IFRI STUDIES

CENTER FOR ENERGY AND CLIMATE

DECEMBER 2024

Europe's Black Mass Evasion

From Black Box to Strategic Recycling

Diana-Paula GHERASIM
Thibault MICHEL

The French Institute of International Relations (Ifri) is a research center and a forum for debate on major international political and economic issues. Headed by Thierry de Montbrial since its founding in 1979, Ifri is a non-governmental, non-profit foundation according to the decree of November 16, 2022. As an independent think tank, Ifri sets its own research agenda, publishing its findings regularly for a global audience.

Taking an interdisciplinary approach, Ifri brings together political and economic decision-makers, researchers and internationally renowned experts to animate its debate and research activities.

ISBN: 979-10-373-0950-1

How to quote this publication:

Diana-Paula Gherasim and Thibault Michel, “Europe’s Black Mass Evasion: From Black Box to Strategic Recycling”, *Ifri Studies*, Ifri, December 2024.

Ifri

27 rue de la Procession 75740 Paris Cedex 15 – FRANCE

Tel. : +33 (0)1 40 61 60 00 – Fax : +33 (0)1 40 61 60 60

Email: accueil@ifri.org

Website: Ifri.org

Author

Diana-Paula Gherasim is a Research Fellow and Head of European energy and climate policies at Ifri's Center for Energy and Climate. She has worked as an advisor in the field of renewable energy and was responsible for monitoring the legislative framework for energy and climate in Europe up to 2030 for Eurelectric. She has also worked within Engie's European Affairs Department, focusing on the European Green Deal. Additionally, she has been active in the field of strategy consulting in developing countries, particularly in Côte d'Ivoire and Kenya.

Thibault Michel is a Research Fellow at Ifri's Center for Energy and Climate since January 2024. Before joining Ifri, he worked as a business intelligence and geopolitical analyst at RTE, the French electricity transmission system operator (TSO), notably on electricity interconnections. He has also worked on security and company protection issues at L'Oréal. Thibault holds a Master's degree from Sciences Po Strasbourg in European affairs and geopolitics, as well as a degree in geoeconomics from IRIS SUP'. He has also studied history and conducted historical research at the Grenoble Alpes University.

Abstract

EV batteries recycling is a building block for boosting the European Union (EU)'s strategic autonomy in the field of critical raw minerals (CRM) value chains. Yet, recent evolutions in the European EV value chain, marked by cancellations or postponements of projects, are raising the alarm on the prospects of the battery recycling industry in Europe.

Battery recycling covers complex and somewhat opaque processes and realities, with different process stages and associated difficulties of scaling up alongside all the industrial stages. It starts with the collection and deactivation of the batteries before they are disassembled and crushed, in a process known as "pretreatment". This stage produces a powder known as "black mass". The challenge is then to refine this powder (post-processing) in order to recover its constituent metals, in particular nickel, cobalt and lithium. Normally, the prices at which lithium, nickel and cobalt from primary sources are being traded on international trading platforms (ex. London Metal Exchange) are high enough to incentivize their recycling, and their presence in the content of the black mass can be used to assign a value to it, an estimate which is commonly known in the industry as a "payable".

Currently, pyrometallurgy (melting of black mass to produce a metallic alloy and remove impurities) and hydrometallurgy (chemical reactions to isolate the metals to be recovered) are the most common methods for material recovery, but others are being explored, like direct recycling. Comparing these methods remains difficult, especially regarding energy consumption or greenhouse gas (GHG) emissions, notably as data and life-cycle assessments on those issues are scarce and existing studies often vary in their findings. Recovered metals are then purified to their metallic form (notably for use in the metallurgical industry) or turned into battery-grade salts to form new battery materials, i.e. pre-active materials (pCAM) and, subsequently, cathode-active materials (CAM).

The EU and the United States are trying to develop their own recycling industries (i.e. EU battery regulation's obligations on minimum recycling and reincorporation rates; US IRA's support framework etc.), which proves to be particularly difficult for the post-treatment phase (material recovery from black mass). Based on existing attempts at mapping capacities, Germany takes an important part in the European landscape in terms of installed facilities, with numerous domestic recyclers. Hungary also has significant recycling capacities, especially thanks to the presence of South Korean SungEel. Beyond South Korean actors, North American companies have installed pretreatment facilities in the EU, while Chinese recyclers have

not been present so far. While the EU market presents an important share of non-EU recyclers, North America is strongly dominated by domestic actors.

Lack of accurate data on real capacities installed in Europe is a huge issue for understanding the state of the EU recycling market. Some studies suggest that Europe's black mass recycling capacities could be of around 300,000 tonnes for pretreatment and 350,000 tonnes for post-treatment, while interviews conducted with industrials lead us to assess Europe's cumulative capacities at around 200,000 tonnes, with few post-treatment capacities, anecdotal data which seems to be confirmed by the differences of payable levels for black mass between Europe and South Korea (with European black mass prices consistently lower than Korean ones).

While the black mass is of strategic value, a major challenge is that European markets favor exports of black mass outside EU's borders, namely to South Korea or South-East Asian nations currently, with anecdotal data indicating that more than 50% of the black mass and factory scrap is currently leaving Europe. This is because of fundamental challenges to build a sustainable business model, starting with the need to secure inputs (gigafactories scrap, end of life batteries) and offtakes (i.e. buyers of recovered materials, notably pCAM and CAM producers), which adds to the issue of energy prices, raw materials prices, technology mastery and capacity to improve outputs quality and recovery.

It is in practice difficult to have a clear view of the precise black mass quantities exported because of the lack of harmonized classification (i.e. product vs. hazardous waste) used to designate black mass by exporters in each Member State, the lack of standardization of secondary metals concentrates and, ultimately, the lack of centralized statistics.

Asia largely dominates the global battery recycling landscape, led by China, which accounts for 80% of pretreatment and post-treatment recycling capacity. South Korea also plays an important role as a major destination for black mass from Europe and North America, although the volumes and flows involved are not precisely documented. Transboundary trade in waste is governed by the Basel Convention (1989), while the OECD has also established a framework for supervision and control among its members (1992), largely based on the provisions of this convention. Nevertheless, these rules remain porous, and the status of "waste" or "hazardous waste" depends largely on national legislation, which interprets the nature of black mass according to the economic interests of the country concerned.

China used to be a black mass importer from the EU and the US, but the country established imports restrictions on a series of secondary materials, including black mass, in 2013 for environmental purposes. These flows were then redirected towards other Asian countries, especially South Korea (which is an OECD member, and hence benefits from its simplified waste exchange framework) and Southeast Asian countries. Despite this, China has recently shown a willingness to relax these restrictions, probably in order to secure greater supplies for the Chinese recycling industry. Moreover, South Korea's recycling capacities recently increased, but not in the same proportions as the black mass supply; hence, its main long-term objective appears to be to secure black mass inflows to feed its post-treatment facilities by benefiting from its status as an OECD member.

The development of a competitive and resilient European recycling industry today appears to be a challenge commensurate with Europe's decarbonization ambitions. To achieve this, four points appear key:

1. Develop an accurate and centralized database on black mass flows and recycling capacities (with a distinction made between pretreatment and post-treatment) in Europe, to enable relevant policy-making by public authorities, and a precise understanding of the market and its opportunities by investors.
2. Maximize efforts to keep black mass in Europe. As a first step, establish clearly that black mass and batteries scrap can only be classified as dangerous waste. Secondly, the EU should seek to deploy a pro-active protective shield for the nascent battery recycling, which should at least take the form of an obligation for black mass producers to give priorities to European recycling facilities, while supporting the structuring of pCAM and CAM production in Europe.
3. Strengthen the business model for black mass recycling in Europe through a combined set of actions: including a fee for recycling the price of the EV battery; ensuring the possibility for recycling to have diversified streams for their outputs to increase their resilience in the short term; creating a European CRM Trading Scheme for recycled metals at a basic level of refining (i.e. not battery-grade, but MHP for instance) to create transparency on volumes available and prices and to ensure European off-take for the metals recycled in Europe; bonus/malus scheme; facilitating black mass flows among EU Member States to favor economies of scale; putting in place rules on batteries' and EVs design that favor disassembly and recyclability.
4. Pursue, develop and support research into battery recycling in Europe, to enable post-processing techniques (pyrometallurgy, hydrometallurgy) to be improved (i.e. environmental impact, energy consumption, but also regarding other battery components and new chemistries), and build the proper financing ecosystem to support the industrialization of innovations.

Résumé

Le recyclage des batteries de véhicules électriques (VE) est un élément essentiel pour renforcer l'autonomie stratégique de l'Union européenne (UE) dans le domaine des chaînes de valeur des matières premières critiques. Pourtant, les évolutions récentes de la chaîne de valeur européenne des véhicules électriques, marquées par des annulations ou des reports de projets, tirent la sonnette d'alarme sur les perspectives de l'industrie du recyclage des batteries en Europe.

Le recyclage des batteries recouvre des processus et des réalités complexes et quelque peu opaques, avec différentes étapes et des difficultés associées à la mise à l'échelle de toutes les étapes industrielles en parallèle. Le processus de recyclage commence par la collecte et la désactivation des batteries, avant qu'elles ne soient désassemblées et broyées, dans un processus appelé « prétraitement ». Cette étape de prétraitement produit une poudre noire communément appelée *black mass*. Le défi consiste ensuite à raffiner cette poudre (post-traitement) afin de récupérer ses métaux constitutifs, en particulier le nickel, le cobalt et le lithium. Normalement, les prix auxquels le lithium, le nickel et le cobalt provenant de sources primaires sont négociés sur les plateformes internationales dédiées (ex. London Metal Exchange) sont suffisamment élevés pour encourager leur recyclage, et leur présence dans le contenu de la *black mass* peut être utilisée pour lui attribuer une valeur, une estimation communément appelée dans l'industrie sous le nom de « payable ».

