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Material circularity in the UK's foundation industries

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ABSTRACT

As the UK advances toward its 2050 net-zero target, moving beyond energy efficiency to comprehensive resource management is essential. This study evaluates how circular economy principles can reshape the use of aluminium, lead, steel, glass, and paper in the UK's foundation industries. Using a circularity index, we assess current performance and identify improvement pathways, quantifying the potential of enhanced recycling and material reuse. Results show that circularity strategies alone could reduce emissions by 42% and energy use by 17%, with reductions rising to 69% and 56% respectively, when combined with best-practice energy intensities. While aluminium and steel offer the largest gains, barriers remain for lead, glass, and paper due to technical and quality constraints. These findings highlight the opportunities and the complexities of industrial circularity, providing evidence to guide policymakers and industry leaders in accelerating the transition to a more sustainable and resource-efficient economy.

1. Introduction

The UK has positioned itself as a global leader in industrial decarbonisation, with a legally binding commitment to reach net zero emissions by 2050 (UK Government, 2021). Despite progress, industry remained a major emitter in 2021, accounting for approximately 82 Mt of CO_2, or around 16 % of the national total (ONS-UK, 2023). Within this, the foundation industries responsible for producing materials such as steel, aluminium, cement, glass, and paper, play a central role. These sectors are designated as 'foundation industries' in the UK industrial strategy because they supply essential inputs to construction, manufacturing, infrastructure, packaging and consumer goods, and together they emitted around 50 Mt of CO_2 to produce 28 Mt of material outputs in 2021 (Innovate UK KTN, 2022). Decarbonising these sectors cannot rely on energy efficiency alone; reductions in material demand, increased recovery of secondary materials and circular economy strategies will also be required (Allwood et al., 2010; Krausmann et al., 2017; Watari et al., 2023). These pressures are intensified by the combined challenges of carbon constraints, resource scarcity and the need to maintain industrial competitiveness.

Significant ambiguity remains in the literature regarding the conceptual overlap and distinction between circular economy (CE), resource efficiency and sustainability. Clarifying these terms is essential for effective implementation within industrial contexts (Geissdoerfer et al., 2017). While resource efficiency and sustainability take a broader, open-ended set of goals that can vary depending on the stakeholders involved, CE strives for a focused approach, advocating for closed-loop systems that minimise resource input and waste output, and often adopting an economic perspective (Geissdoerfer et al., 2017). The implementation of CE through the development and application of circularity metrics has been extensively studied. These metrics are integral to guiding corporations in creating or refining CE assessment models at the company level (Vinante et al., 2021). Furthermore, a critical examination of CE metrics reveals inherent contradictions and complexities, underscoring the imperative for holistic metrics that prevent the transfer of burdens (Corona et al., 2019).

Advancing social development often leads to increased demands for infrastructure. Understanding the relationship between infrastructure, well-being, and carbon emissions is fundamental (Müller et al., 2013). A key issue highlighted in the literature is the need to increase primary production to meet growing material demands (Bataille, 2020; Watari

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et al., 2023). The seminal work by Allwood et al. (2010, 2011) argue that material efficiency (or circularity) is an effective lever for reducing emissions while maintaining or delivering more material services. Ten years ago, a study on steel highlighted that focusing solely on energy efficiency and emissions reduction is unlikely to achieve the required emission targets, and that material efficiency would also be necessary to achieve significant emissions reduction (Milford et al., 2013). A more recent study examining the feasibility of a supply of steel and cement within carbon budgets confirms and underscores the importance of material efficiency actions, which reduce demand for materials (Watari et al., 2023). It is clear that energy efficiency and material efficiency play a critical role in sustainable industrial development, and industry synergies can support gains in these areas (Worrell et al., 2009).

When considering material efficiency, dynamic stock-flow models have examined global material use and its implications for CO_2 emissions (Müller et al., 2014; Wiedenhofer et al., 2019; Kalt et al., 2021). The relationship between material stocks, inflows, outflows, and economic growth indicates that persistent stock growth prevents the key CE strategy of closing material loops, because new virgin material is required to keep growing the stocks of materials in use. (Krausmann et al., 2017; Haas et al., 2015).

In UK-focused research, there has been significant attention on energy use and decarbonisation across various sectors, including chemicals (Griffin et al., 2018b), glass (Griffin et al., 2021), paper (Griffin et al., 2018a), and steel (Griffin and Hammond, 2019). However, studies addressing the impact of material flows and efficiency are less common: for cement (Shanks et al., 2019), glass (Hartwell et al., 2022), and steel (Garvey et al., 2022; Allwood et al., 2019).

This paper investigates the role of material circularity as a decarbonisation pathway within the UK's foundation industries, focusing on five strategically significant materials: aluminium, lead, steel, glass and paper. Rather than reporting circularity performance descriptively, the study applies a comparative analytical framework to assess current conditions and the technical potential for improvement. A circularity index is calculated for each material by integrating recovery rates, material flow balances and the relative energy requirements of primary versus secondary production. This provides a system-level perspective that moves beyond quantification to examine how structural parameters shape circularity outcomes. The analysis also considers the implications of increased circularity for industrial energy demand and emissions, linking material flow dynamics to decarbonisation potential. The overarching aim is to identify the conditions under which circularity can function as an effective resource efficiency and emissions reduction strategy, supporting the development of a more resilient and low-carbon industrial system in the UK. This approach advances a methodological contribution by demonstrating how scenario-based circularity assessment can be used to interrogate the limits and opportunities of material recovery at the sectoral scale.

