The Fifth Industrial Revolution

A Materials-Centric Transformation to Achieve Net Zero in the European Automotive Industry

A deep dive complementing ERTRAC's roadmap on circularity

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Disclaimer

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Executive Summary

The automotive industry leads the Fifth Industrial Revolution, a transformative era blending advanced digital technologies with human-centric, sustainability-driven values. Unlike the efficiency-focused **Fourth Industrial Revolution**, this new phase emphasizes aligning innovation with environmental regeneration, inclusivity, and resilience. Digitalization, AI, robotics, and automation become enablers of smart, connected, sustainable, and circular industrial ecosystems. Production must operate within planetary boundaries, benefiting both people and the environment. The European Union's commitment to **net-zero greenhouse gas emissions by 2050** places the automotive sector at the core of this shift. Manufacturers must urgently decarbonize global supply chains dominated by **steel, aluminium, plastics, and battery metals**, which account for the majority of embedded emissions.

The document identifies **four key pillars** as levers for deep decarbonization of material specific carbon emissions:

1. **Open-Loop Recycling** to create cross-sector pathways where closed loops aren't feasible.
2. **Closed-Loop Recycling** to maximize high-quality material recovery and reduce virgin resource demand.
3. **Green Primary Materials** produced via low-carbon processes such as hydrogen-based steel and renewable aluminium and bio-based materials.
4. **Carbon Removal**, limited to hard-to-abate emissions, using certified permanent methods such as DAC, biochar, and mineralization - **capped at 10% by 2050**.

This whitepaper presents a **data-driven decarbonization scenario** that has been critically tested and refined. The scenario quantifies the emission reduction potential of four key levers and illustrates how they can collectively close the Scope 3 emissions gap by 2050. It is built on the assumption that most emissions reductions by 2030 will come from **powertrain electrification**, while the **post-2030 phase** will be more and more dominated by the need to reduce upstream material emissions - the "holy grail" of long-term climate neutrality in automotive manufacturing.

Battery materials especially lithium, cobalt, nickel, and manganese -are particularly critical. Their efficient recycling and green sourcing are essential to meeting climate targets and ensuring long-term supply security.

The challenge is **vast, urgent, and systemic**. Decarbonizing automotive materials requires re-engineering value chains, infrastructure, market incentives, and governance structures. Yet current progress remains **too slow and fragmented**. Major barriers include:

- High material quality requirements of the automotive industry
- Shortage of affordable green energy
- Underdeveloped hydrogen infrastructure and industrial electrolysis
- Land constraints for biomass
- Geopolitical bottlenecks in raw material supply
- Insufficient circular infrastructure and missing traceability
- Weak carbon pricing and incentives

- Regulatory fragmentation
- Lack of coherent legal and financial frameworks
- Risk aversion across all stakeholder groups

If left unaddressed, these bottlenecks risk derailing 2050 targets and eroding Europe's leadership in sustainable industry. To overcome them, **ten strategic priorities** must be implemented:

1. Invest in smart recycling systems with automation, AI, and digital product passports.
2. Improve end-of-life vehicle (ELV) collection and preprocessing for better recovery.
3. Scale open-loop recycling to capture cross-sector value.
4. Accelerate green primary material production with ESG-aligned sourcing, including new biomass-based technologies.
5. Limit carbon removal to irreducible emissions, prioritizing permanent solutions.
6. Enact robust legal frameworks and incentives, including green contracts for difference, carbon pricing, and green public procurement.
7. Build hydrogen and renewable energy infrastructure for industrial use.
8. Strengthen cross-sector collaboration through pre-competitive ecosystems and just transition principles.
9. Introduce smart secondary material quotas to increase the uptake of recycled materials in combination with green primary material targets.
10. Develop a European venture capital sector capable of making multi-billion-euro strategic investments.

These priorities form **a clear, actionable roadmap** that balances **competitiveness with climate resilience**. For the European Union, this is more than a climate imperative -it is a **strategic opportunity** to lead globally. Reaching net-zero automotive materials will:

- Secure industrial sovereignty over critical resources
- Protect and create future-proof jobs
- Reinforce the EU’s role as a global sustainability standard-setter
- Prove that prosperity and ecological responsibility are not mutually exclusive

Without swift and intensified action, Europe risks losing ground to global competitors such as the U.S. and China -undermining the ambitions of the European Green Deal. The **Fifth Industrial Revolution** offers a once-in-a-century opportunity to reshape industry for a regenerative future. In this context, the path to **net-zero automotive materials** becomes both the ultimate test and a powerful opportunity for enduring innovation, competitiveness, and global leadership.

The road is open -but the time to act is now.

This deep dive on the 5th Industrial Revolution refers to limiting factors of which may are also critical for infrastructure management. There are multiple policies and levers that are currently being deployed (green procurement, CBAM, carbon pricing, regulatory bottlenecks etc) that equally inhibit transformation in infrastructure management. These aspects will be addressed in later steps.

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1 Introduction

The automotive industry stands at the epicentre of the global decarbonization challenge. As road transport continues to decarbonize through electrification, the share of embedded emissions in vehicle materials - so-called Scope 3 upstream emissions - has become the dominant contributor to a vehicle's life-cycle carbon footprint.

The industry is also entering the Fifth Industrial Revolution, an era where digital transformation, sustainability, and human-centric design converge to reshape manufacturing toward regenerative, low-carbon systems. While energy-related emissions (Scope 1, 2, 3 downstream [1]) are gradually being reduced through renewable electricity, electrified powertrains, and efficiency gains, the emissions embedded in primary materials (Scope 3 upstream) remain a significant challenge. The pathway to true net-zero therefore demands a materials-centric transformation.

This paper proposes an integrated strategy focusing on four levers:

1. Open-Loop Recycling and Industrial Symbiosis: Leveraging cross-sectoral recycling chains to maximize resource efficiency.
2. Closed-Loop Recycling: Creating material loops within the automotive value chain.
3. Green Primary Materials: Using radically cleaner material feedstocks and production technologies for virgin materials.
4. High-Quality Carbon Offsetting: Employing permanent carbon storage or nature-based solutions, limited to no more than 10% of a company's Scope 3 upstream footprint.

