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Contents

List of Tables

List of Figures

Executive Summary

This report explores a number of research questions on the rebound effects associated with industrial resource and energy efficiency measures and the potential implications of this for policy appraisal and carbon abatement modelling in the UK. Rebound effects are when some or all of the expected efficiency-based savings are observed to ‘bounce back’, through an increase in consumption induced by the efficiency measure. The project and report are split into two workstreams:

Workstream A: Industrial resource efficiency (RE) rebound effects, with a particular focus on the steel, cement and concrete, automotive and construction sectors in the UK.

Industrial RE measures have been defined by DESNZ as “the optimisation of resource use so that a given level of consumption can be met with fewer resources” (HM Government, 2023).

For Workstream A, the research questions were explored through a literature review, a conceptual framework and mapping exercise, and semi-structured interviews with experts from industry and academia.

Workstream B: Industrial energy efficiency (EE) rebound effects, with a particular focus on the iron and steel, chemicals, oil refining, food and drink, pulp and paper, cement, glass, and ceramics sectors.

Industrial EE measures can be defined as technical or behavioural changes that reduce the energy intensity of production.

For Workstream B, the research questions were answered through a literature review of existing modelling studies on industrial energy efficiency rebound effects. Key insights from Workstream A and Workstream B are summarised below.

Workstream A – Resource Efficiency: Key findings

Resource efficiency rebound effects can be classified by level, type, and mechanisms driving it: Rebound effects can be grouped by the scope at which they are studied - individual firm (micro), sector (meso), or economy-wide (macro) - as well as the type of rebound effect being assessed, whether direct, indirect, or macroeconomic. These distinctions are important for understanding the scope and magnitude of rebound effects. Most studies focus on direct rebound effects within individual firms or sectors.

A wide range of factors drive resource efficiency rebound effects: The scale of resource efficiency rebound effects is influenced by market dynamics, competition, and supply chain interactions. Characteristics such as the sensitivity of the demand and supply of the good or service to price changes play a pivotal role, influencing the extent to which consumers and producers respond to efficiency improvements. At the sectoral level, factors such as a firm’s position in the supply chain, market size, and characteristics significantly shape the nature and magnitude of rebound effects. At the macroeconomic level, efficiency-induced price reductions and productivity gains can amplify economic growth, fuelling greater consumption across sectors and increasing rebound impacts. There remains active debate on whether these effects are inherently linked to specific resource efficiency models or business strategies, highlighting the complex drivers behind rebound impacts.

Significant variations and limited evidence are available on the magnitude of rebound effects: Quantitative evidence on the magnitude of resource efficiency rebound effects is fragmented, varying widely across studies due to differences in scope, methodologies, and assumptions. While macro studies indicate large but uncertain rebound effects – up to 77% in high-demand elasticity sectors like automotive – micro and meso-level effects are smaller and less varied, often around 10% for industries like cement or steel. Studies use a wide range of methodologies, such as econometric models, input-output analysis, and computable general equilibrium models, which contribute to the variation in estimates, and gaps in empirical data remain significant. Some studies suggest that eco-design and new technologies may induce higher rebound effects compared to circular economy strategies.

Metrics for capturing resource efficiency rebound effects are very diverse, highlighting different definitions of rebound effects: Differing metrics like resource displacement, CO_2 emissions, and resource input per output, are used depending on study objectives. Aligning metrics with policy goals—such as CO_2 reduction for climate action—is crucial. Including both absolute and intensity-based metrics would provide a more complete assessment of rebound effects and resource efficiency.

Further research is needed to address transmission channels and long-term impacts: There are significant gaps in understanding indirect and macroeconomic rebound effects from industrial resource efficiency measures, as well as in comparisons between sectors. Most studies focus on direct rebound effects within individual firms or sectors, with limited exploration of broader supply chain dynamics and cross-sector interactions. Furthermore, research on long-term impacts is lacking, with most focusing on short-to-medium-term outcomes and transmission channels from firms to the broader economy.

We provide a conceptual framework of the resource efficiency rebound effects that consolidates key rebound effects and mechanisms identified in the literature: Using this framework, four sector-specific maps were developed to explore rebound impacts along value chains following the introduction of resource efficiency measures. These maps are complemented by qualitative descriptions of the drivers and mechanisms behind resource efficiency rebound impacts, providing a structured approach to understanding sectoral responses. Sector maps were further refined through seven interviews with stakeholders from industry and academia who had experience of industrial resource efficiency measures and / or rebound effects.

Workstream B – Energy Efficiency: Key findings

There is limited relevant quantitative evidence of industrial energy efficiency rebound. Seventeen studies met the literature review criteria, with only 5 UK-based studies, which were among the oldest (four published 2007-2012). The seventeen studies differed in terms of methodological approach, scope of rebound, geographical coverage, sectoral focus and classification, and time period under consideration.

Reviewed studies provide a wide range of estimates of industrial energy efficiency rebound – with methodology the key driver of variation. Three modelling approaches were identified from the existing literature – Computable General Equilibrium (CGE) models, macroeconometric models and econometric analyses, which all differed in terms of their scope, underlying assumptions and drivers. These produced a wide range of rebound estimates, with all studies finding positive effects: 18-134% - CGE model studies, 1-25% - macroeconometric model studies, 20->200% - econometric analyses. We observe that CGE models and econometric models obtain higher rebound estimates than macroeconometric modelling studies, which is due to differences in the scope of rebound assessed by these approaches, the inherent modelling assumptions and the extent to which they account for demand and supply-side effects.

The limited and diverse evidence base makes it challenging to identify precise sector-specific rebound estimates from energy efficiency measures. From this limited literature, it appears that CGE and macroeconometric studies underestimate the variability of rebound effects *within sectors*, which is better captured in econometric analyses as these typically use firm-level data. The studies provide limited evidence that more energy intensive industry sectors experience higher energy efficiency rebound effects, which may be expected as energy is a larger proportion of their overall production costs. We also observe only small differences in sector versus total economy-wide rebound magnitudes, which suggests that most of the rebound effect is occurring within the industrial sector rather than the wider economy. These hypotheses would need to be tested through further studies.

All studies observed a positive relationship between energy efficiency improvements, long-run GDP and industry sector output. This provides evidence of the linkages between industrial energy efficiency measures and increases to firm level productivity and economic growth.

Further research is needed to examine the magnitude and nature of energy efficiency rebound effects across different industrial sectors in the UK.

1 Introduction

1.1 Policy environment

The UK government is committed to delivering a net zero economy by 2050, as stipulated by the updated Climate Change Act, signed into law in 2019 (UK Climate Change Act 2008). The Climate Change Committee's (CCC's) 6th Carbon Budget, published in 2020 (Climate Change Committee, 2020), provides a pathway for the UK to progress towards that goal. The UK government is legally mandated to deliver each carbon budget, so the CCC's work provides a clear direction of travel for policy and targets, for annual emissions between the current day and 2050. There is recognition in the Carbon Budget Delivery Plan (HM Government, 2023) that substantial emissions savings could be delivered through greater industrial resource and energy efficiency.

Resource efficiency (RE) has been defined by DESNZ as "the optimisation of resource use so that a given level of consumption can be met with fewer resources" (HM Government, 2023). RE measures can be introduced at any stage in the life cycle of a product, i.e. production, consumption or end-of-life. Examples of RE measures include: using a reduced quantity of materials in production and/or making lighter products (such as lighter/smaller cars), using recycled materials in production (such as recycled steel, recycled plastic), new circular economy business models (such as car clubs, clothing rental) and improving product lifespan (such as increased product reuse, improved product repairability). These measures can enable the transition from a linear "take, make, and dispose" economy to a circular economy, where materials and products are kept within the economic system at their highest value for as long as possible. Historically, waste management and circular economy were less integrated with climate policy (Cooper-Searle, Livesey, Allwood 2017), but the UK government is progressing plans to develop a Circular Economy Strategy for England (HM Government, 2024), through which the UK government, industry and civil society reduce emissions and accelerate to net zero.

Similarly, energy efficiency (EE) improvements will be an important mechanism for delivering the UK government's transition to net zero. Since 2019, the Industrial Energy Transformation Fund (IETF) has been a flagship funding mechanism to support industry to both develop EE opportunities (through feasibility and engineering studies) and deploy technologies that deliver EE alongside other deep decarbonisation strategies (HM Government, 2024). Alongside the IETF, there have been a range of policies, innovation support, research and industry initiatives that have contributed to improving UK government industrial energy efficiency through a mixture of: mandatory reporting and audits, fiscal incentives, industrial product standards and metering, and funding schemes that will support the commercialisation of new energy efficient technologies[1]

[1] Examples include Energy Saving Opportunity Scheme (audit), Climate Change Agreements (fiscal), Eco Design (industrial product standards and metering), Transforming Foundation Industries Challenge (funding scheme)

However, while policies to deliver resource and energy efficiency are a key component of moving towards a net zero economy, they bring with them inherent challenges. Alongside the difficulty of ensuring that policy interventions lead to the kind of technological and behavioural change required, a major challenge is the existence of potential rebound effects.

Rebound effects can undermine the intended benefits of efficiency measures, where efficiency improvements in technology or processes stimulate energy or resource demand (primarily via cost-savings), in turn partially or wholly offsetting expected reductions in energy or resource use. Understanding the nature, drivers, and scale of potential rebound effects is therefore critical for designing effective policies that achieve their intended goals. Section 2 of this report provides a detailed introduction to rebound effects, expanding on guidance and definitions in the literature, including from the UK Green Book (HM Government, 2022).

1.2 Scope of research

This report combines two research workstreams, which explore rebound effects associated with industrial resource efficiency (Workstream A) and energy efficiency (Workstream B).

Workstream A focused on industrial resource efficiency rebound effects and aimed to address the following research objectives:

- **A1:** Critically review the available evidence on industry resource efficiency rebound effects.
- **A2:** Develop a conceptual mapping and framework of rebound effects occurring from key resource efficiency measures (e.g., lightweighting, lean design, material substitution, reduced overdesign) for four priority industrial sectors, namely (1) steel, (2) cement and concrete, (3) automotive and (4) construction.

Workstream B focused on industrial energy efficiency rebound effects and aimed to address the following research objectives:

- **B1:** Critically review available evidence on magnitude, drivers, and variability of industrial energy efficiency rebound effects, and on valuing related output effects in monetary terms.

The following research questions detailed in Table 1 have been used to structure the analysis in this report, and address the research objectives outlined above.

Table 1: Research questions and sub-questions for this research

Workstream A: Resource Efficiency
1. What are the main factors that contribute to rebound effects for industrial resource efficiency measures, and the mechanisms through which they take effect? 2. What are the key metrics and data that have been used to monitor and measure rebound effect in industrial resource efficiency measures? What are their limitations?

3. Where available, what does the evidence suggest about the potential magnitude of rebound effects for industrial resource efficiency measures? 4. How are industrial resource efficiency rebound effects likely to vary between sectors and different types of measures? Which of the priority measure and sector types are most likely to generate large rebound effects? 5. What is the extent and quality of evidence available on industrial resource efficiency rebound effects, in terms of the methodologies used, relevance of the study population, sample size, etc? 6. What are the main evidence gaps? How could these be addressed by further research?
Workstream B: Energy Efficiency
1. What quantitative evidence is available on the magnitude of rebound effects from industrial energy efficiency measures? 2. What methodologies are used in the literature to value industrial energy efficiency rebound in monetary terms and what are their relative merits? 3. What are the main evidence gaps? How could these be addressed by further research?

1.3 The structure of this report

The remainder of this report is structured as follows:

- **Section 2** defines rebound effects and outlines their key characteristics, including a review of the UK Green Book on Appraisal and Evaluation in Central Government. It also examines the range of potential energy and resource rebound effects magnitudes, the mechanisms behind, existing quantification methodologies and common challenges encountered when measuring rebound effects.
- **Section 3** explores the industrial resource efficiency rebound effect, summarising key findings from a comprehensive review of the existing literature.
- **Section 4** introduces conceptual frameworks for selected priority sectors and resource efficiency measures, illustrating how the industrial resource efficiency rebound effect operates and identifying the mechanisms driving these effects in each sector.
- **Section 5** synthesises evidence on the industrial energy efficiency rebound effect, drawing on the literature to provide an integrated understanding of the scale and implications of these effects.

2 Definitions and key aspects of rebound effects

Rebound effects from resource and energy efficiency measures drive unintended increases in energy and resource consumption. Drawing on the guidance of the UK Green Book on Appraisal and Evaluation in Central Government (2022), herein 'HMT Green Book', and in particular the DESNZ (2023) supplementary guidance '*Valuation of energy use and greenhouse gas (GHG) emissions',* this section explores rebound effects in detail, offering a comprehensive framework for understanding and measuring these effects. It defines energy and resource efficiency rebound effects and categorises them into direct, indirect, and macroeconomic types. It further examines the levels at which these effects occur – micro, meso, and macro – and their cumulative impacts. Key mechanisms driving rebound effects, such as income, substitution, output, and reinvestment effects, are also explored, shedding light on how economic responses influence resource use.

This section introduces the main methodologies for quantifying rebound effects, including modelling approaches such as macroeconometric models, computable general equilibrium (CGE) models, and econometric analyses (these are explored further in section 5). It also outlines some of the key the challenges associated with measuring rebound effects, including variations in model designs, distinguishing between short- and long-term impacts, and the complexities of capturing economy-wide effects.

Green Book guidance on rebound effects and proposed adjustments

The HMT Green Book and supplementary guidance discuss the rebound effect associated with energy efficiency measures. It describes the rebound effect as a phenomenon where improvements in energy efficiency can lead to reduced energy savings or increased energy consumption, partially or wholly offsetting the anticipated environmental and climate benefits.

The resource efficiency rebound effect, which is not referenced in the UK Green Book, is analogous to the energy efficiency rebound effect. It refers to the phenomenon where improvements in resource efficiency can lead to reduced resource savings or increased resource consumption, partially or wholly offsetting the anticipated environmental and climate benefits.

In extreme cases, the rebound can result in a backfire effect, where total energy and/or resource use increases compared to the baseline. As shown in Table 2, the rebound effect can vary widely in magnitude, from super-conservation to backfire, depending on the extent to which increased energy or resource consumption offsets the original efficiency gains.

Table 2: Spectrum of possible energy and resource rebound magnitudes

Rebound size	Rebound type	Description
< 0%	Super-conservation	The energy and/or resource savings exceed those which were expected
0%	No rebound	All of the expected energy and/or resource savings are realised
1-99%	Partial rebound	Some, but not all, of the expected energy and/or resource savings are offset by rebound effects
100%	Full rebound	All of the expected energy and/or resource savings are offset by rebound effects
> 100%	Backfire	Efficiency intervention is counter-productive and leads to an overall increase in energy and/or resource consumption

The HMT Green Book further categorises energy efficiency rebound effects into two types, which are also applicable to resource efficiency rebound effects:

- **Direct rebound effects**, where efficiency improvements lead to increased energy or resource consumption within the same consumption area. For example, improving the energy efficiency of a heating system lowers the cost of heating, which might encourage users to heat their homes for longer periods or to higher temperatures, reducing energy savings or even increasing overall energy consumption despite the efficiency improvement. Direct effects are often estimated using econometric models that analyse the relationship between efficiency improvements and changes in consumption patterns.
- **Indirect rebound effects,** where savings, from resource or energy efficiency improvements, are redirected to purchase other goods and services, thereby increasing overall consumption. For instance, money saved on energy bills, through energy efficiency measures, might be spent on additional travel or purchasing new electronic devices, both of which require energy for production and use. These indirect rebound effects could be estimated using dynamic input-output matrices, CGE models or macroeconometric models, which analyse how changes in output from one sector affect demand throughout the economy.