2. Methodology

This section outlines the analytical framework used to assess material circularity and its implications for energy demand and emissions across the UK's foundation industries of aluminium, lead, steel, glass, and paper. The assessment focuses on quantifying the potential impact of circularity measures within production systems rather than across full product lifecycles. Fig. 1 summarises the framework adopted in this study. It integrates the definition of *Baseline* conditions and two scenarios (*Circular* and *Practical Limit*), calculation of the circularity index, adjustment of material flows through mass balance, and the subsequent evaluation of energy use, emissions, and domestic supply capacity.

Data were compiled through a structured process to ensure transparency, consistency, and reproducibility. Material flows, recovery rates, and energy intensities were sourced primarily from national statistical datasets and were supplemented with peer-reviewed studies and sectoral reports. When multiple values were available, national datasets were prioritised unless more recent or sector-specific sources offered better representativeness. Any discrepancies were reconciled through triangulation to maintain traceability across assumptions and scenarios.

The system boundary is confined to manufacturing-stage material flows and energy requirements. Use-phase dynamics and changes in in-use stocks were excluded, as the objective is to examine production-based circularity potential rather than whole-life system performance. The following subsections provide detailed descriptions of each component of the framework and its implementation.

2.1. Material circularity

The initial assessment of material circularity is conducted using the *Baseline* scenario, defined as the current state in the UK. The *Circular* scenario represents the potential level of material circularity achievable for specific materials within the UK's foundation industries. We chose the following materials for the material circularity analysis, and their primary sources are indicated below. Detailed numerical data is available in Section 2 of the SI.

Aluminium: In 2019, producing aluminium from mine extraction to cast house required 186 MJ kg^{-1} of primary energy (IAI, 2025). Reported values for primary production from a gate-to-gate perspective range between 50 MJ kg^{-1} to 70 MJ kg^{-1} (WEC, 2024a; IEA, 2020), while recycled aluminium requires only 8.3 MJ kg^{-1}, representing a reduction of 90 % to 95 % (IAI, 2025). Evidence from the European sector aligns with this order of magnitude, indicating that recycling consumes about 5 % of the energy required for primary production (EuropeanAluminium, 2024). These values provide a useful reference when considering best practice benchmarks, where the energy intensity for primary aluminium production is 44.3 MJ kg^{-1}, and for secondary production 2 MJ kg^{-1} (with a common range of 2 MJ kg^{-1} to 9 MJ kg^{-1}) (Hydro, 2019; Cusano et al., 2017). The energy intensity for the UK is assumed based on data reported in Bolson et al. (2025). The UK and worldwide material flows are extracted from WBS (2020), BGS (2022). For the circular scenario, it is assumed that the recovered material is processed in the UK and that there are no technical limitations for using this material, which aligns with the report *Action Plan for Aluminium in a Circular Economy*'s position on domestic recyclability (Runton and Pilgrim, 2023). Losses during recovery are assumed to be 10 %, but are dependent on scrap quality, with this value reported in literature around 5 % (Gast et al., 2022).

Lead: Best practice energy intensity for primary production is 4 MJ kg^{-1} and for secondary production is 3 MJ kg^{-1} (Cusano et al., 2017). The UK and worldwide material flows are extracted from WBS (2020), BGS (2022), Klochko (2025). Global performance for energy intensity is collected from Cusano et al. (2017), Norgate and Rankin (2002). Energy intensity in the UK is reported in Bolson et al. (2025). For the circular scenario, recovered material is assumed to be processed in the UK, with no technical limitations on its use. This is supported by the efficiency and environmental performance of the lead recycling process, particularly for lead–acid batteries, which achieve a recycling rate of 97 % (Seban et al., 2020), alongside advances in minimising environmental impacts through new technologies (Li et al., 2019). The process performance and end-of-life treatment are further evidenced by a cradle-to-grave life cycle assessment of an industrial lead–acid battery based on primary industrial data (Jasper et al., 2025). Losses during recovery are assumed as 10 % (Zhang et al., 2016; Global Recycling, 2023).

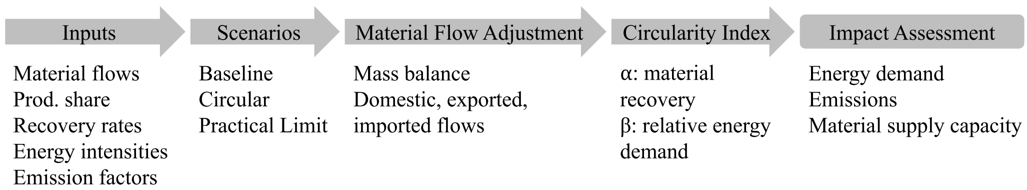

Fig. 1. Analytical framework used to evaluate material circularity and its impacts. The framework integrates baseline data inputs, scenario definition (*Baseline*, *Circular*, and *Practical Limit*), calculation of the circularity index ($CI = \alpha \times \beta$), material flow adjustment through mass balance, and assessment of energy demand, emissions, and domestic supply.

