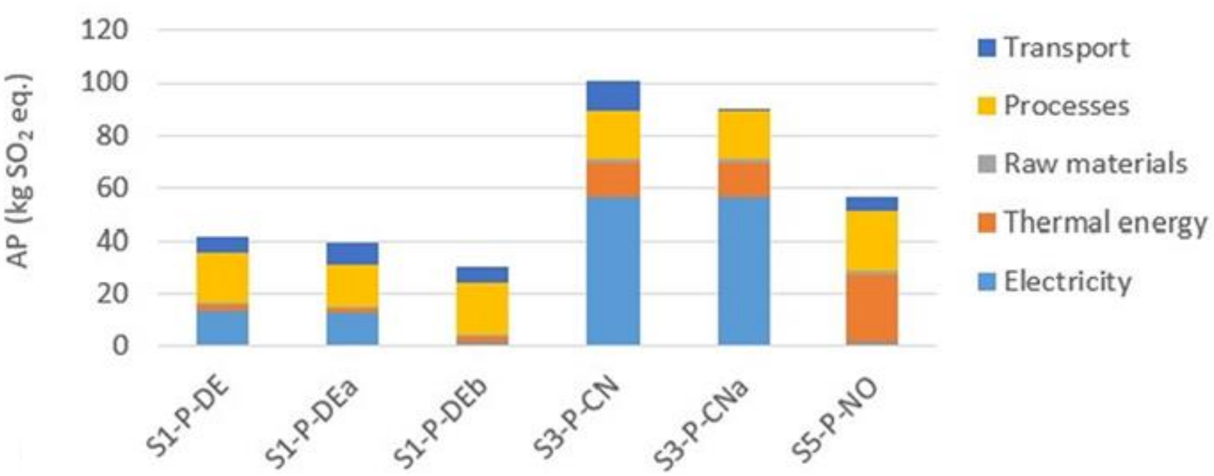


Figure 16. Impact of primary aluminium production on AP (kgSO2-Eq). Source: Luthin et al. (2021).

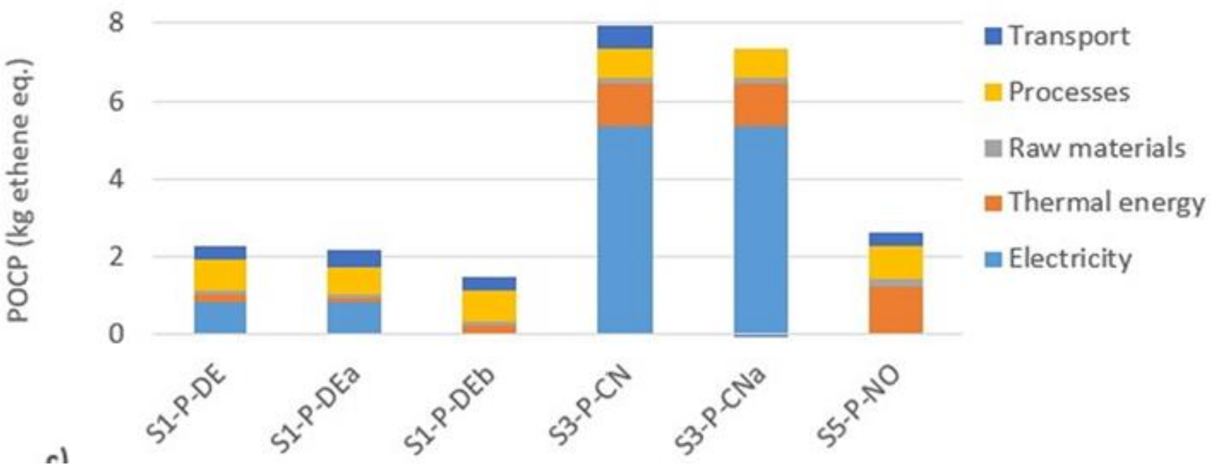


Figure 17. Impacts of primary aluminium production on POCP (kg ethene-Eq). Source: Luthin et al. (2021).

3.5 Environmental effects of a possible supply chain disruptions in short-, medium- and long-term

Short term (2024-2026): Change to an alternative supplier

The short-term scenario assumes that a part of the EU demand for aluminium shifts from one country to another. Because of the complexity of the value chains and the data availability, this scenario can be divided into (1) the change of supplying country for bauxite (extracted raw material) and (2) the change of exporting country for primary aluminium (smelted aluminium).

For the first part, this scenario assesses the environmental impact of switching the EU's bauxite supply from Guinea to Greece. As explained in section 2.4.2, Greece was selected as the best alternative country according to the multi-criteria analysis, reaching an overall score of 58/100. Greece's membership in the EU, EEA/EFTA, and Schengen area makes it a particularly appealing partner, despite its low ranking in bauxite reserves. Greece's strong performance in the WGI also contributed significantly to its overall score (see Annex H). Although Greece's production capacity cannot fully replace the supply of bauxite currently provided by Guinea to the EU, a partial shift is feasible. Guinea is currently the EU's largest supplier of bauxite (Figure 6).

According to section 3.4 the environmental hotspot due to bauxite mining is land-use and impact on biodiversity. In Greece, 90% of the mining operations take place underground, with limited impact on the land-use and deforestation (MiningGreece.com, 2024). In contrast, in Guinea, mines are open-casted, and techniques of drilling-blasting and scraping of the surface's soil destroy biodiversity and deforest some tropical forests. The use of water when mining bauxite is also an environmental impact of concern, especially in regions where water scarcity is high. In the case of Guinea, the overall water risk (based on the Water Risk Index) is much higher than in Greece, as shown in Figure 18.

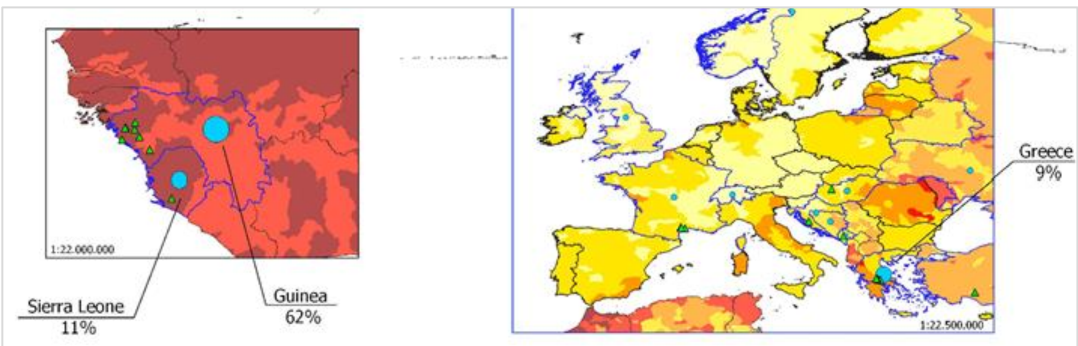


Figure 18. Water Risk Index weighted to mining activities and operating bauxite mines. Source: JRC elaboration, taken from (Georgitikis et al., 2021).

The second part of this short-term scenario assesses the environmental impact of switching the supply of primary aluminium from Russia and Mozambique (largest suppliers to the EU in 2022, see Figure 9 above) to France (largest EU supplying country in 2023, see Figure 8 above). For the comparison, the average data from Ecoinvent is used and grouped by geographical regions. For example, data for France will be based on the average for EU countries, and the data for Mozambique will come from the average for African countries. Maps depicting the countries included in the datasets can be found in Annex J.

To conduct this comparison, Ecoinvent data was used. The considered impact categories for primary aluminium production[10] are:

- Climate change – global warming potential (kg CO_2-Eq).
- Ecotoxicity to water, including freshwater, marine water and terrestrial water's ecotoxicity potential (kg 1,4-DCB-Eq).
- Ozone depletion – ozone depletion potential (kg CFC-11-Eq).

In terms of climate change potential (Figure 19), the production of 1kg of aluminium ingot (molten aluminium produced from the electrolytic process) emits around 7.3 kg CO_2-Eq in the EU (incl. France) but emits up to 15 kg CO_2-Eq in African countries (incl. Mozambique), which is 7.7 kg of CO_2-Eq more per kg of primary aluminium produced compared with France. The Russian production emits slightly more than 9 kg CO_2-Eq per kg of primary aluminum ingot produced, which is 2 kg of CO_2-Eq more, per kg of primary aluminium produced. Those important differences can be a result of the different processes used in the countries as well as the difference in energy source supplying the power grids.

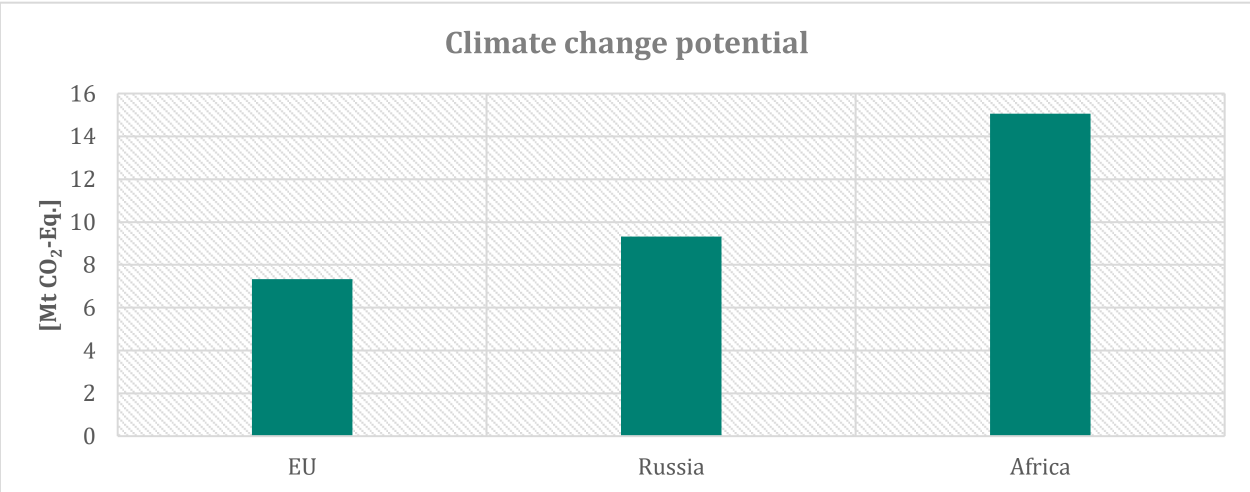


Figure 19. Climate change potential to produce 1kg of aluminium ingot in the EU, Russia and Africa. Source: Ecoinvent database, 2023

The potential pollution of water also varies between geographical areas (Figure 20). Once again, the EU has the lowest value in terms of potential ecotoxicity to water (12,15 kg 1,4-DCB-Eq). In all three regions, terrestrial waters are the most impacted by the aluminium activities.

[10] The product system chosen in Ecoinvent was: *Aluminium production, primary, ingot | aluminium, primary, ingot | APOS, S*

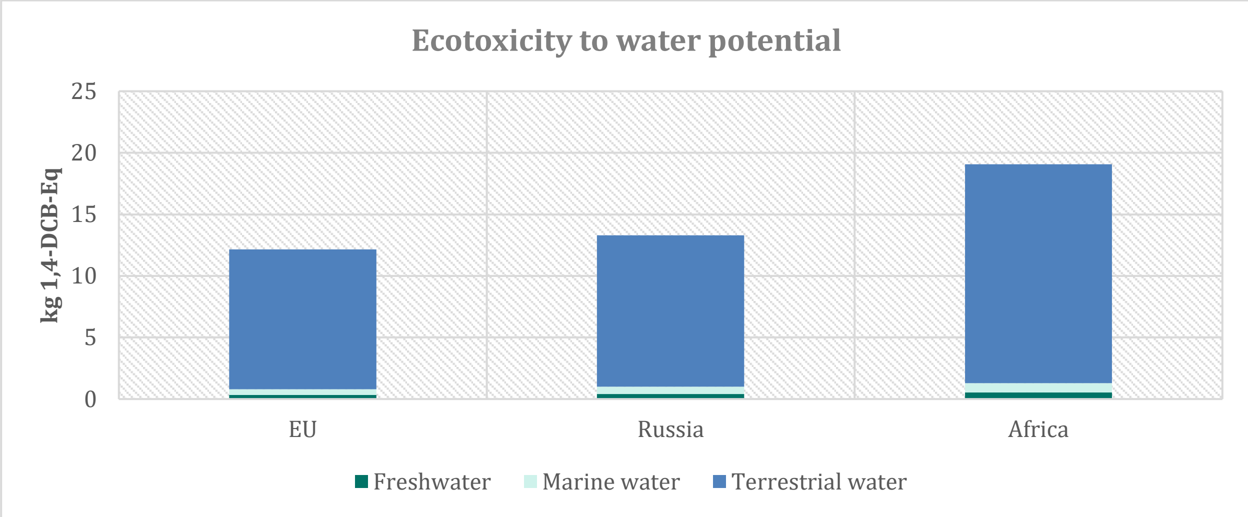


Figure 20. Potential of ecotoxicity to water to produce 1kg of aluminium ingot in the EU, Russia and Africa. Source: Ecoinvent database, 2023.

In terms of ozone depletion potential (Figure 21), EU countries have 12% less ozone depletion potential compared to Russia and 35% reduction compared with African countries.

Based on those observations, shifting the production of aluminum ingot from Russia and Mozambique to France could reduce the pressure on the environment. In France, currently, there are two sites which transform the alumina into primary aluminium. The sites have a cumulated capacity of 450,000 tons per year (Trimet, 2024; Aluminium Dunkerque, 2024; SCRREEN Project, 2020a). This represents 70,000 tons more than the current input of French primary aluminium into the EU supply mix. Assuming both sites located in France could increase by 70,000 tons their input in the EU's supply mix, this would reduce the needed input from other regions such as Russia or Mozambique.

With a reduction of 2kg of CO_2-Eq / kg of primary aluminium between Russia and France, a shift of 70,000 tons of production from Russia to France would translate in an avoided 140,000 tons of CO_2-Eq per year. A shift of 70,000 tons of production from Mozambique to France would translate in an avoided 540,000 tons of CO_2-Eq per year.

In terms of ecotoxicity to water, a shift of 70,000 tons from Russia to France would represent an avoided 70 million kg 1.4 DCB-Eq per year and a shift from Mozambique to France would avoid 420 million kg 1.4 DCB-Eq per year.

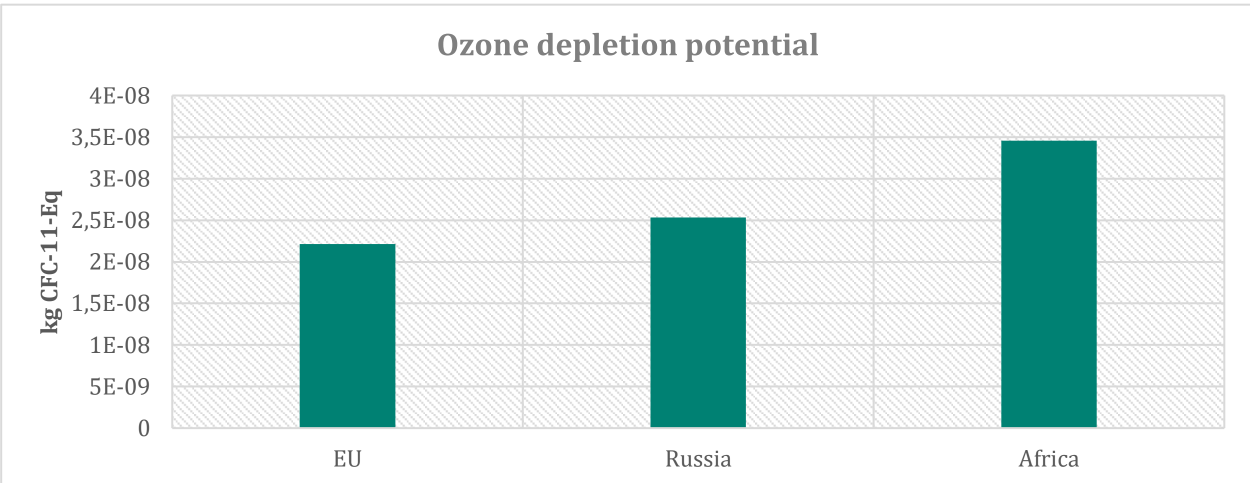


Figure 21. Ozone depletion potential to produce 1kg of aluminium ingot in the EU, Russia and Africa. Source: Ecoinvent database, 2023.

Finally, for the ozone depletion potential, a shift of supply of 70,000 tons from Russia to France would avoid the emission of 21 kg of CFC-11-Eq per year, and a shift from Mozambique to France would avoid the emission of 91 kg of CFC-11-Eq per year.

Medium Term (2026-2030): increase of recycling input

The great potential for GHG reduction in the aluminium sector lies in the recycling of this metal. Aluminium is easily recyclable and retains all its properties, while emitting much less CO_2. Many LCAs compare the environmental benefits of secondary aluminium compared to primary aluminium. The Aluminium Association (representing aluminium companies in North America) highlighted in a report the environmental benefits of secondary aluminium by comparing from a "cradle-to-gate" perspective, the energy demand of primary versus secondary aluminium. Their results show that recycling the metal saves up to 93% energy. This translates into a 94% reduction in carbon footprint (GHG)(Wang, 2022).

Other studies, such as the one conducted by Peng et al., 2022, also show a significant reduction in GHG emissions of recycled aluminium in comparison to primary aluminium. The authors of the study compare the emissions of primary versus secondary aluminium production of different regions in China (with different electricity mix). The conclusion is unequivocal as all the regions show reduced GHG emissions for secondary aluminium.

Figure 22 shows well that recycling processes emits half a tonne of CO_2-Eq which is 92% lower than the average European production (6.7 tonne CO_2-Eq/tonne al). This shows well how increasing the share of recycled aluminium can help reduce the emissions of the sector.

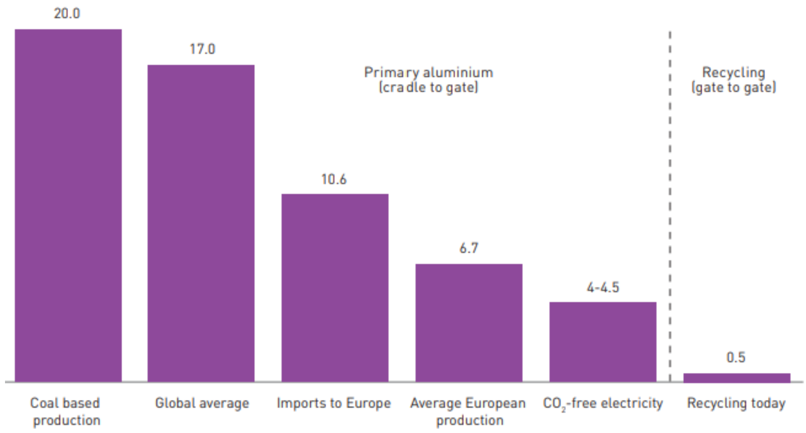


Figure 22. Greenhouse Gas emissions of primary aluminium production and recycling process (tonne of CO_2-Eq / tonne of aluminium production). Source: European Aluminium, 2022

In order to meet its demand, the EU has to rely on both primary and recycled aluminium. This is because the overall consumption of aluminium keeps increasing and because the average in use time of aluminium products is 50 years in construction and 15 years in transportation (making the material unavailable for long periods of time). In 2022, the recycling rates for aluminium were over 90% for the automotive and building sectors and 75% for the aluminium cans. Although these recycling shares are very high (among the highest compared to other materials), there is still some room for improvement to increase even further the input of recycled aluminium in the EU. According to European Aluminium (2022), recycled aluminium already represents 36% of aluminium metal supply in Europe and the amount available for recycling will more than double by 2050 where more than 50% of our needs in aluminium could be supplied by recycled material (European Aluminium, 2022). An important lever for further increasing the quantity of recycled aluminium in the EU's supply is by reducing the export of scrap aluminium. As highlighted in the European Aluminium's report (2022) the EU exports 1 million tonnes of aluminium scrap per year (mainly to Asia) which represents a significant loss for the European economy. Keeping the aluminium scrap and recycling processes within Europe would have significant economic and environmental benefits for Europe (European Aluminium, 2022).

Given the above results, recycling aluminium avoids the emission of 6.2 tonnes CO_2-Eq / tonne of aluminium produced. Assuming that the exported 1 million tonnes of aluminium stay in Europe and are injected in the European value chain (replacing 1 million tonnes of primary metal), this would avoid the emissions of 6.2 million tonnes of CO_2-Eq. per year.

In addition, if the recycling rates of aluminium cans reached 90% (instead of the current 75%), this could avoid the emissions of 706,000 tonnes of CO_2-Eq per year (assuming 114,000 tonnes of additional cans are collected each year) (Metal Packaging Europe and European Aluminium, 2024).

This medium-term scenario, coupled with the short-term scenario above could therefore avoid the emissions of 7.4 million tonnes of CO_2-Eq per year.

Long term (2030-2040) Increase in domestic mining

According to the USGS (2018), Greece holds 250 million tonnes of bauxite reserves, which makes it the largest exploitable bauxite deposit in the EU. However, Greece currently has a bauxite mining output of 1,8 million tonnes per year (USGS, 2018).

