Respect

FOR A COMPETITIVE, CIRCULAR AND SUSTAINABLE EUROPEAN BATTERY MANUFACTURING INDUSTRY.

D4.1 – "Report about Graphite recycling"

WP4 - Direct recycling & Active Materials synthesis and test (incl. cells manufacturing)

T4.1: Direct recycling of active materials from electrode scraps

T4.3: Active materials synthesis from HM outputs coming from end-of-life batteries

Due date of deliverable: 01 07 2025

Actual submission date: 29 10 2025

Project Acronym	RESPECT
Call	HORIZON-CL5-2021-D2-01
Grant Agreement N°	101069865
Project Start Date	01-07-2022
Project End Date	30-06-2026
Duration	48 months

Information

Written By	Garima Jain (VIANODE AS) Gunstein Skomedal (VIANODE AS)	2025-07-04 2025-07-04
Checked by	Antoine Driancourt (CEA), Thangavelu Jayabalan (ORANO)	2025-10-17
Reviewed by	Susan Sananes (CIDETEC) Ane Muguruza (CIDETEC)	2025-08-10
Approved by	Justo Garcia (ORANO) – Project Coordinator	2025-10-28
Status	Final	2025-10-29

Dissemination Level

PU	Public	X
SEN	Sensitive	
C-UE/EU-C	EU Classified	

Versions

Date	Version	Author	Comment
04-07-2025	1.0	Garima Jain, Gunstein Skomedal	The first draft
09-09-2025	2.0	Garima Jain, Gunstein Skomedal	Updated version
28-10-2025	FINAL	Garima Jain, Gunstein Skomedal	Final and submitted version

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

ACKNOWLEDGEMENT

RESPECT is an EU-funded project that has received funding from the European Union’s Horizon Europe Research and Innovation Programme under Grant Agreement N. 101069865.

DISCLAIMER

The sole responsibility for the content of this report lies with the authors. It does not necessarily reflect the opinion of the European Union. The European Commission is not responsible for any use that may be made of the information contained therein.

While this publication has been prepared with care, the authors and their employers provide no warranty with regards to the content and shall not be liable for any direct, incidental or consequential damages that may result from the use of the information or the data contained therein.

ABBREVIATIONS AND ACRONYMS

LIB	Lithium-ion battery
EVs	Electric vehicles
ASG	Production scrap
EOLG	End-of-life battery graphite
EOL	End-of-life
NG	Natural graphite
SG	Synthetic graphite
LCA	Life cycle assessment
SEI	Solid electrolyte interphase
SEM	Scanning electron microscopy
FCE	First cycle efficiency

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

CONTENT

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

EXECUTIVE SUMMARY

Graphite plays a critical role in lithium-ion battery (LIB) technology, functioning as the primary anode material due to its excellent electrochemical properties, structural stability, and compatibility with industrial-scale manufacturing processes. It is used in over 95% of all LIB anodes, especially in electric vehicles (EVs) and portable electronics. Despite emerging alternatives such as silicon and lithium metal, graphite remains irreplaceable at scale because these materials face substantial technical and economic barriers. Global demand for graphite is expected to quadruple by 2030, driven primarily by the rapid growth in EV adoption, stationary energy storage systems, and the expanding consumer electronics market.

The current graphite supply chain is heavily concentrated in China, which controls over 60% of natural graphite production and more than 90% of synthetic graphite manufacturing and processing. This concentration introduces substantial geopolitical and economic risk, particularly in light of growing trade tensions and resource nationalism. In response, countries such as the United States, members of the European Union, and Canada are investing in domestic supply chain development. However, these efforts face significant challenges related to permitting, environmental concerns, and the capital-intensive nature of graphite processing infrastructure.

Despite graphite's ubiquity in batteries, it is rarely recycled. Recycling efforts in the battery sector have traditionally focused on high-value cathode materials like lithium, cobalt, and nickel. Graphite is often incinerated or landfilled, resulting in the loss of valuable material and embedded energy. This lack of recycling is attributed to both technical challenges—such as separating and purifying graphite from other battery components—and the relatively low market value of recovered graphite compared to virgin material. However, as environmental pressures increase and supply risks mount, interest in graphite recycling is rapidly growing.

Recycling methods for graphite are now being developed and tested, targeting both production scrap and end-of-life batteries. Production scrap is relatively clean and homogeneous, making it ideal for closed-loop recycling. Mechanical separation techniques can recover graphite from electrode scrap, but industrial-scale recovery remains rare. End-of-life battery recycling is more complex due to mixed chemistries, degradation, and contamination. Processes such as mechanical shredding, pyrometallurgy, hydrometallurgy, solvent washing, acid leaching, thermal purification, and electrochemical treatments are being evaluated. Of these, thermal purification and regraphitization appear most promising for restoring graphite to anode-grade quality, especially when followed by post-processing.

Within the RESPECT project, VIANODE AS demonstrated the recycling of graphite from both production scrap and end-of-life batteries. Graphite concentrates received from mechanical pre-processing were treated using a multi-step recycling process that included pre-processing to remove organic binders, high-temperature thermal purification to eliminate metal contaminants and heal structural defects, and post-processing to optimize physical characteristics. Physicochemical characterization of the recycled graphite showed excellent purity levels (99.99%), with all metallic impurities reduced to below detection limits and ash contents below 0.01 wt%. Morphological and crystallographic analyses confirmed restored structure and particle quality.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

Electrochemical testing further validated the quality of the recycled material. Graphite recovered from production scrap (ASG) showed a first-cycle efficiency of 94.1% and an average charge capacity of 353.6 mAh/g, closely matching virgin anode-grade graphite. The end-of-life battery graphite (EOLG), which had a higher proportion of natural graphite, achieved a slightly lower first-cycle efficiency of 90.9% but a higher capacity of 361.1 mAh/g. This demonstrates that both production scrap and EOL graphite can be successfully regenerated into high-performance anode-grade material using appropriate purification and processing techniques.

In conclusion, the study confirms that sustainable, high-purity graphite recycling is technically feasible for both production and post-consumer battery waste. The recovered materials show electrochemical and structural properties on par with virgin graphite. As demand grows and supply chain pressures increase, recycled graphite represents a valuable secondary resource that can contribute meaningfully to a circular battery economy.

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

1 INTRODUCTION

1.1 Current graphite value chain

Graphite is a critical raw material in the lithium-ion battery (LIB) value chain, serving as the dominant anode material due to its excellent electrochemical properties, cost-effectiveness, and compatibility with existing manufacturing infrastructure. Graphite is currently irreplaceable in commercial lithium-ion batteries, accounting for over 95% of the anode material used in EVs and portable electronics, see Figure 1. Its layered carbon structure allows for efficient lithium-ion intercalation and deintercalation, enabling high energy density and long cycle life. While alternative materials such as silicon and lithium metal are being explored, they face significant technical and cost barriers to widespread adoption.

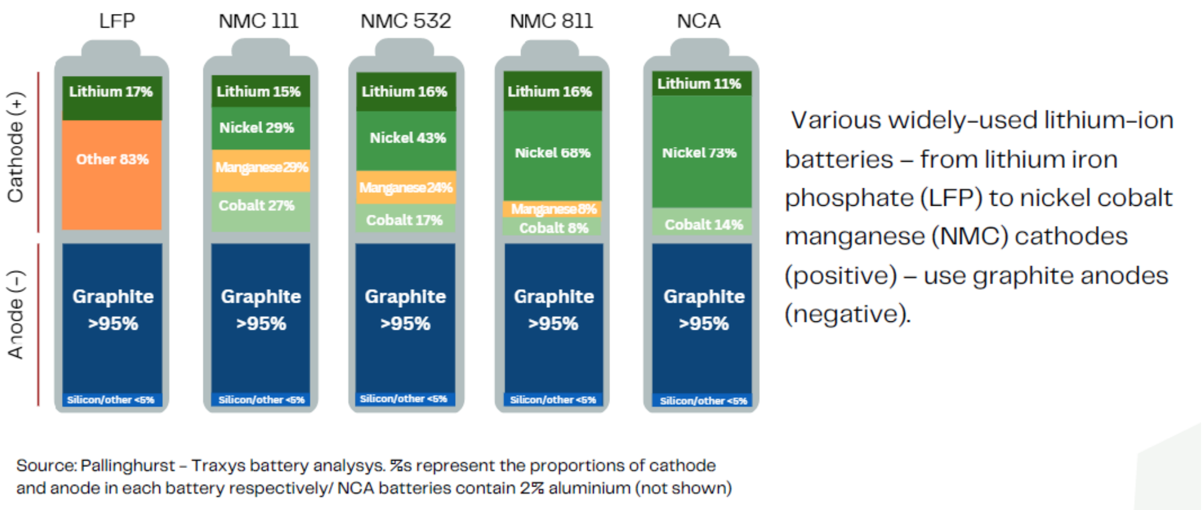

Figure 1: Graphite's central role in today's batteries (Graphite in batteries, February 2022)

As a result, graphite demand is projected to grow fourfold by 2030 compared to 2023 levels, with overall demand doubling during the same period. This surge is driven not only by EV adoption but also by the expansion of stationary energy storage systems and portable electronics. As global demand for electric vehicles (EVs) and energy storage systems accelerates, the graphite supply chain is under increasing pressure to scale sustainably and securely.

