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The Aluminum Value Chain
A Key Component of Europe's Strategic Autonomy and Carbon Neutrality

Thibault MICHEL

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Executive summary

The United States of America (US), Canada and the European Union (EU) all now consider aluminum as strategic. This metal is indeed increasingly used, especially for the energy transition, be it for electric vehicles (EVs), electricity grids, wind turbines or solar panels.

Europe will, therefore, need growing aluminum supplies in the coming years. However, the European aluminum industry has been weakened over the last decades and henceforth only represents a small share of global aluminum production. As a consequence, it cannot entirely meet domestic needs.

Aluminum has a substantial environmental footprint and its production, from bauxite to primary aluminum, comes with major greenhouse gas (GHG) emissions. Those emissions are especially due to the tremendous amounts of energy (gas and electricity) consumed during the industrial process, particularly for electrolysis. The major use of electricity entails an important influence of the structure of the national electricity mix on aluminum's CO_2 emissions. But some emissions are also specific to aluminum production, for instance, the ones produced by the chemical reaction operated within the scope of the electrolysis in order to transform alumina into primary aluminum.

As demand will grow in the coming years, Europe will have to produce more aluminum to meet the needs of its energy transition, while reducing the carbon footprint of its aluminum industry.

To address this challenge, several decarbonization technologies are currently under consideration. As for other industries, energy efficiency or electrification of the industrial processes (using low-carbon electricity sources) can help to reduce aluminum's footprint. However, these two solutions have often already been implemented, especially to reduce energy costs. This partial implementation allows the European aluminum industry to have a carbon footprint of 6.8 tonnes of CO_2 for 1 tonne of primary aluminum, while the global average is of 16.1 tonnes of CO_2.

Recycling also has a key role to play since recycled aluminum consumes 96% less energy and emits around four times less GHG (regarding direct emissions) than primary aluminum. Nevertheless, if improving aluminum recycling in Europe will be a crucial step, additional primary aluminum supplies will remain essential and recycling is no silver bullet. All these solutions are relevant tools for the reduction of the European aluminum industry's carbon footprint but will not be sufficient to reach carbon neutrality.

To do so, the aluminum sector will need disruptive technologies. Two of them are considered at present. First, carbon capture utilization and storage (CCUS), for which several projects are currently developed in Europe, especially in Norway, Iceland and France. Nevertheless, this technology requires major investment amounts while the smoke emitted during the electrolysis process is poorly concentrated in CO_2. The second technology is inert anodes, for which three projects are currently being developed in the world, in Canada, Russia and Germany. Yet, the deployment of these two technologies at an industrial scale is not expected before 2030 and most likely, for later.

Facing rising energy costs while global aluminum prices are kept relatively low due to large Chinese supplies not being exposed to the same production costs, the European aluminum industry is also confronted with competitiveness issues. With the reform of the EU ETS legislation and the creation of the Carbon Border Adjustment Mechanism (CBAM), primary aluminum producers and processed product manufacturers are worried about international competition and a potential loss of competitiveness. If this mechanism appears to be a necessary policy to protect the European industry's competitiveness while allowing the decarbonization of the most emitting industries, it also contains flaws, with circumvention risks.

The EU must take up the challenge of developing a decarbonized, competitive and resilient aluminum industry. To this end, several elements could be considered:

1. Reinforcing primary aluminum production in Europe;
2. Providing a larger support to the development of decarbonization technologies;
3. Improving recycling across Europe and limiting scrap exports;
4. Extending the scope of the CBAM to a larger number of processed products and boosting EU's climate diplomacy abroad;
5. Building resilience, with a focus on Europe alumina supply.

Résumé

Les États-Unis, le Canada et l'Union européenne (UE) considèrent désormais tous l'aluminium comme un élément stratégique. Ce métal est en effet de plus en plus utilisé, en particulier dans le cadre de la transition énergétique, pour les véhicules électriques, les réseaux, les éoliennes ou les panneaux solaires.

L'Europe aura ainsi besoin d'approvisionnements grandissants en aluminium dans les années à venir. Cependant, l'industrie européenne de l'aluminium a été affaiblie au cours des dernières décennies et ne représente désormais qu'une faible part de la production mondiale. En conséquence, elle n'est plus en mesure de subvenir aux besoins européens.

L'aluminium possède une empreinte environnementale conséquente et sa production, de la bauxite à l'aluminium primaire, entraîne d'importantes émissions de gaz à effet de serre (GES). Ces émissions sont particulièrement liées aux quantités extrêmes d'énergie (gaz et électricité) consommées au cours du processus industriel, notamment pour l'électrolyse. La forte consommation d'électricité nécessaire confère à la structure des mix électriques nationaux une influence majeure sur les émissions de CO_2 issues de l'aluminium. Mais certaines émissions sont aussi spécifiques à la production d'aluminium, par exemple celles produites par la réaction chimique opérée dans le cadre de l'électrolyse, qui transforme l'alumine en aluminium primaire.

Avec une croissance de la demande dans les années à venir, l'Europe devra produire plus d'aluminium afin de remplir les besoins de sa transition énergétique, tout en réduisant l'empreinte carbone de son industrie de l'aluminium.

Pour relever ce défi, différentes technologies de décarbonation sont actuellement considérées. Comme pour d'autres industries, l'efficacité énergétique ou l'électrification des processus industriels peuvent aider à réduire cette empreinte carbone. Cependant, ces deux solutions ont généralement d'ores et déjà été mises en œuvre par les industriels, afin de réduire les coûts énergétiques. La mise en place partielle de ces solutions a permis à l'industrie européenne de l'aluminium d'avoir une empreinte carbone de 6,8 tonnes de CO_2 par tonne d'aluminium primaire, quand la moyenne mondiale est de 16,1 tonnes de CO_2.

Le recyclage doit aussi pouvoir jouer un rôle clé, en particulier car un aluminium recyclé consomme 96 % d'électricité de moins qu'un aluminium primaire, avec des émissions de GES environ quatre fois moindres (pour ce qui est des émissions directes). Toutefois, si le développement du recyclage en Europe constituera une étape cruciale, des approvisionnements

supplémentaires en aluminium primaire restent essentiels et le recyclage ne pourra être un remède miracle. L'ensemble des solutions évoquées constitue des outils pertinents pour réduire l'empreinte carbone de l'industrie européenne de l'aluminium mais ne sera pas suffisant pour atteindre la neutralité carbone.

Pour ce faire, le secteur de l'aluminium aura besoin de technologies disruptives. Deux d'entre elles sont aujourd'hui à l'étude. En premier lieu, le captage et séquestration du carbone ainsi que son utilisation (CCUS), pour lequel plusieurs projets sont actuellement développés en Europe, en particulier en Norvège, en Islande et en France. Néanmoins, cette technologie requiert des investissements massifs tandis que les fumées émises lors du processus d'électrolyse sont peu concentrées en CO_2. La seconde technologie est celle de l'anode inerte, pour laquelle trois projets sont développés dans le monde à l'heure actuelle, au Canada, en Russie et en Allemagne. Cependant, le déploiement de ces technologies à une échelle industrielle n'est pas prévu avant 2030 et pourrait se produire plus tard encore.

Face à l'augmentation des coûts de l'énergie alors que les prix mondiaux de l'aluminium sont maintenus à des niveaux relativement bas en raison de l'importance de l'offre chinoise, qui n'est pas exposée aux mêmes coûts de production, l'industrie européenne de l'aluminium est aussi confrontée à des problématiques en matière de compétitivité. Avec la réforme de la législation européenne sur les crédits carbone et la mise en place du Mécanisme d'ajustement carbone aux frontières (MACF), les industriels de l'aluminium primaire et les producteurs de produits manufacturés en aluminium sont inquiets de la concurrence internationale et redoutent une potentielle perte de compétitivité. Si ce mécanisme apparaît comme une politique nécessaire pour protéger la compétitivité des industriels européens tout en permettant la décarbonation des industries les plus polluantes, il contient des failles, avec des risques de contournements.

L'UE doit relever le défi de développer une industrie de l'aluminium décarbonée, compétitive et résiliente. À cette fin, plusieurs éléments pourraient être étudiés :

1. Renforcer la production d'aluminium primaire en Europe ;
2. Fournir un soutien plus large au développement de technologies de décarbonation ;
3. Améliorer le recyclage à travers l'Europe et limiter les exportations de déchets ;
4. Étendre le périmètre du MACF à davantage de produits transformés et intensifier la diplomatie climatique de l'UE à l'étranger ;
5. Développer la résilience de l'industrie européenne, en particulier concernant les approvisionnements en alumine.

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Introduction

In 2018, Europe woke up to the strategic importance of aluminum and its value chains when the United States of America (US) suddenly and unexpectedly imposed sanctions on Oleg Deripaska, a Russian oligarch owner of Rusal. This decision resulted in a halt in Europe's alumina supply as well as in sharply rising prices for aluminum and alumina, not least due to Rusal's ownership of the Irish alumina refinery plant of Aughinish, which is a key supplier of alumina to aluminum plants across Europe.

A second alert came following a *coup d'état* in the bauxite-rich Republic of Guinea in 2021, which led to a rise in aluminum prices. This reminded us that aluminum has a geopolitical footprint, as was already the case during the Cold War when Guinea enjoyed close military and economic relations with the USSR, which had invested in its bauxite production.[1]

The upstream value chain of aluminum is split into several steps and, therefore, divided between a diversity of actors. Like many other metals, aluminum does not exist in nature and cannot be found as a metal in the ground. The production of aluminum relies on the exploitation and the treatment of an ore, bauxite. Following the process developed by German chemist Karl Josef Bayer, bauxite is first transformed into alumina. Alumina (Al2O3) contains both aluminum and oxygen atoms. To remove the oxygen present in alumina, an electrolysis process is used, separating the two chemical elements and allowing them to collect the sole aluminum. The metal obtained using this process, called Hall-Héroult, is defined as primary aluminum.

