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Whittle, J.W. orcid.org/0000-0001-5792-1140, Rihner, M.C.S. orcid.org/0009-0007-7757-2778, Hafez, H. orcid.org/0009-0004-8917-680X et al. (4 more authors) (2026) From symbiosis to scarcity: evaluating disruption associated with decarbonisation to circular waste materials between the UK cement and steel sectors. Resources, Conservation and Recycling, 224. 108560. ISSN: 0921-3449

https://doi.org/10.1016/j.resconrec.2025.108560

Author accepted manuscript for the following research, published in *Resources, Conservation, and Recycling, Volume 224* on *1 January 2026*. Originally accepted for publication on *16 August 2025*. DOI: https://doi.org/10.1016/j.resconrec.2025.108560

Title
From symbiosis to scarcity: Evaluating disruption associated with decarbonisation to circular waste materials between the UK cement and steel sectors

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Attribution
J.W. Whittle Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Data Curation, Visualization, Writing - Original Draft Preparation **M.C.S. Rihner** Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Data Curation, Visualization, Writing - Original Draft Preparation **H. Hafez** Conceptualization, Supervision, Writing - Review & Editing **R.M. Eufrasio Espinosa** Formal Analysis, Writing - Review & Editing **D.I. Fletcher** Supervision, Writing - Review & Editing, Funding Acquisition **B. Walkley** Supervision, Writing - Review & Editing, Funding Acquisition **L.S.C. Koh** Supervision, Writing - Review & Editing, Funding Acquisition, Project Administration

Keywords
Steel, cement, decarbonisation, manufacturing, supply chain, net zero

Highlights

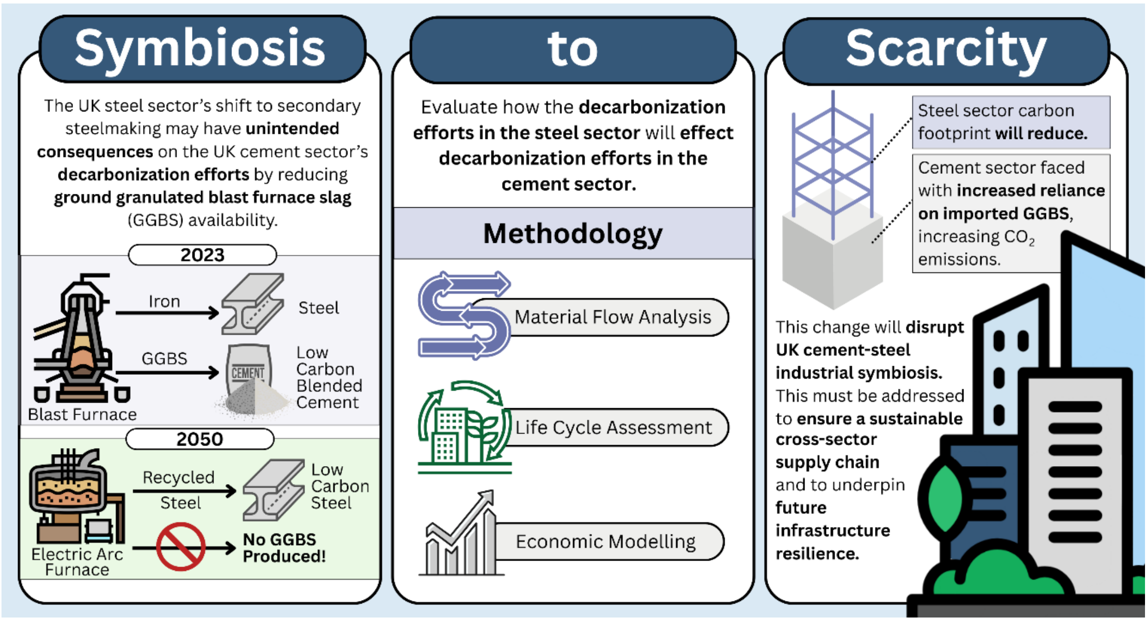
- Decarbonisation pathways will disrupt UK cement-steel industrial symbiosis
- UK steel sector is expected to reach decarbonisation targets through transition to secondary steelmaking
- Shortages in ground granulated blast furnace slag supply due to domestic and global steelmaking shifts could limit the availability of low carbon cement
- Low carbon supplementary cementitious materials threatened by reliance on imports

Glossary

BaU: business-as-usual
BF-BOF: blast furnace - basic oxygen furnace
BFS: blast furnace slag
CC: calcined clays
CCUS: carbon capture, usage and storage
CO_2: carbon dioxide
EAF: electric arc furnace
FA: fly ash
GGBS: ground granulated blast furnace slag
IEA: International Energy Agency
LC^3: limestone calcined clay cement
LCA: life cycle assessment
MFA: material flow analysis
PC: Portland cement
SCM: supplementary cementitious material
SDS: Sustainable Development Scenario
STEPS: Stated Policies Scenario
UK: United Kingdom

Abstract

The UK cement and steel industries are decarbonising rapidly to meet net-zero targets. This study explores the unintended consequences of these efforts, particularly the potential disruption of industrial symbiosis between sectors. Cement production in the UK increasingly relies on ground granulated blast furnace slag (GGBS), a low carbon supplementary cementitious material (SCM). However, the shift from primary to secondary steelmaking threatens domestic GGBS supply. This research uses material flow analysis, life cycle assessment, and economic modelling to evaluate future GGBS availability, carbon intensities, and supply chain vulnerabilities. Findings indicate that although the steel sector is expected to reduce its environmental impact, this will cause the cement sector to face a potential shortfall in domestic SCMs, increasing reliance on imports through cross-sector decoupling and stagnation of decarbonisation. Addressing these challenges is vital to ensure a sustainable cross-sector supply chain and support future UK and global infrastructure resilience.



1. Introduction

Cement and steel are fundamental to modern infrastructure, making them the two most readily consumed materials with over 4 Gt of cement [1] and nearly 2 Gt steel produced globally in 2023 [2]. However, these industries have significant environmental impacts due to their energy- and process- intensive processes [3, 4]. In 2023, both sectors generated a combined 5 Gt of direct carbon dioxide (CO_2) emissions - 15% of total anthropogenic CO_2 emissions released annually [5-7]. This has intensified pressures to decarbonise using innovative solutions and mechanisms to meet net-zero targets by 2050 [3], including an increased use of the circular economy and industrial clustering concepts [8]. These can both be underpinned by the theoretical concept and practical application of industrial symbiosis.

1.1. Industrial Symbiosis

Industrial symbiosis can be interpreted in different ways [9], but is broadly defined as the long-term engagement between different companies or industries in the physical exchange of materials, by-products, energy, or information [9-12]. Against the background of decarbonisation, this is a vital mechanism to help reduce the environmental impact of one or multiple parties. This can be achieved through converting by-product streams in one industry to form a supply chain which supplements or replaces raw and virgin materials within an industrial process typically within a separate industry [13], avoiding early disposal of otherwise useful material [14], and preserving natural resources [15]. Industrial symbiosis also has the potential to unlock further economic and social benefits beyond the parties directly involved [8, 9]. There are innumerable literature examples of industrial symbiosis at range of scales and industries including symbiosis of water sources across all industries in a single city [16], symbiosis between mushroom farmers and beer brewers [17], and synergy in regional minerals mining and production [18].

1.2. Symbiosis between cement and steel

An interesting, and long standing, global application of industrial symbiosis is between the steel and cement sectors. There are several examples of symbiosis including utilising end of life steel scrap from finished construction grade cement products as a steel scrap source [19] and the use of dusts from both industries as carbonation materials [20]. However, by far the most common is the use of ground granulated blast furnace slag (GGBS). This is created as a by-product of the steelmaking process and used within the cement manufacturing process, a symbiosis summarised in Figure 1. Initially studied for its potential as a performance enhancing material within cement, the relationship between both sectors has shifted significantly to a focus on the reduction of environmental impact within both through repurposing of this material [21-23]. However, no literature can be found which assesses the potential effects of a change in the production landscape of both sectors due to global decarbonisation efforts on this long-standing symbiotic relationship.