Beyond these two types of effects, a third type can be added:

- **Macroeconomic rebound effects**, which occur when efficiency improvements lead to a reduction in the real price of resources, which has ripple effects throughout the economy.

These efficiency improvements could arise through a change in industry composition, economic growth, changes in labour supply and changes in investment flows that affect energy and resource use. Macroeconomic rebound effects can happen domestically and internationally. For example, efficiency improvements, and cost savings, in UK production processes could increase the competitiveness of UK businesses, leading to higher UK exports and associated reductions in production, output, and emissions abroad. Alternatively, if cost savings lead to greater consumption of imported goods, production, output and emissions in other countries may rise as a result. Macroeconomic impacts can be estimated using macroeconomic models, such as macroeconometric and computable general equilibrium models.[2]

The total rebound effect is the combination of the direct, indirect, and macroeconomic effects.

Level of rebound effects

Rebound effects can also be observed at multiple levels:

- **Micro level**: Concerning the rebound effects resulting from the actions of individual firms or consumers, this level examines how specific behaviours and decisions by these economic agents influence resource or energy use, potentially leading to unintended increases in consumption. For example, if the adoption of recycled concrete in new buildings lowers construction costs due to relatively lower price of reprocessed materials compared to virgin resources, then this cost reduction could encourage real estate developers to incorporate larger volumes of concrete into their construction than originally planned. Micro level effects are usually assessed through case studies, surveys, and interviews with individual companies or consumers.
- **Meso level**: Concerning the rebound effects at the sector or supply chain level, this level focuses on how efficiencies and behaviours within a specific sector influence resource consumption, production patterns, and interactions with interconnected firms and industries. For example, if efficiency improvements lead to lower material costs, the rebound effect could be higher demand for that material. Meso effects are usually estimated using sectoral analyses, and system dynamics models which quantify how improved efficiencies in one sector can impact overall demand and production across related sectors.
- **Macro level**: Concerning the rebound effects at the economy-wide level, this focuses on the broader economic implications of resource and energy efficiencies, including their impact on overall market dynamics, aggregate consumption patterns, and systemic resource use. For example, if the price of resources decreases due to efficiency gains, there may be widespread price and quantity adjustments across the economy. These effects can be analysed using macroeconometric models, computable general equilibrium models or dynamic input-output tables, which consider the interconnected nature of economic activity and its impact on demand for energy and resources.

Examining rebound effects at the micro level (i.e., focusing on individual households or firms) reveals personal or firm-level responses that may appear minor in isolation but, when

[2] Rebound impacts that arise outside of the UK are outside the scope of this research.

combined, can significantly shape sectoral and regional trends at the meso and macro levels. At the meso level, analysing these cumulative impacts highlights how sectors or communities are affected, providing insights that can inform local policies and planning. At the macro level, rebound effects demonstrate how these influences extend across the wider economy, affecting GDP, employment, and trade dynamics.

Annex 1 builds on the classification of rebound effects in this section by including illustrative examples of each type (direct, indirect, macroeconomic) at each level (micro, meso, macro).

Rebound effects can occur from different feedback mechanisms, which are typically driven by cost savings and the price elasticity of demand and supply. Key mechanisms include:

- **Substitution effects**: where efficiency-induced cost savings lead to lower prices of outputs from the more efficient production line, encouraging consumers to increase consumption of these products. Additionally, firms may substitute production inputs towards cheaper, more efficient alternatives, thereby increasing overall resource and energy use.
- **Income effects**: where efficiency-induced cost savings increase disposable income for consumers or firms. As a result, individuals and firms may increase their overall consumption of goods and services, increasing related resource and energy consumption.
- **Output effects**: cheaper production costs due to efficiency measures allow firms to supply more output at a given price, thereby increasing production and related resource and energy consumption.[3]
- **Reinvestment effects**: where firms choose to reinvest cost savings into expanding operations, which can drive higher production levels and resource use. For example, these savings might fund the purchase of additional equipment, hiring more staff, or entering new markets. The scale of this effect depends on the responsiveness of markets: increased demand for the goods produced and the firm's ability to scale up operations can amplify the rebound effect.

Quantification methodologies

The HMT Green Book focuses more on direct rebound effects for policy appraisal. However, there are a range of different methodologies reported in the wider literature to measure different scope of rebound effects, including indirect and macro-level.

In the context of energy efficiency, three primary methodological approaches are commonly used: (1) Computable General Equilibrium (CGE) models, (2) macroeconometric models, and (3) econometric analysis techniques. CGE models simulate interactions between energy, the economy, and the environment, treating energy efficiency improvements as exogenous (determined outside the model) reductions in energy demand and estimating rebound by comparing expected and actual energy consumption. Another common methodological approach is macroeconometric modelling, which employs regression-based equations to represent entire economies, using scenario analyses to estimate rebound effects by

[3] The change in production levels in response to a change in product prices is referred to as the price elasticity of supply. If firms can readily increase output in response to lower costs, their supply is considered “elastic”.

contrasting energy use after efficiency improvements with baseline scenarios. Lastly, econometric analyses are used to analyse firm-level data, estimating rebound directly through calculated energy elasticities. The differences between these approaches and the implications of this for rebound estimates is discussed in detail in section 5.1 of this report.

For resource efficiency, changes at the firm or consumer level have been typically assessed through case studies, surveys, and econometric analysis. Meso-level effects are examined using sector-specific econometric analysis, production function analysis, and input-output analysis to understand how resource efficiency improvements impact sectors or supply chains. At the macro level, efficiency gains often lead to price adjustments across the economy, which can drive growth in resource-intensive sectors and increase overall resource consumption, offsetting some of the initial gains. These macroeconomic effects are usually analysed with macroeconometric models, CGE models or dynamic input-output matrices, which simulate economic interconnections and feedback loops.

3 Literature review of industrial resource efficiency rebound effects.

The insights from the Workstream A literature review are structured to directly respond to the research questions listed in Table 1. Each research question is a sub-heading in this section. Key insights are presented, with supporting evidence, and a discussion of any limitations – including the limited number of studies that were identified as relevant. The methodology for the literature review is outlined in detail in Annex 2.

3.1 What are the main factors that contribute to rebound effects of industrial resource efficiency measures, and the mechanisms through which they take effect?

The factors that contribute to rebound effects of industrial resource efficiency are inherently tied to:

- The level of analysis – whether at the micro (firm, consumer), meso (sector, supply chain), or macro (economy) scale,
- The type of rebound being measured, which can be classified as direct, indirect, or macroeconomic.
- The specific resource efficiency measure being implemented in a specific industrial sector.

The existing literature is diverse, as studies may only focus on a specific level of analysis or type of rebound effect. From this diverse literature base, the most empirically studied drivers of industrial resource efficiency effects are income and substitution effects on the demand side, and production effects, on the supply side. There can also be factors related to economic growth.

Demand side factors:

Rebound effects can result from increases in overall **demand** due to:

- **Income and substitution effects from a reduction in prices**: rebound effects can occur when there is a net reduction in the price of products due to cost-saving efficiency measures. As efficiency measures decrease costs and/or prices, consumers and firms often find themselves with more income. This can lead to increased spending on both the same goods and services and on other items, further driving up demand for resources in other sectors (Pfaff & Sartorius, 2015). While cost reductions can lead to lower prices, this does not always happen uniformly across industries or markets. Instead, it will depend on:

  - **Cost savings and price elasticity**: When efficiency gains lead to reduced production costs – whether through utilising cheaper resources or using fewer resources overall – this can result in lower prices for goods. In price-sensitive markets, these price decreases can stimulate higher consumption of both primary and recycled materials, triggering a rebound effect. Essentially, price elasticity reflects the responsiveness of resource consumption to changes in prices driven by improvements in resource efficiency (see Table 2).
  - **Market competition**: The level of market competition significantly influences the manifestation of rebound effects following resource efficiency improvements. In highly competitive markets, firms are more likely to pass cost savings from efficiency gains onto consumers through lower prices, leading to increased demand and potential direct rebound effects (Gillingham et al., 2016). Conversely, in less competitive markets, firms may retain these cost savings as higher profit margins, resulting in smaller rebound effects due to stable consumer prices. However, the retained profits in less competitive markets can lead to rebound effects if firms reinvest profits and expanding their operations.
  - **Price stickiness**: Prices can be "sticky," meaning they do not adjust immediately to changes in costs. This can occur for example due to contracts, menu costs, or consumer expectations (Baker et al., 2020). As a result, even if costs decrease from efficiency improvements, prices may not fall in the short term, which limits the potential rebound mechanisms.
  - **Regulatory environment**: Government regulations, taxes, and subsidies can also influence whether cost savings are passed on to consumers.
- **Creation of parallel demand**: In some cases, recycled or refurbished “secondary” products may fail to offer the same performance or appeal as new items, limiting their ability to fully displace demand for new products. Instead, these secondary products may coexist with new products, resulting in less-than-expected reductions in the consumption of primary resources. If recycled products are cheaper, substitution effects can lead consumers to buy more recycled products and fewer new ones. At the same time, income effects from lower prices of recycled or refurbished products may enable consumers to expand their overall consumption. Moreover, the availability of recycled or refurbished products can lower the effective cost of ownership for new products, further increasing demand for new items. Zink & Geyer (2017) also explain that when recycled and refurbished products <u>do</u> compete with primary products, it results in a higher supply of products in the market. This in turn can reduce product prices, enabling new buyers to enter the market because of the lower price and providing more resources to the original buyers who would have paid the original higher price.

Supply side factors:

The rebound effect can also arise through **supply side** factors whereby resource efficiency improvements reduces costs and increases the profitability of production in a company. This can lead to:

- **Output effects**: Resource efficiency measures can drive higher output when cost savings allow companies to produce more goods at a given price. In such cases, the cost savings from efficiency improvements are often passed on to consumers, either by lowering product prices (making the goods more attractive) or by enabling firms to expand production capacity to meet previously unserved demand. For instance, in the packaging industry, reducing the amount of plastic used per unit can lower production costs. However, as companies can produce more packaging at a lower cost, the overall demand for plastic packaging may increase. The role of price elasticity of supply is crucial in determining the scale of the output effect. When supply is elastic, firms can quickly adjust production in response to increased demand, amplifying rebound effects. Conversely, in industries with fixed production capacities, such as steel production via blast furnaces, supply is relatively inelastic and less sensitive to price changes in the short term. In such cases, even if efficiency improvements reduce costs, the resulting change in production is limited, leading to smaller changes in overall production of steel. However, the opposite dynamic may also occur: if demand falls, for example, due to lightweighting or other efficiency measures, production levels are unable to change significantly in the short term.
- **Re-investment**: When firms achieve cost savings through efficiency measures, they may choose to reinvest these savings into improving their operational processes, expanding their capacity, or diversifying into new product lines. For instance, in the case of lightweighting in the automotive industry, while manufacturers initially save materials by using lighter alternatives like aluminium or composites, they often reinvest these savings into enhancing other aspects of vehicle design. As Kawajiri et al. (2020) point out, despite resource efficiency efforts aimed at lightweighting, vehicle weights have paradoxically increased over time due to added features. This could be referred to as a design rebound, where savings from lightweighting are funnelled into making vehicles larger or more feature-rich, which may increase the total resource intensity of each vehicle. Moreover, lightweight materials like aluminium or carbon fibre could require more resource-and energy intensive processes to manufacture or to recover and reprocess than commodity steel. Even though these materials reduce the vehicle’s weight and improve fuel efficiency, they can contribute to higher overall resource use during their production, which undermines the environmental drivers of improving the efficiency of resource use.

Efficiency improvements can also lead to spillover innovation and growth effects. For instance, the development of lighter, stronger materials aimed at improving fuel efficiency in vehicles may not only reduce resource consumption in transportation but could also inspire innovations in other industries, such as aerospace, construction, or manufacturing. These technological advancements can boost productivity and enable the creation of new products or industries, driving broader economic growth. However, this economic growth may also lead to higher overall resource use, as increased production and consumption demand more resources and energy. These growth-driven rebounds are harder to quantify, as they are driven by longer term innovation spillovers and economic expansion rather than shorter term changes in product prices, but they are crucial for understanding the long-term impacts of RE improvements on resource use.

A key consideration is what is motivating the introduction of industrial resource efficiency measures in a specific sector or market as this influences the rebound effect.

The reasons for introducing industrial resource efficiency measures can vary considerably, from external factors like policy-driven mandates or technological advancements assumed to improve efficiency, to internal drivers where firms actively may pursue efficiency gains for cost savings, competitive advantage or to meet corporate sustainability goals. These variations can also influence the way rebound effects are modelled and measured.

More specifically, external (to the firm) factors, such as sector-wide improvements driven by regulation or technological advancements, are likely to have a macro-level impact, which can be analysed using a macroeconomic model. Efficiency gains across an entire sector or economy may stimulate widespread growth in production and consumption. In contrast, internal drivers, such as firm-driven resource efficiency initiatives, are typically modelled at the micro level, reflecting the choices firms can make in response to resource efficiency measures being introduced. For example, firms can recover their investment costs by reinvesting efficiency savings into scaling production, diversifying their offerings, or enhancing competitiveness, which could all lead to increased production or consumption.

The market dynamics, including the level of competition and structure of the supply chain, will also influence the rebound effect. Siderius & Poldner (2021), suggest that rebound effects from circular economy strategies are shaped by broader market dynamics, including the level of competition. Structural factors like supply chain configurations also play a role. Vegter et al. (2023) find that shorter supply chain lead times can lead to producers being more responsive to fluctuations in demand or prices. There may also be larger indirect and macro-level rebound effects in longer supply chains. For example, if there are high transport and distribution needs at each stage of the supply chain, there will be higher energy use and emissions compared to a shorter supply chain (see Chen, 2021). Together, these studies illustrate how both motivations and structural factors interact to shape the scale and nature of rebound effects.

3.2 What are the key metrics and data that have been used to monitor and measure rebound effect in resource efficiency measures? What are their limitations?

Metrics for estimating resource rebound effects varied depending on the focus of the study. Common approaches include measuring resource displacement, CO_2 emissions, resource input per unit of output, and resource intensity. Resource displacement and resource input per output are often used to measure resource efficiency rebound effects at the micro and meso levels. From the reviewed literature, CO_2 emissions were more often assessed in studies focused on macro-level rebound effects. Where possible, both absolute and intensity-based metrics should be used in combination, given they capture the full-scale changes in resource use, independent of output levels or efficiency gains.