Figure: ELV shredding at large scale (generated by AI)

2 The Role of Materials in Automotive Emissions

Materials dominate upstream Scope 3 emissions for automotive manufacturers, often exceeding the operational emissions of factories themselves. Understanding the carbon intensity of key materials is essential for targeting effective decarbonization strategies. Typical emission intensities for critical automotive materials include:

- Steel: Approximately 1.8–2.0 tons CO_2 per ton of crude steel, driven primarily by fossil-fuel-based blast furnace operations. Transitioning to hydrogen-based steelmaking and electric arc furnace recycling offers significant reduction potential. However, it should not increase the cost.
- Aluminium: Extremely energy-intensive, with 8–12 tons $CO_{2,eq}$ per ton due to electricity consumption and carbon anodes in smelting. Increasing the share of renewable electricity and adopting inert anode technology can drastically lower emissions.
- Copper: A critical enabler of electrification, copper has an emission intensity of approximately 4–6 tons $CO_{2,eq}$ per ton, depending on ore grade, mining practices, and energy sources. As electric vehicle production and charging infrastructure expand, copper demand is set to reach unprecedented highs, posing both supply chain risks and environmental challenges. Scaling up efficient copper recycling, improving mining efficiency, and sourcing copper from operations powered by renewable energy are essential to secure sustainable supply and reduce emissions.
- Plastics and Carbon Fiber Reinforced Polymer (CFRP) Composites: Both material families have significant carbon footprints. Plastics typically generate 2–6 tons $CO_{2,eq}$ per ton, mainly due to fossil feedstocks and energy-intensive polymerization processes. CFRP production is even more energy-intensive, emitting between 15 and 25 tons $CO_{2,eq}$ per ton, driven by high-temperature processing of carbon fibers and polymer resin matrices. Reducing their footprint requires innovations such as bio-based feedstocks, development of lower-carbon precursors while enhancing their recycling potential-all essential to decarbonizing automotive materials.
- Battery Materials (Lithium, Cobalt, Nickel, Manganese): Emissions range from 6–80 tons CO_2e per ton, reflecting intensive mining, refining, and chemical processing. Given the surge in EV battery demand, these materials represent both a major emissions hotspot and a critical supply chain risk.
- Rare Earth Elements (REE): Mining and refining of separated REE oxides produce up to 415 tons CO_2e per ton, varying widely with mining methods and energy sources. Improving mining efficiency and adopting cleaner power supplies are critical for sustainability.
- Other Materials: This category includes automotive glass (1.5–3 tons $CO_{2,eq}$ per ton), textiles (2–6 tons $CO_{2,eq}$ per ton depending on fibre type and processing), rubber, adhesives, coatings, and electronic components. Though smaller in mass individually, these materials have varied and sometimes significant carbon footprints, especially due to chemical processing and energy use. Advances in recycling, use of bio-based inputs, and cleaner production methods will be increasingly important.

The transition to electric and autonomous vehicles accelerates the automotive industry's materials challenge. EV sales are projected to exceed 60% of new vehicle registrations in the European Union by 2030, with near-complete decarbonisation expected by 2050 through full electrification (BEV, hydrogen) or the use of synthetic carbon-neutral fuels (bio-based or CO_2-derived). At the same time, autonomous driving technologies will significantly increase demand for rare earth elements, essential for sensors, actuators, and advanced electronic systems. Managing the embedded greenhouse gas emissions from batteries, rare earths, and increasingly from polymers is therefore critical to achieving net-zero targets.

As the share of polymer-based components in BEVs continues to rise -due to their advantages in light-weighting, insulation, and electronics integration -so too do the challenges related to their recycling and sustainable production. Addressing this requires intensified efforts in polymer recovery technologies, the development of low-carbon or bio-based polymer feedstocks, and design-for-recycling strategies. These material-specific challenges -spanning metals, polymers, and composites -must be addressed in parallel to enable a truly circular and climate-neutral automotive industry.

Effective mitigation of upstream Scope 3 greenhouse gas emissions requires an integrated approach across all materials - combining closed-loop and open-loop recycling, green primary materials, and responsible offsetting - to ensure the automotive sector's transition is both deep and resilient.

2.1 Open-Loop Recycling: Enhancing Circularity and Continental Resilience Across Sectors

Open-loop recycling involves reusing recovered materials outside their original industry, typically in applications with lower quality requirements. This paradigm extends the circular economy beyond sectoral boundaries and plays a critical role in reducing overall virgin material demand.

However, the use of open-loop recycled materials within the automotive sector faces significant constraints:

- High-grade material standards in automotive manufacturing: Automotive components require materials that meet strict mechanical, safety, and durability standards. Many recycled materials from other industries - such as construction, packaging, or electronics - do not meet these stringent criteria, limiting their direct application in vehicles.
- Material supply limitations amid rising demand: The rapid growth in automotive material demand, driven by electrification and automation, may outstrip the volume of recycled materials available from other sectors without adversely affecting their own supply chains. Many industries are also intensifying their recycling efforts to meet their respective decarbonization goals.
- Quality degradation through downcycling: Materials recycled in open-loop systems often suffer reduced quality and performance over successive recycling cycles, limiting the number of reuse iterations and their suitability for high-performance applications like automotive manufacturing.

Despite these limitations, open-loop recycling serves as a vital complement to closed-loop systems by:

- Maximizing resource recovery: Redirecting automotive scrap - especially complex consumer scrap - to other industries reduces landfill use and diminishes demand for virgin resources.
- Diversifying material flows and increasing system resilience: Cross-sector recycling pathways add flexibility to material supply chains, helping buffer against shocks and reducing dependence on primary raw materials.

- Supporting broader industrial decarbonization: Open-loop recycling lowers emissions not only in automotive but also in construction, electronics, packaging, and other sectors, amplifying climate benefits.

The distinction between production scrap - usually recycled via closed-loop methods - and consumer scrap - often routed into open-loop pathways - is critical. Production scrap typically attains near-complete closed-loop recycling, whereas consumer scrap recycling rates are lower due to mixed materials, adhesives, and contamination.

Battery recycling exemplifies this dynamic: although closed-loop technologies are progressing, a considerable share of battery materials still undergoes open-loop recycling or downcycling due to current economic and technical challenges.