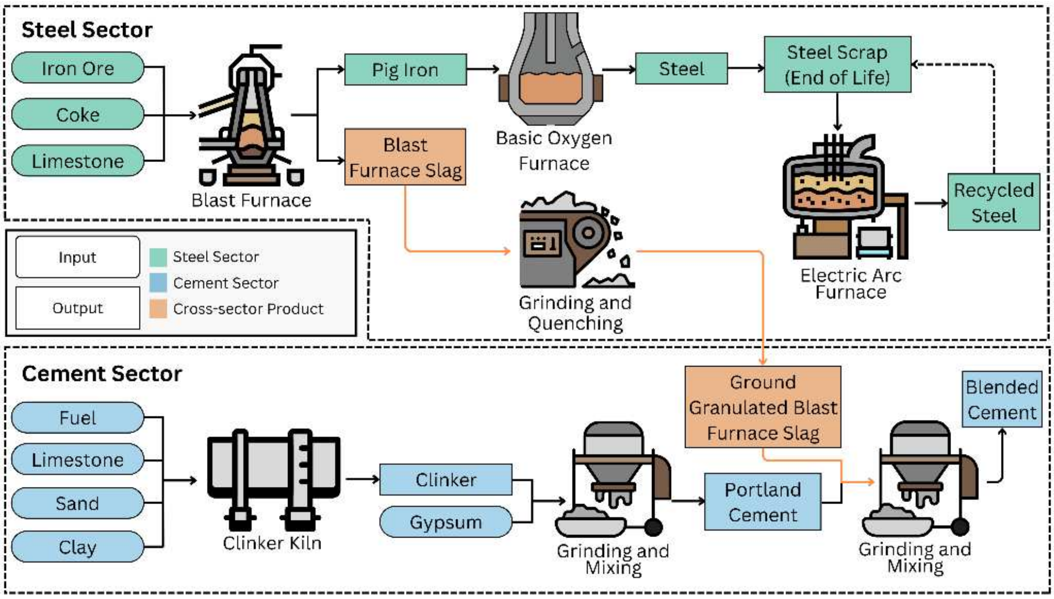


Figure 1: Cement and steel manufacturing industrial symbiosis process flowchart.

The CO_2 emissions associated with the production of cement are mostly (in excess of 90%) caused by the production of clinker, which is the main constituent of cement [24]. Clinker is a mixture of limestone and other materials that are heated within a kiln then subsequently ground into a fine material for use within cement [24], as shown in Figure 1. Globally, the clinker-to-cement ratio, also known as the clinker factor (i.e. the percentage of clinker used within a given cement mix), is approximately 0.70 [25]. Although direct circularity is possible within the cement industry [26] it is challenging [27]. Therefore, a major strategy to reduce CO_2 emissions is replacing ordinary Portland cement (PC) with cement blends that contain a greater proportion of supplementary cementitious materials (SCMs), thus reducing clinker use. These can also enhance performance [28, 29]. Commonly utilised SCMs include GGBS [28], limestone [30], calcined clays (CC) [31], and fly ash (FA) from coal combustion [28, 32]. However, SCM application varies significantly by region. Despite historically high usage and substitution rates within cement manufacture [33, 34], the United Kingdom's (UK) early transition to cleaner energy sources [35-37] has resulted in a decline of FA availability and usage as a SCM, while legacy FA recovery remains uncertain [38]. While limestone calcined clay cement (LC^3) has shown technical success elsewhere [30], poor reactivity of local CC stocks [39] and the limited availability of limestone fines [40, 41] has challenged its use within the UK. As a result, GGBS is the UK's most widely used SCM [2, 41, 42]. GGBS is a fine, glassy substance produced by grinding and rapidly cooling molten blast furnace slag (BFS); a co-product of the iron smelting process within the primary blast furnace-basic oxygen furnace (BF-BOF, or BOF) steelmaking route [43] as shown in Figure 1. Consequently, UK cement decarbonisation is largely dependent on a symbiotic relationship with the steel industry. However, falling domestic steel production, over the past decade, means that the UK has begun relying heavily on GGBS imports to meet industrial demand [2, 42]. Given this, existing literature suggests limiting GGBS use to 20% in the UK for performance and material availability reasons [44]. Maintaining this rate is preferrable, but industrial shifts may result in further GGBS shortages.

The remaining major steel manufacturers in the UK, which currently utilise primary steelmaking, aim to reduce emissions by 85% by 2035 and reach net-zero by 2050 [45]. In the short to medium term this will be achieved through process decarbonisation of primary steelmaking, making use of emerging technologies including hydrogen, carbon capture, usage, and storage (CCUS), and alternative materials [45]. However, all manufacturers expect to completely transition to secondary steelmaking routes, utilising electric arc furnaces (EAF), by 2050 at the latest [46, 47].

This transition process is already underway at one of the two remaining major primary steelmaking sites [48]. Secondary steelmaking relies on implementation of a circular economy within the steel sector, with scrap material becoming the primary iron or steel source. This in turn, significantly reduces the material's environmental impact. Although there are technical [49, 50], regulatory [51], and practical [51, 52] challenges, this may occur much sooner [53]. However, these furnaces do not produce the same co-products as the BOF route. Furthermore, this transition toward cleaner steelmaking is likely to occur on a global scale, albeit at different rates [54]. As a result, the availability of steel, cement, and associated co-products will change, affecting the economic value of each material, and thus industrial decision-making [55, 56]. Changes in value could mean that GGBS is no longer economically viable or environmentally sustainable to continue importing into the UK, resulting in a major shift in the balance of global supply chains - increasing the reliance on SCM imports and potentially an increase in cement-related CO_2 emissions.

This relatively unique position of SCM use, type of steelmaking, and ambitious net-zero related targets for heavy industry make the UK a perfect case study to assess the potential unintended consequences of decarbonisation on industrial symbiosis, which has not been seen previously in literature. This paper aims to conduct a novel study into how shifts in the steel industry, both in the UK and globally, will impact UK cement sector decarbonisation. To achieve this, several steel and cement transition scenarios will be explored, predictions will be made on material economic value, and the environmental impact of GGBS will be assessed. The findings will provide insights into the likely carbon intensity and emissions of both sectors in 2050, aiding informed decision-making and mitigate cross-sector supply chain disruption and risk. This study is structured as follows: Section 2 describes the study methodology, Section 3 presents study findings, and Section 4 discusses the results presented in Section 3, and Section 5 summarises key insights and their implications on steel-cement symbiosis.

2. Materials and Methods

2.1. Outline

To evaluate the impact of decarbonisation strategies between the synergistic steel and cement sectors, as outlined in Figure 1, the carbon emissions produced in each sector must first be assessed. The carbon emissions associated with any given product are defined by the volume of product consumed and its carbon intensity. Therefore, to determine the cement and steel sector's annual consumption volumes and embodied carbon, a material flow analysis and life cycle assessment were performed, respectively. This is a methodology combination which has been found to yield more robust and transparent results, compared to utilising these methods independently [57]. The methodology outline, in addition to the flow of data, is described in Figure 2.

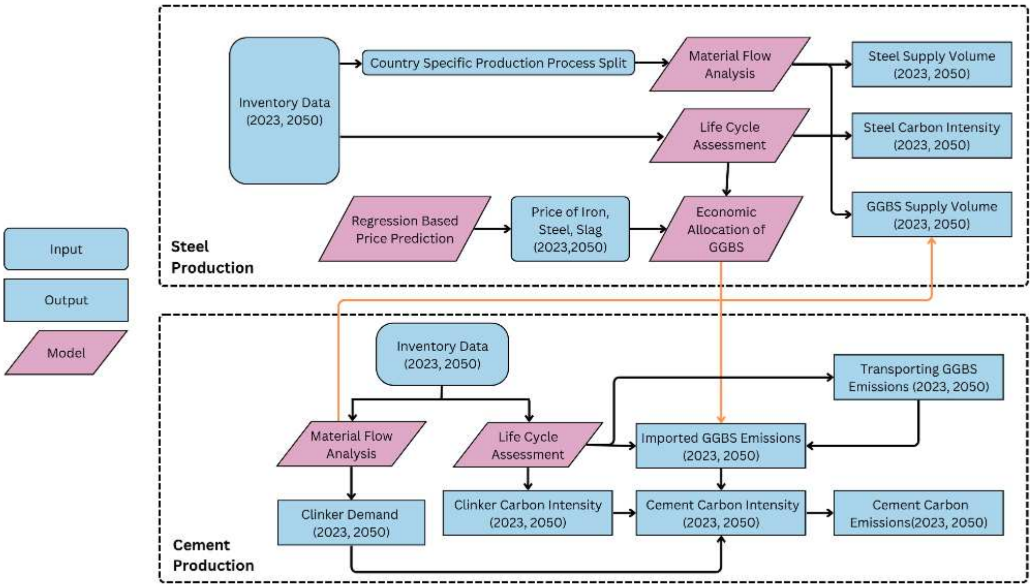


Figure 2: Methodology outline.