For example, a common approach in the reviewed literature was to measure the proportion of **recycled content versus primary content** used in production, as this provides a direct indication of how much virgin resource use is displaced (e.g., Ryter et al., 2022; Di Domenico et al., 2023). If these studies were to also measure absolute volumes of material used (e.g. total recycled and primary materials), they would show if cost savings associated with using recycled materials can lead to increased demand or supply.

For more efficient use of resources through lightweighting or resource substitution, another frequently used metric is the **change in CO_2 emissions,** especially at macro-level (e.g., Morimoto et al., 2021; Kawajiri et al., 2020). Some analyses also use **resource input per unit of output** (such as raw resources per product) or **resource intensity** metrics to capture the overall efficiency of production processes. Other studies focus **on final product use** such as vehicle use (e.g., Greene, 1993), which can also provide insight into how efficiency gains might inadvertently stimulate higher resource use.

Sourabh et al., 2024 uses **demand elasticity** to assess the sensitivity of consumption to changes in production costs due to resource efficiency measures. **Rebound elasticity** measures how resource consumption responds to changes in resource efficiency, typically expressed as the percentage increase in consumption resulting from a 1% decrease in the effective price of resources due to efficiency gains. For example, a rebound elasticity of 0.5 means that a 10% improvement in efficiency, which can lower resource costs, would lead to a 5% increase in resource consumption. Other studies express the rebound effect as the **percentage of observed resource consumption increase relative to the expected resource savings from efficiency improvements**. For example, if efficiency measures are expected to save 100 units of a resource but result in 50 additional units being consumed, the rebound effect would be 50%.

Some scholars suggest that **existing international standards**, such as those from the International Organization for Standardization (ISO) and the Global Reporting Initiative (GRI), should be leveraged to further develop new indicators to monitor rebound effects. Examples of such indicators could include resource efficiency gains relative to total economic output, lifecycle emissions per unit of production, or the ratio of resource savings to increased consumption. These new indicators would help measure rebound effects from a broader perspective, encompassing both environmental and social impacts (Chen, 2021).

Tracking potential increases in both **territorial and global emissions** can be a useful supplementary metric alongside others that more directly measure resource use. Territorial emissions refer to the greenhouse gases emitted within a specific geographic area, while global emissions encompass all emissions associated with a product throughout its entire life cycle, including those generated during extraction, production, and transport, irrespective of which geographic area these processes occur. This distinction is crucial because it can significantly influence how we understand the impacts of resource efficiency measures. For instance, increased resource efficiency may lower production costs, leading to greater competitiveness in global markets. This can lead to an increase in exports of resource-efficient products, which may displace production in other countries. The net effect on global resource use and emissions depends on the relative resource and emissions intensities of production in the exporting and displaced regions. If the exporting country's production is more efficient, global emissions may decrease. However, if overall productive capacity increases due to increased consumption or if the displaced production shifts to regions with lower efficiency, global emissions could rise despite territorial emissions reductions in the exporting country.

Both absolute and intensity metrics can be effectively used in combination to assess the environmental impacts of resource efficiency measures and any rebound effects. Absolute metrics provide a clear picture of total emissions or resource use, capturing the overall environmental burden. Intensity metrics, which measure emissions or resource consumption per unit of output, are useful for contextualising performance and tracking the efficiency improvements resulting from specific measures.

3.3 Where available, what does the evidence suggest about the potential magnitude of rebound effects for industrial resource efficiency measures?

Evidence on the magnitude of rebound effects in industrial resource efficiency remains limited. Despite this, some common themes can be observed across the eight academic studies detailed in Table 3:

- Most of the studies identified focused on estimating direct and macro rebound effects, with few reporting on the indirect impacts.
- Rebound effects at the macro level present wider variations and are more uncertain, due to broad economic interactions and complex feedback loops. Conversely, at the micro and meso levels, the rebound effect tends to be smaller and less variable across publications.
- Some variations exist between and within sectors, which can be partially attributed to variations in resource efficiency measures, geographical scope, time horizon, and the position of sectors within the supply chain.

Table 3: Summary of existing quantitative estimates of rebound effects

	Types and levels of rebound effect	Metrics used	Estimation method	Resource efficiency measure type	Geographic focus
Sector	***General/Whole economy level***				
Di Domenico et al., 2023	**Macroeconomic rebound effect at the macro level:** Depending on the scenario (one or multiple shocks on the energy efficiency of recycling sector),	Change in aggregated material and energy consumption	Agent-Based Stock-Flow Consistent model with a simplified Input-Output (IO)	Reuse, recycle	n/a

	Types and levels of rebound effect	Metrics used	Estimation method	Resource efficiency measure type	Geographic focus
	rebound varies from 0.5% to 3.1%		structure of production		
Pfaff and Sartorius, 2015	**Macroeconomic rebound effect at the macro level:** 3.1%	Changes in material use, energy use, and related input-output multipliers	Static input-output model in Germany. Bottom-up analysis that scales up findings from 16 resource efficiency projects across a range of non-energetic raw resources to the national level.	Eco-design and novel tech	Germany
Karakaya et al., 2024	**Macroeconomic rebound effect at the macro level:** 52%, among EU member countries	Virgin material displacement and total material use changes	Stochastic Frontier Analysis (SFA).[4]	Ex-post assessment of material efficiency improvements and rebound effects at macro-level	EU and its trading partners (1995-2019)
Sector	***Metals and mining***				
Sourabh et al., 2024	**Direct rebound effect at the meso level:** The rebound is found to be elastic in the range of −2.16 ('super-conservation') to 2.57	Aggregate resource consumption	Econometric circular economy model based on the co-flow structure in a multivariate	Reuse, recycle	India

[4] Stochastic Frontier Analysis (SFA) is an econometric method used to measure the efficiency and productivity of firms, industries, or countries.

	Types and levels of rebound effect	Metrics used	Estimation method	Resource efficiency measure type	Geographic focus
	(backfire) (or from -216% to 257%)		framework for metal industries.		
Ryter et al., 2021	**Direct rebound effect at the meso level:** Rebound effects associated with increases in recycling limit mining reductions to ~55% the mass of the scrap supply change on average	CO2 equivalent emissions	Dynamic supply chain simulation model for copper through 2040 incorporating inventory-driven price evolution, dynamic resource flow analysis, and life cycle-assessment alongside mine-level economic evaluation of opening, closing, and production decisions.	Reuse, recycle	Worldwide
Pfaff and Sartorius, 2015	**Macroeconomic rebound effect at the meso level:** 2.5% for rocks and minerals; 4.3% for nonferrous metals	Changes in material use, energy use, and related input-output multipliers	Static input-output model in Germany. Bottom-up analysis that scales up findings from 16 resource efficiency projects across a range of non-energetic raw resources to the national level.	Eco-design and novel tech	Germany
Sector	***Cement & Concrete***				

	Types and levels of rebound effect	Metrics used	Estimation method	Resource efficiency measure type	Geographic focus
Lu and Schandl, 2021	**Macroeconomic rebound effect at the meso level:** Rebound effects for the total resource use of NMM (non-metallic minerals) is expected to be 13% by 2026	Total resource use	Global Trade and Environment Model (GTEM-C) - a computable general equilibrium model with the bottom-up engineering details of energy production.	Eco-design and novel tech	Worldwide
Sector	***Steel***				
Buyle et al., 2023	**Direct rebound effect at the meso level:** From 10.5% for vector autoregressive methodology (VAR)[1] to 19.8% for Structural vector autoregressive methodology (SVAR)[2]; 4.6% increase in total stainless-steel demand in the long term **Indirect rebound effect at the meso level:** 4.6% increase in total stainless-steel demand in the long term.	Aggregate demand	Vector autoregression (VAR) and Structural vector autoregression (SVAR): dynamic models where lagged values of all included variables estimate current state of the system.	Reuse, recycle	Worldwide
Pfaff and Sartorius, 2015	**Macroeconomic rebound effect at the meso level:** 10.6%	Changes in material use, energy use, and related input-output multipliers	Static input-output model in Germany. Bottom-up analysis that scales up findings from 16 resource	Eco-design and novel tech	Germany

	Types and levels of rebound effect	Metrics used	Estimation method	Resource efficiency measure type	Geographic focus
			efficiency projects across a range of non-energetic raw resources to the national level.		
Lu and Schandl, 2021	**Direct rebound effect at the meso level:** 8.6% rebound at the sector level in 2060 **Macroeconomic rebound effect at the meso level:** Rebound effects for the total resource use is expected to be 65% by 2060	Total resource use	Global Trade and Environment Model (GTEM-C)	Eco-design and novel tech	Worldwide
Sector	***Construction***				
Lu and Schandl, 2021	**Direct rebound effect at the meso level:** Rebound effects for construction-based NMM (non-metallic minerals) is expected to be 18% by 2026	Total resource use	Global Trade and Environment Model (GTEM-C)	Eco-design and novel tech	Worldwide
Pfaff and Sartorius, 2015	**Macroeconomic rebound effect at the meso level:** 3.4% for ceramics and innovative construction resources	Changes in material use, energy use, and related input-output multipliers	Static input-output model in Germany. Bottom-up analysis that scales up findings from 16 resource efficiency projects across a range of	Eco-design and novel tech	Germany

	Types and levels of rebound effect	Metrics used	Estimation method	Resource efficiency measure type	Geographic focus
			non-energetic raw resources to the national level.		
Sector	***Automotive***				
Skelton et al., 2020	**Macroeconomic rebound effect at the meso level:** 77% of the assumed 10% efficiency improvement in the automotive sector's use of steel to be offset by economy-wide rebound effects	Share of the efficiency savings negated due to increased demand	GEM-E3 model – A dynamic GCE model.	Eco-design and novel tech	UK

[1] VAR is a statistical model used to capture the linear interdependencies among multiple time series variables. Each variable is regressed on its own lagged values and the lagged values of all other variables in the system. VAR models are useful for forecasting systems of interrelated time series and for understanding the dynamic relationships between them.

[2] SVAR is an extension of the VAR model that incorporates structural information about the relationships among the variables. Unlike standard VAR models, which treat all variables symmetrically, SVAR imposes restrictions based on economic theory to identify the underlying structural shocks affecting the system. This allows to analyse the causal relationships and dynamic effects of these shocks on the variables.

A wide variation in rebound effect estimates is observed both within and across sectors. This is likely to be influenced by the scope of rebound effects estimated in each study and the method used. We observe **differing magnitudes of rebound effects.** For example, while both studies assess rebound effects at the macro level, Pfaff and Sartorius (2015) estimate a 3.1% overall rebound from the measure of applying efficiency-related technology, whereas Di Domenico et al. (2023) report a range of 0.5% to 3.1% when applying reuse and recycling measures to enhance resource efficiency. Additionally, Karakaya et al. (2024) found rebound effects exceeding 50% across EU member states and their trade partners. This substantial variation suggests that **the scope of rebound effects need to be clarified when comparing different estimations of magnitudes**. Besides geographic boundaries, other factors include the time span examined, whether single or multiple resources are considered, the position of the firm implementing the measure within the supply chain (i.e., extraction, primary manufacture, secondary manufacture etc.) and more fundamentally, the study methodology and contextual factors. For instance, while Pfaff and Sartorius (2015) found a 10.6% rebound effect in the steel sector (due to recovery of valuable metal fractions from waste streams and resource efficiency in metal production through optimised processes), Skelton et al. (2020) estimated a 77% rebound in the automotive sector's use of steel (from reduced demand for steel from the automotive sector). While this could indicate a stronger rebound impact for efficiency measures implemented upstream and trickling down to downstream sectors, **the studies employ different methods which are likely to influence the quantitative estimates**.

3.4 How are RE rebound effects likely to vary between sectors and different types of measures? Which of the priority measure and sector types are most likely to generate large rebound effects?

Pfaff and Sartorius (2015) underscore the impact of both **sector size** and **interconnectedness with downstream activities** – particularly their contribution to total product costs – on the rebound effects of resource efficiency measures. Resource intensive, upstream sectors, such as steel, should demonstrate higher rebound values due to demand across various downstream industries. While the rebound effects in these sectors may be substantial in terms of absolute resource use, the magnitude of the rebound effect will also be dependent on resource costs as a proportion of total costs for downstream producers (see, Barlow et al., 2016; Schandl et al., 2016).

The position of a firm enacting the RE measure within the supply chain serves as an important driver of rebound effects. RE measures implemented by upstream firms, such as those engaged in raw resource extraction or primary production, have the potential to influence resource utilisation throughout the supply chain in downstream sectors, for example via changes in output prices. In contrast, firms positioned further downstream may experience varying magnitudes of rebound effects, largely shaped by their dependence on resources and intermediate products supplied by upstream sectors.

If firms do invest in efficiency improvements, the savings generated may initially be used to cover the costs associated with these investments, such as operational expenditures (OPEX) and capital expenditures (CAPEX). In this scenario, rather than leading to increased consumption immediately due to reinvestment in output, the savings are redirected to offset the initial investment, potentially delaying the onset of the rebound effect. This relationship highlights the importance of considering not just the resource savings from efficiency improvements but also how the costs associated with implementing resource efficiency measures could be financed.

The rebound effects from RE measures in industries such as cement, steel, and construction are likely influenced by factors such as substitutability of recycled

resources, inefficiencies in recycling processes, and supply-demand dynamics in resource markets.

Cement and concrete

The UK cement and concrete market mainly supplies materials to construction and infrastructure projects, operating as a business-to-business (B2B) industry. The market is dominated by a few large players selling commodity products, though certain types of concrete are differentiated by their performance. Resource costs, especially for raw materials and energy, play a big role in pricing, making efficient use of these resources essential for staying competitive.

Zhang et al. (2023) investigate the rebound effects associated with resource efficiency measures, associated with recycling concrete. A comparative life cycle assessment (LCA) was used to assess the engineering material footprint (EMF) and the fossil fuel material footprint (FMF) in closed-loop recycling of concrete. The authors identify two triggers of a potential rebound effect:

- **Limited substitutability**: Recycled resources often do not fully substitute virgin resources due to differences in physical and chemical properties. This means that while cement recycling can reduce the amount of virgin resources used, it cannot displace virgin resources entirely without compromising performance.
- **Resource use in the recycling process:** while recycling reduces the resource footprint, the carbon footprint from processing and downcycling (when recycled resources are of lower quality than the original) can partially offset the benefits. The magnitude of the rebound effect, and the implications for carbon emissions, can vary based on transportation distances and energy consumption during recycling processes.

Steel

The steel industry also operates primarily on a B2B model, serving various sectors, including construction, automotive, and manufacturing. This market is characterised by significant global and regional trading of steel commodities, with prices set in regional and global markets. The elasticity of supply is low in the short run, particularly for blast furnaces, which are designed and operated to run continuously, regardless of fluctuations in material prices (e.g. of iron ore, scrap metal or steel). The cost of resources is critical, as it directly affects the overall profitability and pricing strategies within the sector.