In conclusion, open-loop recycling complements closed-loop strategies by broadening recycling capacity and promoting circularity across sectors. However, to meet ambitious secondary material targets and decarbonization goals, significantly increasing closed-loop recycling of post-consumer waste is essential, as production scrap alone cannot supply adequate secondary materials.

Together, these recycling paradigms strengthen the EU's raw material security, reduce emissions, and enhance the resilience of the automotive industry and the broader industrial ecosystem - key factors underpinning Europe's economic sovereignty and climate leadership in a volatile global context.

2.2 Closed-Loop Recycling: Building a Resilient, Low-Carbon Automotive Supply Chain

Closed-loop recycling entails recovering and reprocessing materials from end-of-life vehicles and production scrap directly into automotive-grade inputs with minimal degradation in quality or performance. This approach is fundamental to the automotive industry's goals of decarbonization and securing critical raw materials amid increasing geopolitical volatility.

Key benefits of closed-loop recycling include:

- Control and management of material quality: Maintaining high purity and structural integrity enables materials such as steel, aluminium, plastics, and battery components to be recycled multiple times without compromising strict automotive manufacturing standards.
- Substantial emissions reduction: By significantly reducing the demand for energy-intensive mining, refining, and primary material production, closed-loop recycling lowers greenhouse gas emissions across the supply chain.
- Enhanced supply chain security and cost stability: Recycling materials within the automotive value chain reduces dependency on geopolitically sensitive or scarce raw materials, helping to buffer the industry - and thus the European economy - against global supply disruptions and price volatility.
- Economic and innovation drivers: Investments in recycling technologies foster circular economy business models, stimulate innovation in material recovery processes, and generate skilled green jobs, strengthening regional industrial ecosystems.

While production scrap - characterized by its clean, homogeneous nature - currently achieves high closed-loop recycling rates, it alone will not satisfy the high secondary material quotas targeted for 2050. Over the coming decades, post-consumer waste- including end-of-life vehicles and used batteries - must increasingly be processed within closed-loop systems to provide sufficient secondary raw materials for the industry's decarbonization and circularity objectives. Addressing this requires overcoming challenges related to material complexity, contamination, and collection infrastructure.

Despite these hurdles, rapid technological advances - such as hydrometallurgical removal, direct cathode regeneration, and sensor-based sorting - are improving closed-loop recovery rates and material purity, especially for complex materials like EV batteries.

By maximizing closed-loop recycling across both production and post-consumer streams, the automotive industry can drive deep decarbonization while simultaneously enhancing the resilience of one of Europe's most strategic sectors, contributing to broader continental stability and sustainability.

2.3 Green Primary Materials: Securing Low-Carbon Virgin Inputs for the Automotive Industry

Green primary materials - virgin raw materials produced with substantially reduced greenhouse gas emissions - are indispensable for the automotive industry's net-zero transition. Although advances in closed-loop and open-loop recycling will significantly reduce demand for primary materials, recycling alone cannot meet the anticipated surge in automotive material requirements driven by electrification, automation, and increasing vehicle production volumes. Consequently, the decarbonization of virgin material production is essential to close the emissions gap and fulfil future demand sustainably.

- Hydrogen-based steelmaking: Replaces fossil carbon in blast furnaces with green hydrogen during direct reduction iron (DRI) processes, reducing steel-related $CO_{2,eq}$ emissions from approximately 1.8–2.0 tons per ton of crude steel to around 0,2 tons $CO_{2,eq}$ per ton. Combined with electric arc furnace recycling powered by renewable electricity, this method offers profound decarbonization potential and is rapidly progressing from pilot stages to commercial scale. However, costs is still an issue.
- Aluminium production: An energy-intensive process responsible for 8–12 tons $CO_{2,eq}$ per ton, now being transformed through renewable-powered electrolysis and smelting paired with inert anode technology. This eliminates carbon anode emissions and significantly reduces energy consumption, enabling near-zero emissions aluminium production for secondary aluminium. (However: As long as there is a share of primary production near-zero is not realistic).
- Copper production: As a cornerstone of electrification, copper is vital for motors, wiring, and charging infrastructure, yet its mining and refining emit approximately 4–6 tons $CO_{2,eq}$ per ton depending on ore grade and energy sources. Green primary copper requires transitioning to renewable electricity in mining and smelting, adopting technologies like flash smelting with carbon capture, and improving ore beneficiation efficiency. These measures are essential to mitigate emissions while securing sustainable copper supplies for the anticipated surge in EVs and grid infrastructure.
- Polymers (plastics and composites): Bio-based plastics utilizing Gen 2 and Gen 3 biomass, CO_2-derived feedstocks, and recycled carbon inputs present critical alternatives to fossil-derived materials.

These emerging feedstocks offer pathways to substantially reduce the carbon footprint of automotive plastics and composite polymers, though scaling these technologies to meet stringent automotive-grade performance and sustainability standards requires ongoing research and industrial adaptation.

- Battery materials: Including lithium, cobalt, nickel, and manganese, these materials currently generate 80 tons $CO_{2,eq}$ per ton due to mining and chemical processing. Green mining techniques, renewable-powered refining, and advanced closed-loop recycling are vital to minimize emissions associated with these critical EV components. Novel approaches like direct lithium removal and alternative battery chemistries further support decarbonization efforts.
- Rare earth elements (REEs): Essential for electric motors, sensors, and other critical components, REEs pose environmental and geopolitical challenges. Their removal and refining processes emit up to 415 tons $CO_{2,eq}$ per ton of purified oxides. Improving mining efficiency, integrating renewable energy in processing, and advancing REE recycling technologies are pivotal for reducing lifecycle emissions and enhancing supply chain resilience.

Scaling green primary materials faces several interdependent challenges. Industrial deployment hinges on the availability of abundant renewable electricity and green hydrogen infrastructure. Policy frameworks - such as carbon pricing, emissions regulations, subsidies, and public-private partnerships - are essential to incentivize investments. Furthermore, innovative financing instruments like green bonds and sustainability-linked loans can mobilize capital for the substantial upfront costs of green material production. Collaboration across the automotive and raw materials supply chains is necessary to secure sustainable feedstocks, establish certification standards, and ensure transparency and traceability.