2.2. Scenarios

The baseline year for this study is 2023 as this is the most recent year for which complete data is available. Alongside this, several 2050 scenarios were considered which focus on key transition strategies in each sector: the shift from primary to secondary steelmaking in the steel sector and the increased use of SCMs in the cement sector. These are outlined in Table 1.

Global cementitious material demand is expected to remain constant until 2050, with production rising in the Global South but declining in the Global North [58, 59]. However, in a drive to reduce the emissions associated with cement production, the clinker factor will decrease regionally, reducing clinker demand while increasing SCM consumption. In the UK, the current clinker factor is 0.70 [41], but must drop to 0.50 to achieve net-zero targets [60]. It is also assumed that while the percentage of GGBS used will remain constant to 2050 (17% of the UK cement mix), the consumption of other SCMs will shift from FA to CC and limestone fines due to other industrial shifts.

Similarly, global steel production is expected to continue to grow by 3.5% annually to approximately 1960 Mt by 2050 [2], but steelmaking transition pathways remain unclear outside of a small number of European countries. Accordingly, the UK has been modelled as undertaking a complete shift (100%) from BOF to EAF steelmaking. This means that all steel manufactured in the UK will be produced using secondary steelmaking methods by 2050, though it is likely that this will occur much sooner. Other steel producing countries are the subject of a 25 to 75% shift in route toward EAF steelmaking to assess global sensitivity in absence of reliable transition pathway plans - particularly with respect to GGBS availability. China (90.1% BOF), India (43.6% BOF), and Japan (71.1% BOF) currently produce a combined 65% of global steel [61] and are likely to remain the largest by market share. Therefore, it is assumed that each country assessed (UK, China, India, and Japan) retains the same global production share through each scenario, but the total volume of steel produced in 2050 by BOF decreases by the percentage noted. A global average has also been assessed to understand regional disparities in production. Each country is assumed to satisfy domestic scrap demand to enable sufficient high-quality steel scrap availability [51].

Table 1: Steel and cement transition scenarios from baseline to 2050.

Country / Region	2050 Transition Scenario	Cement Transition (Clinker Factor)	Steel Transition (EAF Shift Percentage)
UK	Low	0.70 [62]	100%
	Medium	0.60	
	High	0.50 [60]	
China, India, Japan, Global Average	Low	0.71 [25]	25%
	Medium	0.63	50%
	High	0.55 [25, 63]	75%

Within the transition scenarios described the effect of different regional and sector specific future decarbonisation strategies have also been assessed. In both sectors, establishing current [61] and predicting future process energy intensity (GJ/tonne of product) is challenging as these values are affected by a multitude of technological, financial, and geopolitical issues. However, there are several common decarbonisation strategies, at various market readiness levels, that could contribute to the reduction of carbon emissions associated with material production. These include CCUS [64, 65], material efficiency [64], technology performance improvements (e.g. recycling concrete fines, or fitment of top-pressure recovery turbines) [64, 65], electrification [64], and use of alternative energy sources [64, 65]. The sector specific values for the decarbonisation potential are extracted from the IEA's Iron and Steel Roadmap pathways ('Stated Policies Scenario' (STEPS) and 'Sustainable Development Scenario' (SDS)) [64], and a recent UK cement market analysis [60] (Supplementary Information (SI), section S1 and S4). In order to contextualise the plans of both sectors, an additional business-as-usual (BaU) scenario has been included which does not see any process decarbonisation, but does consider the decarbonisation of regional electricity, material, and fuel in addition to the transition scenarios noted in Table 1.

2.3. Material Flow Analysis

To quantify the flow and stock of material within the cement and steel sectors, and therefore aggregate sectoral consumption volumes, a material flow analysis (MFA) was performed [66]. The flow of materials is summarised in Figure 1. All data was taken from publicly available regional and international reports [2, 25, 41, 61, 62], and secondary literature sources [67]. The defined system boundary is cradle-to-gate, which encompasses the annual consumption values of clinker, iron, GGBS, other SCMs (FA, CC, and limestone fines), cement, and steel. Downstream flows of finished products such as concrete and reinforced concrete elements were not considered.

2.4. Life Cycle Assessment

Life cycle assessment (LCA) is a computational tool which can provide a general perspective on the environmental impact of a product to support decision making [68, 69]. LCA is standardised by ISO14040 and ISO14044 [70, 71]. The first stage of any LCA is to define the goal. The goal of this LCA is to assess the carbon intensities associated with several products within the UK steel and cement sector including clinker, GGBS, cement, and steel. In line with this, several different scenarios were considered including different temporal (2023 and 2050), geographic (UK, China, India, Japan, global average), and transition scenarios as noted in Table 1. In an LCA, a study's scope is defined by three main components: the system boundary, functional unit, and allocation procedure [70]. The system boundary for this LCA is cradle-to-gate which includes raw material extraction (stage A1), the transportation of those raw materials to the factory (stage A2), as well as the processing and production of the product (stage A3) [72]. Since the study aims to assess the environmental impact of several products in which material function is not necessary, a mass declared unit (e.g. one kilogram) was selected for each product.

When assessing the carbon intensity of co-products, partially on a cross-sector level, special consideration must be given to the allocation procedure selected. ISO14040 defines allocation as the "partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems" [70]. Previous studies have found that within the cement and steel sector there is no clear consensus on how BFS (as well as other co-products) should be allocated within the LCA method [73, 74]. Each sector appears to favour different methods of allocation to best suit study goals which makes cross-sector comparison challenging; contradicting the core principles of LCA [72]. Therefore, in this study, both mass and economic allocation were considered when determining the carbon intensity of BFS (SI, section S5). The core method of producing GGBS is not expected to change, and so therefore the allocation by mass between products will not change between the baseline and 2050. Within the primary steelmaking route, BFS values per country are not typically reported, so a ratio of 0.28 tonnes of BFS produced per tonne of iron was assumed for all countries [75]. The exception to this is in the UK where no iron or BFS is produced in 2050, as defined in Table 1. Allocation by economic values however will change due to fluctuations of supply and demand, and therefore price, over time. By examining import and export trade flow data, the baseline global economic values for crude iron and GGBS were found to be £0.41/kg and £0.02/kg, respectively. In the UK, the export price of iron is significantly higher at £0.86/kg. Given the low supply and high demand for GGBS in the UK, the exporting price of the material is £0.18/kg [42]. To determine the 2050 economic values for both products, the price prediction methodology outlined in Section 2.5 was used.

Inventory analysis is the second stage of an LCA which includes the evaluation and collection of data required to fulfil the study's goal. Data has been compiled from a range of secondary sources through a top-down collection method, for use across and within each sector of analysis. Each source is as spatially, temporally, and technically relevant as possible. A summary of this is outlined below, but all data, detailed calculations, and sources can be found in the associated SI. For both the steel and cement carbon intensity calculations, the electricity and fuel emission factors were regionalised where possible to most accurately model disparities in decarbonisation pathways. All data and decarbonisation pathways are taken from government (UK GHG, China CF) or literature [54] sources (SI, section S2). The carbon intensity for both BOF and EAF steelmaking (kgCO_2eq/kg) (S_{CI}) is derived from electricity (kgCO_2eq/GJ) (E_{CF}), fuel emission factors (kgCO_2eq/GJ) (F_{EF}), the fuel mixture (including electricity) (%) (F_M), and steelmaking process energy intensity (GJ/kg) (S_{PE}) as noted in Equation 1.

$$S_{CI} = S_{PE} \times ((F_M \times F_{EF}) + (F_M \times E_{CF}))$$

Equation 1

The average steelmaking process energy intensity ranges from 19.39 to 14.00 GJ/tonne of steel (SI, Section S1). The fuel mixture used in each steelmaking process is likely to shift in favour of electricity driven, and more sustainable processes. Data supporting the aggregated fuel mixture consumption for each transition scenario is taken from WorldSteel [61] or IEA [64] (SI, section S3).

