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Scalable Decarbonisation for the Invisible Majority:
A data driven framework to support a just transition for UK
manufacturing SMEs

School of Water, Energy and Environment
Environmental Management for Business

MSc
Academic Year: 2024 - 2025

Supervisor: Dr Simon Jude



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Supervisor: Dr Simon Jude

This thesis is submitted in partial fulfilment of the requirements for
the degree of MSc in Environmental Management for Business

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Abstract

Decarbonisation of the UK manufacturing sector is essential to achieving net zero, yet current industrial strategies focused on clusters overlook dispersed sites, which account for nearly half of manufacturing emissions. These sites are largely composed of small and medium-sized enterprises (SMEs), constrained by limited capacity, capability, and capital. Despite accounting for over 99% of UK manufacturing businesses, SMEs remain underrepresented in decarbonisation policy and emissions frameworks. This study addresses that gap by developing a hybrid modelling approach, combining two composite indicators, adapting the Bloomberg industry-implied carbon intensity model and an employment-based estimate from The Data City. By integrating these proxies in a 50:50 weighting and stress-testing through Monte Carlo simulations across the 19,130 manufacturing SMEs in the East of England, this research generates the first probabilistic baseline of SME emissions at regional, sectoral, and organisational scales.

Results show that medium-sized firms contribute nearly 60% of regional SME emissions, while a small number of subsectors account for over 80%, underscoring concentration and volatility. High relative standard deviations highlight structural uncertainty yet also offer actionable insights by pinpointing where interventions can be targeted. By demonstrating that robust regional baselines can be built from imperfect secondary data, the research challenges the notion that SMEs are too fragmented to integrate systematically into decarbonisation policy. The thesis concludes that a just transition requires embedding SMEs into industrial frameworks through tiered fiscal instruments, interoperable digital tools, and place-sensitive strategies, reframing them as active agents of industrial transformation rather than peripheral actors.

Keywords: Net zero, carbon leakage, uncertainty, Measurement, Reporting & Verification (MRV), Place-based, Dispersed, recommendations

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List of Abbreviations

AMR	Automated Meter Reading
API	Application Programming Interface
CCC	Climate Change Committee
CCUS	Carbon Capture, Usage, and Storage
DBT	Department for Business and Trade
DESNZ	Department for Energy Security and Net Zero
DSM	Dependency Structure Matrix
DFES	Distribution Future Energy Scenarios
EEIO	Environmentally Extended Input-Output
EII	Energy Intensive Industry
ETS	Emissions Trading Scheme
FAME	Business Database from Moody's Analytics
FI	Foundation Industry
GSENZH	Greater South East Net Zero Hub
GHG	Greenhouse Gas
LAEP	Local Area Energy Plans
LEP	Local Enterprise Partnerships
LIDP	Local Industrial Decarbonisation Plans
MRV	Monitoring, Reporting and Verification
ONS	Office for National Statistics
REEE	Resource efficiency and energy efficiency
RSD	Relative Standard Deviation
SECR	Streamlined Energy and Carbon Reporting
SME	Small to Medium-sized Enterprise

1 Abstract

Decarbonisation of the UK manufacturing sector is essential to achieving net zero, yet current industrial strategies focused on clusters overlook dispersed sites, which account for nearly half of manufacturing emissions. These sites are largely composed of small and medium-sized enterprises (SMEs), constrained by limited capacity, capability, and capital. Despite accounting for over 99% of UK manufacturing businesses, SMEs remain underrepresented in decarbonisation policy and emissions frameworks. This study addresses that gap by developing a hybrid modelling approach, combining two composite indicators, adapting the Bloomberg industry-implied carbon intensity model and an employment-based estimate from The Data City. By integrating these proxies in a 50:50 weighting and stress-testing through Monte Carlo simulations across the 19,130 manufacturing SMEs in the East of England, this research generates the first probabilistic baseline of SME emissions at regional, sectoral, and organisational scales.

Results show that medium-sized firms contribute nearly 60% of regional SME emissions, while a small number of subsectors account for over 80%, underscoring concentration and volatility. High relative standard deviations highlight structural uncertainty yet also offer actionable insights by pinpointing where interventions can be targeted. By demonstrating that robust regional baselines can be built from imperfect secondary data, the research challenges the notion that SMEs are too fragmented to integrate systematically into decarbonisation policy. The thesis concludes that a just transition requires embedding SMEs into industrial frameworks through tiered fiscal instruments, interoperable digital tools, and place-sensitive strategies, reframing them as active agents of industrial transformation rather than peripheral actors.

Keywords: Net zero, carbon leakage, Monte Carlo, Measurement, Reporting & Verification (MRV), Place-based, Dispersed, recommendations

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2 Introduction

Decarbonisation of the manufacturing industry is critical to achieving national and international net zero targets, as it is responsible for 16% of the UK's greenhouse gas (GHG) emissions (Department for Energy Security and Net Zero, 2024) and nearly 25% of global emissions (UNEP, 2024). Manufacturing underpins modern society, and its products are often hidden from view, while being connected to consumption decisions with profound environmental consequences (Bryson et al., 2022). It also plays a crucial role in developing the technologies and products that will support a decarbonised economy (Make, 2022). The diversity of the manufacturing industry, its subsectors, products, and supply chains, create a complex set of problems that do not easily permit the development of a one size fits all solution to transition into a low-zero carbon industry.

This heterogeneity complicates decarbonisation pathways and increases vulnerability to carbon leakage, where domestic emissions reductions are offset by rising imports from higher emitting economies (Skidmore, 2023). Addressing this risk requires frameworks that extend beyond territorial emissions. The Energy Systems Catapult emphasises the value of consumption-based accounting to prevent leakage and spotlights UK opportunities for innovation in low-carbon manufacturing (2024). This research adopts a similar logic, developing a regional framework to capture embedded carbon risk across dispersed manufacturing activity to address a policy gap affecting the manufacturing base, 99.4% of which are small to medium sized enterprises (SMEs) (Department for Business & Trade, 2024).

While the UK's Industrial Decarbonisation Strategy targets industrial clusters that account for 53% of UK manufacturing emissions (Element Energy, 2020), it fails to address 47% of emissions attributed to dispersed industrial sites, as shown by Figure 2-1 (Department for Business, Energy, & Industrial Strategy, 2021; Frontier Economics, 2021). These sites, predominantly SME-operated, face the triple challenge of limited access to finance, the absence of local low-carbon infrastructure, and reduced capacity to engage in complex transition planning (Rattle et al., 2024). Since 2019, UN-backed initiatives such as the SME Climate

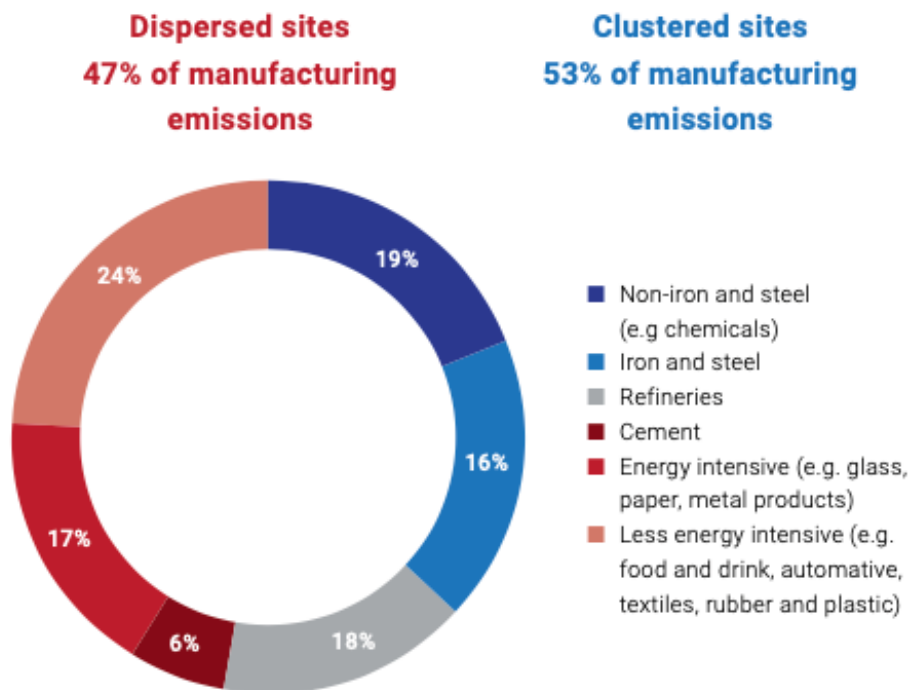
Hub and the *Race to Zero* campaign have mobilised SME climate action (Hampton et al., 2022; SME Climate Hub, 2022). However, uptake remains modest, with voluntary schemes overlooking supply chain emissions and resource impacts. High and volatile UK electricity prices further undermine competitiveness with energy-intensive firms paying twice the European average (Frontier Economics, 2021; DBT, 2025). For SMEs operating in dispersed sites, these structural disadvantages amplify the constraints of limited capacity, capability, and capital.

2.1 Background

In the UK, national decarbonisation policy is anchored by the Climate Change Act 2008, which established a legally binding target to reduce GHG emissions by at least 100% from 1990 levels by 2050. (HM Government, 2019). This legislative foundation is operationalised through the Net Zero Strategy and Industrial Decarbonisation Strategy which has set sector-specific pathways for emissions reduction (DBEIS, 2021). For businesses, net zero entails reducing emissions across operations and supply chains as far as technologically and economically feasible, with residual emissions offset by verified removals such as carbon capture or nature-based solutions (Burnett & Stewart, 2025).

Yet, as Fankhauser et al. (2022) emphasise, credible net zero pathways require urgent, front-loaded emission reductions and comprehensive coverage of all emission sources and industries, including those harder to measure or abate. While UK policy has prioritised large, clustered, energy-intensive industries, this risks sidelining dispersed manufacturing SMEs, which collectively account for a substantial share of emissions. These domestic measures are further situated within the UK's international commitments under the Paris Agreement (2015) and the Glasgow Climate Pact (2021), which reinforce both the ambition to limit global temperature rise to 1.5°C and the principle of a just transition, ensuring that industrial transformation supports fairness and equity.

Manufacturing emissions split by location, based on 2017 emissions



Manufacturing emissions (includes from refineries which are not part of Make UK membership) split by industry type and location, based on 2017 emissions

Source: Industrial Decarbonisation Strategy and Net Zero Industrial Pathways Model

Figure 2-1: UK manufacturing emissions split by location (Make UK, 2023), showing that 53% of emissions are from industrial clusters and 47% from dispersed sites, highlighting policy and infrastructure gap for dispersed SMEs.