Actuellement, la pyrométallurgie (la fonte de la *black mass* pour produire un alliage métallique et éliminer les impuretés) et l'hydrométallurgie (réactions chimiques pour isoler les métaux à récupérer) sont les méthodes les plus courantes pour la récupération des matériaux, mais d'autres sont à l'étude, comme le recyclage direct. La comparaison de ces méthodes reste difficile, notamment en ce qui concerne la consommation d'énergie ou les émissions de gaz à effet de serre, notamment parce que les données et les analyses du cycle de vie sur ces questions sont rares et que les études existantes varient souvent dans leurs résultats. Les métaux récupérés sont ensuite purifiés pour arriver à une forme métallique (notamment pour une utilisation dans l'industrie métallurgique) ou transformés en sels de qualité batterie pour former de nouveaux matériaux de batterie, c'est-à-dire des précurseurs de cathode (pCAM) puis des matériaux actifs de cathode (CAM).

L'UE et les États-Unis tentent de développer leurs propres industries de recyclage (obligations du règlement européen sur les batteries concernant les taux minimaux de recyclage et de réincorporation ; cadre de soutien de l'IRA américain, etc.), ce qui s'avère particulièrement difficile pour la phase de post-traitement (récupération de matériaux à partir de la *black mass*). D'après les tentatives existantes de cartographie des capacités, l'Allemagne occupe une place importante dans le paysage européen en termes

d'installations, avec de nombreux recycleurs nationaux. La Hongrie dispose également de capacités de recyclage importantes, notamment grâce à la présence du sud-coréen SungEel. Au-delà des acteurs sud-coréens, des entreprises nord-américaines ont installé des installations de prétraitement dans l'UE, tandis que les recycleurs chinois n'étaient pas présents jusqu'à présent. Alors que le marché de l'UE présente une part importante de recycleurs hors UE, l'Amérique du Nord est fortement dominée par des acteurs nationaux.

Le manque de données précises sur les capacités réelles installées en Europe est un problème majeur pour comprendre l'état du marché du recyclage de l'UE. Certaines études suggèrent que les capacités européennes de recyclage de la masse noire pourraient être d'environ 300 000 tonnes pour le prétraitement et 350 000 tonnes pour le post-traitement, tandis que les entretiens menés avec des industriels nous conduisent à évaluer les capacités cumulées de l'Europe à environ 200 000 tonnes, avec peu de capacités de post-traitement – des données anecdotiques qui semblent être confirmées par les différences de prix entre la *black mass* (« payables) sur le marché européen par comparaison à ceux en Corée du Sud (les prix de la *black mass* européenne étant systématiquement inférieurs à ceux de la Corée du Sud).

Bien que la *black mass* ait une valeur stratégique, un défi majeur réside dans le fait que la situation actuelle sur les marchés européens favorise les exportations de *black mass* en dehors des frontières de l'UE, notamment en Corée du Sud actuellement, avec des données anecdotiques indiquant que plus de 50 % de la *black mas*s et des déchets d'usine quittent actuellement l'Europe. Cela s'explique par les obstacles majeurs à surmonter pour construire un modèle économique solide, à commencer par la nécessité de sécuriser les intrants (rebuts des gigafactories, batteries en fin de vie) et des contrats d'achat pour les matériaux récupérés (notamment vu le manque de production à l'échelle des pCAM et CAM au sein de l'UE), ce qui s'ajoute à la question des prix de l'énergie, des prix des matières premières, de la maîtrise des technologies et de la capacité à améliorer le degré de récupération des métaux et leur qualité.

Il est en pratique difficile d'avoir une vision claire des quantités précises de *black mass* exportées en raison de l'absence de classification harmonisée (i.e. produit ou déchet dangereux) utilisée pour désigner la *black mass* par les exportateurs dans chaque État membre, du manque de standardisation des concentrés de métaux secondaires et, en fin de compte, du manque de statistiques centralisées qui en résulte.

L'Asie domine largement le paysage mondial du recyclage des batteries, avec en tête la Chine qui représente 80 % des capacités de recyclage en prétraitement et post-traitement. La Corée du Sud joue également un rôle important, en tant que destination majeure de la *black mass* en provenance d'Europe et d'Amérique du Nord, bien que les volumes et les flux concernés ne soient pas précisément documentés. Le commerce transfrontalier de déchets est régi par la convention de Bâle (1989), tandis que l'Organisation de coopération et de développement économiques (OCDE) a également établi un cadre de surveillance et de contrôle entre ses membres (1992), largement basé sur les dispositions de cette convention. Néanmoins, ces règles restent poreuses, et le statut de « déchet » ou de « déchet dangereux » dépend largement des législations nationales, qui interprètent la nature de la *black mass* en fonction des intérêts économiques du pays concerné.

La Chine était autrefois un importateur de *black mass* en provenance de l'UE et des États-Unis, mais le pays a instauré des restrictions d'importation sur une série de matières secondaires, la *black mass* étant également concernée, en 2013, pour des raisons environnementales. Les flux de *black mass* ont ensuite été redirigés vers d'autres pays d'Asie, notamment la Corée du Sud (qui est membre de l'OCDE et bénéficie donc de son cadre simplifié d'échange de déchets) et les pays d'Asie du Sud-Est. Malgré cela, la Chine a récemment montré sa volonté d'assouplir ces restrictions, probablement afin de sécuriser davantage l'approvisionnement de l'industrie chinoise du recyclage. De plus, les capacités de recyclage de la Corée du Sud ont récemment augmenté mais pas dans les mêmes proportions que l'approvisionnement en *black mass*. Son principal objectif à long terme semble donc être de sécuriser les flux entrants pour alimenter ses installations de post-traitement, le pays bénéficiant de son statut de membre de l'OCDE.

Le développement d'une industrie européenne du recyclage compétitive et résiliente apparaît aujourd'hui comme un défi à la mesure des ambitions de décarbonation de l'Europe. Pour y parvenir, quatre points semblent essentiels :

1. Développer une base de données précise et centralisée sur les flux de *black mass* et les capacités de recyclage (en faisant la distinction entre prétraitement et post-traitement) en Europe, pour permettre l'élaboration de politiques pertinentes par les pouvoirs publics ainsi qu'une compréhension précise du marché et de ses opportunités par les investisseurs.

2. Maximiser les efforts pour maintenir la *black mass* en Europe. Dans un premier temps, établir clairement que la *black mass* et les déchets de batteries ne peuvent être classés que comme déchets dangereux. Ensuite, l'UE devrait chercher à déployer un bouclier de protection proactif pour le secteur naissant du recyclage des batteries, qui devrait au moins prendre la forme d'une obligation pour les producteurs de *black mass* de donner la priorité aux installations de recyclage européennes, tout en soutenant la structuration de la production de pCAM et de CAM en Europe.

3. Renforcer le modèle économique du recyclage de masse noire en Europe par un ensemble combiné d'actions : inclure dans le prix de la batterie du VE une redevance pour le recyclage ; assurer la possibilité pour les acteurs du recyclage d'avoir des flux diversifiés pour leurs produits afin d'augmenter leur résilience à court terme ; créer un système européen d'échange des métaux recyclés (à un niveau de raffinage de base) pour créer une transparence sur les volumes

disponibles et les prix mais aussi pour assurer que les métaux recyclés en Europe sont consommés au niveau domestique ; système de bonus/malus ; faciliter les flux de *black mass* entre les États membres de l'UE pour favoriser les économies d'échelle ; mettre en place des règles sur la conception des batteries et des VE qui favorisent le démontage et la recyclabilité.

4. Poursuivre, développer et soutenir la recherche sur le recyclage des batteries en Europe, pour permettre d'améliorer les techniques de post-traitement (pyrométallurgie, hydrométallurgie) (i.e. impact environnemental, consommation énergétique, mais aussi concernant d'autres composants des batteries et de nouvelles chimies), et construire l'écosystème de financement adéquat pour soutenir le passage à l'échelle des innovations.

Table of Contents

INTRODUCTION **11**

GETTING TO THE BLACK MASS:
INPUTS, PROCESSES AND COST ANALYSIS **13**

THE MURKY GEOECONOMICS OF BLACK MASS FLOWS **20**

RECOMMENDATIONS FOR IMPROVING THE BUSINESS MODEL
OF BATTERIES RECYCLING IN EUROPE **30**

Introduction

EV batteries recycling is a building block for boosting EU's strategic autonomy in the field of critical raw minerals (CRM) value chains, especially beyond 2035, and contributing to reducing EU's material footprint through reduced need for primary material extraction. Our previous work on the value chain of batteries[1] shows that, by 2050, if all recycling potential (i.e. end of life batteries and scrap) is used, more than half of EU needs for main battery metals would be covered. The establishment of a recycling industry in Europe up until 2035 depends chiefly on the scrap input received from European gigafactories, on being able to secure offtake (i.e. precursors and Cathode Active Materials (CAM) producers), on the implementation of recycling and incorporation obligations, but also on energy prices, raw materials prices, technology mastery and capacity to improve outputs quality and recovery.

Recent evolutions of these different key elements are raising the alarm on the prospects of the battery recycling industry in Europe: Northvolt is facing important difficulties to scale up its battery production, sales of EVs have been slowing down, some recyclers postpone projects due to lack of operational pCAM facilities ready to buy resulting output, as well as due to anticipated insufficient gigafactories scrap volumes, technology uncertainty, while foreign companies have increased their presence in the European market in the last years, benefitting from scale and technology mastery. At the same time, energy prices have gone down compared to 2022, yet they remain too high for EU energy-intensive companies to thrive in a highly price-competitive environment. Last but not least, raw material market prices have collapsed, which weakens the perspectives for returns on investments in the recycling industry.