Increasing the mining output of Greece and increase the share of bauxite from Greece in the EU's supply can help reduce the environmental impacts of the sector. However, the amount by which Greece can increase its mining capacities remains unclear making it difficult to quantify the avoided environmental benefits of this scenario. There are currently very few other bauxite deposits identified in the EU. Bauxite deposits have been found in Romania and Italy, however the scale of those deposits remain practically unsignificant as they cumulate 3.5 million tonnes of bauxite (SCRREEN Project, 2020a).

Nevertheless, another important lever to minimise the impacts on the environment is by adopting substitutions or by reducing initial consumption of the metal. For example, because electricity networks need huge amount of aluminium, adoption of high-voltage direct current (HVDC) which only uses two cables, as opposed to an alternating current (AC) electricity network which uses three cables, could reduce the combined copper and aluminium demand by 15% by 2040[11] (IEA, 2021).

As it has been shown in the medium-term scenario, recycling has a huge potential to reduce the carbon footprint of the aluminium sector.

Summary of findings (aluminium) in terms of CO_2 emissions

Figure 23 shows the cumulated avoided emissions of CO_2 per year in a situation where the short-term (shift from Mozambique to France) and medium-term scenario (explained above) were implemented. Due to the lack of quantification of CO_2 emissions in the long-term scenario, this scenario has not been added in the Figure 23. This means that the total potential emissions avoided could increase further.

Already with a short-term and medium-term scenario implemented, the reduction of emissions could amount to 7.4 million tonnes of CO_2-Eq. per year.

[11] In a scenario of sustainable development to reach the Paris Agreement goals.

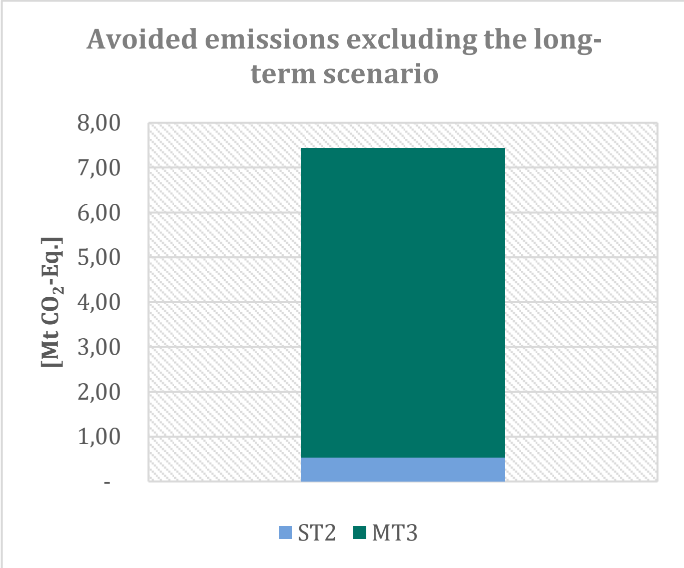


Figure 23. Cumulated avoided CO_2-Eq emissions for the aluminium sector, per year, considering the short-term scenario (ST2: shift from Mozambique to France) and medium-term scenario (MT3: increase in recycled aluminium input)

4 Case study 2: Lithium potential supply disruptions and environmental impacts

4.1 Lithium supply chain

The properties and applications of lithium are reported in Annex F. The extraction and processing stages and technologies for lithium can vary significantly depending on the type of lithium ore deposit, impurities and the local context (Khakmardan et al., 2023). The main end-products from the processing stages are lithium carbonates, lithium chloride (LiCl), lithium hydroxide (LiOH) and other compounds such as lithium bromide and butyllithium (Matos et al., 2020b).

For continental lithium brine deposits, the most commonly used processing method is the evaporitic technology, also known as the lime soda evaporation process (Meng et al., 2019), which relies on open air evaporation to concentrate the brine. The main stages for this processing method consist of concentration by evaporation, impurity removal and precipitation by carbonation. As shown in Figure 24Figure , in this process, brines are pumped to open air ponds, in which over 90% of original water is lost through solar evaporation. Concentrated brines are then transferred to a refining plant for removal of impurities, followed by precipitation of lithium carbonate via the addition of sodium carbonate (Na_2CO_3). Freshwater is needed at multiple steps of the process, including to dissolve CaO (needed to precipitate Mg^{2+}) and Na_2CO_3, in the scrubbing of organic solvents (used for the removal of borates), for washing Li_2CO_3 crystals and for steam generation. Over 90% of the salts other than lithium chloride (LiCl) in the original brines spontaneously crystallize in the ponds and are considered as waste (Vera et al., 2023). The processing steps and precipitation agents may vary depending on the type of brine and its impurities. This process has relatively low electricity consumption since the initial step uses solar evaporation (Alessia et al., 2021). However, brine mining is criticized for its intensive water consumption, particularly due to the exploitation of both brine and fresh water aquifers (Vera et al., 2023). It is estimated that 100-800 m^3 of water will be used to extract one tonne of lithium carbonate. Other challenges associated with the evaporation method include presence of other ions with similar chemical characteristics, its lengthy process (between 10-24 months), high production cost (Vera et al., 2023; Farahbakhsh et al., 2024).

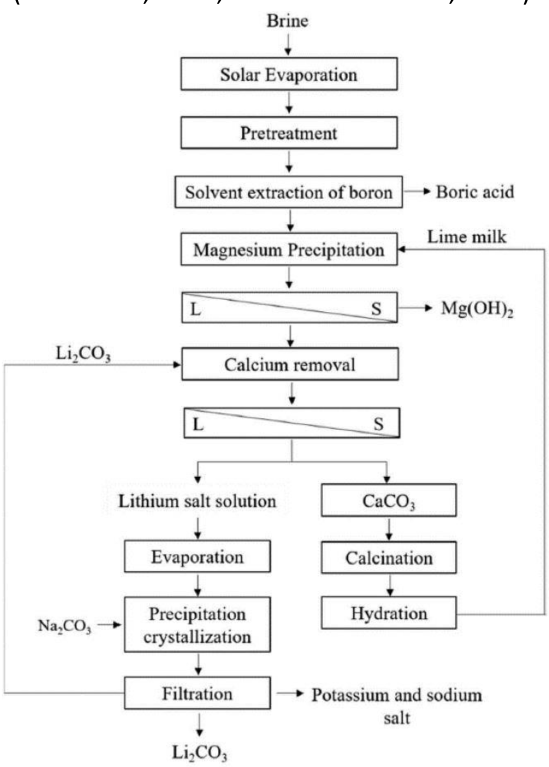


Figure 24. General steps for the production of lithium carbonate from continental brines. Source: (Meng et al., 2019)

To overcome the challenges associated with the evaporation techniques explained above other extraction technologies have been proposed and developed in the recent years. These methods, collectively known as Direct Lithium Extraction (DLE) methods, are claimed to be more environmentally friendly, cost effective (Farahbakhsh et al., 2024; IEA, 2024; Vera et al., 2023) and effective for less concentrated lithium brines such as geothermal brines and oilfield brines (Vera et al., 2023; Murphy and Haji, 2022). The common approach of these technologies is based on selective extraction of lithium ions directly from lithium-bearing solutions through various methods such as ion exchange, adsorption, membrane separation, solvent extraction, direct carbonation and electrochemical processes with their own advantages and disadvantages (Vera et al., 2023; Farahbakhsh et al., 2024). While most of these technologies have been implemented for decades in chemical engineering process, their application for extraction of lithium from brines are at in most cases at laboratory level and there are ongoing studies to make the necessary adaptations (Vera et al., 2023; Farahbakhsh et al., 2024).

In hard rock deposits including pegmatites and lithium bearing clays, the process for production of lithium hydroxide LiOH and Li_2CO_3 is more complex than the brine mining. The complexity of the process can increase significantly when these deposits are associated with other valuable materials such as tin and tantalum, where extraction of these byproducts would necessitate additional operations (Tadesse et al., 2019). The general steps for processing of pegmatites with spodumene and petalite minerals and lithium bearing clays containing lepidolite and zinnwaldite are shown in Figure 25 (Meng et al., 2019). The general steps after mining include beneficiation, calcination, leaching, filtration, purification. The beneficiation process could include various stages such as gravity separation, magnetic separation and floatation and sorting (Tadesse et al., 2019).

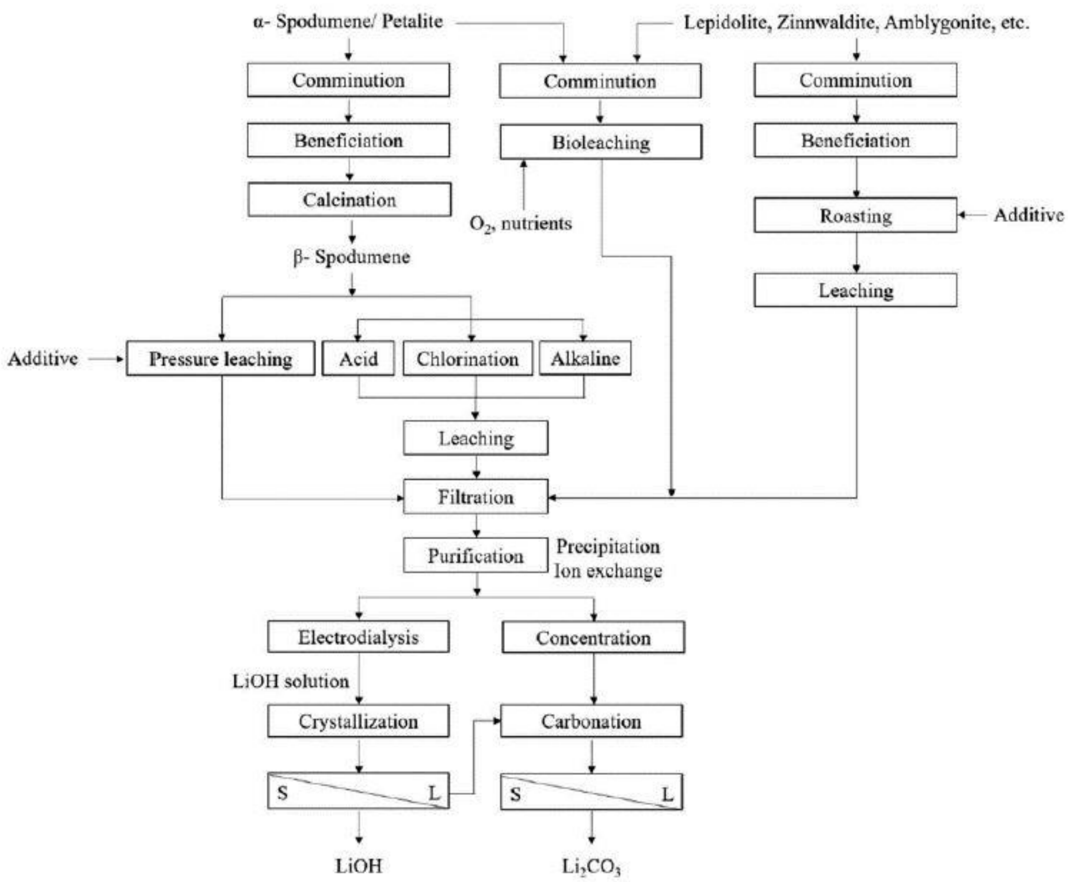


Figure 25. General steps to produce lithium carbonate and lithium hydroxide from mineral ores and clays. Source: (Meng et al., 2019)

Lithium chemicals can be recycled from end-of-life batteries or manufacturing scrap from gigafactories (IEA, 2024). While many companies and technology developers have engaged in lithium-ion battery recycling, their primary focus has historically been on recovering higher-value metals like nickel and cobalt, with less emphasis on lithium recovery (Swain, 2017; IEA, 2024; Bae and Kim, 2021).

As shown in Figure 26 (Bae and Kim, 2021), lithium can be extracted from lithium-ion batteries through two main stages: pre-treatment and chemical extraction. In the pre-treatment stage, the battery is first discharged, and then the lithium-containing active material is separated from the battery pack. Separation methods generally fall into three categories: mechanical separation, solution treatment, and calcination treatment. Once separated, various technologies such as pyrometallurgy, hydrometallurgy, and electrochemical extraction are employed to recover lithium from the active materials.

Depending on prices, the uptake of lithium recycling may require policy incentives. A number of recycling companies have developed technologies to recover lithium via pyrometallurgical or hydrometallurgical route and claim to achieve 70-75 % recovery rate for lithium (Umicore, 2023; Peplow, 2023), and policy makers are strengthening recycling targets significantly, such as with the EU Battery Regulation which requires to recover 50% of the lithium by 2027 and 80% by 2031. Based on the IEA recent study, in the Announced Pledges Scenario (APS), where all national energy and climate goals are met in full, the share of secondary lithium supply increases from a low level today to 10% by 2040 (IEA, 2024).

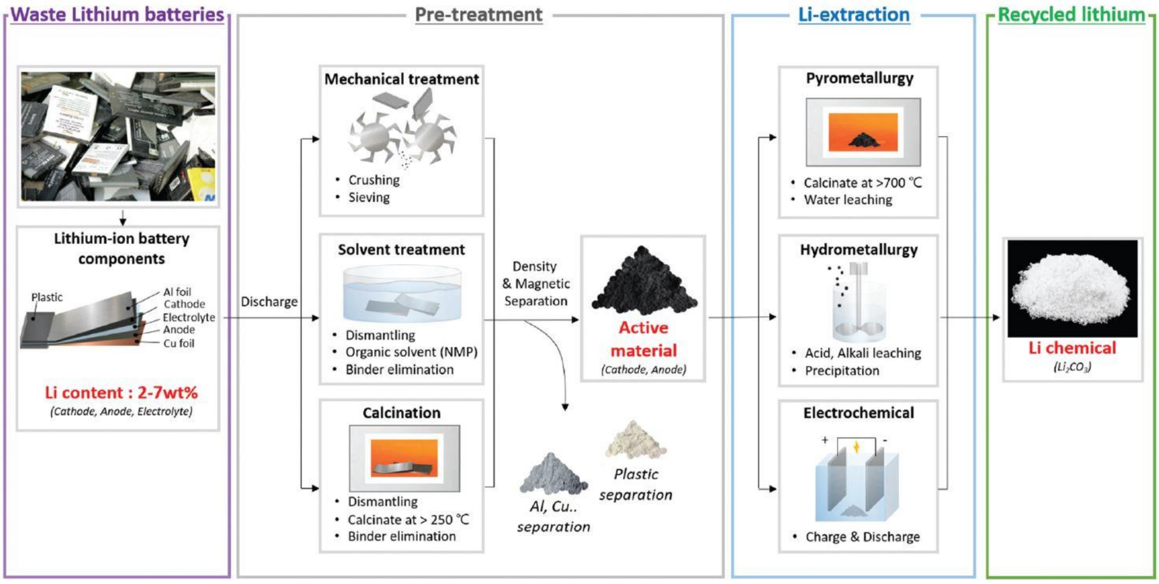


Figure 26. Schematic diagram of the lithium recycling stages and methods from lithium-ion batteries. Source: (Bae and Kim, 2021)

4.2 Overview of global and European supplying countries

According to USGS (USGS, 2024b), due to increasing number of exploration projects, the measured and indicated resources of lithium have increased in the recent years. Currently the largest known resources in the world are reported to be in Bolivia, Argentina and Chile (lithium triangle) followed by Australia, China, Germany, Canada, the Democratic Republic of the Congo (DRC), Mexico and other countries. In the EU, lithium resources are identified and estimated in Germany, Czechia, Serbia, Spain, Portugal, Finland and Austria. The largest reserves of lithium are identified in Chile, Australia and Argentina followed by China, the United States, Canada, Brazil, Zimbabwe and Portugal (USGS, 2024b).

As illustrated in Figure 27 global primary lithium production in terms of extraction and mining was relatively flat from 2000 until 2015 and has since then significantly increased until 2021 (Joint Research Centre, 2024). According to the IEA 2024 study, lithium production has more than doubled since 2021 and is expected to nearly double again by 2030 (IEA, 2024). In 2023, global production of lithium raw material (from brines, pegmatites and clays) amounted to around 190 kilo tonnes (kt), where 70 kt was produced from brines and 120 kt from hard rock.

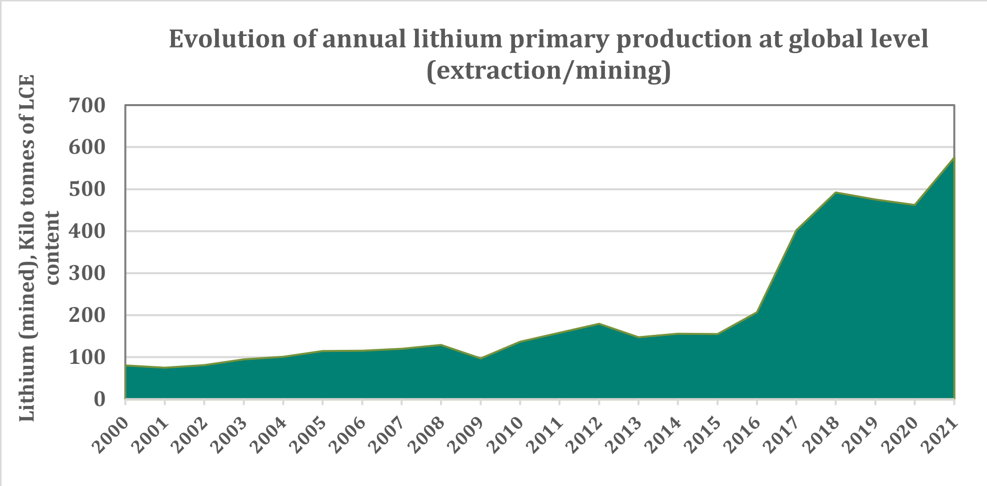


Figure 27. Lithium global production between 2000 and 2021. Source: Joint Research Centre 2024

As of 2021, the main primary lithium producing countries are reported to be Australia (48.9%), Chile (28%), China (13.1%), Argentina (5.5%) and Brazil (2.4%) followed by the USA (1.1%), Zimbabwe (0.7%), Bolivia (0.2%) and others (0.3%) (Figure 28) (Joint Research Centre, 2024). By 2030, Australia is expected to remain a key player in the lithium market, accounting for one-third of global production and capitalizing on its spodumene deposits through the expansion of major mines as well as innovative tailings retreatment facilities (IEA, 2024). Despite its significant output, Australia exports most of its lithium to China for refining. During the high-price period of 2021-2023, China saw a surge in production of lithium (mainly lepidolite type) contributing 12 kt of lithium to the market in 2023. Lithium extraction from brines occurs mainly in the salt lakes of Latin America, with Chile producing 46 kt and Argentina 9 kt. While Chile is expected to remain the largest producer in the continent, there are growing interests in Argentina with several brine extraction projects in the pipeline. Despite Bolivia's substantial lithium resources, significant projects have yet to materialize in the country (IEA, 2024). Additional lithium mining projects are expected to increase in the coming years, with most planned for implementation in China, followed by Australia, Africa, Argentina, and North America. Africa is emerging as a new lithium-producing region, primarily due to growing production in Zimbabwe and new projects planned in Ethiopia, Mali, Namibia, the Democratic Republic of Congo, and Ghana (IEA, 2024).

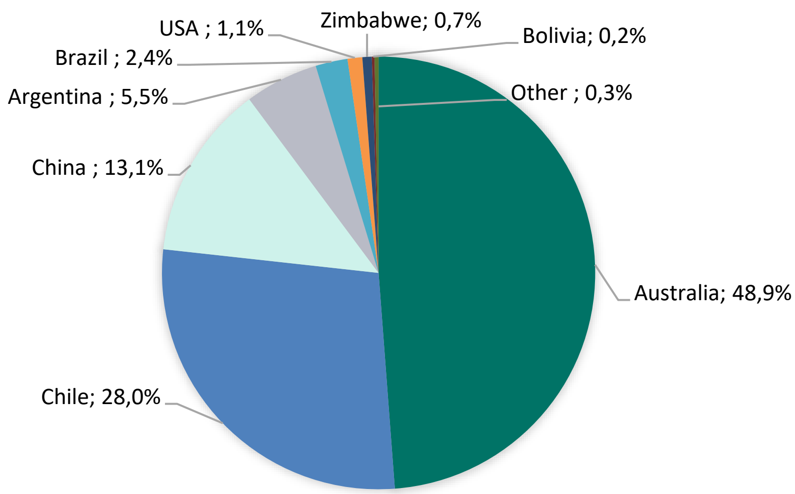


Figure 28. The main lithium producing countries in 2021. Source: Joint Research Centre 2024

Global lithium refining has seen a significant increase since 2016. As illustrated in Figure 29 after a steady rise from 2011 to 2015, the global output of refined lithium more than doubled by 2020, reaching 338 kilo tonnes of lithium carbonate equivalent (LCE) (Joint Research Centre, 2024). China is the largest refiner of primary lithium, accounting for 56% of the global share, followed by Chile at 32% and Argentina at 11% (Joint Research Centre, 2024). Since 2016, China's share of global lithium mining has grown from 6% to 17% in 2023, and the country has made notable investments in domestic mine to boost the supply. However, despite these efforts, China still relies on sourcing feedstock from other countries (IEA, 2024).

