UK Critical Minerals
Intelligence Centre

An Economic Analysis of Midstream Manufacturing in the EU Defence and Aerospace Sectors and Opportunities for a More Circular Economy in the UK

Front cover image:
Barrie Taylor. 2014. digihanger-airshow-440513_1920. Pixabay.

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1 Introduction

The defence and aerospace sectors are foundational to national security, sovereign industrial capability and technological competitiveness in both the European Union and the United Kingdom. These sectors are characterised by high material intensity, stringent certification standards and long product lifecycles. They rely heavily on a concentrated group of high performance and critical raw materials, including nickel, rare earth elements, graphite and lithium. Although the absolute volumes of waste generated in the aerospace and defence sectors are small relative to sectors such as automotive or construction, the **strategic value per tonne is extremely high**. Scrap streams often contain concentrated high-value alloying elements, which are costly and geopolitically sensitive.

In recent years, geopolitical instability, supply chain disruption and accelerating global demand linked to the green energy transition have heightened concerns regarding material security. EU legislative and industrial responses, including the Critical Raw Materials Act (CRMA)[1] and the Net-Zero Industry Act,[2] reflect a strategic shift towards strengthening domestic processing, recycling and circular economy capability. The UK has similarly set out ambitions within its Critical Minerals Strategy[3] and related industrial policy initiatives.

While upstream extraction and end-of-life recycling have received considerable policy attention in recent years, there has been comparatively limited analysis focused on midstream manufacturing, which refers to the Tier 1, Tier 2 and Tier 3 segments of the supply chain, where semi-processed materials are transformed into high-value components and sub-assemblies prior to final integration by original equipment manufacturers (OEMs).

This summary presents the findings of a study examining waste and scrap valorisation in EU defence and aerospace midstream manufacturing, and the implications for strengthening circular economy approaches and industrial resilience in the UK.

The analysis focuses on four strategically significant material groups[4]:

1. Nickel, primarily in nickel-based superalloys
2. Rare earth elements, particularly in permanent magnets and specialist alloys
3. Graphite, especially in carbon composites and high-temperature applications
4. Lithium, in batteries, aluminium lithium alloys and advanced glass ceramics.

The study draws upon structured desk research; supply chain mapping; a technology maturity assessment; a comparative country analysis covering France, Germany, Italy, the Netherlands and Norway; and a cost-benefit modelling of nickel and rare earth elements.

The study has found that:

- Significant quantities of high-grade scrap are generated at Tiers 1 to 3 of the supply chain.
- Recovery practices vary widely by material and geography.
- Much of the value from waste materials is captured downstream by recyclers and melters rather than by midstream manufacturers.
- Closed-loop arrangements remain limited outside certain mature alloy systems.

Midstream waste valorisation is therefore a strategic lever for:

- Reducing import dependence
- Enhancing supply resilience

[1] European Commission. 2026. 'European Critical Raw Materials Act.' As of 12 March 2026: https://commission.europa.eu/topics/competitiveness/green-deal-industrial-plan/european-critical-raw-materials-act_en
[2] European Commission. 2026. 'Net Zero Industry Act.' As of 12 March 2026: https://commission.europa.eu/topics/competitiveness/green-deal-industrial-plan/net-zero-industry-act_en
[3] UK Government. 2026. 'UK Critical Minerals Strategy.' As of 12 March 2026: https://www.gov.uk/government/publications/uk-critical-minerals-strategy
[4] These specific materials are within scope of this study.

- Retaining economic value domestically
- Supporting net-zero and resource-efficiency objectives.

2 Structure of Midstream Supply Chain

Midstream manufacturing sits between raw material processing and final assembly by OEMs. In relation to the defence and aerospace supply chain, there are three relevant types of suppliers:

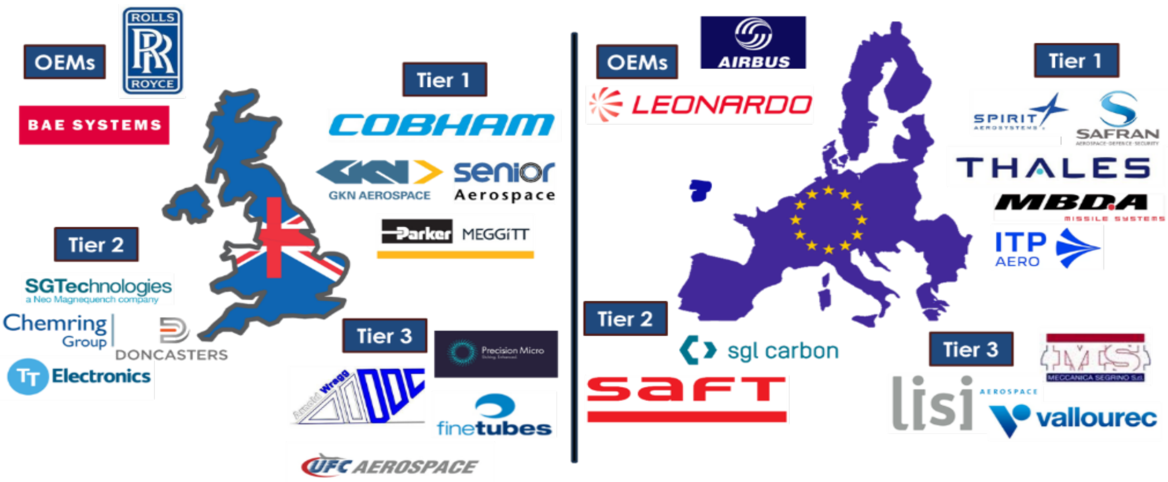
1. Tier 1 suppliers produce major systems using high-value, material-intensive processes, making them key generators of valuable scrap and strategically important material waste.
2. Tier 2 suppliers manufacture specialised components using alloy machining, composites, batteries and electronics, creating diverse and dispersed waste streams.
3. Tier 3 suppliers make precision parts through specialised machining and finishing, generating small but collectively significant quantities of high-performance material waste.