The highly insufficient recycling of e-waste (waste electrical and electronic equipment, excluding EV batteries) is already a major and growing issue: reports show that, between 2010 and 2022, the quantity of e-waste worldwide has almost doubled, from 34 billion kg to 62 billion kg (containing 31 billion kg of metals, 17 billion kg of plastics and 14 billion kg of other materials). Yet only 22.3% of the e-waste in 2022 was properly collected and recycled[2], and an almost equal share has been landfilled, with consequences for the environment and communities (ex. exposure to hazardous substances) and a loss in critical raw materials (copper, aluminum, cobalt,

1. M.-A. Eyl-Mazzega, D. Gherasim, C. Vannier and A. Contu, "Comment gagner le pari industriel de la mobilité électrique en France et en Europe ?", *Études de l'Ifri*, Ifri, November 2023.
2. "Global E-Waste Monitor 2024", International Telecommunication Union and United Nations Institute for Training and Research, 2024, available at: https://ewastemonitor.info.

nickel...). The challenge is to avoid that battery EV waste further drives up the unsustainable e-waste piling up, while improving our collective capacity to secure critical minerals supply.

In the new "metallic era", the EU has stepped up its ambitions for recycling critical raw materials. Next to existing legislations such as the Extractive Waste Directive, the Waste Framework Directive, the Waste Electrical and Electronic Equipment (WEEE) Directive, the End-of-Life Vehicles (ELV) Directive, the EU reviewed its battery regulation to include recovery and recycling targets on EV batteries materials and adopted the Critical Raw Materials Act which sets an overall benchmark of ensuring that 25% of EU's strategic raw materials (SRMs) needs are met via recycling. The challenge will not be easy to meet, as currently this indicator stands at around 12% as an average for the 17 SRMs identified in the EU. Indeed, based on most recent estimates[3], of the list 34 CRMs identified at the EU level, only 10 currently have 10% or more of their EU demand met via secondary raw materials (among which some are key for EV batteries: copper 55%, aluminum/bauxite 32%, cobalt 22%, nickel 16%), while lithium (battery grade) and silicon metal account for less than 1%, natural graphite (battery grade) for 3% and manganese at 9%.

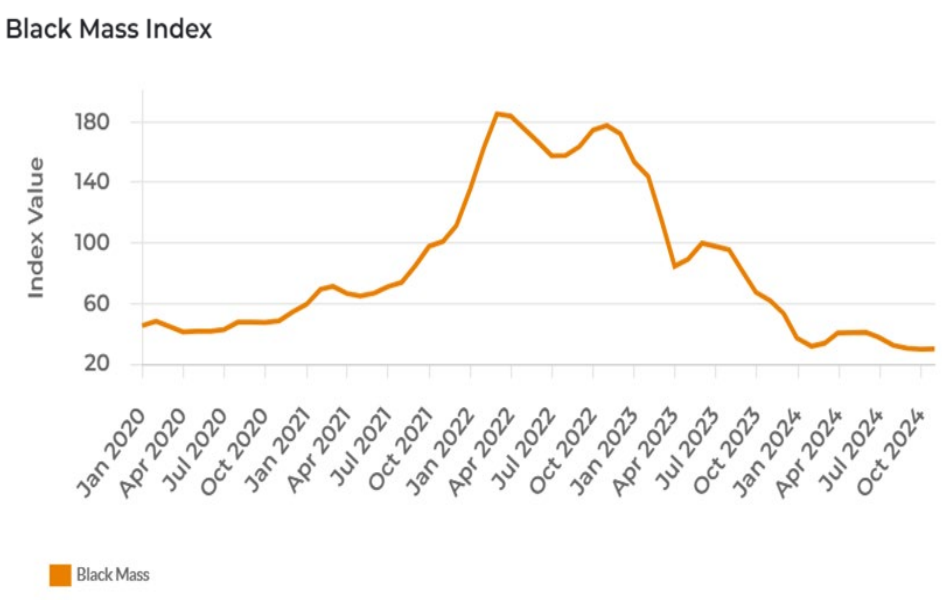
This paper aims to provide a technical and geopolitical understanding of black mass flows in Europe and globally, identify key actors in the value chain and propose solutions for strengthening the business case of battery recycling in Europe, amidst a so far challenged and slowed deployment of the EV battery value chain in the EU.

3. E. Watkins, E. Bergeling and E. Blot, "Circularity gaps of the EU Critical Raw Materials Act – How could the CRMA promote material circularity", Institute for European Environmental Policy, October 30, 2023, available at: https://ieep.eu.

Getting to the black mass: inputs, processes and cost analysis

The EV battery industry relies on two types of critical material sources for their cells production, with mineral concentrates from primary sources (i.e. from mining sites) being so far the main source, while secondary concentrates (i.e. coming from recycling of batteries) are expected to make an important contribution to the European CRM supply, namely after 2035. As a secondary source, black mass takes its name from the graphite powder present in the mix of materials that is obtained after the pretreatment phase of the recycling process. With time, black mass has become increasingly standardized and more homogeneous, allowing it to be traded on markets (ex. Fastmarkets) based on the spec characteristics (between 10-25% nickel, 10-20% cobalt; 3-5% lithium). A direct competitor to black mass spec (especially in instances of lower prices of metals from primary sources) can be the MHP (Mixed Hydroxide Precipitates), a mix of nickel and cobalt hydroxides, an intermediary product using primary sources of materials, especially imported by China.

Figure 1: Black mass prices index



Source: Benchmark Mineral Intelligence.

Battery recycling covers complex and somewhat opaque processes and realities, the focus on the black mass risking to overshadow the different process stages and the difficulties of scaling up alongside all the industrial stages. Hence, it is useful to underline that several steps are involved in the batteries recycling process, each with specific concerns and needs:

1. **Collection:** This step includes having the appropriate (safe and sufficiently granular) collection networks to reduce transport costs and prevent accidents from stored EVs. There are three main ways to collect used batteries and scrap: directly from OEMs; battery or module manufacturers (ex. faulty batteries/modules / cells, gigafactories scrap); wasteyards, dedicated EV collection networks.

   The second phase of collection aims at separating the batteries to select the ones that can be repurposed (cascading recycling), i.e. used in other applications like energy storage systems or electric tools with low energy demand, and the batteries that must be recycled to recover their materials (dismantling recycling). These end-of-life batteries also need to be sorted according to their rated voltage and to their chemistries, ensuring that the CRM content can be accessed and removed – NMC batteries with silicium additions for example are more challenging to recycle.

2. **Deactivation and discharge:** Batteries are then deactivated to make sure they can be handled safely further down in the recycling process (reduction of electrical and ignition risks), entailing a discharge, during which the electricity is fed into a conductor liquid or into the electricity system. Around 20% of the remaining energy can be recovered this way[4].

3. **Pretreatment:** According to the different techniques used in the next phase, this stage can include the manual dismantling of casing or a thermal pretreatment such as a pyrolysis process allowing for the removal of organic compounds, followed by mechanical comminution, shredding, sieving and magnetic separation. As a result of pretreatment, several outputs emerge: iron-containing scrap, non-ferrous metals scrap, copper and aluminum foils, and black mass (the fraction containing the active anode and cathode materials in the battery, which is estimated at about 50% of the weight of a battery).

4. **Post-treatment:** This process allows for the separation and purification of metals, with the current main possible routes being pyrometallurgy, hydrometallurgy or, a more recent and innovative one, direct recycling. In some instances, these technologies can be mixed, also knowing that other techniques are being developed, such as Sunchem's Nano filter technology for precision separation of CRM[5]):

   - Pyrometallurgy aims at melting the entire battery at highly elevated temperatures (1,300°C-1,500°C). It enables the recovery of a metal alloy (cobalt, copper, nickel accumulation), which has economic value, and of a lithium-rich slag (from

4. R. Girard and L. Hurel, "La fin de vie des batteries des véhicules électriques. Un impensé de la transition énergétique ?", Zenon Research, September 2024, p.20.
5. See more at: www.activate.org.

which lithium can be recovered requiring a hydrometallurgical process), which can be used, for instance, in the construction industry. Consequently, pyrometallurgy is not able to recover the different metals individually (unless combined with hydrometallurgy in a second stage, as for instance done by Umicore[6]). The combination of pyrometallurgical and hydrometallurgical processes indeed allows to streamline pretreatment (with less steps needed in the case of pyrometallurgy) and to recover lithium anyway, thanks to the hydrometallurgical process.

- Hydrometallurgy aims at dissolving battery components and separating them according to their chemical properties. Lithium is separated from the rest of the black mass as a first step (obtaining a lithium-rich filtrate that is further concentrated through boiling, refiltering or drying). Then, a process called leaching is applied to remove impurities (especially aluminum, copper and iron), by exploiting the fact that these metals precipitate at low pH. Other metals (nickel, cobalt and manganese) precipitate at higher and closed pH, leading to the obtention of MHP, as output[7]. Nickel, cobalt and manganese are then usually separated in the form of high-purity salts, using solvent extraction, and can be further transformed to reach their metallic form, to supply the metallurgy industry. With the development of supply needs for the manufacturing of new batteries, the demand for having MHP as the final output has gained importance. Global battery recyclers are currently largely positioned on hydrometallurgical processes, as are also expected to be European and American actors[8]. It can be noted that recently, the Canadian Li-Cycle shifted from a plan to transform black mass in battery grade outputs (lithium carbonate, nickel and cobalt sulfate)[9] at its hub in Rochester (USA) to only producing lithium carbonate and MHP which will allow it to better integrate into the supply chain via a more versatile product as the MHP is, resulting in an offtake agreement with Glencore covering 100% of the MHP produced at the facility[10].
- Direct recycling is a new and emerging technique for battery recycling. Although it currently remains at an experimental stage, i.e., far from the industrial development scale of pyrometallurgy and hydrometallurgy, it appears promising in several aspects. It aims at recovering the cathode material, but

6. "The R&D Journey behind Umicore's Unique Approach to Battery Recycling", Umicore, August 17, 2023, available at: www.umicore.com.
7. K. Davis and G. P. Demopoulos, "Hydrometallurgical Recycling Technologies for NMC Li-ion Battery Cathodes: Current Industrial Practice and New R&D Trends", *RSC Sustainability*, Royal Society of Chemistry, 2023, p. 1936-1941.
8. "Recycling of Critical Minerals: Strategies to Scale Up Recycling and Urban Mining", International Energy Agency, November 2024, p. 63.
9. C. Voloschuk, "Li-Cycle Provides Business Update along with 2023 Financials", *Recycling Today*, March 21, 2024, available at: www.recyclingtoday.com.
10. "Li-Cycle and Glencore Establish Commercial Framework for Rochester Hub Products", Li-Cycle, October 31, 2024, available at: https://investors.li-cycle.com.

also the electrolyte and the graphite through an optimized separation (washings, purifications and light thermal treatments), in order to recreate directly reusable components. Its final objective is to introduce these materials into new batteries. In the US, OnTo Technology has developed a process of direct recycling that has been tested and patented.