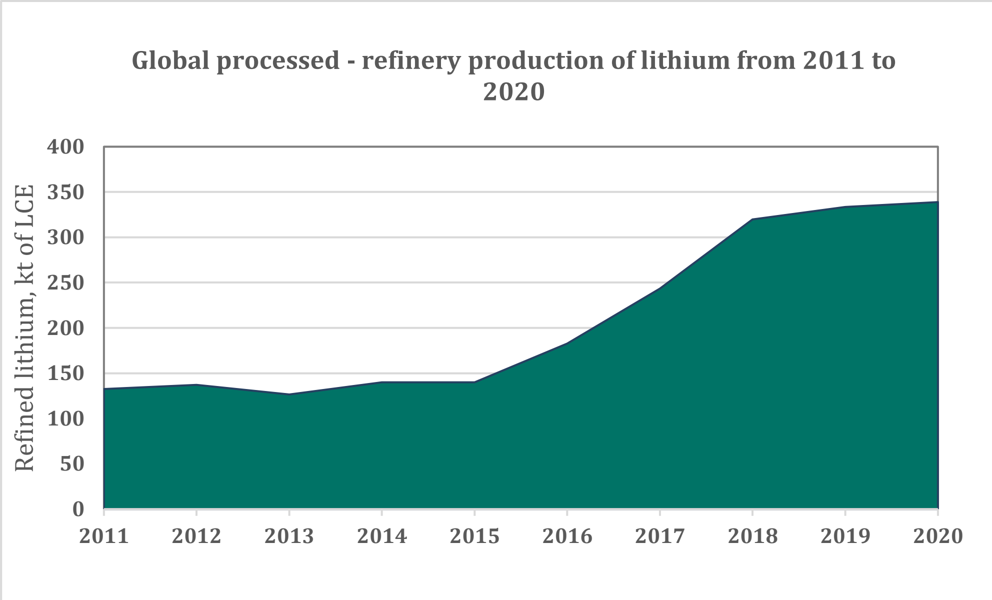


Figure 29. Global processed - refinery production of lithium from 2011 to 2020. Source: Joint Research Centre 2024[12]

The **European Union** holds 3.1% of the world's lithium reserves and accounts for just 0.1% of global primary lithium production (RMIS 2024). Portugal is currently the leading producer within the EU, mining hard rock lithium (in the form of lepidolite), which is primarily used in ceramics and glass applications (SCRREEN Project, 2020b).

The EU imports various lithium compounds and more specifically lithium carbonates (HS 283691) and lithium oxides and hydroxides (HS 282520), which are key for battery production. In 2020, the EU import reliance for primary lithium materials (minerals and brines) was 81% while the import reliance for refined lithium was 100% (data for year 2020) (EC, 2023)[13]. Supply chain information from the EU Materials System Analysis (MSA) study is provided in Figure 30 (EC, 2020).

[12] Source: https://rmis.jrc.ec.europa.eu/rmp/Lithium (accessed June 2024). Based on World Mining Data.

[13] Also provided in the RMIS raw materials dashboard (https://rmis.jrc.ec.europa.eu/rmp/Lithium).

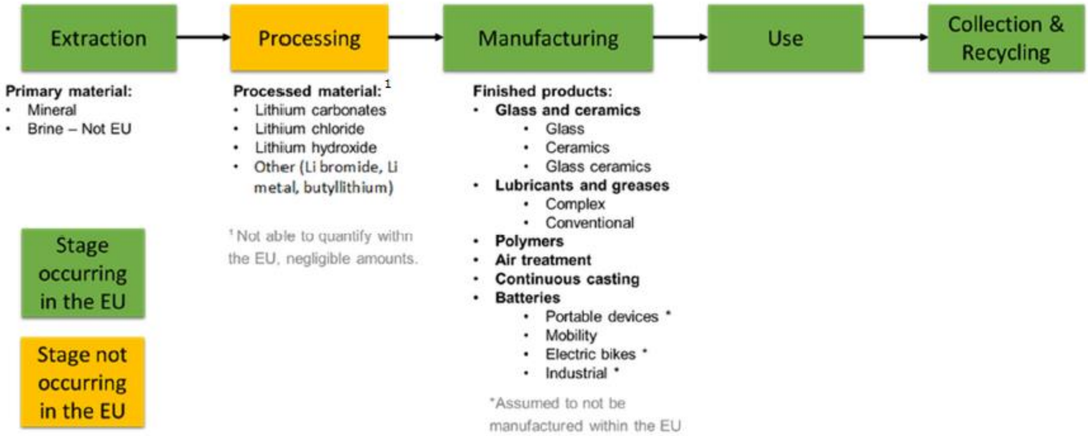


Figure 30. Value chain of lithium according to the EU MSA Study. Source: (EC, 2020)

The supply of lithium oxide & hydroxide and lithium carbonates for the EU is largely dominated by Chile. Figure 31 which shows the global supplying countries for the EU, reveals a decrease in the dependency from Chile, which appears to be replaced by an increase in supply from China.

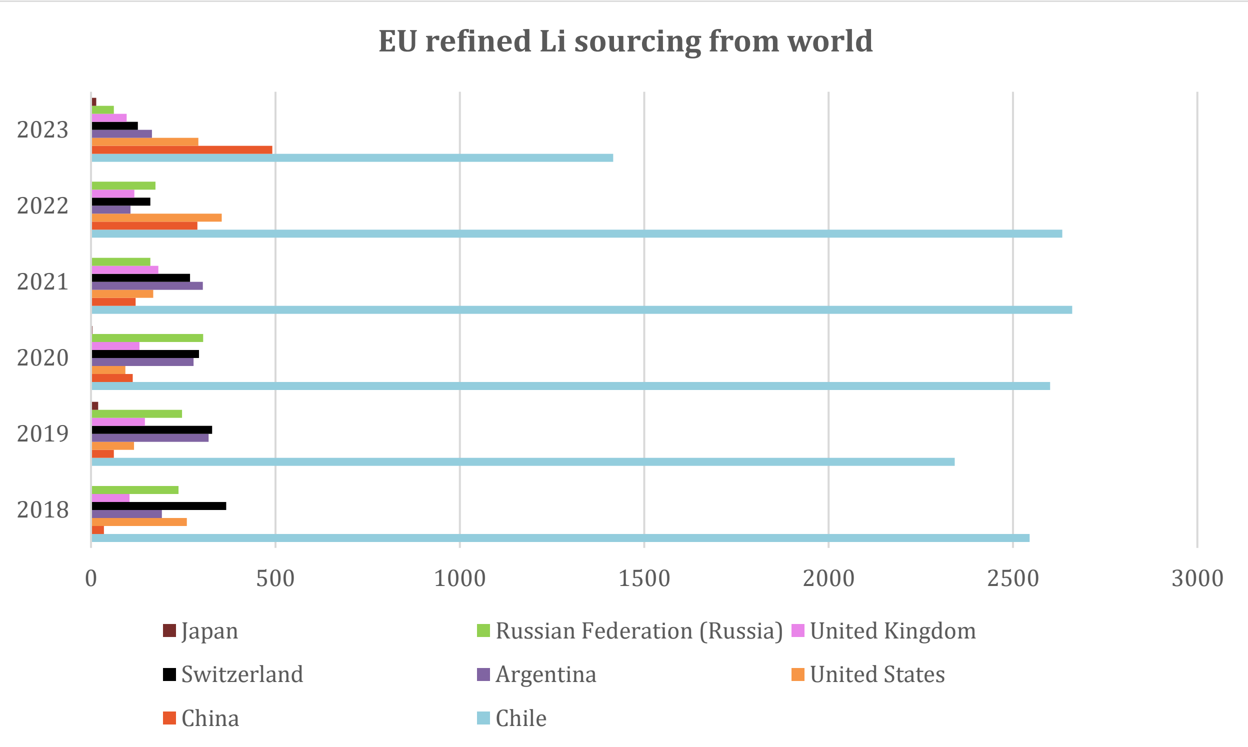


Figure 31. EU's sourcing countries for refined lithium in tonnes, Source: Joint Research Centre, 2024.

The consumption of lithium for battery production increased significantly in recent years and is known to grow at the fastest pace among major minerals needed for clean energy transition (IEA, 2024). The IEA study, under the Stated Policies Scenario (STEP), predicts that the global lithium demand will nearly triple by 2030, increase more than fivefold by 2040, and grow about sevenfold by 2050 (IEA, 2024). Based on the same study, The electric vehicle industry is expected to contribute to 90% of future lithium demand growth between today and 2050 in an Announced Pledges Scenario (APS), where all national energy and climate goals are met in full (IEA, 2024). According to the Joint Research Centre foresight study (Carrara et al., 2023), the EU's demand for lithium used in batteries is projected to increase 12-fold by 2030 and 21-fold by 2050 compared to 2020 levels.

4.3 EU trade structure and dynamics for lithium

Figure 32 shows recent trends in EU import quantity, import value and average unit prices of lithium products. The quantity of imported lithium (just trade codes related to processing) remained somewhat constant in the past decade. Although consumption of the lithium has massively increased in the EU this past decade, the majority of it is imported as part of Li-ion batteries and is therefore not reflected in the graphic (Matos et al., 2022). The monetary value of import however, increased by a factor of three in 2022-2023 with respect to 2020-2021. This increase was directly linked to higher prices, just partially compensated by a slight reduction of quantities. Most of the price increase was due to few specific product codes.

As part of this analysis, the ratio of average prices from 2021–2023 to those from 2014–2020 was calculated for lithium (See Annex G for more details on these ratios by product code). The analysis show that the ratio is the highest (5.57) for Fluorosilicates and the lowest (1.06) for Fluorides. This suggests that price peaks of 2022 and 2023 where more acute for the raw materials (lower product codes) rather than more processed products (higher product codes), whose prices moved in line with their longer-term trends.

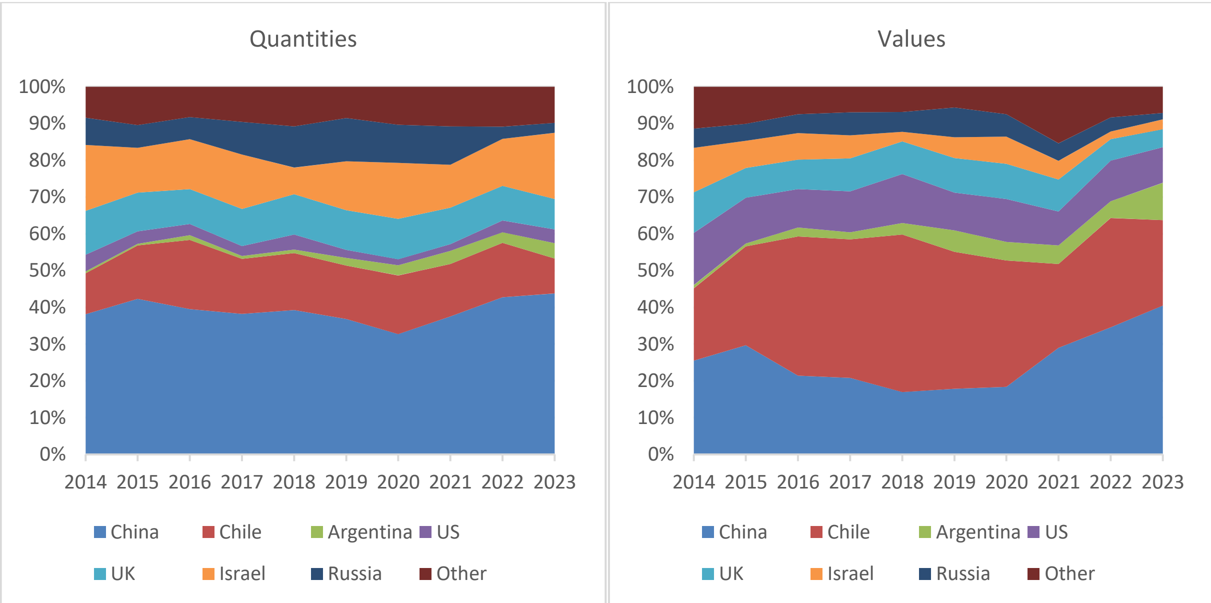
Notes: product codes of the CN8 classifications are reported in Annex B. Totals do not take into account of heterogeneous aluminium content across different product codes.

Figure 32. Main import trend for processed lithium products Source: ETC-CE elaboration on COMEXT Eurostat data

Figure 33 illustrates the structure and the changes in the position of top EU trading partners for lithium products (all trade codes), both in quantity (left) and monetary value (right). China structurally dominates the procurement of the EU. As of 2023, more than 40% of lithium (in value and quantity) comes from China. Chile is the second major supplier, but its share is not stable in time and its position of second major supplier in quantities is alternating with Israel (mostly exporting to the EU bromides and bromide oxides). In same years, Russia and the UK alternated in being the third and fourth supplier.

Then, given the structural dominance of China, there has been some degrees of flexibility in importing lithium from other major suppliers that, however, are few and one of them, Russia, is problematic. In any case, no other suppliers challenged the role of China in EU import.

When looking at the trends in the values of import in Figure 33, it can be observed that China and Chile alternate as the dominating suppliers, and, when comparing this with their shares in import quantities, it can be concluded that importing from Chile can be very expensive. This is then case also for the US, which supplies relatively low quantities but at very high unit values.[14] The implication of this observation is that changing the structure of import in trying to escape China's dominance can be not only difficult (see above) but may also entail very high costs for the EU.



Notes: product codes of the CN8 classifications are reported in Annex B. Totals do not take into account of heterogeneous lithium content across different product codes.

Figure 33. Main trade partners for lithium. Source: ETC-CE elaboration on COMEXT Eurostat data

4.4 Environmental impacts of Lithium production

Lithium production from primary resources into different end products has significant impacts on the environment. As described in section 4.1, there are two main supply routes for lithium chemicals which differ on the primary lithium source as well as on the required processing methods:

- production from spodumene ore which is mainly mined and concentrated in Australia followed by refining of the spodumene concentrate into lithium chemicals in China

[14] As discussed in section 2.4.1, differences in unit price of import across partners reflect both true price differences and different composition of trade flows in terms of products with different unitary prices.

- and production from brine mainly taking place in Chile and Argentina with integrated refining of brine concentrate into lithium chemicals.

Because the processing route is significantly different for spodumene ore and brine, also the environmental impacts depend on the primary resource. There are numerous LCA studies published in recent years comparing impacts of lithium from different primary resources, processing routes, and end products. Majority of these studies are focused on battery grade lithium chemicals, i.e. lithium carbonate (Li_2CO_3) and lithium hydroxide (LiOH, or lithium hydroxide monohydrate LiOH H_2O). In general, production of Li_2CO_3 or LiOH from ore-based resources has significantly higher carbon footprint compared to the production from brine-based resources (Kelly et al., 2021; Chordia et al., 2022; Jiang et al., 2020; Grant et al., 2020).

Impacts also depend on the lithium end product. For the lithium-ion battery applications, lithium carbonate Li_2CO_3 is typically used for low nickel NMC and LFP production, whereas for the production of high purity nickel rich NMC such as NMC811 LiOH is required (IEA, 2024). In the case of brine, LiOH is typically produced via conversion from Li_2CO_3, resulting in higher carbon footprint for LiOH compared to Li_2CO_3. In the case of spodumene ore, both LiOH and Li_2CO_3 can be produced directly from spodumene concentrate (Kelly et al., 2021). Typically for brine-based route climate change impact of 3-5 t CO_2-eq./t for Li_2CO_3 end product and 5-8 t CO_2-eq./t for LiOH end product have been reported, whereas for the ore-based route 15-22 t CO_2-eq./t for Li_2CO_3 and 15-19 t CO_2-eq./t for LiOH have been reported for the current main supply routes (Kelly et al., 2021; Chordia et al., 2022; Grant et al., 2020; Schenker et al., 2022; KU Leuven, 2022). As an example, climate change impact of brine and spodumene based LiOH·H_2O is presented in Figure 34.

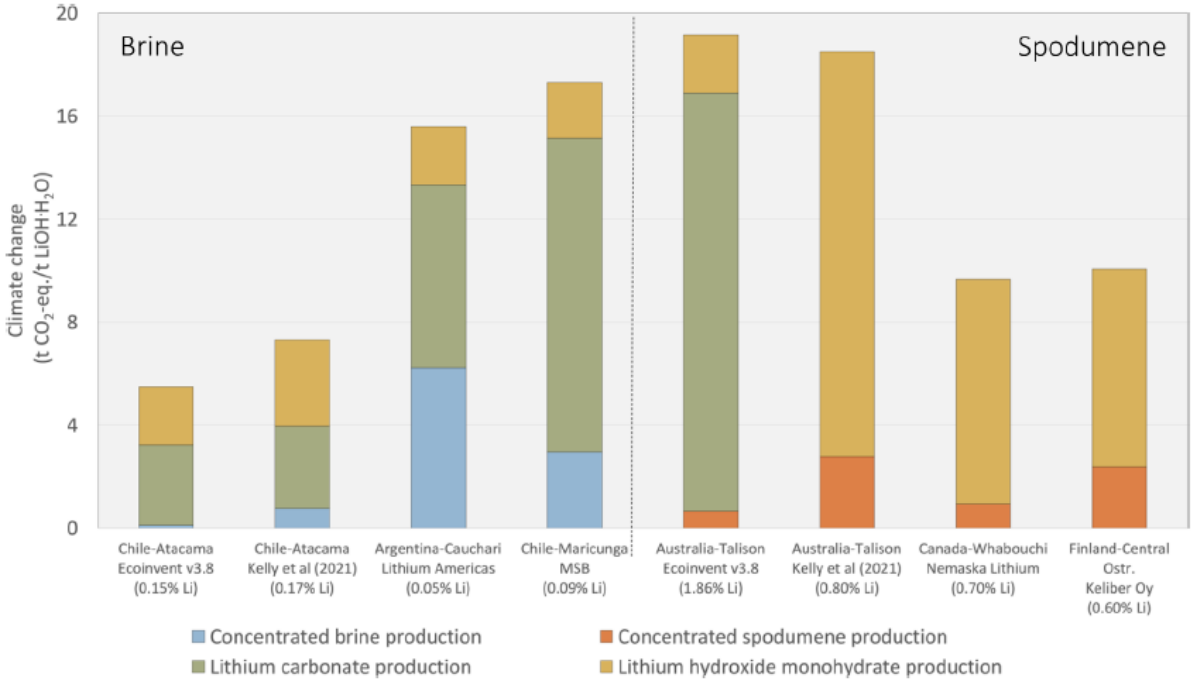


Figure 34. Climate change impacts for brine- and spodumene-based lithium supply routes. Source: (Chordia et al., 2022)

The higher carbon footprint of the ore-based route results from the high energy use in the refining phase to obtain Li_2CO_3/LiOH, followed by the energy use for the extraction and processing to obtain spodumene concentrate. Both of these process steps currently rely on fossil fuels, for example, (Kelly et al., 2021) consider a process that uses diesel as the only source of fuel for site operations to produce spodumene concentrate. Furthermore, the following refining is carried out using the carbon-intensive Chinese energy mix. Should there be a change in energy sources used for the spodumene mining, processing, and refining, significantly different GHG emissions could be observed.

Production of lithium chemicals from brine is considerably less energy intensive compared to production from spodumene ore, in addition the electricity mix in Chile is less carbon intensive than in China (Kelly et al., 2021). Large part of the climate impact in the brine-based route results from the energy use to convent brine concentrate to Li_2CO_3 and from the onsite chemical use (especially Na_2CO_3) (Kelly et al., 2021; Schenker et al., 2022). Minor share of the climate impact results from the concentration of brine which is traditionally based on evaporation ponds using solar energy.

For brine-based processing, water use is also a significant aspect, due to the large amount of brine and fresh water consumed and considering that the production takes place in one of the most arid regions of the world (Kuzma et al., 2023). The process relies on evaporation of large volumes of water, 100–800m^3 per t of Li_2CO_3 (Vera et al., 2023). Although the evaporated water is mainly brine water, and the direct use of freshwater may be less than in the ore-based route (Kelly et al., 2021), pumping of the vast amounts of brine can affect the hydrogeological systems of the area, thus increasing the risk of freshwater availability. Currently over half of the global lithium production comes from areas of extremely high water stress (IEA, 2021). Other impacts such as soil degradation, deforestation, and loss of biodiversity (during mining) or air emissions and marine and freshwater ecotoxicity (during refining) have been reported in the literature (e.g., see (Das et al., 2024; Sankar et al., 2023)).

Impacts are also highly dependent on the source material grade which can significantly affect the impacts of the future production routes. Especially in the case of brine, each brine in different locations of the world has a unique chemical composition and the production processes need to be adapted to specific brine chemistries in order to obtain the desired end product, resulting in different impacts (Kelly et al., 2021). Several studies suggest that lower grade brines have higher environmental impacts than higher grade brines in terms of carbon footprint and water use (Chordia et al., 2022; Mas-Fons et al., 2024). Also, higher freshwater ecotoxicity impacts can be observed compared to high-grade brines due to the high chemical and energy use needed in processing of low-grade brines (Chordia et al., 2022). Similar trend in climate impact and water use is reported for low grade spodumene based on process simulation, however the difference is not as clear as in the case of brine (Mas-Fons et al., 2024).

Two recent LCA studies compare the current brine site in Salar de Atacama (Chile) to existing or future brine sites in Salar de Cauchari (Argentina) and Salar de Maricunga (Chile) (Chordia et al., 2022), and Salar de Olaroz, Salar de Cauchari-Olaroz, Salar del Hombre (all in Argentina) (Schenker et al., 2022). Notable difference between these brine sites is the lithium concentration, which is highest at Salar de Atacama, 0.15%- 0.17% wt Li, compared to 0.05-0.09% wt Li in the other sites. As a result, Schenker et al. report 235% higher climate change impacts for the brines in Argentina than for Li_2CO_3 extracted from Salar de Atacama in Chile (< 4 kg CO_2eq/kg Li_2CO_3 for Salar de Atacama vs. 7.4-8 kg CO_2eq/kg Li_2CO_3 in Salar de Olaroz, Salar de Cauchari-Olaroz and Salar del Hombre Muerto). Similar trend is reported in the study by Chordia et al. which reports over 3-fold climate change impact for the LiOH produced from Cauchari and Maricunga brines compared to Salar de Atacama. This is explained by the lower lithium concentration in the brine, which implies that greater volumes of brine need to be processed to produce equivalent grades of LiOH.