Steel: Best practice energy intensity for primary production is 14.8 MJ kg^{-1} and for secondary production is 2.6 MJ kg^{-1} (UNIDO, 2014). Global energy intensity for steel production was taken as 21.4 MJ kg^{-1}, using 2019 as the baseline year. For reference, the average value reported for 2022 is 20.99 MJ kg^{-1} (IEA, 2021; WorldSteel, 2024). The energy intensity for the UK was taken from (Bolson et al., 2025). Route-specific values for cross-checking are summarised in WEC (2024b). The UK and worldwide material flows are extracted from WBS (2020), BGS (2022). For the circular scenario, it is assumed that the recovered material is processed in the UK and no technical limitation is found for material use, an assumption conditional on advances in current technologies not being economically viable at present (Allwood et al., 2019). Losses during recovery are assumed to be 5 %, but are dependent on scrap quality, with this value reported in literature as up to 15 % (Gast et al., 2022).

Glass: Best practice energy intensity for primary production is 5.00 MJ kg^{-1} and for secondary is 3.70 MJ kg^{-1} (Bianca Maria et al., 2013). The global share of recovered glass is taken from Harder (2018). In the case of glass, there is no clear difference between processes for primary and secondary manufacturing; we allocate the recovered material as secondary production. As a rule of thumb, a reduction of approximately 2.5 % to 3 % in melting energy is achieved for every additional 10 % of cullet incorporated (AGC, 2025; Miserocchi et al., 2024). For the UK, the material flows, recovered materials, waste streams, and final destination are extracted from Hartwell et al. (2022), British Glass (2021), DEFRA-UK (2023), and energy intensity is taken from (Bolson et al., 2025). The circularity scenario estimates for the UK, are based on the data reported by Day (2023), that estimates 1.7 Mt of required glass for recycling. For the balance of import/export materials, trade data was used for Ref. (ONS, 2023b,a). Losses during recovery are assumed to be 10 %, based on reported data for glass waste flows and recycling processes (DEFRA-UK, 2023; Dyer, 2014).

Paper: Best practice energy intensity for primary production is 7.92 MJ kg^{-1} and for secondary production is 5.04 MJ kg^{-1} (Suhr et al., 2015). Global and UK material flows are collected from BIR (2021). The energy intensity of primary and secondary production is based on data from IEA (2022), incorporating sectoral progress and technological advancements reported in IEA (2024), EPRC (2025). For the UK, energy intensity is taken from (Bolson et al., 2025), apparent consumption is10 Mt and recovered material fluctuates around 70 % (CPI, 2023; Forest Research, 2018), while production data was from Forest Research (2022), CPI (2021). The breakdown between non-recovered and material that remains in stock is based on the waste flows reported by DEFRA-UK (2023). For the circularity scenario, an increase in packaging paper production is assumed to match the current consumption of 5.8 Mt (CPI, 2023). Losses during recovery are assumed to be 20 %, which aligns with other studies (Gast et al., 2022).

Table 1 summarises the values used in this study for Global and UK production. At the global level, the material flows for consumption and production are assumed to be identical. Given our focus on global best practices, this serves as a benchmark for the UK.

In this study, 'Global' refers to averages of energy intensities, material production, and recycling, derived from country-level data across diverse geographic, technological, and economic contexts. As shown in Table 1, these averages are calculated by weighting national figures by production and accounting for trade flows, providing a holistic view of material use and recycling. Similar methodologies are employed in Cusano et al. (2017), IEA (2020), Norgate and Rankin (2002), IEA (2021), with variations in data handling.

In this study, the term 'Best Practice' refers to performance levels that have already been demonstrated at an industrial scale, rather than theoretical or experimental efficiencies. It encompasses commercially mature technologies and process configurations that represent the upper range of current practice within each sector. These benchmarks are typically identified through technical surveys, industry assessments, and empirical case studies. For example, the US Department of Energy bandwidth studies (DoE-US, 2015; DoE - US, 2017) and the EU Best Available Techniques (BAT) reference documents (Suhr et al., 2015; Bianca Maria et al., 2013; Cusano et al., 2017) provide documented ranges for achievable energy and material performance across multiple industries. In the Practical Limit scenario, we use these demonstrated values to define what is technically attainable without assuming transformative system redesign. These values should be interpreted as indicative of feasible directional change rather than as predictive of uniform sector-wide outcomes.

2.2. Circularity index

The circularity index (CI) is based on the framework introduced by Cullen (2017). Eq. (1) provides the main expression and a breakdown of the principal components:

$$
\begin{aligned}
&CI = \alpha \times \beta \\
&\alpha = \frac{\text{Recovered Material}}{\text{Total Material Demand}} \\
&\beta = 1 - \frac{\text{Sec. Prod. Energy Use}}{\text{Prim. Prod. Energy Use}}
\end{aligned}
\tag{1}
$$

α represents the fraction of material recovered compared to demand. β represents the proportional change in energy demand of secondary production relative to primary production.

The circularity index is calculated for the following scenarios:

- Baseline: represents the current UK proportion of recovered material and material demand, where only domestically recovered material in the UK is considered, and energy use is based on the current mix of primary and secondary production. The baseline scenario is also presented for a global context.
- Circular: assumes that all material available for recovery is effectively utilised and the current UK mix of primary and secondary production continues. This scenario is designed to probe the impact of changes in α on the circularity equation. This scenario reflects the material flows of the circular scenario presented in Section 2.1

Table 1
Summary of material flows, production, energy intensity and best practices for Global and the UK.