OEMs focus on final assembly and certification rather than material-intensive manufacturing, but they strongly shape supplier practices and recycling potential through specifications and procurement control.

The mapping concentrates on civil and defence aerospace supply chains, where evidence on midstream manufacturing processes and waste streams is most accessible. Other defence segments (e.g. naval and space systems) are not covered in depth, and the companies cited represent indicative examples rather than a comprehensive inventory of the sector.

Figure 2.1 shows some indicative examples of OEMs and Tier 1, 2 and 3 aerospace and defence suppliers in the UK and EU. The mapping concentrates on civil and defence aerospace supply chains, where evidence on midstream manufacturing processes and waste streams is most accessible. Other defence segments (e.g. naval and space systems) are not covered in depth, and the companies cited represent indicative examples rather than a comprehensive inventory of the sector.

Figure 2.1 Aerospace and Defence Sector Stakeholders in the UK and the EU



3 Material Specific Findings

For each of the four focus materials (nickel, rare earth elements, graphite and lithium), the analysis in this report links:

- Where the material is used in relevant midstream manufacturing processes
- What waste and scrap streams are generated

- What recycling and reprocessing routes are currently in use or under development.

More information on the specific materials can be found in in Appendix 1.

3.1 NICKEL

Nickel, primarily in the form of nickel-based superalloys, is critical for aerospace and defence applications due to its high temperature strength, corrosion resistance and fatigue performance. It is widely used in engine 'hot section' components and other high-stress environments. The recycling ecosystem for nickel alloys is comparatively mature.

Key findings:

- Machining and casting processes generate significant swarf[5] and revert[6].
- Open-loop recycling (sale of scrap) is common.
- Closed-loop recycling is technically feasible and commercially established in some supply chains.
- Value recovery depends heavily on scrap segregation and contractual arrangements with melters.
- Where closed-loop systems are well structured, manufacturers can receive credits for high-value alloying elements, improving material efficiency and reducing virgin input demand.

Policy implication: Nickel represents a near-term opportunity to scale closed-loop models, provided contractual, qualification and financing barriers are addressed.

3.2 RARE EARTH ELEMENTS

Rare earth elements (REEs) are used in comparatively smaller quantities in aerospace and defence applications but are strategically important due to their role in high-performance magnets, sensors, actuators, coatings and specialist alloying applications. Their supply chains are typically more constrained than those of base and alloy metals, and recycling routes for REEs are generally less mature.

Key findings:

- Magnet waste arises from machining, coating and component rejection.
- UK capacity for high-purity separation and reprocessing is limited.
- Open-loop recovery (e.g. downcycling or export) is more common than closed-loop reuse.
- Chemical and hydrometallurgical recycling technologies exist but are not yet widely commercialised domestically.

Policy implication: Without targeted investment and market-shaping measures, high-value REE-containing scrap risks being exported or downcycled, weakening strategic autonomy.

3.3 GRAPHITE

Graphite is used in aerospace and defence applications where high thermal stability, low density and friction or wear performance is required. It features most prominently in carbon–carbon (C/C) composite components and in precision-machined graphite parts used in high-temperature or chemically aggressive environments.

Key findings:

- Composite waste streams are heterogeneous and challenging to recycle.
- Some carbon fibre and graphite recovery technologies are maturing.
- Aerospace-grade qualification remains a barrier to high-value reuse.

Policy implication: Innovation funding and standards development are critical to prevent persistent downcycling.

3.4 LITHIUM

Lithium arises in aerospace and defence supply chains through a small number of distinct applications, including batteries (lithium-ion and some nickel–cadmium-related systems),

[5] Leftover metallic chips or debris producing during machining processes.

[6] Management process that involves the proper disposal and recycling of swarf.

aluminium–lithium alloys used in lightweight structures and lithium-containing glass-ceramics used in specialist components.

Key findings:

- Manufacturing-stage lithium waste volumes in aerospace are small.
- Recycling technologies are more mature in automotive battery than aerospace contexts.
- Certification constraints limit reuse in safety-critical applications.

Policy implication: Alignment between defence, aerospace and broader battery-sector innovation ecosystems could unlock shared infrastructure benefits.

Across the four focus materials, the analysis indicates that the most readily recoverable streams are generally clean, segregated midstream production scrap generated within controlled manufacturing environments (e.g. revert, offcuts, unused powders and certain battery production wastes). Conversely, fine particulates, mixed-material residues, coatings overspray and contaminated fluids tend to face greater technical and economic barriers to recovery.

4 Comparative Recycling Maturity

Table 4.1 synthesises findings across materials and processes to assess the relative maturity of recycling and reprocessing pathways in the UK and EU. The maturity levels provide a high-level comparison of where systems are commercially established, where activity is emerging but not yet scaled, and where routes remain at an early stage of development.

The maturity designations are based on evidence gathered through the literature review and, where possible, qualitative validation through stakeholder engagement. They are intended to support comparative, sector-wide interpretation rather than act as a formal technology evaluation.