The environmental hotspots of the battery recycling are specific to the used recycling processes, and dependent on recovery efficiency and electricity used in the recycling. In case of pyrometallurgical recovery, impacts mainly stem from the high energy consumption due to the high temperature processing. Furthermore, many materials such as aluminium, lithium and manganese are typically lost in the slag and not recovered (Mohr et al., 2020; Abdelbaky et al., 2021). For hydrometallurgical recovery, environmental impacts arise especially from the use of extraction solvents, and also wastewater treatment and potential emissions to water are hotspots for significant impacts (Abdelbaky et al., 2021). In theory direct recycling methods, in which cathode and anode materials are recovered in their original composition, could be most beneficial from environmental perspective (Ciez and Whitacre, 2019; Tao et al., 2021), however it is uncertain if and when these methods will be implemented in large scale. Although battery recycling in itself is rather resource intensive, the impacts of producing batteries from recycled materials (Ni, Co, Cu) is usually beneficial compared to using primary resources (Mohr et al., 2020; Abdelbaky et al., 2021).

Considering the impacts of recycled lithium vs primary lithium, RecycLiCo Battery Materials, a Canadian company has patented a hydrometallurgy-based lithium-ion battery recycling process. The company reports 3.3 kg of CO_2 equivalent emissions per 1 kg of the lithium hydroxide monohydrate produced with the RecycLiCo process, thus significantly lower than an estimated 12.7 kg of CO_2 emissions per 1 kg of the lithium hydroxide monohydrate from traditional mining and refining (industry average) (RecycLiCo, 2022). Similar results have been reported in a simulation based LCA study where significantly lower GWP impacts were calculated for the lithium carbonate from a hydrometallurgical recycling compared to lithium carbonate from primary materials (mass-based allocation) (Ali et al., 2024). However, it should be noted that the battery recycling is a multi-material process where several different metals are recovered, and the impacts of specific recovered material depend on the allocation approach. Thus, with economic value-based allocation approach less favourable results may be obtained for recycled lithium. Finally, Yoo et al have reported LCA of lithium ion battery recycling process developed by SK Innovation (Yoo et al., 2023). Similarly in this study, the GHG emissions of recycled LiOH were 37–72% lower compared to those of primary LiOH, although the impacts were higher than reported by (Ali et al., 2024; RecycLiCo, 2022) both for the primary and recycled lithium.

4.5 Environmental effects of a possible supply chain disruptions in short-, medium- and long-term

Short term (2024-2026) - Change to an alternative supplier

In this short-term scenario, it is assumed that part of the EU demand for lithium shifts from one country to another. However, because of complicated value chains and significant differences in the processes depending on the type of deposit, a comparison between countries is difficult. For this reason, this section will rather highlight the challenges of the value chains and differences between countries. Furthermore, this section considers the impacts of both primary extraction as well as the refining to lithium chemicals (oxides, carbonates, hydroxides, etc.). The rationale for this is that for both brine and ore-based production routes, a major part of the (climate) impacts arises from the refining stage, which is also significantly different for ore and brine concentrates. In addition, the majority of lithium imported by the EU is in refined from, and over half of this supply is from Chile where the extraction and refining of lithium from brine is closely integrated. Given that the major environmental impacts occur during the refining stage and that the EU primarily imports refined lithium, it is most logical to compare the impacts at the refined stage.

According to the multi-criteria analysis (explained in section 2.4.2), the best alternative supply for lithium is Portugal. Portugal scores 62/100 of the MCA. Although the reserves endowment and the mining production of Portuguese lithium are very low, the membership of Portugal to the EU and the EEA/EFTA and Schengen area, as well as its very high scores in the WGI, make it the best alternative country. The amount of lithium extracted in Portugal is minor, but it is currently the only country to extract lithium in the EU in the form of lepidolite (SCRREEN Project, 2020b). The output is lithium rich feldspar used by the glass and ceramics industry, and filling 17 % of the demand in this sector (in 2016) (Matos et al., 2020a). However, the amount extracted in Portugal has declined in recent year from 425 tonnes (Li content) in 2018 to 98 tonnes in 2022 (source: Joint Research Centre, 2024). Because of this decreasing capacity, choosing Portugal as an alternative supplier is not the most realistic scenario. Therefore, this report will rather look into the second best alternative country which according to the multi-criteria analysis (explained in section 2.4.2) is Australia that extracts lithium from spodumene ore. Australia achieves a score of 49/100 of the MCA, mostly due to its significant mining output and very good performance in the WGI. Notably, Australia stands out in Political Stability and No Violence, Regulatory Quality and Control of Corruption (see Annex H). These strong results across all criteria compensate the fact that Australia Is not a member of the EU, EEA/EFTA or the Schengen area, making it the best alternative to supply lithium to the EU. However, currently Australia does not have its own lithium refining capacity but mainly ships spodumene concentrate to China for refining (see section 4.2 for more detailed description of the global supply chains and section 4.3 for EU trade structure). Thus, in the short term, switching to Australian spodumene would mean refining stage taking place in China, whereas in the medium to long term, EU refining capacity will become increasingly available.

For comparing the impacts of EU import of lithium from Chile vs. Australia/China, Ecoinvent datasets[15] for lithium carbonate production are available for China and global for the spodumene based production route, whereas as for the brine-based production route, only global dataset is available. However, there are several peer reviewed LCA studies as well as reports which compare the current lithium production routes, (e.g. Kelly et al., 2021; Chordia et al., 2022). These are discussed in section 4.4, but as a summary the climate impact of brine based lithium and spodumene ore based lithium are significantly different, for example one study (Chordia et al., 2022) reports 2.5 times higher climate impact for spodumene based $LiOH \cdot H_2O$ compared to brine based $LiOH \cdot H_2O$. Furthermore, the water use impacts as well as the freshwater ecotoxicity impacts are higher for spodumene based $LiOH \cdot H_2O$ compared to brine based $LiOH \cdot H_2O$.

Considering the current geopolitical tensions and the past restrictions China has placed on the export of certain battery materials (Liu and Patton, 2023), as well as the high carbon footprint of the lithium products refined in China, increasing the supply from China may not be the most preferred option. Although lithium plays only a minor role in the total carbon footprint of the battery, the forthcoming requirements to declare the battery carbon footprint in the EU market (later also carbon footprint classes introduced, followed by carbon footprint thresholds), may cause that battery material manufacturers will seek material options with lower carbon footprint. For medium to long term, potentially the import of Australian spodumene concentrate could be increased and further refined in the EU. Currently EU sources lithium containing ores and concentrates (such as spodumene) mainly from Australia, in 2023 close to 600 tonnes in Li content (Joint Research Centre, 2024). The climate impact of lithium from Australian spodumene would be 34 % lower if refined in the EU compared to Australian spodumene refined in China (Figure 35) and on the same level as the climate impact of domestically sourced and refined lithium.

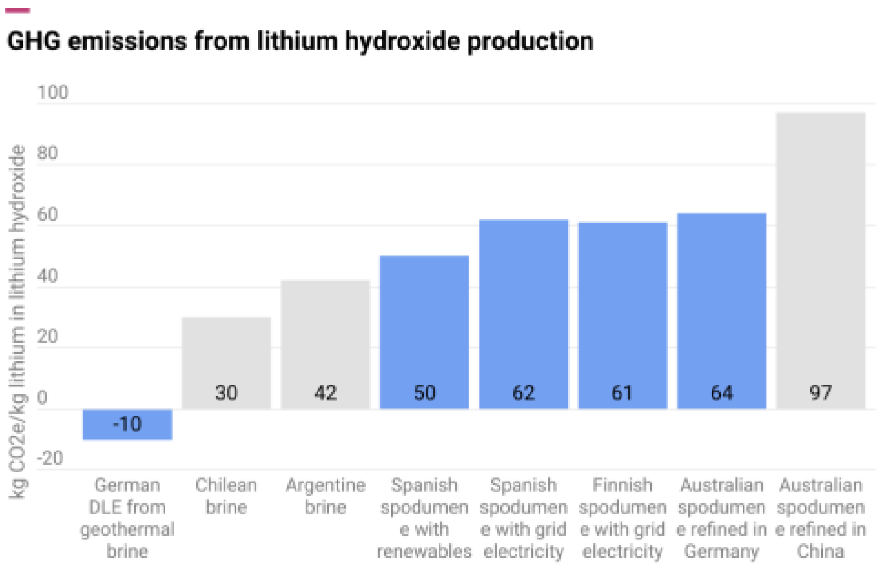


Figure 35. GHG Emissions from lithium hydroxide production. Source: (Transport & Environment, 2024)

Medium term (2026-2030) – improving lithium recycling from end-of-life batteries

Current recycling rates of lithium are negligible, but in the future the recycling of lithium-ion batteries will be an important secondary supply for lithium (SCRREEN Project, 2020b). In addition to the mandatory

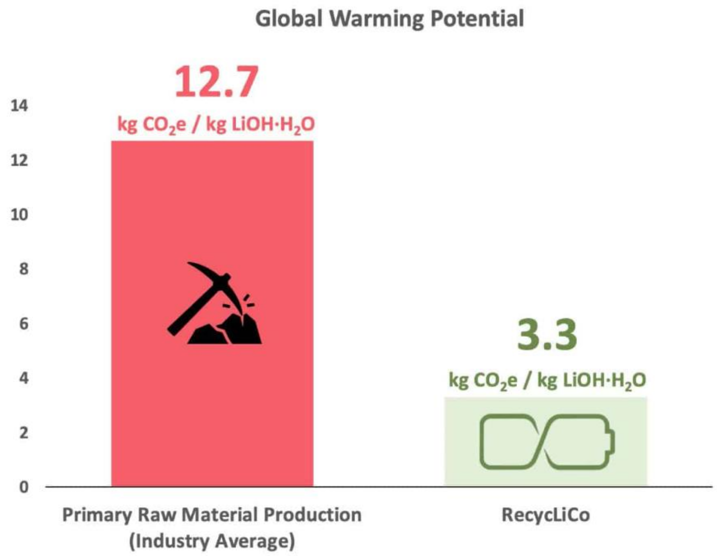
[15] https://ecoinvent.org/

targets for lithium recovery in the EU Battery regulation, there will be mandatory recycled content for the lithium in batteries placed on the EU market, starting from 2031. Thus, increasing demand from the battery sector for the secondary materials (Li, Co, Ni) is expected.

The volume of recovered lithium from end-of-life batteries and manufacturing scrap depends on the material available to recycling (volumes and lifetimes of applications on the market, manufacturing losses) and the recycling process efficiency. In the past, significant amount of end-of-life batteries or recovered black mass has been exported outside EU for recycling (Wu and Lindman, 2022). However, to secure the supply of materials and feedstock for the recycling operations, battery waste should be recycled domestically. Lithium-ion battery recycling capacity already exist in the EU and is set to increase significantly in the coming years. In 2030, the treatment capacity for the waste batteries could total 900 kt per year considering all announced projects in Europe (Transport & Environment, 2024; Stephan, 2024). However, due to the long lifetimes of EV batteries and strongly increasing market for the EV batteries, it takes years before lithium from secondary sources can replace the lithium from primary sources in larger quantities. Recent analysis from (KU Leuven, 2022) estimates that even though recycling has a potential to provide more than 75 % Europe's lithium demand by 2050, the quantities of recycled lithium will remain low until 2040. Similar results have been presented in a recent report by (RMI, 2024) which calculates that recycling will begin to lower the net lithium demand after 2038.

Recycling has the potential to decrease the environmental impacts of battery materials. Environmental impacts of secondary Li from the recycling of lithium-ion batteries are described in section 4.4. Most battery LCA studies consider the overall impacts of recycling of the whole battery. There are only couple of studies in which the impacts are allocated to different recovered metals. For the medium-term scenario, the climate impact data of RecycLiCo (Figure 36) is used as a proxy to climate impacts of recycling to compare impacts of improved recycling. RecycLiCo is a hydrometallurgical recycling technology developed by a Canadian company. There are no details of their LCA study available (RecycLiCo, 2022). However, the reported climate impact is on the same level as in a simulation based LCA study by (Ali et al., 2024). Hydrometallurgical recycling route is one of the two main recycling routes, and perhaps most suitable for the lithium recovery.

JRC estimate that in 2030 5% of the EU battery raw material consumption could come from secondary supply (old and new scrap). This would equal to roughly 20 kt of lithium supply from secondary raw materials (in LCE) (Joint Research Centre, n.d.). Another analysis by Transport & Environment estimates that 8 % of the lithium demand of the EU battery value chain could be met with secondary sources in 2030, this would equal to 41 kt in LCE (Transport & Environment, 2024). Assuming that lithium from recycling replaces both import from Chile and China, the climate impact could be reduced from 12.7 kg CO_2-Eq / kg



LiOH·H_2O (industry average for primary raw material) to 3.3 kg CO_2-Eq / kg LiOH·H_2O (hydrometallurgical refining). With 23-47[16] kt supply of LiOH·H_2O from secondary sources, 216-442 kt of CO_2-Eq / year could be avoided (in 2030). Furthermore, the volumes of end-of-life batteries to recycling is increasing rapidly, and thus also the potential to reduce the demand for primary resources and related impacts. Transport & Environment (2024) estimates the amount recycled lithium to increase from 41 kt (in LCE) in 2030 to 80 kt in 2035.

Figure 36. Global warming potential of recycled lithium from RecycLiCo process (right) compared to primary Li (industry average, left). Source: (RecycLiCo, 2022)

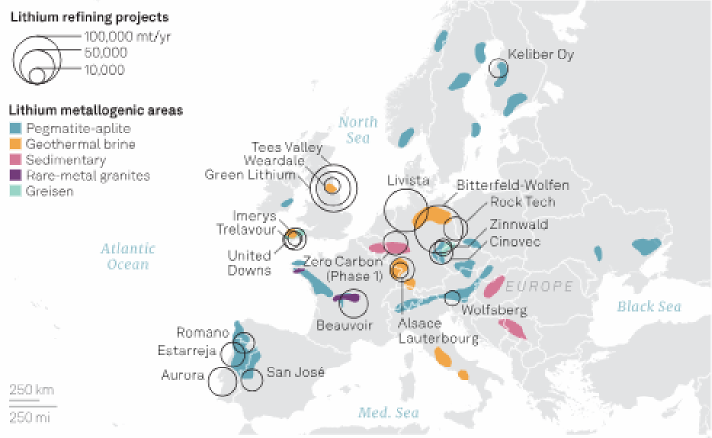
Long term (2030-2040) – improving domestic mining and refining capacity

In recent years, lithium has been mainly extracted in Portugal in the form of lepidolite. There has been no refining of chemical grade (e.g. battery grade) lithium compounds, but downstream lithium compounds such as butyl-lithium, lithium chloride, and lithium metal have been produced in Germany from imported lithium carbonate. (SCRREEN Project, 2020b)

Recently, several new lithium mining projects have been announced in Austria, the Czech Republic, Germany, Finland, Portugal, Spain, and Serbia, with a projected total output of 130 kilotons by 2030 (KU Leuven, 2022). However, many of these projects are still in early stages and face challenges such as local community opposition, particularly in Portugal and Spain. Nevertheless, if these projects progress under favourable conditions, the EU could meet 55% of its 2030 lithium needs for domestic battery production (KU Leuven, 2022).

Beyond mining, the EU aims to expand its lithium refining capacity, potentially reaching 155 kilotons by 2030—25 kilotons more than the projected mining capacity (KU Leuven). Several early-stage domestic projects are advancing toward commercial production, with their locations and capacities shown in Figure 37 (S&P Global, 2023). Given the early stage of these projects, they are primarily seen as potential capacity post-2030. However, securing the raw ore (spodumene) is expected to remain a significant challenge in the coming decade (S&P Global, 2023).

[16] 23-47 kt LiOH·H_2O equals to 20-41 kt of LCE (lithium carbonate)



Extraction | Processing | ■ Lithium Hydroxide | ● Lithium Carbonate

Project name	Owner	Start	Category	Capacity ('000 mt/yr)	Product
Bitterfeld-Wolfen	AMG Lithium	2024	Processing	100.0	■
Cinovec	European Metals-CEZ	2024	Extraction, Processing	22.5	●
United Downs	Geothermal Engineering	2024	Extraction, Processing	12.0	●
Tees Valley Lithium	Tees Valley Lithium	2025	Processing	96.0	■
Lauterbourg (First Phase)	Viridian Lithium	2025	Extraction, Processing	25.0	■
Keliber Oy	Sibanye-Stillwater-FMG	2025	Extraction, Processing	15.0	■
Wolfsberg	European Lithium	2025	Extraction, Processing	8.8	■
Livista	Livista Energy	2026	Processing	80.0	■●
Aurora	Galp-Northvolt	2026	Processing	35.0	■
Rock Tech Lithium	Rock Tech Lithium	2026	Processing	24.0	■
Zero Carbon Lithium (Phase 1)	Vulcan Energy Resources	2026	Extraction, Processing	24.0	■
Imerys British Lithium	British Lithium-Imerys	2026	Extraction, Processing	20.0	●
San José Lithium Project	Infinity Lithium-Valoriza Minera	2026	Extraction, Processing	19.5	■
Zinnwald Lithium Project	Zinnwald Lithium	2026	Extraction, Processing	12.0	■
Trelavour	Cornish Lithium	2026	Extraction, Processing	7.8	■
Green Lithium	Green Lithium	2027	Processing	50.0	■
Estarreja Lithium Refinery	Bondalti-Neometals	2027	Processing	25.0	■
Romano Mine	Lusorecursos Portugal Lithium	2027	Extraction, Processing	18.0	■
Beauvoir	Imerys	2028	Extraction, Processing	34.0	■
Weardale Lithium	Weardale Lithium	NA	Extraction, Processing	10.0	●
Alsace	Eramet-Electricite de Strasbourg (ES)	NA	Extraction, Processing	10.0	●

S&P Global Commodity Insights

Source: S&P Global Market Intelligence, FRAME project, EuGeLi, US Geologica

Credit: Euan Sadden, CI Information Design. Copyright © 2023 by S&P Global I

Figure 37. Location and capacity of early-stage lithium mining and refining projects in Europe. Source: S&P Global, 2023

A major part of the EU lithium mining projects plan to extract lithium from hard rock ore, according to Transport & Environment analysis, 77% of the planned annual mining capacity (Transport & Environment, 2023). A minor part of the projects develops direct lithium extraction (DLE) technologies to recover lithium from geothermal brines. Although there is high uncertainty for the realization of some the EU mining projects and it seems likely that all the planned mining and refining capacity may not materialize, some of these projects are rather advanced. For example, the Keliber project in Finland (now owned by Sibanye-Stillwater) is currently building a refining facility to produce battery grade LiOH. The spodumene ore will be sourced from several open-pit and underground mine sites from the lithium deposits in Central Ostrobothnia area. The company has announced to begin the production of LiOH in 2025 using imported ore and from own ore in 2026 (European Investment Bank, 2024). The mining and refining capacity is expected to be 15 kt of LiOH per year.

A recent LCA study (Chordia et al., 2022) compares the environmental impacts of current and potential future supply routes for battery grade lithium hydroxide including the Keliber project (see Figure 35 in short term scenario). Due to the lack of Ecoinvent data for the European lithium mining and refining, the result of this study was used to discuss the impacts of shifting lithium mining and refining to Europe. This assessment estimates the climate change impact of LiOH produced in Finland to be approximately 10 t CO_2-Eq / t $LiOH{\cdot}H_2O$, which is significantly lower than for the current Australian/Chinese supply route (19 t CO_2-Eq / t $LiOH{\cdot}H_2O$), but higher than for the Chilean supply route (5.5-7.3 t CO_2-Eq / t $LiOH{\cdot}H_2O$). It is thus clear that the environmental benefits of the EU lithium production depend on whether the domestic supply replaces the lithium import from China or Chile. Assuming that the spodumene based LiOH from Keliber project would replace spodumene based LiOH imported from China, the climate change impact would reduce approximately 9 t CO_2-Eq / t LiOH·H_2O. With an annual production of 15 kt of LiOH, this would reduce the impact by 135 kt CO_2-Eq / year.

If spodumene based lithium produced in the EU would replace lithium imported from Chile, the climate impact would increase. However, the environmental hotspot in the brine-based supply route is related to water use in the extremely dry area of Salar de Atacama in Chile.