In conclusion, while recycling strategies reduce demand for virgin inputs, they will not suffice alone to satisfy the expected growth in automotive materials. The decarbonization of primary raw material production is therefore indispensable for meeting the industry's net-zero goals. Integrating green primary materials with circular economy principles enhances the resilience, sustainability, and competitive position of the European automotive sector, underpinning the continent's climate leadership and industrial sovereignty.

2.4 Carbon Removal: Addressing Residual Emissions Through Negative Emissions Technologies

Even with maximal deployment of closed-loop recycling, open-loop recycling, and green primary materials, a residual portion of greenhouse gas emissions - typically around 10% - will remain within the automotive value chain due to technical, material, and process limitations. This residual cannot be fully eliminated by current decarbonization methods and requires active removal of $CO_{2,eq}$ from the atmosphere or emission streams, a process known as carbon removal.

Carbon removal is an essential complement to deep emissions reductions, involving the permanent removal and secure storage of carbon dioxide. It differs from traditional carbon offsetting by focusing on negative emissions, which extract more $CO_{2,eq}$ than is emitted, effectively reducing atmospheric concentrations and enabling true net-zero or net-negative emissions outcomes.

Principal Carbon Removal Pathways:

- Engineered Carbon Capture and Storage (CCS): CCS technologies capture $CO_{2,eq}$ directly from industrial point sources - such as steelmaking or chemical processes - or from ambient air through Direct Air Capture (DAC). The captured $CO_{2,eq}$ is compressed and injected into geological formations, including depleted oil and gas reservoirs or deep saline aquifers, where it can be stored securely for millennia. CCS offers a scientifically validated and near-permanent carbon sink but currently faces challenges including high energy requirements, cost, and the need for supportive infrastructure and regulatory frameworks.
- Nature-Based Carbon Removal: This pathway enhances natural carbon sinks via reforestation, afforestation, wetland and peatland restoration, and soil carbon sequestration. These solutions provide important biodiversity and ecosystem service co-benefits, though permanence is less assured due to vulnerability to disturbances like fire, disease, or land-use change. Robust monitoring and risk mitigation are required to ensure long-term carbon storage.
- Emerging Negative Emission Technologies: Innovations such as enhanced mineralization - where $CO_{2,eq}$ reacts with abundant minerals to form stable carbonates - and bioenergy with carbon capture and storage (BECCS) show promise for scalable carbon removal. However, they are at varying stages of development, requiring further research to reduce costs and environmental impacts.

Carbon removal must be viewed as a last-resort, complementary strategy, employed only after all feasible emissions reductions through material circularity and green production methods have been realized. Overreliance risks diverting focus from essential systemic transformation and may raise ethical and reputational concerns. Key challenges include:

- Energy Intensity and Sustainability: Many removal technologies require substantial renewable energy inputs to avoid indirect emissions that undermine their net climate benefit.
- Scalability: Achieving meaningful climate impact demands large-scale deployment, necessitating investment in infrastructure, technology development, and supply chains.
- Verification and Permanence: Ensuring long-term, verifiable carbon storage through stringent monitoring, reporting, and verification (MRV) frameworks is essential to maintain environmental integrity.
- Cost and Policy Support: Current costs remain high, requiring supportive policy instruments such as carbon pricing, incentives, and clear regulatory pathways to stimulate adoption.

For the automotive industry, carbon removal enables the neutralization of residual emissions that cannot be abated through recycling or green materials. By integrating carbon removal responsibly - capped at approximately 10% of total emission mitigation - the sector can credibly claim net-zero status, aligning with EU climate ambitions and global scientific consensus.

Carbon removal enhances the resilience of the automotive supply chain and European industrial base by:

- Providing a dependable solution for emissions that are otherwise locked in due to process or material constraints.
- Supporting the transition to climate-neutral manufacturing while maintaining competitiveness in a global market increasingly demanding sustainable products.
- Complementing circular economy efforts and green innovation by closing the remaining emissions gap.

3 The Road to Net Zero: A Scenario

Based on available data, a scenario has been developed -and challenged multiple times -to explore how the automotive industry could reach its Scope 3 emission reduction targets by 2050. This scenario, illustrated in Figure 1, shows the potential contribution of the four key pillars to achieving deep decarbonization. It assumes that the bulk of emission reductions up to 2030 will stem from powertrain electrification. However, after 2030, the reduction of Scope 3 upstream emissions - primarily from materials and supply chains -emerges as the central challenge and the key lever for further progress.

Achieving net zero emissions from material production is one of the most complex and demanding tasks societies face in the next 25 years. If this transformation fails, the broader net-zero objective will be out of reach - with all associated environmental, economic, and geopolitical consequences.