The carbon intensity of cement (kgCO_2eq/kg) (Ct_{CI}) in the UK is derived from the carbon intensity of clinker (kgCO_2eq/kg) (Cl_{CI}), the cement's clinker factor (C_F), the average carbon intensity of SCMs (kgCO_2eq/kg) (SCM_{CI}), the carbon intensity of GGBS (kgCO_2eq/kg) (G_{CI}), the cement's GGBS factor (i.e. the amount of GGBS used within a given cement mix) (G_F), the carbon intensity of the transport of both GGBS (kgCO_2eq/kg) (G_T) and clinker (kgCO_2eq/kg) (Cl_T), the electric energy required for indirect processes (GJ/kg) (EC_R), and the emission factor of electricity (kgCO_2eq/GJ) (EC_{EF}). This calculation is summarised in Equation 2.

$$Ct_{CI} = Cl_T + (Cl_{CI} \times C_F) + (SCM_{CI} \times (1 - (G_F + C_F)) + (G_{CI} \times (G_F)) + G_T + (EC_R \times EC_{EF})$$

Equation 2

The carbon intensity of the clinker component consists of process emissions occurring from calcination in the cement kiln and the carbon intensity of the kiln's fuel mix (SI, section S4). The clinker factor is noted in Table 1. The average SCM carbon intensity was determined by taking the mass ratio of all three other SCM types considered (limestone, CC, and FA) in addition to gypsum and multiplying each by their respective consumption volume and carbon intensity value. All these materials were assumed to have negligible transportation distances given current material stocks. To determine carbon intensity of GGBS, the same calculation procedure was applied as was done for the other SCMs.

In addition to the emissions arising from the clinker and GGBS production process, those arising from importation must also be accounted for. In the case of clinker, this includes clinker sold as a product and cement products containing clinker (e.g., CEM1). While countries that are in close proximity to the UK such as the Netherlands, Spain, Germany and France have consistently been some of the UK's largest exporters of GGBS, a shift to relying on slag exports from China, India, and Japan is likely due to pan-European decarbonisation targets [76]. This shift has already begun in the case of Japan. Since 2019, it has become one of the largest slag exporters to the UK with the country accounting for 22% of all UK GGBS imports annually. To determine the carbon intensity of transportation for the 2023 baseline scenario, a weighted average was taken between the top four exporting countries of each product. To account for regional production process differences, carbon intensity values for clinker and GGBS production were retrieved from literature sources for each of the four exporting countries considered. The processing of BFS into GGBS was assumed to take place in the country of origin and all slag imported into the UK is GGBS (SI, section S5). Transportation distances were determined using secondary data sources [77, 78] (SI, section S6). When assessing the impact of transportation in 2050, the top four exporters of clinker and cement products were assumed to be the same from the 2023 baseline. For GGBS however, several importation scenarios for 2050 were considered and are detailed in the interpretation step. Lastly, the electric energy required for indirect processes values were taken from secondary sources [25, 79].

In line with the study scope, embodied carbon is the only impact indicator analysed at the impact stage. The interpretation of the LCA results include examining several decarbonisation pathways in both the steel and cement sector. In addition, several transportation scenarios were considered for GGBS. For the baseline scenario, a weighted average between the top four GGBS importers (comprising 77% of all slag imports to the UK) was considered which include the Netherlands, Spain, France, and Japan. Six different importation scenarios were considered for 2050: (1) the 2023 GGBS import countries and their import ratios, (2) equal import from the assumed top three steel producers (China, India, and Japan), (3) all GGBS import from China, (4) all GGBS import from India, (5) all GGBS import from Japan, and (6) a global transport average. The global average scenario considers a weighted average based on the GGBS amount of the seven exporting countries assessed.

2.5. Economic Modelling

To perform a sensitivity analysis on the impact of the allocation method, the economic value of iron and GGBS in 2050 must be predicted. A robust, time series methodology was tailored to address the inherent volatility and inconsistencies in trade flow data [80, 81]. Outliers were removed to reduce variation in the dataset. An ARIMA [82] model was used to predict future trends and cyclical patterns, and the model was implemented in Python. The prediction provided insights into the long-term price movements of slag and steel up to 2050 (SI, section S7). Although regional differences were observed, the volatility of material production and value results in wide confidence intervals regardless of source. Therefore, the same changes in economic value of material were applied to all countries of interest to enable useful comparison.

3. Results

3.1. Material Flow Analysis

The results of each MFA conducted are shown in Figure 3a through Figure 3d, where Figure 3d shows the effects of a high transition in both sectors globally. The MFA of both the low and medium transition scenarios can be found in the SI (SI, section S8), but the numerical outcome of both analyses is discussed below. Examining the UK baseline (Figure 3a), it was determined that 7.5 Mt of steel and 15.24 Mt of cementitious materials are consumed annually. Although not directly relevant to the analysis, the UK exported 2.6 Mt, imported 4.5 Mt, and domestically produced 5.6 Mt of steel. This indicates that the trade of steel is broadly driven by specialisation of UK manufacturers in different steel grades and products but also highlights that the domestic circular economy in steel is fractured. Consequently, this may be limiting the domestic availability of sufficient high-quality grades of scrap as well as increasing UK reliance on complex global supply chain routes (in a similar parallel to the cement industry as noted below). Currently 1.1 Mt of UK steel is produced via EAF, however the expected complete shift to secondary steelmaking by 2050 (Figure 3b) will increase the UK global market share of EAF steel to 0.59-0.83%, depending on global trends (Figure 3d). China, India, and Japan are expected to remain dominant producers in 2050, accounting for at least 263 Mt of global EAF steel (37.5% of production). While the total consumption of cementitious materials is expected to stay constant to 2050, the reduction in clinker factor in the UK cement sector will increase demand for SCMs from 3.23-6.86 Mt, whilst reducing clinker demand from 10.74-7.62 Mt. This will reduce reliance on existing material sources (Spain, France, Algeria, and Ireland), but at least 2.54 Mt will still need to be imported. The assumption that GGBS demand will stay as a constant proportion of SCM use in the UK (17% of cement mix design) means the demand volume falls slightly to 2.59 Mt in 2050. This is a major supply chain risk to the sector, as the global demand for GGBS (366 Mt) will outstrip supply (274 Mt to 353 Mt available, depending on the transition scenario) due to increased SCM consumption (a 62% rise) as global clinker rates drop and BOF steelmaking decreases globally as illustrated in Figure 3d. As shown in Figure 3c, the consumption of CC (2.13 Mt) and limestone filler (2.13 Mt) also rises dramatically in the UK (accounting 62% of SCMs by 2050). However, this is also true globally which will demand approximately 871 Mt of each by 2050. Although the analysis of these materials is not the core focus of this study, this will compound issues surrounding the UK's reliance on imported material. This could leave UK manufacturers vulnerable to material availability and cost, and therefore impact the sector's competitiveness and rate of decarbonisation.