There are also several projects focusing on geothermal brines in various stages of planning and implementation. For example, the Zero Carbon Lithium project[17] by Vulcan energy in Germany has announced in April 2024 the start of lithium chloride production in its Lithium Extraction Optimisation Plant (LEOP) which is an optimisation, operational training and product qualification testing facility. The aim of Vulcan energy is to further refine the extracted LiCl to battery grade chemicals with an annual production capacity of 24 kt of LiOH (Vulcan Energy, n.d.), but the timeline of the commercial scale plant is uncertain. Vulcan energy claims that their LiOH product is carbon negative since the DLE plant producing LiCl and the subsequent chemical plant converting LiCl to LiOH utilize geothermal energy and decarbonized electricity instead of fossil fuels. Furthermore, the excess energy of the geothermal plant is supplied to the CO_2 intensive German grid, resulting in net saving of 2.9 t CO_2-Eq / t LiOH·H_2O. (Vulcan Energy, 2021)

However, it should be noted that DLE is a new technology and there is less data available and more uncertainty of the environmental impacts. LCA study by (Schenker et al., 2024) presents more critical results for the impacts of lithium from geothermal brines, e.g. climate impact 5.3–46 kg CO_2eq/kg Li carbonate at the Upper Rhine Graben, compared to 2.1–11 kg CO_2eq/kg Li carbonate in existing Ecoinvent data sets. These results highlight the importance of site specific and technological conditions for the early phase assessment of the new technologies. Assuming that the LiOH from geothermal brines would be carbon neutral and would annually supply 24 kt, the climate impact would reduce 168 kt CO_2-Eq / year when compared to LiOH imported from Chile or 456 kt CO_2-Eq / year when compared to LiOH imported from China.

In addition to new mining activities, lithium demand could be lowered by innovations in battery technology and demand-side changes. Emerging battery technologies, such as solid-state batteries, sodium-ion batteries, and lithium-sulphur batteries, offer potential alternatives that use less lithium or eliminate it entirely (Armand and Tarascon, 2008). For example, sodium-ion batteries rely on abundant sodium instead of lithium (Slater et al., 2013), while solid-state batteries increase efficiency and reduce the need for raw materials in general (Janek and Zeier, 2016), but depending on the material choices could require even more lithium per kWh (Fastmarkets, 2023; Tanneeru, 2023). As these technologies are still in development stage, there is a lack of data on their environmental impacts, and it is difficult to compare them with mature technologies such as lithium-ion batteries, as the material content, manufacturing and recycling processes, and the performance differ significantly. However, several studies suggest that the climate impact of e.g. sodium ion batteries may be on similar level with lithium ion batteries, and the benefits mainly stem from the lower mineral resource scarcity impacts (Peters et al., 2021; Wickerts et al., 2024).

Advances in battery energy density could also mean smaller batteries with equivalent performance, reducing overall material needs. For example, the RMI's Battery Mineral Loop outlines a path toward reducing reliance on mined battery minerals (lithium, nickel, and cobalt) through efficiency, innovation, and circularity (RMI, 2024). Key solutions include changing battery chemistries, recycling and reuse, extended lifetime, energy density improvements, and better vehicle and mobility efficiency. Implementing such strategies, by the mid-2030s, peak demand for virgin minerals may be reached, with net-zero mineral demand achievable by the 2040s. End-of-life batteries will eventually replace mining as the primary source of minerals, significantly lowering the need for extraction and reducing overall environmental impacts.

[17] https://v-er.eu/zero-carbon-lithium-tm-business/

On the demand-side, shifting toward public transportation, shared mobility, and energy efficiency improvements in electric vehicles and grid storage could lower the number of new batteries required.

Summary of findings (lithium)

The above scenarios show the important potential for reducing CO_2-Eq. emissions in the lithium sector. Figure 38 gives an overview of the cumulated avoided emissions of CO_2-Eq. in the case where the medium-term and long-term scenarios are implemented. The short-term scenario was not considered in the Figure 38 because of the complicated supply routes for lithium, as explained in the short-term scenario above.

As shown in this figure, the avoided emissions are given in a range depending on the scenario as explained in the paragraphs above. The minimum amount of avoided $C0_2$-Eq. emissions would be 0.52 million tonnes per year and could go up to 1.03 million tonnes per year.

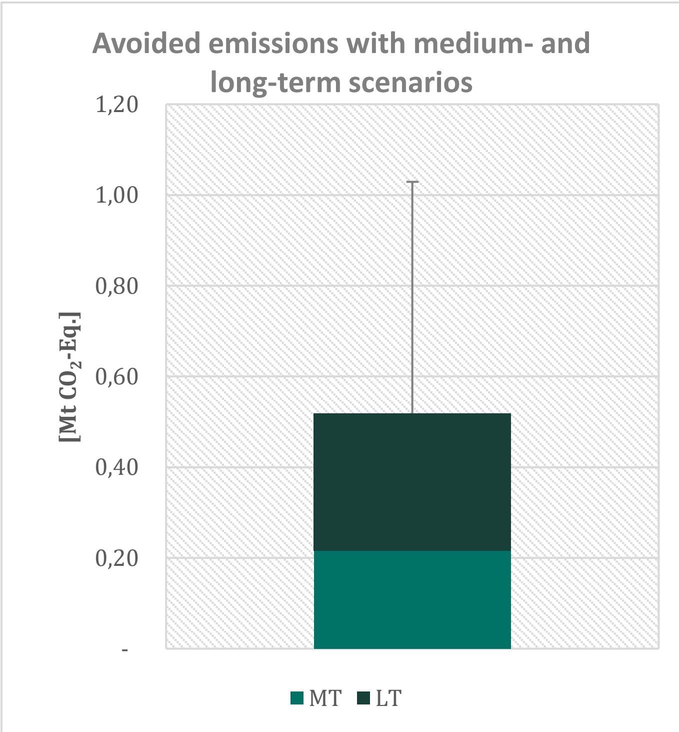


Figure 38. Range of avoided CO_2-Eq. emissions for the lithium sector, per year, considering the medium-term (MT) and long-term (LT) scenarios.

5 Key findings and conclusions

This report proposes a methodology to address the environmental implications of possible international supply disruption of industrial materials. While the economic and strategic dimensions of international supply disruption are high on the European agenda through the 'open strategic autonomy' direction the EU is undertaking, the environmental consequences are not generally considered. This report tries to fill this gap.

Although the focus is on the possible environmental implications of supply disruption and responses to them, their analysis must also be embedded into the analysis of international commodity markets and trade in which the disruption can take place. The methodology developed in this report demonstrates how complex a complete dynamic analysis can be when incorporating the economic and environmental implications of supply disruption. Moreover, applying it to case studies requires a number of simplifications, particularly regarding the consequences of the importing country's responses to supply disruption in the short, medium, and long term.

The three core responses to supply chain disruptions considered in the report are: (i) Establishment of trade relations with alternative supplying countries, (ii) Growth in domestic capacity for recycling to meet demand and (iii) Growth in domestic capacity for primary extraction, processing and refining to satisfy demand. The first response critically needs the analysis of trends in trade and trading partners, and the identification of preferrable, more reliable supplying countries.

Other simplifications have been adopted, or were forced, by limitations in data and information for the scope and the approach of environmental analysis. In practice, the environmental analysis focuses on the potential implications of shifting from one supplying country to another and developing domestic capacity for that commodity, framed as an ex-ante 'what if' scenario.

5.1 For Europe

The key findings relevant for Europe and for each case study are summarized below.

Case study aluminium

EU trade data: The structure of EU trade within the aluminium value chain highlights distinct sourcing patterns. While Guinea remains the largest supplier of bauxite to the region, the EU primarily sources primary (refined) aluminium from Russia and Mozambique. For many years, this trade structure remained relatively stable. However, recent increases in prices have driven a notable shift in trade composition. The focus has moved increasingly toward aluminium at the processing stage and scrap for recycling, accompanied by a reorientation toward suppliers such as Norway and South Korea. Within the EU in 2022, Greece was the leading supplier of bauxite, followed by France, Croatia, and Hungary. For primary aluminium, the main suppliers included France, Germany, Romania, Greece, Sweden, Slovakia, and Slovenia.

In the simplified framework ('what if' scenario) used in this study, shifting to alternative suppliers can therefore either take place for the bauxite supply, or for the primary aluminium supply with different environmental implications.

Short-term scenario (2024-2026): For bauxite mining, the environmental impacts seem lower in Greece than in Guinea. For primary aluminium, production in an EU country (France in that case) has less environmental impacts (climate change, ecotoxicity to water and ozone depletion) than production in Russia or Mozambique.

Medium-term scenario (2026-2030): The medium-term scenario shows significant potential to reduce the aluminium sector's carbon footprint. While aluminium recycling is already well established in the EU, potential remains to increase the collection rate and recycling rates (especially for aluminium cans) and reduce the loss of scrap aluminium exported from the EU. This would increase the overall input of secondary aluminium in the sector and significantly reduce the GHG emissions as recycled aluminium emits up to 95% less GHG than primary aluminium.

Long-term scenario (2030-2040): In the long-term, the EU should increase its domestic mining capacities, especially in Greece where this activity is already well developed. Although it is difficult to quantify the avoided CO_2 emissions from this scenario, given that there is no data on the potential increase in production capacity from Greece. However, because of the nature of the mines in Greece (underground mining), those have less impacts on the environment than mines in Guinea (open-casted mining) and replacing some of the imported bauxite by increasing domestic mining would have less impact on the environment (especially in terms of biodiversity).

Overall, the scenarios all showed potential to reduce the environment impact and simply the short- and medium-term scenarios, if implemented, could avoid up to 7.4 million tonnes of CO_2-Eq. each year.

Case study lithium

EU trade data: The EU is heavily dependent on imports of both primary lithium materials and refined lithium, with demand for these materials projected to rise significantly in the coming years and decades. In 2023, the supply of refined lithium was predominantly sourced from Chile, followed by China and Argentina. However, recent years have seen a shift, with decreasing dependency on Chile and growing reliance on China. Notably, when considering the aggregated trade of all types of lithium products, China has emerged as the dominant supplier to the EU. Trade data reveals that while the quantity of imported lithium (based on trade codes related to processing) remained relatively stable over the past decade, the monetary value of imports surged fivefold in 2022–2023 compared to earlier years. Portugal is currently the leading producer within the EU, mining hard rock lithium, which is primarily used in ceramics and glass applications.

Short term scenario (2024-2026): Shifting to alternative lithium suppliers is challenging in the short term, as Australia, the largest producer, refines much of its spodumene in China, posing potential geopolitical risks. Changing supply from Chile, already the largest supplier, may also be difficult, while Portugal's lithium production remains small relative to EU demand. Environmental impacts of producing lithium in China and Australia seem higher than in Chile or Portugal.

Medium term scenario (2026-2030): Currently, the recycling rate of lithium is negligible. However, by 2030, it is estimated that secondary sources could meet 5% to 8% of the EU battery value chain's lithium demand. In the medium term, ramping up recycling could help mitigate supply shortages and reduce environmental impacts. However, recycling technologies need further development and understanding when lithium will become available from in-use stock is crucial for preparing future recycling streams. Tools such as product passports and dynamic material flow models will be critical for forecasting and preparing future recycling streams.

Long-term scenario (2030-2040): In the long term, lithium mining could expand in the EU, with new projects in Austria, Germany, Finland, Portugal, Spain, and others, though many face challenges like community opposition. Most projects plan to extract lithium from hard rock ore, while some explore direct lithium extraction (DLE) from geothermal brines, like companies in Germany, which aim for carbon-negative production. The environmental benefits of EU lithium depend on replacing imports from high-emission sources like China, though DLE technology is still new and uncertain. Emerging battery technologies, such as solid-state and sodium-ion batteries, could reduce future lithium demand, but data on their environmental impacts is limited. Reducing battery demand through efficiency, recycling, and shared mobility could lower the need for raw materials in the long term. To bring back more mining to the EU, mine permitting processes need to be streamlined, and domestic mining and circular economy skill sets further established, e.g., via designated educational programs.

Overall, the medium- and long-term scenarios, if implemented, could avoid the emissions of between 0.5 and 1 million tonnes of CO_2-Eq. per year, showing the importance of decisions in choice of supplying countries, investment in recycling technologies and domestic production.

5.2 Potential implication of this analysis for the world or at global level

The complexity and interdependency of raw material supply chains, coupled with the limitations of this study, make it challenging to apply its findings at a global level. The environmental impacts of supply disruptions depend heavily on demand-supply dynamics, supplier diversity, technological advancements, geopolitical conditions, and policy responses. It is unclear if supply chain disruption would necessarily have any net environmental impact, therefore, potential EU benefits do not necessarily translate into global environmental gains.

Switching to cleaner or domestic suppliers may reduce environmental impacts locally—for example, sourcing aluminium from France instead of Russia and Mozambique, combined with increasing recycling capacity in the EU, could avoid up to 7.4 million tonnes of CO_2-Eq. each year. However, this assumes that Russia's or Mozambique's excess supply is not absorbed elsewhere, and France has the capacity to meet the demand of this material. Consequently, the global environmental impacts will largely depend on the supply response from the original exporting countries.

A comprehensive assessment must consider the applications of raw materials and their role in the clean energy transition. Supply reductions delaying fossil fuel phase-outs could have severe climate consequences. To address these challenges, investing in sustainable and circular supply chains is essential. Advancing recycling technologies and expanding capacity can significantly lower CO_2 emissions and support net-zero targets. Additionally, policy measures like reducing demand, fostering resource-efficient innovations, and substituting lower-impact materials are critical to mitigating the global environmental impacts of supply disruptions.

5.3 Applicability of the framework & next steps

Assessing the environmental impacts of supply risk disruptions faces challenges such as limited data on supply-chain-specific impacts (e.g., from life cycle inventory data) and difficulties in accounting for the dynamic nature of supply-demand shifts when transitioning to alternative suppliers or technologies. However, a comprehensive review of existing literature, including data on current suppliers, recycling technology advancements, domestic mining efforts, available reserves, and trade data for both aluminium and lithium, offers an initial framework to evaluate the potential benefits and trade-offs of various policy options. This approach provides a foundation for understanding the environmental implications of different supply chain strategies and highlights the need for more detailed, dynamic assessments. Synergies, in terms of data needs, exist with EU policies such as the critical raw materials act, the critical raw materials assessment, or ESG reporting.

A specific extension of analysis could take into consideration research and technological innovation for Critical Raw Materials. According to the report by the European Parliament (2024), significant research, development and innovation (R&D&I) efforts are under way.

In Horizon Europe, 90 relevant projects on Critical Raw Materials (CRMs) are active:

- 11 projects on the exploration stage of the CRM supply chain, 20 projects on the extraction stage, 17 projects on the processing stage
- Six projects are developing catalytic technologies with no or low CRM content: Five projects are working on capacitors or super-capacitors without CRM; At least three projects are developing innovative batteries without CRMs
- Around ten projects focus on the design or usage optimization of specific technologies
- Around 35 projects target the recycling or recovery stage of the CRM supply chain
- The five most represented CRMs in the 90 Horizon Europe projects are cobalt (Co), lithium (Li), platinum group metals (PGM), nickel (Ni) and manganese (Mn)

Within Important Projects of Common European Interest (IPCEIs), cross-border innovation and infrastructure projects led by EU Member States are carried out. For batteries, there is the IPCEI first

Summer initiative (from December 2019) and the European Battery Innovation (EuBatIn) (from January 2021). Together they amount to 1 billion in national subsidies (state aid). Already at present, according to the same report, in the area of patents: “Excluding exploration, the EU has a strong position in most of the remaining CRM supply chain, including mining and processing technologies, mining-specific transport technologies, environmental technologies and recycling”. The patenting level of the EU-27 matches or surpasses that of the USA in all these categories.

List of abbreviations

AC	Alternating Current
Al	Aluminium
$Al(OH)_3$	Aluminium hydroxide
Al_2O_3	Aluminium Oxide
AZE	Alliance for Zero Extinction
CaO	Calcium Oxide
CCS	Carbon Capture and Storage
CFC	Chlorofluorocarbons
CIF	Cost, Insurance and Freight
CO_2	Carbon Dioxide
CRM	Critical Raw Material
CRMA	Critical Raw Materials Act
DCB	Dichlorobenzene
DLE	Direct Lithium Extraction
EEA	European Environment Agency
EFTA	European Free Trade Association
ETC-CE	European Topic Centre, Circular Economy and Resource Use
EU	European Union
GHG	Greenhouse Gas
HVDC	High-Voltage Direct Current
IEA	International Energy Agency
LCA	Life Cycle Assessment
LCE	Lithium Carbonate Equivalent
Li	Lithium
Li_2CO_3	Lithium Carbonate
LIB	Lithium-Ion Battery
LiCl	Lithium Chloride
LiOH	Lithium Hydroxide
MCA	Multi-Criteria Analysis
Na_2CO_3	Sodium Carbonate
Na_3AlF_6	Sodium hexafluoroaluminate
NaOH	Sodium Hydroxide
NIMBY	Not In My Backyard
NZIA	Net-Zero Industry Act
NZSP	Net-Zero Strategic Projects
REE	Rare Earth Elements
USGS	United States geological Survey
WGI	Worldwide Governance Indicators
WSI	Water Stress Index
WTO	World Trade Organisation

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Annexes

A. Demand reaction to price shocks in the short- and long term

Own price elasticity of demand plays a crucial role in the assessment of possible reaction to price shocks possibly induced by supply disruption. Elasticity is defined as the relative change in the quantity that is demand of a given good or commodity for a marginal change in the price of the same good and commodity.[18] With few exception (i.e. Giffen goods), own price elasticities have negative signs, suggesting that as the price increases, the quantity that is demanded decreases. Price elasticity is pivotal as it provides guidance to understand whether a large price shock will result into substantial changes in quantities (i.e. high elasticity in absolute value) or into substantial changes in expenditure (i.e. low elasticity in absolute value). A large (in absolute value) elasticity is generally because a product or commodity is essential for the satisfaction of a basic need or the production of an important product.

It is common to distinguish between short- and long-term price elasticities. In general, short-term elasticities are smaller (in absolute terms) than long-term ones. As discussed in section 2, in the short(er) term there are: i. substantial practical constraints to update production processes that enable the shift to substitute commodities/products; ii. limited possibilities to search for new and cheaper trading partners.

The estimation of price elasticities is a challenging task. Indeed, it is not enough to observe quantities and prices for different units and/or in different periods as these observations reflect distinct equilibria of demand and supply on markets. What is generally needed, instead, is an empirical setting where exogenous shift in supply allow to isolate specific segments of the demand curve and estimate price elasticities. This is the main reason why the present assessment does not provide ad hoc estimates of price elasticities for aluminium and lithium.

There exists an extensive literature that estimates own price elasticities for specific markets, products and commodities.[19] For the purpose of the current assessment, we searched standard scientific databases (ISI-WOS and Scopus) to identify scientific results about the estimation of own price elasticities of aluminium and lithium. As expected, the number of studies on aluminium exceeds by far the one on lithium. In Table 2: Price change of aluminium and lithium products and estimated price elasticities. Source: ETC-CE elaboration on the sources indicated. Table 2 we summarise the results of a selection of these studies. In general, results suggest that both short-term and long-term own price elasticities for aluminium and lithium are negative but close to zero.

Table 2: Price change of aluminium and lithium products and estimated price elasticities. Source: ETC-CE elaboration on the sources indicated.

Authors	Year	Commodity	Short-term price elasticity	Long-term price elasticity	Price elasticity (not specified)	Notes
Fernandez	2018a	Aluminium (Europe)		-0.055*		
Shojaeddini et al.	2024	Lithium			-0.11***	
Fernandez	2018b	Aluminium		-0.201*** (FR) -0.176*** (DE) -0.030*** (HU) -0.113*** (IT) -0.189*** (PL) -0.146*** (PT)		

[18] We just consider own price elasticities. However, it should be noted that the demand of a given commodity or product also depends on shifts in the price of other commodities or products (cross-price elasticities). More specifically, as the price of substitute commodities/products increases, the demand of the focal commodity/product also increases as it turns out to be relatively cheaper than its substitutes. Conversely, as the price of complementary commodities/products increases, the demand of the focal commodity/product decreases.

[19] Often these studies focus on specific countries and/or specific segments/uses of these products and commodities, thus limiting the possibility to generalise the results.

Authors	Year	Commodity	Short-term price elasticity	Long-term price elasticity	Price elasticity (not specified)	Notes
				-0.085*** (RO) -0.153*** (ES) -0.223*** (SE)		
Blomberg and Hellmer	2000	Aluminium	0.07*			Secondary aluminium alloy market
Zink et al.	2017	Aluminium	-0.20 (primary) -0.53 (secondary)	-0.34 (primary) -1.03 (secondary)		

The weak link between prices and quantities for lithium and aluminium has important implications for the current assessment. Price shocks are expected to result into limited responses in terms of quantities, while quantity shocks might lead to very large changes in prices, which are then passed through downstream throughout the supply chain.

It should be noted, however, that own price elasticities (or elasticities in general) describe what happens to quantities as a consequence of a small (marginal) change in prices. It could well be the case that larger price changes influence the whole structure of the demand curve. Moreover, standard estimates of own price elasticities say nothing about reactions by market operators and governments aimed at contrasting price or quantity shocks.

B. Trade codes of lithium and aluminium

Table 3: Trade codes for lithium (just processing).

CN8	Description
28273985	Chlorides (excl. ammonium, calcium, magnesium, aluminium, iron, cobalt, nickel, tin and mercury chloride)
28369100	Lithium carbonates
28261990	Fluorides (excl. of ammonium, sodium, aluminium and mercury)
28275900	Bromides and bromide oxides (excl. of sodium, potassium and mercury) (2007-2500);Bromides and bromide oxides (excl. of sodium and potassium)(1988-2006)
28299010	Perchlorates (excl. inorganic or organic compounds of mercury) (2007-2500);Perchlorates(1988-2006)
28269080	Fluorosilicates, fluoroaluminates and other complex fluorine salts (excl. sodium hexafluoroaluminate "synthetic cryolite", dipotassium hexafluorozirconate and inorganic or organic compounds of mercury)
28252000	Lithium oxide and hydroxide
28051990	Alkali metals (excl. sodium)

Table 4: Trade codes for aluminium (all stages).