Aluminum is a strategic metal, used by the defense, aerospace, building and digital industries but also increasingly for the energy transition. It is indeed a crucial component of EVs, electricity grids, wind turbines and solar panels. The US, Canada and the EU have all included aluminum in their critical minerals list.

Europe[2] is still producing aluminum, but its industry has been weakened over the last decades, especially in the EU, due to very high energy costs. This was particularly exacerbated by the recent energy crises. Despite European production being limited in comparison with the rest of the world, this

1. "The Soviet Response to Instability in West Africa: An Intelligence Assessment", US Directorate of Intelligence, Central Intelligence Agency, July 15, 1985, available at: www.cia.gov. For updated analyses on the Guinean bauxite industry, see the Observatoire guinéen des mines et métaux, available at: www.linkedin.com.

2. In this paper, "Europe" refers to geographical Europe, including the EU, the United Kingdom (UK), the European Free Trade Association (EFTA) countries and countries from the Balkan Peninsula (and especially aluminum producers, i.e. Bosnia-Herzegovina and Montenegro).

industrial activity remains an important emitter of GHGs for the EU, in particular regarding primary aluminum production. The GHG emitted during the production of aluminum mainly results from the important quantity of energy used by smelters, with major amounts of electricity consumed. GHG emissions from the aluminum sector, therefore, strongly vary according to the national electricity mix' structures.

Within the scope of international competition and amidst increasing demand for aluminum supplies entailed by the energy transition process and the need for lowering its emissions, Europe, and particularly the EU, is at a crossroads. Its aluminum industry is in a difficult situation. It suffered from the energy price crisis, hence its competitiveness is a central concern. This industry is, however, vital for Europe within the scope of its energy transition, with growing demand expected in the coming years. Being a major CO_2 emitter, the European aluminum industry needs to regain competitiveness and resilience as well as to decarbonize at the same time. This appears to be a particularly complex challenge to take up.

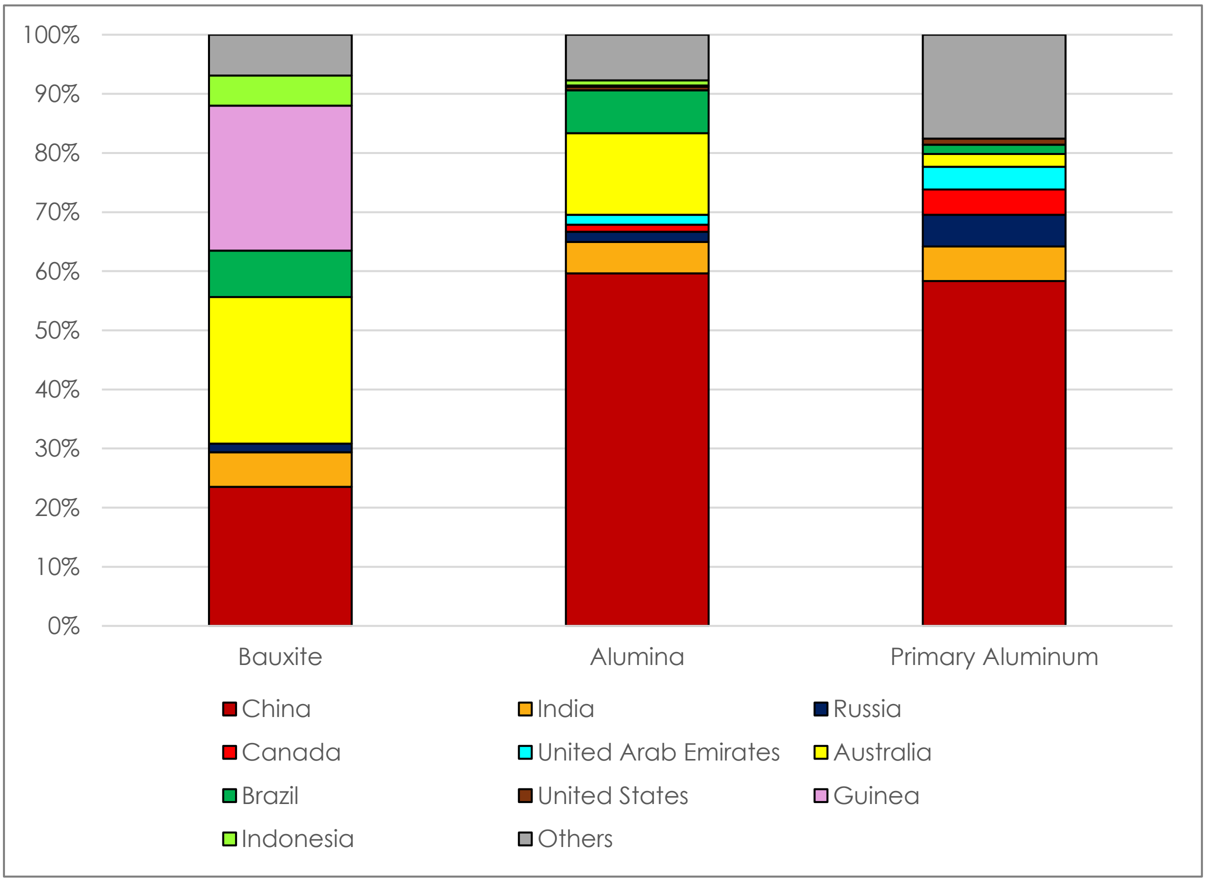
This paper intends to analyze the challenges faced by the European aluminum industries and aims to reflect on the different decarbonization tools of the European aluminum industry, highlighting their potential as well as their limits. The focus will be on the upstream value chain of aluminum since more than 93% of aluminum's GHG emissions are produced during three upstream steps of this chain: refining, anode production and electrolysis.[3] This paper also reflects on the need to make this industry more competitive and resilient regarding the upstream value chain of aluminum and outlines several recommendations for the industry and policymakers.

3. See Figure 7, p. 15.

Europe is a marginal global aluminum player, but its industry matters

Bauxite extraction remains geographically spread across the globe, the main producers being Australia, Guinea, China and Brazil (see Figure 1). Alumina and primary aluminum productions are more concentrated: China represents around 60% of each and its main competitors – Australia and Brazil for alumina, India and Russia for primary aluminum – are far below the Chinese levels of production. European producers represent a tiny share of the global supply: Norway and Iceland are part of the top 15 primary aluminum producers (ranked respectively 8th and 13th in 2022) but with only 2% of the global production for Norway and 1% for Iceland.

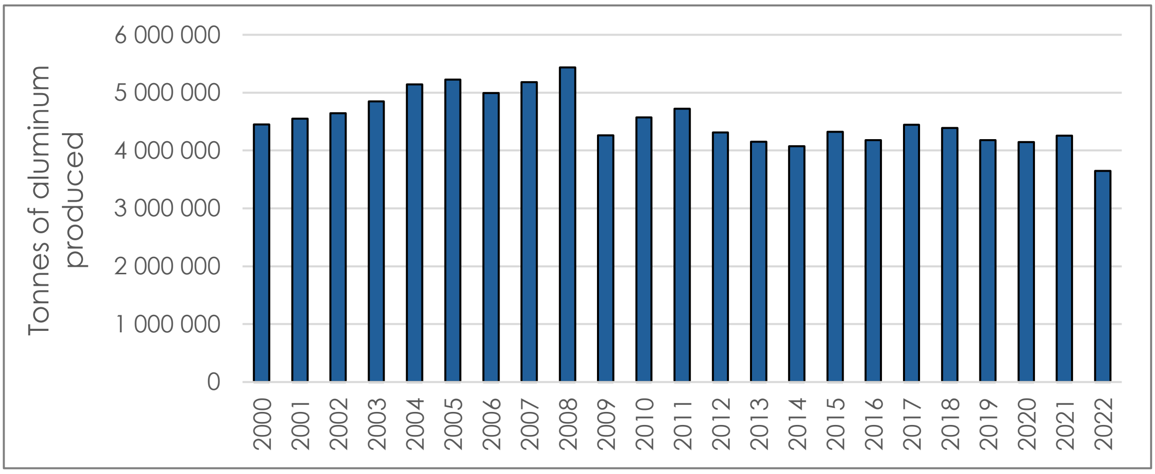
Figure 1. Bauxite, alumina and primary aluminum production in 2023 by country



Source: Ifri based on "U.S. Geological Survey", U.S. Department of the Interior, January 31, 2024, available at: https://pubs.usgs.gov.