Comparing these three methods remains difficult, on several points, especially regarding energy consumption or GHG emissions. Indeed, the outcomes of the comparison can depend on the chemistry of the batteries considered, while data and life-cycle assessments on those issues are scarce, especially because emission monitoring is often not performed in lab-scale processes. Furthermore, the studies trying to compare the three techniques often vary in their findings.

Energy consumption makes no consensus between studies. While hydrometallurgy could appear to be less energy-intensive than pyrometallurgy since it requires less heat and as it is shown by several papers[11], other work consider that hydrometallurgy has a slightly[12] or even highly[13] superior energy consumption than pyrometallurgy. Both would remain more energy-intensive than direct recycling if it is to be further developed in the future.

The same situation occurs regarding GHG emissions, but most studies consider their emission levels comparable. Most pyrometallurgical emissions are directly linked to the recycling process, while emissions from hydrometallurgy mostly rely on material input (especially chemicals)[14]. Hydrometallurgy consumes more water than pyrometallurgy, and produces more wastewater, often contaminated with chemicals, that needs to be further treated. Hydrometallurgy and pyrometallurgy also both produce harmful gases that need to be eliminated. As it requires less pretreatment steps, pyrometallurgy entails a lower production of scrap and waste during the pretreatment phase[15]. Direct recycling presents GHG emission levels lower than the two other techniques and results in a limited production of waste and almost no harmful gases.

11. A. Zanoletti, E. Carrena, C. Ferrara and E. Bontempi, "A Review of Lithium-Ion Battery Recycling: Technologies, Sustainability, and Open Issues", *Batteries*, January 2024, p. 11; R. Girard and L. Hurel, "La fin de vie des batteries des véhicules électriques. Un impensé de la transition énergétique ?", *op.cit.*, p. 26.

12. L. Gaines, Q. Dai, J. T. Vaughey and S. Gillard, "Direct Recycling R&D at the ReCell Center", *Recycling*, Vol. 31, 2021, p. 7.

13. K. Davis and G. P. Demopoulos, "Hydrometallurgical Recycling Technologies for NMC Li-ion Battery Cathodes: Current Industrial Practice and New R&D Trends", *op.cit.*, p. 1941; G. Wei *et al.*, "Direct Recycling of Spent Li-ion Batteries: Challenges and Opportunities Toward Practical Applications", *iScience*, Vol. 26, No. 9, September 2023, p. 3.

14. K. Davis and G. P. Demopoulos, "Hydrometallurgical Recycling Technologies for NMC Li-ion Battery Cathodes: Current Industrial Practice and New R&D Trends", *op.cit.*, p. 1941.

15. S. Xiodong and V. Ishchenko, "Environmental Impact Analysis of Waste Lithium-Ion Battery Cathode Recycling", *Journal of Ecological Engineering*, Vol. 25, June 2024.

Considering the recycling process itself, pyrometallurgy presents a strong operability. It does not require over-discharge and electrolyte removal, leading to an easier and faster pretreatment phase. It can also treat heterogeneous flows of batteries, while hydrometallurgy usually needs homogeneous inputs, often requiring disassembly carried on manually. Direct recycling must be tailored to each cathode chemistry and therefore needs highly homogeneous input flows. Manual disassembly can represent an important cost, estimated to be between 34 and 80 USD per kWh of initial capacity[16]. Furthermore, direct recycling requires end-of-life batteries that are not too degraded and in good condition. Hydrometallurgy also entails numerous steps as part of the recycling process and is therefore time-consuming.

In average, hydrometallurgy nevertheless presents higher recovery rates than pyrometallurgy, even if rates of the latter are elevated as well. Direct recycling appears promising in terms of cost and as it enables to reach high recovery rates as well, even higher than the two other techniques as some studies suggest[17]. These findings are summarized in the table below.

Table 1: Qualitative comparative assessment of recycling technologies

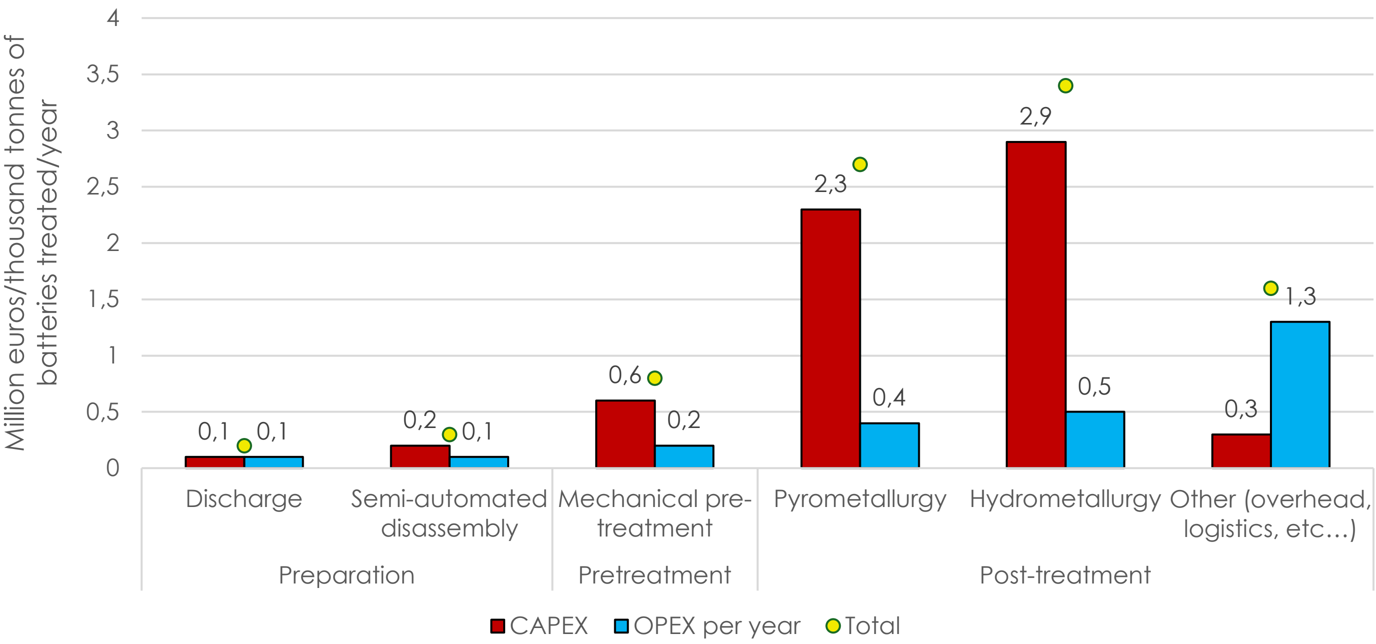
		Pretreatment	Inputs	Outputs	Recovery rates	Energy consumption	Pollution	Technology readiness	Investments
Pyrometallurgy	**Strengths**	Requires less pretreatment stages	Can treat heterogeneous flows of batteries (strong operability)				No wastewater production	High level of maturity	
	Drawbacks			Cannot recover metals individually No recovery of lithium	Lower recovery rates than hydrometallurgy	Significant energy consumption (comparable to hydrometallurgy)	Release of pollutants (e.g. gases) Production of slags		High degree of CAPEX and OPEX, slightly lower than hydrometallurgy
Hydrometallurgy	**Strengths**			Can recover metals individually and in the form of high purity salts	High recovery rates			High level of maturity	
	Drawbacks	Requires more pretreatment stages than pyrometallurgy	Needs homogeneous flows of batteries (requires spent batteries selection upstream)			Significant energy consumption (comparable to pyrometallurgy)	High water consumption Use of numerous chemicals Release of pollutants Wastewater (often contaminated)		High degree of CAPEX and OPEX
Direct Recycling	**Strengths**			Can recover a wide range of battery materials	Good recycling efficiency	Low energy consumption	Low GHG emissions Limited production of scrap and waste		Investments remain hard to estimate (no development on an industrial scale)
	Drawbacks	Requires numerous and thorough pretreatment stages	Requires homogeneous flows of batteries and batteries in good condition (not too degraded)					Experimental stage	

Source: Ifri

16. R. Girard and L. Hurel, "La fin de vie des batteries des véhicules électriques. Un impensé de la transition énergétique ?", *op.cit.*, p. 20.
17. *Ibid.*, p. 25; G. Wei *et al.*, "Direct Recycling of Spent Li-ion Batteries: Challenges and Opportunities Toward Practical Applications", *op.cit.*, p. 3.

Regarding investments, the first two techniques require major investments, somewhat lower in the case of pyrometallurgy. As shown in Figure 2, post-treatment processes imply far more investments, both CAPEX and OPEX, than pretreatment. As part of the OPEX, according to one study, energy represents the larger share for pyrometallurgy (energy costs estimated at 45% of the OPEX, the most important OPEX cost) than for hydrometallurgy (32% of OPEX), as well as labor costs seem to impact more pyrometallurgy than hydrometallurgy (estimated 23% of OPEX vs. 11% of OPEX). Hydrometallurgy's most important OPEX cost is related to material costs (linked to the chemicals needed for the process)[18]. Hence, pyrometallurgy being more sensitive to energy prices and labor costs means that it is less of an attractive refining process for European actors which prefer hydrometallurgy, a process that is also offering a broader range of outputs with commercial value.