Buyle et al. (2023) investigate the impact of recycling ferrochrome from carbon and stainless steel slags, specifically examining how this influences resource consumption and market demand in the metals sector. Utilising a vector autoregression (VAR) model[5], the research

[5] A Vector Autoregression (VAR) model is a statistical method used to capture the linear interdependencies among multiple time series variables, treating each variable as a function of its own past values and the past values of all other variables in the system.

quantitatively assesses the income and substitution effects associated with reclaimed ferrochrome which is an alloy used in the production of stainless steel. The study shows that a drop in ferrochrome prices results in a projected 6% decrease in stainless steel prices, which subsequently boosts total stainless steel demand by 4.6% in the long term. This outcome demonstrates the existence of a rebound effect and highlights the importance of evaluating the wider impacts of resource efficiency improvements across entire supply chains, rather than limiting the focus to individual markets. It also points out that the expected one-to-one replacement of primary resources with secondary ones is often unrealistic, due to the complex interplay of rebound effects, including shifts in consumption patterns and increased overall demand**.**

Sourabh et al (2023) focus on the implementation of circular economy measures in India's metal industry, particularly copper production, over time. The authors employ an econometric model that captures the relationships between primary and secondary metal production. The analysis reveals that the direct rebound effect resulting from these circular economy practices show significant year-on-year fluctuations in rebound elasticity (from −257% to +216%). Building on the definitions outlined in Table 2: Spectrum of possible energy and resource rebound magnitudes the copper industry experiences partial rebound effects in certain years (2022, 2023, 2025, 2026, and 2028), while a "backfire" effect occurs in 2027, where increased secondary copper production coincides with peak primary copper production, leading to oversupply and limited displacement of primary materials. Conversely, super-conservation is observed in 2024, 2029, and 2030 due to declines in primary production. Resource displacement shows minimal variation initially but surges in 2026, driven by a spike in secondary production, before collapsing thereafter. **This complexity underscores the need to assess rebound over a long period of time given the potential annual variability in rebound impacts.**

Construction

The construction sector operates predominantly as a B2B market, with firms providing services to property developers, government agencies, and other clients. The industry is fragmented, consisting of many small and medium-sized enterprises, alongside a few large players. Construction materials can be differentiated (e.g., sustainable building materials vs. traditional ones), but many inputs are commodities. The elasticity of supply varies significantly, influenced by the specific project, geographic location, and regulatory environment. Resource costs, including labour and materials (including cement, concrete and steel), are crucial to final project costs.

Lu and Schandl (2021) analysed how sectoral resource efficiency improvements in the **iron and steel sector, non-ferrous metals (NFM), and non-metallic minerals (NMM) for construction sector** can lead to GHG emissions reductions at both sectoral and economy-wide levels. Using the Global Trade and Environment Model, a computable general equilibrium (CGE) model, the authors explore the impact of different resource efficiency measures including: using fewer inputs in the production process, improving the production process and also changing demand for products. **The findings show varied rebound effects: while the output efficiency improvement in the iron and steel sector results in only an 8.6%**

rebound effect at the sector level by 2060, the economy-wide (macro) rebound effect reaches 65%. When looking at the rebound effect of resource efficiency improvements in NMM for use in construction, (e.g., aluminium for window frames, copper for roofing and plumbing, and zinc for cladding and gutters), the estimate of the economy-wide rebound effect is smaller than the rebound effect within the sector (13% vs 18%). The authors propose that this might be because reducing NMM use in infrastructure and buildings will not significantly reduce the cost of construction projects or services provided by the construction industry, as NMM only accounts for ~15% of construction-sector output in value terms although they make up almost half of total material use in tonnes. **A key consideration is therefore the extent to which resource efficiency measures impact overall production costs and product prices.**

In Pfaff and Sartorius (2015)**,** the study examines the rebound effects related to ceramics and innovative construction resources. They estimate that resource efficiency improvements in these sectors could lead to a 3.4% rebound effect. The rebound is relatively low due to the limited substitutability of these materials.

Automotive

The automotive sector predominantly operates in a Business to Customer (B2C) context, with large auto manufacturers supplying vehicles in a competitive market to dealerships and directly to drivers. Vehicles are differentiated products, and the supply is moderately elastic, influenced by production capacity, labour availability, and technological advancements. Resource costs, particularly metals and plastics, play a vital role in overall manufacturing costs, impacting vehicle pricing and, in turn, consumer demand.

Skelton et al. (2020) studied efficiency improvements in the steel and automotive sectors through a recursive dynamic[6] global and EU-specific computable general equilibrium (CGE) model. Efficiency gains are categorised into three types: upstream energy efficiency, which reduces energy demand in the steel sector; resource efficiency, which specifies a 10% reduction in steel used for car production by minimising scrap generation which could be achieved by reducing the amount of scrap steel that is generated when making cars; and downstream product service efficiency, which reduces car demand to meet travel needs. The modelling showed substantial macro level rebound effects, with estimates of a rebound of 7% for energy efficiency, 77% for resource efficiency, and 85% for demand reduction scenarios. The monetary savings are similarly large, amounting to EUR 9 billion for energy efficiency, EUR 15 billion for resource efficiency, and EUR 50 billion for product service efficiency. However, the authors also highlight the limitations of the study, including that the modelling results are significantly impacted by income and price elasticities, assumptions that cost savings are passed on to consumers without profit, and the assumption that efficiency improvements are implemented without any cost incurred.

[6] Recursive dynamic CGE models simulate the economy over multiple periods, where the outcome of one period influences the next

Measure-specific variations

The type of industrial RE measure directly influences the magnitude of the rebound effect. Specifically, measures that focus on eco-design and novel technologies tend to be more susceptible to larger rebound effects compared to those centred around circular economy strategies or the use of recycled content, as the former can boost demand by making products more affordable or desirable, without any specific aim to maintain or reduce consumption levels by promoting reuse, recycling, and resource efficiency. Circular economy strategies also face specific challenges due to the lack of full substitutability and creation of parallel demand, and the need for further resource and energy inputs (for example with recycling or reprocessing).

Eco-design, which typically aims to create more resource-efficient products, can unintentionally lead to greater demand due to lower operating costs and incentivising increased consumption. This rebound effect is more likely to occur in instances where product design makes items more accessible or affordable to a larger market. Zink and Geyer (2017) highlight if more resource efficient products lower costs to use, it can encourage more consumption of these products which could increase overall resource use. Another potential rebound effect associated with eco-design is the creation of a parallel source of demand alongside conventional products (e.g. lightweight steel vs crude steel), so more resources are consumed overall if they attract new consumers who previously did not purchase such products. For instance, Gillingham et al. (2016) discussed how the development of lighter, stronger resources for the automotive sector, while improving fuel efficiency, can spur demand for lightweight materials in other industries. Finally, novel technologies can trigger rebound effects when they lead to enhanced product performance or functionality, which in turn can increase overall market demand.

Advocates of circular economy practices like recycling, remanufacturing, and resource reuse assume that these measures will primarily displace virgin resources without considerably expanding overall market demand, as they do not usually offer the improved functionality or cost reductions for product manufacturers that can drive increased production or demand (Zink and Geyer, 2017). Widmer et al. (2018) found that, compared to other resource efficiency measures, refurbishing and remanufacturing are more likely to trigger rebound effects in terms of CO_2 footprint as these activities often require extensive transportation over long distances and continue to rely on some new parts and materials.

The European Commission (DG ENV, 2011) finds that **general-purpose technologies, which can be applied across a range of uses, tend to cause stronger rebound effects than specific-purpose technologies**. Once a threshold level of operational efficiency is reached, these technologies tend to permeate the entire economy, contributing to consumption growth and economy-wide rebound effects.

3.5 What is the extent and quality of evidence available on industrial RE rebound effects, in terms of the methodologies used, relevance of the study population, sample size, etc?

The evidence base on industrial resource efficiency rebound effects remains limited. While many studies focus on specific aspects of the resource efficiency rebound effect—such as firm-level or macro impacts—the connection between the key channels and causal pathways through which the rebound effect is triggered remains largely unexplored.

The literature on rebound effects underscores the need to address several important trade-offs when assessing the scope and magnitude of these effects across various contexts. One major challenge is the **methodological diversity** present in the literature, where different approaches offer varying strengths in capturing distinct dimensions of rebound effects. For instance, some methods are adept at analysing firm-level dynamics, such as production decisions and technological adoption, while others focus on broader economic systems, examining macroeconomic feedbacks and indirect effects. These differences in methodological focus complicate the task of providing a holistic view of rebound effects, as the findings from one approach may not always be directly ‘connectable’ to another (i.e., from micro to meso level).

Furthermore, as some researchers (e.g., Siderius and Poldner, 2021) have pointed out, **new assumptions** and **quantification models** are needed to better describe rebound effects, particularly for circular economy strategies. For instance, traditional neoclassical assumptions, such as the idea that consumers and firms are rational actors always maximising utility or profits, may be less applicable in circular economy contexts, where factors like sustainability goals, environmental consciousness, and non-monetary incentives can play significant roles in decision-making. As a result, **alternative behavioural models** that consider bounded rationality, social preferences, or institutional constraints may offer more accurate representations of how firms and consumers respond to resource efficiency measures.

Moreover, macroeconomic models like CGE models can often be seen as a **"black box"** when it comes to understanding the **specific transmission channels** of rebound effects. While they capture broad economic trends, they do not always explain the precise mechanisms through which resource efficiency improvements in one sector translate into broader economic responses. This lack of transparency in the modelling process can hinder efforts to identify the **key channels** through which rebound effects are transmitted, such as changes in price signals, shifts in consumer preferences, or adjustments in production processes. As a result, the insights provided by these models may be useful for estimating the **magnitude** of rebound effects, but less effective in uncovering the **causal pathways** through which these effects materialise.

Differences in model design – such as geographical and sectoral coverage, as well as the handling of financial systems and markets – lead to considerable **variability in estimates**. Some models may focus on specific sectors or countries, while others take a broader approach, resulting in a wide range of rebound effect estimates. Another challenge in quantifying rebound effects lies in **distinguishing between short-run and long-run impacts**. Short-run rebound effects capture the immediate response to a resource or energy efficiency improvement. Long-run rebound effects, however, represent the cumulative impacts that emerge once all iterative and interactive economic effects have fully stabilised. Furthermore, CGE and macroeconomic models define the short and long run differently (see section 5.1).

3.6 What are the main evidence gaps? How could these be addressed by further research?

Key evidence gaps include a lack of empirical data on indirect and macro-level rebound effects from industrial resource efficiency measures, as well as limited cross-sectoral comparisons. Most studies focus on direct rebound effects within specific sectors or firms, leaving broader supply chain impacts and cross-sector interactions underexplored. Additionally, research on the long-term impacts of resource efficiency measures is insufficient, with the majority of studies concentrating on short- to medium-term outcomes.

There is a noticeable **lack of firm-level studies that explore the specific motivations and strategies firms adopt when implementing resource efficiency measures and the conditions for different demand side and supply side rebound effects to occur**. While macroeconomic models and industry-wide studies offer valuable insights, they often overlook the complex decision-making processes within firms, such as how profit incentives, regulatory pressures, or supply chain dynamics shape resource efficiency strategies. Future research could benefit from detailed case studies, firm-level surveys or balance sheets analysis that delve into these decision-making processes, particularly across different sectors.

Research often overlooks the **costs associated with implementing resource efficiency measures,** including operational expenditures (OPEX) and capital expenditures (CAPEX). This can also be observed from the literature reviewed in Workstream B in section 5. These OPEX and CAPEX costs can significantly influence rebound outcomes by affecting firms' pricing strategies and, in turn, consumer demand. For instance, high implementation costs may limit firms' ability to lower prices despite improved efficiency, reducing the income and re-spending effects arising from any cost-savings. Conversely, if firms can pass on cost savings to consumers through lower prices, this could stimulate increased consumption, leading to a rebound effect. However, empirical data on how these costs impact firms' pricing strategies and consumer demand is minimal. Consequently, the cost of implementing resource efficiency measures is not always included in macroeconomic modelling studies (see Workstream B for further examples of this).

The existing research often overlooks the competition dynamics, for instance cost pass-through associated with resource efficiency measures. More empirical studies are needed to investigate how changes in production costs stemming from resource efficiency measures influence pricing strategies for products. For example, the magnitude of the rebound effect could be bounded by the ability or preferences of firms to pass-through the reduction in costs to prices. These preferences may also differ between firms in the same sector.

Examining how different sectors respond to cost reductions through price adjustments can provide insights into the broader implications of resource efficiency on market behaviour.

Another significant gap lies in the lack of studies that assess how industrial resource efficiency measures and their associated rebound effects **evolve over time**. Most studies, such as those by Skelton et al. (2020) and Figge & Thorpe (2019), tend to focus on static or short-term analyses. This limits the ability to assess how long-term technological advancements, market dynamics, or regulatory changes influence the persistence or mitigation of rebound effects. **Longitudinal research that tracks the implementation of resource efficiency measures and associated economic outcomes over multiple years would be valuable for understanding the durability of efficiency gains and potential rebound effects**.

In addition, many studies lack granularity when it comes to understanding how different circular economy strategies—such as recycling, remanufacturing, and reuse—**interact with one another to influence rebound effects**. Figge's (2019) research emphasise that as resources cannot be reused and recycled simultaneously, there is an opportunity cost associated with the decision between recycling and reuse and that will have consequences for overall resource use over time. While studies like Widmer et al. (2018) and Niero et al. (2021) touch on these strategies, they often treat them as distinct or isolated processes. Future research could explore hybrid models of circularity where multiple strategies are implemented simultaneously, assessing how they complement or exacerbate one another in terms of resource consumption and rebound effects.

Finally, the **link between micro, meso and macro level rebound effects needs further exploration.** The rebound effect is often measured at the micro level (individual or company), but translating these effects to higher levels of aggregation (such as regional or national economies) can be complex. In addition, some of these estimates are thus limited to the scope of the study and not easily transferable. The rebound effect can vary considerably across sectors. Studies show that industries such as energy or manufacturing may experience different rebound magnitudes compared to sectors like transportation or household goods (Berkhout et al., 2000). There is a need for more detailed sectoral studies to understand how resource efficiency improvements translate into rebound effects.

Ultimately, the validity of existing studies is highly context-dependent. Rather than definitive conclusions, these findings should be viewed as a means to identify key mechanisms, triggers, and conditions under which rebound effects can occur.

4 Mapping industrial resource efficiency rebound effects in key sectors

4.1 Method to develop a conceptual framework and maps

This section outlines the four-step method that was used to develop the resource efficiency maps presented in section 4.3 of this report.

The **first stage** was a review of existing sources of literature which included a conceptual map or framework showing aspects of resource efficiency rebound effects. A total of 23 studies were identified that were relevant for developing the conceptual maps but these studies had different scope, definitions and theoretical frameworks.

The **second stage** was to organise the insights from these 23 literature sources into a consolidated conceptual framework (see Annex 4). The conceptual framework was structured around four sequential questions:

1. Why is the firm introducing a resource efficiency measure?
2. What impact does the resource efficiency measure have on expenditure of factors of production and consumption along the value chain?
3. What rebound effect could be triggered at the micro, meso and macro level?
4. Why is this rebound effect triggered?