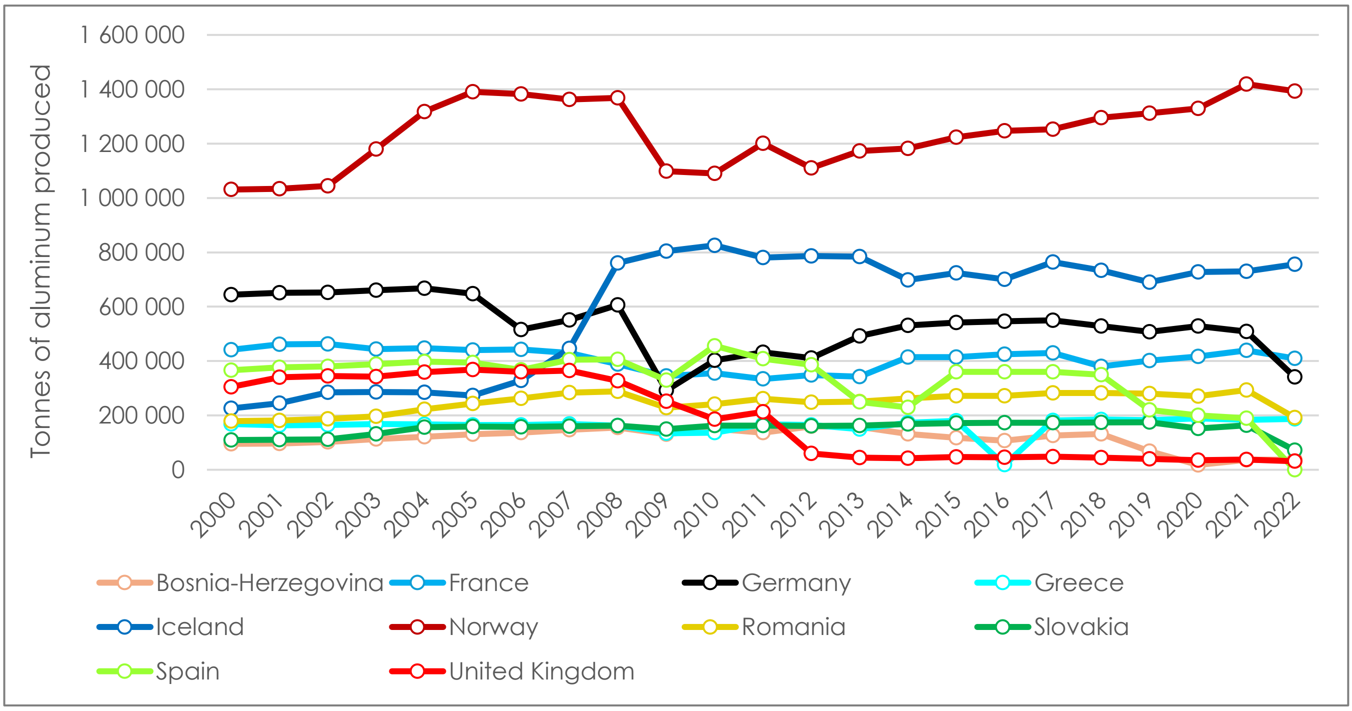
From 2005 onwards, primary aluminum production started to decrease inside Europe (see Figure 2), with stagnations in most of the EU countries and even declines in Germany or Spain (see Figure 3). For 2022, the repercussions of the European energy crises are clearly visible, with a decrease in the production of almost every EU Member State. It should be noted that production in Norway and Iceland has increased overall since 2000, albeit discontinuously.

Figure 2. Primary aluminum production in Europe, 2000-2022



Source: Ifri based on "World Mineral Production 2018-2022", British Geological Survey, www.bgs.ac.uk.

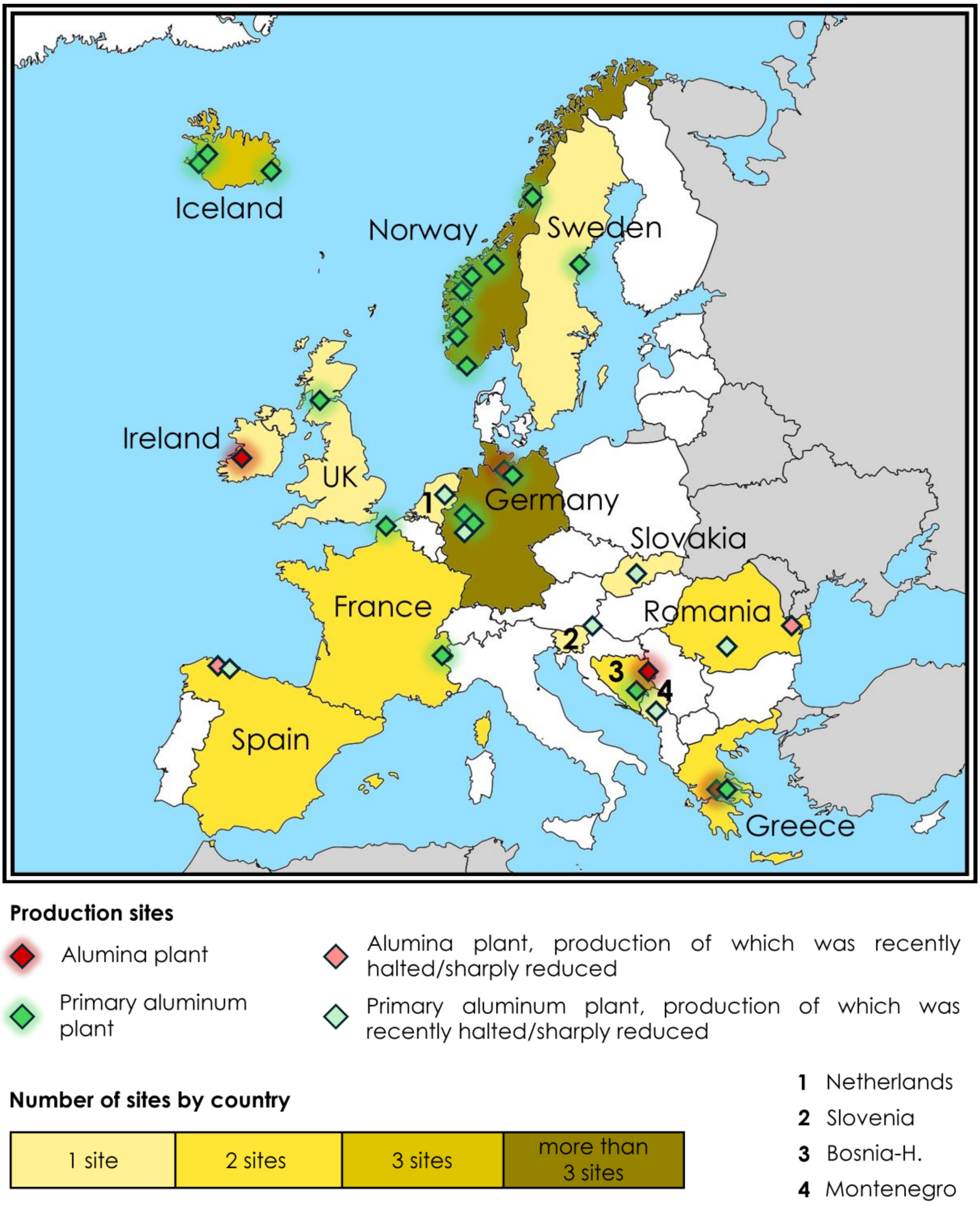
Figure 3. Main European primary aluminum producers, 2000-2022



Source: British Geological Survey, op. cit.

Europe currently holds around 30 alumina or primary aluminum production sites, most of them located in Norway, Germany and Iceland (see Figure 4). However, an important part of them were recently forced to halt or sharply curtail production.

Figure 4. Europe's alumina and primary aluminum production sites



Source: Ifri based on "The Aluminium Industry", European Aluminum, https://european-aluminium.eu.

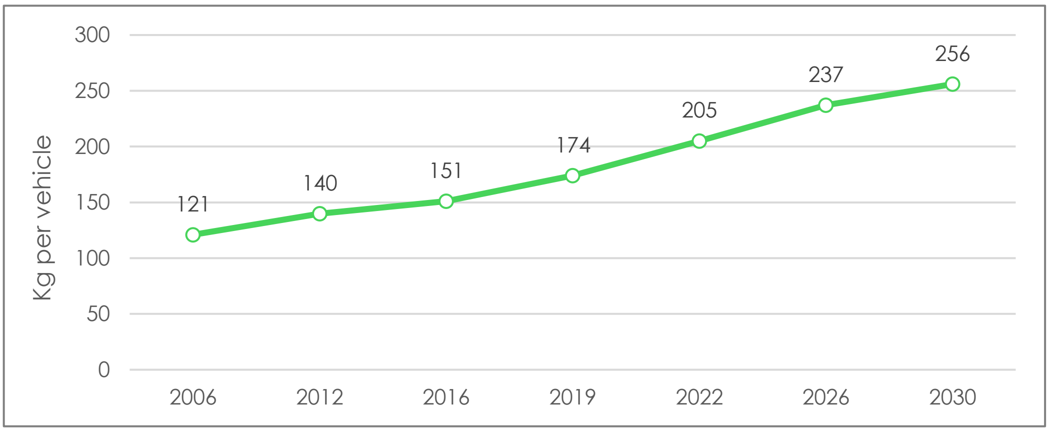
Aluminum for the energy transition: producing more but emitting less

In the past few years, the importance of aluminum in our modern economies has become more obvious, especially considering the key role it plays within the scope of the energy transition. Aluminum is crucial for renewable energy sources, such as wind and overall solar photovoltaic. It is also largely used in electricity grids, notably in overhead electricity lines, since its weight/conductivity ratio makes it a more relevant material than copper in this type of line.

Weight is the main strength of aluminum. This characteristic led to an important substitution of steel for aluminum in cars over the last decades: a lighter car means a car with a lower oil consumption and thus a reduction of costs in the end. But aluminum also bears a huge importance in the field of electric vehicles (EVs). This metal is indeed used in the EV technology itself, but it is also, in the same way, a means to lower the overall weight of the vehicle. An EV requires a battery, whose weight can rapidly become very important, even more should the vehicle have an important size. Using a light metal like aluminum in other parts of the vehicle is an efficient strategy to reduce the overall weight of the car and to lower the power required for the battery.