Figure 2: Average annual investment required for the various recycling stages in the EU, 2023



Source: Ifri, based on "The EU Recycling market – a viable and sustainable business". Joint study between Strategy& and PEM of RWTH Aachen University, PwC, RWTH Aachen University, 2023, p.15, available at: www.strategyand.pwc.com.

5. **Further purification:** In both cases, the metal alloy, the hydroxide outputs, the lithium carbonate and graphite need further treatment to be broken down into high purity metals and to reach battery-grade salts. Alternatively, these outputs can be used in lower-purity applications like the glass, ceramic or construction industry. It is to be noted that, according to industry feedback, Asian gigafactories have such purification methods integrated into their industrial ecosystem, whereas

18. R. Woeste, E. Sebastian Drude, D. Vrucak, K. Klöckner, E. Rombach, P. Letmathe and B. Friedrich, "A Techno-Economic Assessment of Two Recycling Processes for Black Mass from End-of-Life Lithium-Ion Batteries", *Applied Energy*, Vol. 361, May 2024.

the European gigafactories are still currently optimizing their production processes using primary metals.

6. **Production of precursors of cathode and anode:** The last step of the recycling loop is the use of recycled and purified CRMs in the production of active materials for cathodes and anodes. The existence of precursors of cathode active materials (PCAM) and CAM / Anode Active Materials (AAM) producers in Europe is therefore essential for completing the business case of recycling facilities, as they are the main buyers of these materials. As long as they are not on European soil, it makes little sense for all the previous recycling steps to be placed in Europe (except for the steps up until the production of the black mass, which remain necessary to facilitate transport and reduce incidents' risks). Umicore currently has the only operating pCAM facility in Europe (Kokkola site), while BASF's pCAM project in Finland, planned to start by the end of 2024, is being delayed by an appeal against the granted permits before the Vaasa Administrative Court[19]. Eramet announced the suspension of its recycling project in France and Stellantis withdrew from the MoU with Orano on battery recycling and pCam[20]. A slowdown of cell production in Europe is also playing in favor of delays in developing the European recycling industry.

19. "BASF's Finnish pCAM plant start delayed due to permit appeals", S1P Global, March 1st, 2024, available at: https://cilive.com.

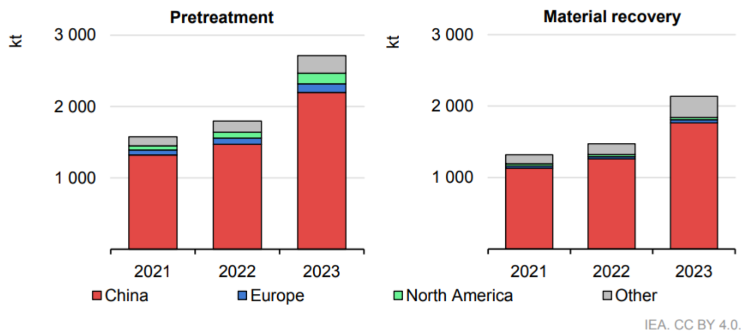
20. "Stellantis et Orano abandonnent leur projet de coentreprise de recyclage de batteries", *Les Echos investir*, September 26, 2024, avaialable at : https://investir.lesechos.fr.

The murky geoeconomics of black mass flows

As is the case for post-treatment techniques comparison, accurate data on national battery recycling capacities are relatively scarce. Maps and figures presented in this section must, therefore, be interpreted in an indicative approach rather than as a precise inventory of battery recycling facilities and capacities. China currently dominates worldwide capacities, covering at least half of them[21]. The International Energy Agency estimates Chinese capacities as of 2,700 kt of battery cell-equivalent for pretreatment in 2023 and 2,100 kt for post-treatment, which would represent around 80% of global capacity in both cases. Other Asian countries also play a significant role as well, especially South Korea and, to a lesser extent, Southeast Asian countries, such as Singapore, Malaysia or Thailand.

Europe and North America appear far behind in terms of capacities. Their combined share would be 10% for pretreatment and 4% for post-treatment. This inequality, both between battery scrap or end-of-life batteries feedstock and recycling capacities, as well as between pretreatment and post-treatment, entails massive feedstock and black mass exports every year, especially from Europe to Asian countries, particularly South Korea.

Figure 3: Historical battery recycling capacity for pretreatment and post-treatment (material recovery)



Note: Capacity in kilotonnes of cell-equivalent mass of total recyclable material.

Source: "Recycling of Critical Minerals. Strategies to scale up recycling and urban mining", International Energy Agency, November 2024, p.56.

21. On that point, the IEA talks about 80% of capacities located in China in 2023, which can appear relatively high. See: "Expected Battery Recycling Capacity by Region Based on Current Announcements, 2023-2030", International Energy Agency, March 15, 2024, available at: https://origin.iea.org. Other publications, such as the one based on data from ACS Energy Lett. assess China's share among global recycling capacities as around 50%. See: "China Is the World Leader in Battery Recycling. Existing and PLanned Lithium-ion Battery Recycling Capacity in Tons per Year", Statista based on ACS Energy Lett, 2021.

Based on existing attempts at mapping capacities[22], Germany takes an important part in the European landscape in terms of installed facilities, with numerous domestic recyclers. Hungary also has significant recycling capacities, especially thanks to the presence of South Korean SungEel, with two facilities within the country, a company that is also established in Germany and Poland and has projects in Spain and Germany. Non-European companies are indeed well established in Europe, as illustrated by SK TES, another South Korean company[23], with projects in France, Hungary and the Netherlands.

North American Recyclers are also developing their activities in Europe, with the presence of Li-Cycle (Canada) in the United Kingdom, which has also projects in France and Norway, Ecobat (US), with a facility in Darlaston, United Kingdom, or Ascend Elements (US) that has recently signed a joint-venture to own and operate a pretreatment facility in Zawiercie, Poland.

Chinese recyclers have not been present in Europe so far but are developing projects and joint ventures, such as the collaboration between XTC and French Orano.

Remarkably, most of the announced post-treatment capacities are expected to come from EU actors, whereas pretreatment investments are more diversified, with Canadian, South Korean, and other European countries signaling involvement. Yet, the realization of these announcements cannot be taken for granted in the absence of measures to secure black mass inputs and buyers of post-treatment outputs.

According to several publications, North America remained behind Europe in terms of recycling capacities over recent years[24], but new estimations, especially by the IEA, present European and North American capacities as equal. As is the case for Europe, North American facilities are concentrated on pretreatment operations, and a lot of the black mass they produce is currently shipped to be refined overseas. According to the US Department of Energy (DoE) and as of October 2023, the US held 174,500 tonnes of pretreatment capacities and only 35,500 tonnes of post-treatment

22. M. Stephan, "Battery Recycling in Europe Continues to Pick up Speed: Recycling Capacities of Lithium-Ion Batteries in Europe", Fraunhofer Institute for Systems and Innovation Research, August 7, 2024, available at: isi.fraunhofer.de.

23. In 2022, SK Ecoplant, a South Korean company focused on chemistry became the exclusive owner of TES, a Singapore-based battery recycler. In 2024, the company was rebranded SK TES.

24. "Battery Atlas", *Battery News.de*, available at: https://battery-news.de/en/battery-atlas/; "Lithium-Ion Battery Recycling – Overview of Techniques and Trends", *ACS Energy Letters*, Vol. 7, No. 2, January 2022, p. 712-719; "China Is the World Leader in Battery Recycling: Existing and Planned Lithium-ion Battery Recycling Capacity in Tons per Year", Statista based on *ACS Energy Letter*, 2021; K. Hantanasirisakul and M. Sawangphruk, "Sustainable Reuse and Recycling of Spent Li-Ion Batteries from Electric Vehicles: Chemical, Environmental, and Economical Perspectives", *Global Challenges,* January 2023, available at: www.researchgate.net; "Why Asia is Dominating the Lithium-ion Battery Recycling Market", Circular Energy Storage Research and Consulting, May 17, 2018, available at: https://circularenergystorage.com.

(in terms of end-of-life battery inputs)[25]. Attractive areas for recycling projects are notably the Great Lakes (Li-Cycle in New York and Ontario, Cirba Solutions in Michigan, both also having projects in Ohio), Southwest states (SungEel and Ascend Elements in Georgia, Li-Cycle in Alabama, Cirba Solutions and Redwood Materials projects in South Carolina), as well as Southeastern states (Li-Cycle in Arizona, Redwood Materials and American Battery Technology Company in Nevada). Nevada is developing as a post-treatment hub, as does South Carolina.

While the EU market presents an important share of non-EU recyclers, North America is strongly dominated by domestic actors, especially Li-Cycle, Cirba Solutions, Ascend Elements or Redwood Materials. The only external company established in North America is SungEel (South Korea), with one pretreatment facility in Georgia and a pretreatment project in Whitestown (Indiana).

To catch up and foster the development of their domestic recycling capacities, the EU and the US are developing acceleration strategies. In 2023, the EU revised its Battery Regulation, followed by the Critical Raw Materials Act in 2024. The Battery regulation establishes mandatory incorporation levels of recycled metals inside manufactured batteries and minimal efficiency rates for the recycling of those metals. The EU aims at reaching waste batteries recycling rates of 65% at the end of 2025 and 70% at the end of 2030 (based on average weight).