The **third stage** was using the conceptual framework to build a set of maps that visually represent the key effects and mechanisms through which rebound occurs for each of the prioritised resource efficiency sectors (steel, cement, construction and automotive) and measures (lightweighting, material substitution). These are the maps presented section 5.2 and they are supplemented by explanatory text.

The **fourth stage** involved validating the maps through seven 60-minute semi-structured interviews with stakeholders from industry and academia. Interviewees were selected based on their expertise in resource efficiency and their experience working in the four priority sectors. The interviews were all conducted online. A project brief describing the project aims and broad guiding questions/themes was shared with interviewees in advance. Interviewees were invited to share their feedback and reflections on the literature review findings (section 3) and maps (section 5.2).

The interviewer talked through each conceptual map that was relevant to the interviewee's expertise and experience. The interviewee then provided reflections on each aspect of the map based on their experience working in industry and expertise in resource efficiency rebound impacts. Interviewee feedback was incorporated into the description accompanying each map. For example, explaining the circumstances in which might be a divergence between an expected rebound impact, as described in the literature, and the experiences in industry reported by interviewees.

4.2 Introduction to the key sectors of interest

The literature review in section 3 showed that any resource efficiency rebound effect at the sector (meso) level will, in part, depend on the market and supply chain characteristics as well as the drivers for introducing a resource efficiency measure.

This section outlines the key market and supply chain characteristics of the four priority sectors – steel, cement, automotive and construction, to provide context for the detailed maps that follow in section 5.2.

Steel

Steel producers are motivated to reduce resource and energy use to enhance profitability, sustainability and global competitiveness. Globally, the sector faces pressure to reduce its carbon footprint and overall environmental impact. Regulatory requirements, such as emissions reduction targets and waste management regulations, further incentivise the industry to optimize resource use. In response, the steel sector is adopting several strategies, including the increased use of electric arc furnaces (which are lower emission), implementing energy-efficient production processes, and investing in advanced technologies for waste heat recovery and fuel/feedstock switching to reduce process and production emissions. In the UK, the steel sector is moving away from blast furnace production towards greater use of electric arc furnaces. Steelmakers are also focusing on product innovation to create high-strength, lightweight steels that improve the efficiency of end-use applications.

As suggested by Cambridge's Use Less Group, 50 years of process improvements means that the current mainstream approaches for steel production are very energy efficient. The global average energy intensity of steel making is little more than 10% above current best practice (The Use Less Group. (n.d.)). Resource efficiency measures such as greater lightweighting, through reduced overdesign, represent options for further reducing emissions associated with steel production and use. Steel is widely recycled, due to its magnetic properties, which make it easy to separate from other resources. There is a large stockpile of secondary steel globally which has been accumulated over the past century, for example in buildings and infrastructure, which means that the volume of steel recycling is projected to triple in the next thirty years (The Use Less Group. (n.d.)). Moreover, around half of the steel produced annually is wasted due to scrap generated in downstream manufacturing and construction (The Use Less Group. (n.d.)). Resource efficiency opportunities also exist therefore in downstream sectors that use steel, including construction and vehicles.

Cement

The production of cement is highly energy-intensive and generates CO_2 emissions, mainly through the production of clinker, which is driving the sector to seek cost-effective and environmentally friendly alternatives. The cement sector is increasingly using supplementary cementitious resources (SCMs) like fly ash and slag to replace a portion of clinker in cement, thus reducing energy consumption and CO_2 emissions. Innovations in manufacturing processes, such as the development of carbon capture and storage (CCS) technologies and the use of alternative fuels like biomass and waste-derived fuels, are also being developed. Additionally, the sector is introducing process efficiency improvements and promoting the secondary use of cement, by downcycling concrete and other construction resources as aggregate.

As suggested by The Concrete Centre, due to its widespread availability and low cost, the incentives to further improve resource efficiency will be lower than for resources that are scarce and/or expensive (The Concrete Centre. (n.d.)). Despite this, resource efficiency opportunities exist across the supply chain:

- **Resource efficient manufacturing**: concrete includes recycled resources and by-products from other industries. Globally, it is a net consumer of waste. The concrete industry uses 210 times more waste in the production of concrete and its components than it sends to landfill (The Concrete Centre. (n.d.)).
- **Designing for resource efficiency in use**: concrete's versatility allows for more efficient designs. For example, leaving the concrete surface exposed can eliminate the need for interior finishes, improving energy efficiency, while this exposed concrete requires less maintenance and replacement of finishes over time (The Concrete Centre. (n.d.)).
- **Designing for longevity and reuse**: the long service life and robustness of concrete facilitate the reuse of existing concrete frames. A building's lifespan can also be extended through the use of re-mountable and reusable concrete elements (The Concrete Centre. (n.d.)).
- **Designing for resource recovery:** recovered concrete can be segregated and crushed for reuse as hard core, fill or in landscaping or used as recycled aggregate in new concrete (The Concrete Centre. (n.d.)).

Construction

Rising costs, concerns about the sectors environmental footprint and regulatory pressure from building codes and standards are key drivers for greater resource efficiency in the construction sector. The sector is already adopting various strategies including the use of recycled and renewable resources, implementation of modular and prefabricated construction techniques to minimise waste, and the use of digital tools like Building Information Modelling (BIM) to optimise resource use throughout the project lifecycle.

Several guidance documents are available to help architects and civil engineers with ways to become more resource efficient, such as British Standard BS 8895-1:20131 (Allplan, 2019). Evidence from the World Green Building Council suggests that resource efficiency measures in construction are most efficient when planned at the outset, particularly with support from 3D modelling and simulation (Allplan, 2019).

The Cambridge Centre for Smart Infrastructure and Construction suggests numerous areas where there are opportunities to reduce waste and improve efficiency of resource use in construction including: choice of structural form; reducing overdesign; reducing the overspecification of structure; reducing overspecification of resources; better management of onsite waste and end of life resource recovery. The estimated improvements achievable from these opportunities varies depending on resource source, construction stage, and construction process, with one of the biggest opportunities being in reducing overdesign, where waste can be as high as 50 per cent (Cambridge Centre for Smart Infrastructure and Construction, 2021).

Automotive sector

The automotive sector is motivated to pursue resource efficiency due to a combination of economic, environmental, and regulatory pressures. Rising resource costs and supply chain vulnerabilities make resource efficiency a cost-saving imperative. In fact, it is not uncommon that component suppliers are contractually committed to achieving weight reductions every year. A 2020 survey from the Center for Automotive Research shows that almost all automaker interviewees said lightweighting and resource substitution are an essential factor for resource selection in vehicles. However, the introduction of resource efficiency measures into automotive manufacturing depends on multiple variables such as cost, system integration, supply base/chain, sustainability, vehicle program targets and timing, and production volume. Vehicle performance requirements must be met regardless of lightweighting importance (Bailo, C., et al.,2020).

The automotive industry is adopting various resource efficiency strategies, including lightweighting vehicles through the use of advanced resources like aluminium and composites, increasing the recyclability of components, and implementing circular economy principles such as remanufacturing and resource recovery.

Despite this, the literature suggests that overall vehicle weight is increasing rather than being reduced. A UK study showed that more than half of the vehicle models analysed had weight increases of over 35% when compared to the first generation. Only two cars in the sample did not change weight and only one car was 6% lighter (Saxton 4x4, 2021). This is likely due to increased vehicle dimensions and more features that are ancillary to driving, such as entertainment and computer systems.

4.3 Mapping the rebound effects of resource efficiency measures

The sector specific characteristics outlined in Section 5.1 provide important context for understanding both the direct response of a sector to a resource efficiency measure (e.g. lightweighting, material switching) as well as helping to understand potential rebound impacts and drivers along the value chain. Table 4 provides an overview of what each of the maps contain, outlining which resource efficiency measure is applied in which supply chain.

Table 4: Summary of resource efficiency rebound maps

Sub-section	Description of map	Assumptions
4.3.1	Lightweight design of steel components in construction	That there is overspecification of steel use. Lightweight design can reduce the steel used in each component without affecting the component's performance.
4.3.2	Lightweighting through material substitution in automotive	Substituting steel with lighter materials, such as aluminium and biobased plastics, to reduce the average vehicle weight.
4.3.3	Lightweight design of cement for use in construction	That there is overspecification of cement. Lightweight design can reduce the cement used in each component without affecting the component's performance.
4.3.4	Lightweighting through material substitution in construction	Substituting cement with lighter and/or less emissions intensive materials, to reduce the weight of construction products.

As shown in Figure 1, the sector maps should be read across two dimensions, representing the rebound impacts along the supply chain (left to right) and impact pathways for firms in a particular sector:

- **Stages of the supply chain (left to right):** as illustrated in Figure 1, reading maps from left to right, shows how resource efficiency rebound effects can impact sectors along the supply chain. Upstream sectors are on the left-hand side of the diagram, downstream sectors are on the right-hand side. The sectors listed in each of the maps are specific to the resource efficiency measure under consideration.
- **Impacts pathway leading to rebound effect (top to bottom):** as illustrated in Figure 1, reading maps from top to bottom shows the impact pathways of introducing a resource efficiency measure, including any potential rebound effects. The maps illustrate how the introduction of resource efficiency measures is expected to directly impact expenditure on factors of production at the firm level (i.e. material resources, labour, energy, and capital). In turn, any changes to firm level expenditure on factors of production could then have an

aggregated impact at the firm or consumer level. For example, in terms of changes to output, revenues, emissions and/or income.

If there are changes at the aggregate firm or consumer level there could in turn be a rebound effect, for example if increased income leads to increased expenditure or consumption in other sectors of the economy.

Red arrows guide the reader in interpreting the linkage across the different impact pathways impacts. The red coded letters correspond to explanatory text below the map and should be read alphabetically. The signs "-", "+", "=", "?" indicate the expected direction of change in impact.