Material	Mat. Flows (Mt)		Prod. (%)		En. In. (MJ/kg)		Best P. (MJ/kg)	
	Prod.	Cons.	1st	2nd	1st	2nd	1st	2nd
Global								
Aluminium	–	–	66	34	51.00	5.10	44.30	2.00
Steel	–	–	71	29	21.40	5.20	14.80	2.60
Lead	–	–	61	39	4.50	4.00	4.00	3.00
Glass	–	–	79	21	8.00	5.00	5.00	3.70
Paper	–	–	42	58	26.70	17.00	7.92	5.04
UK								
Aluminium	0.19	0.33	21	79	52.20	5.22	–	–
Steel	7.20	9.90	79	21	17.50	4.00	–	–
Lead	0.33	0.28	52	48	4.70	3.70	–	–
Glass	3.50	3.50	69	31	7.67	5.75	–	–
Paper	3.85	10.00	31	69	17.30	11.00	–	–

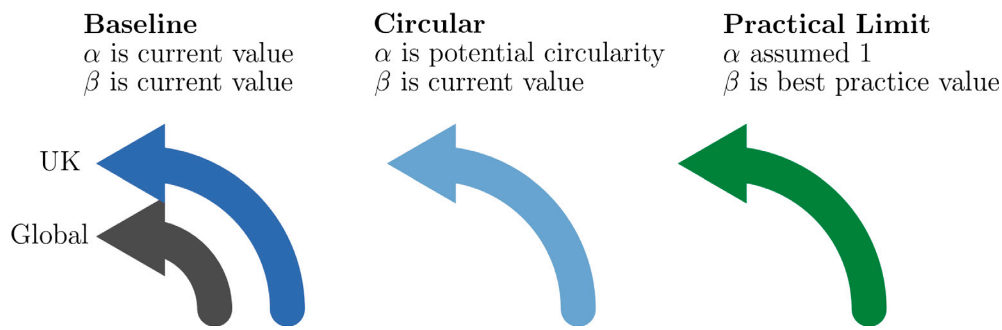

Fig. 2. Circularity index scenarios: *Baseline* scenario, α and β are based on current values, baseline scenarios are presented for the UK and Global as a benchmark. *Circular* shows the potential α that can be achieved with enhanced material circularity. *Practical Limit* shows perfect material circularity and assumes the best practice energy intensities for β.

- Practical limit: assumes that material demand shifts to be entirely sourced from recovered material (i.e. is entirely circular), and that the energy intensity of primary and secondary production shifts to best practice values.

The calculation of recoverable material is derived from the following mass balance:

$$\text{Recoverable Material} = \text{Consumed} + \text{Exported} - \text{Imported} \quad (2)$$

Consumed is the material utilised within the UK.

Fig. 2 illustrates the different scenarios covered in this study.

For the *Baseline*, a global scenario provides a benchmark for the UK. In the global context, α is derived from global primary and secondary production share ratios. In the UK scenario, α is determined by considering total material demand and secondary production. When direct values for energy intensity are unavailable, they are inferred by extrapolating from the sector's total energy intensity and primary production ratios, assuming they are similar to the reported best practice values within the sector.

In the context of this study, the circularity index is applied specifically as a diagnostic tool to evaluate how material substitution influences energy demand and associated carbon emissions within manufacturing systems. The scope is confined to production-related processes in the foundation industries, where energy intensity and recovery rates constitute the primary determinants of emissions. As such, the index is not used here as a comprehensive measure of circular economy performance, but as a targeted comparative framework aligned with the operational boundaries of the analysis.

2.3. Energy use and emissions

The study evaluates the impacts of material circularity on emissions and energy consumption at the UK level. The baseline scenario assumes the continuation of current practices and existing levels of material circularity. An analysis assesses the potential impact of increased material circularity, examining current manufacturing practices and a scenario incorporating best manufacturing practices. In the best practices scenario, the carbon intensity of energy remains constant. Table 1 presents the assumed sector-specific data on energy and carbon intensity.

3. Results

The results present insights into material circularity, the circularity index, and an assessment of how material circularity impacts energy use and emissions at the UK level.

3.1. Material circularity

Fig. 3 compares the *Baseline* and proposed *Circular* scenarios. Implementing material circularity reduces the exported material flows of aluminium, steel, and paper, but requires a substantial expansion of secondary production capacity within the UK. For glass, the priority is to increase material recovery, particularly for flat glass, where collection and end-of-life separation remain limited (Westbroek et al., 2021). Improving recovery rates is essential to enable higher secondary input and to reduce dependence on primary production. The *Others* category balances the flows and represents diverse sources, such as delays in the material cycle or products reaching end of life in different years.

Calculating material flows for glass and paper is challenging due to the way these products are used. For glass, while reliable data exists for recovered container glass, estimating flows for flat glass is more uncertain because of its long service life, with a large share likely remaining in stock for decades. For paper, end-of-life pathways diverge: tissue paper is discarded immediately after use, while paper used in books and documents may remain in stock for many years.