CN8	Description	Stage
26060000	Aluminium ores and concentrates	1 Extraction/mining
28181011	Artificial corundum, whether or not chemically defined, with < 50 % of the total weight having a particle size > 10 mm (excl. with aluminium oxide content < 98,5% by weight)	2 Processing
28181019	Artificial corundum, whether or not chemically defined, with >= 50 % of the total weight having a particle size > 10 mm (excl. with an aluminium oxide content < 98,5% by weight)	2 Processing
28181091	Artificial corundum, whether or not chemically defined, with < 50 % of the total weight having a particle size > 10 mm (excl. with an aluminium oxide content >= 98,5% by weight "high purity")	2 Processing
28181099	Artificial corundum, whether or not chemically defined, with >= 50 % of the total weight having a particle size > 10 mm (excl. with an aluminium oxide content >= 98,5% by weight "high purity")	2 Processing
28182000	Aluminium oxide (excl. artificial corundum)	2 Processing
28183000	Aluminium hydroxide	2 Processing
28269080	Fluorosilicates, fluoroaluminates and other complex fluorine salts (excl. sodium hexafluoroaluminate "synthetic cryolite", dipotassium hexafluorozirconate and inorganic or organic compounds of mercury)	2 Processing
28273200	Aluminium chloride	2 Processing
28274990	Chloride oxides and chloride hydroxides (excl. copper, lead and mercury)(2007-2500);Chloride oxides and chloride hydroxides (excl. copper and lead)(1988-2006)	2 Processing
28332200	Sulphate of aluminium	2 Processing
28333000	Alums	2 Processing
28499050	Carbides of aluminium, of chromium, of molybdenum, of vanadium, of tantalum, and of titanium, whether or not chemically defined	2 Processing
28500020	Hydrides and nitrides, whether or not chemically defined (excl. compounds which are also carbides of heading 2849, and inorganic or organic compounds of mercury)(2012-2500);Hydrides and nitrides, whether or not chemically defined (excl. compounds which are also carbides of heading 2849)(1998-2011)	2 Processing
38029000	Activated kieselguhr and other activated natural mineral products; animal black, whether or not spent (excl. activated carbon, calcinated diatomite without the addition of sintering agents and activated chemical products)	2 Processing
38249996	Chemical products and preparations of the chemical or allied industries, incl. those consisting of mixtures of natural products, not predominantly composed of organic compounds, n.e.s.	2 Processing
76011010	Aluminium slabs, not alloyed, unwrought	2 Processing
76011090	Aluminium, not alloyed, unwrought (excl. slabs)	2 Processing
76012030	Unwrought aluminium alloys in the form of slabs	2 Processing
76012040	Unwrought aluminium alloys in the form of billets	2 Processing
76012080	Unwrought aluminium alloys (excl. slabs and billets)	2 Processing
76031000	Powders of aluminium, of non-lamellar structure (excl. pellets of aluminium)	2 Processing
76032000	Powders of aluminium, of lamellar structure, and flakes of aluminium (excl. pellets of aluminium, and spangles)	2 Processing
28539090	Inorganic compounds, n.e.s.; amalgams (excl. of precious metals)	3 Fabrication
76041010	Bars, rods and profiles, of non-alloy aluminium	3 Fabrication
76041090	Profiles of non-alloy aluminium, n.e.s.	3 Fabrication
76042100	Hollow profiles of aluminium alloys, n.e.s.	3 Fabrication
76042910	Bars and rods of aluminium alloys	3 Fabrication
76042990	Solid profiles, of aluminium alloys, n.e.s.	3 Fabrication

CN8	Description	Stage
76051100	Wire of non-alloy aluminium, with a maximum cross-sectional dimension of > 7 mm (excl. stranded wire, cables, plaited bands and the like and other articles of heading 7614, and electrically insulated wires)	3 Fabrication
76051900	Wire of non-alloy aluminium, with a maximum cross-sectional dimension of <= 7 mm (other than stranded wires, cables, ropes and other articles of heading 7614, electrically insulated wires, strings for musical instruments)	3 Fabrication
76052100	Wire of aluminium alloys, with a maximum cross-sectional dimension of > 7 mm (excl. stranded wire, cables, plaited bands and the like and other articles of heading 7614, and electrically insulated wires)	3 Fabrication
76052900	Wire, of aluminium alloys, having a maximum cross-sectional dimension of <= 7 mm (other than stranded wires, cables, ropes and other articles of heading 7614, electrically insulated wires, strings for musical instruments)	3 Fabrication
76061130	Aluminium Composite Panel, of non-alloy aluminium, of a thickness of > 0,2 mm	3 Fabrication
76061150	Plates, sheets and strip, of non-alloy aluminium, of a thickness of > 0,2 mm, square or rectangular, painted, varnished or coated with plastics (excl. Aluminium Composite Panel)	3 Fabrication
76061191	Plates, sheets and strip, of non-alloy aluminium, of a thickness of > 0,2 mm but < 3 mm, square or rectangular (excl. such products painted, varnished or coated with plastics, and expanded plates, sheets and strip)(2022-2500);Plates, sheets and strip, of non-alloy aluminium, of a thickness of > 0,2 mm but < 3 mm, square or rectangular (excl. such products painted, varnished or coated with plastics, and expanded plates, sheets and strip)(1988-2021)	3 Fabrication
76061193	Plates, sheets and strip, of non-alloy aluminium, of a thickness of >= 3 mm but < 6 mm, square or rectangular (excl. such products painted, varnished or coated with plastics)(2022-2500);Plates, sheets and strip, of non-alloy aluminium, of a thickness of >= 3 mm but < 6 mm, square or rectangular (excl. such products painted, varnished or coated with plastics)(1988-2021)	3 Fabrication
76061199	Plates, sheets and strip, of non-alloy aluminium, of a thickness of >= 6 mm, square or rectangular (excl. such products painted, varnished or coated with plastics)(2022-2500);Plates, sheets and strip, of non-alloy aluminium, of a thickness of >= 6 mm, square or rectangular (excl. such products painted, varnished or coated with plastics)(1988-2021)	3 Fabrication
76061211	Beverage can body stock, of aluminium alloys, of a thickness of > 0,2 mm	3 Fabrication
76061219	Beverage can end stock and tab stock, of aluminium alloys, of a thickness of > 0,2 mm	3 Fabrication
76061230	Aluminium Composite Panel, of aluminium alloys, of a thickness of > 0,2 mm	3 Fabrication
76061250	Plates, sheets and strip, of aluminium alloys, of a thickness of > 0,2 mm, square or rectangular, painted, varnished or coated with plastics (excl. beverage can body stock, end stock and tab stock, and Aluminium Composite Panel)(2022-2500);Plates, sheets and strip, of aluminium alloys, of a thickness of > 0,2 mm, square or rectangular, painted, varnished or coated with plastics (excl. strip for venetian blinds)(1988-2010)	3 Fabrication
76061292	Plates, sheets and strip, of aluminium alloys, of a thickness of > 0,2 mm but < 3 mm, square or rectangular (excl. painted, varnished or coated with plastics, expanded plates, sheets and strip, beverage can body stock, end stock and tab stock)(2022-2500);Plates, sheets and strip, of aluminium alloys, of a thickness of > 0,2 mm but < 3 mm, square or rectangular (excl. painted, varnished or coated with plastics, expanded plates, sheets and strip, beverage can body stock, end stock and tab stock)(2019-2021);Plates, sheets and strip, of aluminium alloys, of a thickness of > 0,2 mm but < 3 mm, square or rectangular (excl. painted, varnished or coated with plastics, expanded plates, sheets and strip)(2011-2018)	3 Fabrication
76061293	Plates, sheets and strip, of aluminium alloys, of a thickness of >= 3 mm but < 6 mm, square or rectangular (excl. such products painted, varnished or coated with plastics)(2022-2500);Plates, sheets and strip, of aluminium alloys, of a thickness of >= 3 mm but < 6 mm, square or rectangular (excl. such products painted, varnished or coated with plastics)(1988-2021)	3 Fabrication
76061299	Plates, sheets and strip, of aluminium alloys, of a thickness of >= 6 mm, square or rectangular (excl. such products painted, varnished or coated with plastics)(2022-2500);Plates, sheets and strip, of aluminium alloys, of a thickness of >= 6 mm, square or rectangular (excl. such products painted, varnished or coated with plastics)(1988-2021)	3 Fabrication
76069100	Plates, sheets and strip, of non-alloy aluminium, of a thickness of > 0,2 mm (other than square or rectangular)	3 Fabrication
76069200	Plates, sheets and strip, of aluminium alloys, of a thickness of > 0,2 mm (other than square or rectangular)	3 Fabrication
76071111	Aluminium foil, not backed, rolled but not further worked, of a thickness of < 0,021 mm, in rolls of a weight of <= 10 kg (excl. stamping foils of heading 3212, and foil made up as christmas tree decorating material)	3 Fabrication
76071119	Aluminium foil, not backed, rolled but not further worked, of a thickness of < 0,021 mm (excl. stamping foils of heading 3212, and foil made up as christmas tree decorating material and in rolls of a weight <= 10 kg)	3 Fabrication
76071190	Aluminium foil, not backed, rolled but not further worked, of a thickness of >= 0,021 mm but <= 2 mm (excl. stamping foils of heading 3212, and foil made up as christmas tree decorating material)	3 Fabrication
76071910	Aluminium foil, not backed, rolled and further worked, of a thickness of < 0,021 mm (excl. stamping foils of heading 3212, and foil made up as christmas tree decorating material)	3 Fabrication
76071990	Aluminium foil, not backed, rolled and further worked, of a thickness (excl. any backing) from 0,021 mm to 0,2 mm (excl. stamping foils of heading 3212, and foil made up as christmas tree	3 Fabrication

CN8	Description	Stage
	decorating material)(2011-2500);Aluminium foil, not backed, rolled and worked, of a thickness of >= 0.021 mm but < 2 mm (excl. stamping foils of heading 3212, and foil made up as Christmas tree decorating material)(1988-1993)	
76072010	Aluminium foil, backed, of a thickness (excl. any backing) of < 0,021 mm (excl. stamping foils of heading 3212, and foil made up as christmas tree decorating material)	3 Fabrication
76072091	Aluminium Composite Panel, of a thickness <= 0,2 mm(2022-2500);Aluminium foil, backed, rolled and worked, of a thickness (excl. any backing) of >= 0,021 mm but <= 0,2 mm, self-adhesive (excl. stamping foils of heading 3212, and foil made up as christmas tree decorating material)(1994-2010)	3 Fabrication
76072099	Aluminium foil, backed, of a thickness (excl. any backing) of >= 0,021 mm but <= 0,2 mm (excl. stamping foils of heading 3212, foil made up as christmas tree decorating material, and Aluminium Composite Panel)(2022-2500);Aluminium foil, backed, of a thickness (excl. any backing) of >= 0,021 mm but <= 0,2 mm, not self-adhesive (excl. stamping foils of heading 3212, and foil made up as christmas tree decorating material)(1994-2010)	3 Fabrication
76081000	Tubes and pipes of non-alloy aluminium (excl. hollow profiles)	3 Fabrication
76082020	Tubes and pipes of aluminium alloys, welded (excl. hollow profiles)	3 Fabrication
76082081	Tubes and pipes of aluminium alloys, not further worked than extruded (excl. hollow profiles)	3 Fabrication
76082089	Tubes and pipes of aluminium alloys (excl. such products welded or not further worked than extruded, and hollow profiles)	3 Fabrication
76090000	Aluminium tube or pipe fittings "e.g., couplings, elbows, sleeves"	3 Fabrication
26204000	Slag, as and residues containing mainly aluminium	4 Recycling
76020011	Turnings, shavings, chips, milling waste, sawdust and filings, of aluminium; waste of coloured, coated or bonded sheets and foil, of a thickness "excl. any backing" of <= 0,2 mm, of aluminium	4 Recycling
76020019	Waste of aluminium, incl. faulty workpieces and workpieces which have become unusable in the course of production or processing (excl. slag, scale and other waste from the production of iron or steel, containing recyclable aluminium in the form of silicates, ingots and other primary forms, of smelted waste or scrap, of aluminium, ash or the residues of the production of aluminium, and waste in heading 7602.00.11)	4 Recycling
76020090	Scrap of aluminium (excl. slags, scale and the like from iron and steel production, containing recoverable aluminium in the form of silicates, ingots or other similar unwrought shapes, of remelted waste and scrap, of aluminium, and ashes and residues from aluminium production)	4 Recycling

C. Aluminium properties and applications

Aluminium is essential in our daily lives and in the products on which we rely. The element itself is highly versatile and has numerous useful properties that has made it one of the most important commodities traded in significantly large quantities in modern society. It is also a critical component to technologies important for the green energy and digital transitions and the phasing out of fossil fuels. It is estimated that regardless of the extent of the various climate change mitigation scenarios, the demand for aluminium will continue to increase, due to its usage in many low carbon technologies such as wind, energy storage and specifically in solar photovoltaics (Hund et al., 2020). Some estimates suggest a 40% demand increase already by the year 2030, which poses a problem given that the mining and production of primary aluminium is itself intensive in greenhouse gas emissions (Aleksic and Vargas, 2023; IEA, 2021).Thus, there needs to be a balance between aluminium's utilization for green energy production and its carbon reduction technologies and environmentally friendlier, responsible sourcing.

Aluminium has some fundamental important properties that allow for this utilization in a number of different applications. Atomic element number 13, aluminium is a silvery-grey, soft, extremely lightweight metal with a high strength to weight ratio and a specific weight that is about one-third that of steel (Georgitikis et al., 2021). Some particularly useful properties are also that it is a good conductor of electricity, is corrosion resistant, making it ideal for use outdoors, and is extremely malleable, making it highly workable (SCRREEN Project, 2020a; European Aluminium, 2024b). Aluminium is easily recycled without losing any of its useful properties. This last aspect makes it one particularly interesting material to consider in a circular economy.

These wide ranging and useful characteristics of aluminium gives rise to its numerous applications in energy efficient and low carbon technologies. Accounting for more than 85% of the materials used in solar energy production, aluminium is the single most widely used material and is utilized in everything from the panel frame and structural support to the internal wiring. Furthermore, in wind energy it is utilized in the turbine platform and its components, as well as for the transformer stations. Not to mention that it has been used for decades in high voltage transmission grid cables and wires and has been said to be currently the most economical way to transmit power. Heat pumps are built with aluminium heat exchangers also due to its efficient conductivity properties. Moreover, in the rapidly advancing field of hydrogen and alternative fuel cells, aluminium is used as the base plate metal due to its properties of thermal management. Aluminium is also widely used in battery cathode materials and composes their enclosures. Finally, aluminium has numerous uses in diverse types of mobility, specifically for usage in electric vehicles. The light weight nature of frames made with aluminium components allows for efficient energy usage and aids in extending the time and distance the car can drive on a single charge of the battery (European Aluminium, 2024b).

Aluminium is the most abundant metal in the earth's crust (second when compared to silicon which is classified as a metalloid). Due to its affinity for oxygen, it is extremely rare to find aluminium in its native form, instead it is found most in oxides or in silicate minerals. Bauxite is by far the most important primary ore of aluminium. It is a sedimentary deposit formed from the intense weathering of aluminium rich rocks forming what are known as a lateritic bauxite deposit. The ore consists primarily of the aluminium containing hydroxide minerals gibbsite, böhmite and dispore, the minerals chiefly mined for production (IAI, 2022). A second type of bauxite deposit is associated with karst topography in carbonate formations (Mongelli et al., 2017, 2021; Bardossy, 1982). The aluminium content of bauxite ores general ranges from low (about 30% aluminium) to high (about 60% aluminium) grades (Patterson et al., 1986). The majority of the world's bauxite deposits are found in tropic to subtropic regions around the world, where they often make up large, shallow deposits and commonly in areas of dense vegetation (SCRREEN Project, 2020a) and little overburden. Most of the global bauxite mines are using large open cast extraction methods, with very few underground bauxite mines existing. Thus, the mining of bauxite is normally associated with vast disturbances of land and issues of biodiversity loss (IAI, 2022).

D. Trade analysis: detailed results by value chain stage for aluminium

Figure 39: Main import trend for aluminium products (trade codes for extraction). Source: ETC-CE elaboration on COMEXT Eurostat data.

Notes: product codes of the CN8 classifications are reported in Annex II. Totals do not consider heterogeneous aluminium content across different product codes.

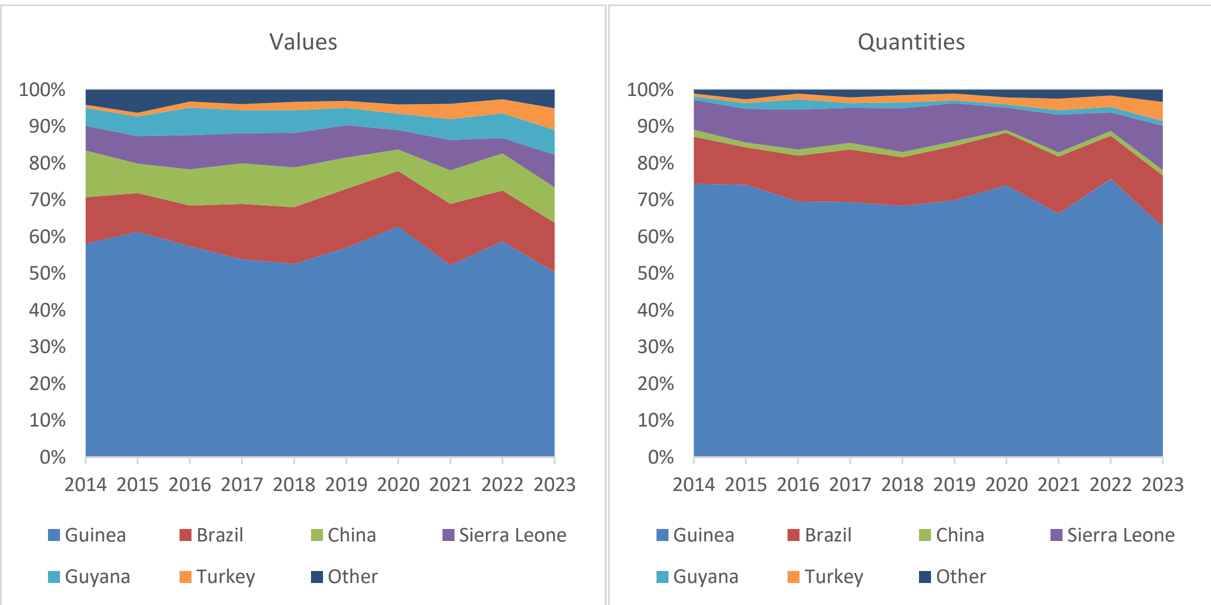


Figure 40: Main trade partners for aluminium (trade codes for extraction). Source: ETC-CE elaboration on COMEXT Eurostat data.

Notes: product codes of the CN8 classifications are reported in Annex II. Totals do not consider of heterogeneous aluminium content across different product codes.

Figure 41: Main import trend for aluminium products (trade codes for processing). Source: ETC-CE elaboration on COMEXT Eurostat data.

Notes: product codes of the CN8 classifications are reported in Annex II. Totals do not take into account of heterogeneous aluminium content across different product codes.

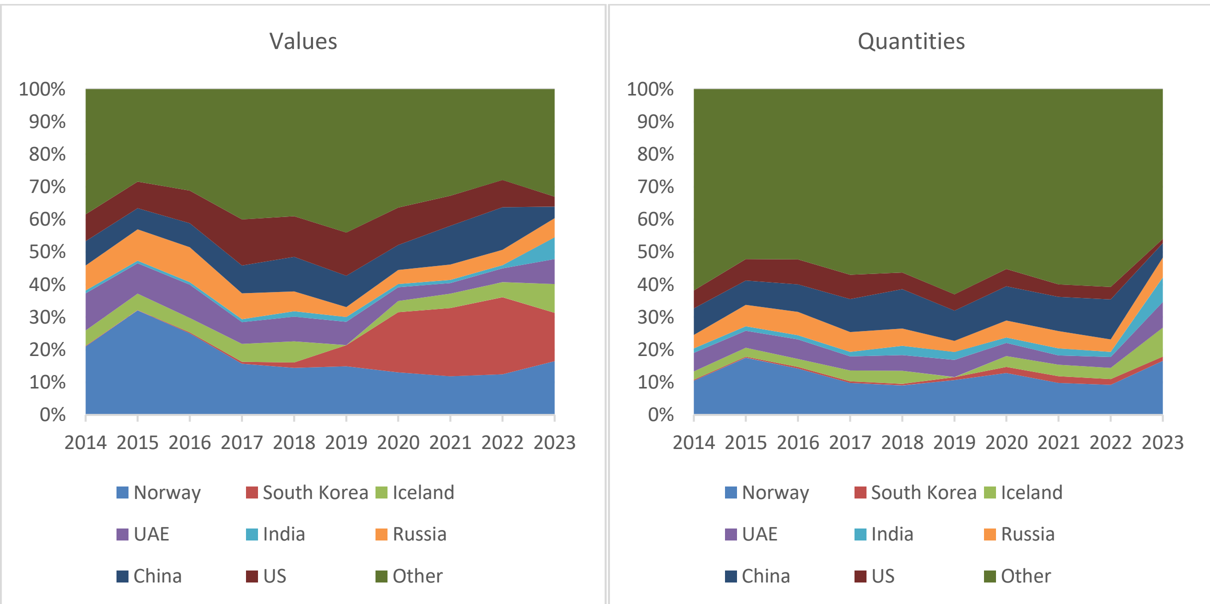


Figure 42: Main trade partners for aluminium (trade codes for processing). Source: ETC-CE elaboration on COMEXT Eurostat data.