The global graphite supply chain is currently highly concentrated, with China accounting for over 60% of natural graphite production and more than 90% of synthetic graphite manufacturing and processing capacity (Park, 2025). This dominance extends across mining, purification, shaping, and coating processes, making the global battery industry heavily reliant on Chinese supply chains. Such concentration introduces significant geopolitical and economic risks, particularly in light of recent trade tensions and export restrictions.

Efforts to diversify the supply chain are underway, with countries like the United States, Canada, and members of the European Union investing in domestic graphite projects and processing capabilities. However, these initiatives face challenges related to permitting, environmental concerns, and the high capital intensity of graphite processing infrastructure.

Despite its critical role and growing demand, graphite is not currently recycled at scale. Most recycling efforts in the battery sector have focused on high-value cathode materials such as lithium, cobalt, and nickel. Graphite, by contrast, is often incinerated or discarded during both production and end-of-life

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

(EOL) battery recycling processes. This results in the loss of valuable material and embedded energy, while also contributing to environmental impacts.

The absence of graphite recycling is due in part to technical challenges in separating and purifying spent graphite, as well as the relatively low market value of recovered graphite compared to virgin material. However, as sustainability pressures mount and supply risks intensify, interest in graphite recycling is growing rapidly.

1.2 Graphite as anode material

Graphite has been the cornerstone of lithium-ion battery (LIB) technology since its commercial introduction in the early 1990s. Its success is rooted in a unique combination of favorable electrochemical properties, structural stability, and compatibility with industrial-scale manufacturing processes (Asenbauer, 2020)

The shift from lithium metal to graphite anodes was driven by safety concerns. Lithium metal, while offering high energy density, posed significant risks due to dendrite formation and thermal instability. In the late 1980s, researchers discovered that lithium ions could reversibly intercalate into graphite without forming metallic lithium, enabling safer and more stable battery operation. Sony’s launch of the first commercial LIB in 1991, using a graphite anode and $LiCoO_2$ cathode, marked a turning point in battery technology

Since then, graphite has undergone continuous optimization, including improvements in particle morphology, surface coatings, and electrolyte compatibility. These developments have enabled better rate performance, longer cycle life, and improved safety.

Graphite’s layered structure allows lithium ions to intercalate between graphene planes, forming LiC_6 during charging. This process is highly reversible and occurs at a low potential (~0.1 V vs. Li/Li^+), which maximizes the cell’s energy density. Key advantages include:

- **Theoretical Capacity**: 372 mAh/g
- **High Coulombic Efficiency**: >99.9% after formation cycles
- **Excellent Cycle Life**: Thousands of cycles with minimal degradation
- **Mechanical and Thermal Stability**: Maintains integrity under repeated cycling
- **Stable SEI Formation**: Forms a protective solid electrolyte interphase (SEI) that enhances long-term performance

Despite its advantages, graphite has a moderate specific capacity compared to emerging materials. Fast-charging also remains a challenge due to sluggish lithium-ion diffusion and interfacial kinetics, which can lead to lithium plating and safety concerns.

Alternatives such as silicon and lithium metal offer higher capacities but face significant challenges. Silicon, in particular, has been the focus of intense research. While it offers more than ten times the capacity of graphite, its large volume changes during lithiation lead to mechanical failure and unstable SEI formation. Hybrid materials, such as silicon-graphite or silicon oxide composites, are being developed to mitigate these issues.

Even though graphite is often referred to as a single class of anode material, there are in fact numerous different variations of graphite and many ways to optimize and tailor the graphite to different

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

application requirements. The two most common differences stem from the two main sources of anode graphite, namely natural and synthetic graphite.

1.3 Natural graphite

Natural graphite (NG) is a crystalline form of carbon that forms over millions of years under high temperature and pressure conditions in the Earth’s crust. It is mined from deposits found in regions such as China, Mozambique, Madagascar, and Brazil. For use in lithium-ion batteries, natural graphite must undergo extensive processing to meet stringent purity and performance requirements. The production of battery-grade natural graphite involves several key steps summarized in Figure 2 (Adham, 2023).

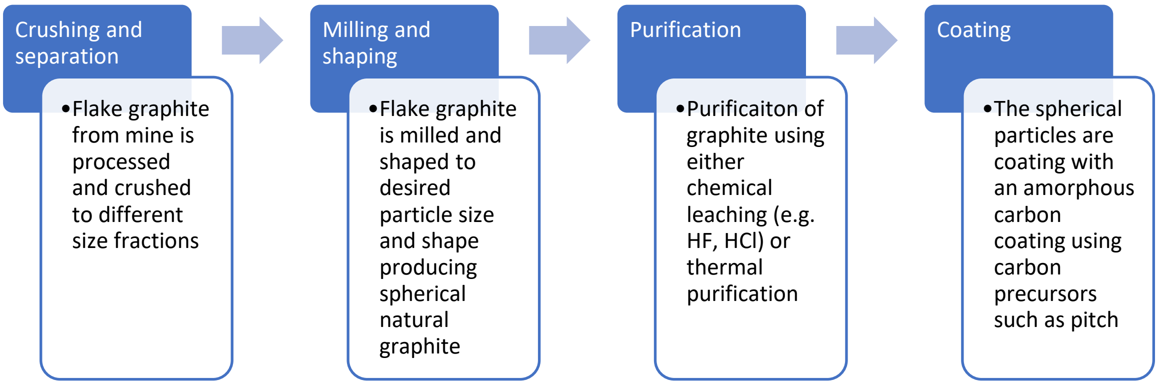

Figure 2: Schematic illustration of the process of natural graphite for anodes in batteries.

Natural graphite production is relatively energy-efficient compared to synthetic graphite, but it involves significant chemical usage and waste generation during purification. Hydrofluoric acid, in particular, poses environmental and safety risks. Chemical purification has certain limits in achievable purity thus, thermal purification is necessary to achieve purity beyond 99.9% graphite. Emissions are primarily associated with mining operations, chemical treatments, and transportation. In addition, the milling and shaping into potato shaped particles have high yield losses.

In terms of performance, natural graphite possesses very high capacity due to its highly crystalline origin, close to the theoretical maximum at around 360-365 mAh/g. However, this is also a disadvantage in terms of fast charge performance as the highly anisotropic structure has long diffusion pathways for lithium and relatively low edge to basal plane ratio. Natural graphite is also, due to its highly crystalline nature, more prone to exfoliation than synthetic graphite, particularly during fast charge or when exposed to aggressive leaching (see next chapter).

1.4 Synthetic graphite

Synthetic graphite (SG) is manufactured from carbon-rich precursors such as petroleum coke or coal tar pitch. It is engineered to have consistent properties and high purity, making it ideal for demanding battery applications. The main production steps are outlined in Figure 3.

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

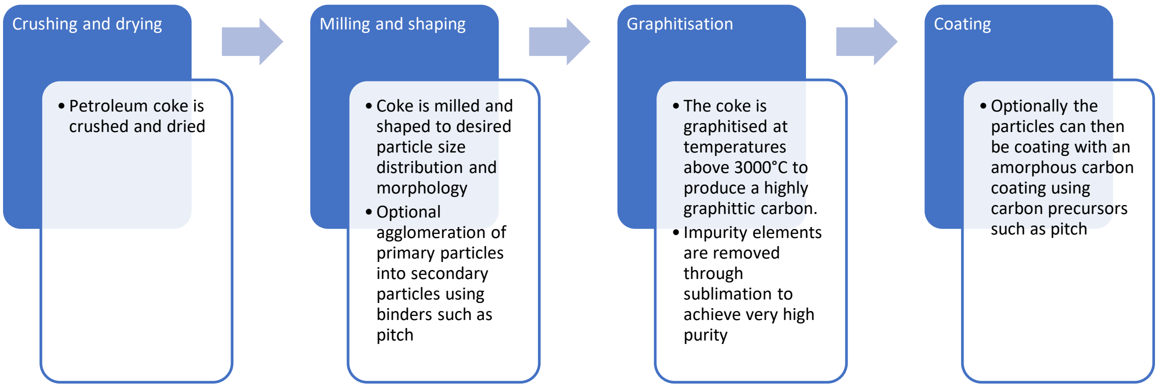

Figure 3: Schematic illustration of the process of synthetic graphite for anodes in batteries

Synthetic graphite production is highly energy-intensive due to the graphitization step, which requires sustained high temperatures. This results in significantly higher carbon emissions compared to natural graphite. The environmental footprint is influenced by electricity sources, feedstock purity, and furnace efficiency. Life Cycle Assessment (LCA) studies show that synthetic graphite can have up to three times the carbon footprint of natural graphite per kilogram of anode material produced. Recent LCA studies by VIANODE AS have shown that graphite produced with lower energy use, direct emissions and higher yield can reduce carbon emission from 10-30 kgCO2eq/kg product for traditional processing down to ~2 kgCO2eq/kg product (Life Cycle Assessment for Vianode: Advancing Sustainable Battery Materials)

Due to its more isotropic nature compared to natural graphite, synthetic graphite typically has lower specific capacity, around 350-360 mAh/g, but also much better intercalation kinetics. Since the capacity disadvantage is relatively modest compared to the huge potential benefits in fast charge, synthetic graphite has over the last years taken over the throne as the preferred anode material, particularly for applications where fast charging is important such as for EVs. By correct selection of raw materials combined with sizing, agglomeration and coating strategies, very advanced synthetic graphite-based anodes are now available on the market with excellent fast charge capabilities and very long cycle life.