The ratings in this report reflect an overall judgement of commercial deployment, scale and operational track record in the UK and EU context. The categories used do not correspond to UK Research and Innovation (UKRI) technology readiness levels (TRLs)[7] or any other TRL framework, as the available evidence did not support the robust assignment of specific TRL scores, and several entries reflect grouped pathway types rather than discrete technologies or individual facilities, making precise TRL classification inappropriate.

The findings show that recycling is most developed where waste is clean and well separated, such as nickel alloy scrap, and less advanced where materials are mixed or harder to recover. The main UK and EU difference is in lithium-ion battery recycling, where the EU currently has more established industrial capacity. In other areas, capabilities are broadly similar, with differences mainly reflecting scale rather than technical gaps.

This points to opportunities for closer UK–EU cooperation to scale up emerging recycling projects, improve collection and sorting of key materials, and ensure efficient cross-border movement of scrap and recovered materials.

[7] https://www.ukri.org/councils/stfc/guidance-for-applicants/check-if-youre-eligible-for-funding/eligibility-of-technology-readiness-levels-trl/

Table 4.1: Recycling Technology Maturity Across Materials and Processes

Process	Material(s)	UK Recycling Technology Maturity Level	EU Recycling Technology Maturity Level
Scrap/revert recycling	Nickel	High: Commercially operational	High: Commercially operational
Dust recycling	Nickel	Low to medium: Limited dedicated UK operations	Medium: Industrial-scale dust recycling
Powder recycling	Nickel	Low to medium: Limited domestic reprocessing (e.g. research and development stage)	Low to medium: Commercial providers exist
Fluid recycling	Nickel	High: Active in aerospace machining firms where there is recovery from waste metal sludge from fluids	High: Similar maturity to UK; commercial providers exist
Thermal coating recycling	REEs	Low: Very limited commercial-scale projects; mostly EU-led	Low to medium: Limited projects, mainly EU LIFE-funded projects
Recovering REEs from magnet waste	REEs	Low to medium: Pilot, constrained by separation and magnet liberation from EoL products/waste	Low to medium: Multiple pilot/demo projects; maturity varies
Graphite recycling	Graphite	Medium: Commercial in some forms; limited to downcycling or non-structural reuse	Medium: Commercial recycling and research and development; limited closed-loop into aerospace
Recovering from batteries	Graphite/ lithium/ nickel	Low to medium: Demonstration trials exist; industrial scale mainly in EU	Medium: Full industrial recycling pipelines exist[8]

5 Economic Assessment

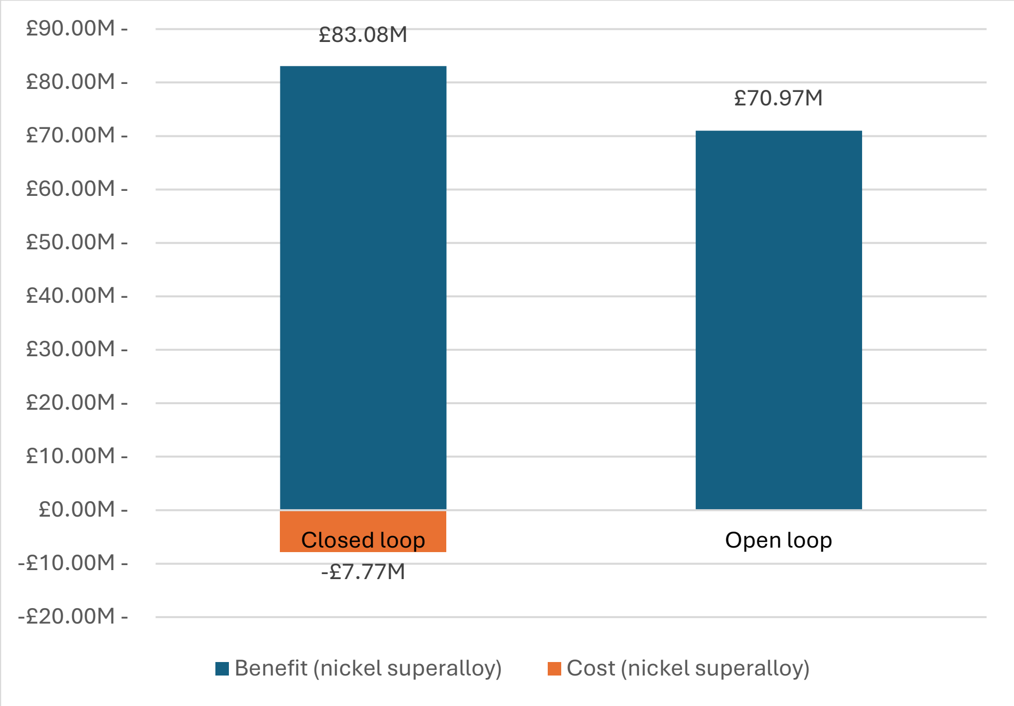
This assessment examines the annual financial costs and benefits of current open-loop and closed-loop recycling practices for key midstream manufacturing waste streams in the defence and aerospace sectors, focusing on nickel superalloys and rare earth permanent magnets. The results show a clear divergence in economic maturity across materials. For nickel-based superalloys, midstream recycling already presents a strong commercial opportunity, while for magnet alloys, the economic case remains limited under current technological and market conditions.