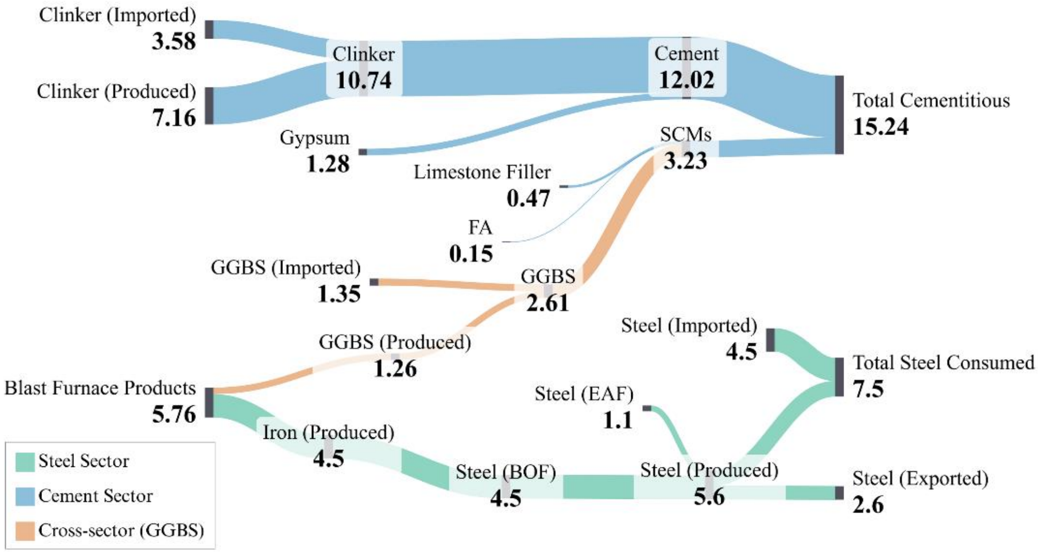


Figure 3a: UK MFA 2023, where all values are in Mt/year.

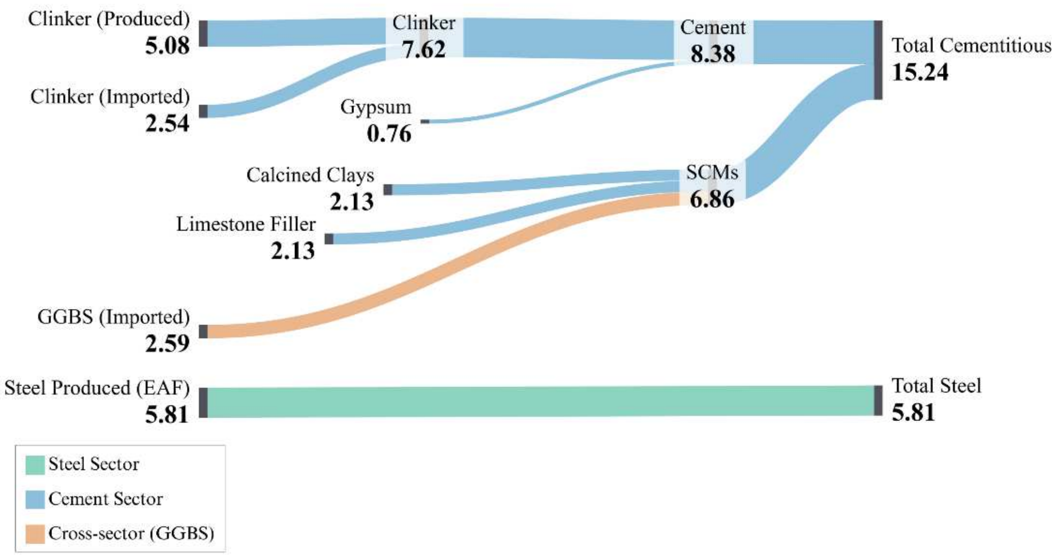


Figure 3b: UK MFA 2050, where all values are in Mt/year.

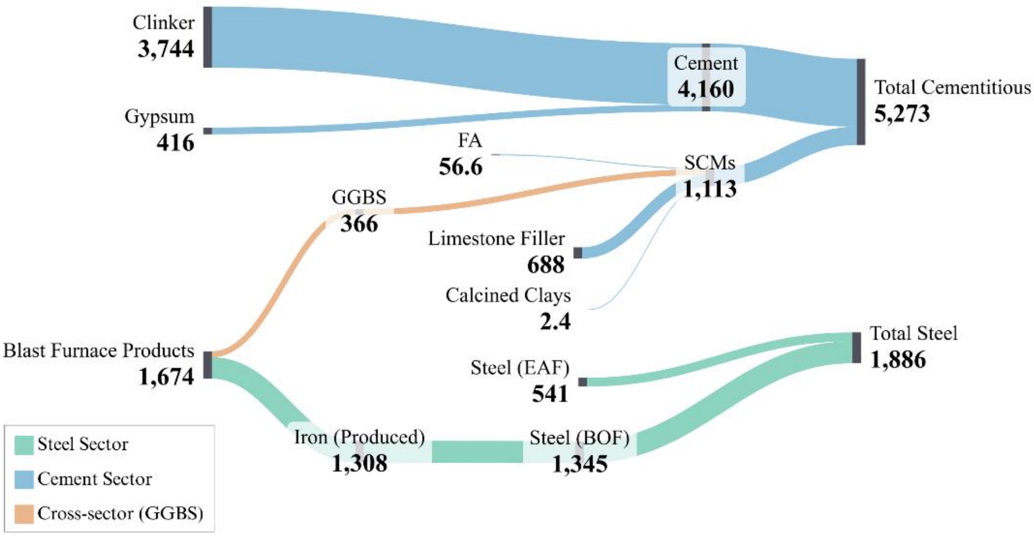


Figure 3c: Global MFA 2023, where all values are in Mt/year.

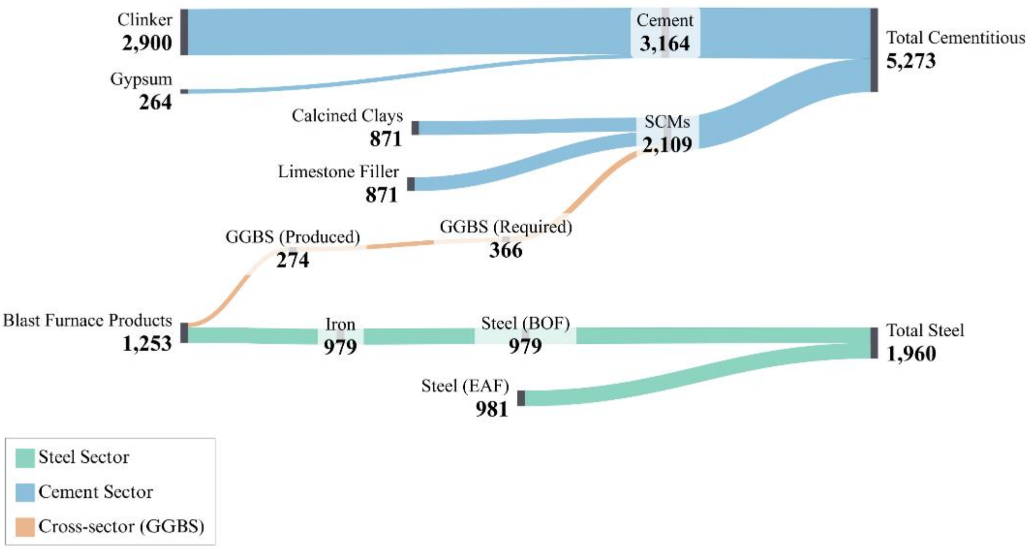


Figure 3d: Global MFA 2050 under the high scenario, where all values are in Mt/year.

3.2. Carbon Emissions

The analysis conducted indicates that the current combined global baseline carbon emissions for both the cement and steel sector is approximately 6.6 $GtCO_2eq/yr$. Whilst the cement sector value is in broad agreement with figures reported by the IEA [25], the steel sector value is approximately 20% higher [2]. As outlined, this study relies on a range of secondary data sources and a top-down data collection approach, which due to error truncation, is likely to result in an overestimation of values. However, the correlation of this combined global value gives confidence that the analysis performed is accurate enough to make predictions on the likely outcomes of the described transition scenarios and decarbonisation pathways. If both the highest rate of steel and cement production route transition is undertaken, as outlined in Table 1, alongside the implementation of all sector specific decarbonisation pathways, it is likely that the combined global carbon emissions will fall to approximately 2.9 $GtCO_2eq/yr$ by 2050, representing a joint emissions reduction of 56%. The effects of each scenario are explored on a sectoral level in Section 3.3.