1.5 Cell manufacturing

Lithium-ion battery (LIB) cell manufacturing is a complex, multi-step process that transforms raw materials into high-performance energy storage devices. Anode materials—primarily graphite—are central to this process, and their handling significantly influences both yield and waste generation.

The key stages in cell manufacturing, with emphasis on the anode side, include:

1. **Slurry Preparation:** Graphite is mixed with conductive additives and binders (e.g. CMC, SBR) in a solvent (typically water) to form a homogeneous slurry. Often a blend of different active components are used, such as synthetic and natural graphite or silicon-based material (SiOx, Si-C).
2. **Coating:** The slurry is applied to copper foil using slot-die or roll-to-roll coating methods. Uniform coating thickness is critical for consistent electrochemical performance.
3. **Drying:** The coated foil is dried in ovens to remove the solvent. This step is energy-intensive and must be carefully controlled to avoid binder degradation.
4. **Calendaring:** The dried electrode is compressed to achieve the desired porosity and density, improving particle contact and electronic conductivity.

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

5. **Slitting and Cutting:** Electrodes are cut into specific dimensions for different cell formats (e.g., pouch, cylindrical). This step generates edge scrap, a major source of production waste.
6. **Cell Assembly:** Electrodes are stacked or wound with separators and cathodes, inserted into cell housings, filled with electrolyte, and sealed.
7. **Formation and Testing:** Cells undergo initial charging cycles to form the solid electrolyte interphase (SEI). Cells that fail quality checks are rejected, contributing to formation scrap.

Production scrap accounts for a significant portion of total battery waste, especially during electrode manufacturing and cell assembly. The main sources of scrap include:

- Slitting Scrap: Trimmed edges from coated electrodes.
- Coating Defects: Non-uniform or misaligned coatings.
- Calendaring Issues: Cracks or delamination due to excessive pressure.
- Assembly Errors: Misalignment or contamination during stacking/winding.
- Formation Failures: Cells that fail during initial charging cycles.

These scraps contain valuable graphite and binder materials. Although is very hard to find good sources on the actual amount of scrap of different types, industrial data suggest that 4–12% of material can be lost as scrap during production of cells, depending on process control and equipment precision, and all the way up to 15-30% during ramp-up face of a new production line (Wang, 2024) This represents a major opportunity for closed-loop recycling and cost reduction.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

2 DEGRADATION MECHANISMS

Graphite can be affected in many of the processing steps leading up to a finished battery cell, as well as continuous cycling and storage during use phase. Depending on what potential degradation source the graphite has experienced, this will affect how it can be processed for new use, and to what extend degradation caused can be healed in preceding graphite recycling processes.

2.1 During cell manufacturing

During slurry mixing, graphite is mixed with F binders, viscosity modifiers and conductive additives in the slurry formulation. These materials are mainly carbon based but not graphitizable and therefore must be removed from the material. CMC and SBR are commonly used materials for anodes, but also other kinds of binders can be used such as copolymers with acrylic or nitrile rubbers. Also, some fluorinated polymers can be used. Conductive additives can be carbon black, nanotubes, VGCF (vapor grown carbon fiber), graphite fines or graphene. In addition, silicon can be added to the anode to improve charge capacity. Silicon itself cannot be directly recycled due to irreversible damage to the crystal structure during charge/discharge. Small amounts of silicon in the anode can be removed during recycling of graphite anode, but very high amounts of silicon (>5-10wt%) can be problematic for graphite recycling.

2.2 In use phase

There are several degradation mechanisms in graphite during use phase, and there exist numerous studies breaking down the degradation to different mechanisms. Some of these effects will result in impurity build up without affecting the surface and bulk structure of the graphite itself. Other effects can also cause irreversible damage/change to the graphitic surface and structure and therefore need extra consideration when discussing the recyclability of the graphite.

2.2.1 Surface

Two main effects are considered when looking at surface degradation of graphite. First and foremost is the formation of the SEI on the graphite surface during initial cycling. Over time, it thickens, consuming lithium and clogging pores. Furthermore, upon continued cycling, graphite and binder swelling can lead to electrode delamination and increased internal resistance as exemplified in Figure 4.

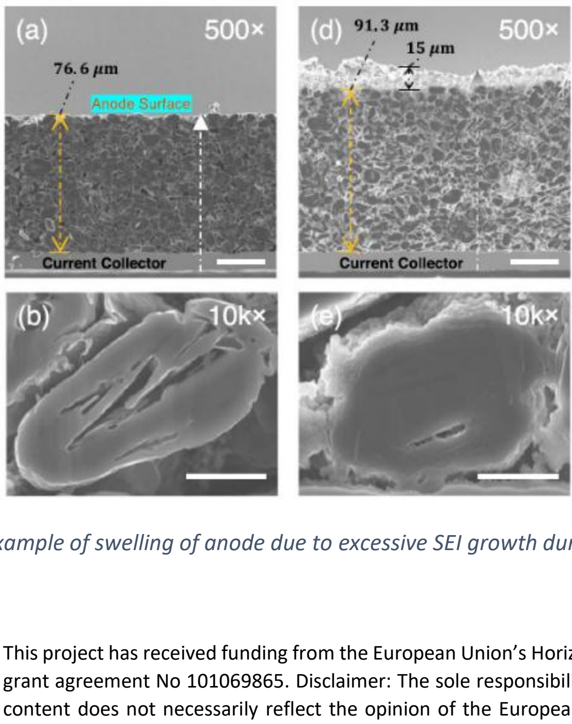

Figure 4: Example of swelling of anode due to excessive SEI growth during cycle (Pidaparthy, 2021)

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

2.2.2 Bulk

Graphite is generally a very stable material, however, the graphitic layers are bonded by weak van der Waals forces that can easily delaminate if molecules larger than Li-ions are co-intercalated during charging. This is especially an issue at high C-rates. Therefore, bulk degradation mechanisms are often related to exfoliation and delamination of graphite planes due to gas generation and co-intercalation of solvents, which can cause internal layer separation. Also, reports have shown that d-spacing increase near-surface expansion of interlayer spacing can be observed, especially under high charge rates, see Figure 5.

These effects will also strongly depend on the type of graphite used. Synthetic graphite, with smaller crystallites, lower anisotropy and more structural disorder in the lattice, tends to exhibit less severe aging compared to natural graphite. More generally, materials designed for high energy applications that are used at high C-rates will show a higher degree of irreversible damage to the graphite particles.

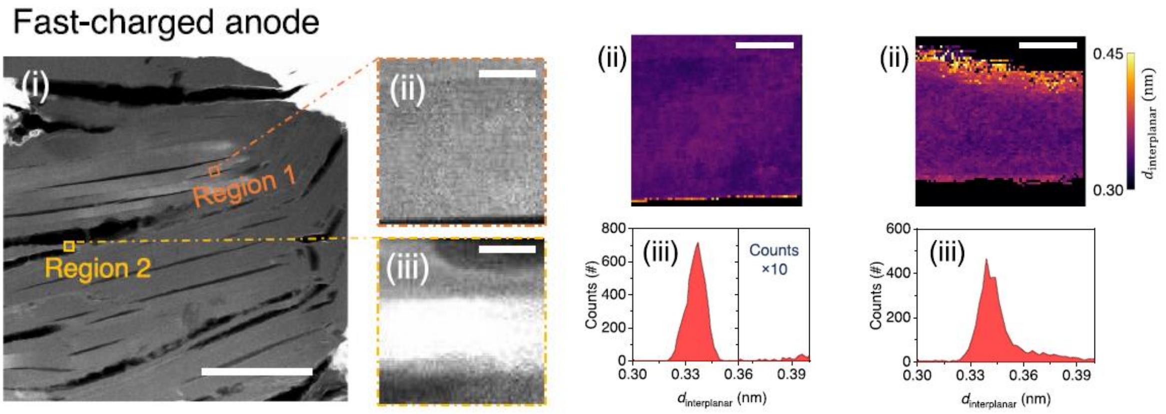

Figure 5: Example of d-spacing increase near particle surface during fast charging (Pidaparthy, 2021)

2.3 During end-of-life handling

In addition to degradation during production and use phase, graphite can also undergo degradation during the recycling operation itself. Old batteries are typically subjected to mechanical crushing, thermal treatment, and chemical processing. These steps can therefore introduce further degradation. Some examples are:

- **Contamination**: With metals (e.g., Cu, Al), salts, and electrolyte residues.
- **Morphological Changes**: Particle breakage, fines generation, and altered particle size distribution (PSD).
- **Internal Damage**: Penetration of contaminants into graphite particles, making purification more difficult.

2.4 Overview over different degradation mechanisms

As shown, several different degradation mechanisms exist that needs to be accounted for when designing a proper recycling system for graphite. The main effects are listed in Table 1

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

Table 1: Overview over different degradation sources of graphite and the potential impact on the graphite quality.