For nickel superalloys, closed-loop recycling delivers materially higher value retention than the open-loop sale of scrap: £83.08 million vs. £70.97 million, respectively (Figure 5.1). The associated cost of closed-loop recycling is estimated at £7.77 million, although this is a conservative estimate given uncertainties around scale and process efficiency. Overall, approximately 38–44 per cent of the total value of nickel superalloy manufacturing waste is currently offset through recycling.

[9] Information sourced from stakeholder interviews.

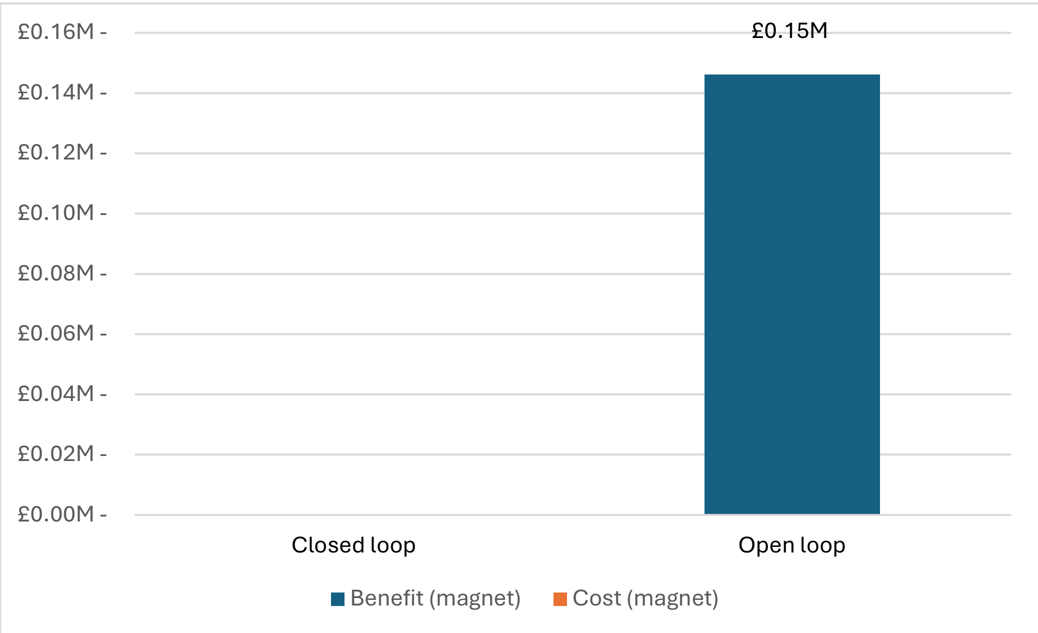
Figure 5.1. Annual Estimated Costs and Benefits Associated with Recycling Nickel-Based Superalloys

Benefits (blue) are represented as positive numbers, while costs (orange) are displayed as negative.



In contrast, the economic benefits of recycling rare earth permanent magnet manufacturing swarf are currently modest (Figure 5.2). Existing recycling practices are estimated to deliver only ~£150k in annual benefit to midstream manufacturers, equivalent to around 4 per cent of the total value of the waste generated. Stakeholder engagement suggests that around only 5 per cent of magnet alloy feedstock is currently recycled, with most waste material downcycled or diverted into other metal recycling streams. The closed-loop recycling of permanent magnets is not yet commercially established in the UK.

Figure 5.2. Annual Estimated Costs and Benefits Associated with Recycling Permanent Magnet Alloy NdFeB (Neodymium-iron-boron)



Benefits (blue) are represented as positive numbers. There are no costs associated with open loop recycling, and closed loop recycling practices for magnets are not yet commercially practiced.

Overall, the economic assessment demonstrates that midstream recycling can deliver meaningful economic benefits when recycling pathways are mature and aligned with manufacturing processes, as in the case of nickel superalloys. For materials such as rare earth magnets, there needs to be targeted policy, innovation funding and market-shaping measures to unlock future economic and security benefits.

6 Policy and Regulatory Context

6.1 EUROPEAN UNION

The European Union has embedded critical raw materials (CRM) security within a broader strategic autonomy and industrial competitiveness agenda. The Critical Raw Materials Act establishes benchmarks for domestic extraction, processing and recycling capacity, and introduces accelerated permitting for designated strategic projects. It places clear emphasis on strengthening EU-based refining, separation and recovery capabilities, including recycling infrastructure.

The Net-Zero Industry Act complements this framework by supporting domestic manufacturing scale-up in strategic sectors, reinforcing demand for the resilient midstream processing of materials such as rare earth elements, nickel and lithium.

Additional measures, including the EU Battery Regulation and reforms to state aid rules, support investment in recycling facilities and supply chain traceability. EU member states have increasingly used these flexibilities to co-fund rare earth separation, battery recycling and alloy remelting capacity.

Collectively, the EU policy environment is characterised by alignment between industrial competitiveness, strategic autonomy and circular economy objectives. Recycling is increasingly framed not solely as an environmental objective but as an instrument of supply chain security.

Table 6.1 shows EU policies, their relevance to midstream manufacturing circularity and lessons that can be learned in the UK.