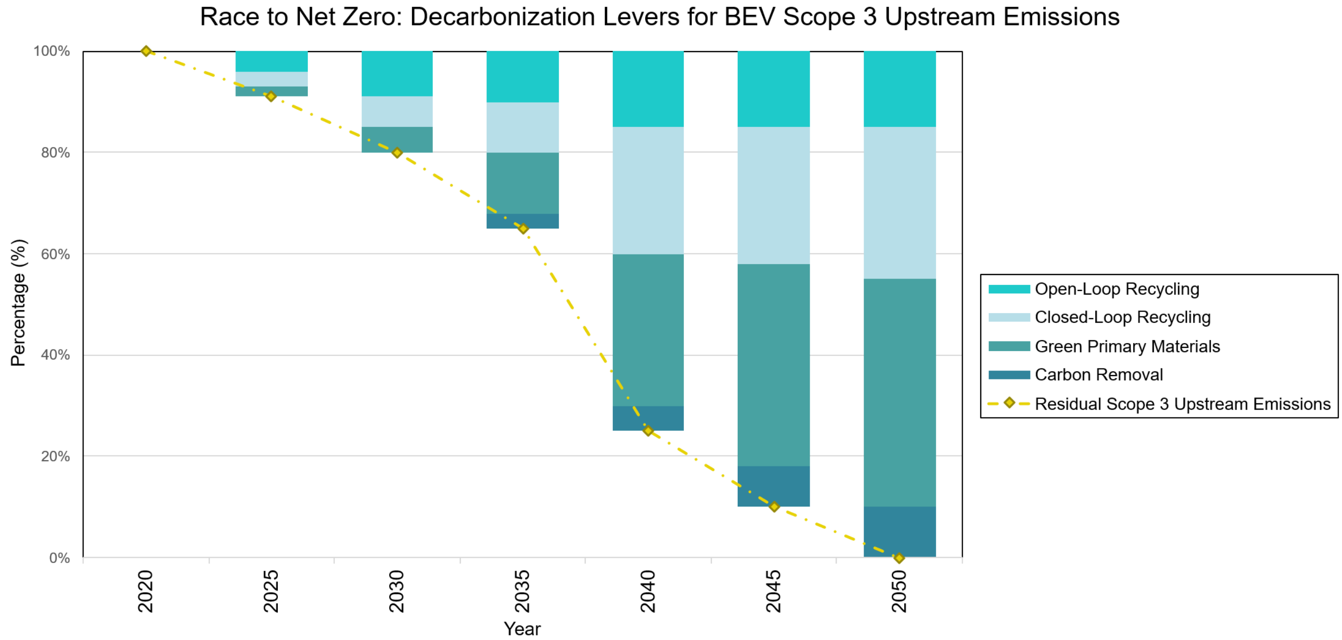

Figure 1: The Road to Net Zero regarding Scope 3 Upstream

Global material demand currently stands at approximately 100 gigatons annually, with the automotive sector alone accounting for around 9 gigatons, making it one of the most resource-intensive industries. Decarbonizing this sector will require strong political leadership, substantial financial investment, and - most importantly - swift and coordinated action across all value chains.

The scenario highlights two primary levers:

1. Closed-loop recycling to retain materials within the system, and
2. Green primary material production to significantly reduce the footprint of virgin inputs.

Open-loop recycling is expected to play a supportive role in the early phase of transition but has limited potential in the long run. As all industries move toward net zero, competition for recycled content will increase, restricting the effectiveness of cross-sector material flows.

Carbon removal technologies are expected to address residual, hard-to-abate emissions. Yet, given their currently high energy requirements and low scalability, they are unlikely to play more than a complementary role in the foreseeable future.

Many of the necessary technologies are still at low Technology Readiness Levels (TRLs) and are expensive to scale. Accelerated innovation, rapid industrial deployment, and global coordination are therefore essential to close the Scope 3 emissions gap by mid-century.

4 Limiting Factors for the Transition to Net-Zero Automotive Materials

Despite growing momentum toward climate-neutral mobility and the rising availability of technological pathways for low-emission material production, the automotive sector faces a complex landscape of structural, infrastructural, and systemic constraints. These limiting factors threaten to delay or even derail the full decarbonization of material supply chains unless they are addressed through coordinated policy, investment, and industrial action.

a) Shortage of Low-Cost, Green Energy

The availability of abundant, affordable renewable electricity is a foundational enabler for material decarbonization. Both direct electrification (e.g., electric arc furnaces for secondary steel) and indirect pathways (e.g., electrolytic hydrogen for primary steel or chemical feedstocks) depend on secure, low-cost access to green power.

However:

- Grid congestion, long permitting times, and local resistance slow down renewable energy deployment.
- Competing demand from electrified transport, data centres, and synthetic fuels limits supply for material producers.
- Industrial consumers often lack access to 24/7 renewable baseload at competitive prices.

This constraint drives up production costs for decarbonized materials and limits the scalability of green industrial processes.

b) Underdeveloped Hydrogen Infrastructure

Green hydrogen plays a key role in future-ready material processes - such as direct reduced iron (DRI), ammonia-based fuels, and low-emission aluminium and copper refining. Yet, the current hydrogen economy is immature:

- Electrolyzer capacity is far below projected industrial demand.
- Hydrogen transport, storage, and refuelling infrastructures are fragmented or non-existent in most regions.
- Hydrogen-ready industrial assets remain in early development or demonstration stages.

In the absence of scaled, integrated hydrogen infrastructure, most material producers are unable to commit to hydrogen-based decarbonization.

c) Land-Use Constraints for Biomass and Biogenic Carbon

Biomass is needed as a carbon-neutral reducing agent in metallurgical processes and as a feedstock for biobased automotive materials. However:

- Agricultural land is increasingly contested by food production, biodiversity protection, and energy crops.
- Biomass cultivation raises environmental concerns around land-use change and water consumption.
- High transport costs limit the use of biomass in regions distant from biogenic sources.

Consequently, biomass-based material solutions will remain geographically limited and cannot serve as a global substitute for fossil carbon in material production.

d) Critical Raw Material Bottlenecks

Even in a circular economy, key components of net-zero materials - such as lithium, cobalt, nickel, rare earths, and platinum-group metals - must be sourced from primary removal in the medium term. The sector faces:

- High geopolitical concentration of supply chains (e.g., China, Russia, DRC)
- Environmental and social governance (ESG) risks in mining regions
- Multi-decade timelines for opening new mines and refining capacity

Supply insecurity and fluctuating prices make strategic planning difficult and may lead to delayed transitions or material substitutions with lower performance or higher lifecycle emissions.

e) Insufficient Circular Infrastructure and Traceability

Although circularity is key to reducing material-related emissions, the infrastructure to support closed-loop and high-quality open-loop recycling is still nascent:

- Many end-of-life vehicles (ELVs) are not properly collected, especially when exported or dismantled informally.
- Current recycling systems struggle with low material purity, especially for complex alloys and composites.
- Material passports, traceability systems, and digital product identifiers are underdeveloped, making it hard to verify recyclate content or quality.

As a result, the automotive industry loses access to high-quality secondary materials and fails to close material loops at scale.

f) Missing Market Signals and Carbon Pricing

Low-emission materials are often 20–50% more expensive than their conventional counterparts. However, market mechanisms do not yet reward decarbonization:

- Carbon pricing is fragmented and often excludes embedded emissions in imported materials.
- The EU ETS applies to basic materials but does not fully capture Scope 3 emissions from the automotive value chain.
- The EU's Carbon Border Adjustment Mechanism (CBAM) does not yet cover finished goods or many automotive components.