Table 2: Minimal recycling efficiency rates and incorporation rates for recycled metals

Metals	Minimal efficiency rates for recycling processes		Minimal incorporation rates of recycled metals in new manufactured batteries	
	2027	2031	2031	2036
Nickel	90%	95%	6%	15%
Cobalt	90%	95%	16%	26%
Lithium	50%	80%	6%	12%
Copper	90%	95%	-	-

Source: EU Battery Regulation

The US is developing an incentivizing framework for domestic battery recycling, especially through the two key support frameworks put in place within the Bidenomics: the Bipartisan Infrastructure Law (BIL), announced in November 2021, and the Inflation Reduction Act (IRA), announced in August 2022. The IRA notably provides a tax credit (30D) of 7,500 USD for

25. "FOTW #1350, July 8, 2024: In 2023 the United States Had Battery Recycling Facilities Capable of Reclaiming More Than 35,000 Tons of Battery Materials", US Department of Energy, Vehicle Technologies Office, July 8, 2024, available at: www.energy.gov.

the purchase of an electric vehicle. To be eligible to this tax credit, an EV needs to meet two requirements: having at least 60% (in 2024) of its components manufactured in North America and having at least 50% (in 2024) of its critical minerals being supplied from the US or US-FTA countries. These two thresholds will be progressively increased (10% per year), until reaching 100% for the first one and 80% for the second. Battery materials produced through recycling processes made in the US will be considered as fulfilling both criteria and therefore present a significant advantage.

The BIL provides several funds dedicated to the battery industry, for an approximative amount of 6.360 billion USD[26]. The support provided is mainly located in two funds, entitled "Battery Manufacturing and Recycling Grants" and "Battery Materials Processing Grants", with 3 billion USD of grants each. Within the scope of these programs, the DoE has awarded 14 projects during a first round, including 2 recycling projects: Cirba solutions in Ohio and Ascend Elements in Kentucky (391.2 million USD in total for the two projects). In September 2024, the DoE selected 25 new projects, including 4 recycling projects (Ohio, Oklahoma, and two in South Carolina), with 460.5 million USD for the four projects[27]. However, with Donal Trump elected as the next President of the US, the future of the IRA and the BIL and the preservation of their support schemes appear highly uncertain. The continuation or disappearance of the mechanisms developed for the battery industry by the federal government to date seems to have a lot to do with the nature of the relationship between Donald Trump and Elon Musk in the years to come. Musk's support earlier this year led the Republican candidate to radically change his position on EVs.

While Europe and North America seek to develop their own recycling industry, most battery recycling operations are currently conducted in Asia. Transboundary trade in waste is governed by the Basel Convention, drafted in 1989 and ratified by 164 countries worldwide (the US and Haiti have signed but not ratified the Convention). In 1992, the OECD set up a supervision and control system for transboundary waste movements specific to its members, based on the Basel Convention rules.

Waste is divided into two categories, with a green list (for waste presenting a low risk to human health and the environment) and an amber list (for waste considered hazardous). Green-listed wastes are not subject to any controls other than those normally applied to commercial transactions, while amber-listed wastes are subject to specific controls by customs authorities[28].

26. "A guidebook to the Bipartisan Infrastructure Law", White House, January 2024, available at: www.whitehouse.gov.
27. "Bipartisan Infrastructure Law: Battery Materials Processing and Battery Manufacturing Recycling Selections", US Department of Energy, Office of Manufacturing and Energy Supply Chains, www.energy.gov.
28. "Transboundary Movements of Waste", OECD, available at: www.oecd.org.

The Basel Convention only authorizes the movement of hazardous wastes if a "Prior Information Consent" procedure is carried out between the importing, exporting and transit countries. This procedure involves notifying and obtaining the consent of the authorities of the various countries (import/export/transit), generally through their environmental protection agencies. Within the OECD and its simplified system, it is possible to obtain "pre-consents" from the importing country, concerning a certain type of waste and destined for certain plants, which facilitates transboundary movements.

In 1994, non-OECD states wanted to reduce exports of hazardous waste from OECD countries, and to this end worked on a "Ban Amendment" to the Basel Convention. This finally came into force in 2019: the amendment prohibits transfers of hazardous waste from OECD countries to the rest of the world. It is not necessary for both countries involved in the transaction to have ratified the amendment in order to prevent the transaction from taking place, so there is no significant advantage for the US (which has not ratified the Basel Convention)[29].

The system of rules is, however, very porous, as neither the Basel Convention nor the OECD framework clearly define whether used lithium-ion batteries are considered waste or products, and whether they should be classified as hazardous materials or not (and therefore part of the green or amber lists). This classification depends to a large extent on the interpretation given to it by national authorities and can therefore lead to major discrepancies, particularly in view of a country's economic interests: a country with a highly developed battery recycling industry, for example, has an interest in facilitating imports and defining used batteries as products, rather than as waste, a fortiori hazardous waste.

China used to be a black mass importer from the EU and the US, but the country established imports restrictions on a series of secondary materials, with black mass included in 2013 for environmental purposes. Black mass flows were then redirected towards other Asian countries, especially South Korea (which is an OEDC member, and hence it benefits from its simplified waste exchange framework) and Southeast Asian countries. According to some sources, a part of the black mass shipped to Asia was indeed treated in Malaysia or Thailand to obtain MHP[30]. The latter was then exported to China and used to manufacture new batteries. SungEel holds for instance recycling facilities in Malaysia and India and is developing a project in Indonesia[31].

Nevertheless, China has recently shown its willingness to soften black mass import restrictions. Chinese battery recyclers, as shown by declarations

29. E. Moïsé and S. Rubínová, "Trade Policies to Promote the Circular Economy: A Case Study of Lithium-ion Batteries", *OECD Trade and Environment Working Papers*, OECD, January 2023, p. 18-23, available at: www.oecd.org.

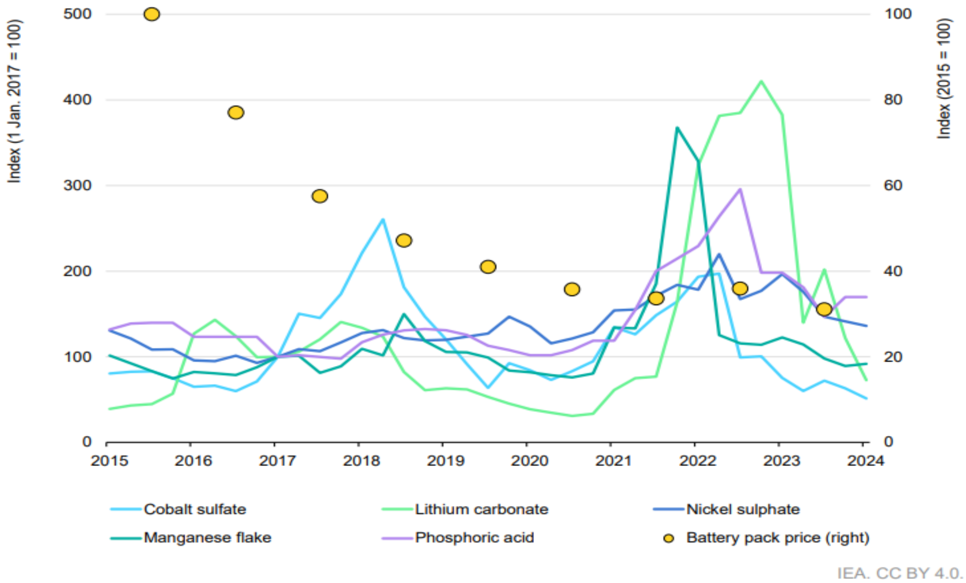
30. "China Mulls Easing Restrictions on Black Mass Imports: Sources", Fastmarkets, June 20, 2024.

31. SungEel website, available at: www.sungeelht.com.

of Huayou Cobalt's chairperson in March 2024, are concerned that China's recycling industry is starting to face overcapacities, i.e., recycling facilities do not receive sufficient black mass supplies. Chen Xuehua, a delegate to China's National People's Congress talked about "severe overcapacities". China could therefore try to make black mass imports easier, for instance classifying black mass as a "product" and no longer as a "hazardous waste" as it is currently the case[32].

Low prices for battery metals are also strongly impacting the Chinese industry. As illustrated in Figure 4, most battery metal components' prices are on a downtrend phase, especially nickel and cobalt sulphates, manganese flake and above all lithium carbonate. This leads to lower revenues for battery recyclers, especially considering that the prices of these components in their metallic form (to supply the metallurgy industry) have declined as well since the beginning of 2023, notably regarding nickel and cobalt – although copper and aluminum saw slight increases in their prices.

Figure 4: Price of selected battery metals (left) and lithium-ion battery packs (right), 2015-2024



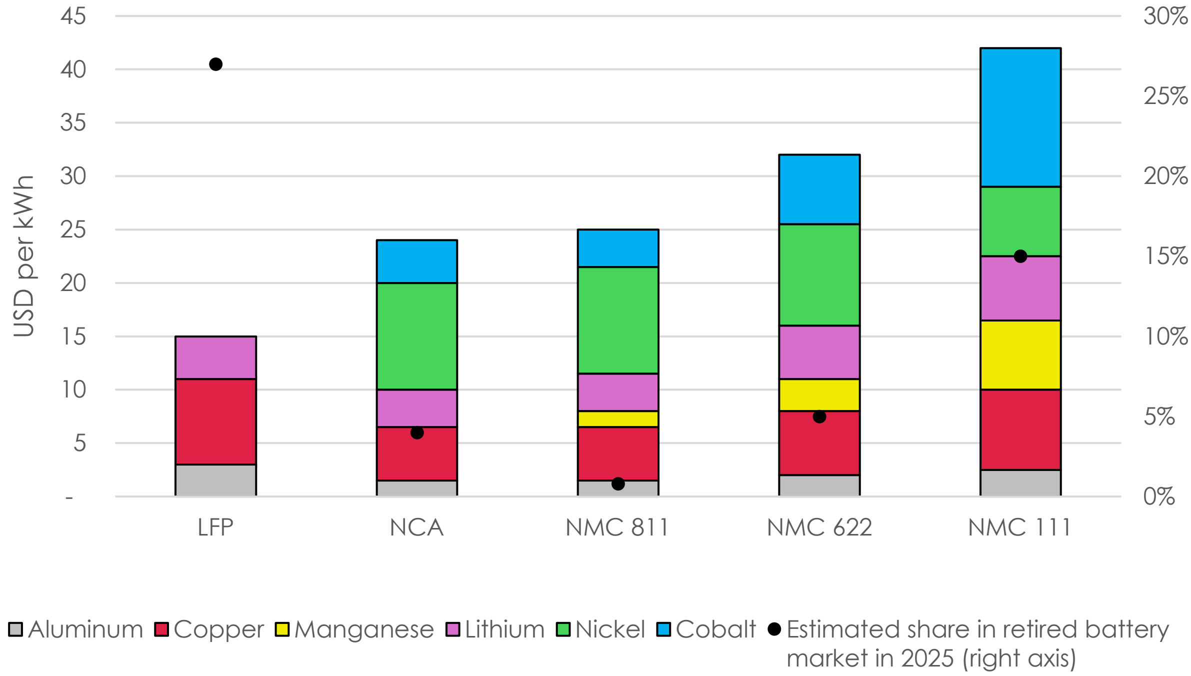
Source: "Global EV Outlook", IEA, p. 83.