Notes: product codes of the CN8 classifications are reported in Annex II. Totals do not take into account of heterogeneous aluminium content across different product codes.

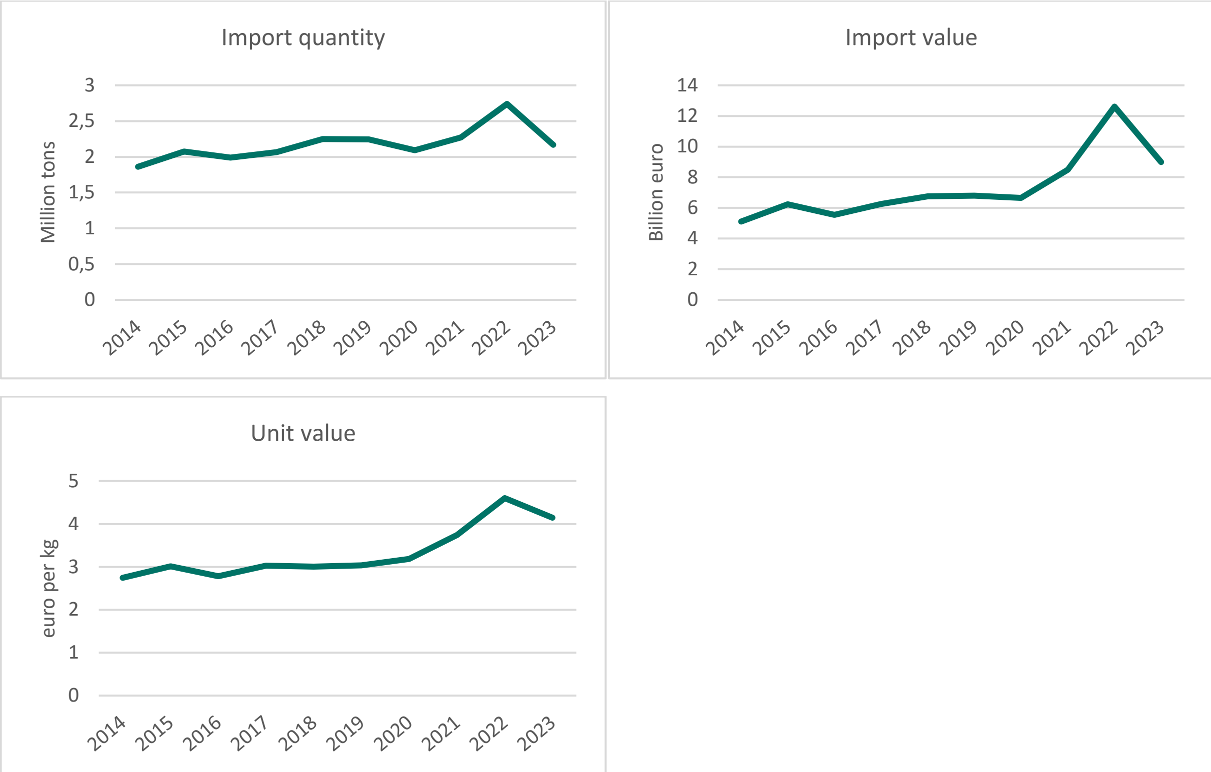


Figure 43: Main import trend for aluminium products (trade codes for fabrication). Source: ETC-CE elaboration on COMEXT Eurostat data.

Notes: product codes of the CN8 classifications are reported in Annex II. Totals do not take into account of heterogeneous aluminium content across different product codes.

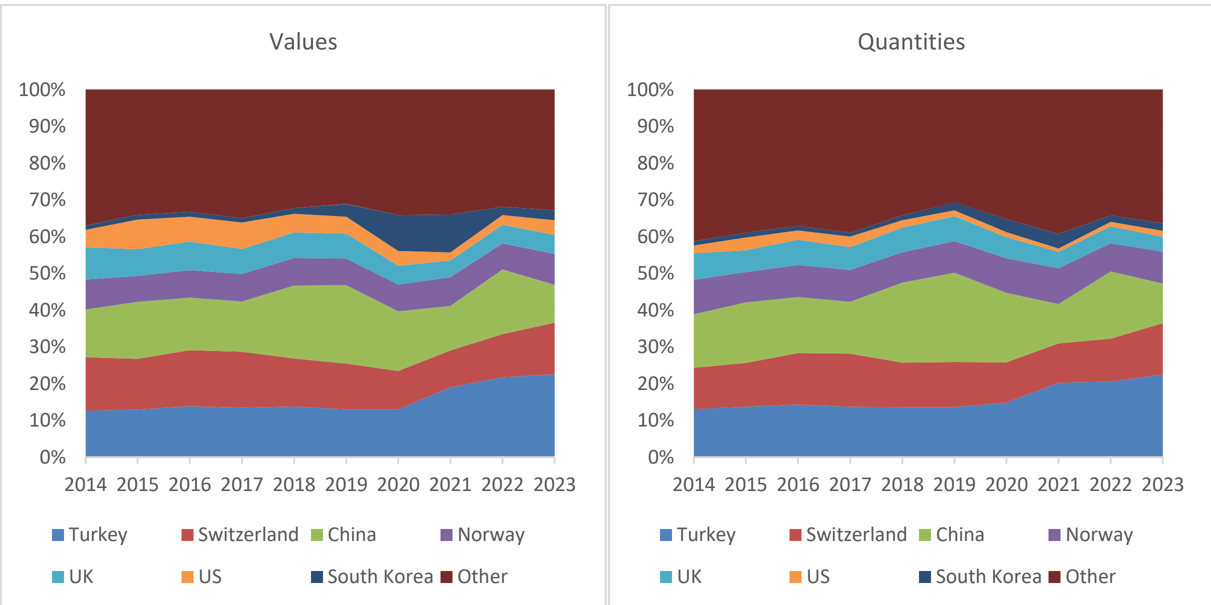


Figure 44: Main trade partners for aluminium (trade codes for fabrication). Source: ETC-CE elaboration on COMEXT Eurostat data.

Notes: product codes of the CN8 classifications are reported in Annex II. Totals do not consider of heterogeneous aluminium content across different product codes.

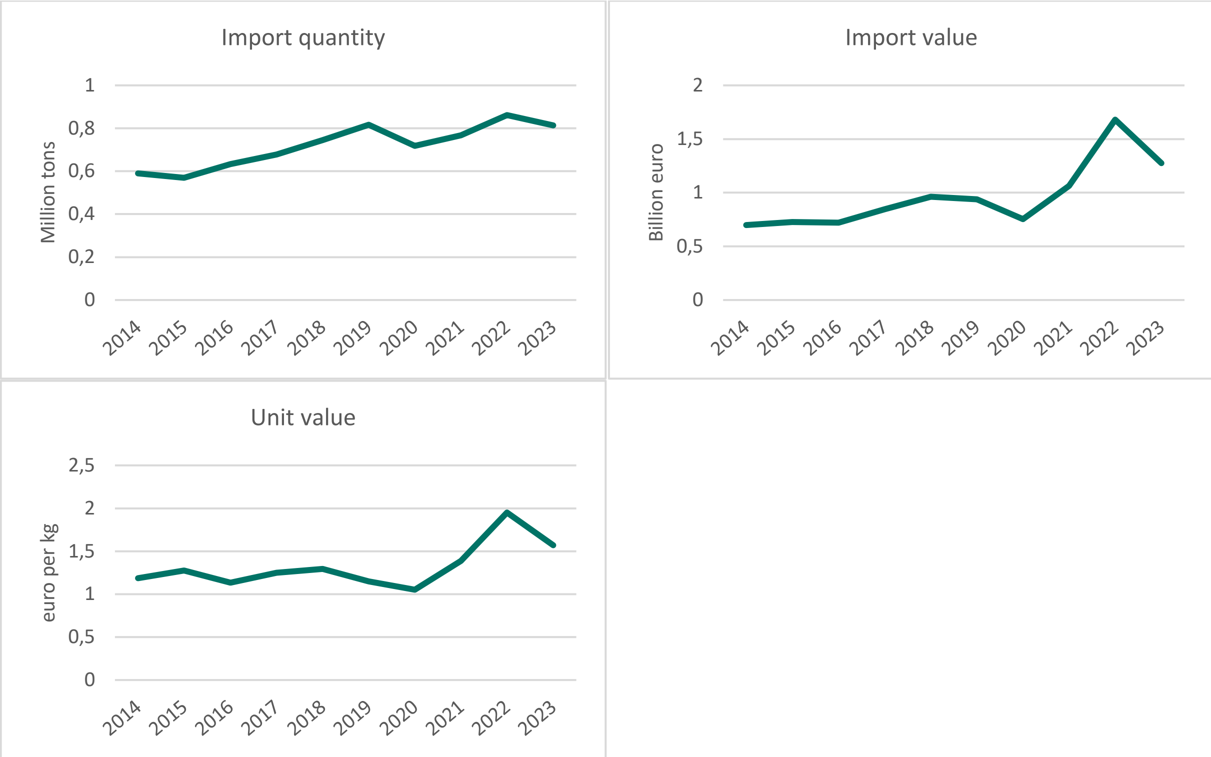


Figure 45: Main import trend for aluminium products (trade codes for recycling). Source: ETC-CE elaboration on COMEXT Eurostat data.

Notes: product codes of the CN8 classifications are reported in Annex II. Totals do not take into account of heterogeneous aluminium content across different product codes.

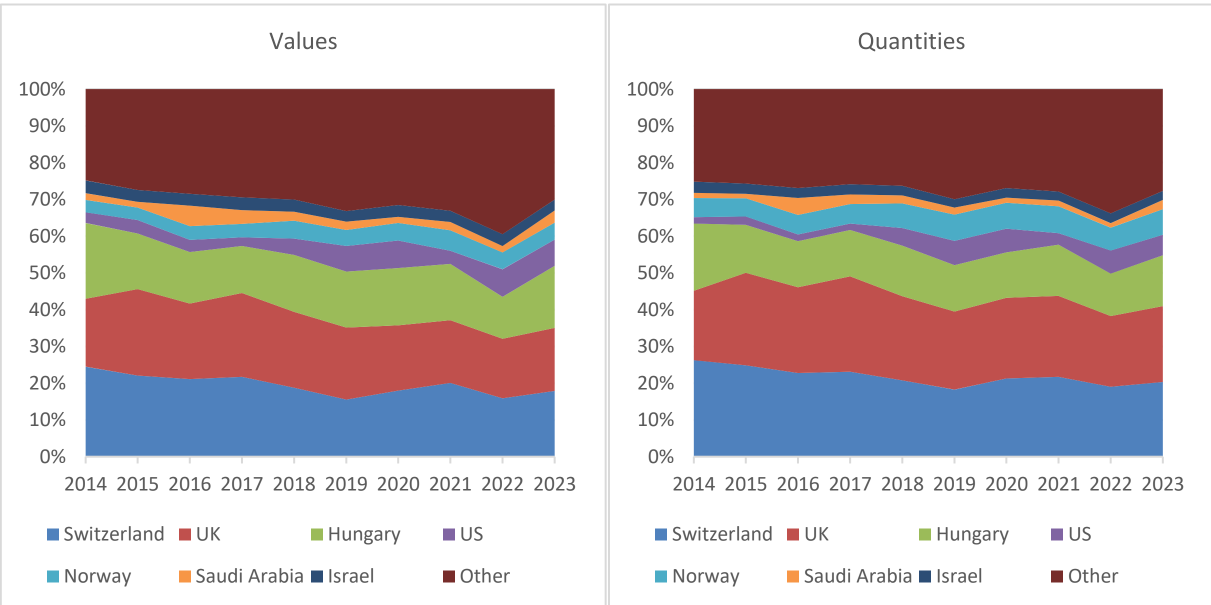


Figure 46: Main trade partners for aluminium (trade codes for recycling). Source: ETC-CE elaboration on COMEXT Eurostat data.

Notes: product codes of the CN8 classifications are reported in Annex II. Totals do not take into account of heterogeneous aluminium content across different product codes.

E. Price change of aluminium product codes between 2021-2023 and 2014-2020 for the top 10 product codes in terms of price change

Table 5: Price change of aluminium product codes between 2021-2023 and 2014-2020 for the top 10 product codes in terms of price change. Source: ETC-CE elaboration on COMEXT Eurostat data.

CN8	Product description	Stage	Ratio between price 2021-2023 and price 2014-2020
28269080	Fluorosilicates, fluoroaluminates and other complex fluorine salts (excl. sodium hexafluoroaluminate "synthetic cryolite", dipotassium hexafluorozirconate and inorganic or organic compounds of mercury)	2 Processing	4.70
38249996	Chemical products and preparations of the chemical or allied industries, incl. those consisting of mixtures of natural products, not predominantly composed of organic compounds, n.e.s.	2 Processing	1.98
76069100	Plates, sheets and strip, of non-alloy aluminium, of a thickness of > 0,2 mm (other than square or rectangular)	3 Fabrication	1.83
28181099	Artificial corundum, whether or not chemically defined, with >= 50 % of the total weight having a particle size > 10 mm (excl. with an aluminium oxide content >= 98,5% by weight "high purity")	2 Processing	1.73
76061193	Plates, sheets and strip, of non-alloy aluminium, of a thickness of >= 3 mm but < 6 mm, square or rectangular (excl. such products painted, varnished or coated with plastics)	3 Fabrication	1.67
38029000	Activated kieselguhr and other activated natural mineral products; animal black, whether or not spent (excl. activated carbon, calcinated diatomite without the addition of sintering agents and activated chemical products)	2 Processing	1.66
76071910	Aluminium foil, not backed, rolled and further worked, of a thickness of < 0,021 mm (excl. stamping foils of heading 3212, and foil made up as Christmas tree decorating material)	3 Fabrication	1.63
28274990	Chloride oxides and chloride hydroxides (excl. copper, lead and mercury)	2 Processing	1.61
76061199	Plates, sheets and strip, of non-alloy aluminium, of a thickness of >= 6 mm, square or rectangular (excl. such products painted, varnished or coated with plastics)	3 Fabrication	1.59058
76081000	Tubes and pipes of non-alloy aluminium (excl. hollow profiles)	3 Fabrication	1.59

F. Lithium properties and applications

Lithium is a crucial element in the energy transition due to its role in the development of high-capacity, rechargeable lithium-ion batteries. Due to their high energy densities, these batteries can store a larger amount of renewable energy for a given volume to mass ratio and this property makes them essential for powering electric vehicles (EVs) (Kundu et al., 2023). Additionally, lithium-ion batteries are key to storing renewable energy from sources like solar and wind, ensuring a stable and reliable energy supply. As the world shifts towards cleaner energy solutions, the demand for lithium is expected to rise, making it a vital component in achieving sustainable and efficient energy systems.

Lithium, an alkali metal with atomic number 3, is the lightest metal on the periodic table. It is silvery-white, soft and the least solid element at room temperature (SCRREEN Project, 2020b; Kundu et al., 2023). With an atomic mass of approximately 6.94 amu, lithium exhibits high reactivity, especially in water, where it forms lithium hydroxide and hydrogen gas. Due to its high reactivity, lithium is not found in its pure form in nature but occurs in mineral compounds such as silicates, phosphates, carbonates, chlorides, fluorides, oxides, and hydroxides (Heuberger and Morgenthaler, 2023). Its single valence electron enables it to readily form ionic compounds. The low density of the element combined with its electrochemical properties, including a high electrode potential and small ionic radius, make it exceptionally suited for use in batteries, contributing to its significant role in modern technology and energy storage applications (SCRREEN Project, 2020b; Kundu et al., 2023).

Owing to its unique properties, lithium has a wide range of end-uses and applications. According to USGS estimates in 2024, approximately 87% of global lithium demand was for the manufacture of batteries followed by ceramics and glass (4%), lubricating greases (2%), air treatment (1%), continuous casting mold flux powders (1%), medical (1%) and other uses (4%) (USGS, 2024b). For these applications various compounds of lithium in particular lithium carbonate (Li_2CO_3), lithium hydroxide (LiOH) and lithium metal and butyllithium are used (Tadesse et al., 2019). The lithium hydroxide and lithium carbonate market is primarily driven by their use in battery chemistries. Lithium hydroxide is essential for nickel-rich chemistries, while lithium carbonate is utilized in both older nickel manganese cobalt (NMC) batteries and emerging chemistries, such as lithium iron phosphate (LFP) cathodes. Demand for these two chemicals is projected to grow concurrently, with hydroxide accounting for 55% of total demand by 2030. However, if LFP chemistries gain a larger market share, hydroxide demand could decrease by 25%, necessitating adjustments in regional sourcing strategies and project development planning (IEA, 2024).

As illustrated in Figure 47, in the EU the share of lithium consumption for battery production is estimated to have changed from 23% in 2010 to 71% in 2020 (SCRREEN Project, 2020b). This increase is primarily driven by the growing use of rechargeable batteries in electric vehicles, portable electronic devices, electric tools, and energy grid storage applications.

Substitution of lithium is possible in batteries (e.g., using calcium, magnesium, and zinc as anode materials in primary batteries, or nickel-metal hydride batteries) ceramics and manufactured glass (e.g., sodic and potassic fluxes), and greases (using calcium and aluminium soaps) (USGS, 2024b; Graedel et al., 2015). In rechargeable batteries, a wide range of non-lithium types are available on the market, such as nickel-metal hydride (NiMH) and lead-acid batteries, with different advantages and disadvantages compared to lithium-ion types. However, lithium is still the preferred material, specially where high-energy density and light weight is required (SCRREEN Project, 2020b). Recently, alternative technologies such as sodium-ion batteries and vanadium flow batteries for low-range vehicles and storage markets are becoming popular (IEA, 2024). Sodium is considered a viable alternative due to its similar chemical behaviour and much greater natural abundance (1,000 times more abundant). Sodium-ion batteries offer benefits such as high power, fast charging capacity, and efficient low-temperature operation, potentially leading to lower environmental impacts, reduced production costs, and shorter supply chains. However, lithium-ion batteries still hold an advantage with their higher energy density, directly affecting the driving range of electric vehicles. This higher energy density means fewer batteries are needed to provide the same amount of energy, which also influences the overall environmental impact of sodium-ion technology, which is assumed to be a greener alternative (Physics Magazine, 2024). According to the IEA study, even if sodium-ion batteries become more popular in the EV market, total lithium demand is projected to decrease by only 10% by 2030 (IEA, 2024).

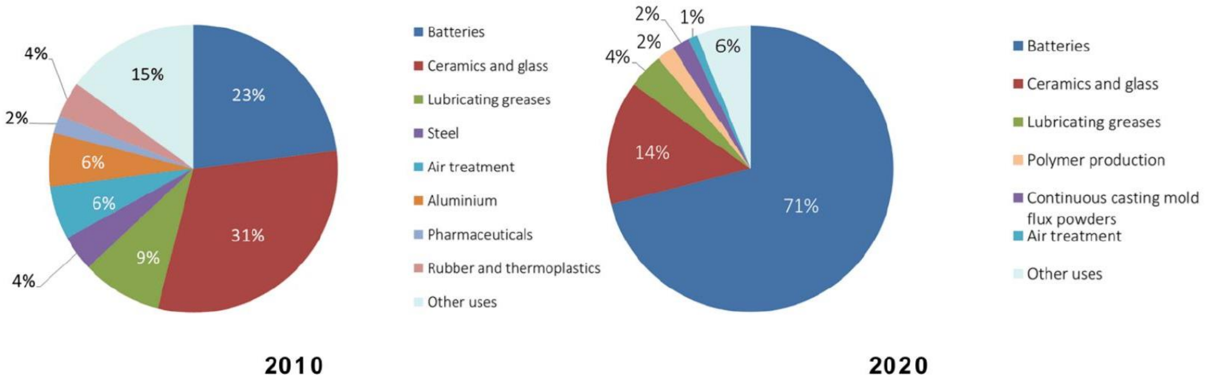


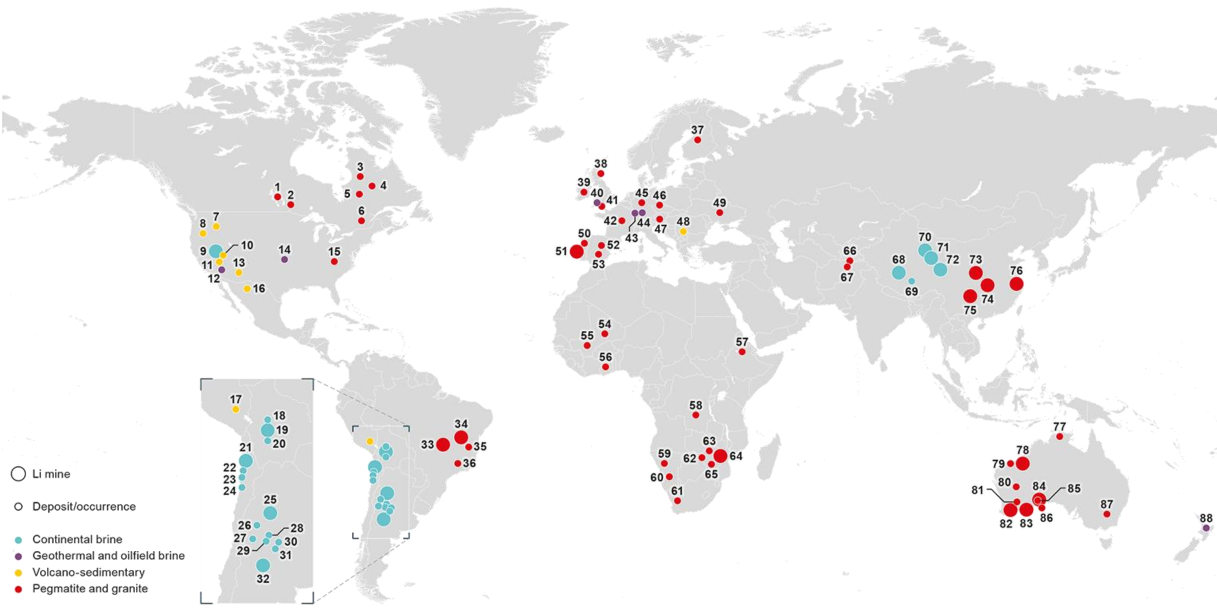
Figure 47. EU uses of lithium under any forms, and evolution of the share of different sector in lithium consumption between 2010 and 2020. Source: IFPEN Report, 2021.