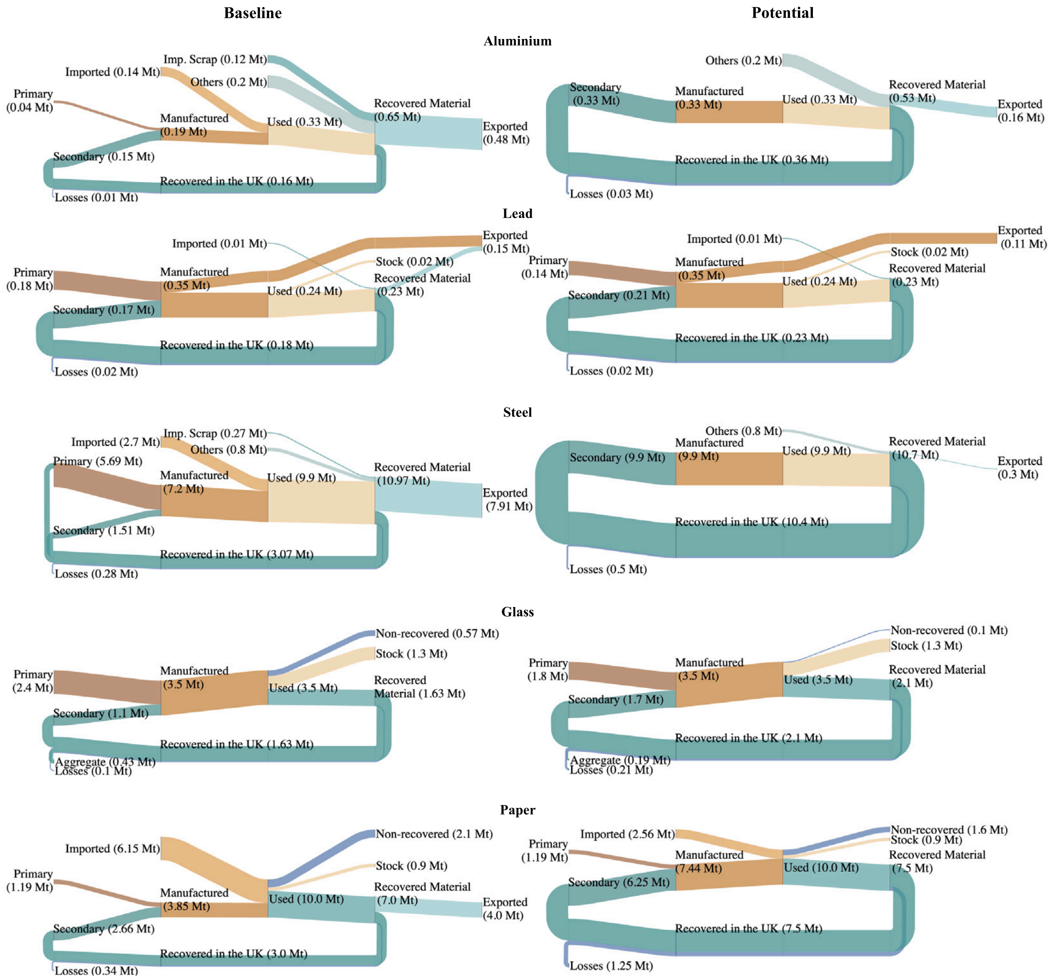

Fig. 3. Material *Baseline* and *Circularity* scenarios. The left column illustrates the *Baseline* scenario, while the right column shows the proposed *Circular* scenario, tailored for the UK. The *Circular* scenario does not account for potential constraints related to the technical substitution of materials and can thus be regarded as a best-case scenario.

3.2. Circularity index

The circularity index provides a more holistic measure of circularity by accounting for the energy required to recover materials. Fig. 4 presents the circularity index for the materials examined in this study. The black arrow indicates the global circularity index, while the dark blue arrow shows the UK baseline. The light blue arrow represents a scenario where material circularity in the UK reaches its full potential, and the green arrow reflects a practical limit that combines full material circularity with best-practice energy intensity. The global performance is a benchmark, and adopting best-practice energy intensity can bring the UK closer to this practical limit.

For aluminium and steel, the UK demonstrates potential to approach maximum feasible circularity thresholds while simultaneously offering opportunities for performance enhancement toward best-practice adoption. In contrast, lead, glass, and paper exhibit lower performance metrics that are constrained by material circularity limitations and are further compounded by marginal energy differentials between secondary and primary production processes, resulting in diminished overall performance scores.

In exploring the disparities in circularity among foundational materials, it is crucial to understand the inherent technical limitations and process efficiencies. The notable gap in the practical limits of circularity indices, ranging from 0.25 to 0.36 for lead, glass, and paper, compared to 0.82 to 0.95 for steel and aluminium, arises from fundamental differences in the recycling processes and the differences in the resultant energy savings. Steel and aluminium benefit from a switch to secondary production, yielding higher circularity rates due to more substantial energy intensity gains compared to primary production. In contrast, the relative energy intensity savings from recycling glass and paper are less pronounced, resulting in lower potential circularity indices. This discrepancy reflects the role of the circularity index in identifying which materials should be prioritised for recycling. However, material-level assessment remains essential to determine whether improvements are needed in collection and recycling rates or in the efficiency of secondary production processes. This is particularly relevant for materials with lower baseline circularity, where targeted interventions are required to increase overall circularity within the UK's foundation industries.