Without strong carbon price signals and full lifecycle accounting, low-carbon materials struggle to achieve market competitiveness.

g) Institutional Gaps and Regulatory Complexity

Beyond price signals, regulatory frameworks often fail to support the transition:

- There are no harmonized standards for “green steel,” “net-zero aluminium,” or recycled plastics with verified carbon content.
- Public procurement and automotive regulations rarely mandate or reward low-carbon materials.
- Permitting processes for renewable energy, hydrogen infrastructure, and CO_2E storage are slow and fragmented.

These institutional voids delay investment decisions, fragment innovation ecosystems, and prevent rapid scaling of sustainable material technologies.

h) Lack of a Coherent Legal and Incentive Framework

A supportive legal and financial architecture is critical to de-risk investments, coordinate actors, and create a functioning market for climate-neutral materials. Yet, several key elements are missing:

- No universally accepted standards or labelling schemes for green or low-carbon materials, creating market confusion and inhibiting demand.

- Limited support for first movers: Industrial pioneers face high capital expenditures, long return periods, and technological risks -especially during later stages of innovation when scaling industrially -without adequate public co-investment or financing mechanisms. Examples include the absence of sufficient carbon contracts for difference, innovation guarantees, and large European venture capital funds capable of investing billions in a single round.
- Weak demand-side incentives: Public procurement does not mandate green materials, and automotive subsidies ignore embedded carbon. This results in underwhelming early market pull.
- Complex access to innovation funding: EU innovation instruments (e.g., IPCEIs, Innovation Fund) are slow, bureaucratic, and not easily accessible to smaller players or cross-sector collaborations.

Without a holistic incentive and regulatory framework that rewards carbon performance, penalizes inaction, and ensures demand for clean materials, the transition will remain stuck in a pre-commercial phase - technically feasible but economically unviable.

The transformation toward net-zero automotive materials faces a broad set of interconnected barriers: constrained access to cheap renewable energy, missing hydrogen infrastructure, material and land limitations, and institutional gaps. At the core lies the absence of a robust legal and financial framework that translates climate ambition into material-specific action.

Policymakers must urgently:

- Establish binding standards for carbon content and recyclability
- Expand carbon pricing to cover full material life cycles
- Incentivize demand for green or low-carbon materials through procurement and regulatory levers
- Accelerate infrastructure development, permitting processes, and funding support for first movers
- Partner with the financial sector to create large-scale European venture capital funds capable of investing billions in a single venture

Only through coordinated action across industry, finance, and government can the transition be made realistic, cost-effective, and timely.

i) Risk aversion amongst all stakeholders

Europe's innovation ecosystem is often marked by a cultural risk aversion shared among investors, policymakers, and corporations, which can slow breakthrough advancements and industrial scaling. While Europe boasts a world-class research infrastructure and generates many groundbreaking inventions, these innovations are frequently industrialized and commercialized elsewhere - particularly in the U.S. and China -where risk-taking and rapid scaling are more deeply embedded. To change this dynamic, e.g., European universities must more fully embrace the spin-off and entrepreneurship mindset, actively fostering start-ups and bridging the gap between research and industry. Exemplary institutions like UnternehmerTUM and the Technical University of Munich demonstrate how cultivating strong innovation hubs can translate academic excellence into successful industrial ventures. Europe need not replicate the American or Chinese models wholesale but can build on its unique strengths by combining its rigorous research foundations with a more supportive ecosystem for bold, sustainable innovation aligned with social and environmental values.

5 Strategic Priorities for a Net-Zero, Circular Automotive Materials Economy

To achieve net-zero automotive manufacturing by 2050, the industry must embrace a multi-path, materials-centric transformation that balances closed-loop and open-loop circularity, green primary material substitution, and carbon removal where necessary. This requires an integrated approach combining infrastructure, technology, regulation, and finance.

1. Improve End-of-Life Vehicle (ELV) Collection and Preprocessing

Currently, a significant share of ELVs is lost to informal or overseas channels. To close the loop:

- Offer economic incentives and deposit-refund schemes for vehicle returns.
- Digitize reverse logistics using geolocation and vehicle ID data to enable predictive ELV flows.
- Install smart preprocessing hubs using XRF, NIR, and AI-based disassembly protocols to improve separation and reduce downcycling.

2. Build Infrastructure for Open-Loop Recycling Across Sectors

Where closed-loop recycling is unfeasible, materials must flow efficiently into other high-value sectors. Key enablers include:

- Mapping and optimizing cross-sectoral material flows (e.g., automotive polymers into building materials or textiles).
- Establishing open-loop quality standards to facilitate reuse across industries.
- Co-locating recycling hubs with multi-industry material users to reduce transport emissions and support urban mining.

3. Expand and Digitalize the Recycling Infrastructure (Closed Loop)

Recycling companies and related stakeholders must invest in high-throughput, automated recycling systems capable of preserving material quality and value. Key actions include:

- Deploying robotic dismantling, AI-assisted sorting, and next-generation shredding technologies.
- Rolling out Digital Product Passports (DPPs) for all vehicle components to enable traceability, material verification, and automated separation.
- Creating an open, cloud-based tracking infrastructure for real-time monitoring of materials across multiple lifecycles.
- Scaling up battery recycling, including direct cathode regeneration and hydrometallurgy, to retain critical elements in domestic supply chains.

4. Scale the Production of Green Primary Materials

Some virgin input will remain necessary. Priority actions include:

- Secure cost-competitive green steel and aluminium through long-term agreements with DRI–H_2 producers and renewable-powered smelters.
- Incentivize bio-based and recycled plastics with low carbon intensity.
- Develop ESG-compliant supply chains for critical minerals, backed by traceability, sovereignty agreements, and refining capacity expansion.
- Support low-carbon cement, glass, and foster new biomass production technologies that increase sustainable bio-based material supply while minimizing land-use impacts

5. Enable Carbon Removal for Irreducible Emissions

Offsetting should be the last resort. For residual emissions:

- Mandate offsetting only for hard-to-abate process emissions.
- Prioritize permanent removal technologies: DAC (direct air capture), biochar, enhanced rock weathering.
- Develop industry-specific removal credits under transparent, science-based certification (e.g., Verra, Gold Standard).
- Align corporate offset use with science-based targets and public disclosure.