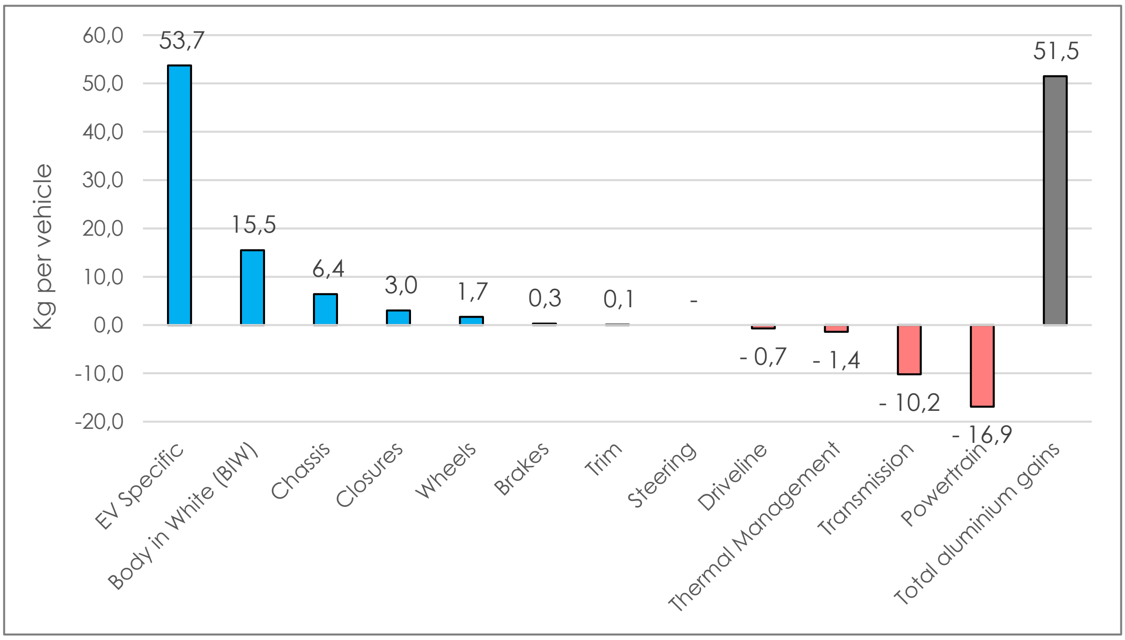
In 2022, a passenger vehicle contained on average 205 kilograms (kg) of aluminum in the EU or UK and this number is expected to increase in the coming years, reaching 256 kg (see Figure 5). This increase is due to EV specific components but also traditional ones, such as the body in white or the chassis (see Figure 6). With 16.5 million cars produced in 2030 in Europe according to a forecast conducted by Ducker Research & Consulting for European Aluminium, the aluminum demand for passenger cars is expected to reach 4.2 megatons (Mt) in 2030, compared with 2.5 Mt in 2022. According to the same forecast, 9.9 million of these cars would be battery EVs at that time, i.e. 60%.

Figure 5. Aluminum average content per vehicle for passenger cars in the EU and the UK, 2006-2030f



Source: Ifri based on "Aluminum Content in Passenger Vehicles (Europe). Assessment 2022 and Outlook 2026, 2030", Ducker Research & Consulting for European Aluminium, April 2023, p. 14, available at: https://european-aluminium.eu.

Figure 6. Aluminum content per vehicle gains and losses by 2030



Source: Ifri based on Ducker Research & Consulting for European Aluminium, op. cit., p. 10.

Thus, transport represents a major end use of aluminum in Europe (40%), with other end uses being: building and construction (24%), packaging (19%), engineering (11%) and consumer durables (6%).[4] Demand is expected to increase for all of these sectors with major aluminum needs in the coming years.[5]

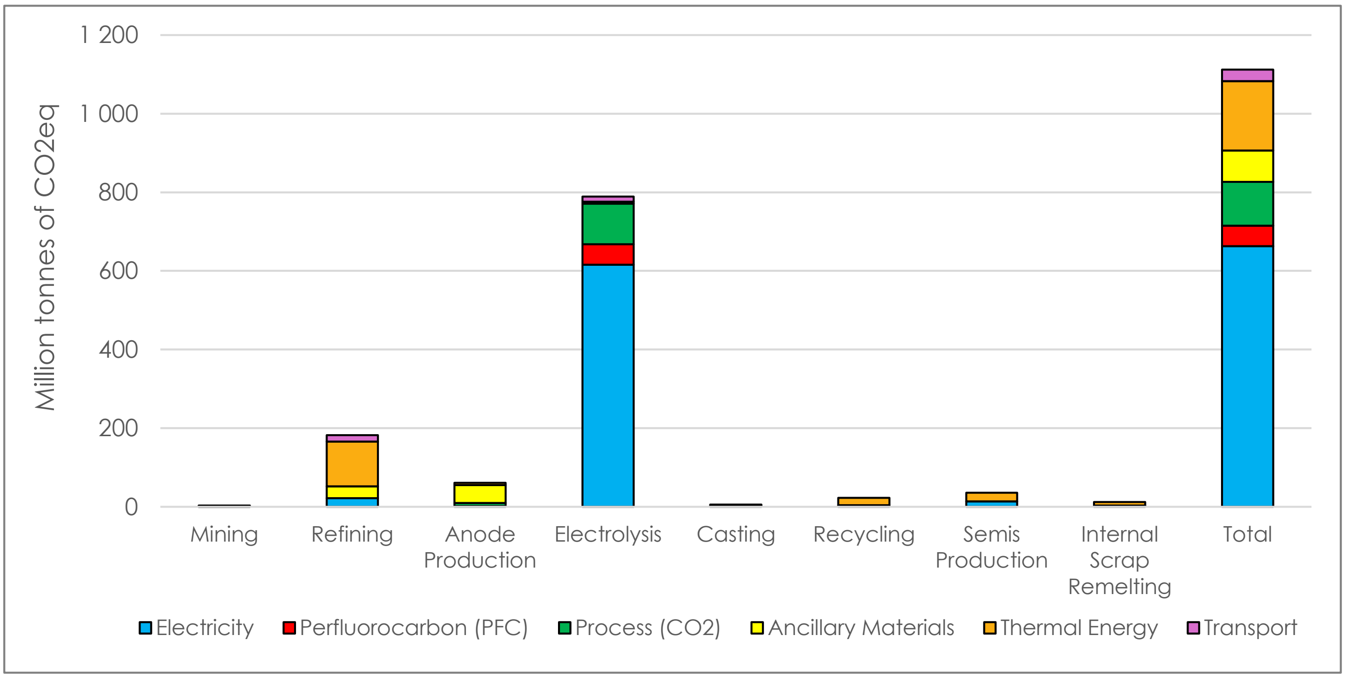
4. "Net-Zero by 2050: Science-based Decarbonisation Pathways for the European Aluminium Industry", European Aluminium, November 2023, p. 15, available at: https://european-aluminium.eu.
5. "Circular Aluminium Action Plan: A Strategy for Achieving Aluminium's Full Potential for Circular Economy by 2030", European Aluminium, August 2022, p. 8, available at: https://european-aluminium.eu.

However, the different processes used to transform bauxite into primary aluminum currently entail major GHG emissions. The global average for producing 1 tonne (t) of primary aluminum is of 16.1 tonnes of CO_2 (tCO_2).[6]

A large share of these emissions is due to the energy-intensive characteristic of aluminum production. Aluminum smelters consume tremendous amounts of electricity, especially during the electrolysis process (see Figure 7). In France, Aluminium Dunkerque, the largest primary aluminum producer, accounts for 0.9% of the French electricity consumption[7] (4 TWh in 2023), equivalent to consumption from the city of Marseille, ranking second behind the SNCF (the national railway company). In Iceland, the three aluminum industries of the country represent 70% of the national electricity consumption.[8] Due to the increasing demand for aluminum, these very high levels of electricity consumption are expected to rise in the coming years.

Gas is also used to transform bauxite into alumina. Some steps of this process are carried out using high steam pressure, for which electricity is no substitute. Gas could be replaced by hydrogen, but this technology is so far not mature enough.

Figure 7. GHG emissions from the global aluminum sector in 2022



Source: Ifri, based on "Greenhouse Gas Emissions – Aluminium Sector", International Aluminium Institute, available at: https://international-aluminium.org.

6. "Our Environmental Profile Reports 2018 & 2022", European Aluminium, October 17, 2022, available at: https://european-aluminium.eu.
7. B. Bonnefous, "À Dunkerque, la difficile décarbonation de l'industrie", *Le Monde*, March 23, 2024.
8. N. Mann, "Dans sa fonderie islandaise, Norðurál parie sur le captage de CO_2 pour décarboner son aluminium", *L'Usine Nouvelle*, September 23, 2022.

Furthermore, emissions of the aluminum industry don't come only from energy consumption. The electrolysis of alumina, in order to produce primary aluminum, uses electrodes made of carbon. During the chemical reaction, dioxygen (O_2) from alumina combines with the carbon of the anode, creating carbon dioxide (CO_2). This carbon dioxide is then released into the atmosphere, in the form of smoke. This also constitutes an important source of costs for the aluminum industry since the anodes, once disaggregated, need to be changed, with a regular turnover.

Energy efficiency, electrification and recycling: first steps but insufficient to reach carbon neutrality

The expected growth in demand is a major challenge to European aluminum industries: reducing their GHG footprint while increasing their production. As for many industrial processes, a first way to lower GHG emissions is to reduce as much as possible the use of fossil fuels. This can especially be done through electrification and a decarbonized mix to produce the related electricity.

However, the electricity mix of European countries is already relatively decarbonized, especially in the case of Norway, Iceland and France. This allows aluminum industries to emit less CO_2 than in other regions of the world. While the global average emissions for 1 t of aluminum are of 16.1 tCO_2 and 20 tCO_2 in China, the average for European producers is of only 6.8 tCO_2 and 4.5 tCO_2 in the case of France[9]. On the other hand, it also means that only a few emission reductions can be achieved through electrification in the European aluminum industries.

For their electricity supply, European producers need affordable electricity prices and the recent crises resulted in serious difficulties, some of them surviving only thanks to state aid on power prices. In August 2022, the Slovakian producer Slovalco, for instance, announced that it was stopping its production, citing high energy costs and its impossibility to sign a long-term power contract.[10] To avoid this kind of situation, the EU intends to develop the model of Power Purchase Agreements (PPAs), long-term contracts usually concluded between a renewable energy provider and an industrial consumer, with an agreed tariff over a given period (up to 15 years or more). Nevertheless, barriers still exist to PPAs, such as permitting issues, grid bottlenecks, insufficient flexibility, and costs associated with matching variable renewables supply with baseload consumption. This is particularly true in which concerns aluminum industries, which need a continuous power supply and for whom fluctuations often entailed by renewable energy sources are highly challenging.