China has become the world leader for a new generation of batteries, with a different chemistry: LFP batteries. These batteries represented more than 40% of global EV sales in 2023 (with a growing share)[33] and could represent 27% of spent battery flows in 2025[34]. Instead of containing nickel and cobalt as most batteries produced, the cathodes of these batteries are based on a combination of lithium, iron and phosphate, which are metals that are less expensive, making the batteries much cheaper (an average of 20%

32. "China's Huayou Cobalt Chief Proposes Battery Material Policy to Tackle Overcapacity", Reuters, March 4, 2024.
33. "Global EV Outlook", *op.cit.*, p. 85.
34. G. Wei *et al.*, "Direct Recycling of Spent Li-ion Batteries: Challenges and Opportunities Toward Practical Applications", *op.cit.*, p. 3.

cost difference) than NMC batteries. Nonetheless, if the inclusion of less valuable materials is a way to lower the battery price, it also entails less profitability for recycling and a harder business model to develop for recyclers. As illustrated in Figure 5, depending on the batteries' chemistry, nickel and cobalt represent at least 50% of the battery mineral value for chemistries in which they are present. This jeopardizes the profitability of recycling for LFP batteries, while they constituted almost 70% of EV sales in China in 2023[35].

Figure 5: Average value of recycled electric vehicle batteries in 2020, by cathode chemistry



Source: Ifri, based on data from Statista and G. Wei et al., *"Direct Recycling of Spent Li-ion Batteries: Challenges and Opportunities Toward Practical Applications", op.cit., p. 3.*

Another major Asian player in the field of recycling is South Korea, a significant destination for European and American black mass exports. Korean recycling capacities recently increased, but not in the same proportions as the black mass supply. Those additional capacities could rely on newer industries established within the peninsula and aiming at developing their own recycling supply chains for batteries. Black mass demand in Korea was exceeding black mass supply, especially considering high-quality black mass, containing low rates of impurities, especially less than 2% copper and 2% aluminum. In June 2024, the degree of competition within the Korean market was so high that payables (amounts paid to buy black mass) reached unprofitable levels. However, most recyclers continued

35. "Global EV Outlook", *op.cit.*, p. 85.

to buy this black mass anyway, with the necessity of maintaining operating rates[36]. Since then, payables have decreased and tensions on the black mass have eased. Nonetheless, for South Korea, the main long-term objective appears to be to secure black mass inflows to feed its post-treatment facilities, by benefiting from its status as an OECD member.

Most likely, as part of a strategy to reinforce domestic black mass supplies, the Korean government announced a national initiative on battery recycling with the objective of creating a more structured system for battery recycling. The plan relies on the evaluation of used batteries, in order to assess precisely their remaining capacity among other information and to classify them into 3 categories: remanufacturing (batteries that can be reinstalled into new EVs after repairs), reuse (batteries that can be directed towards other applications like energy storage), and recycling (batteries that will be processed to extract valuable materials). From 2027 onwards, owners of end-of-life EVs will have to get a mandatory performance evaluation by the Ministry of Land, Infrastructure and Transport, before the battery is removed from the car, in order to make this classification easier[37].

A battle for black mass could emerge between recyclers worldwide, if post-treatment capacities were to strongly exceed pretreatment facilities or supply flows of end-of-life batteries and factory scrap.

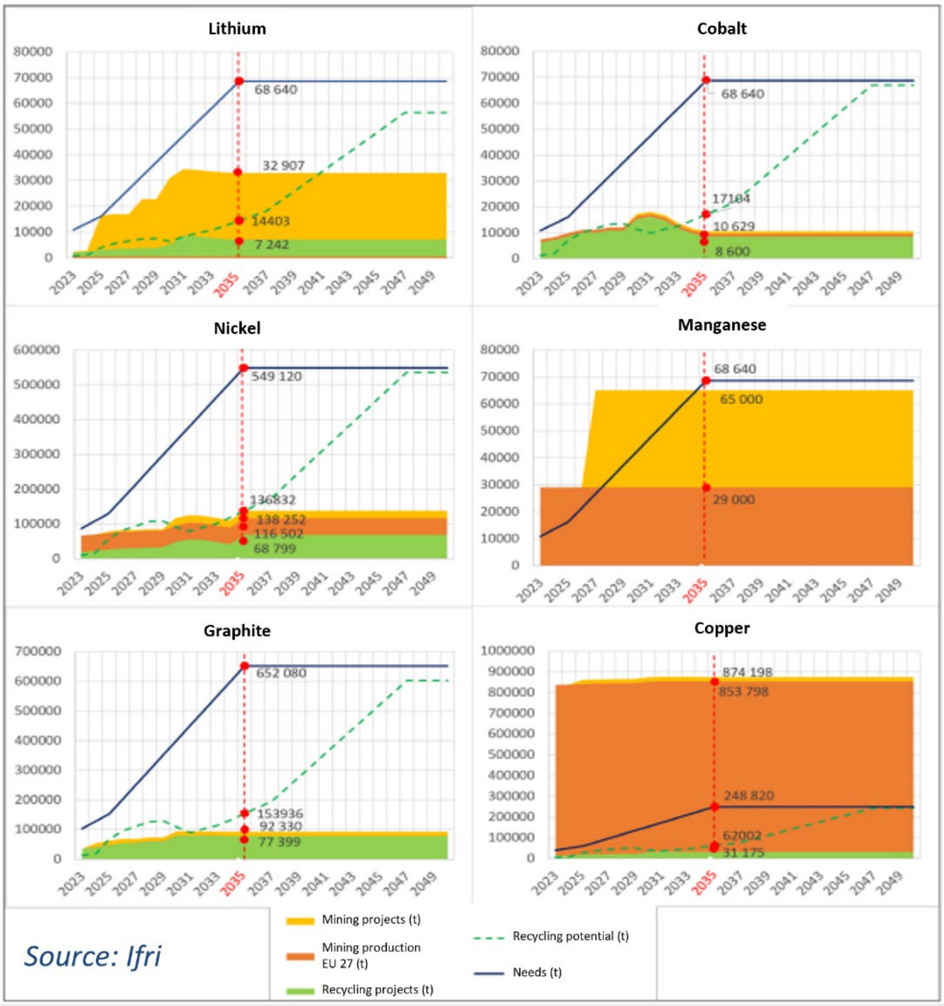
Aiming to develop its own battery recycling industry, Europe faces a difficult challenge. While it holds significant potential for recycling (see Figure 6), it does not only need to develop new post-treatment capacities but also to ensure that announced projects are realized, implying that black mass is treated in Europe and that recycled metals find buyers, meaning active materials producers, on the European soil. This implies that the EU needs to have a strong base of battery manufacturing companies committed to sourcing their metals consumption as much as possible from secondary sources based in Europe, yet this is far from being a deal done. The EU seems to stand dangerously at the beginning of a wave of cancellations or suspensions of projects in the field of electric mobility (Northvolt scaling back ambition and firing hundreds, ACC putting on hold factories development in Italy and Germany, BASF pausing the construction of a recycling plant in Spain), as in the case of Eramet's project in Dunkirk, where the CEO cites "major uncertainties concerning both the plant's supply of raw materials and the outlets for the metal salts produced by recycling[38]".

36. "Recycler Competition Pushes up Korean Black Mass Payables, SEA Lags on Weak Lithium", Fastmarkets, July 5, 2024.

37. M. Joon-huyn, "Korea to Boost Affordability of EVs with New Battery Recycling Scheme", *The Korea Herald*, July 10, 2024.

38. E. Goetz, "'Il n'y a pas aujourd'hui de modèle économique en Europe pour le recyclage des batteries', affirme la PDG d'Eramet", *Les Echos*, October 24, 2024.

Figure 6: Evolution of Europe's domestic supply needs and capacity up to 2050, for the BAU scenario (in tonnes)



Source: M.-A. Eyl-Mazzega, D. Gherasim, C. Vannier and A. Contu, "Comment gagner le pari industriel de la mobilité électrique en France et en Europe ?", op.cit.

For the battery recycling sector, the core of the issue is that there are major hurdles to overcome in order to build a sustainable business model: if pretreatment facilities are rather easily built (and enable black mass exports outside Europe, increasing the payables for European black mass), the post-treatment facilities are much more CAPEX intensive at a time when interest rates are still too high and support schemes are insufficient, when the metals prices have dwindled compared to 2022-2023, reducing the market value of secondary materials, while Asian actors have reinforced their hold on the sector thanks to massive capacities pushing them to look for black mass abroad and pay higher prices for acquiring it than European actors can afford to pay. Hence, the current situation in European markets favors exports of black mass outside EU's borders, namely in South Korea currently, but maybe increasingly to Indonesia or China in the future, with industry representatives reporting that 80% of the black mass and 60% of factory scrap is currently leaving Europe.

The US recycling industry is also catching up, with American companies being supported via schemes like the IRA and enjoying a well-established position at home, seeking now to import European black mass, as the payables for European black mass are lower than for the Asian one. The European black mass risks more and more ending up in the hands of industries other than European ones. It is however difficult to have a clear view of the precise black mass quantities exported because of the lack of harmonized classification (i.e. product vs. hazardous waste) used to designate black mass by exporters in each MS, the lack of standardization of secondary metals concentrates, and ultimately, the lack of centralized statistics as a consequence.