Table 6.1: EU Policies and Lessons for the UK

Policy	Levers	Function	Outcome/Relevance to Midstream Manufacturing Circularity	Lessons for the UK
European Green Deal (2019)	Regulatory; financial; governance; market-shaping	Sets EU-wide climate-neutrality strategy and binding targets	Provides overarching justification for midstream circularity via climate, industrial and resource-efficiency framing	Strategic framing matters: circularity gains traction when embedded in economy-wide, legally binding goals
Green Deal Industrial Plan (2023)	Regulatory; finance/state aid; skills; trade	Bundles industrial policy tools to accelerate net-zero manufacturing	Indirectly supports CRM recycling by aligning finance, regulation and CRMA around supply-chain resilience	Package-based policy (regulation + finance + skills) de-risks midstream investment more effectively than standalone measures
Legislative framework of measures and regulations under the Green Deal Industrial Plan				
Net-Zero Industry Act (2024)	Regulatory; market-shaping; governance; skills	Scales EU manufacturing of net-zero technologies with targets and permitting reform	Enables recycling and material-efficient manufacturing as part of net-zero value chains, but no sector-specific scrap rules	Clear targets and fast-track permitting reduce investor uncertainty; effectiveness depends on implementation
Critical Raw Materials Act (2023)	Regulatory; market-shaping; trade controls; governance	Strengthens extraction, processing and recycling of CRMs; reduces dependencies	Most direct driver of midstream circularity: processing and recycling benchmarks, strategic projects, accelerated permitting	Prioritise conversion and qualification capacity, not just extraction; fast-track critical midstream facilities
EU Batteries Regulation (2023/1542)	Regulatory; market-shaping; digital traceability	Governs battery lifecycle with collection, recycling and recycled-content mandates	Creates strong demand-pull for secondary lithium, nickel, cobalt; aerospace benefits indirectly via shared capacity	Mandated recycled content and digital passports are powerful market-creation tools despite defence exemptions

6.2 UNITED KINGDOM

The United Kingdom has articulated similar ambitions to the EU through its Critical Minerals Strategy and Defence and Security Industrial Strategy, both of which emphasise supply diversification, domestic capability and resilience.

Recycling is recognised as an important lever, particularly for battery materials and rare earth elements. However, the UK framework is more strategy led and less target driven than the EU approach, and there are no equivalent quantitative benchmarks for domestic processing or recycling capacity.

Innovation funding through bodies such as the Aerospace Technology Institute and Innovate UK supports advanced materials and manufacturing efficiency; however, large-scale midstream recycling infrastructure remains comparatively underdeveloped.

Planning, permitting and waste classification frameworks can present barriers to the rapid scale-up of metallurgical and chemical processing facilities. Greater clarity on end-of-waste criteria and stronger alignment between defence procurement and recycled content objectives would help strengthen incentives for domestic recovery.

6.3 UK–EU COMPARISON

Following the analysis in this report, there are several distinctions between the EU and UK contexts:

1. The EU has established quantitative benchmarks for processing and recycling capacity at the EU level, while the UK framework remains more strategy led and less target driven.
2. The EU has created formal mechanisms to designate and accelerate strategic projects, including recycling facilities, whereas UK processes rely more heavily on general planning and industrial policy instruments.
3. State aid flexibility within the EU has enabled coordinated member state support for materials processing infrastructure. The UK approach is more decentralised and subject to domestic subsidy control rules.

There is a similarity in terms of both jurisdictions recognising the importance of recycling for material security, but neither has yet fully integrated midstream manufacturing scrap into defence procurement frameworks.

For the defence and aerospace sectors, the regulatory environment influences not only environmental compliance but also traceability, certification, export control and data transparency. Certification requirements for aerospace grade alloys and magnets can limit the uptake of recycled content unless standards bodies and OEMs adapt qualification pathways.

6.4 UK–EU COLLABORATION OPPORTUNITIES

Framing midstream recycling as a shared resilience agenda rather than a purely national priority opens several strategic advantages. In particular, a coordinated UK–EU approach would:

- Increase aggregate processing scale, improving the commercial viability of advanced recycling technologies.
- Enhance bargaining power in global raw materials markets.
- Reduce the duplication of infrastructure investment.
- Strengthen collective defence supply chains through trusted material loops.
- Support innovation spillovers across aerospace and defence ecosystems.

The UK and EU face shared challenges in critical material supply, including heavy reliance on third-country imports, limited domestic separation and midstream processing capacity, high qualification and certification barriers for aerospace and defence materials, and the capital intensity of recycling and refining infrastructure. UK firms remain closely integrated with EU aerospace and defence supply chains, creating opportunities for efficient collaboration rather than parallel investment.

Rare earth element recycling offers the most immediate strategic opportunity, with UK firms able to embed EU-led initiatives such as CREEM, SUSMAGPRO, HARMONY and REE4EU.

Actionable measures for the UK include:

- Securing long-term feedstock supply agreements with EU OEMs and Tier 1 suppliers.
- Specialising in alloy production or precursor materials while leveraging EU hydrometallurgical capacity.
- Developing joint UK–EU qualification programmes for aerospace-grade magnets.
- Implementing shared magnet liberation and extraction infrastructure to improve feedstock economics and scale UK long-loop recycling capabilities.

In nickel superalloys, where recycling is already mature, opportunities lie in formalising trusted UK–EU scrap corridors, coordinating investment in additional qualified remelting capacity, and collaborating on contamination-tolerant remelting and advanced solid-state reprocessing research and development (R&D). Harmonised furnace qualification and standards would also reduce capital barriers and improve cross-border efficiency.

For lithium and battery supply chains, UK participation in interoperable data, traceability and battery passport standards, along with joint ventures linking UK dismantling and pre-treatment with EU refining operations, would allow UK firms to integrate directly into EU-compliant supply chains. In addition, engagement in EU-aligned industrial clusters focused on defence-grade battery systems would reduce dependence on foreign cathode and precursor supply while retaining recycled materials within allied markets.