The overall carbon emissions of each country or region of analysis are a function of material volume produced, split in production route, and the carbon intensity of each production route. As expected, results shown in Figure 4a indicate that carbon emissions arising from the UK steel sector will reduce by between 74% and 84%, depending on the decarbonisation pathway, due to the transition to EAF steelmaking. This represents a reduction in overall emissions to approximately 2 MtCO_2eq from 10.2 MtCO_2eq at the baseline. Emissions within the UK cement sector are expected to decrease between 2% and 56% compared to the baseline depending on the decarbonisation scenario; significantly less than the reduction potential expected from the steel sector. The higher range present in the expected cement sector reduction potential is attributed to the lack of certainty in decarbonisation strategy implementation. The UK steel sector's action calling for a complete shift to EAF steelmaking allows for a greater predicted emission reduction, whereas the cement sector can only estimate reductions based on minimum reported reduction values. Despite cement having a lower carbon intensity value (0.281 kgCO_2eq/kg) when compared to steel produced by EAF (0.312 tCO_2eq/t) under the 2050 UK SDS high cement decarbonisation scenario, the overall emissions associated with cement production (3.71 MtCO_2eq) are more than double that of steel production (1.81 MtCO_2eq) due to the predicted production volume of cement being higher than that of steel.

Examining the global market, as shown in Figure 4b, the current cement and steel sector baseline carbon emissions are 2.8 GtCO_2eq/yr and 3.8 GtCO_2eq/yr respectively. Also as indicated by Figure 3b, in the cement sector, these values are expected to decrease in 2050 by 25-66% depending on the cement transition scenario as well as the rate of implementation of regional decarbonisation strategies which have been modelled. The global steel sector will likely see a reduction in carbon emissions by 14-49% depending on the implementation of each decarbonisation pathway and EAF transition, and this rate of decarbonisation will have a direct impact on the cement sector as symbiosis through GGBS is present globally. This means that a reduction of overall emissions arising from the steel sector to between 3.3 to 1.9 GtCO_2eq/yr, by 2050, is likely. The results shown in Figure 4 are a global average, but analysis indicates that in relative terms, India is likely to experience the greatest reduction in carbon emissions due to the modelled increase in EAF steelmaking despite having the most carbon intensive sources of electricity and fuel. The world's largest steel producer, China, is also predicted to see a reduction in emissions and a small move towards EAF steelmaking. However, the country is still likely to contribute to at least half the global sector's emissions, even under the most ambitious decarbonisation targets. The production dominance of China, India, and Japan means that they contribute significantly to the global scenario.

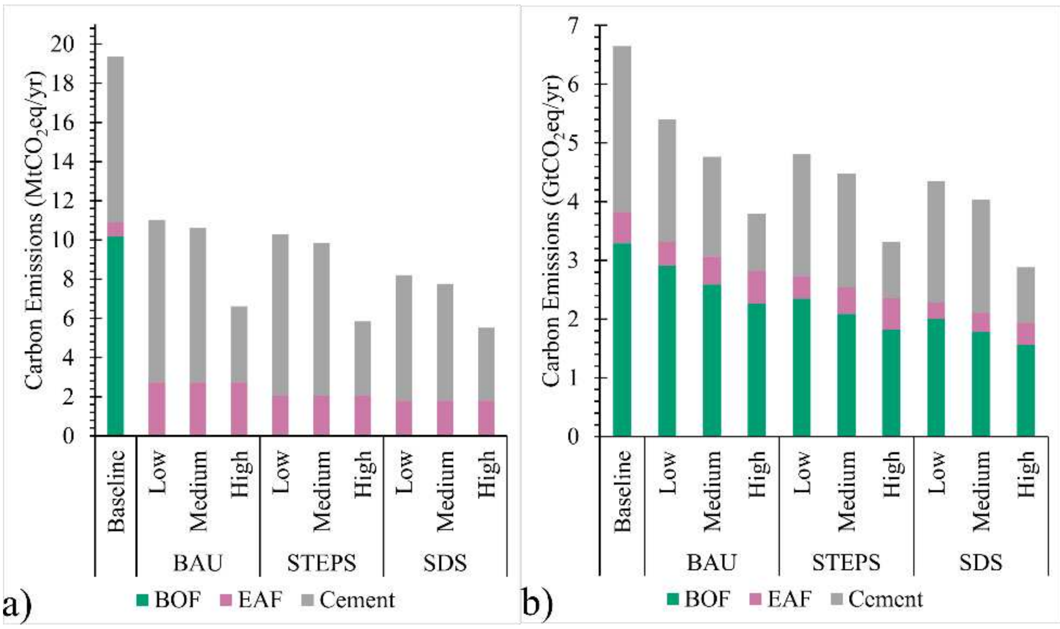


Figure 4: (a) UK, (b) global combined steel and cement sector emissions at the baseline (2023) and in 2050 under the specified scenario.

3.3. Sector Level Carbon Intensity

3.3.1. Steel

Using the LCA methodology described in Section 2.4, the carbon intensity of both steelmaking routes within each country under each decarbonisation scenario was determined as shown in Figure 5. It has been calculated that the baseline global carbon intensity of BOF and EAF steelmaking is 2.45 and 0.99 tCO_2eq/t respectively. Depending on the decarbonisation pathway selected, these values are likely to reduce to between 2.31 and 1.59 tCO_2eq/t and 0.57 and 0.39 tCO_2eq/t respectively. The analysis indicates that the UK is likely to have the lowest EAF steelmaking carbon intensity (between 0.47 and 0.31 tCO_2eq/t) primarily due to ambitious regional electricity decarbonisation targets that should result in an overall grid intensity that is at least half that of the global average. Although not directly explored here, if the UK were to retain a complementary BOF steelmaking capability, this analysis indicates that it could significantly reduce its carbon intensity from 2.28 tCO_2eq/t to between 2.23 and 1.53 tCO_2eq/t. The potential reduction in intensity is very similar to India and Japan, highlighting the minimal influence of regional decarbonisation efforts (e.g. electricity grid) in comparison to process decarbonisation through technology improvements (e.g. CCUS or hydrogen).

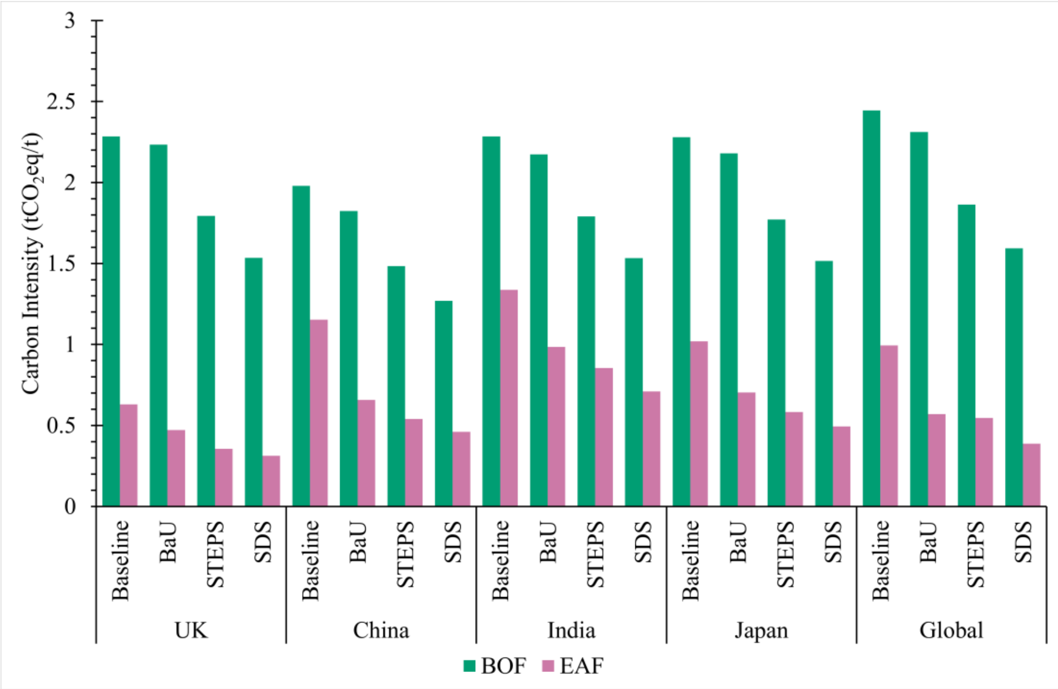


Figure 5: Carbon intensity (tCO_2eq/t) of steelmaking in each assessed country or region, under each decarbonisation scenario.