On top of these issues, the European regulatory framework, while clearly oriented towards supporting a circular economy approach in the battery sector, fails to protect recyclers based in Europe, as none of the recycling or reincorporation targets in the Battery Regulation imply the need to recycle batteries in Europe. Hence, it currently seems much easier for OEMs to fulfill these obligations by partnering with Asian actors which can provide recycled content or for Chinese actors to increase their EV market share in Europe thanks to their existing refining and recycling capabilities.

In this difficult setting, the European recycling actors that manage to survive are threading a careful line combining more realistic ambitions (i.e. initial lower recycling capacities to be installed), with an optimized inputs base (ex. contracts with OEMs, own pretreatment facilities, multiple sites of pretreatment serving one site of post-treatment) and a diversified buyers' base (i.e. beyond the battery industry, selling to glass, ceramics, construction, defense industries).

Recommendations for improving the business model of batteries recycling in Europe

First, the EU should develop an accurate and centralized database on black mass flows and recycling capacities. To put in place relevant policies and establish effective support schemes, public authorities need to have a clear view of the battery recycling market's realities. This knowledge is also crucial to investors and companies, allowing them to have a precise understanding of the market and its opportunities. Having a clear identification of Europe's recycling landscape and capacities is highly important, and project announcements can be challenging to track and categorize, especially regarding the numerous stages of battery recycling (collection, pretreatment, post-treatment, pCAM/CAM production, etc…) and the different units to estimate capacities (end-of-life vehicles, tons of batteries or of cells). Some studies suggest that Europe's recycling capacities could be of around 300,000 tonnes for pretreatment and 350,000 tonnes for post-treatment, while interviews conducted with industrials lead us to assess Europe's cumulative capacities as around 200,000 tonnes, with few post-treatment capacities, anecdotal data which seems to be confirmed by the differences of payable levels for black mass between Europe and South Korea (with European BM prices consistently lower than South Korean ones).

Second, the EU needs to fix the issue of having massive flows of material leaving Europe, predominantly for Asia but also for the US. The EU should put an end to the opacity created by the different interpretations by national border authorities regarding exports of black mass as waste or products. Hence, the EU must establish clearly that black mass and batteries scrap can only be classified as hazardous waste: this will have the effect of avoiding exports of black mass to treatment sites abroad that do not have the required permits for processing dangerous waste

Black mass remains a dangerous material and can scientifically be considered a hazardous waste, as demonstrated by a recent study by Tuscia University, highlighting "the inherently hazardous nature of black mass," especially due to its flammable character[39]. This demonstration is supported by explosions over the last few years. Two incidents of this type occurred in SungEel's Hungarian factories (in July 2022 in Batonyterenye and in March 2023 in Szigetszentmiklós, injuring four people[40]), due to a lack of security regarding battery waste storage, while a significant explosion happened[41] in a battery recycling plant in Missouri on October 30th 2024. Higher security standards also need to be put in place for black mass and battery scrap utilization and storage.

Yet, this first step (classifying black mass as hazardous waste) will not be enough, as the key buyers of European black mass are based in OECD countries (hence authorized to import hazardous waste) such as South Korea or the US, while Indonesia, a potential new destination for black mass, has also applied for OECD membership. Hence, as a second step, the EU should seek to deploy a proactive protective shield for the nascent battery recycling, namely for black mass post-treatment, in Europe. This should come in the context where the Battery Regulation imposes targets on the reincorporation of recycled materials in batteries, yet without requiring that this obligation be satisfied by recycling within EU borders, which could ultimately lead to boosting the business models of Asian competitors who already have an extensive recycling base and expertise, dedicated treatment facilities for further purifying recycled minerals and hence will likely be able to satisfy the Battery Regulation requirements at lower prices than European producers. If the EU's objective is to decrease its dependence on imports of CRMs and develop its own "urban mine", it must be proactive in protecting its home industries. One option is an outright ban on black mass exports outside the EU's borders, which would have the advantage of clarity of direction and creating pressure to deploy post-treatment capacities in Europe for material recovery. Yet, in practice, this needs to be accompanied by a guaranteed success of the deployment of a full battery value chain in Europe, implying the establishment of pCAM and CAM producers, which would themselves need to be incentivized/obliged to buy materials recovered in the EU from European black mass. One other way forward, which may be more operational in the short term, could be to request that black mass producers in Europe ensure that their black mass is processed in Europe, unless they can prove that no EU-based recycler is interested in buying it. Making sure European black mass is recycled within EU's borders makes environmental sense (EU doing its own share of effort to reduce domestic material footprint, lower GHG emissions linked to the transport of materials, and avoid a transfer of potential negative externalities abroad), as well as feeds into the need for increased resilience of supply chains, pertaining to economic security considerations.

39. M. Gianvincenzi, E. Maria Mosconi, M.Maroni and F. Tola, "Battery Waste Management in Europe: Black Mass Hazardousness and Recycling Strategies in the Light of an Evolving Competitive Regulation", University of Tuscia, February 4, 2024.

40. H. Bienvenu, "Orban Wants to Turn Hungary into a 'Major Battery Powerhouse'", *Le Monde*, September 10, 2023.

41. "Dramatic VIdeo Shows Explosion at Large Battery-Recycling Plant in Missouri", *USA Today*, November 1st, 2024.

Thirdly, the issue of the business model must be addressed: currently, too many changing parameters make battery recycling in Europe too uncertain with respect to future quantities of black mass available (inputs for recycling), to the existence of offtakers (i.e. PCAM / CAM producers) of metal salts resulting from recycling, the variation in metals prices on international markets, the evolution of batteries' chemistries. Some key steps to redress this business model are:

- Include a by-default recycling fee in the price of the EV batteries, in order to guarantee a minimum revenue to recyclers. This fee could be higher for LFP batteries than for NMC ones, as the minerals available in LFP batteries have less value on the markets and hence there is a higher environmental risk of them not being recycled due to insufficient value available for extraction. The Battery Regulation should be modified to include rates of recovery of iron and phosphorus of batteries.
- During a transition period, recyclers should be allowed to choose to which extent they refine black mass (i.e. the degree of purity of metals recovered) depending on the demand available (i.e. if gigafactories are not ready to consume these metals, other industries, ex. inox, catalyzers, should be able to secure these metals' supply). This will allow recyclers to build robust and diversified revenue streams, avoiding overdependence on one industry (ex. car industry) or buyer (ex. partnership with a battery manufacturer), while boosting scale and technology mastery.
- Creating a European CRM Trading Scheme for recycled metals at a basic level of refining (i.e. not battery-grade, but MHP for instance) to create transparency on volumes available and prices, as well as ensure European off-take for the metals recycled in Europe. Participation on this market should be voluntary in a first stage, in exchange of benefits such as tax credits, labelling, priority in public procurement markets etc. This scheme could be rendered mandatory overtime and connected to any future joint procurement platform or dynamic stockpiling mechanism.
- Another option is to create a bonus/malus scheme at the European level to be applied in public procurement or for state aid schemes (ex. support for consumers to buy EVs) depending on the share of virgin vs. recycled materials present in the final product.
- The European regulatory framework must be adapted to the need to create a European Single Market for recycling, by which black mass flows among EU Member States are facilitated (in order to ensure sufficient volumes for recycling sites, create economies of scale and European value chains), recycling standards (safety, environmental etc.) are harmonized and strategic projects (ex. CAM/PCAM) have access to EU level funding where national funding is not available.

- To increase recycling rates, the design of batteries and EVs must favor disassembly and recyclability, including by taking into account constraints such as placement of batteries in the EV to allow for easy access and identification, enforcing the digital passport rules regarding access to information on the composition of batteries, and support for R&D in the field of advanced recycling technologies should be ensured.

Fourthly, research on recycling processes needs to continue and to receive adequate support, including in the industrialization and scaling-up phases, when it is also important to foster the appropriate financing ecosystem (ex. private equity, investment funds etc.), in order to ensure a true European mastery of circular economy in the clean technologies field and to bring forward more environmentally friendly and efficient recycling techniques. More precisely:

- Conventional techniques like pyrometallurgy or hydrometallurgy can be improved, especially regarding their carbon and environmental footprints: experimentations have for instance shown that pyrometallurgy heat requirements could be lowered, using microwave irradiation within the scope of a hybrid heating process[42]. Alternatives to conventional hydrometallurgy are also being developed, based on microorganisms as leaching agents (biometallurgy) or ionic liquids and deep eutectic solvents (solvometallurgy), requiring less water and chemicals[43].
- Battery recycling also needs to be approached from a broad perspective. Cathode materials play a crucial role in recycling as they constitute the valuable material of the battery. Yet, research also needs to be conducted on other battery materials (electrolyte, anode materials...). If it may not be economically profitable, their recycling could be profitable for the lowering of batteries' carbon footprint. It could also reduce the need for graphite production and its environmental impacts, be it natural or synthetic. Furthermore, even cathode materials could present profitability issues in the future, within the arrival of the LFP chemistry. In that prospect, direct recycling appears to be a promising process to develop.
- While research is conducted to improve post-treatment processes, efforts need to be made on upstream stages as well (collection, discharge, disassembly). A focus on these areas will be key to develop efficient recycling loops. Manual disassembly can, for instance, represent a significant matter of cost and could be improved using artificial intelligence but also developing battery designs more suited for recycling. Enabling a more efficient recycling process relies on efforts at every stage of the battery value chain.

42. A. Zanoletti, E. Carrena, C. Ferrara and E. Bontempi, "A Review of Lithium-Ion Battery Recycling: Technologies, Sustainability, and Open Issues", *op.cit*, p. 8.
43. *Ibid.*, p. 10.

ifri
french institute of international relations
since 1979

27 rue de la Procession 75740 Paris cedex 15 – France

Ifri.org