Source	Title	Potential degradation	Potential impact on graphite reuse
Production scrap	Slurry	Contamination with other slurry component, particularly non-graphite carbon materials (and natural graphite)	Increase amount of non-graphitizable carbon → reduced capacity/density
	Casted electrodes	Possible contamination with Cu, damage during crushing/separation	Impurities in graphite → reduced cycle life Fines/dust generation and changed particle morphology → affect PSD and density
	Cells (not cycled)	Contamination with other cell components, damage during crushing/separation	
	Formation cycled cells	Damage of surface (SEI formation)	Increased surface contamination and change to surface properties → lower first cycle efficiency and lifetime
EOL LIB		All of the above, in addition severe SEI formation, swelling, exfoliation and contamination of the interior of the graphite particles with metal/salt ions	Natural graphite not possible to separate from synthetic graphite. Contamination in graphite particle interior more difficult to remove and can lead to exfoliation → lower cycle life

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

3 DIFFERENT WAYS OF RECYCLING GRAPHITE

The rapid growth of lithium-ion battery (LIB) production and deployment—especially in electric vehicles—has created an urgent need for scalable, sustainable recycling solutions. Recycling addresses two major waste streams: production scrap from manufacturing and end-of-life (EOL) batteries from vehicles and devices. Both streams contain valuable materials, including graphite, lithium, cobalt, and nickel, and are essential to enabling a circular battery economy (Brochure Recycling of Lithium ion batteries, 2022)

3.1 Production scrap recycling

Production scraps, such as electrode offcuts, misaligned coatings, and failed cells, can account for 5–15% of total material input in battery manufacturing (see previous section). These materials are typically cleaner and more homogeneous than EOL batteries, making them ideal for closed-loop recycling.

Mechanical separation is already used to recover materials like metals and plastics from production scrap. For the anode electrode, copper is typically separated from the graphite by a combination of crushing and sieving operations. While today graphite recovery is not yet industrialized and mostly end up in landfills or incineration, it is gaining importance due to its growing demand and environmental footprint.

3.2 End-of-life battery recycling

EOL batteries are more complex due to degradation, contamination, and diverse chemistries. There are majorly three different areas of recycling that are being used today (Figure 6).

1. **Mechanical Recycling**: Involves shredding and sorting to isolate materials like "black mass" (graphite, cobalt, nickel, manganese). Electrolyte residues pose safety risks and must be removed via drying or pyrolysis.
2. **Pyrometallurgy:** High-temperature smelting recovers metals like cobalt, nickel, and copper. Graphite and aluminum are typically lost in slag or burned off. Energy-intensive but robust against impurities.
3. **Hydrometallurgy:** Uses acid leaching to dissolve and recover metals from black mass. Offers high selectivity and potential for battery-grade material recovery. Graphite can be recovered if separated early in the process.

Process Combinations: Combining mechanical, thermal, and chemical steps can increase recovery rates to over 90%. Graphite, electrolyte, and conducting salt recovery are emerging priorities.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

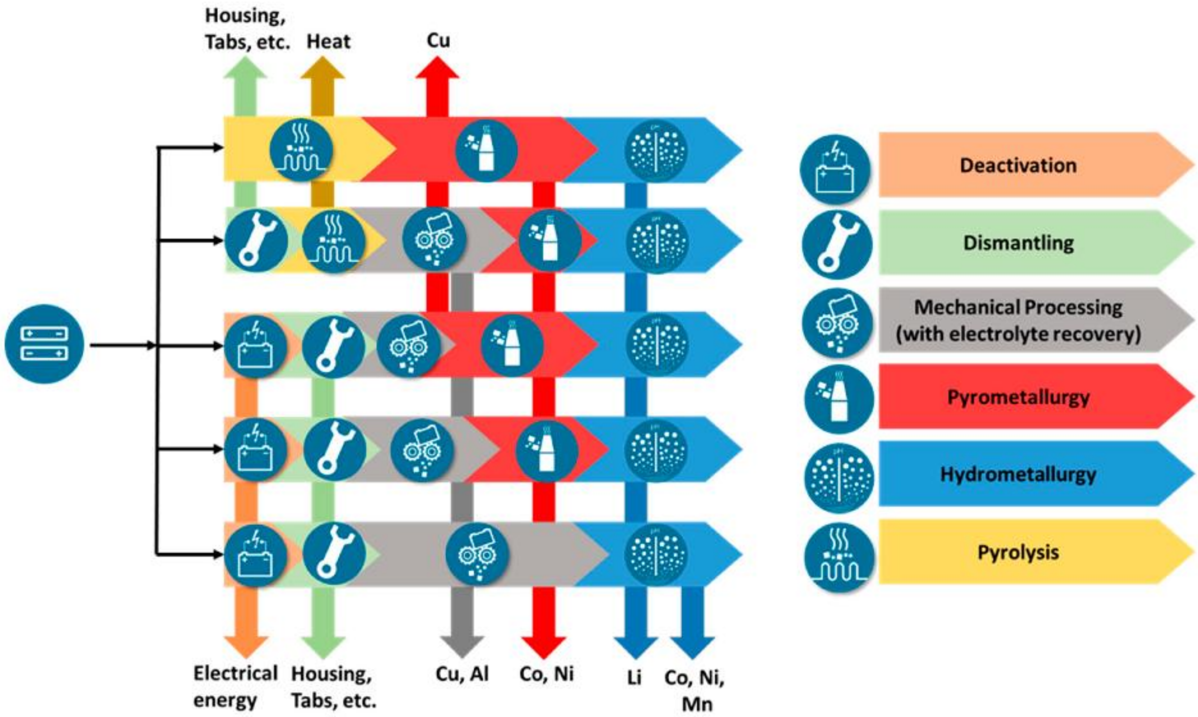

Figure 6: General overview of different LIB recycling methods, (Doose, 2021)

3.3 Graphite recycling

All the processes described above are optimized for cathode regeneration and metals recovery. There has not been great focus so far on the recovery of graphite anode material from the spent LIBs. However, recently there has been some efforts to recover graphite using various methods. These includes mechanical recycling, chemical treatment (acid leaching), washing with solvents, thermal purification or combination of thermal and chemical treatment, and electrochemical recovery (see Figure 7). Some research has been done on recovering graphite from the black mass using flotation as well. But with flotation alone, graphite of high purity to be used as battery material cannot be obtained (Abdollahifar, 2022).

In the thermal purification method, high temperatures (often >2000 °C) are used to remove volatiles, binders and impurities. This method can produce high quality graphite that can be re-used for battery applications. Regraphitization, can also be used as it helps to cure the crystalline defects that has occurred in the graphitic structure.

In the washing method, after the battery is discharged and disassembled, first anode powders are separated from the current collectors mechanically or thermally (removal of binders and electrolytes), afterwards they are subjected to washing with solvents like DMC, and N-methyl-2-pyrrolidone (NMP). In chemical purification method, solvent washing is replaced by acid leaching (e.g., using HCl, H_2SO_4). Battery-grade graphite can also be produced using this recycling method (Abdollahifar, 2022).

In the electrochemical method, the anode material obtained after disassembly and separation is electrochemically treated to remove impurities. It is a fast and complex method done at room temperature with higher recovery rate and is suitable for battery applications.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