3.3.2. Cement

Ensuring the consistent use of the most representative allocation method within a system is vital to allow for effective cross-study, and cross-sector, comparison. The mass allocation of carbon intensity between iron and BFS was taken as 78.12% to 21.88%. Figure 6a illustrates the differences in proportion between economic allocation procedure by country. The economic allocation between iron and GGBS produced in the UK was calculated as 94.5% and 5.5%, respectively. Examining the values for China, India, and Japan it was found that the percentage allocation for iron and GGBS was similar between China and Japan (99.5% and 0.5%). In India the lower value of iron resulted in a higher percentage of emissions being allocated to GGBS (96.1% and 3.8%, respectively). The economic allocation of these materials is in broad agreement with existing studies [83]. Price volatility over the last decade underscores why future price estimation is necessary to accurately assess a co-product's future environmental impact. It was determined that from 2023 to 2050, the price of iron and GGBS is expected to increase by 283.5% and 24.6%, respectively. This results in the economic allocation between iron and GGBS in the UK shifting to 97.5% and 2.5% respectively. As shown in Figure 6b, the use of economic allocation results in a significant reduction in the carbon intensity of GGBS because of the reduced allocation proportion associated with the material. The carbon intensity of GGBS at the UK baseline is 0.48 $kgCO_2eq/kg$ when mass allocation is selected. However, when economic allocation is applied, this drops to 0.15 $kgCO_2eq/kg$. In 2025, the MPA reported that the carbon intensity value (with economic allocation applied) for GGBS is equal to 0.155 $kgCO_2eq/kg$ [84]. The similarity between this study's calculated carbon intensity value and the reported MPA value supports the accuracy of the inventory data and economic values utilised. The difference in carbon intensity values present between the two allocation methods is primarily due to the economic value of GGBS. As its value is significantly lower than that of iron, the percentage allocated is also much lower. Out of the three countries assessed, GGBS from China exhibits the lowest carbon intensity with the value being 16% lower than the UK current economic baseline, despite the emissions associated with material transport. It is evident that economic allocation it is the best method to represent a complex, interlinked system because it better represents real world changes over time.

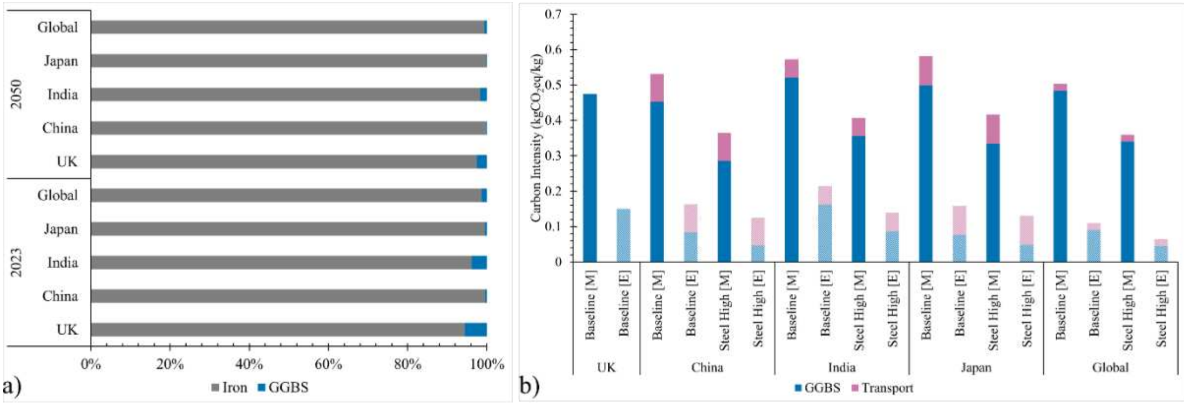


Figure 6: (a) Economic allocation percentages, (b) Impact of mass [M] and economic [E] allocation on GGBS carbon intensity.

Figure 7 illustrates the carbon intensity for the UK cement sector. The baseline carbon intensity for cement in the UK is approximately 0.65 $kgCO_2eq/kg$ with clinker production comprising 81% of the total intensity. As expected, the overall cement carbon intensity decreases from the low to high transition scenarios, with the carbon intensity contribution from SCMs (CC, limestone, and FA) and GGBS increasing and the carbon intensity contribution of clinker decreasing. This shift is largely due to the decrease in clinker factor, with the lowest overall intensity at 0.29 $kgCO_2eq/kg$ – in which GGBS is sourced equally from China, India, and Japan under the high cement transition scenario. Although the mass ratio between all SCMs remains constant throughout each 2050 scenario, the change in clinker factor results in an increase in SCM consumption, resulting in a greater contribution from all SCM's (including GGBS) toward overall intensity. The utilisation of sector wide decarbonisation pathways including CCUS, electrification, and the use of alternative fuels has the potential to reduce cement carbon intensity and thus emissions by over 50% in the best case. However, the route to implementation of these strategies is unclear.

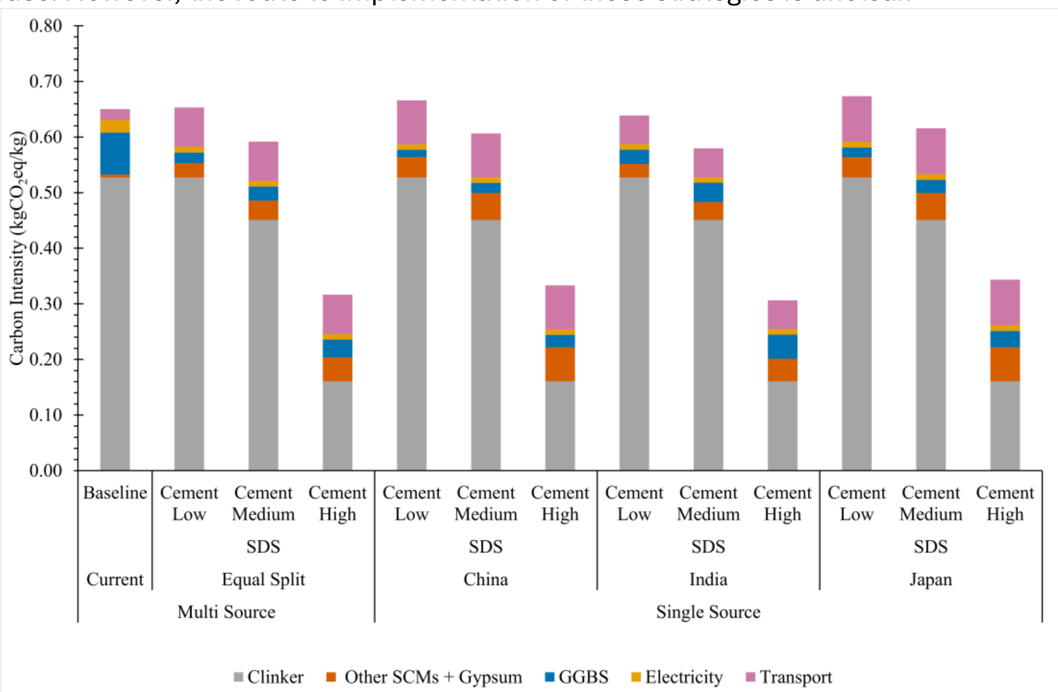


Figure 7: UK cement sector carbon intensity at the baseline and in 2050 under the best-case steel (SDS) and cement decarbonisation scenario (mass allocation).

3.4. Sensitivity Analysis

The core assumption of this study is that the UK will source GGBS in the future in an equal split between the dominant steel producers (China, India, and Japan), primarily as a method of supply chain risk management. However, it is likely that there will be periods of time where this is not the case, therefore it is important to understand the effect of sourcing from a single country; under the assumption that the material quality threshold is met. The average transportation distance between the UK and each country by sea is shown in Table 2, where the average is defined as the mean distance between the three busiest ports by material volume of each country.

Table 2: Sea transportation distance (km) between the UK and relevant countries.