The Climate Change Committee (CCC) cautions that the manufacturing industry is “off-track,” with a widening gap to 2030, slow progress on electrification and resource efficiency, and policy support concentrated in clusters rather than the wider manufacturing base (CCC, 2023). It highlights the lack of policy targeting dispersed sites outside industrial clusters, which represent around 40% of industrial emissions but are not covered by the UK Emissions Trading Scheme (ETS). While the £5 million Local Industrial Decarbonisation Plans (LIDP) competition is a positive step (Innovate UK, 2023), it remains modest in scale given the size of the challenge. Closing this gap will require a coherent approach

that extends beyond clusters to smaller and dispersed firms, combining stronger resource-efficiency standards, targeted demand-side measures, and accelerated investment in grid infrastructure. In response, the 2025 Industrial Strategy elevates Advanced Manufacturing and Clean Energy as priority sectors for achieving net zero while reinforcing commitments to the foundational industries and their supply chains that provide essential materials such as steel and chemicals (DBT, 2025).

Industrial decarbonisation strategies have prioritised scaling low-carbon industrial technologies, modernising production processes, and embedding clean energy generation and storage in manufacturing hubs to address capability and infrastructure gaps (Element Energy, 2020; BEIS, 2021; Hafez et al., 2024). A substantial and growing body of literature has focused on Energy-Intensive (EI) and Foundation Industries (FI), the resource intensive subsectors that supply essential materials within industrialised economies. In the UK, these typically include metals, ceramics, glass, chemicals, cement, and paper, industries that underpin manufacturing supply chains but carry high carbon footprints (Balderson et al., 2022; Cinderby & McKendree, 2024; Cox et al., 2024; Gerres et al., 2019; Griffin et al., 2018; Hafner et al., 2022; Hafez et al., 2024; Lai et al., 2025; Nurdiawati & Urban, 2021). This research has increasingly interrogated the feasibility of net zero pathways for these sectors, many of which rely on technologies not yet viable at scale, overlook cross-sectoral abatement possibilities; or require improved sector specific carbon accounting methods assess true process-level impacts.

By contrast, dispersed UK manufacturing has received comparatively little policy attention, despite the collective significance clear in Figure 2-1 (Balderson et al., 2022; Make UK, 2022). These sites, defined broadly as operations located outside of industrial clusters, are typically less emissions-intensive at the firm-level and face structural challenges including long grid connection delays, exclusion from planned hydrogen/CCUS networks, and limited dedicated policy support (Rattle et al., 2023). Current approaches rely on incremental efficiency improvements, leaving unresolved gaps in data collection, tailored advice, and

SME-specific transition frameworks (Norman et al., 2020; GSENGH, 2024). Addressing these barriers and developing tailored support mechanisms is essential to ensure dispersed SMEs are not disadvantaged by a policy landscape designed for large, clustered industries, and to uphold the principle of a just and equitable transition.

2.2 SMEs: Business as usual?

Dispersed industrial sites are predominantly composed of SME manufacturing businesses (Make, 2022). SMEs, defined as organisations with fewer than 250 employees and turnover below €50 million, account for over 99% of UK businesses, 60% of private sector employment, and 52% of national turnover (Foreign Commonwealth & Development Office, 2022; DBT, 2024). Manufacturing SMEs have been considered “hard to abate” due to their high energy and emissions intensity, complex supply chain integration, raw material use, and waste generation (Rattle et al., 2023). The definitions shown in Table 2-1 matter for policy and finance design, as technical assistance and monitoring tools may need tailoring by SME size to ensure equitable participation in the transition.

Table 2-1: Definition of an SME (Foreign, Commonwealth & Development Office, 2022).

Turnover or balance sheet total	Headcount	Business size
Turnover less than €50 million, or balance sheet total less than €43 million	<250	Medium sized
Turnover less than £15 million, or balance sheet total less than £7.5 million	<50	Small
Turnover less than £1 million, or balance sheet total less than £500,000	<10	Micro

The growing body of academic and industry literature focuses on structural barriers to decarbonisation, including limited financial and human resources, complex supply chain dependencies, difficulty accessing low-carbon technologies, fragmented policy support, and competing operational priorities (Afolabi et al., 2023; Hampton, 2018; Baranova et al., 2017; Mazhar et al., 2024; Khosravi et al., 2024). Despite initiatives at local, regional, and sectoral levels (Blundel & Hampton, 2021; Mole & Belt, 2023), only 25% of manufacturers believe they can achieve net zero by 2050 (Federation of Small Businesses, 2025). Moreover, recent research by the UKERC found that existing programmes have reached fewer than 1% of SME and remain fragmented, underlining the need for coordinated and transformative approaches (Eadson et al., 2024).

Financial constraints further compound these challenges. FSB (2025) research shows that nearly half of SMEs installing green technologies used business cash reserves, 28% relied on personal savings, and reliance on self-funding rose to 64% in manufacturing firms. Rural firms were significantly more likely to draw on personal savings than urban counterparts, suggesting unequal access to external finance. Emerging initiatives, such as the Perseus pilot, show potential by automating Scope 2 reporting and linking energy and emissions data directly to green finance (Icebreaker One, 2024), but the preference for self-funding highlights that scalable engagement will require cultural shifts and the development of financial instruments that reflect SMEs prevailing behaviours.

Understanding SME carbon impacts requires clarity on the different sources of emissions. Figure 2-2 illustrates the widely adopted Greenhouse Gas Protocol categorisation of Scope 1 (direct), Scope 2 (purchased energy), and Scope 3 (value chain) emissions (GHG Protocol, 2024). This distinction is particularly important, because while large UK firms face mandatory GHG reporting under frameworks like SECR (The Carbon Trust, 2019), most SMEs fall outside of formal reporting obligations (Hampton et al., 2023; Mazhar et al., 2024). Without reliable monitoring, reporting, and verification (MRV), SMEs risk exclusion from sustainable finance and supply chains (Eadson et al., 2024), a concern that is

already visible in a fragmented and inconsistent data landscape that undermines SMEs ability to engage competitively (Icebreaker One, 2024).

In response the forthcoming UK SME Voluntary Emissions Standard represents a timely and proportionate framework for enabling structured, scalable carbon reporting (Bankers for Net Zero, 2025b). However, challenges remain in engaging SMEs at scale. Many lack the technical infrastructure or capability to calculate emissions, particularly for Scope 3, where responses can default to “not currently recorded” which will limit standardisation. Moreover, without automated data flows or tangible incentives tied to reporting, SME uptake may remain uneven. Ultimately, while the Standard is likely to deliver an improved baseline, its impact will depend on widescale adoption, embedded infrastructure, and meaningful benefit pathways that enable SMEs to participate fully and effectively.

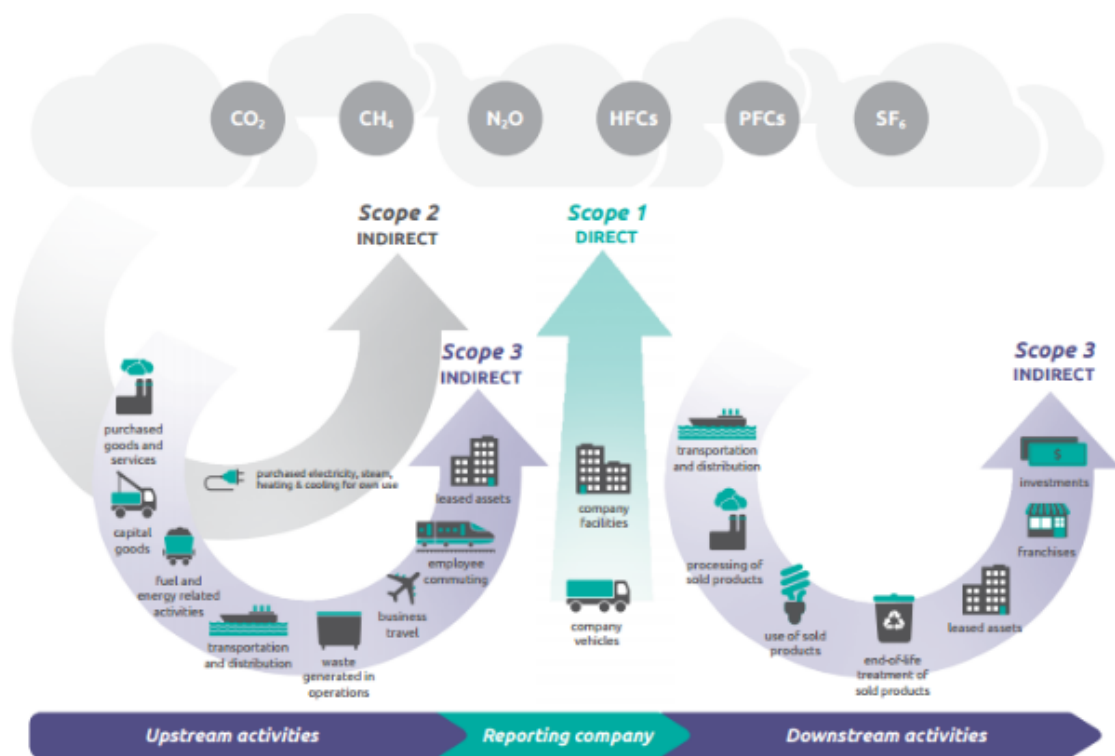


Figure 2-2: Overview of Scopes and Emissions across the value chain (GHG Protocol, 2024).

Similarly, there is a growing consensus to reframe SME decarbonisation as a source of innovation and growth (The Willow Review, 2025; Bankers for Net Zero,

2025a). Rather than framing emissions disclosure as a compliance exercise, recent policy and finance reviews emphasise the strategic role SMEs can play in driving local and national green growth. The 2025 Industrial Strategy reinforces this, describing the transition to net zero as “the economic opportunity of the century,” with the UK’s net zero economy growing three times faster than the wider economy since 2023 (DBT, 2025). Positioning SMEs as key enablers within supply chains and regional economies is essential to ensuring they are active participants in the transition. This research builds on these developments by modelling the emissions profile of manufacturing SMEs in the East of England, with the aim of informing place-based strategies that integrate data, finance, and policy support.

2.3 Case Study: East of England

The East of England region, as shown in Figure 2-3, classified by the Office for National Statistics (2021) will serve as the primary case study through the remainder of this paper. Historically comprised of the counties of Bedfordshire, Cambridgeshire, Essex, Hertfordshire, Norfolk, and Suffolk, this region presents a multifaceted case study. The region is climate-vulnerable, with extensive coastline and low-lying land at sea level at high flood risk (East of England APPG, 2023). It hosts 52% of the UK’s offshore wind capacity and has the potential to be a major renewable power exporter. However, this potential has not yet translated into full industrial benefit for a region that is home to over 10% of England’s SMEs (Mole & Belt, 2023). Despite the concentration of clean energy assets, the region has faced persistent grid connection delays. The 2025 Industrial Strategy highlights that some firms face decade long-waits for new or reinforced connections, identifying accelerated grid access as essential to enabling dispersed sites and regions like the East of England to fully leverage their renewable capacity (DBT, 2025).