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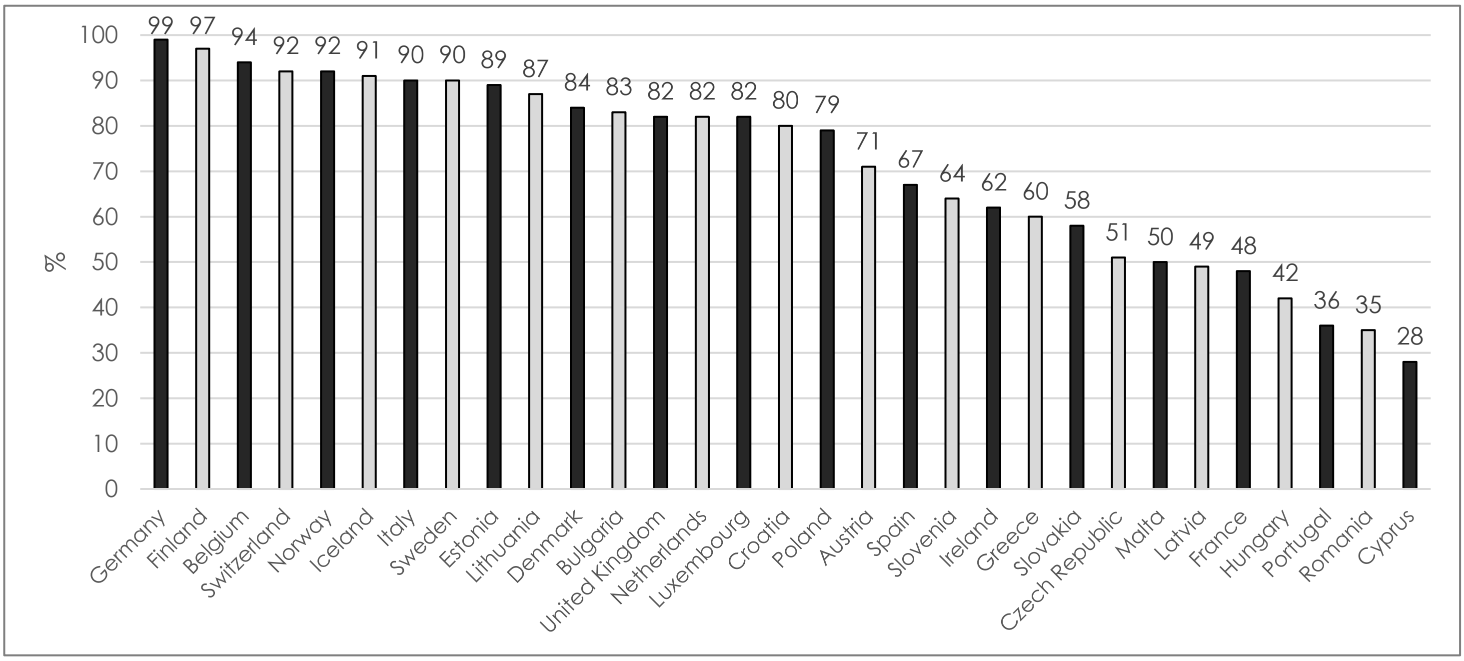
9. "Our Environmental Profile Reports 2018 & 2022", European Aluminium, October 17, 2022, available at: https://european-aluminium.eu.
10. M. Hudec, "Leading Slovak Aluminium Factory Shuts Down Amid Record Electricity Prices", *Euractiv*, August 23, 2022.

As for many industries, some improvements can also be made in energy efficiency to further reduce the European aluminum carbon footprint, but much of what can be done has already been implemented.

Another way to lower GHG emissions from the aluminum sector is also to develop recycling. A ton of recycled aluminum indeed consumes 96% less energy and emits around four times less GHG (regarding direct emissions) than primary aluminum. Moreover, aluminum – as for many other metals – can, in theory, be recycled endlessly. Ensuring a part of the European aluminum supply using recycled aluminum could, therefore, be a way to diminish the GHG emitted during the production of aluminum future needs.

Nevertheless, this entails well-established and performing recycling routes and facilities. Aluminum recycling is developed in Europe but remains unequally spread, with important differences between Member States. Figure 8 illustrates this heterogeneity in the case of beverage cans, with recycling rates located between 28% for Cyprus and 99% for Germany. In this example, the differences between national rates highlight the major role played by the implementation of deposit systems.

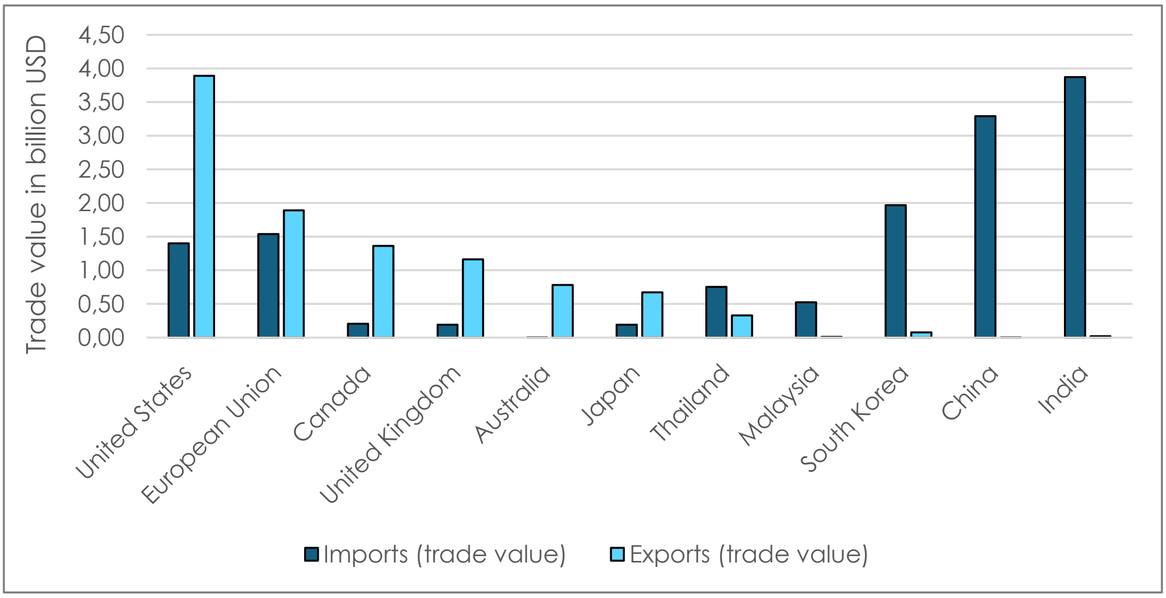
Figure 8. European countries aluminum beverage cans recycling rates in 2021



Source: Ifri based on "Aluminium Beverage Can Recycling in 2021 at a New Record Level of 76%", European Aluminium and Metal Packaging Europe, February 21, 2024, available at: https://european-aluminium.eu.

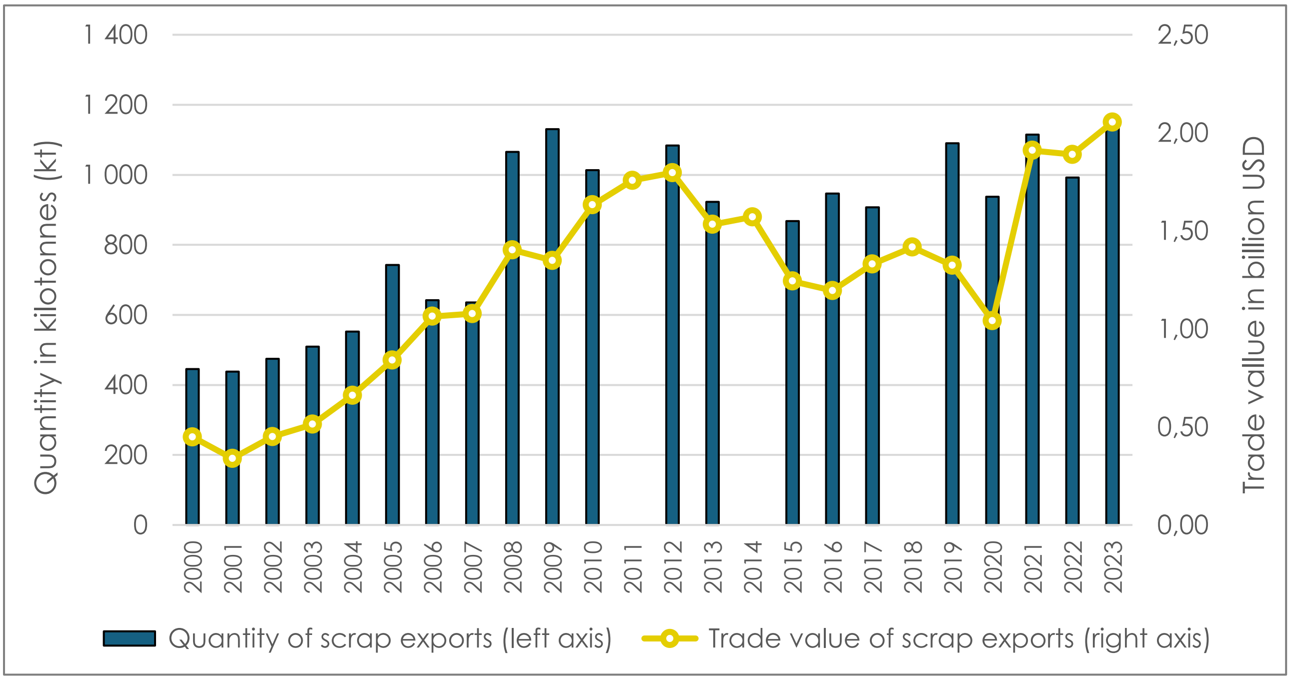
Recycling in Europe is also hindered by the important amounts of scrap that are exported from Europe to other regions of the world. Since 2002, Europe has become a net exporter of aluminum scrap and 1,16 Mt of scrap, was sent abroad in 2023, for a total amount of almost 2 billion USD (see Figure 9). Since the end of the 2000s, these exports have remained at stable levels, as illustrated in Figure 10: 80% of the scrap exported from the EU goes to Asia (China, India, South Korea, Malaysia).