More broadly, designing complementary UK–EU end-to-end supply chains is key. For example, the UK could specialise in magnet alloy production, advanced machining, niche separation and high-value aerospace certification expertise, while EU partners focus on large-scale hydrometallurgical separation, battery-grade precursor production and industrial-scale magnet manufacturing.

In terms of strategic initiatives, these could include establishing UK–EU co-designation or associated partner status for UK recycling and refining facilities, enabling participation in EU Strategic Projects, and negotiating trusted recycler corridors for aerospace alloys, battery materials and magnet waste. Recognition of qualified UK facilities as equivalent to EU-permitted sites would reduce friction, enable two-way flows of high-value scrap, and strengthen supply chain resilience while supporting shared CRMA and allied market objectives.

By aligning policy signals, certification standards and investment strategies, the EU and UK can build an integrated ecosystem for critical material recovery and reuse. Such cooperation would reinforce sovereign capability on both sides while preserving the deep industrial interdependencies that characterise European defence and aerospace supply chains. In this context, midstream recycling becomes not only a circular economy measure but a practical instrument of shared industrial strategy and long-term strategic stability.

7 Recommendations

7.1 STRATEGIC IMPLICATIONS

Across the EU and UK defence and aerospace midstream supply chains, waste and scrap from key materials (nickel superalloys, rare earth magnets, carbon/carbon composites, graphite and lithium-ion batteries) primarily arise during material- and process-intensive manufacturing stages, such as melting and machining, electronics production, composite fabrication, and battery manufacturing. The most recoverable streams are those generated in controlled environments and easily segregated, including clean revert, offcuts, and unused powders, whereas fine, mixed, or contaminated wastes often require additional treatment and are more likely to be downcycled or leave aerospace-grade loops.

Recycling maturity varies by material: nickel superalloy revert recycling is well-established, supported by commercial incentives and closed-loop relationships, while rare earth recycling remains underdeveloped outside China due to feedstock access, separation capacity, and energy costs. Graphite and C/C composite recycling frequently results in lower-value applications, and lithium battery recycling, though expanding, is constrained by feedstock availability, regulatory barriers, and variable recovery performance. Improving circularity will require not only deployment of appropriate technologies but also stronger segregation and traceability, clearer end-of-waste rules, and reduced friction in cross-border secondary material flows, all while maintaining security and quality standards.

For the UK, the strongest near-term opportunity lies in protecting and valorising high-quality midstream production scrap, where economic returns are immediate and technological risk is low. Without targeted action, regulatory complexity and cross-border frictions risk continued leakage of high-value materials to overseas processors. Evidence suggests that recycling and midstream processing should be considered strategic industrial capacity rather than waste management, particularly in defence and aerospace, where qualification barriers, security requirements, and complex supply chains shape material flows.

Divergences in technology maturity imply differentiated policy priorities: for nickel, the focus should be on system efficiency and the retention of aerospace-grade scrap; for rare earths, addressing upstream feedstock aggregation and magnet liberation is critical; and for lithium batteries, regulatory clarity and predictable demand are essential to drive investment. Over the longer term, selective alignment with EU standards on recycled content, traceability and strategic project designation would reduce trade frictions and support UK firms' integration into European supply chains.

7.2 RECOMMENDATIONS

Across short-, medium- and long-term horizons, the UK can capture significant economic value by reframing recycling and midstream processing as strategic industrial capacity rather than waste management.

Short term (0–2 years): The focus should be on reducing regulatory friction and uncertainty. Key actions and measures include:

- Simplifying and clarifying waste-shipment and classification rules for high-value industrial scrap, particularly batteries, advanced alloys and defence-relevant materials.
- Streamlining approvals and documentation for high-quality recycling, both domestically and for controlled exports.
- Fast-track permitting and planning for advanced recycling and processing facilities, along with the national designation of certain projects as strategically significant, would shorten development timelines and improve investor confidence.
- Targeting measures that protect material quality at source, such as segregating clean revert, offcuts, unused powders and selected battery production wastes, alongside pre-treatment support, would prevent downcycling and retain high-value materials.
- Public procurement guidance and defence-industry engagement could further stimulate early demand for recycled materials, shifting industry expectations and reinforcing circular practices.

Collectively, these measures would reduce compliance risk, lower capital costs and improve the bankability of early-stage recycling projects.

Medium term (2–5 years): Policy should pivot towards creating predictable demand and targeted investment incentives.

Key actions and measures include:

- Fiscal tools such as enhanced capital allowances, tax credits or co-funded grants should support advanced recycling, metallurgical recovery and qualification R&D, particularly for high-value applications and critical materials.

- Demand-side measures, including recycled-content requirements and contracts-for-difference for secondary materials, would provide recyclers with long-term revenue certainty, supporting scale-up and market formation. Defence procurement can serve as an anchor, offering guaranteed offtake for pilot closed-loop recycling schemes in nickel alloys or rare earth magnets once quality and security standards are met.
- Policy levers should be tailored to material-specific challenges: for nickel, incentives should enhance system efficiency and pre-treatment capacity to retain aerospace-grade scrap; and for rare earths, upstream bottlenecks such as magnet liberation and feedstock aggregation must be addressed to enable effective recycling at scale.

These actions are expected to increase domestic value retention, lower unit processing costs and reduce exposure to volatile international material markets.

Long term (5–10 years): The UK should pursue selective alignment with EU standards on recycled content, traceability and strategic project designation to minimise trade frictions and facilitate integration into European value chains.