International competitiveness pressures intensify the decarbonisation challenge. Many East of England SMEs operate in supply chains linked to export-facing

sectors such as automotive and aerospace, where exposure to international markets is high (GSENGH, 2024). The forthcoming UK Carbon Border Adjustment Mechanism (CBAM) is expected to reduce carbon leakage but imposes additional compliance burdens on SMEs (DBT, 2025). In contrast, increased UK-EU energy market cooperation may stabilise regional electricity pricing and support export-intensive manufacturing.



Figure 2-3: Map of the East of England and its counties (Free World Maps, 2021).

The East of England also falls under the remit of the Greater South-East Net Zero Hub (GSENGH), one of five regional energy hubs funded by the DESNZ. A recent regional mapping exercise by the GSENGH mapped 551 industrial sites across the Greater Southeast, with a significant portion within the East of

England counties. Emission hot spots are evident, particularly in Essex, Suffolk, and Cambridgeshire where over ten sites were reported to emit over 1,000 tCO₂e annually (GSENZH, 2024). Despite this, GSENZH acknowledges the persistent underrepresentation of SMEs in net zero planning and the inadequate support structures for dispersed and rural sites. Furthermore, the GSENZH report confirms several systemic challenges faced by local industrial clusters, including a lack of governance for data collection, insufficient SME engagement and limited mechanisms for long-term, cross-firm collaboration.

Using the East of England as an exploratory case study, this research develops an operational and replicable framework to support SME manufacturing decarbonisation. It aligns with national-level, whole-systems approaches (Energy Systems Catapult, 2024) that integrate territorial and consumption-based perspectives, while explicitly quantifying uncertainty through Monte Carlo simulations. By extending this practice to simulate emissions within the SME manufacturing landscape, this thesis aims to capture embedded risks and opportunities across subsectors, firm sizes, and regions, and situating SMEs within a systems-based innovation agenda to achieve Net Zero by:

1. Profiling the SME manufacturing landscape, by linking employment and turnover data to environmentally extended input-output (EEIO) intensity factors and establishing a territorial and consumption-sensitive emissions baseline.
2. Quantifying uncertainty through Monte Carlo simulation, generating thousands of emissions estimates to capture variability across data gaps, sector heterogeneity, and firm-level reporting quality.
3. Diagnosing regional, subsector and firm-size transition barriers by disaggregating simulation outputs, to identify where structural constraints most shape SME transition capacity.

4. Synthesising a scalable and replicable framework that can address operational, financial, and data constraints and enable policy alignment with place-based industrial strategies.

3 Methods

This research addresses a significant gap in SMEs engagement with decarbonisation, particularly among dispersed manufacturing firms. SMEs face barriers in emissions reporting due to limited capacity, resources, and the absence of a regulatory requirements, yet their aggregate contribution to GHG emissions is significant. Developing a regional emissions baseline can inform both policy design and targeted data collection. Figure 3-1 provides a visual summary of the methodological framework applied in this research, from SME identification through to hybrid estimation and Monte Carlo simulation.

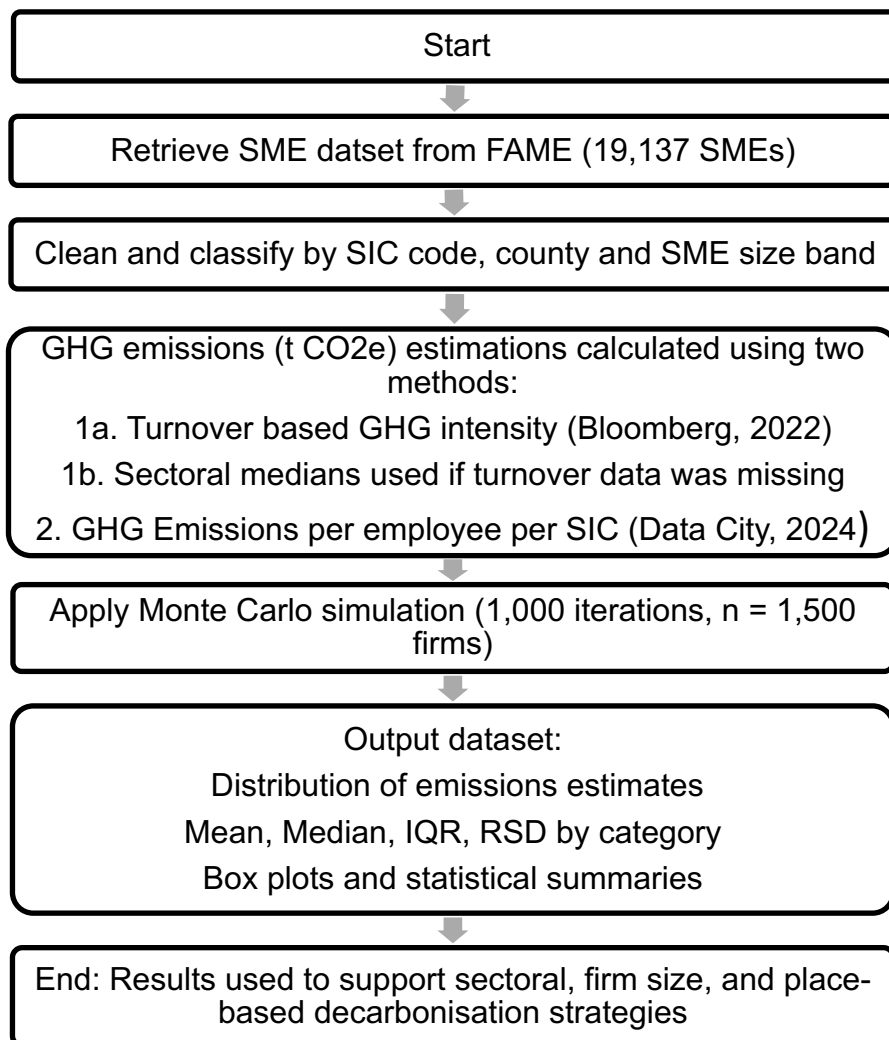


Figure 3-1: Summarises the methodological workflow, from SME identification to uncertainty analysis and statistical outputs.

3.1 Research Design

The East of England was selected as a case study due to its concentration of dispersed manufacturing SMEs, climate vulnerability, and significant renewable energy potential. An initial dataset was extracted from FAME, a leading UK company research database, on 13th June 2025. This search covered all manufacturing firms with a Standard Industrial Classification (SIC) code between 10-34 and a primary registered address within the East of England. The results identified 20956 registered companies, of which 1,819 exceeded SME thresholds and were excluded (FAME, 2025). The remaining 19,137 businesses were stratified into micro, small and medium size bands turnover and employee data. Where turnover was missing, common among micro and small firms, classification was imputed using employment proxies in line with Office for National Statistics practice (ONS, 2024). After excluding seven firms in tobacco manufacturing, (SIC 12), the final modelling data set comprised 19,130 SMEs. A full breakdown of dataset refinement and SME band classification is provided in Appendix B.

3.2 Hybrid Estimation Framework

To address widespread data gaps, a secondary-data hybrid model was developed by integrating Environmentally Extended Input–Output (EEIO) factors with firm level attributes. EEIO is a widely used tool for analysing the relation between economic and environmental flows (European Commission, 2021). Two complementary indicators were developed:

- Turnover-based estimates, adapted from the Bloomberg’s industry implied model that applies sectoral GHG intensity per unit of GVA to firm turnover (Bloomberg, 2022).
- Employment-based estimates, adapted from The Data City’s emissions per employee model, derived from ONS emissions and employment datasets (The Data City, 2024).

Bloomberg provides global financial and carbon intensity metrics enabling emissions estimation from revenue, while The Data City generates UK-specific operational measures for policymaking. Each approach captures a different measure of business activity, using financial and operational proxies. However, each also carries limitations. Turnover-based estimates can overstate emissions in capital intensive sectors, while employee-based measures may overlook variations in productivity or automation. To balance these risks, both were combined in a 50:50 weighting of both indicators was implemented. Equation 1 presents the hybrid formula.

Equation 1. Hybrid Estimate (Turnover + Employment)

$$E(\textit{hybrid}) = 0.5(E \textit{Turnover}) + 0.5(E \textit{Employment})$$

The component equations and a worked example is provided in Appendix C. This hybrid approach avoids over reliance on any single proxy and produces a representative firm-level emissions estimate.

3.3 Uncertainty Analysis

Given that 85% of firms required proxy estimation, a Monte Carlo simulation was integrated to quantify uncertainty. A stratified sample of 1,500 SMEs was drawn from the population of 19,130, with 1,000 iterations per firm. Each iteration stochastically varied input values for turnover, employment, and sectoral intensity factors to generate estimated emissions distributions. Detailed simulation parameters, including distribution assumptions, stratified sampling logic, and diagnostic tests are reported in Appendix D.

Key outputs included:

- Mean emissions per SME.
- Median and interquartile range (IQR), reflecting tendency and variability.
- Standard deviation and Relative Standard Deviation (RSD), to express volatility across iterations.

Results were aggregated across three levels of analysis:

1. Geographic (county-level): to highlight spatial emissions hotspots and variability.
2. Sectoral (SIC codes): to expose concentration and replication potential.
3. Organisational (SME size bands): to explore differential uncertainty by firm scale.

This Monte Carlo approach aligns with methods used by leading UK energy system research bodies including the Energy Systems Catapult. In its 2024 modelling, the Catapult implemented Monte Carlo simulations across multiple net zero scenarios to stress test decarbonisation pathways under conditions of high uncertainty. By embedding stochastic variation across energy system parameters, it identified “low regret” innovation pathways that remain robust regardless of future technology or market conditions. This approach was deliberately policy agnostic and technology neutral, allowing for exploratory insights rather than prescriptive predictions. Similarly, the use of Monte Carlo simulations in this study serve not to predict exact SME emissions but to map volatility, risk exposure, and resilience within industrial decarbonisation strategies. By doing so, it identifies systemic features and sectoral configurations that require tailored support to achieve a net zero future.

3.4 Methodology Limitations

A detailed discussion of the modelling weaknesses, SIC classification challenges and simulation-specific biases is provided in Appendix E, but the following summarises the limitations that constrain precision:

Data availability: Many micro-enterprises and sole traders are exempt from filing full accounts under the Companies Act 2006 (FRC, 2024), leading to widespread turnover gaps. Employment proxies mitigate this but remain imperfect.

Proxy reliance: Around 85% of firms required imputation. The hybrid model reduces bias by combining revenue and employment perspectives but cannot

eliminate volatility inherited from both. Sectoral medians help stabilise outliers but leave gaps in several SIC codes.

SIC classification: Broad SIC categories mask intra-sector heterogeneity. Only primary SIC codes were considered, which risks under or over-estimation for multi-activity firms.