Country	Average distance to the UK by sea (km)
China	22,354
India	14,639
Japan	23,309

As shown in Figure 7, the transportation distance and source can have a significant impact on the emissions associated with GGBS, and ultimately the resultant cement produced within the UK. Despite the very similar transportation distance between China and Japan (a difference of 3.9%), importing wholly from China could result in a maximum reduction in GGBS intensity of 1% compared to multi sourcing - primarily due to ambitious regional electricity decarbonisation targets despite the transport distance. Importing solely from India would result in a maximum GGBS intensity reduction of 16%, despite a greater than average steelmaking intensity. Whilst Japan's greater transportation distance (a difference of 44.6% compared to India) results in a minimum increase in GGBS intensity of 8% when compared to multi sourcing – highlighting the 'hidden' contribution of transport. This is significant as many LCA studies choose to exclude the effects of transport [72]. Although single sourcing could substantially reduce the emissions associated with GGBS, this could leave the UK cement sector vulnerable to significant supply chain, geopolitical, and transport related risks which could negate the environmental benefits.

4. Discussion

4.1. Theoretical Implications

This study has investigated the current and future carbon intensity and emissions, of key global steel producers (China, India, Japan, and the UK) and the global average, under three steelmaking route transition scenarios as well as quantifying the effects of regional and global decarbonisation efforts. These efforts are intrinsically linked to those of the global cement sector, particularly in the UK, due to the reliance on GGBS as a SCM. Therefore, this study assumed the industry will continue to use GGBS sourced from the dominant global steel producers due to a complete reduction in domestic production and consequently investigated the current and future carbon intensity and emissions associated with UK produced cement.

Our findings show that carbon emissions of steel produced in the UK will drop by up to 84% by 2050, against a global reduction of 49%; and could leave the UK responsible for just 0.09% of global steelmaking emissions. This is due to the predicted 'green' nature of the UK's electricity grid, and the use of this as primary fuel within entirely secondary steelmaking. However, the predicted volumes of steel produced are only enough to satisfy domestic demand. These reductions in emissions rely on regulatory change to ensure scrap steel supply chains can satisfy domestic demand. Otherwise scrap imports will continue, and such supply chain dependency will reduce resilience and security of UK steelmaking. China, India, and Japan will see a reduction in emissions and associated intensities but due to differences in production volumes, regional decarbonisation pathways, and the scale of EAF transition these are reduced compared to the UK decarbonisation rate. Implementation of these strategies within the global steel industry means that the UK cement sector will, consequently, also decarbonise. Emissions associated with cement production in the UK are predicted to fall by up to 56%, driven by regional and sectoral decarbonisation strategies, but also the reduction in the carbon intensity of GGBS as a result of decarbonisation efforts within the steel sector. The reduction potential is much smaller because of the emissions incurred through GGBS transportation and source. Consequently, the use of potential decarbonisation technologies in the cement sector (including CCUS and electrification) must be accelerated at a similar pace to the steel sector.

4.2. Industrial and Policy Implications

The positive efforts to reduce the environmental impact of UK steelmaking does have the potential to destabilise, disrupt, and decouple the symbiotic link between two of the UK's most important foundation industries - the products of which are vital to support continued economic growth. Although it is difficult to predict global changes with absolute certainty, it is likely that global steelmakers will accelerate steelmaking transitions in effort to decarbonise their own economies. This will ultimately reduce the global supply of GGBS further, leading to greater than modelled value increases, which could leave UK cement producers severely exposed to global supply chain failure. If the cement industry does not seek to accelerate its own pathway at the same rate as steelmaking, supported by overarching policy [85] with targets to capitalise on novel technological solutions (i.e. EAF derived low carbon cement), it will struggle to effectively decarbonise. This, compounded by the fact that there are few viable short to medium term SCM alternatives readily available in the UK, could ultimately result in a return to domestically produced PC; the adverse environmental impact of which would be higher than that studied in the baseline case. This would significantly hamper the UK's efforts to meet wider climate change mitigation targets in pursuit of net zero by 2050.

4.3. Study Limitations

This study has taken a robust approach to its analysis of cement and steel production; there are three key limitations to the study which could be tackled within a larger assessment, or as data availability changes. Firstly, the scenarios which have been modelled are relatively simplistic. This implies that the transitions toward secondary steelmaking or a lower clinker factor are discrete (i.e. only low, medium, or high) and are not currently assessed comparatively (i.e. low cement, high steel). This means that the study results are at the extreme ends of likelihood, and policy makers may benefit more from an increased number of scenarios. Secondly, although all data has been taken from a range of high-quality secondary sources which are regionalised where possible, the precision of the analysis could be enhanced by introducing additional, primary, data sources as these become available. Finally, introducing additional scenarios related to UK steelmaking which examine the effect of a reducing percentage of steel production transitioning toward secondary steelmaking would reflect the expected future trajectory of changes in domestic priorities. Therefore, the effect of this on steel-cement symbiosis could be holistically assessed.

5. Conclusion

Cement and steel are materials which are fundamental to modern infrastructure, but both have significant environmental impacts as a result of their energy- and process- intensive processes. However, both are intrinsically linked through the symbiotic use of GGBS which is primarily used as a performance enhancing, and carbon intensity reducing material within blended cements. This research has effectively characterised current and future carbon emissions, carbon intensities, and general landscape of global and UK steel production. Consequently, it has also characterised the current and future carbon emissions, carbon intensity, and general landscape of UK cement production using GGBS as a SCM - a key by-product of the BOF steelmaking route. In the work presented, it has been shown that UK steel production is projected to reduce carbon emissions by up to 84% by 2050, significantly exceeding the anticipated global reduction of 49%. This outcome is primarily driven by the decarbonisation of the electricity grid and the adoption of secondary steelmaking processes. This reduction in carbon emissions in the steel sector will also contribute to a 56% decrease in emissions from the domestic cement industry, due to the lower carbon intensity of GGBS. However, these benefits are contingent upon the development of resilient domestic scrap steel supply chains and coordinated sectoral strategies. To achieve long-term industrial decarbonisation, parallel advancements in cement sector technologies and supportive policy interventions are imperative.

This work provides a robust methodology to analyse and effectively describe the effect of decarbonisation on the anticipated emissions of both the global and UK steel sectors, and the UK cement sector. Thus, also the effect on the symbiotic relationship between the cement and steel sectors in the UK. The enhanced understanding of the trajectory of both sectors will allow for more effective domestic planning in relation to meeting wider climate change mitigation targets. However, opportunity exists to extend this research to assess how a change in domestic steel supply chains can be supported, through technical and regulatory processes. This would ensure that high-quality steel scrap can be reused to produce further high-quality steel products to support both UK and global infrastructure. Additionally, the supply chain risk to the UK cement sector, with respect to GGBS, is clear. Therefore, a detailed supply chain analysis should be carried out to gain a better understanding of which manufacturers are producing GGBS within the regions of dominant BOF based steel production, what their decarbonisation pathways and targets are, and ultimately whether this poses a true risk to the UK supply of GGBS. Additionally, extending the methodology adopted in this study to assess other SCMs (e.g. CC) would enhance the understanding of the true emissions associated with cement production. This new understanding could also be linked to the development of more effective sustainability indexes for these materials (much like those developed for the chemical industry) [86]. There is also an opportunity to advance the attributional LCA methodology into either a consequential or dynamic model to account for fluctuations in material volumes and coefficient values (e.g. emission factors) over time, respectively. Such further research will solidify the understanding of the symbiotic relationship between two major foundation industries and ensure that regional and global decarbonisation efforts towards net-zero do not bring additional risk or result in deindustrialisation of vital segments of global economies.

Acknowledgements
The Authors would like to thank the Engineering and Physical Sciences Research Council (EPSRC) through the Advanced Metallic Systems Centre for Doctoral Training (EP/S022635/1), EPSRC and the Energy Institute at The University of Sheffield, for a DTP PhD Scholarship (EP/T517835/1), the Grantham Centre for Sustainable Futures (GCSF), and British Steel Limited.

Supplementary Information
Data supporting this publication is contained within both the Supplementary Information and the and University of Sheffield research data repository at https://doi.org/10.15131/shef.data.29224874.v1, and can be freely used under the terms of the Creative Commons Attribution (CC BY) license.

Declaration of Conflicting Interest
The Authors declare that there is no conflict of interest.

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