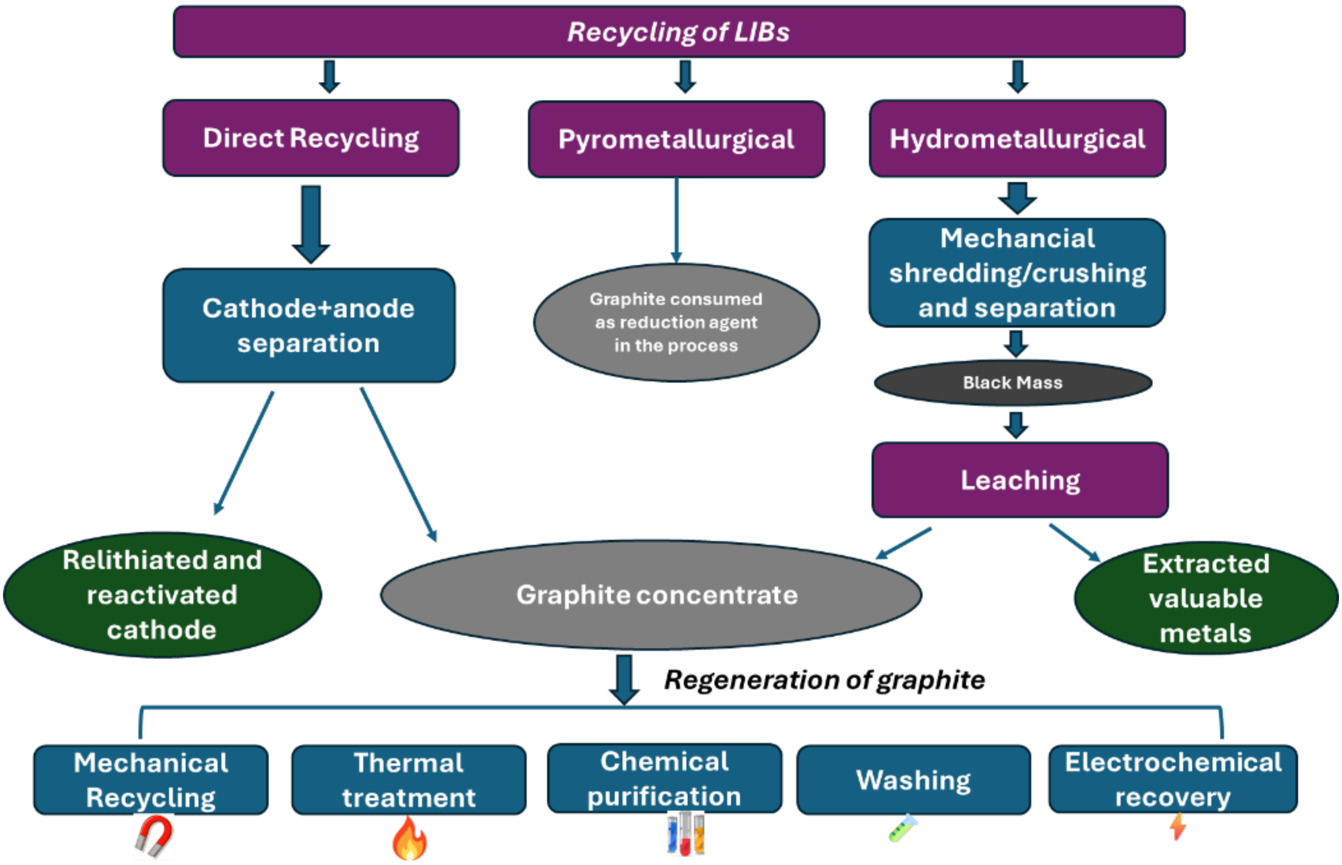

Figure 7: Different ways of recycling graphite

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

4 RESPECT PROJECT: EXPERIMENTAL WORK AND FINDINGS

The main objective of Task 4.1 is to recycle active material from electrode scraps and VIANODE AS is mainly responsible to regenerate the anode active material, where it will receive graphite concentrate (Purity>95%) from different feedstocks of varying qualities and it will process and purify the graphite concentrate to anode-grade graphite that can be used in batteries. It will be carried on a scale of 1-10 kgs and can be done at a larger scale depending on the availability from WP2. Another objective (Task 4.3) is to regenerate the anode active material coming from end-of-life batteries where similar processing has been applied as for production scrap graphite regeneration.

4.1 Experimental

4.1.1 Graphite separation

ORANO’s innovative pretreatment process is distinguished by its proactive approach to graphite recovery, which is implemented before the commencement of the hydrometallurgical phase. This early-stage recovery not only contributes to the overall efficiency of the recycling process but also supports sustainability goals by enabling the reuse of high-value materials such as graphite, which is critical for battery manufacturing.

The graphite separation workflow consists of several carefully designed steps:

1. **Chemical Deactivation of Battery Modules/Cells**

   The process begins with innovative deactivation of lithium-ion battery modules or cells. This step is essential to neutralize any residual energy, ensuring safe handling and preventing thermal or chemical hazards during subsequent operations.

2. **Dismantling and Stack Recovery**

   Once the batteries are rendered safe, they are dismantled to extract the stacks from each cell. These stacks contain active materials, including graphite, which are targeted for recovery.

3. **Material Separation**

   The stacks undergo a two-step process, leading to destacking and material selective recovery. This stage is designed to:

   - Break down the stacks into individual sheets,
   - Retrieve any residual electrolyte (if present),
   - Selectively separate graphite.

   This stage is performed in a specific environment to prevent the formation of harmful acids, which can result from $LiPF_6$ reactivity. After destacking, the graphite is recovered and filtered. The remaining material, referred to as the "sheet bed" undergoes physical separations, which aims to:

   - Release and extract residual anode and cathode active materials,
   - Sort others materials as copper and aluminium.

   Graphite is concentrated and recovered in solid form.

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

As part of the RESPECT project, two distinct types of input materials were produced and supplied to VIANODE AS from ORANO.

- **Graphite from End-of-Life (EOL) cells**
  Graphite recovered from EOL batteries, referred to as **EOLG**, underwent all the comprehensive treatment sequence. After pretreatment, the graphite was purified to remove contaminants.

- **Graphite from production scraps**
  Graphite obtained from manufacturing scraps, designated as **ASG**, was processed without the deactivation sequence.

The Figure 8 below summarizes the graphite separation and recovery steps.

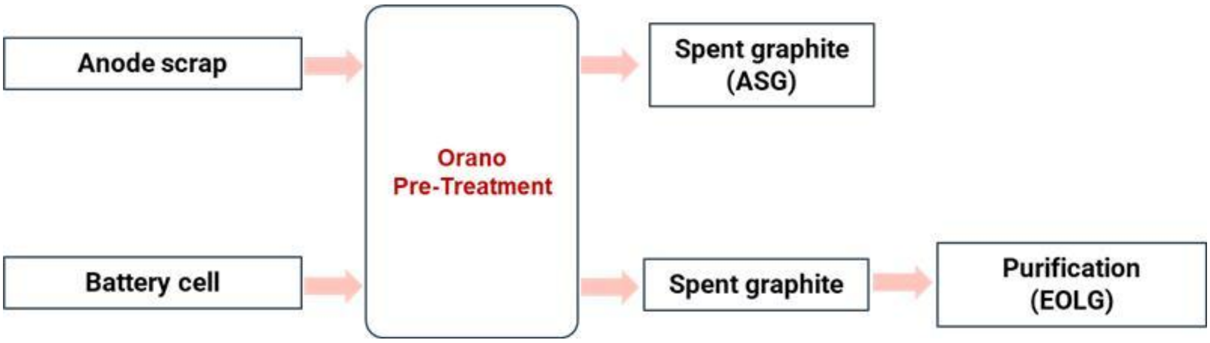

Figure 8: Graphite separation and recovery steps from scraps and EOL batteries

4.1.2 Regeneration of graphite

The graphite concentrates were recycled back to anode-grade graphite using thermal purification method. In VIANODE AS’s graphite recycling process, the graphite concentrates were pre-processed to remove any organic binders and volatiles that can interfere with the further purification processes. Then, they were treated at high temperatures to remove all the metallic impurities and to heal the crystalline defects that had occurred in the graphitic structure due to cycling and various other factors. Later, a post-processing step was done to attain the desirable anode-grade properties. A general overview of the process is found in **Error! Reference source not found.**

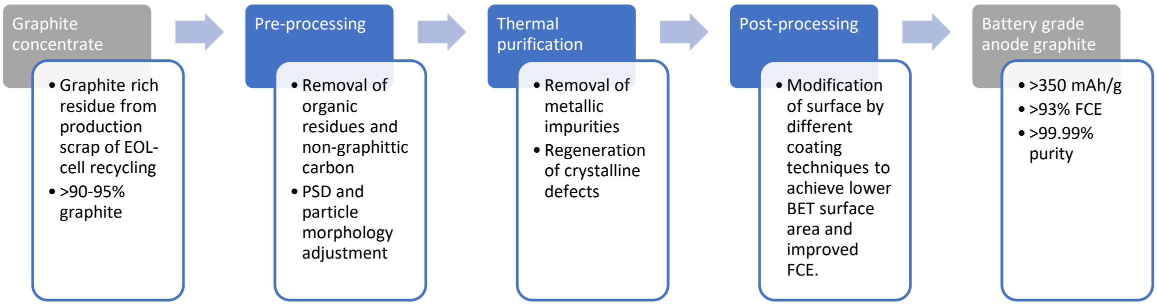

Figure 9: Schematic diagram of the VIANODE AS’s recycling process for graphite.

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

4.1.3 Characterization

Quality check was done on as-received graphite concentrate and the recycled samples using various physical and chemical characterization techniques. Powder properties were evaluated by testing for particle size distribution (Malvern Mastersizer 3000), tapped density (Quantachrome Autotap), BET surface area (Quantachrome Novatouch), degree of graphitization from X-Ray Diffractometer (Bruker D8 Advance), ash and volatiles were measured using muffle furnace from Carbolite-Gero. Moisture content was analysed using dry weight method (Metler Toledo HE 73/01). Morphological analysis was carried out through scanning electron microscopy (Hitatchi TM4000II Plus). Chemical analysis on as-received graphite concentrate was done at an external lab using Glow Discharge Mass Spectrometry (GDMS) and for the purified sample was done using total reflection X-ray fluorescence spectroscopy (BRUKER Nano S4 T_STAR) at our facility.

4.1.4 Electrochemical testing

Electrochemical testing was done in half-coin cells configuration in water-based formulation with 50% solid content and 96% active material, carbon black C65 from Imerys Graphite & Carbon, Carboxymethylcellulose from Daicel Miraizu Ltd., and Styrene Butadiene Rubber TRD 104A from ENEOS Materials Europe Belgium BV were used. Graphite electrodes with loading of 3.2-3.4 mAh/cm^2 cut to 12mm were fabricated. The electrolyte used was 1M LiPF6 in EC:EMC 2:8 (vol.) + 0.5wt% VC, 99.9% from Solvionic. Coin cells were assembled using coin cell assembler from Cellerate inside the glove box (Universal (1800/750/900) from Mikrouna). Cell testing is done with Neware (BTS-4000 Series 5V20mA controlled with BTS Client 8.0.0.471) at 25± 2°C. Electrochemical testing in half cell consists of three C/10 formation cycles, first cycle efficiency is calculated from the first cycle and average charge capacity is calculated from second and third cycles.