6. Strengthen Legal and Financial Incentives

To turn strategic intent into commercial viability:

- Introduce Minimum Recycled Content (MRC) and Maximum Carbon Content (MCC) standards for automotive materials.
- Create green materials tax credits and Contracts for Difference (CfDs) to de-risk investment in first-of-a-kind low-carbon material projects.
- Harmonize green material labelling, ESG disclosure, and LCA reporting requirements across the EU and beyond.
- Expand carbon pricing to cover embedded emissions in imported components (extension of CBAM and Scope 3 obligations).

7. Accelerate Hydrogen and Green Energy Infrastructure

All green material strategies hinge on energy availability:

- Prioritize industrial access to 24/7 renewable power via power purchase agreements and dedicated transmission corridors.
- Build a European hydrogen backbone with pipelines, storage terminals, and industrial demand hubs.

- Fast-track permitting and finance for green hydrogen electrolysis projects collocated with material producers.

8. Foster Multi-Stakeholder Collaboration and Innovation Ecosystems

Decarbonization is a systems problem. Necessary actions:

- Establish pre-competitive consortia to co-develop technologies, standards, and digital platforms (e.g., Catena-X-type ecosystems [2] for materials).

9. Foster market-driven circularity through smart incentives and transparent carbon pricing

Circularity will not emerge from top-down quotas or micromanaged targets. It must be driven by clear market signals, stable framework conditions, and transparent data that reward low-carbon materials and designs across the value chain:

- Make CO_2 pricing the central steering mechanism, reflecting the true cost of carbon in all material streams - from primary extraction to end-of-life recovery.
- Enable free material substitution - whether recycled, biogenic, or low-carbon — as long as verified life-cycle emissions fall.
- Create transparent data ecosystems (e.g., digital product passports) so that carbon and circularity data become tradable and comparable across markets.
- Reward companies for verified CO_2 reductions, not for bureaucratic quota compliance - through tax advantages, green public procurement, and access to innovation funding.
- Invest in circular infrastructure (sorting, reprocessing, logistics) and harmonized EU standards to make high-quality secondary materials economically viable at scale.
- Ensure international consistency, preventing carbon leakage and maintaining competitiveness of European manufacturing.

10. Build a European venture capital sector capable of multi-billion strategic investments.

To scale breakthrough technologies and secure Europe’s competitiveness in the circular economy, targeted action is needed to build a powerful and risk-tolerant VC ecosystem.

- Establish large-scale European venture capital funds that can provide multi-billion euro investments in circular and green industrial innovations.
- Increase public co-investment and risk-sharing mechanisms to attract private capital and reduce barriers for strategic, long-term investments.
- Create a dedicated EU Circular Innovation Fund to accelerate the scale-up of recycling technologies, green materials, and circular business models.
- Reduce regulatory hurdles and align investment frameworks across member states to improve VC effectiveness and cross-border collaboration.

- Support the emergence of industrial champions in circularity, comparable to China's state-backed leaders, through targeted capital allocation.
- Incentivize patient capital and long-term performance metrics, rather than short-term financial returns.
- Embed venture capital strategies into the Green Deal Industrial Plan, ensuring alignment with Europe's climate, resource, and competitiveness goals.
- Ensure VC-backed innovation is supported by infrastructure, legal frameworks, and demand-side policy signals to accelerate deployment at scale.

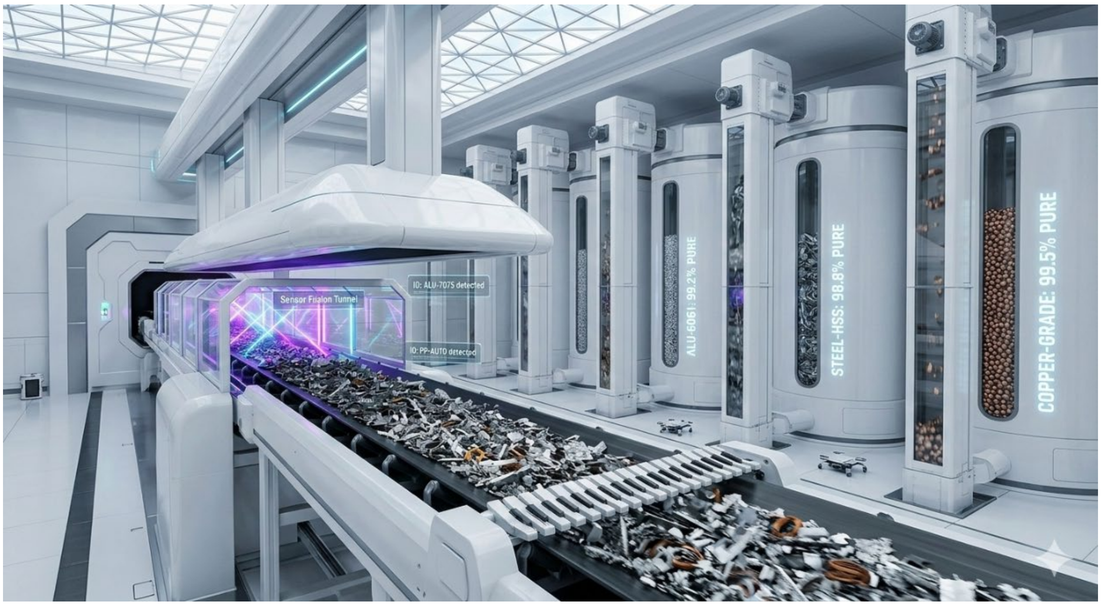

Figure: Advanced sorting of shredder fractions (generated by AI)

6 Conclusions and Recommendations

Toward a Materials-Centric Fifth Industrial Revolution

Achieving net-zero automotive manufacturing by 2050 is not merely a sectoral target - it is a litmus test for the Fifth Industrial Revolution. Unlike its predecessors, this revolution is not driven by digitization or automation alone, but by the convergence of climate responsibility, resource efficiency, and industrial regeneration. At its core lies a radical shift in how we design, source, use, and circulate materials.