Figure 9. Aluminum waste and scrap exports and imports by country in 2022



Source: Ifri based on "Waste and Scrap, Aluminum Exports and Imports by Country", World Integrated Trade Solution (WITS), World Bank, available at: https://wits.worldbank.org.

Figure 10. EU aluminum waste and scrap exports (2000-2023)

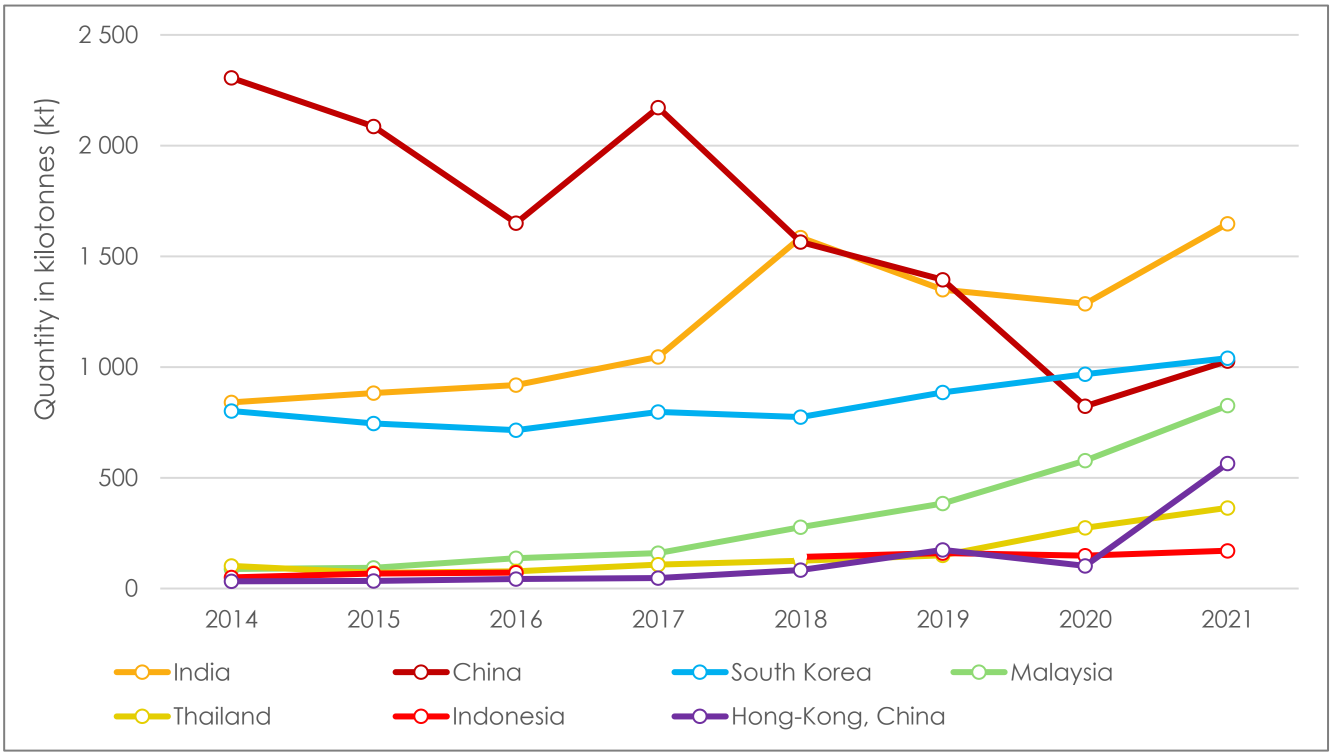


Source: Ifri based on WITS, op. cit.

Since 2019, China has put restrictions on its copper and aluminum scrap imports, rejecting the low-content scrap. Low-quality aluminum waste is more challenging to recycle and cannot henceforth be exported to China. On the other hand, high-content scrap, more interesting to recycle, continues to leave Europe and to be recycled in China, with concurrently low prices. As shown in Figure 11, if China has reduced its imports since the 2010s, waste supplies did not stop and have actually been redirected to other Asian countries, especially India, South Korea, Malaysia or Thailand.

If Europe wants to use recycling as an efficient tool to reduce its carbon footprint, these exports must decrease and be converted into secondary aluminum production.

Figure 11. Main Asian aluminum waste and scrap importers, (2014-2021)

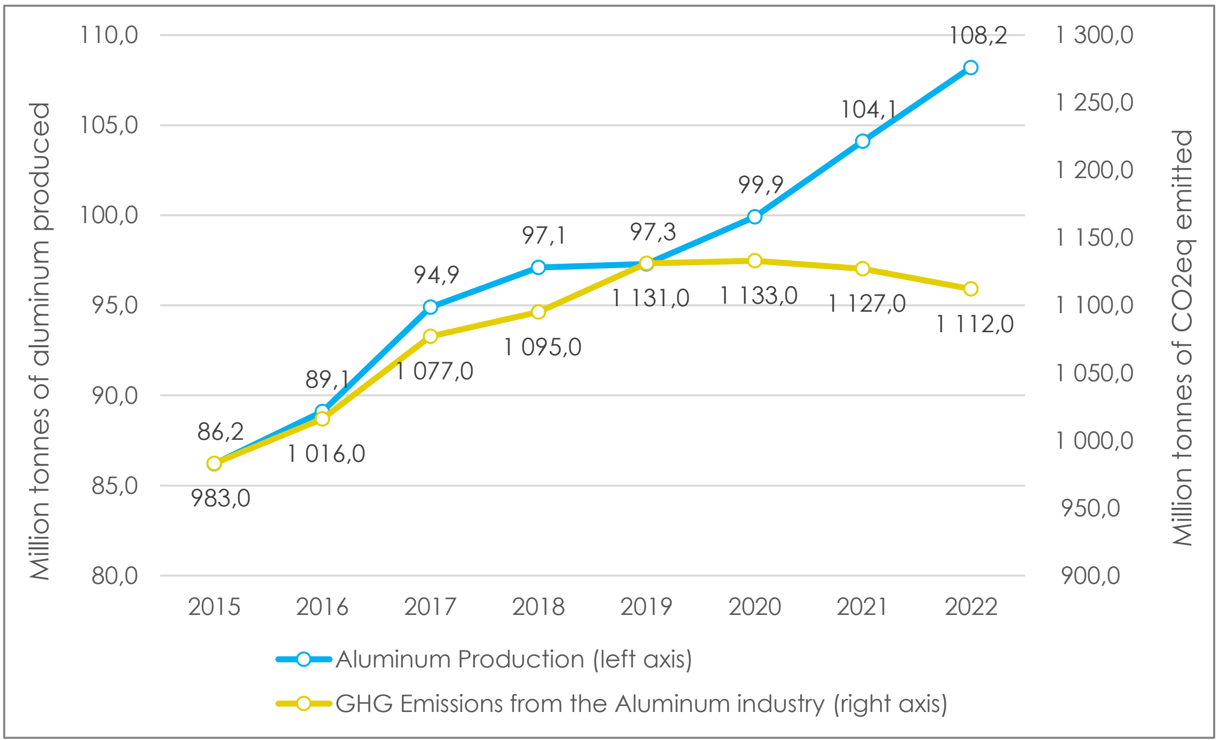


Source: Ifri based on WITS, op. cit.

Nonetheless, as demand will be increasing in the coming years, recycling cannot be a silver bullet. Europe will need more aluminum than it currently uses and will therefore have to find new supply, produced or imported. Besides, the EU is currently seeking to develop products with a longer lifespan, especially in the field of EVs, which is likely to result in delayed aluminum scrap production in the future, should the policies be successful. In addition, some of the aluminum recycling processes also need primary aluminum supplies, as it is the case when scrap to recycle is various and heterogeneous. Hence, the supply of primary products remains essential.

Electrification of the industrial processes, low carbon electricity generation and recycling are thus important tools to reduce the European aluminum industry's carbon footprint, but not to reach carbon neutrality. Moreover, these measures are partly already in place in Europe and have therefore already acted to lower this footprint. As shown in Figure 12, the global GHG emissions of the aluminum sector recently peaked, especially due to the implementation of this kind of action. But their effects remain light in comparison to the decarbonization targets set in the agenda. In the case of French Aluminium Dunkerque, the factory intends to combine energy efficiency, recycling and operational excellence as tools to diminish its footprint towards 2025, but these measures correspond only to a 5% reduction of its GHG emissions.[11]

Figure 12. Global GHG emissions from aluminum production, 2015-2022



Source: Ifri based on "Aluminium Industry Reports Decline in Greenhouse Gas Emissions", International Aluminum Institute, February 28, 2024, available at: https://international-aluminium.org.

11. "Notre projet de décarbonation", Aluminium Dunkerque, available at: www.aluminiumdunkerque.fr.

The need for disruptive technologies: CCUS and inert anodes

All of the actors agree indeed that without disruptive technologies, net zero emissions status is not achievable for the aluminum industry. Two technologies are currently under serious consideration.

First, carbon capture and storage (CCS). Aluminum industries are major CO_2 emitters. As explained above, their GHG emissions come both from their energy and electricity consumptions as well as from the CO_2 emitted during the electrolysis process that leads to the obtention of primary aluminum. CCS would consist of the capture of the CO_2 emitted throughout the aluminum production and its storage underground.

This carbon could also be reused. Some industries, like chemicals, use carbon as raw materials for their activities. Within this model, called Carbon capture and utilization (CCU), the carbon captured by an aluminum producer could be recycled, for instance, being sold to another industrial.