3.3. Impacts of material circularity on energy and emissions

Fig. 5(a) illustrates the primary and secondary manufacturing share across different materials. The *Baseline* share is characterised by darker colours in the first column, while the *Circular* scenario is represented by lighter colours in the second column. In the *Circular* scenario, for the UK, aluminium and steel have the potential to shift towards reliance on secondary production. However, primary production remains predominant for the remaining materials, with primary glass

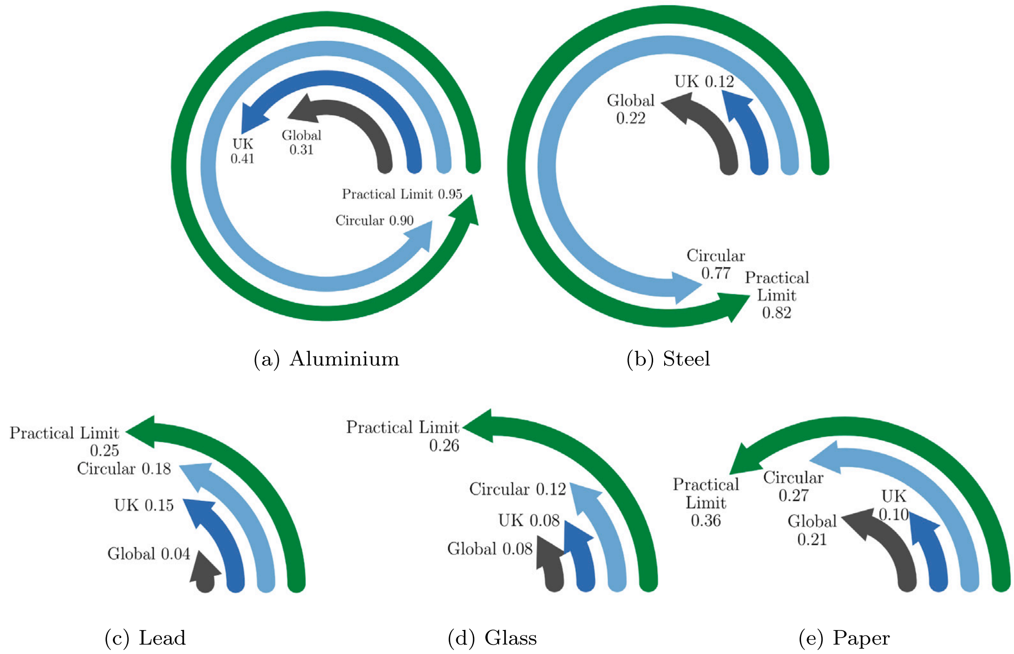

Fig. 4. Circularity index. Black and dark blue arrows show the global and UK *Baseline* scenarios, respectively; light blue shows the UK *Circular* scenario; green is the *Practical Limit* with full material circularity and best-practice energy intensities.

accounting for more than 50 % of total production share, due to flat glass manufacturing requirements.

Fig. 5(b) provides insights into the domestic material supply within the UK. The black dashed line indicates the manufacturing capability to meet the present material demand. The darker colour indicates the *Baseline* supply, while the lighter shade represents the potential capacity under the *Circular* scenario. This data underscores the opportunity for foundation industries to strengthen their capacity to manufacture and meet domestic demand, thereby enhancing the economy's resilience.

Fig. 5(c) shows CO_2 emissions for two scenarios: *Circular* which focuses on material circularity, and *Practical Limit* which extends the analysis by incorporating the adoption of best practices. Adopting circularity leads to a 42 % reduction in emissions, while combining circularity with best practice energy intensities yields a 69 % reduction.

Fig. 5(d) focuses on energy use, with the same two scenarios. Here, adopting circularity leads to a 17 % reduction in energy use, whereas integrating circularity with best practice energy intensity results in a substantial 56 % reduction in energy consumption.

Analysis of emissions and energy consumption reductions in the steel industry reveals a critical finding: implementing circular economy principles through increased secondary manufacturing represents the most significant intervention strategy for reducing emissions and energy consumption. Within the broader analytical framework, adopting best-practice energy and carbon intensity measures yields only marginal improvements. This phenomenon occurs because the majority of emissions and energy consumption are concentrated in primary production processes, rendering even suboptimal secondary production performance environmentally superior to primary production pathways. A similar trend would be expected for aluminium; however, with 79 % of UK production already sourced from secondary material, most of the major savings have already been realised.

A distinct result emerges for the paper sector, whereby implementing circularity increases domestically manufactured paper goods in the UK, resulting in almost twice the production capacity shown in the baseline. This results in domestic emissions and energy use shifting from overseas to the UK. However, a circular approach coupled with implementing best practices leads to significant energy savings and reduced overall emissions.

4. Discussion

This section assesses the implications of adopting the proposed circularity scenarios for manufacturing, energy use, and emissions in the UK's foundation industries, while also identifying barriers that may constrain their implementation. The results highlight the current configuration of material flows and the opportunities for enhanced circularity. As shown in Fig. 3, increasing material recovery and secondary production could bring the UK close to self-sufficiency in aluminium, lead, steel, and glass. This shift would deliver emissions reductions and also reinforce resource security and economic resilience.

The paper sector presents an exception, as shown in Fig. 3, where up to 20 % to 25 % imports would still be needed to satisfy domestic demand, even at circularity limits. This highlights the unique challenges in the paper recycling sector, which is constrained by technological and quality requirements that limit the use of recycled paper. These findings underscore the complex nature of transitioning to a circular economy, where technological innovation and policy reforms are crucial in addressing the current limitations to achieving full material circularity. The particular case of paper, diverging from the circular potential of other materials, emphasises the need for dedicated research and development to understand and overcome this gap. It reinforces the importance of a differentiated approach to circularity that recognises and addresses the specific challenges of each material.