4.2 Results and discussion

4.2.1 Physicochemical characterization on as-received graphite concentrates

Table 2 shows the powder and chemical properties of the as-received graphite concentrates. Production scrap graphite (ASG) has D50 of 14.4 µm, low tap density of around 0.79 g/cc. Moisture content is 1.46%, volatiles and ash are 1.6 and 6.9% respectively. Whereas graphite concentrate from end-of-life batteries have high moisture and volatiles levels (3.7% and 16.6% respectively) compared to ASG. Ash level in end of life graphite (EOLG) is around 5.5%, from the chemical analysis it can be observed that EOLG has higher levels of metallic impurities, Al (0.6 wt%), Co (~0.4 wt%), Cu (~0.2 wt%), Li (~0.2 wt%), Mn (~0.4 wt%), Ni (~0.74 wt%), F (0.14 wt%), and S (~3.5 wt%). Particle size distribution and tap density could not be measured for EOLG since it was lumpy and solid (large agglomerates). Figure 10 shows the SEM images of the ASG and EOLG graphite concentrates. ASG has more flake-like graphite particles indicating higher share of synthetic graphite. This is also indicated from its low DOG value of 94%. Brighter particles on the top of the graphite particles indicates the metallic impurities present in the ASG sample.
SEM images of the EOLG sample shows large agglomerates of graphite particles (100-1000 µm) with metallic impurities on the top of the particles. Morphologically most of the graphite particles are rounded and potato-shaped indicating the higher share of natural graphite in the sample. This also aligns with the high DOG value of 98%.

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

Table 2: Properties of as-received graphite concentrates

Parameter	Unit	ASG-as received	EOLG-as received
D10	µm	7.1	Lumpy (solid)
D50	µm	14.4	-
D90	µm	27.1	-
D99	µm	52.3	-
TD	g/cc	0.79	-
DOG	%	94	98.08
Moisture	wt%	1.46	3.69
Ash	wt%	6.91	5.55
Volatiles	wt%	1.61	16.58
Al	wt%	0.01	0.58
Co	wt%	0.01	0.379
Cu	wt%	0.16	0.219
Li	wt%	0.01	0.199
Mn	wt%	0.01	0.423
Ni	wt%	0.05	0.745
Si	wt%		0.0023
F	wt%		0.14
S	wt%		3.56

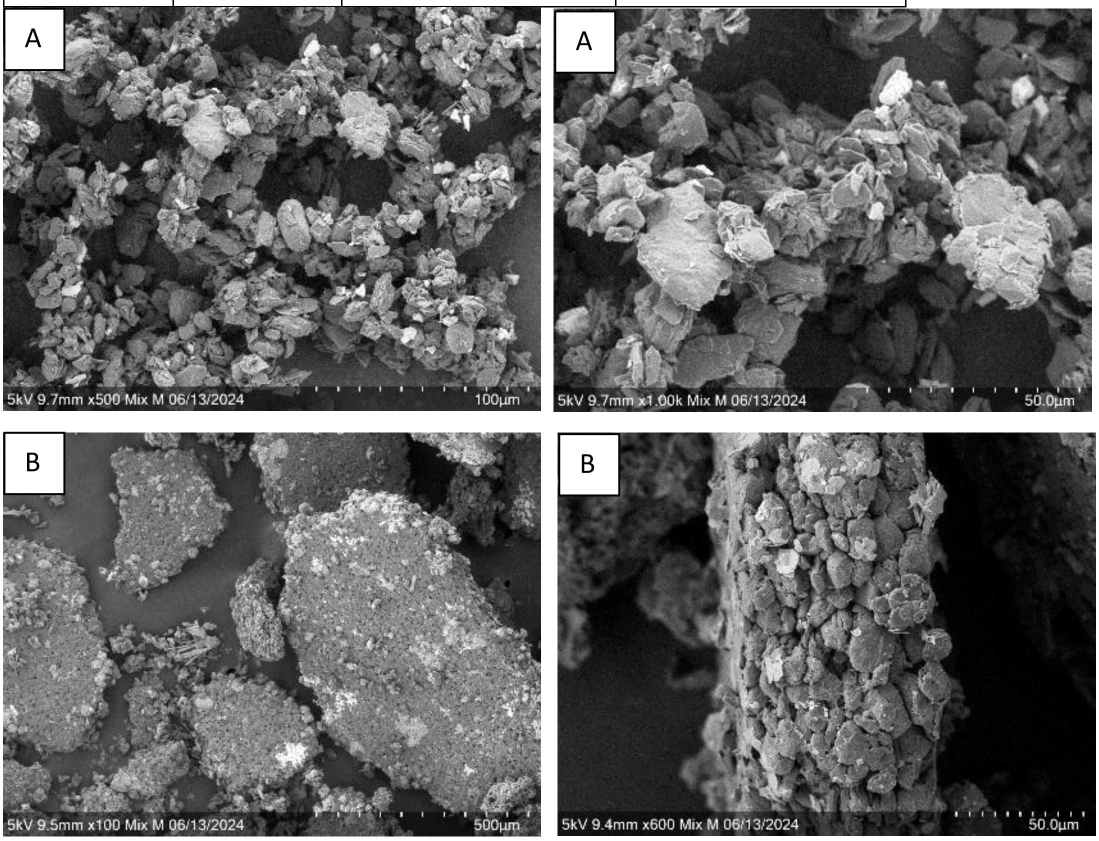

Figure 10: SEM images of A) as-received graphite concentrate based on anode-scrap B) as-received graphite concentrate based on end-of-life scrap.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

4.2.2 Physicochemical characterization on the recycled graphite

Table 3 shows the powder properties of the recycled graphite samples. Tap density of both recycled ASG and recycled EOLG is ~1 which is in line with the virgin anode-grade graphite samples. BET surface area of recycled ASG sample is <2, which is typical for the anode-grade graphite samples, however, BET for recycled EOLG is >2. This is due to the high share of natural graphite in EOLG sample with high degree of graphitisation (~99%) that typically gives high surface area.
SEM images (Figure 11) of the recycled graphite samples, both ASG and EOLG shows no metallic impurities as previously seen on the graphite concentrates. Ash content measured for both the recycled samples is <0.01 wt%. Chemical analysis (Table 4) measured by T-XRF shows the presence of all metals are below detection level <10ppmwt. All these results indicate that the samples after recycling are 99.99% pure.
Overall, the physical and chemical properties of the recycled ASG and recycled EOLG samples are comparable with the anode-grade graphite samples.

Table 3: Powder properties of the recycled graphite

Parameter	Unit	Recycled ASG	Recycled EOLG
D10	µm	5.9	9
D50	µm	11.5	15.7
D90	µm	20.9	25.6
D99	µm	39.1	45
TD	g/cc	0.99	1.01
DOG	%	94.9	99.1
BET	m^2/g	1.44	3.7
Ash	wt%	0.01	<0.01

Table 4: Chemical analysis (T-XRF) of the recycled graphite samples

Elements	Unit	Recycled ASG	Recycled EOLG
Mg	ppm	0.0	0.0
Al	ppm	0.0	1.3
P	ppm	1.1	1.4
S	ppm	0.5	22.1
Cl	ppm	1.0	0.6
K	ppm	0.0	0.2
Ca	ppm	3.8	1.3
Ti	ppm	1.6	0.9
Cr	ppm	0.0	0.2
Mn	ppm	0.0	0.1
Fe	ppm	2.4	4.2
Co	ppm	0.0	0.1
Ni	ppm	0.3	0.5
Cu	ppm	0.1	2.2
Zn	ppm	0.0	0.2

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

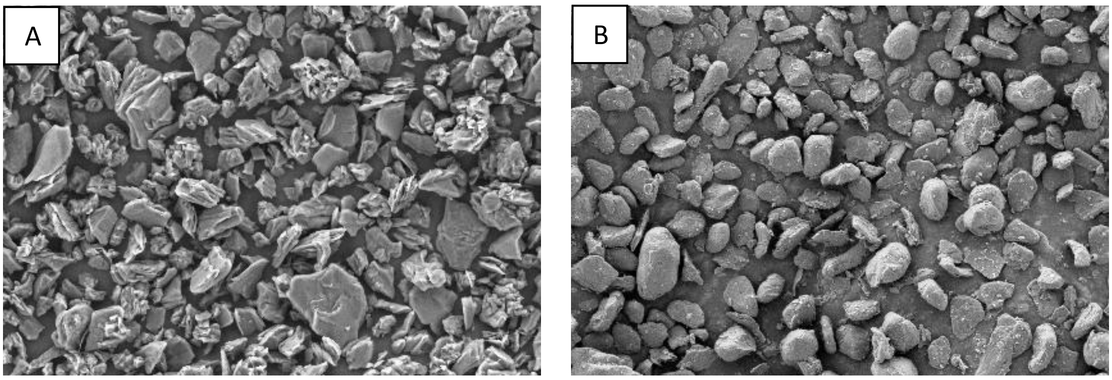

Figure 11: SEM images of Recycled graphite A) from anode-scrap B) from end-of-life batteries