Simulation assumptions: Normal distributions may not fully reflect skewed real-world emissions. Proportional stratified sampling means SME-dense counties dominate results, limiting spatial comparability.

Dynamic change: Estimates assume stable relationships between turnover, employment, and emissions intensity, whereas low-carbon technology adoption and regulatory shifts can alter trajectories.

4 Results and Discussion

This section presents findings from the GHG emissions estimation model for manufacturing SMEs within the East of England. The results are organised thematically across four principal dimensions:

1. Geographical variation examines the spatial distribution of SME emissions and regional hotspots.
2. Sectoral insights identify industry subsector emissions concentration.
3. SME band analysis classifies firm-level readiness for decarbonisation.
4. Policy and equity considerations to ensure a just transition for SMEs.

These findings are contextualised within UK decarbonisation policy and SME engagement strategies, highlighting data limitations, estimation volatility, and implications of the hybrid methodology. The discussion proposes actions to enhance the precision and policy relevance of SME accounting methods, including smart metering, emissions dashboards, and targeted sampling of high-intensity sectors, ideally facilitated or overseen by local authorities or cross-regional delivery bodies such as the Greater South-East Net Zero Hub.

4.1 Geographic variation

To evaluate the spatial distribution and uncertainty of regional GHG emissions, a Monte Carlo simulation resampled a representative subset of 1,500 manufacturing SMEs across 1,000 iterations, producing a total of 1.5 million observations of firm-level GHG outputs. While SME counts vary across counties in the simulation sample, this reflects the distribution of manufacturing firms across the region. Table 4-1 reveals significant regional variation. Essex and Bedfordshire emerge as emissions hot spots, with mean firm-level emissions exceeding 1,000 tCO₂e, while counties like Cambridgeshire, Norfolk, and Suffolk show higher median emissions but lower means, implying a more uniform base of high emitters rather than dominant outliers. High relative standard deviation (RSD) values, which exceeded 300% in some counties, indicate major internal county variation driven by sectoral and firm-level differences, which aligns with observations that dispersed-site emissions are

highly uneven, largely driven by sector mix, energy intensity, and integration into energy and transport intensive supply chains (BEIS, 2021).

Table 4-1: Summary Statistics from Simulation Sample (1,500 SMEs).

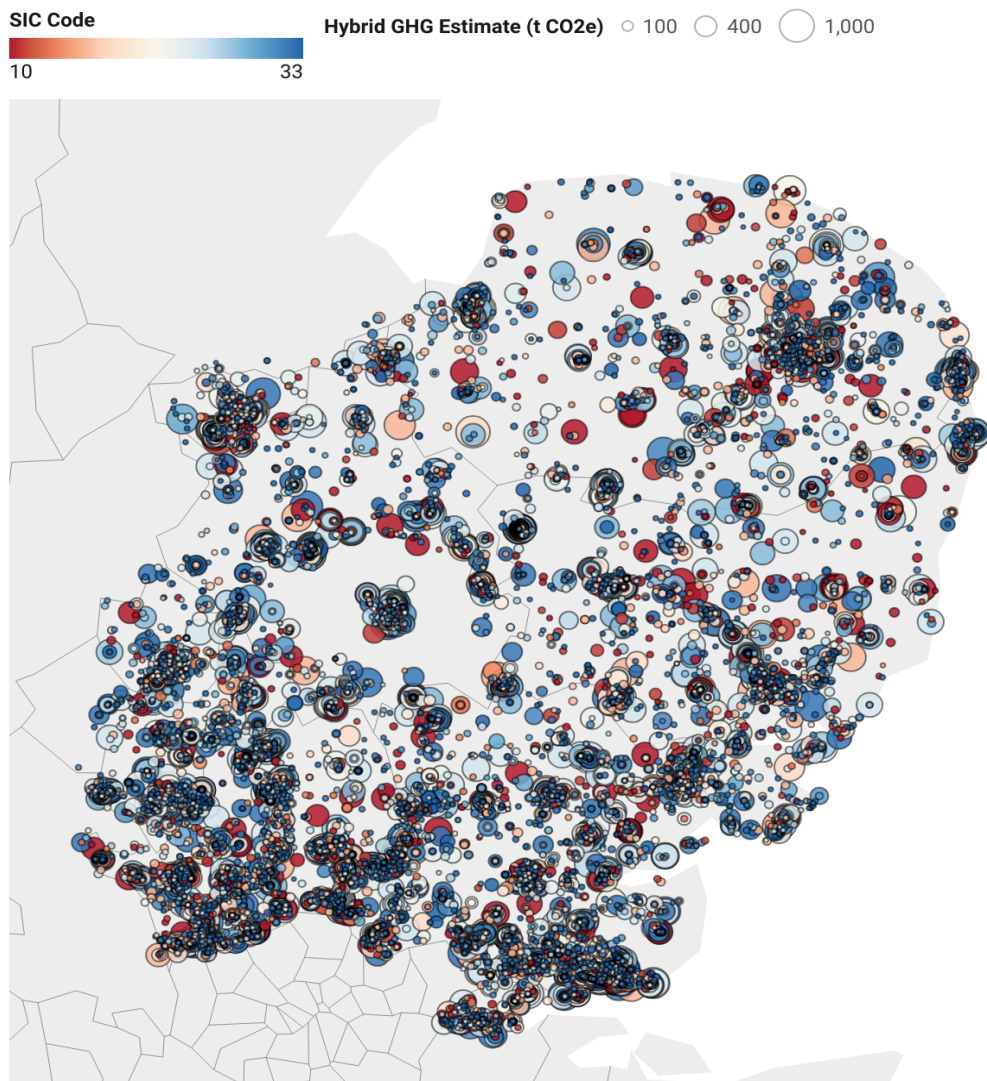
County	No. Co's	Total GHG Emissions (tCO₂e)	Mean (tCO₂e)	Median (tCO₂e)	IQR (tCO₂e)	RSD (%)
Bedfordshire	149	156917	1053.14	224.66	533.6	459.73
Essex	408	418899	1026.71	220.96	653.03	374.21
Cambridgeshire	210	208066	990.79	364.24	1024.98	200.82
Norfolk	217	205442	946.74	344.17	840.4	186.18
Suffolk	219	184992	844.71	305.75	850.51	236.96
Hertfordshire	297	238625	803.45	269.75	752.17	323.06

These statistical patterns are spatially visualised in Figure 2-1, which visualises the emissions estimate for each firm and SIC code. These spatial concentrations align closely with regional economic geography and infrastructure, reinforcing the Monte Carlo model's validity. All counties show concentration of emissions around cities and urban areas, but Essex, Bedfordshire and Hertfordshire display the highest spatial density. This correlates with their association to the London-Stansted-Cambridge corridor, a logistics and energy intensive area with strong links to London and manufacturing clusters (GSENGH, 2024).

Cambridgeshire and Suffolk, despite having lower aggregate SME counts, reveal more dispersed but consistent mid-range emitters. This is supported by the observation that these areas have distributed manufacturing bases in rural technology parks and food processing centres. Their high median emissions, as identified in the simulation outputs, are thus reinforced by the spatial spread of similarly sized emitters rather than singular large outliers. In Norfolk, emissions appear relatively moderate in density, though concentration exists near Norwich and King's Lynn, which are areas flagged by the GSENGH as emerging industrial zones (2024). The county's high emissions, though not as volatile as Bedfordshire's, stem from a consistent base of mid-scale manufacturers that are likely to have substantial Scope 3 impacts.

Carbon footprint modelling of Manufacturing SMEs: East of England

GHG Estimates for 19,130 manufacturing SMEs across Bedfordshire, Cambridgeshire, Essex, Hertfordshire, Norfolk, & Suffolk



Map: Ned Chappell • Created with Datawrapper

Figure 4-1: Spatial distribution of Hybrid GHG estimates from 19,130 Manufacturing SMEs in the East of England (Chappell, 2025). Circle size represents estimated GHG emissions (tCO₂e); Colour denotes dominant SIC sector. Dense clusters indicate industrial emissions convergence zones.

The Monte Carlo model's integration of EEIO factors captures not only direct Scope 1 and 2 emissions, but also upstream Scope 3 impacts from raw material extraction, energy generation, intermediate goods, and logistics (DESNZ,

2023). This provides a consumption-based perspective, highlighting embedded carbon risks that are usually excluded from territorial inventories. For example, Bedfordshire's reported territorial industrial emissions (excluding large installations) are 160.8 ktCO₂e, closely matching the simulated 157 ktCO₂e from the modelled SMEs. This demonstrates how the hybrid model can reveal emissions otherwise concealed in official datasets, particularly those embodied in imported goods and services.

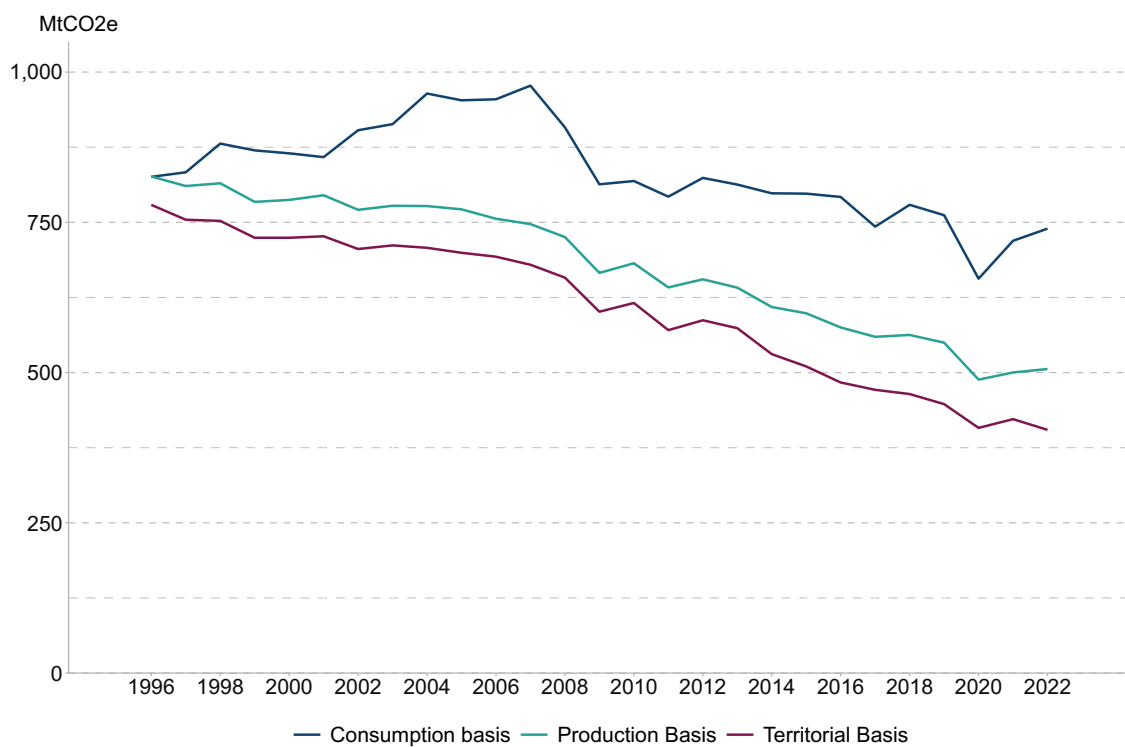


Figure 4-2: Breakdown of UK GHG missions by region of import 1990-2022 (DEFRA, 2025). Shows slower decline in consumption-based emissions (-10%) compared to territorial (-48%) since 1996.