Fig. 4 illustrates how the implementation of a circular economy delivers combined benefits for material recovery and energy efficiency. The circularity index shows that aluminium and steel achieve the highest performance, as both exhibit strong recovery potential and significant energy savings when shifting from primary to secondary production. These advantages result in circularity indices approaching the practical limit under best-practice conditions. In contrast, lead, glass, and paper display more constrained outcomes. For lead, high existing recycling rates narrow the scope for further improvement. Glass is limited by the technical challenges of recovering flat glass and by relatively modest energy savings in remelting compared to primary production. Paper exhibits even lower gains due to quality losses during recycling and the smaller differential between primary and secondary energy intensities. Together, these results emphasise

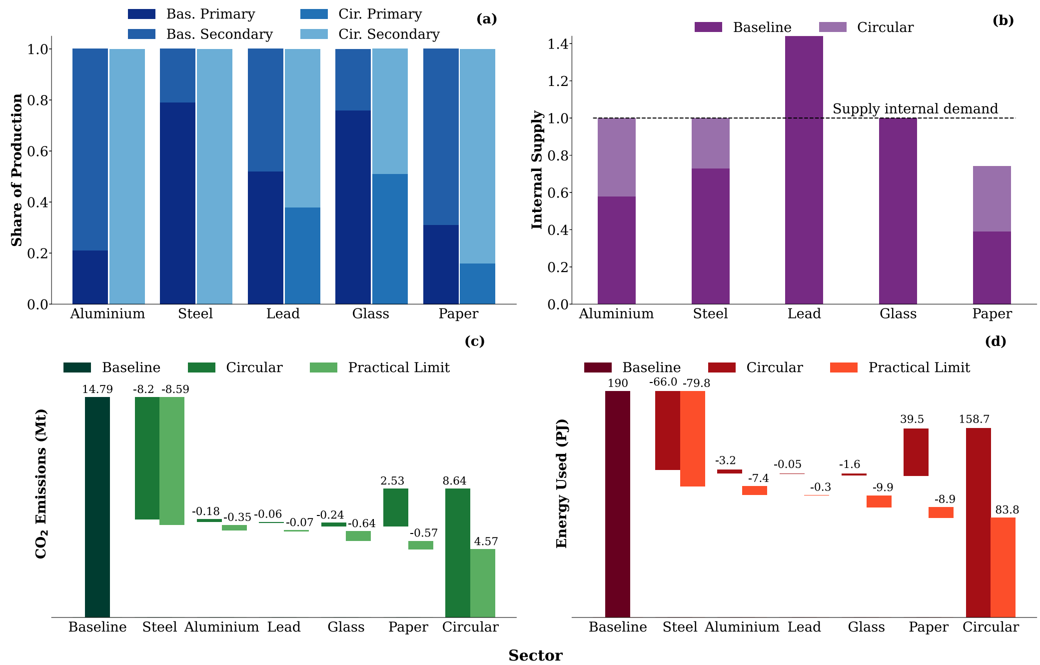

Fig. 5. Benefits of material circularity. *Baseline* scenario reflects current practices, *Circular* scenario focuses on material circularity, and the *Practical Limit* assumes adoption of best practices on top of material circularity. (a) Share of primary and secondary manufacturing. (b) Internal supply of materials. (c) CO_2 emissions and (d) energy use associated with the different scenarios and the reduction/gain by each sector.

that while aluminium and steel can anchor progress toward industrial circularity, achieving higher performance for lead, glass, and paper will require targeted technological innovation and policy interventions to overcome structural limitations.

Fig. 5 shows the implications of adopting material circularity for manufacturing capacity, energy use, and emissions in the UK's foundation industries. Across the scenarios, aluminium and steel demonstrate the largest gains, as increased reliance on secondary production sharply reduces energy demand and carbon emissions. These sectors highlight how circularity alone can drive decarbonisation, with best-practice energy intensities providing only incremental improvements beyond the benefits already achieved through secondary production. By contrast, glass and paper display more limited outcomes. For glass, circularity increases recovery; however, primary production remains dominant due to flat glass requirements, which restrict overall reductions. Paper presents a different challenge, as greater recycling boosts domestic production capacity, but shifts energy use and emissions from overseas to the UK. Only when best-practice energy intensities are combined with higher circularity, significant system-wide reductions emerge. Lead lies between these extremes, with high recycling rates already achieved and further improvements constrained by diminishing returns. Together, these results underscore that circularity can deliver substantial progress; however, maximising benefits across all materials requires the complementary adoption of best practices and targeted innovation to address material-specific barriers.

A related point concerns how future changes in material demand could be interpreted using the existing results. A useful way to explore this is by considering Figs. 3 and 5(b) together. Fig. 5(b) reflects current manufacturing capacity and illustrates how the *Circular* scenario operates under present demand levels, with lead as an exception due to its existing net exports. However, insights into the extent to which increased demand could be met in the future can be inferred from the Sankey diagram in Fig. 3. For aluminium and steel, the recovery of material currently exported, approximately 0.16 Mt and 0.3 Mt respectively, offers a degree of additional supply potential. In contrast, for lead, glass and paper, primary production is not fully displaced, implying that increases in demand would likely require further reliance on primary production unless alternative measures are taken. For lead, this could involve reducing exports, while for glass and paper it would entail accessing non recovered material currently lost from the system. An alternative pathway could involve importing additional secondary material, although this introduces challenges related to resource availability, international competition and market dependency.