Key actions and measures include:

- Formalising strategic midstream designations within industrial strategy, rather than waste policy, would anchor investment in domestic refining, separation and qualification capacity, particularly for defence and aerospace-grade materials.
- The alignment of skills, industrial standards and procurement rules would ensure that domestic capacity is effectively utilised, allowing the UK to compete on quality and reliability.

Collectively, these long-term measures would sustain investment flows, reduce input cost volatility, improve supply chain resilience, increase gross value added from midstream activities, and reduce strategic dependence on imported refined material.

Appendix 1 Material Specific Findings

NICKEL

Table A.1 summarises the main midstream manufacturing processes in which nickel alloys are used and highlights their applications in aerospace and defence.

Table A.1: Nickel Manufacturing Processes

Manufacturing Process	Applications in Aerospace/Defence
Vacuum investment casting of superalloys	Turbine blades, vanes, heat shields, combustor parts
Powder consolidation	Turbine discs
Forging/ring rolling of nickel-alloy discs and shafts	Compressor/turbine discs, casings, engine shafts
Hot Isostatic Pressing (HIP)	Densification of turbine castings (e.g. blades/vanes), near-net-shape turbine discs
Superplastic forming	High-temperature ducting, combustor liners, exhaust components, thermal management structures in aero engines or hypersonic systems
Diffusion bonding	Seals, combustors, integrated turbine parts
Precision machining of superalloy components	Engine structures, mounts, fasteners
Additive manufacturing	Engine brackets, heat exchangers, combustor components, structural mounts, prototype turbine parts
Thermal coatings including Physical Vapor Deposition (PVD), Chemical Vapor Deposition (CVD), and Thermal Barrier Coating (TBCs)	Turbine blades, combustors, seals

Table A.2 summarises the waste streams generated by each of the identified nickel manufacturing processes. Waste and scrap arisings are closely tied to the manufacturing route. Processes such as investment casting, HIP and additive manufacturing tend to generate process-specific rejects and surplus feedstock, whereas machining-intensive routes (including finish machining of forgings and castings) generate larger volumes of chips and swarf, which are often co-mingled with cutting fluids.

Table A.2: Nickel Waste Streams[9]

Manufacturing Process	Waste Streams
Vacuum investment casting of superalloys	• Surplus alloy from gates/runners • Defective cast parts
Powder consolidation	• Unused metal powders
Forging/ring rolling of nickel-alloy discs and shafts	• Nickel alloy offcuts from trimming • Oxidised surface scale • Spent high-temperature lubricants and oils
Hot Isostatic Pressing (HIP)	• Defective parts
Superplastic forming	• Offcuts from trimming • Failed or defective formed parts • Lubricant residue
Diffusion bonding	• Oxide scale • Scrapped parts due to incomplete bonding/mismatch

[9] Information sourced from stakeholder interviews.

Precision machining of superalloy components	• Chips and swarf from Computer Numerical Control (CNC) and Electrical Discharge Machining (EDM) • Used cutting fluids • Worn tooling (e.g. EDM wires/electrodes)
Additive manufacturing (e.g. Laser Powder Bed Fusion, Electron Beam Melting, Directed Energy Deposition)	• Unused powder • Spatter/partially sintered particles • Failed builds • Post-machining swarf
Thermal coatings (PVD/CVD, TBCs)	• Overspray of thermal coatings (often mixed materials)

The recycling potential of nickel waste streams depends heavily on composition control and contamination risk. Clean, segregated revert and offcuts can often be remelted into high-grade feedstock, while dusts, overspray and fluid-contaminated residues typically require additional pre-treatment steps. **Table A.3** summarises nickel reprocessing and recycling pathways by outlining the processes that generate input waste streams.

Table A.3: Nickel Recycling Processes[10]

Reprocessing/ recycling process	Processes generating input waste streams
Scrap/revert recycling	• **Vacuum investment casting of superalloys:** surplus nickel alloy from discarded gates/runners; off-spec cast parts • **Forging/ring rolling of nickel-alloy discs and shafts:** nickel alloy offcuts from trimming • **Hot Isostatic Pressing:** defective HIP parts • **Superplastic forming:** trim scrap and offcuts; defective formed parts • **Diffusion bonding:** scrapped parts due to incomplete bonding or mismatch • **Precision machining of superalloy components:** nickel alloy chips and swarf from CNC/EDM • **Additive manufacturing:** failed parts; post-machining swarf
Dust recycling	• **Forging/ring rolling of nickel-alloy discs and shafts:** oxidised surface scale; fine metal dust from grinding and trimming • **Diffusion bonding:** oxidised surface scale • **Precision machining of superalloy components:** fine particulate residue and dust
Powder recycling	• **Powder consolidation:** Unused metal powders • **Hot Isostatic Pressing (HIP):** Unused metal powders • **Additive manufacturing:** unused metal powders
Fluid recycling	• **Forging/ring rolling of nickel-alloy discs and shafts:** spent lubricants and cutting oils used in forging operations and high-speed machining • **Superplastic forming:** spent high-temperature lubricants used to prevent sticking • **Precision machining of superalloy components:** used cutting fluids contaminated with metal fines

RARE EARTH ELEMENTS

Table A-4 summarises the main midstream manufacturing processes in which rare earth elements are used and highlights their applications in aerospace and defence.

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[10] Information sourced from stakeholder interviews.