This approach aligns with Barrett et al. (2013), who argue that consumption-based frameworks should complement UK climate policy, a notion further reinforced by the UNEP's *Emissions Gap Report* (2024) that states high-income economies systematically understate their true carbon footprint when relying solely on territorial inventories. DEFRA's national data presented in Figure 4-2 confirms this pattern, by showing that since 1996 UK territorial emissions have fallen by 48%, while consumption-based emissions have declined by only 10%

(2025). Importantly, the UK Government itself recognises this distinction, publishing both territorial and consumption-based estimates and outlining the methodological differences. Yet despite this acknowledgement, the UK’s decarbonisation strategies use territorial inventories as the primary benchmark which leave embedded emissions largely unaddressed. For manufacturing SMEs embedded into global supply chains and reliant on imported intermediaries, a significant share of their carbon footprint is embedded upstream. Excluding these emissions from policy frameworks risks underestimating SME contributions, especially if they are not mandated to report them, while overlooking opportunities to reduce consumption-driven impacts through circular economy practices and supply chain interventions.

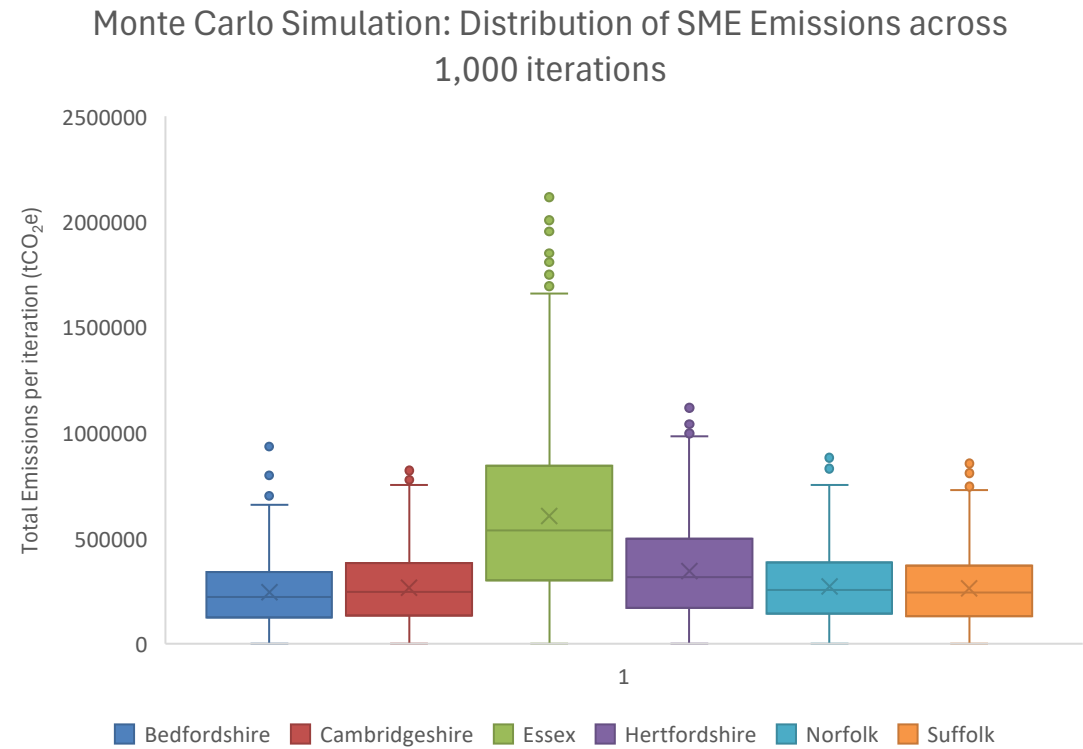


Figure 4-3: Box Plot of County-Level SME Emissions Variability Across 1000 Monte Carlo Iterations, showing total simulated emissions (tCO₂e) per county

The widening gap between territorial and consumption-based emissions illustrates how the structural economic shift from domestic manufacturing to service-led, import-reliant growth supports reduced territorial emissions by

displacing carbon abroad. This experience is recognised as carbon leakage, which threatens the integrity of Net Zero targets by offsetting domestic progress with rising international emissions (Skidmore, 2023). The risk is particularly acute in highly traded, energy-intensive sectors such as steel, chemicals, cement, and textiles, all of which are represented in the East of England's SME base. Regions like Essex and Hertfordshire, whose territorial emissions appear to be trending down, are in fact embedded in emissions-intensive supply chains, carrying significant upstream carbon risk. This is reflected in the county-level simulations shown in Figure 4-3, which identify Essex as both the largest and most volatile emitter, driven by a dense concentration of high-emitting SMEs in logistics-linked subsectors such as food, plastics, and fabricated metals. Bedfordshire and Hertfordshire also show elevated emissions with high variability, reflecting their integration into energy and transport-intensive value chains. By contrast, Cambridgeshire, Norfolk, and Suffolk present more statistically compact emissions profiles, yet their consistent mid-scale emitters still embed substantial upstream carbon risk.

The use of RSD and probabilistic simulation outputs provides a more robust estimation of emissions risk than static inventory models. For instance, Essex's simulated emissions range from between 300,000 and 900,000 tCO₂e, highlighting how turnover, sector composition, and supply chain integration drive regional carbon exposure. These simulation outputs can serve as a complementary tool to the SME emissions data quality scale introduced in the UK SME VES which classifies disclosures from low confidence estimates to real-time data (B4NZ, 2025a). In areas where SME reporting remains inconsistent or falls within lower quality data tiers, probabilistic models help address uncertainty by generating credible risk band and baselines. Applied regionally, this approach can enable Local Enterprise Partnerships (LEPs), Combined Authorities, and Net Zero Hubs to align emissions patterns with Local Area Energy Plans (LAEP) and Local Industrial Decarbonisation Plans (LIDP), to target hotspots, anticipate supply chain effects, and balance resilience with equity.

4.2 Sectoral Insights

Disaggregating GHG emissions by SIC code reveals strong sectoral concentration within a limited number of manufacturing subsectors. As illustrated by Figure 4-4 the top ten sectors account for over 60% of total estimated emissions. This concentration aligns closely with the priority sectors identified in the UK's Industrial Decarbonisation Strategy, yet these firms are located outside designated industrial clusters. Consequently, they will be disconnected from emerging decarbonisation infrastructure like CCUS networks or hydrogen distribution systems.

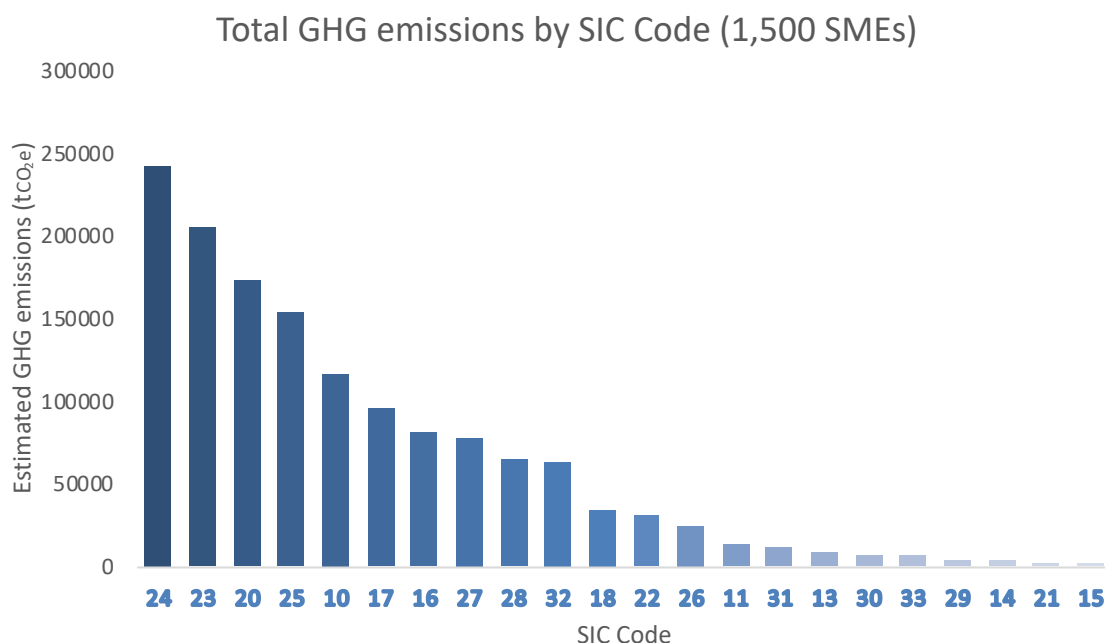


Figure 4-4: Total estimated GHG emissions by SIC Code

However, aggregated emissions totals do not provide a complete picture. Considerable variation exists in both per-firm intensity and statistical volatility across sectors. As presented in Table 4-2, subsectors such as SIC 17 (Textiles), SIC 20 (Chemicals), and SIC 23 (Minerals) all report median emissions above 2,300 tCO₂e per firm. These results challenge prevailing assumptions that mitigation efforts should focus primarily on large industrial

zones. Instead, they highlight the significant of smaller firms operating in geographically dispersed and infrastructure-poor locations.