4.2.3 Electrochemical properties of the recycled graphite powder

The electrochemical performance of the recycled graphite was tested in half-cells format at VIANODE AS. First cycle efficiency is coulombic efficiency of cell during the first charge and discharge cycle and is calculated as:

$$FCE(\%) = 100 \times (First\ charge\ capacity\ (mAh) \div First\ discharge\ capacity\ (mAh))$$

Average charge capacity expressed in mAh/g was calculated from second and third cycles as follows:

$$Average\ charge\ capacity\ (mAh) = (2nd\ charge\ capacity + 3rd\ charge\ capacity)\ \div 2$$

The FCE for the recycled ASG was 94.1% and for recycled EOLG it was 90.9%. The average charge capacity for recycled ASG was calculated 353.6 mAh/g and for recycled EOLG it was 361.1 mAh/g.
FCE for the recycled ASG is line with the virgin graphite used for LIBs whereas for recycled EOLG, it is bit lower, and this is related to its high BET surface area. Recycled EOLG has much higher average capacity compared with recycled ASG, and this is due to the high share of natural graphite in EOLG sample.
From Figure 12, the comparison between the two recycled graphite samples, recycled ASG (blue) and the recycled EOLG (red) reveals distinct electrochemical behaviour throughout formation and high-rate cycles. During the first cycle, recycled EOLG exhibits an earlier lithiation onset, indicative of a more reactive surface likely resulting from increased defect density, residual impurities, and structural disorder typical of EOL materials. This enhanced reactivity promotes accelerated SEI formation, consuming more lithium and leading to a thicker and less uniform interphase.

In subsequent formation cycles, particularly by cycle 3, recycled EOLG displays a less distinct staging behaviour and instead shows a more linear lithiation profile. This suggests overlapping intercalation stages arising from increased polarization and potential drops across the electrode, caused by higher interfacial and charge-transfer resistance. Consequently, the lithiation and delithiation processes for the recycled EOLG lag behind those of the recycled ASG, as more overpotential is required to drive Li^+ insertion and extraction through the resistive SEI layer.

During 3C lithiation (cycle 4), this difference becomes more pronounced. The recycled EOLG exhibits significantly higher polarization, confirming greater interfacial resistance. In contrast, recycled ASG shows a characteristic positive voltage bump, commonly associated with Li^+ accumulation (or nucleation) at the surface when diffusion limitations are reached. The absence of this feature in the recycled EOLG does not imply the lack of such processes but rather that the elevated overpotential suppresses the voltage rise, as the accumulated electrons counteract the potential increase from Li^+

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

generation. Thus, the 3C data adds to the conclusion that the recycled EOLG experiences higher resistance and slower interfacial kinetics than the recycled ASG.

Overall, with VIANODE AS’s method of recycling graphite it is demonstrated that it is possible to convert both types of scraps, either production or end-of-life back to the anode-grade graphite with removal of all the impurities, crystalline defects, and surface SEI. Both the recycled samples have shown good cell performance and structural properties.

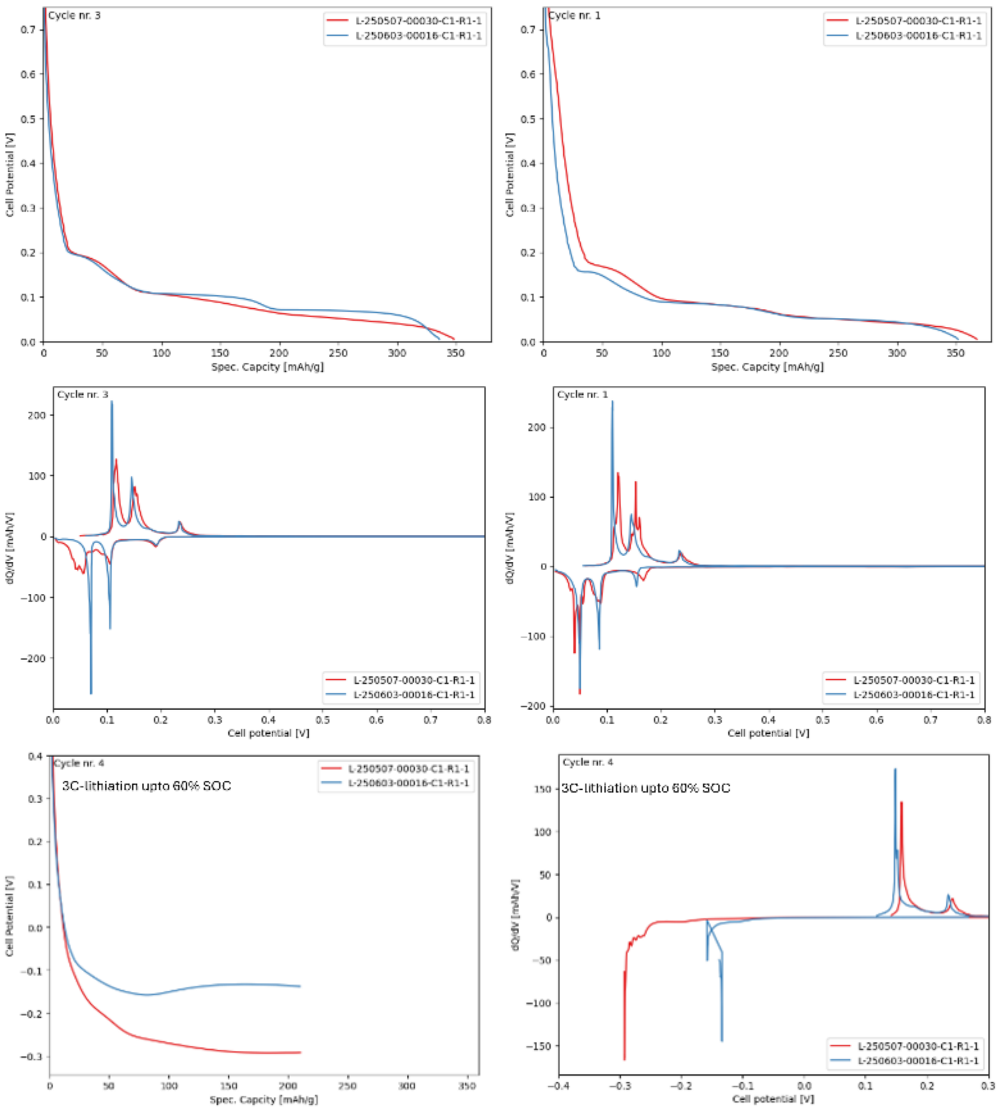

Figure 12: Voltage profiles and dQ/dV curves for the recycled graphite samples. Red color (end-of-life graphite) and blue color (anode scrap).

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

Further the verification of electrochemical performance of the recycled samples was done by CIDETEC for which the results are discussed below.

Electrochemical validation of recycled graphite performance and its comparison with pristine graphite sample (CIDETEC):

Half-coin cells were assembled with graphite recycled from scrap (RG-1) and EoL cells (RG-X) with a water-based formulation: 94% active material / 2% Carbon Black C45 (Imerys Graphite & Carbon) / 2% Carboxymethylcellulose from (Bondwell BVH8 2545C) / 2% Styrene Butadiene Rubber BM451-B from Zeon. The slurries were coated on a 8 µm Furukawa copper current collector with a loading level of 3.30 mAh/cm^2 or 20.35 mg/cm^2. CR2025 coin cells were assembled with 1M LiPF6 in EC:DMC 1:1 (vol.) + 2wt% VC, from Solvionic.

The recycled materials were compared with pristine graphite anodes (AG4) with the same formulation. The electrochemical validation was performed in a Basytec Cell Test System potentiostat at 25 °C ± 1 °C controlled by air conditioning. The voltage profiles of the forming cycle at C/10 that is shown in Figure 13 proves that initial capacity values for the recycled graphite from EoL cells obtained the highest capacity values with high coulombic efficiency, even compared with the pristine graphite (Table 5).

The voltage curve for the RG-X sample shows a very similar lithiation curve compared with the pristine AG4 material, but a smaller hysteresis between the lithiation and the delithiation lines; which, in the case of the pristine graphite, is more similar to the RG-1 graphite (**Error! Reference source not found.**). This difference could be due to the higher DOE of the RG-X graphite (round particles, natural graphite), remains of the SEI from the previous cyclings or even small doping of different elements that have been measured in the T-XRF (Table 4), such as, Fe, Al or Cu.