An additional consideration concerns the implications of material circularity within the framework of policy instruments such as Emissions Trading Systems (ETS) and the Carbon Border Adjustment Mechanism (CBAM) (European Commission, 2023b,a; UK Parliament, 2022; UK Government, 2023). While ETS directly focuses on emissions reduction, CBAM addresses the carbon footprint associated with imports, protecting against potential competitive disadvantages from strict carbon policies. Implementing the identified measures to enhance material circularity can reduce the carbon footprint of UK industries, making them more competitive. Consequently, this elevation of competitiveness raises the standard for decarbonisation efforts in other countries.

4.1. Limitations on material circularity

The material circularity scenario outlined represents a best-case scenario. In this section, we aim to clarify potential barriers that could impede the achievement of the proposed levels of circularity. An initial concern lies in waste categorisation, a process acknowledged for its complexity and subjectivity in certain circumstances (DEFRA-UK, 2023). This subjectivity, coupled with the complex nature of waste, complicates the determination of the recovery potential of resources. Availability alone does not guarantee recovery, as the quality control and practical feasibility conditions necessary to sustain circularity may not always be met.

Evaluating material circularity becomes more complex when international trade is taken into account, as it requires tracking multiple interconnected material flows. This complexity stems from intricate global supply chains and inconsistent product classification systems, which make it challenging to trace materials back to their foundational industries. Materials embedded within manufactured goods can easily be overlooked in the analysis, particularly when data on material composition percentages is unavailable. Consider the following example: when the UK imports food or beverages in glass containers, the embedded glass content is not captured in raw material flow statistics; yet, this glass eventually enters the domestic waste stream as a recoverable material. This tracking challenge applies across numerous traded goods entering and leaving the economy.

This study operates under the assumption that reducing the import of goods is the primary focus. However, it is important to recognise that this assumption is only realistic for goods that are currently produced domestically or have viable domestic production potential. In practice, complete reliance on secondary material production is infeasible due to material losses and degradation in material quality during use (Cullen, 2017). A portion of materials must inevitably be sourced from primary production to compensate for these losses and maintain material quality. The strategic and political ramifications of complete dependence on secondary sources should be considered, as diversification of supply chains and the cultivation of strategic partnerships to manage demand volatility and ensure a resilient supply (Garvey et al., 2022; Daehn et al., 2017). Sourcing materials from a balance of primary and secondary sources helps mitigate against technical and material quality issues while accommodating broader economic and security concerns.

While the comparative framework captures system-wide trends, the practical strategies, constraints and circularity pathways differ across materials. These material-specific details, including technological, policy and flow considerations, are further elaborated in Section 1 of the Supplementary Information.

4.2. Observations on the material circularity index

The circularity index introduced by Cullen (2017) provides a practical and physically grounded means of assessing circularity through the relationship between material flows, energy demand, and their carbon emissions implications. Its formulation in fundamental units enables transparent comparison across sectors and aligns with the manufacturing-focused system boundary adopted in this study.

Subsequent work, such as Carmona et al. (2023), has advanced the index by incorporating broader system dynamics, including the fate of materials once they leave the value chain and the integration of environmental impact proxies. While these developments are valuable for whole-life system modelling, they extend beyond the manufacturing phase and introduce additional layers of complexity that were intentionally excluded here.

In this analysis, the original index is maintained because it directly captures the two parameters most relevant to decarbonisation in the foundation industries: the substitution of secondary for primary material and the corresponding shift in energy intensity. The aim is not to provide a holistic measure of circular economy performance, but to quantify the manufacturing-stage implications of material recirculation using a consistent and comparable framework. Although we acknowledge the importance of wider environmental metrics, energy and material flows remain the primary determinants of emissions in production systems and therefore form the most appropriate basis for the scenarios assessed.

5. Conclusions

This study examines the potential for material circularity within the UK, focusing on strategically selected materials. The findings demonstrate that enhanced material circularity can deliver substantial benefits for the UK, strengthening economic resilience and advancing sustainability objectives through significant reductions in emissions and energy consumption.

By employing the circularity index, we extend our assessment beyond material circularity alone, enabling a comprehensive evaluation of energy requirements for delivering circularity. This analysis is invaluable from a manufacturing perspective, as it permits an objective performance assessment of best practices and the current global average.

However, while this study presents a best-case scenario for material circularity, it also identifies potential limitations that may impede the attainment of the targeted objectives. Challenges related to material quality and the specific technical requirements of certain products require maintaining a minimum input of primary manufacturing. These considerations highlight the need for a balanced approach to material circularity initiatives in the UK.

While the present study focuses on fundamental resource flows, future research may explore the socioeconomic benefits and assess the economic viability of capital expenditure (CAPEX) and operating expenditure (OPEX) associated with these circularity pathways. Additionally, the influence of initiatives such as Emissions Trading Systems (ETS) and the Carbon Border Adjustment Mechanism (CBAM) could be investigated. Such work is essential for translating these technical potentials into actionable industrial and policy strategies.

CRediT authorship contribution statement

Natanael Bolson: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Masoud Ahmadinia:** Writing – review & editing, Writing – original draft, Validation, Resources, Investigation, Formal analysis. **Rossi Setchi:** Writing – review & editing, Validation, Supervision, Resources, Formal analysis. **Sam Evans:** Writing – review & editing, Validation, Supervision, Resources, Formal analysis. **Jonathan Cullen:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jonathan Cullen reports a relationship with Neutreeno, which includes employment. Neutreeno is a Cambridge-based start-up that is engineering a new paradigm for decarbonisation. The other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.resconrec.2025.108728.

Data availability

Data will be made available on request.

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