The transformation required is unprecedented in both scale and complexity. All major industrial material streams - steel, aluminium, plastics, glass, critical minerals - must be either decarbonized at source or fully integrated into circular value chains. This must happen under tight time constraints: most industrial assets and value chain architectures are locked into multi-decade life cycles, and the 2050 target is now less than 25 years away. For vehicles entering the market in 2035 or later to be truly climate-neutral over their full lifecycle, decisive action must be taken now.

Europe's Strategic Imperative: Industrial Sovereignty through Sustainability

For the European Union, this transformation is not optional - it is a strategic necessity. The EU has publicly committed to becoming the world's first climate-neutral continent and a powerhouse of sustainable industrial innovation. Realizing this vision depends heavily on decarbonizing the material backbone of its economy.

Success in building a net-zero, circular automotive materials ecosystem would:

- Reduce the EU's dependence on fossil-based and geopolitically concentrated raw materials.
- Protect and create future-proof industrial jobs in regions undergoing transformation.
- Reinforce Europe's global leadership in regulatory frameworks and sustainability standards (e.g., CBAM, Ecodesign, EU Battery Regulation).
- Demonstrate that climate-neutral mobility can be achieved without deindustrialization, strengthening economic resilience and global competitiveness.

Failing to lead in material transformation, by contrast, would leave Europe exposed to rising global competition (e.g., from the U.S. IRA or Chinese state-supported clean tech) and risk turning climate ambition into economic vulnerability.

Current Momentum Is Insufficient

While there is growing momentum - via regulatory frameworks like the EU Battery Regulation [3], the Critical Raw Materials Act [4], and the Carbon Border Adjustment Mechanism (CBAM) [5] - the pace and scope of transformation remain far below what is needed. Many key enablers are still missing or underdeveloped:

- Green hydrogen and renewable electricity are not yet available at scale for material producers.

- Circular infrastructure is immature, and digital traceability systems are only beginning to emerge.
- Generation 2 and 3 biomass production, collection and processing are not scaled yet.
- Legal and financial frameworks to reward low-carbon materials remain fragmented and weak.

Without massively accelerated investment, policy reform, and cross-sector collaboration, the window to meet the 2050 target will close rapidly jeopardizing Europe's leadership position.

Integrated, High-Ambition Action Is Needed Now

To stay within the net-zero trajectory, the automotive industry and its ecosystem must commit to an integrated material transformation strategy built on four mutually reinforcing pillars:

1. Closed-loop and high-quality open-loop recycling, enabled by automated disassembly, advanced sorting, and full digital traceability (via Digital Product Passports).
2. Industrial deployment of green primary materials, including hydrogen-based steel, low-carbon aluminium, and bio- or chemically recycled polymers.
3. Strict limitation of carbon offsetting to hard-to-abate residuals, and prioritization of permanent carbon removal (DAC, biochar, enhanced weathering).
4. Robust, supportive policy architecture, including carbon pricing for embedded emissions, mandatory recycled content standards, and first-mover investment incentives (e.g., CfDs, green procurement).

Second-life use of EV batteries in stationary storage must also be scaled up as an intermediate step, maximizing resource efficiency before end-of-life recycling and supporting renewable energy integration.

Recommendations for Stakeholders

For Industry:

- Align corporate material strategies with net-zero science-based targets, including Scope 3.
- Invest in future-proof supply chains that prioritize recyclability, traceability, and ESG-compliant sourcing.
- Collaborate pre-competitively to accelerate shared standards, platforms, and circular innovation ecosystems.

For Policymakers (with emphasis on the EU):

- Expand carbon pricing and extend CBAM to cover all automotive components and materials.
- Accelerate permitting and support infrastructure build-out for green hydrogen, renewables, and CO_2E storage.
- Introduce mandatory lifecycle disclosure, minimum recycled content, and procurement-based incentives for low-carbon materials.

- Direct public and blended finance to first-of-a-kind industrial decarbonization projects.
- Make material transition a strategic pillar of the Green Deal Industrial Plan, positioning the EU as a global standard-setter for sustainable materials.

Final Note: Europe Must Lead

The transition to net-zero materials is not only about compliance - it is about strategic leadership in the defining and solving industrial challenge of our time. For Europe, this is a generational opportunity to show that industrial strength and ecological responsibility can be mutually reinforcing.

The Fifth Industrial Revolution will not be measured by the next digital product - it will be measured by our ability to reinvent the material foundations of prosperity while operating within planetary boundaries. Europe has the vision, the tools, and the talent to lead. But only if action accelerates now.

7 Annex

7.1 List of Abbreviations

Abbreviation	Meaning
AI	Artificial Intelligence
BECCS	Bioenergy with Carbon Capture and Storage
BEV	Battery Electric Vehicle
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CfD	Contracts for Difference
CFRP	Carbon Fiber Reinforced Plastics
DAC	Direct Air Capture
DPP	Digital Product Passport
DRC	Democratic Republic of Kongo
DRI	Direct Reduction Iron
ELV	End-of-Life Vehicle
ESG	Environmental, Social, and Governance
EV	Electric Vehicle
Gen	Generation
IPCEI	Important Project of Common European Interest
IRA	U.S. Inflation Reduction Act
LCA	Life Cycle Assessment
MCC	Minimum Recycled Content
MRC	Maximum Carbon Content
MRV	Monitoring, Reporting and Verification
NIR	Near-infrared spectroscopy
REE	Rare Earth Element
TRL	Technology Readiness Level
VC	Venture Capital
XRF	X-Ray Fluorescence

7.2 References

[1] European Parliament and of the Council (2022), Directive (EU) 2022/2464, “Corporate sustainability reporting”, http://data.europa.eu/eli/dir/2022/2464/oj, last visit 19.02.2026

[2] Catena-X, https://catena-x.net/, last visit 19.02.2026

[3] European Parliament and of the Council (2023), Regulation (EU) 2023/1542, “Batteries and waste batteries”, http://data.europa.eu/eli/reg/2023/1542/oj

[4] European Parliament and of the Council (2024), Regulation (EU) 2024/1252, “Framework for ensuring a secure and sustainable supply of critical raw materials”, http://data.europa.eu/eli/reg/2024/1252/oj, last visit 19.02.2026

[5] Carbon Border Adjustment Mechanism (CBAM), https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en, last visit 19.02.2026