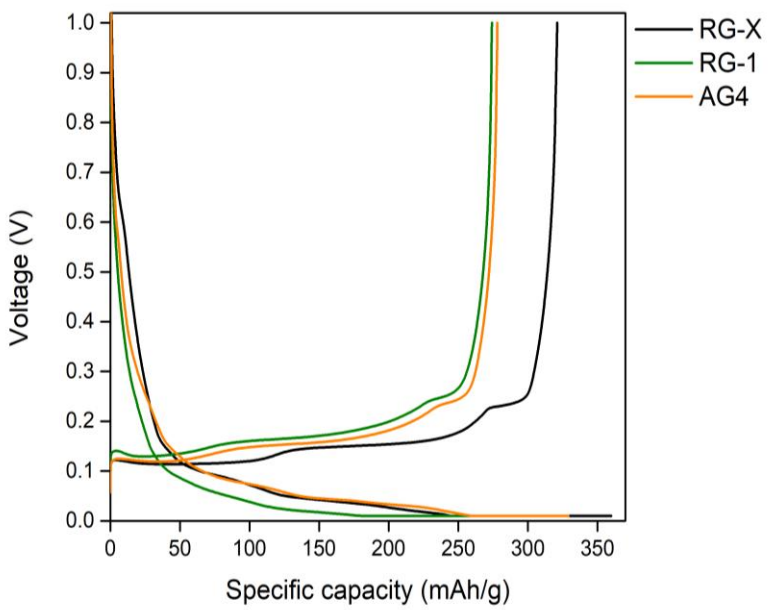

Figure 13: Voltage profile of the initial charge and discharge cycles of lab-scale electrodes for a comparison of recycled materials (RG-X and RG-1) and pristine graphite (AG4). HCC were assembled using lithium foil as counter electrode and cycled at C/20 in the voltage window of 0.01-1.00 V.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

Table 5: Electrode loading and initial electrochemical data of the electrodes prepared in lab-scale with pristine graphite (AG4) and recycled samples (RG-X, RG-1).

	LL	$\mathbf{Q_{lithiation}}$	$\mathbf{Q_{delithiation}}$	**CE%**
	mAh/cm^2	mAh/g		
RG-X	3.30	359.72	321.11	89.3
RG-1	3.31	305.33	274.10	89.8
AG4	3.48	329.17	277.97	84.4

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

5 MARKET OUTLOOK

5.1 Available graphite for recycling

The availability of graphite for recycling is set to increase dramatically over the next decade, driven by the growing volume of end-of-life lithium-ion batteries and production scrap from gigafactories. By 2030, approximately 130,000 tons of graphite will be available for recycling, rising to over 1 million tons by 2040.

Currently, production scraps such as slurry, anode, and cell scrap constitute the dominant feedstock for recycled recycled graphite. However, as electric vehicles reach the end of their first life, end-of-life batteries (EOLB) will become the primary source of recyclable graphite. Thus, transition is mainly driven by the exponential growth in EV adoption and the corresponding increase in battery retirement volumes. The graphite concentrate used in recycling is primarily produced by hydrometallurgical battery recyclers, who extract metals like lithium, nickel, and cobalt from black mass. Historically, graphite has been considered a low-value byproduct in these processes and is often filtered out, incinerated, or sent to landfill due to the lack of economically viable recovery pathways.

Recent developments, however, indicate a shift in industry perception. Partnerships such as those between Fortum and VIANODE AS, and Altilium and Talga, are actively working to recover and repurpose graphite from battery waste for use in new anode materials. These collaborations aim to close the loop in battery production and reduce reliance on virgin graphite, which is increasingly constrained by geopolitical and environmental factors. Academic studies have demonstrated that regenerated graphite from spent LIBs can achieve electrochemical performance comparable to commercial-grade graphite (1). This shift not only supports circular economy goals but also addresses supply chain vulnerabilities, especially in Europe and North America where domestic graphite processing capacity remains limited.

5.2 Regulatory opportunities and barriers

Graphite concentrate, recovered from spent lithium-ion batteries and often present in significant quantities within black mass, is increasingly recognized as a strategic material. In North America, graphite’s inclusion in the USGS Critical Materials List and the Critical Minerals Strategy unlocks funding and permitting support for domestic recovery projects. The DOE Battery Recycling Grants further incentivize innovation in recycling technologies, with a focus on improving recovery rates of battery anode materials, particularly graphite.

In the EU, graphite concentrate is gaining regulatory attention through multiple initiatives. The EU Battery Regulation, Circular Economy Action Plan, and Green Deal Industrial Plan collectively promote battery circularity, mandate recycled content and support the establishment of graphite recycling infrastructure. The proposed inclusion of graphite in recycling rate calculations from January 2030 marks a significant step toward recognizing its value in the circular economy.

Despite these opportunities, regulatory fragmentation, especially around black mass classification—poses barriers to scaling graphite concentrate recovery. The EU’s restrictive stance contrasts sharply with China’s more enabling approach, potentially shifting value-added recycling activities away from Europe.

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

5.2.1 Hazardous waste classification

A major regulatory bottleneck for graphite concentrates recovery is the classification of black mass as hazardous waste in the EU. This designation complicates logistics, restricts exports, and introduces uncertainty for recycling investments. Since graphite concentrate constitutes a large portion of black mass, these restrictions directly impact its recovery and reuse.

China’s recent policy shift allows the import of black mass—provided it meets strict quality and environmental standards—without classifying it as waste. This enables Chinese recyclers to secure high-grade graphite concentrate feedstock, addressing underutilized capacity and strengthening their control over critical battery materials. The EU’s current approach risks losing strategic materials to more agile markets and undermines its competitiveness in graphite recycling.

5.2.2 Battery regulations

The EU Battery Regulation (2023/1542) introduces several provisions that directly impact graphite concentrate recovery:

- Mandatory recycled content for key battery materials.
- Carbon footprint disclosure requirements, now extended to include graphite.
- Battery passport and QR code systems to track sustainability and material origin.

The 2025 Delegated Regulation further refines the methodology for calculating recycling efficiency and recovery rates, explicitly including carbon-based materials like graphite in the input/output fractions. This ensures graphite is no longer overlooked in recycling metrics and supports its integration into circular battery supply chains.

5.2.3 Critical Raw materials act

The CRMA identifies graphite as a strategic raw material essential for the green and digital transitions. It sets ambitious benchmarks for domestic capacity by 2030:

- 10% of EU demand from extraction.
- 40% from processing.
- 25% from recycling.

These targets are designed to reduce reliance on single-country suppliers and promote investment in EU-based recycling infrastructure. For graphite concentrate, this means increased regulatory and financial support for pilot plants, permitting, and technology development—critical steps toward achieving battery-grade purity and closing the loop in the graphite value chain.

This project has received funding from the European Union’s Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

CONCLUSION

The above results suggest that it is possible to recycle graphite originating from both end-of-life graphite and production scrap back to anode-grade graphite using the process developed at VIANODE AS with good recovery rate and properties in-line with the typical virgin anode graphite. Recycled graphite from anode scrap achieved tap density around ~1 and BET surface area <2 which is usually expected for a virgin synthetic graphite. However, recycled graphite from end-of-life batteries achieved tap density equal to 1 and bit higher BET surface area of 3.7 due to which it has lower FCE compared to the recycled ASG graphite. High BET surface area can be attributed to the presence of natural graphite in the graphite concentrate from end-of-life cells. EOLG graphite concentrates have more defects, due to its cycling history which also contributes to high BET surface area after recycling. Therefore, in future it is required to optimize the process more for recycling of EOLG graphite concentrates to achieve lower surface area and hence better first cycle efficiency.

Overall, the present work shows the feasibility of the VIANODE AS's graphite recycling process and generation of anode-grade graphite from graphite concentrate rather than the conventional raw material source of synthetic virgin graphite. It lays the foundation for future sustainability and helps close the battery economic chain.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

REFERENCES

Abdollahifar, M. (2022). Graphite Recycling from End-of-Life Lithium-Ion Batteries: Processes and Applications. *Advanced Materials Technologies*, 2200368.

Adham, K. (2023). A Comparison of Production Routes for Natural Versus Synthetic Graphites Destined for Battery Material. *In: Proceedings of the 62nd Conference of Metallurgists, COM 2023.* Springer, Cham.

Asenbauer, J. (2020). The success story of graphite as a lithium-ion anode material – fundamentals, remaining challenges, and recent developments including silicon (oxide) composites. *Royal Sociey of Chemistry*, 5387-5416.

Brochure Recycling of Lithium ion batteries. (2022). RWTH Aachen & TU Braunschweig.

Doose, S. (2021). Challenges in Ecofriendly Battery Recycling and Closed MaterialCycles: A Perspective on Future Lithium Battery Generations. *Metals*, 11(2), 291.

(February 2022). *Graphite in batteries.*

(n.d.). *Life Cycle Assessment for VIANODE AS: Advancing Sustainable Battery Materials.* https://www.minviro.com/resources/case-studies/life-cycle-assessment-VIANODE AS.

Park, J. (2025). Overview of graphite supply chain and its challenges. *Geosciences Journal*, 29:329–341.

Pidaparthy, S. (2021). Increased Disorder at Graphite Particle Edges Revealed by Multi-length Scale Characterization of Anodes from Fast-Charged Lithium-Ion Cells. *Journal of The Electrochemical Society*, 100509.

Wang, J. (2024). *Looming EV raw materials supply crunch has OEMs eyeing battery recycling and production scrap.* S&P Global Mobility.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

LIST OF TABLES

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.

List of Figures

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101069865. Disclaimer: The sole responsibility for any error or omissions lies with the editor. The content does not necessarily reflect the opinion of the European Commission. The European Commission is also not responsible for any use that may be made of the information contained herein.