The most common sources of lithium with economic importance are classified into the following ore types:

Brines: Continental brine deposits are the most common type of lithium ore deposits comprising more than half of the world's lithium resources. These deposits are found in arid regions where high evaporation rates exceed precipitation, resulting in the formation of large salt flats (SCRREEN Project, 2020b) also known as salt lakes (Murphy and Haji, 2022). The purity and concentration of salts in these brines can range from very high to less rich areas, where salts are mixed with other components and are generally classified into four main types based on their composition including carbonate, sodium sulphate, magnesium sulphate and chloride with various ionic concentrations (Murphy and Haji, 2022). The average lithium grade in brine deposits is approximately 0.1% LiO_2 (SCRREEN Project, 2020b). As shown in Figure 48, these type of lithium deposits are mainly located in South America, North America and China. The brine resources found in Chile, Argentina and Bolivia, in an area known as Lithium Triangle, contain half of the world's lithium resources (SCRREEN Project, 2020b). Two other types of brines are geothermal and oil and gas field brines, which have lower concentration of lithium in comparison with continental brines. Due to an increasing demand for lithium and the emergence of new direct lithium extraction (DLE) technologies that facilitate economic extraction at relatively low concentrations (Bunker et al., 2022), these less conventional types of brines have also been identified and considered for lithium extraction (Szlugaj and Radwanek-Bąk, 2022).

Pegmatite or hard rock lithium deposits: These types of deposits are the second major economic resource of lithium. In pegmatites, which are coarse-grained igneous rocks formed from crystalized magma, lithium is mainly found in form of silicate ore minerals spodumene, lepidolite, petalite and amblygonite (Swain, 2017). Spodumene with the highest lithium content at 3.73% (Murphy and Haji, 2022) is considered as the most important mineral in these types of ores. The average lithium content in pegmatitic ore deposits is estimated to be between 1.5-4% Li_2O (Szlugaj and Radwanek-Bąk, 2022). As is illustrated in Figure 48, large occurrences of these types of lithium deposits are found in Australia, China, Brazil, Zimbabwe and Portugal.

Lithium bearing clays: With the rising demand for lithium, the potential of lithium-bearing clays as an alternative source has been recognized, despite its low grades and complex mineral components (Zhao et al., 2023). The primary minerals in these types of deposits are lepidolite and zinnwaldite, which have lower lithium content compared to other minerals found in pegmatites. Many lithium bearing clay mineral resources have been identified in China and Europe, as shown in Figure 48.



1 Tanco, Canada
2 Separation Rapids, Canada
3 James Bay, Canada
4 Rose, Canada
5 Whabouchi, Canada
6 Val-d'Or, Canada
7 McDermitt, USA
8 Kings Valley, USA
9 Silver Peak, USA
10 Bonnie Claire, USA
11 Boron, USA
12 Salton Sea, USA
13 Clayton North, USA
14 Magnolia, USA
15 Kings Mountain, USA
16 Sonora, Mexico
17 Falchani, Peru
18 Salar de Coipasa, Bolivia
19 Salar de Uyuni, Bolivia
20 Salar de Pastos Grandes, Bolivia
21 Salar de Atacama (2 operators), Chile
22 Salar de Aguilera, Chile
23 Salar de Pedernales, Chile
24 Salar de Maricunga, Chile
25 Salar de Olaroz, Argentina
26 Salar de Cauchari (2 projects), Argentina
27 Salar del Rincón (3 projects), Argentina
28 Salar de Pozuelos, Argentina
29 Salar de Pastos Grandes, Argentina
30 Salar de Ratones, Argentina
31 Salar de Diablillos, Argentina
32 Salar del Hombre Muerto (3 projects), Argentina
33 Mibra, Brazil
34 Mina da Cachoeira, Brazil
35 Jequitinhonha, Brazil
36 Volta Grande, Brazil
37 Länttä (and 5 others), Finland
38 Glenbuchat, United Kingdom
39 Aclare, Ireland
40 United Downs, United Kingdom
41 St Austell, United Kingdom
42 Chédeville (and 4 others), France
43 Rittershoffen, France
44 Upper Rhine Valley, Germany
45 Zinnwald (and 4 others), Germany
46 Cinovec, Czech Republic
47 Wolfsberg, Austria
48 Jadar, Serbia
49 Polokhovskoe (and 2 others), Ukraine
50 Mina do Barroso (and 3 others), Portugal
51 Alijó, Portugal
52 Valdeflórez/San José, Spain
53 Alberta I, Spain
54 Bougouni, Mali
55 Goulamina, Mali
56 Ewoyaa, Ghana
57 Kenticha, Ethiopia
58 Manono-Kitotolo, Democratic Republic of Congo
59 Uis, Namibia
60 Karibib, Namibia
61 Orange River Area, South Africa
62 Kamativi, Zimbabwe
63 Zulu, Zimbabwe
64 Bikita, Zimbabwe
65 Arcadia, Zimbabwe
66 Parun area, Afghanistan
67 Nuristan area, Afghanistan
68 Zhabuye Salt Lake, China
69 Dangxiongcuo, China
70 West Taiji Nai'er, China
71 East Taiji Nai'er, China
72 Qinghai Salt Lake, China
73 Sichuan Aba, China
74 Maerkang, China
75 Jiajika, China
76 Ningdu, China
77 Finniss, Australia
78 Pilgangoora, Australia
79 Wodgina, Australia
80 Kathleen Valley, Australia
81 Mount Holland, Australia
82 Greenbushes, Australia
83 Mount Cattlin, Australia
84 Mount Marion, Australia
85 Bald Hill, Australia
86 Buldania, Australia
87 Narraburra, Australia
88 Ohaaki, New Zealand

Figure 48. Global lithium mines, deposits and occurrences. Source BGS, 2021.

According to the USGS data (USGS, 2024b), 58% of lithium resources come from brines, 26% from pegmatites, 7% from lithium clays, and 9% from other types of lithium deposits including oil-field, geothermal brines, and lithium zeolites.

G. Price change of lithium products between 2022-2023 and 2014-2021.

Table 6: Price change of lithium products between 2022-2023 and 2014-2021. Source: ETC-C elaboration on COMEXT Eurostat data.

CN8	Product description	Ratio between price 2021-2023 and price 2014-2020
28269080	Fluorosilicates, fluoroaluminates and other complex fluorine salts (excl. sodium hexafluoroaluminate "synthetic cryolite", dipotassium hexafluorozirconate and inorganic or organic compounds of mercury)	4.84
28252000	Lithium oxide and hydroxide	3.80
28369100	Lithium carbonates	2.18
28273985	Chlorides (excl. ammonium, calcium, magnesium, aluminium, iron, cobalt, nickel, tin and mercury chloride)	1.99
28051990	Alkali metals (excl. sodium)	1.73
28299010	Perchlorates (excl. inorganic or organic compounds of mercury)	1.35
28275900	Bromides and bromide oxides (excl. of sodium, potassium and mercury)	1.09
28261990	Fluorides (excl. of ammonium, sodium, aluminium and mercury)	0.97

H. Results of the Multi-Criteria Analysis

Result for **aluminium** supplying countries

MCA Aluminium (Bauxite)					WGI ranking 2022	WGI ranking 2022	WGI ranking 2022	WGI ranking 2022	WGI ranking 2022	WGI ranking 2022	
	Reserves endowment 2024 (x1000 tons)_USGS	Mining production of bauxite 2022 (x1000 tons)_JRC data	EU country 2024 (0=no; 1=yes)	EEA/EFTA/Schengen country 2024 (0=no; 1=yes)	Voice & accountability	Political Stability & No Violence	Government Effectiveness	Regulatory Quality	Rule of Law	Control of Corruption	Overall score
Kazakhstan	160000	4175	0	0	19.81	32.55	58.49	52.83	35.85	48.58	
Saudi Arabia	180000	5930	0	0	7.73	32.08	70.75	65.09	58.02	63.68	
Greece*	250000	1173	100	100	76.81	49.06	66.51	67.45	59.91	56.6	
Russia	480000	6712	0	0	14.49	16.04	25.94	13.21	12.26	19.34	
India	650000	23831	0	0	49.28	24.53	63.21	50.94	55.19	44.34	
China	710000	74300	0	0	6.28	28.3	68.4	36.79	52.83	55.19	
Guyana*	850000	705	0	0	55.07	47.17	43.4	32.55	41.04	45.28	
Indonesia	1000000	28808	0	0	52.66	29.25	66.04	59.43	45.28	37.74	
Jamaica	2000000	4364	0	0	64.25	57.55	71.7	58.96	51.89	54.25	
Brazil	2700000	31608	0	0	55.56	33.96	30.66	43.87	43.4	32.08	
Australia	3500000	100478	0	0	93.24	81.6	92.92	99.53	91.04	95.28	
Vietnam	5800000	4000	0	0	13.53	45.75	59.43	36.32	47.64	45.75	
Guinea	7400000	103525	0	0	19.32	16.98	15.57	15.57	14.15	18.4	

DECISION MATRIX ALUMINIUM

Performance/decision matrix Each cell = (x - Min)/(Max - Min) of the column of table above											**With weights as stated (changing weights changes results)**
Kazakhstan	0	3	0	0	16	25	55	46	30	39	7
Saudi Arabia	0	5	0	0	2	24	71	60	58	59	9
Greece*	1	0	100	100	81	50	66	63	60	50	58
Russia	4	6	0	0	9	0	13	0	0	1	3
India	7	22	0	0	49	13	62	44	54	34	14
China	8	72	0	0	0	19	68	27	51	48	25
Guyana*	10	0	0	0	56	47	36	22	37	35	8
Indonesia	12	27	0	0	53	20	65	54	42	25	15
Jamaica	25	4	0	0	67	63	73	53	50	47	14
Brazil	35	30	0	0	57	27	20	36	40	18	17
Australia	46	97	0	0	100	100	100	100	100	100	46
Vietnam	78	3	0	0	8	45	57	27	45	36	15
Guinea	100	100	0	0	15	1	0	3	2	0	36
Weight assigned to criteria in column **(without** yellow criteria)	**0.104**	**0.248**	**0.237**	**0.237**	**0.029**	**0.029**	**0.029**	**0.029**	**0.029**	**0.029**	1

Results for **lithium** supplying countries

MCA Lithium					WGI ranking 2022	WGI ranking 2022	WGI ranking 2022	WGI ranking 2022	WGI ranking 2022	WGI ranking 2022	
	Reserves endowment 2024 (x1000)_USGS	Mining production of lithium 2022 (tons)_JRC data	EU country 2024 (0=no; 1=yes)	EEA/EFTA/ Schengen country 2024 (0=no; 1=yes)	Voice & accountability	Political Stability & No Violence	Government Effectiveness	Regulatory Quality	Rule of Law	Control of Corruption	Overall score
United States	1100000	1640	0	0	72.95	45.28	86.79	91.04	88.68	82.55	
Argentina	3600000	14210	0	0	62.8	46.7	41.98	25.94	34.91	36.32	
Australia	6200000	149800	0	0	93.24	81.6	92.92	99.53	91.04	95.28	
Brazil	390000	7863	0	0	55.56	33.96	30.66	43.87	43.4	32.08	
Canada	930000	0	0	0	95.65	73.58	94.34	95.75	92.92	93.4	
Chile	9300000	110350	0	0	78.26	51.42	69.34	81.13	72.64	80.66	
China	3000000	57900	0	0	6.28	28.3	68.4	36.79	52.83	55.19	
Portugal	60000	210	1	1	89.86	75.94	80.19	75	83.96	75.94	↓
Zimbabwe	310000	3540	0	0	18.84	16.51	10.85	6.6	11.32	8.49	

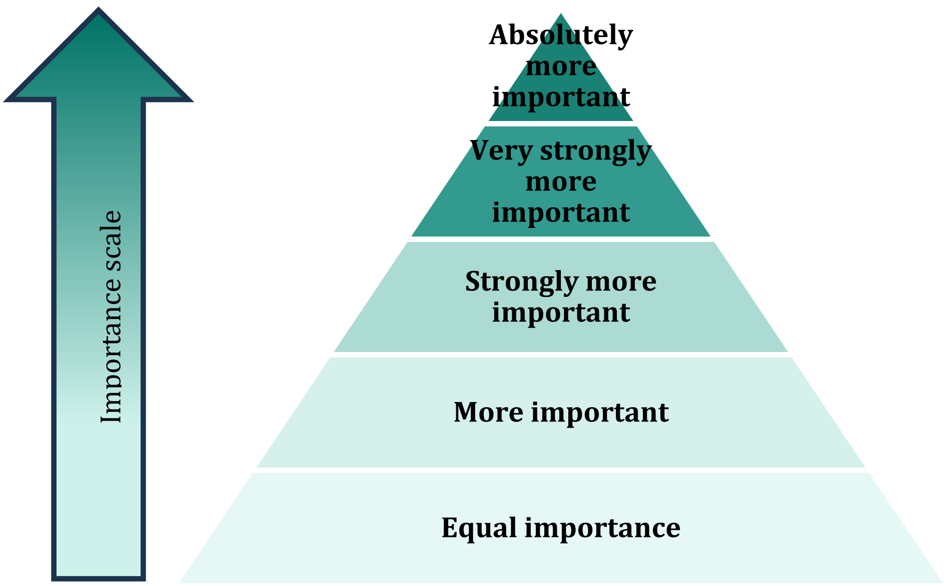
DECISION MATRIX LITHIUM

Performance/decision matrix Each cell = (x - Min)/(Max - Min) of the column of table above											**With weights as stated (changing weights changes results)**
United States	11	1	0	0	75	44	91	91	95	85	15
Argentina	38	9	0	0	63	46	37	21	29	32	13
Australia	66	100	0	0	97	100	98	100	98	100	49
Brazil	4	5	0	0	55	27	24	40	39	27	8
Canada	9	0	0	0	100	88	100	96	100	98	18
Chile	100	74	0	0	81	54	70	80	75	83	41
China	32	39	0	0	0	18	69	32	51	54	19
Portugal	0	0	100	100	94	91	83	74	89	78	62
Zimbabwe	3	2	0	0	14	0	0	0	0	0	1
Weight assigned to criteria in column **(without** yellow criteria)	**0.104**	**0.248**	**0.237**	**0.237**	**0.029**	**0.029**	**0.029**	**0.029**	**0.029**	**0.029**	**1**

I. Multi-Criteria analysis: Analytical Hierarchy Process for the attribution of weights.

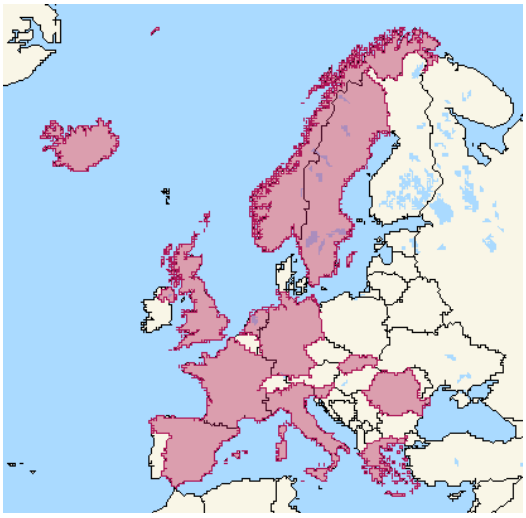
Level of importance given to the criteria

	Reserves endowment	Mining production	EU country	EEA/EFTA/Schengen country	WGI all categories
Reserves endowment					
Mining production	Mining production is strongly more important than reserves endowment				
EU country	EU country is very strongly more important than reserves endowment.	EU country is slightly less important than mining production.			
EEA/EFTA/Schengen country	EEA/EFTA/Schengen countries are very strongly more important than reserves endowment.	EEA/EFTA/Schengen countries are slightly less important than mining production	EEA/EFTA/Schengen countries are equally important to EU countries		
WGI all categories	The WGI is strongly less important than reserves endowment	The WGI is strongly less important than mining production	The WGI is absolutely less important than EU countries	The WGI is absolutely less important than EEA/EFTA/Schengen countries	



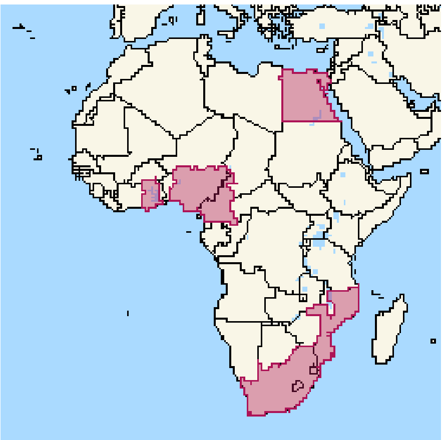
J. Countries included in the Ecoinvent dataset

For EU&EFTA countries:



For Russia and Europe outside EU countries:

For Africa:



K. Trade barriers

Figure 49 reports the recent trend in average tariffs for aluminium and lithium.[20] Overall, tariff barriers are very small on average, between 1.5% and 2% of the import value for aluminium and less than 0.5% of the import value for lithium. Figure 50 instead shows the distribution of average tariff across different product codes and across different trading partners. Even when considering these two dimensions of heterogeneity, tariffs remain very low, well below 10% for both aluminium and lithium. By combining this evidence with the observation of very large increases in the price of import since 2021-2022, it is clear that further reduction of import tariffs is likely to play a minor role in mitigating price shocks.

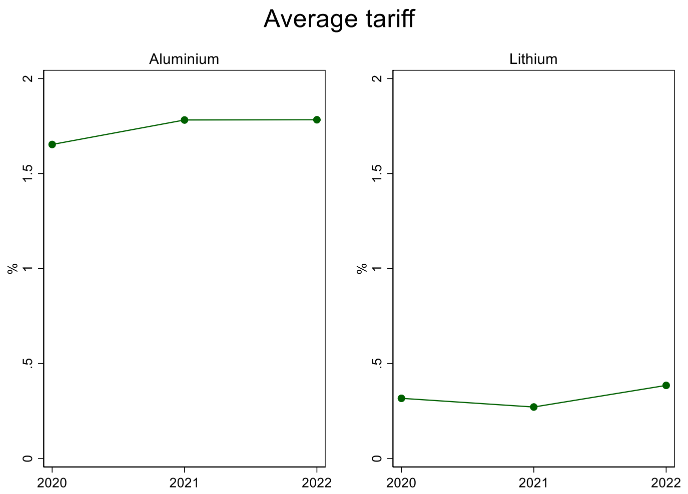


Figure 49. Average tariff from 2020 to 2022. Source: ETC-CE elaboration on WTO data

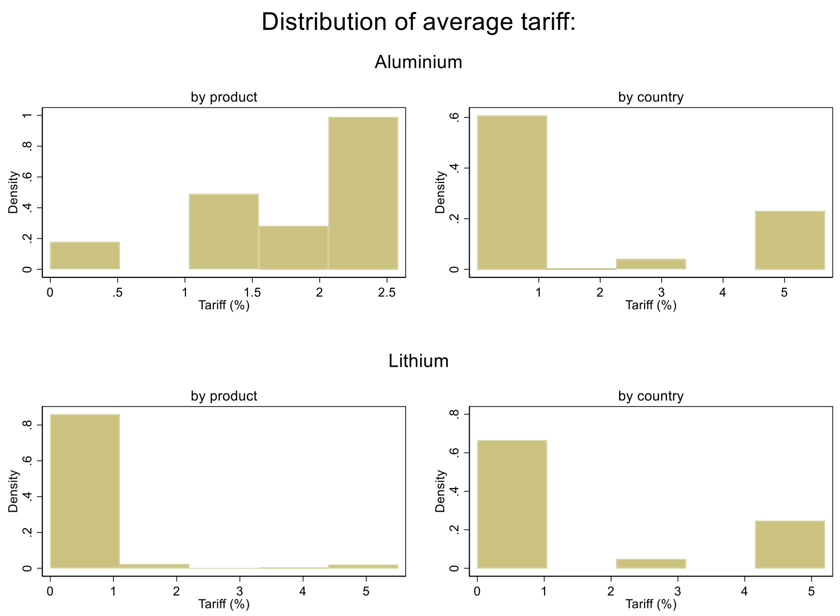


Figure 50. Distribution of average tariff (elaborate and insert source)

[20] For each trade code we compute the unweighted average of tariffs across all trade partners. Then, average tariffs by product code are aggregated by considering the relative weight of each product code in terms of its value of import in the EU.