Table 4-2: SIC Code Emissions Summary Statistics

SIC Code	Median	IQR	RSD
10 – Food	730.37	2330.97	111.13
11 – Beverages	33.23	325.65	174.2
13 – Textiles	18.56	895.22	138.68
14 – Apparel	6.88	34.93	213.8
15 – Leather	1.76	0.6	19.1
16 – Wood & Cork	840.24	1250.76	148.57
17 – Paper	2631.33	1554.13	57.24
18 – Recorded Media	202.17	592.87	126.56
20 – Chemicals	2366.29	5028.06	97.34
21 – Pharmaceutical products	58.34	178.93	90.09
22 – Rubber/Plastic	301.83	441.93	75.23
23 – Mineral products	2326.31	7959.91	124.26
24 – Basic metals	273.28	6775.61	181.81
25 – Fabricated metals	461.62	1134.94	100.16
26 – Computer, electronic & optical	175.52	327.69	85.12
27 – Electrical equipment	538.9	1710.38	99.18
28 – Machinery	396.11	474.9	85.8
29 – Vehicles	151.74	431.87	109.26
30 – Other transport	141.33	291.63	113.38
31 – Furniture	18.14	505.96	122.84
32 – Other	259.59	566.35	93.32
33 – Repair & installation	49.54	92.56	116.29

Statistical dispersion measures further reinforce these insights. The RSD and interquartile range (IQR) metrics included in Table 4-2 demonstrate significant variation in data quality and emissions consistency between sectors. These trends are visualised in Figure 4-5, which presents a box and whisker plot of simulated emissions derived from 1,000 Monte Carlo iterations. Sectors such as SIC 28 (Machinery & Equipment) exhibit relatively low uncertainty (RSD 65%), suggesting data consistency and potential for targeted replication. By contrast, sectors such as SIC 18 (Printing) and SIC 31 (Furniture) show RSDs over 150%, indicating fragmented data and underreporting. These data fragile sectors are likely to require capacity building and simplified MRV tools before strategic interventions can be scaled.

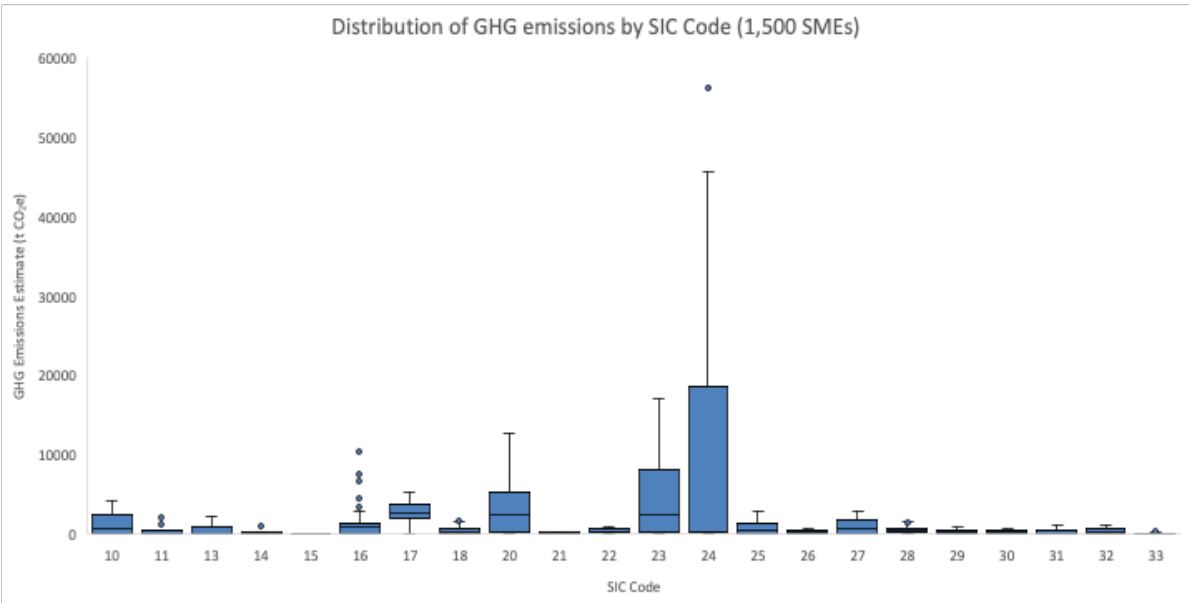


Figure 4-5: Distribution of GHG emissions by SIC code (Monte Carlo sample, n = 1,500 SMEs)

These distinctions have direct implications to design a strategy for SMEs excluded from decarbonisation pilots designed for larger firms in anchor clusters (GSENGH, 2024; BEIS, 2020; Rattle et al., 2024). Where emissions profiles are stable and the data quality relatively high, sectoral playbooks can be developed and deployed. Sherif et al. (2023) develop a Dependency Structure Matrix (DSM) technique to identify shared energy-intensive processes like

pyroprocessing, drying, or material extrusion across sectors, which could form a foundation for cross-sector interventions. The development of sector-agnostic shared resources to augment local and regional infrastructure could support decarbonisation for dispersed SMEs. Furthermore, the modular replication of decarbonisation tools developed for industrial clusters, such as shared MRV systems or pooled procurement schemes, could be reengineered to support dispersed manufacturing sites (Frontier Economics, 2021). Conversely, sectors with high data volatility require targeted capacity building, simplified digital tools and advisory support to raise data quality before meaningful interventions can be deployed at scale.

The simulation results reinforce the value of these recommendations by identifying which SIC categories are both emissions intensive and replicable. Table 4-3 provides tiered strategic recommendations by emissions concentration. High-concentration sectors should be targeted for replication, medium-concentration sectors for digital enablement and governance alignment, and low-concentration sectors for experimentation and capacity building through cross-sector data sharing initiatives.

Table 4-3: Tiered Strategic Recommendations by Emissions Concentration

Tier	Strategic Focus	Recommended Action
High Concentration (e.g. SIC 10, 20, 23, 24)	Sectoral Replication	Develop sector-specific decarbonisation playbooks based on common processes; deploy standardised MRV templates and modular audits.
	Infrastructure Anchoring	Prioritise low carbon hubs and energy pooling systems; integrate SMEs into localised industrial hubs with access to logistics and procurement.

	Innovation Deployment	Identify feasible hydrogen, CCUS and waste heat recovery pilots through public-private funding mechanisms.
Medium Concentration (e.g. SIC 17, 25, 28, 32)	Digital Enablement	Implement sub-metering and supplier-linked MRV systems; establish shared digital infrastructure for Scope 1 & 2 emissions tracking.
	Governance Coordination	Create sector-specific working groups and embed SMEs into regional industrial strategies.
Low Concentration (e.g. SIC 11, 13-15, 18, 31, 33)	Capacity Building	Support data-gathering and reporting readiness through local Net Zero Hubs, Sustainability Champions, advisory networks and training schemes.
	Innovation Pilots	Incentivised and targeted trials on MRV, voluntary carbon disclosures and circular economy initiatives; link funding to digital compliance tools.

4.3 SME Band Analysis: Decarbonisation readiness

A differentiated analysis by SME size band reveals clear divergences in emissions impact, data quality, and decarbonisation readiness. Micro (<10 employees), small (10–49), and medium-sized (50–249) firms differ not only in scale, but also in their capacity to engage with the net-zero transition. Using the full dataset of 19,130 manufacturing SMEs reveals that medium-sized firms account for 60% of total simulated GHG emissions, supported by more consistent turnover disclosures and lower relative uncertainty.

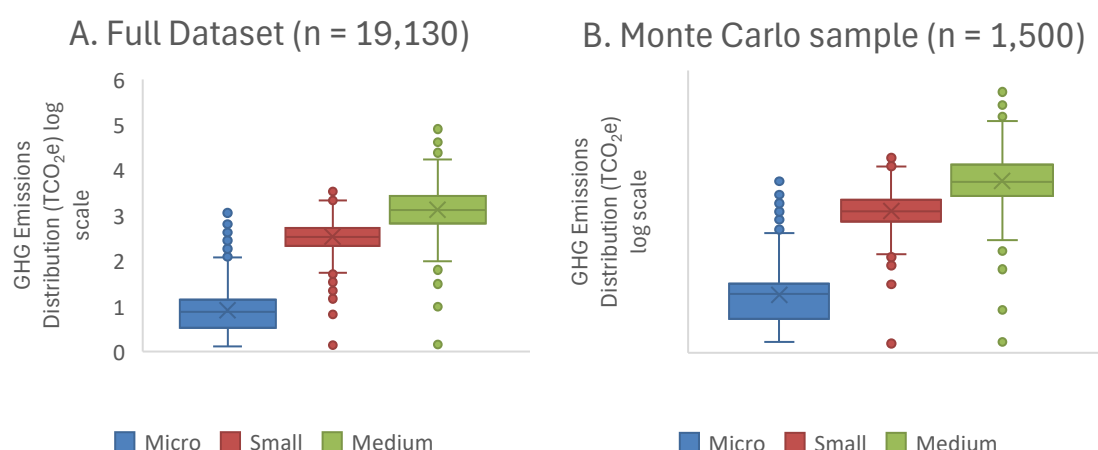


Figure 4-6: Emissions Distribution by SME Band (Full Dataset vs Sample).

Figure 4-6 compares emissions distributions across the full data set in Panel A, and the stratified Monte Carlo sample in Panel B. In Panel A, medium-sized firms exhibit pronounced positive skew, with extended upper whiskers reflecting extreme outliers. This is attenuated in the stratified sample, which provides a more proportionate representation of distributions. Nevertheless, substantial variation remains, consistent with the summary statistics presented in Table 4-4. Micro firms contribute only 9% of emissions but show the highest volatility at 274%, reflecting sparse disclosures and fragile data. Medium firms account for 57% of emissions with a lower but still significant RSD of 231%, while small firms sit between 33% of emissions and an RSD of 114%.

Table 4-4: Summary statistics of SME band GHG emissions, highlighting structural differences in scale and data reliability.

SME Band	Median Emissions (t CO ₂ e)	Interquartile Range (IQR)	RSD (%)	Emissions Share (%)
Micro	7.49	10.8	274%	9%
Small	334.8	320.9	114%	33%
Medium	1318.8	1989.9	231%	57%

These findings show that uncertainty is not confined to the largest emitters but is also most acute among the smallest firms, where data fragility is greatest.

Consequently, while medium firms drive aggregate emissions and require priority intervention, micro firms represent a distinct challenge for emissions accounting due to both their volume and disproportionate statistical volatility. This reinforces the need to interpret these results probabilistically rather than deterministically, particularly when comparing emissions intensity and decarbonisation readiness across firm size bands. Together, these results strengthen the argument that SME decarbonisation interventions should be tailored according to both emissions magnitude and organisational capacity.

Validation of the model through regional primary data collection was planned but not feasible within project constraints. Instead, modelled estimates were benchmarked against voluntary disclosures from the SME Climate Hub.

However, the evidentiary weight of this exercise is limited as the SME Hub dataset includes only 68 manufacturing SMEs, and applies different size band definitions, with its 11-100 category spanning both the small (10-49) and medium (50-249) size band categories as defined in this study.

Table 4-5: Comparison of modelled SME emissions against voluntary self-reported data from the SME Climate Hub.