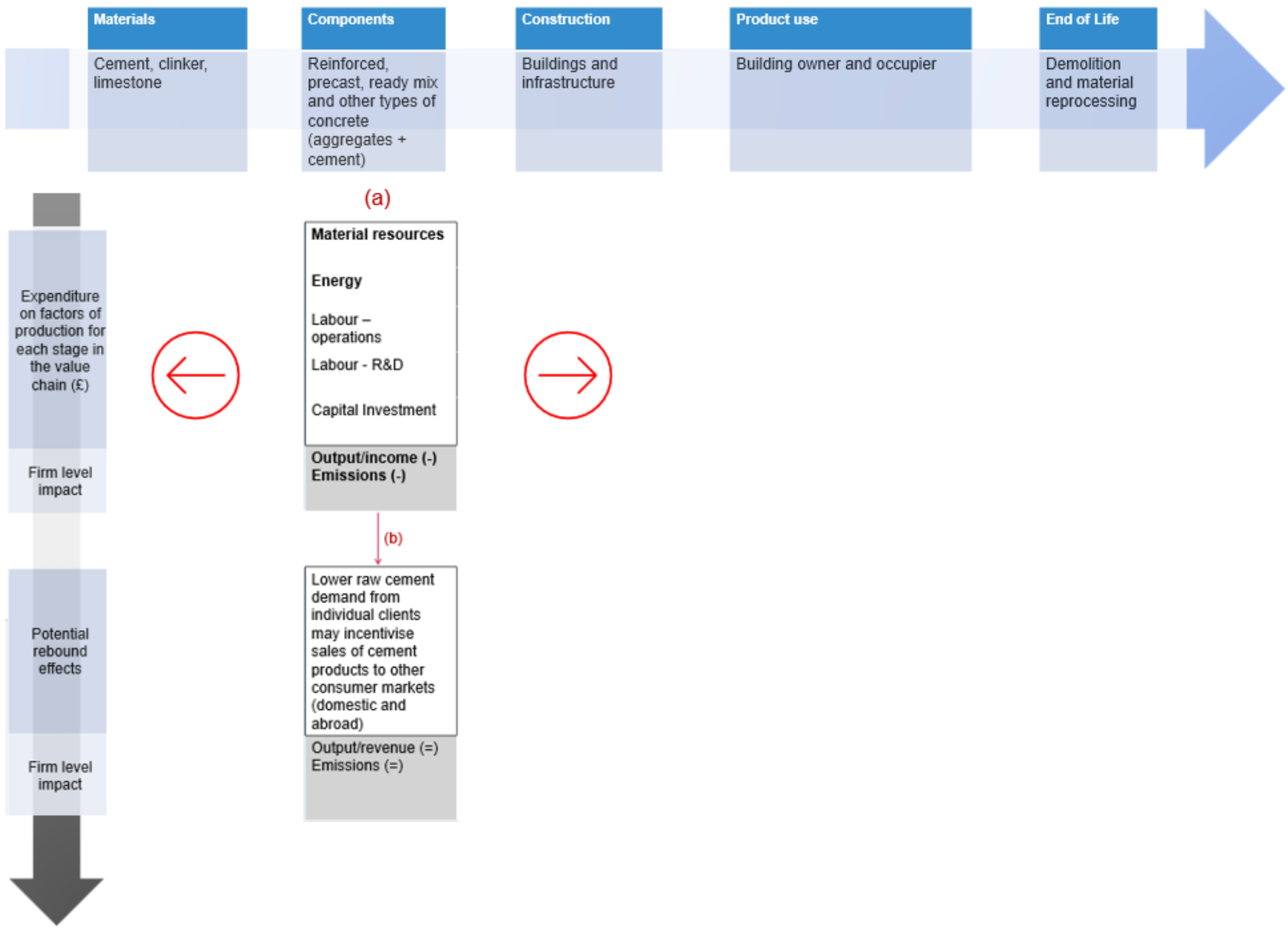
- Decrease

+ Increase

= no change

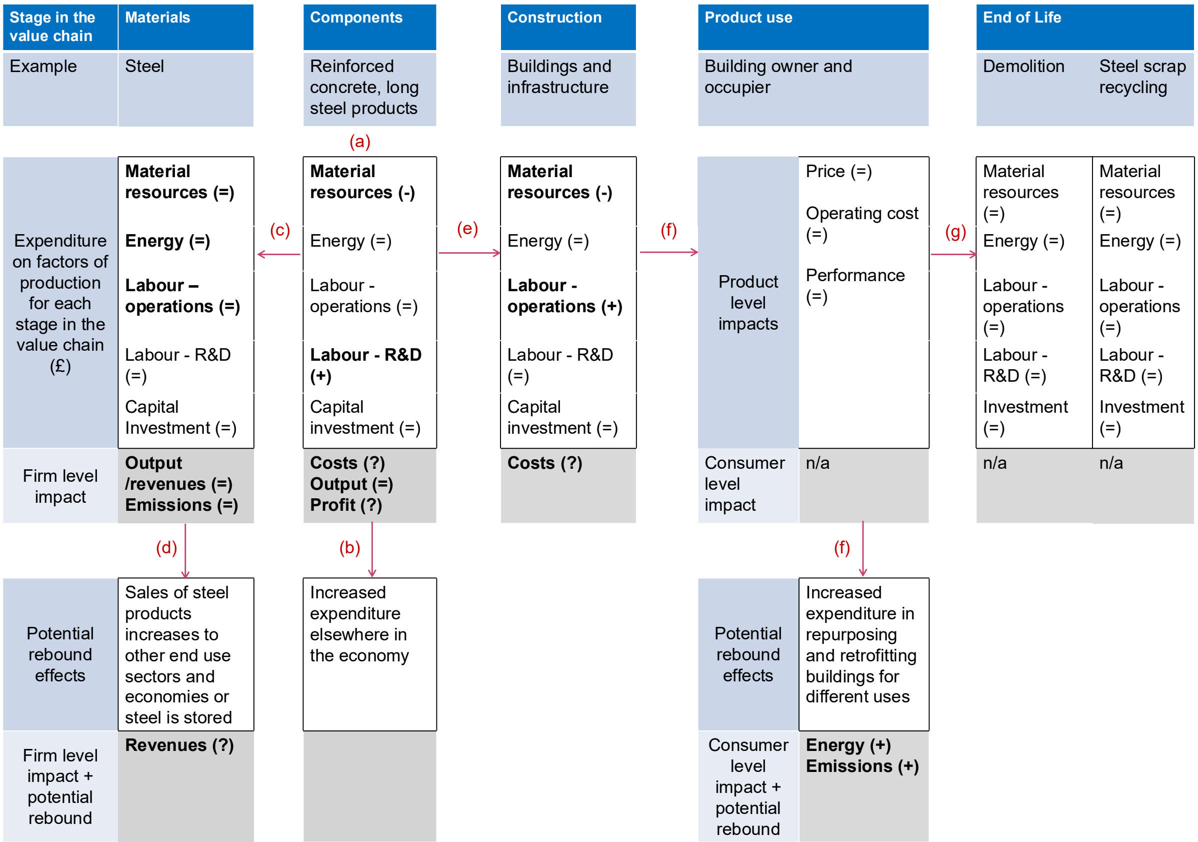
? unclear on the direction of impact

Figure 1: Illustrative example maps outlining resource efficiency rebound effect



4.3.1 Map of lightweight design of steel components for use in construction

Figure 2 - Map of lightweight design of steel components for use in construction



Construction components manufacturing (a), (b): Architect and structural engineers will design lightweight structures and components that minimise material use but still meet required industry standards. We assume that components are designed using software tools which include the functionality to lightweight. As a consequence, we do not expect any further capital investment in the component manufacturing sector (e.g. on new software or equipment). Interviewees advised that optimising the design of lightweight components requires additional time and expertise from both engineers and designers, as they move away from standard design of components **(labour R&D +).** We assume that lightweight component comprises less steel overall (e.g. via reduced over specification), ultimately leading to lower expenditure on steel by component manufacturers **(material resources -)**. Expenditure on material resources could increase if lightweighting happens through material switching and the greater use of high strength steels. Interviewees advised that higher strength steels tend to be sold at a premium price reflecting innovative manufacturing processes. The emissions and energy profile of these higher strength steels will depend on the processes used in steel production (e.g. heat processing, rolling) and the material composition of the steel alloy (e.g. mixing steel with nickel, copper etc).

Interviewees also highlighted that lightweighting of steel components can sometimes create more waste during the component manufacturing process. For example, specialized fabricated components like cellular beams, which are structural beams with a round opening, are designed to use less material while maintaining structural integrity. Fabricating these components can generate more waste compared to standard components resulting from cutting and shaping steel into non-standard sizes and shapes.

If lightweight design leads to lower expenditure on steel by component manufacturers, then *ceteris paribus,* the overall material cost per unit of output in the component manufacturing sector will also fall. However, interviewees advised that material costs are a relatively small proportion of overall costs for component manufacturers, particularly compared to labour costs. Interviewees suggested that overall costs for construction components manufacturers will be largely unaffected or could even increase as a result of increased time and resources spent on designing optimal lightweight components **(costs ?)**. Interviewees also noted that while potential cost changes could affect profit margins for component manufacturing firms **(profits ?)**, changes in costs would likely be relatively small and insufficient to drive potential changes in output **(output =)**. Consequently, there is unlikely to be a rebound effect at this stage of the supply chain.

Steel manufacturing (c), (d): According to interviewees, the reduction in steel demand from the lightweighting components does not necessarily imply reduced sales for UK steel manufacturers (**output/revenue =)**. The reasons given for this is threefold:

- First, the steel industry operates most efficiently when running at full capacity due to the high costs associated with operating blast furnaces and electric arc furnaces. Supply is relatively inelastic in response to changes in demand. Blast furnaces, for example, are designed for continuous operation and are most cost-effective when run close to capacity and benefiting from economies of scale. UK steel manufacturers are gradually moving away from blast furnaces, towards electric arc furnaces which offer comparatively more operational flexibility. However, electric arc furnaces are similarly most cost-effective when running at full capacity. Consequently, even if lightweight components reduce steel demand from the construction sector, steel manufacturers may choose to maintain output levels, and sell surplus steel to other downstream sectors, such as automotive and manufacturers of industrial equipment and metal products.
- Second, UK is a net importer of steel, meaning that potential reduced demand of steel from the construction components manufacturers, would more likely lead to a reduction in steel imports. These international steel producers would sell more steel into other markets, outside of the UK.
- Third, some stakeholders also acknowledged that, as steel is a globally traded commodity with regional pricing, steel producers are likely to either reduce the price of any surplus steel or it will be stored (e.g. in stockyards).

It follows that a rebound effect is likely to occur, as lightweighting of steel components in the construction sector will simply result in more steel being sold elsewhere. Steel output is expected to remain broadly unchanged **(output =)**, meaning that the expenditure on material resources and labour in the steel sector (e.g., iron ore, coking coal, scrap steel) will also remain unaffected (**material resources and labour =)**. Consequently, the energy requirements for fuelling the steel production process, and in the case of a blast furnace, as a chemical feedstock, will not change **(energy =)**. As a result, no impact in expected on emissions in the steel manufacturing industry **(emissions =)**. However, it is unclear whether steel manufacturers reduce the price of any “surplus” steel, meaning that it is also unclear what the impact on final output and revenues will be **(revenues ?)**.

Buildings and infrastructure (e): Due to the reduced content of steel in construction components, the construction industry can also be expected to reduce its expenditure on **material resources (-)**. However, interviewees noted that the adoption of lightweighted steel components can increase the time required at the project construction stage, due to the need for more precise fabrication and assembly of different sized lightweighted components **(labour +)**. Due to opposing costs impacts on labour and material resources, it is challenging at this stage to determine what the net impact on construction sector costs will be **(costs ?)**. However, there was consensus among interviewees that any changes in costs for the construction firm, from greater resource efficiency, is going to be relatively small and not affect the overall profit margins or lead to further rebound effects.

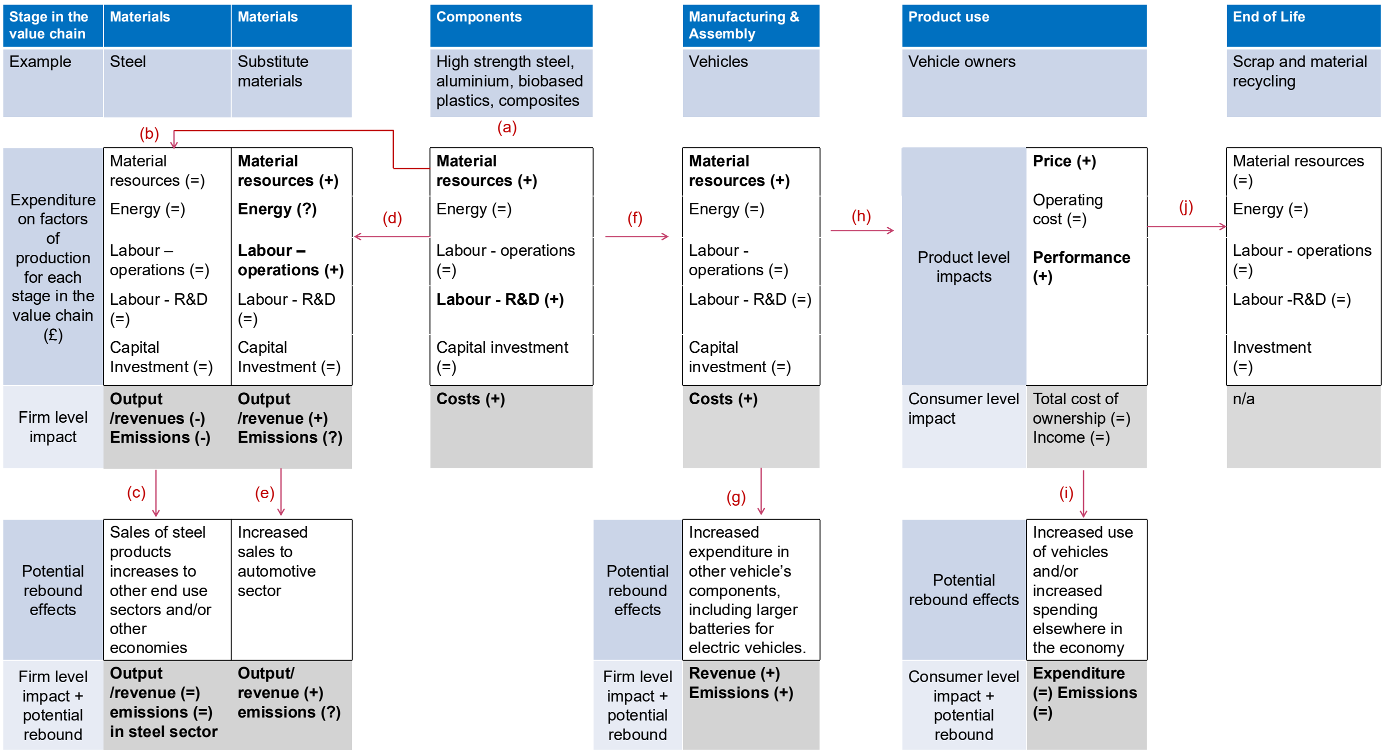
Buildings owners and occupiers (f): While we expect that lightweight design of steel components will have no substantial impact on building owners and users **(consumer level impact – n/a)**, some of the interviewees suggested buildings erected using lightweighted components with lower carbon content could be marketed and sold at a premium. However, this hypothesis requires further analyses and investigation. An alternative proposal from interviewees was that any changes in the costs of lightweight steel components are unlikely to be passed on to final consumers, given that materials represent a relatively small portion of the overall cost of a construction project. From this, we conclude that the price of buildings is unlikely to be impacted by the use of lightweight steel components **(price =)**.

As confirmed by the interviewees, lightweight design does not inherently affect the strength or durability of the building materials themselves, as the materials used in lightweight construction are designed to meet the same standards and specifications as non-lightweight components. This also means that thermal insulation of buildings would not be impacted by the adoption of lightweight steel. Nevertheless, some interviewees advised that lightweighting steel could reduce the adaptability of buildings over their lifespan. Specifically, if a building is designed with less material, it might not be flexible enough to accommodate changes in use, for example from residential to commercial. Increased **energy use (+)** and **emissions (+)** from demolishing and repurposing buildings for different uses could be a potential rebound effect in the future.

Building demolition and steel scrap recycling (g): The costs of demolition or deconstruction are expected to remain the same for both lightweight and non-lightweight steel components at the end of their working life, assuming similar time, equipment, and labour requirements. Although stakeholders have noted that steel recycling processes in the UK are already quite advanced, the volume of steel extracted following the demolition of a building would be lower in the case of lightweight components.

4.3.2 Map of lightweighting through material substitution in the automotive sector

Figure 3 - Map of lightweighting through material substitution in the automotive sector



Vehicle components manufacturing (a): Steel can be substituted for lighter materials, such as high strength steel, aluminium, biobased plastics and composites to reduce the weight of a vehicle. Decisions on materials are made during the design and manufacturing of vehicle components, where additional labour is required to develop and test parts **(labour R&D +)**. Substituting conventional steel with lightweighted steel (i.e., high strength steel) is expected to lead to higher expenditure on material resources for the manufacturing components sector as high strength steels tend to have higher prices (**material resources +**). On this basis, it can be concluded that the total costs of production for the components manufacturing sector are expected to increase, due to higher costs of purchasing lightweight steels compared to commodity steels **(costs +)**. However, interviewees noted that any increase in costs are only expected to be marginal, and not represent a major disruption for the industry.

Steel manufacturing (b), (c): Substituting steel for lightweight alternatives in automotive components manufacturing can be expected to lead to lower demand for steel, except in cases where lightweighting is achieved through greater use of high-strength steels. Interviewees indicated that lower demand for steel from the automotive components industry will mean steel manufacturers will simply sell more steel to alternative end users and markets as steel manufacturer will tend to keep their overall production level unchanged (see explanation in section 5.2.1). Additionally, the UK imports more steel than it produces, so a drop in steel demand from the automotive sector would likely reduce imports rather than domestic steel sales. Global market conditions also play a role, with growing steel demand in emerging economies offering alternative markets for UK steel manufacturers. Consequently, steel output is expected to remain stable **(output =)**. As output remains unchanged, the expenditure on material resources (e.g. iron ore, coking coal, scrap steel), labour, energy and remain unaffected, as well as emissions associated with steel production **(material resources, labour, energy and emissions =)**. As a result, a rebound effect at this stage of the value chain is likely to occur.

Steel substitutes manufacturing (d), (e): Substitution of steel for lightweight alternatives will mean component manufacturers increase their expenditure on alternative materials. Alongside high strength steels, this could include aluminium, biobased plastics and composites **material resources (+)**. Increased demand for steel substitutes is likely to lead to expanded production, resulting in higher **labour (+)** and **energy (+)** consumption in these material production sectors. As production scales up, firms manufacturing these material substitutes are expected to see increased **output (+)** and **revenues (+)** which will also lead to higher embodied **emissions (+)**. Interviewees highlighted that while some steel substitutes are characterized by lower carbon content, aluminium has a higher carbon intensity compared to commodity steels.

Overall, it can be concluded that increased expenditure in the substitute materials sector is expected to trigger a rebound effect. This effect would boost sales of alternative materials (such as high-strength steel, aluminium, and biobased plastics) generating higher output and emissions during the production process.

Vehicles manufacturing (f) (g): We assume that components made of lightweight materials are more costly than components made of commodity steels. This means that expenditure by vehicle manufacturers on components will increase **(material resources +)** which, ceteris paribus, will translate into higher costs for the vehicle manufacturing industry **(costs +)**. Vehicle manufacturers will be very mindful of any cost changes as it is a highly competitive sector which relies on economies of scale to ensure profitability.