While this process appears promising, it remains far from a deployment at an industrial scale, which is not expected before 2030.[12] Some of the European aluminum industries have invested in CCS technologies specific to aluminum production for their facilities, as is the case for Norsk Hydro in Norway[13] or Norðural in Iceland, which is working on this project with a Norwegian startup, Ocean GeoLoop.[14] German Trimet created a consortium project in October 2023 with Aluminium Dunkerque, Fives and Rio Tinto. The project is called "C4Capture". Trimet operates the French aluminum factory of Saint-Jean-de-Maurienne; Fives is a manufacturer of industrial equipment that provides technologies for aluminum primary production. Rio Tinto, for its part, has sold most of the aluminum assets it held in France but still has an engineering activity in aluminum production tanks, based in Voreppe, near Grenoble. C4Capture's ambition is to develop a CCS technology operational by 2028.

The development of CCS technology, however, presents major challenges to take up. First of all, it requires huge investments, hundreds of millions of euros in the case of C4Capture, for the technology itself and for

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12. ADEME, *op. cit.*, p. 14.

13. "Developing Carbon Capture and Storage Technology for Aluminium Smelters", *Hydro*, May 15, 2024, available at: www.hydro.com.

14. N. Mann, "Dans sa fonderie islandaise, Norðurál parie sur le captage de CO_2 pour décarboner son aluminium", *op. cit*.

the transport and storage infrastructures associated that do not currently exist in Europe. This technology also requires heat for the carbon capture, which is likely to be generated from gas, which could represent some additional costs. Finally, the smokes emitted during the production of primary aluminum are poorly concentrated in CO_2, with around 1% of CO_2 among the overall gas emitted. Therefore, in comparison with other industries, a larger quantity of smoke needs to be treated to capture the same amount of CO_2. The objective of C4Capture is to increase this CO_2 rate, in order to reach a concentration between 3% and 5%.[15]

The second technology relies on the electrolysis process used to transform alumina into primary aluminum. As mentioned above, this process results in the release of smoke, containing CO_2. This phenomenon is due to the disintegration of the anode used within the chemical reaction, which is made of carbon. An efficient way to limit this formation of CO_2 would, therefore, be to use anodes made from materials other than carbon. Such anodes are called "inert anodes".

Several projects to develop this type of anodes have emerged over the last years. "Elysis" was developed in Canada through a cooperation formed in 2018 between Alcoa (US) and Rio Tinto, a British-Australian company. A second project is developed by Rusal in Russia, while the last one is conducted by Trimet and the Icelandic company Arctus Aluminium.

The actual technologies and materials used to produce these anodes are not precisely known yet and the future of these projects is hard to estimate, especially their potential industrial deployment dates. Elysis expects a commercial demonstration by 2024 and a first production in 2027,[16] while Rusal said in July 2023 that it had successfully developed a prototype of the inert anode in its smelter in Krasnoyarsk.[17] These inert anode projects will anyway take time until they are able to be deployed at an industrial scale, which may not occur before 2032.[18]

15. N. Mann, "L'alliance de quatre vieux briscards pour inventer le captage de CO_2 pour l'aluminium en France", *L'Usine Nouvelle*, October 12, 2023.
16. "Alcoa Announces Agreement on Industrial-Scale Demonstration of ELYSIS™ Carbon-Free Smelting Technology", Alcoa, Press Release, June 28, 2024, available at: https://news.alcoa.com.
17. "Russia's Rusal Says Inert Anode Cell Aluminum Vastly Reduces Carbon Footprint", S&P Global, July 14, 2023.
18. ADEME, *op. cit.*, p. 14.

CBAM: a relevant tool with flaws

European aluminum industries are under specific pressure to decarbonize as free allowances within the EU ETS system will be progressively phased out, which could result in substantial costs for industries.

To make sure that European players compete in the European market on a level playing field with imports from abroad, the EU has developed and started to implement the Carbon Border Adjustment Mechanism (CBAM). At first, several products will be included in this mechanism, i.e. cement, electricity, fertilizers, steel, hydrogen and aluminum. The mechanism's aim can be summarized in the following way: since European producers in the CBAM sectors are subject to EU ETS and the cost of the CO_2 allowances is expected to go up in line with the EU's decarbonization ambitions, there is a risk that their products become less competitive compared to imports, and that non-EU producers gain market share in Europe at their expense. To ensure a level playing field and incentivize decarbonization efforts abroad, imported products listed under the CBAM will be subject to an equivalent CO_2 tariff as European products under EU ETS. The imported products would be taxed according to their carbon footprint.

Nevertheless, this measure has raised high concerns among the aluminum industries. Indeed, the CBAM regulation, in its Annex I (that defines the scope of the CBAM), enlists only raw materials such as unwrought aluminum and a limited number of processed products from primary aluminum, like wires, tubes, pipes or bars. On the other hand, the CBAM is not targeting a large number of other processed materials made of aluminum, like a knife, a chair, a stepladder or a car door.[19] This means that a European manufacturer producing a car door with Chinese aluminum would be taxed by the CBAM (when importing the aluminum in Europe) while a Chinese manufacturer exporting the same car door in Europe would not be taxed, hence incentivizing the manufacturing of finite or semi-finite goods outside the EU and reducing the pool of off-takers for European aluminum producers.

Aluminum products manufacturers are worried as well. Since the EU is currently not producing enough primary aluminum, it must import every year major amounts of this material. Manufacturers are therefore concerned that the cost of their raw materials will strongly increase due to the CBAM

19. Regulation (EU) 2023/956 of the European Parliament and of the Council of May 10, 2023, establishing a carbon border adjustment mechanism, Annex I.

and that potential new supplies coming from Europe will not be available as quickly as needed to become substitutes. The price of their final products is thus likely to grow as well and to entail a loss of competitiveness.

Circumvention risks also exist in relation to the CBAM. Aluminum scrap or recycled aluminum is not included in Annex I of the CBAM and, therefore, targeted by this regulation, and the question of their footprint calculation is an issue. As explained above, recycled aluminum emits less GHG than primary aluminum and has therefore a lower footprint. However, it is not easy to distinguish recycled aluminum from primary aluminum.

The question of precisely defining what is aluminum scrap is complex. For instance, offcuts gathered during the process of aluminum materials and products are logically considered as recoverable waste. But an industrial could easily transform primary aluminum material into scrap, for instance piercing or slicing it, and hence avoiding taxation. More broadly, it is easy to disguise unwrought and base aluminum material as processed, and thus circumvent the CBAM.

This regulation is currently under a transition period that will end in January 2026. It is a necessary policy to protect the European industry's competitiveness and to allow the decarbonization of the most emitting industries, without high economic and social costs for Europe. However, this mechanism presents serious flaws at the time being and must be enhanced to avoid a deceleration, or even a closure, of some European industries.

Conclusion and recommendations

Several issues could be considered to foster the decarbonization, resilience and competitiveness of the European industry.

1. Reinforcing European primary aluminum production

The aluminum produced in Europe presents a lower GHG footprint than in other parts of the world, like in Asia for instance. Moreover, no real actions are currently undertaken in Asia to reduce the aluminum direct GHG emissions, as summarized by the International Energy Agency: "Despite the current concentration of production in China, and expected future growth in Asia more broadly, there are no known R&D projects underway in Asia to address direct emissions".[20] Encouraging the European domestic production of aluminum would, therefore, be a way to reduce the global GHG emissions of the aluminum industry.

To restore strong primary aluminum production in Europe, investments and financial support are needed. This support could rely on an "industrial plan" designed by the EU within the scope of the next European Commission's agenda and incentives to attract private funds, with the involvement of the European Investment Bank (EIB) as well. Member States could also be active in this process, with financial guarantees mechanisms for new facilities projects, securing land and electricity connections. Aluminum is and could be a great asset to tap into excess electricity from renewables during the day, and to consume nuclear electricity at night, especially in France.

European producers also need competitive power. Long-term contracts, especially PPAs will be important in that prospect as laid out in the recent electricity market design reform. Yet, electricity supplies will have to lie in a low range as external competitors typically buy electricity in a 20-30 EUR/Megawatt-hour (MWh) range, and not in the 70-80 EUR/MWh range for the complex and comprehensive PPAs that can currently be found on the market. Major improvements could still be made to develop the use of these contracts, as highlighted by the Florence School of Regulation.[21] To sign PPAs, industries also need financial guarantees and the current development

20. "Energy Technology Perspectives 2023", International Energy Agency, January 2023, p. 201, available at: www.iea.org.

21. L. Hancher, G. Dezobry, J.-M. Glachant and E. Menegatti, "Leveraging the Energy Transition: the Role of Long-Term Contracts", Florence School of Regulation, May 22, 2024, available at: https://fsr.eui.eu.

of such a tool by the EIB is an encouraging step, and permitting for renewables and grids must be accelerated to reduce project costs.

Another obstacle to the conclusion of PPAs is also the general mismatch between the profiles of renewable energy producers, whose production is often fluctuating (especially in countries like Germany, Spain or Greece), and of industries that need steady power supplies for their facilities (although some tiny variations could be possible). Therefore, a better and easier connection between renewable energy sources and aluminum plants is needed and could be improved for instance in developing renewable energy coordination mechanisms, to ensure fluid energy supplies towards the industries. Also, research on electrical flexibility need to be carried on by European industrials and supported by the EU and national governments. Such research and development efforts are already conducted, with for instance the EnPot system[22] or the "Aluminum Electrolysis 4.0" project, conducted by Trimet and the University of Wuppertal.[23]

Overall, current existing schemes in Member States to allow the supply of electricity at very competitive prices to energy intensive industries exposed to international competition, and to hand back some of the ETS costs, will need to be maintained and aligned across Europe.