SME Size Band	Model sample size (N)	Model median (tCO ₂ e)	SME Climate Hub sample size (N)	SME Climate Hub median (tCO ₂ e)
Micro (0-10)	16149	7.49	17	10.47
Small (10-49) / 11-100*	2282	334.8	48	55.00
Medium (50-249) / 101-250*	699	1318.8	3	4249.81

Table 4-5 presents both sample sizes and medians to clarify the imbalance. The model is built from a broad population base, whereas the Hub medians are based on just 17 micro companies, 48 small, and only 3 median firms. This makes Hub values highly sensitive to outliers and self-selection effects, creating an apparent paradox. The SME Climate Hub medians for micro and medium firms are higher than those in the hybrid model, even though the latter

incorporates upstream Scope 3 emissions. This reflects the fragility of the Hub sample. With only three medium-sized firms reporting, one or two outliers can heavily distort the median. Similarly, engaged Climate Hub participants are firms that have decided to commence their decarbonisation journey which creates a self-selection bias and could mean that the dataset is not representative of the wider SME population.

Participation rates further underline this limitation. Since 2022, only 6.7% of micro, 17.6% of small, and 16.1% of medium sized manufacturing firms in the UK have reported their Scope 1 & 2 emissions (SME Climate Hub, 2025). This very low engagement rate highlights a broader policy risk, that voluntary disclosure alone cannot achieve widespread SME decarbonisation. Recent research advocates for a more active legislative framework that combines mandatory signals with capacity building (Hampton et al., 2024; Khosravi et al., 2024). Furthermore, FSB (2025) and the Willow Review (2025) echo this, calling for simplified carbon accounting, access to tailored advice, and embedded tools within business platforms.

The discrepancies highlighted in Table 4-5 also highlight methodological considerations. The Hub dataset generally excludes upstream Scope 3 categories, yet may overstate emissions where firms misclassify or partially include them within Scope 1 and 2. Outlier effects and definitional inconsistencies further complicate comparability. In the hybrid model, small firm medians are more affected by proxy substitutions, with missing turnover disclosures and an overreliance on employee-based imputation, which can dampen estimates relative to outlier-driven voluntary data.

To address both the SME participation and regulatory gaps left unaddressed in the UK Government's recent *Plan for Small and Medium sized Businesses* (DBT, 2025), the recommendations in Table 4-6 blend the modelling results with evidence from literature to propose a readiness-based intervention framework. This framework aligns interventions with emissions contribution, data quality, and firms' capacity to engage.

Table 4-6: Tiered decarbonisation strategy for manufacturing SMEs, integrating structural barriers and policy recommendations by firm size.

SME Tier	Challenge	Recommendation
Micro	High energy costs disproportionate to scale (Frontier Economics, 2021).	Targeted regional equity measures such as subsidised standing charges or capped tariffs for firms <100k turnover (Willow Review, 2025).
	Overreliance on self-funding for investment into decarbonisation (FSB, 2025).	Help-to-Green style vouchers to offset upfront costs and encourage uptake of heat pumps, sub metering, and REEE upgrades (Skidmore, 2023)
	Minimal engagement with net zero policies due to complexity (Willow Review, 2025).	Auto-calculated Scope 1 & 2 templates embedded in accounting, tax or utility software to enable passive reporting (Energy Saving Trust, 2024). A Net Zero passport: pre-filled emissions profiles using sector medians and utility APIs, engagement incentivised via energy discounts or business rates relief.
Small	Capex sensitivity and knowledge gaps block investment (FSB, 2025; Energy Saving Trust, 2024).	Peer-led mentoring networks to build trust and support decarbonisation among SMEs in hard-to-reach sectors (Willow Review, 2025).
	High perceived risk with low ROI for sustainability upgrades (Willow Review, 2025; ERC, 2023).	Subsidised access to carbon accounting tools, conditional on anonymised data sharing to feed into national inventories (Energy Saving Trust, 2024; Haahr & Volz, 2024)

	Weak awareness of existing schemes (FSB, 2025).	Targeted regional grant schemes (via LEPs or Combined Authorities) to co-fund sub-metering and emissions tracking (Frontier Economics, 2021; DESNZ, 2023).
Medium	Uncertainty over return on investment for sustainability upgrades (FSB, 2025; Bankers for Net Zero, 2025).	Enhanced Capital allowances or VAT relief on qualifying decarbonisation measures (Skidmore, 2023; Innovate UK & PwC, 2023).
	Barriers to technology adoption and lack of tailored finance instruments (Blundell & Hampton, 2024; FSB 2025)	Integrate firms into platforms like Perseus for streamlined data exchange with banks/utilities (Icebreaker One, 2025).
		Automated Metering (AMR) incentive schemes linked to verified CO ₂ e savings (Willow Review, 2025).
	Uneven energy cost burdens (Frontier Economics, 2021).	Place-based industrial anchoring; embed medium firms in local decarbonisation zones, leveraging shared infrastructure, pooled procurement and logistics co-location (Poulter et al., 2025).
		Regional price balancing mechanisms for medium sized manufacturers exposed to above average energy costs, based on FSB's findings for regional disparities and offshore risk (Frontier Economics, 2021; FSB, 2025)

This analysis demonstrates that SME decarbonisation pathways must be tiered and adaptive. Micro firms require low-friction, integrated tools in systems or services that they already utilise, while small enterprises need digital infrastructure, mentoring, and access to grants to overcome capital sensitivity. Medium firms, though most emissions-intensive, are better positioned for deeper interventions if given fiscal or regulatory incentives, integration into data-sharing platforms, and protection from uneven energy costs. These findings reaffirm the central argument of this study, that tailored support must be designed with both emissions data and behavioural insights in mind.

4.4 Implications for a just transition

The Monte Carlo simulation confirms that SMEs are structurally embedded in the decarbonisation challenge. Three main themes emerge: emissions are geographically clustered, are largely concentrated across relatively few SIC codes, and are strongly shaped by SME size band. Policy action must therefore focus on the intersection of sector, scale, and place, considering not only where emissions occur, but who is responsible, what their capacity to act is, and which tools can support transition.

Despite its significant industrial base, the East of England remains under-engaged in programme delivery and SME participation with fewer than 1% of SMEs having accessed net zero support programmes (Mole & Belt, 2023; Hampton et al., 2024). Limited uptake of voluntary tools such as the SME Climate Hub, alongside low response rates to primary data collection, highlights systemic barriers in reaching smaller firms. Unless complemented by stronger policy mechanisms, reliance on voluntary disclosure risks deepening inequalities by privileging better-resourced business and leaving many SMEs excluded from transition pathways.

Therefore, a just transition requires a tiered, data-integrated policy framework that combines digital tools, fiscal nudges, and regionally leveraged interventions. Initiatives such as Perseus, or novel concepts like a Net Zero Passport for SMEs, demonstrate how emissions reporting could be embedded

into existing financial or utility platforms, reducing transaction costs. Evidence reinforces that capacity building must be tailored to firm maturity (Hampton et al., 2022). Micro enterprises benefit from simplified embedded tools, while medium-sized firms require targeted finance instruments and capital allowances to overcome investment barriers. Such a framework reflects the attributes of a credible net zero pathway, which demand social and environmental integrity and alignment with broader sustainable development goals. Embedding SME transitions within this framing helps to safeguard fairness, prevent greenwashing, and ensure that decarbonisation contributes to wider-sociological sustainability (Fankhauser et al., 2022).

Equally important is place sensitivity. Lai et al. (2025) put emphasis on embedding local voices and governance capacity, aligning with research on decentralised energy systems that highlight the role of community engagement in equitable transitions (Ashtine et al., 2021; Poulter et al., 2025). An over-reliance on clusters risks overlooking dispersed SMEs who require bespoke interventions, which could include shared infrastructure and pooled procurement (Frontier Economics, 2021).

The simulation framework itself is scalable and transferable. A combined spatial-sectoral matrix could guide Net Zero Hubs, Local Enterprise Partnerships, and Combined Authorities in prioritising hotspots while aligning interventions with firm-level readiness. Further development could include integration into a regional or national dashboard, paired with sectoral MRV pilots such as Perseus, which would strengthen visibility, benchmarking, and accountability.

Embedding SMEs into Net Zero pathways also requires recalibrating governance priorities. The UK Government's *Plan for Small and Medium-Sized Businesses* (2025) recognises SMEs as the “engine room” of the economy but emphasises growth and advisory services rather than the targeted fiscal and regulatory instruments advocated by business, industry and academia. Without a more interventionist industrial strategy, combining long-term regulatory clarity,

fiscal equity, and integration with local energy planning, SMEs remain reliant on fragmented voluntary schemes and limited technical support.

These results should be interpreted within uncertainty bounds. Limitations include under-representation of smaller firms, reliance on turnover and employment proxies, aggregation at the SIC 2-digit level, and EEIO factors that mask local process-specific variation. Future refinement should draw on administrative datasets, smart metering pilots in high-emission sectors, expanded cross-sector MRV schemes, and alignment of regional infrastructure with sectoral forecasts. This methodologically novel and policy-relevant framework underscores the urgency of embedding SMEs into decarbonisation pathways. Applying spatially sensitive, data-led strategies can safeguard a just transition while preserving the diversity and embeddedness of SMEs within the UK's industrial base.

5 Conclusion

This thesis set out to address a critical omission in the UK's decarbonisation strategy: the near invisibility of manufacturing SMEs in emissions accounting and policy design. Using the East of England as a case study, it developed a hybrid estimation framework combining turnover and employment-linked intensity factors with EEIO multipliers, stress-tested through Monte Carlo simulation. The approach generates a probabilistic baseline of SME emissions at regional, sectoral and organisational scales, demonstrating that credible evidence can be produced under data scarcity. Three findings stand out: Medium-sized firms account for nearly 60% of estimated, ten SIC categories dominate sectoral intensity, and county level hotspots reflect infrastructure and logistics corridors. Importantly, high RSDs transform uncertainty from a barrier into a design parameter. Probabilistic outputs identify where estimates are more robust, where data is fragile, and where interventions should be calibrated.

Industrially, a just transition cannot be delivered by cluster-only strategies. To capture nearly half of manufacturing emissions and avoid offshoring carbon, SMEs must be built into policy architecture through tiered fiscal instruments, interoperable digital MRV tools, and place-sensitive delivery. As the hybrid model explicitly captures upstream impacts, the findings support a shift toward consumption-aware policy that reduces carbon-leakage risk and aligns regional action with supply-chain realities, accelerating abatement while protecting UK competitiveness. Institutionally, the method reframes uncertainty as a design parameter rather than a barrier. Turning probabilistic outputs into adaptive policy enables targeted interventions where estimates are robust, and staged learning where data is fragile. This is a practical route to meeting near-term carbon budgets, to focus public support on medium-sized firms and high-intensity SIC codes, while targeting capacity building for the rest.

Limitations remain, particularly in proxy reliance and aggregation, which future work should address through purposive sampling, sector pilots in priority subsectors, and integration into regional dashboards. Overall, the study

reframes SMEs as central agents in a fair and competitive net zero transition. The potential payoff is material, delivering faster emissions reductions, reduced leakage, stronger regional economies, and more resilient supply chains.