One observed rebound effect of greater lightweighting in automotive through material substitution, is the inclusion of additional components and accessories in the vehicle. For example, interviewees advised that in case of hybrid and fully electric vehicles, any weight saved in the vehicle's structure through lightweighting measures is often offset by the addition of larger batteries to increase the vehicle's range. In the case of internal combustion engine vehicles, potential weight savings from the use of lightweight components is expected to be offset by the introduction of additional electronic devices to improve comfort and performance. Interviewees therefore reported that the introduction of additional components due to lightweighting is likely to result in higher emissions embedded in these materials at the vehicle assembly stage, thereby increasing the overall lifecycle emissions of the vehicle **(emissions +)**. Enhanced vehicle performance allows manufacturers to offer a more attractive product to the market, positively impacting their sales and profitability **(revenues +).**

Vehicles owners (h), (i): For vehicle owners and users, lightweighting through material substitution is expected to improve vehicles performance because, ceteris paribus, lighter vehicles have better fuel efficiency. As noted by interviewees however, even if weight savings from material substitution are offset by inclusion of additional features, the driving experience is likely to be enhanced **(performance +)**. If lightweighting through material switching is offset by the inclusion of additional features, it follows that **operating costs (=)** are expected to remain unchanged. However, vehicles with lightweight materials and more features could be sold at a premium **(price +)**.

Since the impacts of lightweighting through material substitution are not expected to improve fuel and energy efficiency of vehicles, it is unlikely that end-users will experience cost savings. This reduces the likelihood of a rebound effect associated with owning and driving the vehicle.

Vehicles scrap and materials recycling (j): Further lightweighting through material switching in the automotive sector is not expected to have any impact on the downstream the scrap and material recycling industry, as vehicles already comprise of multiple materials which are recycled and downcycled. However, interviewees reported that the introduction of lightweighting measures, alongside the integration of larger battery packs in electric vehicles, is likely to add complexity to repairs and recycling. First, due to structural lightweighting, manufacturers pack components more closely to create space for larger batteries, making battery modules more inaccessible and harder to repair and recycle. Second, the challenges in repairing faulty batteries mean that when they fail and are not easily repairable, it can result in the entire vehicle being prematurely scrapped, with unintended impacts on material resources used and emissions embedded in these processes. Interviewees also noted that, while recycling for steel and aluminium is relatively well established, this is not the case for composite recycling, which could be introduced as an alternative to steel. This means that new technologies and processes may be needed to improve the recovery of composites in end-of life vehicles.

4.3.3 Map of lightweight design of cement components for use in construction

Figure 4 - Map of lightweight design of cement components for use in construction

Stage in the value chain	Materials	Components	Construction	Product use		End of Life
Example	Cement, clinker, limestone	Reinforced, precast, ready mix and other types of concrete (aggregates + cement)	Buildings and infrastructure	Building owner and occupier		Demolition and material reprocessing
Expenditure on factors of production for each stage in the value chain (£)	(b) **Material resources (-)** **Energy (-)** Labour – operations (=) Labour - R&D (=) Capital Investment (=)	(a) **Material Resources (-)** Energy (=) Labour - operations (=) **Labour - R&D (+)** Capital investment (=)	(d) **Material resources (-)** Labour - operations (=) **Labour - R&D (+)** Capital investment (=)	(e) Product level impacts	**Price (=)** Operating cost (=) Performance (=)	(g) Material resources (=) Energy (=) Labour - operations (=) Labour -R&D (=) Investment ()
Firm level impact	**Output/income (-)** **Emissions (-)**	**Costs (?)** Output (=) **Profit (?)**	**Costs (-)**	Consumer level impact	n/a	n/a
Potential rebound effects	(c) Lower raw cement demand from individual clients may incentivise sales of cement products to other consumer markets (domestic and abroad)			Potential rebound effects	(f) Increased expenditure in repurposing and retrofitting buildings for different uses	
Firm level impact	Output/revenue (=) Emissions (=)			Consumer level impact + potential rebound	**Energy (+)** **Emissions (+)**	

Construction components manufacturing (a): Lightweighting structural concrete components requires additional **labour R&D (+)**, expertise, and research to develop and test new formulations with reduced cement content. Lightweight design will also lead to lower expenditure on material **(material resources -)**. The overall impact on costs is uncertain and dependent on the net change in labour and material **(costs?)**. Interviewees advised that even if costs do change, the difference will be very small and likely insufficient to drive changes in production levels or trigger a rebound effect in the component manufacturing sector.

Cement manufacturing (b), **(c):** If the design of lightweight concrete structures reduces cement demand, this can in turn reduce overall raw **material extraction (-)** and **energy (-)** used in cement manufacturing. UK cement companies will likely need to reduce their overall production levels **(output -)** and no instance of the rebound effect as the cement sector mainly supplies to the construction sector and cannot readily sell into other markets as the steel sector can (see section 5.2.1). If output reduces, there would be a corresponding reduction in the use of raw materials and labour for cement production **(material resources and labour -)**. Additionally, the energy requirements for the cement production process are expected to decrease, leading to a likely reduction in emissions **(emissions and energy -)**.

Buildings and infrastructure (d): If construction elements are lighter, then ceteris parabis, transportation costs (in the form of fuel use) will decrease, as will the overall load on the building, which interviewees speculated could lead to savings on material used in foundations **(material resources -)**. Interviewees also noted that precast concrete and other lightweight concrete components may require more construction time, as connections between lightweighted components can become more complex and require greater effort to join together **(labour +)**. However, any net changes in costs are only expected to be marginal **(costs ?)**, which means it is unlikely that there will be a rebound effect associated with the construction stage.

Building owners and occupiers (e), (f): It is unclear from the literature whether adopting cement lightweighting strategies could change property values. Interviewees noted that buildings might be sold at a premium to reflect the use of lightweight materials but that as materials represent a small proportion of overall building costs, lightweighting is not expected to significantly increase overall building price **(price =)**.

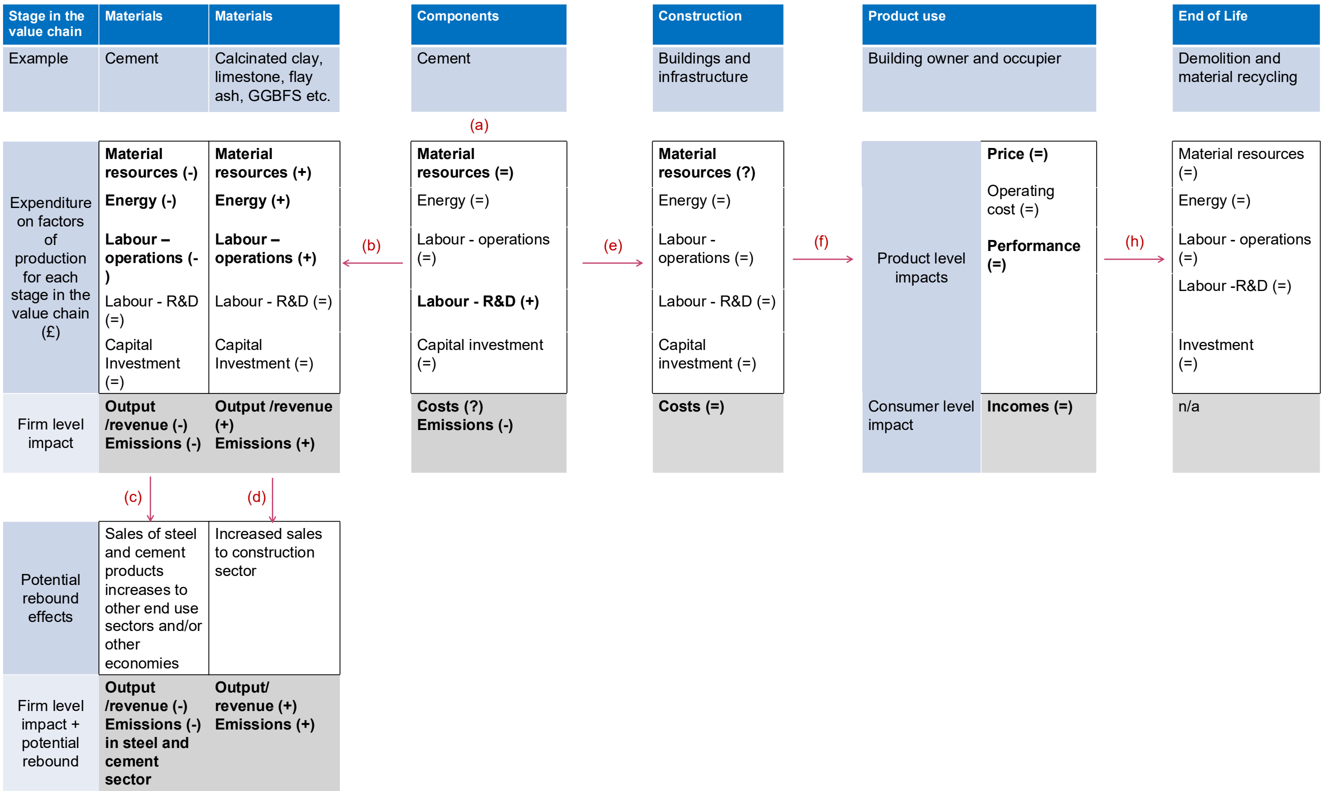
Interviewees also reported that the use of lightweighted cement in construction does not affect the thermal insulation properties nor the overall performance of a building, which means there is little visible benefit for built environment users/consumers (**Consumer impact n/a).**

Some interviewees expressed concerns that lightweighting of cement might reduce the adaptability of buildings over their lifespan. If a building is designed with reduced material, it might not be flexible enough to accommodate changes in use, such as converting an office to a retail space or a hotel, which could have higher loading requirements. Although the longevity of the building for its specific design use is not expected to be altered, interviewees advised that any reduction in the adaptability of buildings could lead to buildings being demolished sooner, which is an energy-intensive process with implication in terms of higher emissions **(energy and emissions +)**. This represents a potential intertemporal rebound effect, the occurrence of which is strictly dependent on the decision to repurpose buildings for a different use.

Buildings demolition and materials reprocessing (g): At the end of life a building's life, cement components are typically downcycled. This means that cement is crushed and reused as filler aggregate. This process remains the same regardless of whether the concrete is lightweighted or not and overall costs at the demolition and material reprocessing stage is expected to be unchanged. However, interviewees noted that while lightweighting of cement can reduce the amount of material used within a building, it can also lead to more waste during the manufacturing process of specialized materials. This is because the production of such components often involves more complex fabrication processes, which can generate additional waste.

4.3.4 Map of material substitution of cement in the construction sector

Figure 5 - Map of material substitution of cement in the construction sector



Construction components manufacturing (a): Material substitution in construction means replacing conventional cement with alternative specialised materials, such as high-strength concrete and supplementary cementitious materials (SCMs). Material substitution, including the use of alternative materials, occurs during the design and manufacturing of key structural components. Although, it is expected that material substitution does not require major changes to the technology or machinery used **(capital investment =)**, we can expect more time spent on development and testing of alternatives to cement **(labour R&D +)**. Interviewees highlighted that the substitution of cement with alternative materials does not affect the volume of overall material resources used for the manufacturing of construction components. The literature shows mixed results regarding the cost of substitute materials compared to conventional concrete which means the expenditure on material resources is likely to be unchanged (**material resources =)**. While some studies suggest that substitutes can be less expensive (e.g. fly ashes for traditional Portland cement), others highlight potential additional labour, transport or processing costs that could offset these savings (e.g. in the case of ground granulated blast furnace slag, limestone powder). Some interviewees noted that alternative materials are generally cheaper than cement, but price fluctuations make it difficult to predict the exact price differential. Regardless, the potential cost savings from using cheaper cement substitutes are expected to be marginal, with only a slight impact on the profit margins of component manufacturing firms. Therefore, the overall impact on construction costs depends on factors such as scale of use, supply chain dynamics, market demand, regional availability and material prices, as well as increased design and labour resources **(costs ?)**. In terms of emissions, both the literature and the interviewed stakeholders indicate that cement substitutes generally are less emissions intensive to manufacture that cement **(emissions -).**

Cement manufacturing (b), **(c):** Substitution of cement by component manufacturers will translate into lower sales for the cement sector. Interviewees advised that, despite the reduced demand for cement, in the short-term firms may maintain their production levels. This is because operating large cement kilns at reduced volumes is not efficient nor economically feasible. However, interviewees also highlighted that in the long run it is unlikely that cement firms would be able to increase their sales to other sectors to offset reduced sales toward the construction component sector, as cement is primarily used within the construction sector. Additionally, as the UK is a net importer of cement, it is unlikely that UK cement firms would export their production to other economies. Instead, a decrease in cement imports can be expected, ultimately leading to a lower dependency on imported cement. Should UK cement production fall as well there will also be a corresponding decrease in the quantity of raw material and labour used in cement production **(material resources and labour -).** It can also be expected that the energy requirements in the cement production process will be reduced **(energy -)** and that consequently there will be a likely reduction on emissions **(emissions -).**

Cement substitutes manufacturing (d): As highlighted by interviewees, reduced sales of cement are not expected to be particularly disruptive for the cement industry. This is because cement firms are vertically integrated, meaning that the manufacturing of cement and cementitious components for construction are produced within the same firm. Therefore, changes in expenditure in the cement production would be partially or entirely offset by increased expenditure by component manufacturers on the alternative materials, with associated increased expenditure on **material resources (+), labour (+)**, and ultimately an impact on the firm's **output (+)** in these sectors.

Despite the lower carbon content of cement alternatives, higher demand for these materials in the construction sector is likely to expand their production and **energy consumption (+)**, thereby increasing the environmental impact of the industry **(emissions +)**. This can be considered as a rebound effect triggered by the substitution of cement with lower-carbon content alternatives.

Buildings and infrastructure (e): While the overall volume of material resources used in construction is expected to remain unaffected **material resources (=)**, from the literature it is unclear how the price of alternative materials is expected to change, and how material resource expenditure will be affected. According to the interviewees, the costs of construction components manufactured using cement alternatives is likely to increase slightly in the short term, will likely align with the price of cement in the long run. Stakeholders also highlighted that potential changes in the final costs of cement alternatives are only expected to be marginal, hence not affecting the overall costs of construction projects nor the profitability of construction firms **(costs and revenues =)**.

Building owners and occupiers (f): According to the literature, up to 60% of clinker in cement can be replaced without damaging the strength and durability of the final material (Zhang, Y., & Li, H, 2018), ultimately maintaining the same level of performance of construction material unaltered, as well as end-users operating costs **(performance =)**. This has been broadly confirmed by interviewees, who noted that strength of buildings is not compromised by the use of alternative materials and, in some cases, durability can even be improved following substitution of clinker for other materials in the production of cement.

Some interviewees reported that, in the short term, buildings constructed with lower carbon content materials could be viewed as a premium product due to innovative construction practices resulting from material switching. However, this premium is expected to decrease substantially in the long run as more buildings are erected using reduced carbon content components. Any potential premiums are unlikely to significantly increase overall building prices as materials are a small proportion of overall build costs. Therefore, it can be concluded that the price of buildings is likely to remain broadly unchanged following material switching **(price =)**. It follows that end-users are also not expected to experience any variation in their disposable **income (=)**.

Buildings demolition and materials recycling (g): The demolition and recycling industries are not expected to experience major changes in their expenditures as a result of material substitution in construction.