2. Providing a larger support to the development of decarbonization technologies

CCUS and inert anodes could be game changers for the European aluminum industry. Trimet's inert anodes project is supported by the government of North Rine-Westphalia but could receive broader and more intense support at a European scale. This support could be financial or delivered through cooperation with the EU Joint Research Center. As for it, the Elysis project is supported by the Quebec and Canadian governments[24] and could be extended in the future to the US territory, where it could benefit from the Industrial Demonstrations Program, whose total amount is 6.3 billion USD.[25]

The EU or its Member States could provide larger support to Trimet's project or to other inert anodes projects if they were to emerge,[26] as well as to

22. International Energy Agency, *op. cit.*, p. 201.
23. "Aluminium Electrolysis 4.0", Bergische Universität Wuppertal, available at: www.lfa.uni-wuppertal.de.
24. The Quebec government is investing 140 million CAD (around 103 million USD) in a demonstration factory, which represents 37.3% of the total project investment. In 2018, the Canadian Prime Minister, Justin Trudeau, announced a 60 million CAD investment (around 47 million USD at that time) in the Elysis project. See V. Boutin, "Une usine de demonstration sera construite à Arvida pour Elysis", *Radio Canada*, June 28, 2024; "Alcoa and Rio Tinto Announce World's First Carbon-free Aluminum Smelting Process", Prime Minister of Canada, May 10, 2018, available at: www.pm.gc.ca.
25. I. Wells and S. Ahmed, "The Role of Inert Anodes in Aluminum Decarbonization", Natural Resources Defense Council, August 10, 2023, available at: www.nrdc.org.
26. Arctus Aluminium explains in an internal layout that it will apply for the EU Innovation Fund in 2024.

CCUS initiatives such as the C4Capture project, for instance through the creation of a specific fund for hard-to-abate industries' decarbonization. The European Commission is currently working on an Industrial carbon management strategy, which is an encouraging initiative, while more projects specific to aluminum could be supported by the EU Innovation Fund.

Private investments will be key as well and European aluminum industrials need to focus on their ability to attract these funds. In the case of Elysis, Apple has invested in the project[27] (10 million USD pledge in total) through Green Bonds and has announced that it would use the aluminum produced for its iPhone SE.[28]

It would also be interesting and important to develop a cooperation framework between the different actors carrying research on the decarbonization of the aluminum industry in Europe, to make sure that innovations are developed as fast as possible and industrial players join forces.

3. Improving recycling across Europe and limit scrap exports

The EU continues to export wide quantities of aluminum scrap every year (1.16 Mt in 2023), which is more than copper scrap (530 kilotons in 2023) and stainless-steel scrap (288 kilotons in 2022).[29] As previously shown in Figure 10, these exports have not decreased over the last years and remain at stable levels. This scrap is an opportunity to rapidly strengthen European low-carbon aluminum production. To do so, new recycling facilities must be opened and the existing ones enlarged.

The Critical Raw Materials Act (CRMA) is an important step forward in that prospect. This text puts an ambition of having 25% of strategic raw materials recycled in 2030, while it also facilitates the opening of new recycling sites through a reduction of permitting procedures time for strategic projects (article 11) and asks the Member States to develop national plans on circularity (article 26).

The CRMA's success will now rely on its implementation. If it is an important text to improve Europe's metal recycling capacity, it could also be relevant to limit more strictly the amount of metallic scrap exported every year.

27. "Annual Green Bond Impact Report: Fiscal Year 2022 Update", Apple, 2023, available at: https://s2.q4cdn.com.

28. "Apple's $4.7B in Green Bonds Support Innovative Green Technology", Apple, March 24, 2022, available at: www.apple.com.

29. "Waste and Scrap, Copper Exports by Country", WITS, available at: https://wits.worldbank.org; "Waste and Scrap, Stainless Steel Exports by Country", WITS, available at: https://wits.worldbank.org.

4. Extending the scope of the CBAM to a larger number of processed products and boosting EU's climate diplomacy abroad

As mentioned above, the current CBAM model entails fragilities for some of the European industries. Therefore, its scope could be progressively extended to a larger number of processed products.

It will be difficult to ensure that non-European producers of aluminum, steel or cement declare their actual levels of emissions to European actors within the scope of the emissions declaration process. In view of this, the EU would not take much risk in extending the CBAM – and, therefore, this declaration process – to a wider range of products.

The EU and its aluminum industrial players could conduct thorough investigations and assessments to identify the products for which a risk of circumvention is the most important. Indeed, such a circumvention appears, for instance, more likely to be prejudicial to European aluminum industrials in the case of low-value-added products, for which the cost of aluminum represents a larger share in the final price of the product. In the case of products with more added value, a higher aluminum cost could be softened by its minor share in the overall price of the final processed product. This added-value level would, however, be a component of this assessment, not the alpha and the omega. Once the assessment to identify the most vulnerable products is done, the CBAM scope could be extended to those products. In addition, virtuous practices (such as low-carbon aluminum production) should be recognized and showcased via a system of labels or a framework of incentives for the final consumers to promote sustainable products.

On the opposite, keeping the current format of the CBAM could create a risk of incentivizing European industrial players to manufacture their finite products outside of Europe, in order to avoid taxation of their imported raw materials.

The CBAM is also likely to become inefficient if it remains limited to the sole EU. Over the last years, China has developed major production capabilities of aluminum, especially through the State, creating market distortions alongside the value chain (particularly downstream).[30] There is nothing prohibiting China or other foreign countries from supplying in the future the EU with low-carbon aluminum – produced using relatively decarbonized processes – with the aim of circumventing CBAM while selling the high CO_2 footprint aluminum to other parts of the world.

30. "Measuring Distortions in International Markets: The Aluminium Value Chain", *OECD Trade Policy Papers*, No. 218, Paris: OECD Publishing, January 2019, p. 105, available at: http://dx.doi.org/10.1787/c82911ab-en.

To be efficient, the EU must pursue its climate diplomacy to support other countries in adopting a robust CO_2 price at home, using the collected revenues for their industries' decarbonization, and making sure imports in their markets pay the same price. The EU must thus conduct an active diplomacy on this field to enable carbon pricing to gain ground and increase in value around the world while, in parallel, supporting industries in developing countries to decarbonize in a just transition spirit.

Another potential international cooperation format in the field of low-carbon steel and aluminum is the Global Arrangement for Sustainable Steel and Aluminum (GASSA), a potential agreement between the US and the EU. Negotiations on GASSA were launched on October 31st, 2021, when both the US and EU agreed to remove the tariffs on steel and aluminum products that were targeting each other. The tariffs on the EU industry were introduced by the US in 2018, under Donald Trump's mandate, and the EU applied retaliatory measures. Negotiations and a tariffs truce were to last until an arrangement on GASSA was reached, which was expected for the end of 2023.

Nevertheless, negotiations on GASSA are currently at a standstill. In October 2023, it was announced that no deal had been concluded, but that negotiations and tariff exemptions would be extended to 2025. No major steps have been achieved since then, creating concerns among US and EU's industries, with calls from metal industrial associations to continue working on this agreement. If a common will is present between the US and EU, details appear more challenging to manage, especially regarding the carbon emissions calculation of steel and aluminum productions.

Yet, if ultimately achieved, such an agreement could be further extended to other countries, concerned in the same way both by the reduction of their steel and aluminum's carbon footprint and the protection of their domestic industries. This could be the case in the UK, Japan, Canada and emerging countries such as Brazil. The Brazilian steel industry has indeed recently shown its worry about the Chinese competition in its market and the repercussions for its economic survival.[31] GASSA could consist not only of a trade agreement but also of a cooperation model including provisions on labor rights, on R&D collaboration around decarbonization technologies and on the development of a strategic approach to overcapacity.[32]

Anyway, continuing negotiations on that point will take time and with major elections both in the US and the EU, year 2024 will be key for GASSA's future. While the EU elections allow for a continuity in the ambition to decarbonize the European economy, the return of Donald Trump to the White House could be a major setback for this agreement. Whereas a Trump 2.0 presidency would probably be coherent on the determination to fight

31. A.-D. Correa, "Confrontée à la concurrence de la Chine, au Brésil, l'industrie sidérurgique 'en état d'alerte'", *Le Monde*, June 27, 2024.
32. R. Mulholland, T. Sutton and T. Meyer, "Designing a New Paradigm in Global Trade", Center for American Progress, May 20, 2024.

overcapacities, especially Chinese, this would most likely not be done in cooperation with the EU. The US strategy would also very probably not be based on the development of a low-carbon steel and aluminum production (with less support to the efforts on decarbonization technologies), but primarily on costs and employment considerations. The aim would indeed be to protect the US industry from international competition, not to promote a reduction in steel and aluminum's carbon footprint, even if these two goals are not incompatible.

5. Building resilience, with a focus on Europe's alumina supply

While there are large volumes of bauxite reserves across the world, a major bottleneck appears to be alumina production, which is environmentally challenging and very energy-intensive. The EU should focus on this key segment currently dominated by China, especially since two of its metallurgical alumina refineries (San Ciprian in Spain and Tulcea in Romania) have recently stopped or curtailed their productions.[33] The EU henceforth only holds a few alumina plants, and its production, which is declining, represents 3% of the world's total.

Increasing resilience in the field of alumina could imply supporting the construction of refineries in new partner countries such as Guinea, not least through national support measures and the Global Gateway initiative especially since infrastructure, such as hydro, gas pipelines and grids, will be needed. Guinea appears particularly strategic in as much as it comes with good quality reserves, well suited for lower cost and lower emission aluminum value chains. Local authorities have already shown interest in building up a refinery, and feasibility studies are ongoing, led by the Guinean group United Mining Supply (UMS).[34] As in other sectors, a more effective and flexible EU approach to project finance and support would be helpful in order to help develop projects which are key to the EU's strategic autonomy.

33. L. Bottero, "Alteo arrête sa production d'alumine 'rouge' à Gardanne : une perte de souveraineté pour le député Lambert (qui interpelle Castex)", *La Tribune*, March 30, 2022.
34. F. Wazni, "UMS : le rachat d'Alteo en France est utile pour nos projets autour de la bauxite en Guinée", *La Tribune Afrique*, February 17, 2021.

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