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Appendices

Appendix A Ethical approval letter



9th June 2025

Dear Ned Chappell,

Reference: : CURES/25600/2025

Project ID: 29170

Title: Pathways to Net Zero: Decarbonisation Strategies and Climate Risk Resilience in UK Manufacturing SMEs

Thank you for your literature review application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/25600/2025, has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your research.

Regards,

CURES Team

Appendix B SME Dataset and Classification

B1. Dataset extraction

An extract of all manufacturing firms registered in the East of England was generated using the FAME database on 13 June 2025. The query applied SIC codes 10–34 to cover all manufacturing subsectors, and restricted primary company addresses to Bedfordshire, Cambridgeshire, Essex, Hertfordshire, Norfolk, and Suffolk. The extract included the following firm-level fields: registered company name and number, address, SIC code(s), turnover, employment, legal status, and trade description. The search was restricted to active firms, excluding dissolved or inactive companies, which produced an initial population of 20,956 companies.

Firms exceeding SME thresholds (>250 employees or turnover >£50m) were excluded, removing 1,819 cases.

B2. Final population

The remaining 19,137 SMEs were classified into micro, small, and medium categories using EU/UK thresholds. Seven firms in SIC 12 (tobacco products) were removed due to limited emissions data within ONS datasets, yielding a final dataset of 19,130 firms.

B3. Size banding method

SME size bands were determined using turnover and employment disclosures, as shown in Table. B-1. Where both were available, the stricter threshold was applied. Where turnover was missing, proxies were generated using employee counts, consistent with ONS statistical imputation practices (ONS, 2024a). This ensured consistent banding across the sample while acknowledging potential misclassification risks. Approximately 85% of micro and small firms lacked turnover data, necessitating employee-based proxy classification. These “assumed” categories were retained in full to avoid bias against smaller firms, but their reliance on proxies is explicitly acknowledged.

Table B-1: Breakdown of SME size bands in the East of England

SME Band	No. companies (Turnover & Employees)	No. companies (Employees only)
Micro	202	10625
Micro (assumed)	15953	5546
Small	99	603
Small (assumed)	2184	2351
Medium	505	6
Medium (assumed)	194	6

B4. SIC Code classification

The dataset was further disaggregated by SIC subsector (10-34). Table B2 summarises the population by SIC code and size band.

It should be noted that SIC codes are broad groupings that may not fully capture the diversity of SME activities. Many firms operate across multiple subsectors and register more than one SIC code. This research applied only the primary SIC code for each firm to its methodology, which may over or underestimate emissions in certain categories. Despite this, Table B2 broadly aligns with ONS regional business structure datasets, providing confidence in representativeness.

Table B-2: Breakdown of the number of SMEs by SIC code with a registered primary address in the East of England (FAME, 2025).

SIC Code	SIC description	Micro	Small	Medium	Total
10	Food Products	1380	178	59	1617
11	Beverages	352	37	8	397
12	Tobacco	6	1	0	7
13	Textiles	503	37	7	547
14	Apparel	501	23	4	528
15	Leather & related products	93	6	1	100
16	Wood & cork	1062	67	15	1144
17	Paper and paper products	194	41	33	268
18	Printing & recorded media	1300	133	39	1472
19	Coke and refined petroleum	15	3	5	23
20	Chemicals and chemical products	445	60	33	538
21	Pharmaceutical products	88	15	12	115
22	Rubber & plastic products	311	103	44	458

23	Non-metallic mineral products	448	65	20	533
24	Basic metals	169	33	8	210
25	Fabricated metals	1738	394	90	2222
26	Computer, electronic and optical products	592	142	60	794
27	Electrical equipment	448	111	43	602
28	Machinery & equipment	555	204	59	818
29	Motor vehicles, trailers & semi-trailers	355	37	8	400
30	Other transport equipment	275	33	13	321
31	Furniture	731	65	17	813
32	Other manufacturing	2058	308	93	2459
33	Repair & installation of machinery & equipment	2536	187	28	2751
Total		16155	2283	699	19137

Appendix C – Hybrid Model Equations

C.1 Overview

The hybrid model combines two proxy-based composite indicators, turnover and employment-based, into a single emissions estimate per firm. In line with OECD (2008) guidance on composite indicators, the use of proxy variables is a recognised method for addressing data gaps, thereby ensuring methodological robustness when direct emissions data are unavailable; this underpins the application of EEIO-based factors in the present Monte Carlo framework, balancing financial and workforce perspectives and reducing over-reliance on any single method.

Equation 1: Hybrid Estimate

$$E(\textit{hybrid}) = 0.5(E \textit{ Turnover}) + 0.5(E \textit{ Employment})$$

Using the Bloomberg approach, industry specific carbon intensity figures (t CO₂e per £ GVA) published by the Office for National Statistics (2025), were applied to turnover data to calculate a firm-level GHG estimate in tonnes CO₂e. This is presented in Equation 2.

Equation 2: Turnover-based estimate (Bloomberg, 2022)

$$E(\textit{Turnover}) = I_{\{SIC\}} \times T$$

Where I_{SIC} = industry GHG intensity (tCO₂e/£GVA), T = company turnover.

When turnover was missing, Equation 3 substituted turnover for sectoral medians by SME size band. Median values were preferred to mean values to reduce bias from extreme or high-turnover firms (those with higher turnover).

Equation 3: GHG Proxy

$$\textit{GHG Proxy Estimate} = \textit{Median GHG estimate (SIC \& SME band)}$$

Sector-specific emissions intensities per employee for Equation 4 were calculated using ONS Atmospheric emissions by Industry and Business

Register Employment Survey datasets (ONS, 2024b; ONS, 2025). Territorial emissions were divided by sectoral employment to generate per-employee coefficients, which were then multiplied by firm level employment data. Where employee data was missing, a value of one employee was assumed to account for the owner/operator of the business.

Equation 4: Employment-based estimate (The Data City, 2024)

$$E(\text{Employment}) = F_{\{SIC\}} \times N$$

Where F_{SIC} = sectoral emissions factor (tCO₂e pr employee), N = number of employees.

This hybrid model provides a pragmatic solution to the absence of primary SME emissions data by ensuring that estimates are neither overly dependent on financial disclosure, nor solely tied to workforce size. By integrating two complementary methods, it establishes a replicable framework that can be adapted to different sectors or scaled to a local or national level. The model is designed to be stress-tested, with uncertainty analysis embedded as a core component to recognise that transparency about assumptions is as critical as the estimates themselves.

C.2 Worked example

A small metal fabricator (SIC 25) with turnover £3m and 45 employees:

1. Turnover method: $I_{SIC} = 0.24 \text{ tCO}_2\text{e} \times \text{£3m} = 720 \text{ tCO}_2\text{e}$
2. Employment method: $F_{SIC} = 9.2 \text{ CO}_2\text{e} \times 45 = 414 \text{ tCO}_2\text{e}$
3. Hybrid: $(720 + 414) / 2 = 567 \text{ tCO}_2\text{e}$

Appendix D - Monte Carlo Simulation Framework

The hybrid estimate is further refined through a Monte Carlo simulation, designed to incorporate and quantify uncertainty across imputed data points, sectoral intensity factors and business attributes. A Monte Carlo approach was selected due to the non-linear and stochastic interventions between variables, the use of multiple proxy inputs, and the scale of imputation. Monte Carlo simulation is increasingly used in GHG modelling to manage high input variability, missing data, and non-linear relationships between proxy indicators and emissions outcomes (Energy Systems Catapult, 2024; Pozzer et al., 2025; Tushar et al., 2025). Unlike confidence intervals, it allows repeated random sampling to capture the range and likelihood of results under uncertainty. This makes Monte Carlo simulation suitable for high-uncertainty, model-based estimations such as SME emissions modelling.

The simulation was implemented across a stratified sample of 1,500 manufacturing SMEs, drawn proportionally by size band and regional representation from the full dataset of 19,130 firms. The sample size of 1,500 was chosen to stabilise statistical outputs while keeping runtime manageable for 1,000 iterations per firm, enabling random sampling of emissions intensity values and turnover/employee estimates

The simulation produced distributions of hybrid GHG estimates, from which the following metrics were derived simulation:

- Mean emissions per SME
- Median and interquartile range (IQR), reflecting tendency and variability
- Standard deviation and Relative Standard Deviation (RSD), to express volatility across iterations

These results were aggregated across three levels of analysis:

4. Geographic (county-level): to highlight spatial emissions hotspots and variability
5. Sectoral (SIC codes): to expose concentration and replication potential

6. Organisational (SME size bands): to explore differential uncertainty by firm scale

Appendix E - Methodology limitations

Despite a robust methodological approach, this research acknowledges several limitations that constrain the precision of the firm-level results. The first relates to the availability of financial and operational data for SMEs. Many micro-enterprises and sole traders are exempt from filing full accounts under the Companies Act 2006 and the associated FRS 102,105 reporting regimes (Financial Reporting Council, 2024). This results in widespread gaps in turnover data, which necessitates the inclusion of employment-based proxies that provide an approximate reflection of firm-level emissions intensity.

A second limitation concerns the reliance on proxies more broadly. Approximately 85% of companies in the dataset required estimation through either turnover or employment substitutions. The hybrid model was designed to mitigate this by combining both financial and operational perspectives however it cannot fully remove the weaknesses inherent in each source of data. Furthermore, even with the utilisation of the median GHG estimate to model assumed SME size bands, gaps in the data remained in six of the analysed SIC codes. Primary data collection for small companies in the textile, apparel, leather, and basic metals industries is required, while tobacco had no registered GHG intensity associated with its industry.

The classification of companies by SIC codes also introduces structural challenges. SIC groupings are broad and encompass diverse industrial activities with differing emissions profiles. This study considered only the primary SIC code reported by each firm, which risks overstating or understating emissions where businesses operate across multiple subsectors. A more nuanced approach, such as applying weighted averages across several registered SIC codes per firm, could reduce this bias and better capture the complexity of SME operations.

Simulation assumptions provide an additional source of uncertainty. Monte Carlo simulations were run based on normal distributions for emissions intensities, however real-world emissions distributions may be skewed, meaning that extreme or atypical firms are underrepresented in the probabilistic outputs.

Similarly, proportional stratified sampling was employed to reflect the underlying population structure. This means that counties with higher concentrations of SMEs dominate the insights. A more balanced sampling frame could strengthen geographic comparability but may also reduce proportional representation of the SME population.

Finally, there are dynamic factors that extend beyond the limits of this study's design. The model assumes stability in the relationship between financial turnover, employment, and emissions intensity. In practice, these relationships evolve over time as firms adopt new technologies, shift production processes, or respond to regulatory changes. As such, the estimates presented here reflect a baseline for current conditions rather than predictive values for future emissions trajectories.

Appendix F – Supporting Data

The supporting datasets used in this research have been made publicly accessible on Zenodo:

Chappell, N. (2025). GHG Modelling for East of England Manufacturing SMEs [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.17010647>