Table A.4: Rare Earth Elements Manufacturing Processes

Manufacturing Process	Applications in Aerospace/defence
Thermal coatings (PVD, CVD, TBCs)	Turbine blades, combustors, seals
Magnet powder processing, bonding, sintering and integration	Sensors, actuators, motors, guidance and radar systems
Sensor/optic manufacturing	Lasers, displays, sensors in functional components (e.g. a laser emitter in a rangefinder)
Superalloy production	Rare earths added in small amounts to alloys to improve properties (e.g. creep resistance, high-temperature behaviour) in engine components or structural parts

Table A.5 Error! Reference source not found. summarises the waste streams generated by each of the identified rare earth element manufacturing processes.

Table A.5: Rare Earth Elements Waste Streams

Manufacturing Process	Waste Streams
Thermal coatings (PVD, CVD, TBCs)	• Overspray of thermal coatings (often mixed materials) • Spent PVD/CVD gases/vapours
Magnet powder processing, bonding, sintering and integration	• Broken/off-spec magnets • Dust from powder handling and sintering residues • Assembly rejects
Sensor/optic manufacturing	• Doping residue (i.e. residue from doping processes when rare earth ions are not fully absorbed into the host crystal or precipitate out of solution) • Crystal offcuts • Contaminated polishing slurry
Superalloy production	• Slag/dross with REE traces • Machining swarf and offcuts

Table A.6 summarises rare earth element reprocessing and recycling pathways, outlining the processes that generate input waste streams.

Table A.6: Rare Earth Elements Recycling Processes

Reprocessing/ Recycling Process	Processes Generating Input Waste Streams
Recovering REEs from magnet and rare-earth doped crystal waste	• **Magnet powder processing, bonding, sintering and integration:** dust from powder handling and pressing; off-spec or broken magnets during pressing, sintering or machining • **Sensor/optic manufacturing:** doping residue; crystal offcuts
Thermal coating recycling	• **Thermal coatings (PVD/CVD, TBCs)**: overspray of thermal coatings during application processes

GRAPHITE

Table A-7 summarises key graphite manufacturing processes and highlights their applications in aerospace and defence.

Table A-7: Graphite Manufacturing Processes

Manufacturing Process	Applications in Aerospace/Defence
Producing carbon–carbon (C/C) composite components	Aircraft brake discs, missile/ spacecraft heat shields, re-entry vehicle nose tips
Precision machining graphite components	Rocket nozzle inserts, thermal insulation parts, insulative liners/ igniter components in missile systems

Table A.8 summarises the waste streams generated by each of the identified graphite manufacturing processes. Compared with metals, graphite waste streams often present as dust, fine particulates, and composite offcuts, which can raise both handling considerations and recycling complexity.

Table A.8: Graphite Waste streams

Manufacturing Process	Waste Streams
Producing C/C composite components	• Trim waste • Carbonised fabric scraps • Scrapped parts
Precision machining graphite components	• Graphite dust • Machining offcuts • Failed and broken parts

Table A.9 summarises graphite reprocessing and recycling pathways, outlining the processes that generate input waste streams.

Table A.9: Graphite Recycling Processes

Reprocessing/ recycling process	Processes generating input waste streams
Graphite recycling	**Producing C/C composite components**: trim waste from layup, offcuts, scrapped parts **Precision machining of graphite components**: graphite dust from machining, offcuts, broken parts

LITHIUM

Table A.10 summarises key lithium manufacturing processes and highlights their applications in aerospace and defence.

Table A.10: Lithium Manufacturing Processes

Manufacturing Process	Applications in Aerospace/Defence
Electrode coating, cell assembly and battery pack assembly	Aircraft emergency power, UAV/vehicle power, defence energy systems
Lightweight aluminium-lithium alloy production	Fuselage skins, cryogenic tanks, wing components
High-performance glass-ceramics production	Radomes[11] (aircraft, missile, UAV), infrared and multispectral sensor windows, optical covers and

[11] A structure that protects antennas, radars and other communication systems from environmental factors or impacts, while allowing electromagnetic signals to pass through its surface without distortion. Can be found on the nose of commercial and military aircraft, on tactical or strategic drones, and also on land or naval systems. (Source: https://www.iberiacompositech.com/what-is-a-radome-and-why-is-it-so-important-in-aeronautics-and-defence/)

Manufacturing Process	Applications in Aerospace/Defence
	protective housings, high-temperature structural ceramic components

Table A.11 summarises the waste streams generated by each of the identified lithium manufacturing processes.

Table A.11: Lithium Waste Streams

Manufacturing Process	Waste Streams
Electrode coating, cell assembly and battery pack assembly	• Off-spec coated foils • Al/Cu foil trimmings • Rejected cells and modules
Lightweight aluminium-lithium alloy production	• Al-Li dross (oxidised Al/Li compounds) • Trimming/machining scrap • Off-spec plates
High-performance glass-ceramics production	• Rejected panels • Offcuts/trim waste

Table A.12 summarises lithium reprocessing and recycling pathways by outlining the processes that generate input waste streams. Battery manufacturing scrap is often relatively consistent in composition compared to end-of-life batteries, which can make it an attractive feedstock for recovery where collection and segregation systems exist.

Table A.12: Lithium Recycling Processes

Reprocessing/recycling process	Processes generating input waste streams
Recovering graphite/lithium/nickel from batteries	Electrode coating, cell assembly and battery pack assembly (lithium-ion or nickel–cadmium batteries): off-spec coated foils; cell rejects from formation, testing or assembly.