4.4 Resource Efficiency: Key findings

The key findings from the resource efficiency research (workstream A) are set out below and expanded on in the Executive Summary of this report:

- Resource efficiency rebound effects are classified in the literature by their level, type, and mechanisms driving it.
- The scale of resource efficiency rebound effects is influenced by market dynamics, competition, and supply chain interactions.
- Significant variations and limited evidence is available on the magnitude of rebound effects in the existing literature.
- Metrics for capturing resource efficiency rebound effects are diverse, employing both absolute and intensity metrics.
- Further research is needed to understand transmission channels and long-term impacts.

5 Literature review of industrial energy efficiency rebound effects

The insights from the literature review are structured to directly respond to the research questions listed in Table 1. Each research question corresponds to a sub-heading in this section and includes supporting evidence and a discussion of any limitations to the insights – including the limited number of studies that were identified as relevant. The full methodology for the literature review is outlined in Annex 5.

These studies are detailed in Annex 6.

5.1 What is the quantitative evidence on the magnitude of rebound effects from industrial energy efficiency measures?

5.1.1 Summary of the seventeen studies reviewed

From an extensive review of academic and grey literature, seventeen of the total 32 shortlisted studies met our literature review selection criteria and estimated meso-level (sector) rebound effects from industrial energy efficiency measures for one or more of the eight priority sectors identified by DESNZ .[7] Consistent with Dahlqvist et al. (2021), we found relatively few studies in the literature that estimate sector level rebound effects, with studies more commonly focussing on rebound estimation at micro or macro scales.[8]

All seventeen sector-level studies are geographically focused on advanced economies which can be considered comparable to the UK context. Five focused on the UK region (4 in the UK and 1 in Scotland). However, these UK studies are also amongst the oldest studies in our review: four of the UK studies were published 2007-2012, with only one published in 2021. The more recent approach of using econometric analysis at the firm-level (e.g. Amjadi et al, 2022) have currently only been applied in non-UK countries (Germany, Sweden and the USA), meaning any advances in methodology or best practice since 2012 have not been applied yet to the UK.

From the seventeen studies, we identified three approaches for estimating the magnitude of rebound effects from industrial energy efficiency measures. These are (1) Computable General Equilibrium (CGE) models, (2) macroeconometric models and (3) econometric analyses. These three modelling approaches differ in terms of their scope, underlying assumptions and drivers (see Section 6.1.4 and Annex 7 for further discussion of these methodologies and effect on rebound estimates). The seventeen studies also differ in terms of their geographical coverage, sectoral focus and classification, and time period under consideration. **The limited and diverse evidence base makes it challenging to identify representative sector-specific or cross-sector rebound estimates.** With this caveat in mind, we can however still make useful observations from the seventeen studies and identify areas for further research.

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[7] The 8 priority sectors were iron, steel, chemicals, oil refining, food and drink, pulp and paper, cement, glass and ceramics, consistent with those sectors in the 2015 Industrial Decarbonisation and Energy Efficiency Roadmaps

[8] At the micro (firm or consumer) level, direct rebound effects are typically estimated via survey data or price elasticities, while indirect rebound effects are estimated via cross-price elasticities (and associated sectoral energy intensities). Macro-level studies assume a percentage improvement in energy efficiency across the whole economy, without any consideration of industry or specific sectors. These can be estimated using aggregated modelling frameworks, such as capital-labour-energy (KLE) aggregate production functions (e.g. Saunders, 2015; Adetutu et al. 2016). However, as they estimate whole economy rebound (from whole economy efficiency gains), these macro-level studies can be considered alongside meso-level studies as providing an upper bound of total rebound effects.

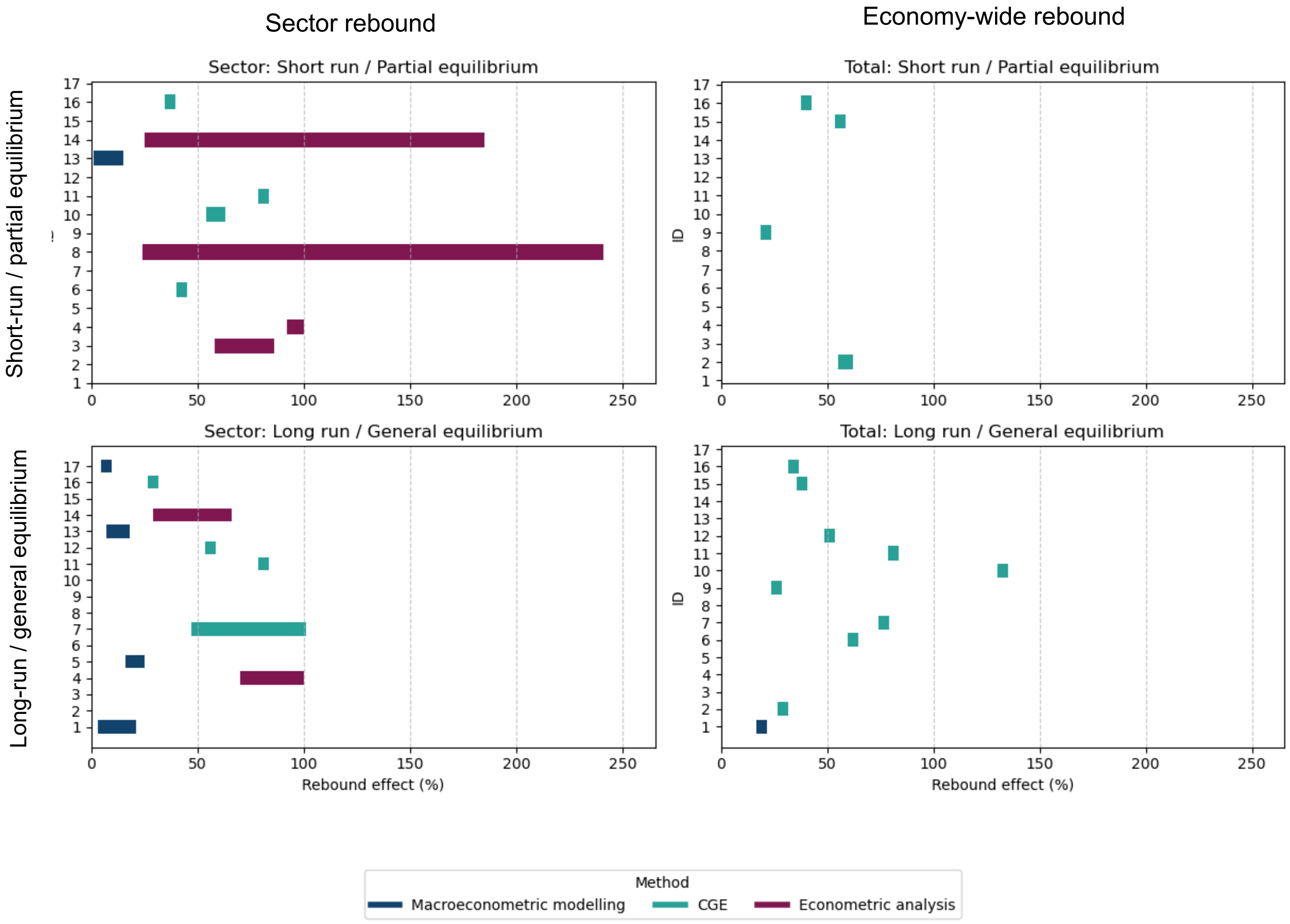
5.1.2 General observations on quantitative estimates from the seventeen studies

Figure 6 presents quantitative estimates from the 17 studies, categorised by the scope of estimated rebound effects, using the definitions in Table 13 (Annex 7), as follows:

- The two left hand side charts show sector-level rebound estimates.
- The two right hand side charts show total economy-wide rebound estimates.
- The top two charts show short-run / partial equilibrium estimates
- The bottom two charts show long-run / general equilibrium estimates.

The labels in Figure 6 correspond to the article ID number (see Table 12 in Annex 6).

Figure 6: Range of energy rebound estimates following an industry energy efficiency improvement by study ID number



Even with the limited number of studies, we can make some general observations and propose areas for further research:

- **All studies observe positive rebound effects**, suggesting that there is strong agreement that the rebound effect phenomenon could affect planned energy demand savings from industrial energy efficiency improvements.
- **There is large variation in estimates, with methodology and definition of rebound being key drivers,** for example ranging from 1% to over 200% (backfire) for short-run sector rebound, 3% to 100% for long-run sector rebound. The three methodological approaches provide considerably different ranges: 1-25% for macroeconometric model studies, 18-134% for CGE model studies, and 20->200% for econometric analyses.
- **CGE models and econometric models consistently show bigger rebound estimates than macroeconometric modelling studies**. There are many differences between the construction and assumptions of these models, which are discussed further in section 5.1.2 and Annex 7. One notable difference is that macroeconometric studies focus on demand side drivers of rebound effects, while CGE and econometric models focus on supply side

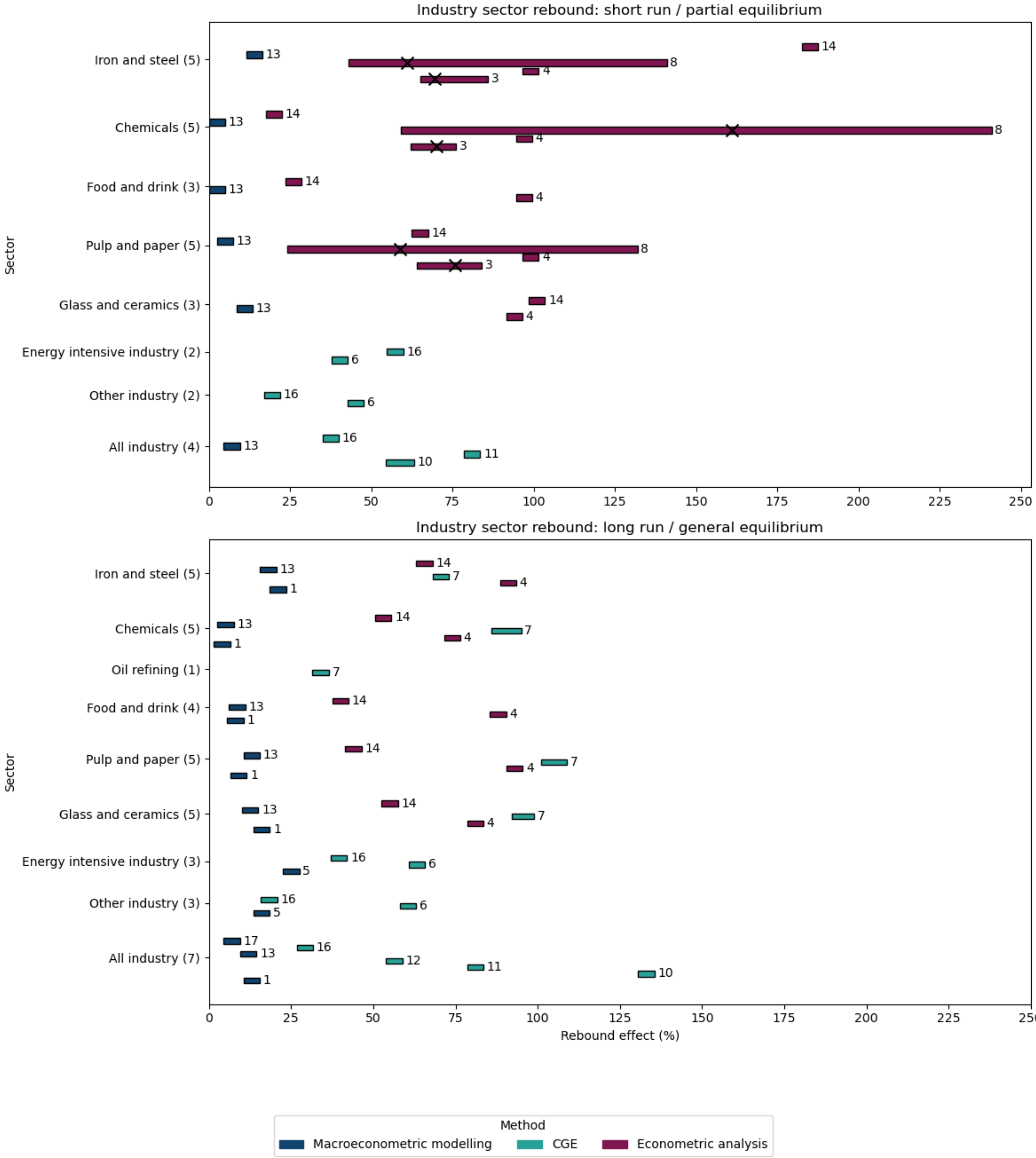
effects. However, it is not possible to determine the extent to which this drives the observed result, given the myriad other differences between methodological approaches and study contexts.

- **Econometric analyses show the biggest variability in estimates** because they capture how individual firms in the same sector have different rebound effects and are estimated using real world firm-level data. For example, in the econometric study by Amjadi et al., (2018) using firm level data, the authors found high standard deviations for estimates within sectors. They conclude that firms respond differently to energy efficiency improvements. From observing the variation in rebound estimates in econometric analyses, we can hypothesise that there is more sector variability in the rebound effects than shown in the estimates from CGE and macroeconometric models which report a single rebound estimate.
- **CGE models focused more on estimating the macro-level rebound effects while econometric models focused more on sector level.** This observation is a consequence of how these studies were designed. As outlined in Table 13 (Annex 7), both CGE and macroeconometric models can be used to estimate rebound effects at both the macro and sector level. By comparison, econometric analyses can only estimate partial equilibrium, sector level rebound effects because they are based on firm level data and do not account for wider sectoral or economy linkages.
- **We only observe a small difference in sector versus total economy-wide rebound magnitudes in Figure 6:** This suggests that most of the rebound effect from industrial EE measures is occurring within the industrial sector rather than propagating out into the wider economy. The four CGE studies show the smallest difference between sector and total rebound effects. This is likely due to two effects of the underlying model structure, noted by Turner et al., (2012). First via a negative multiplier effect, where further energy reductions take place in energy supply sectors (i.e. they need less input energy to make less output energy). Secondly via a disinvestment effect, where lower profitability forces energy supply sectors to constrain future capital investment and raise energy prices, reducing energy demand and hence rebound in the wider economy. Macroeconometric models also show larger, positive economy-wide rebound effects compared with CGE models because of the way these studies treat capital investment costs, as noted in Annex 7.
- **Findings give some indication that rebound effects from industrial energy efficiency measures may be greater than those in the domestic context.** The average (mean) magnitude of short-run / partial equilibrium industry-level rebound effects (70.3%, 9 studies) are, on average, higher than the 41-52% reported from a recent study of partial equilibrium household level rebound effects, in a review of 43 consumer level rebound studies by Schütt et al. (2024). CGE modelling studies that estimate rebound effects at the economy-level also produce large rebound estimates – for example Brockway et al.’s (2021) review of 21 CGE-based estimates of long-run, economy-wide rebound, obtained a mean (median) of 65% (60%) from 14 producer studies and 55% (50%) from 7 consumer studies. **However, given the limited evidence, particularly in the industrial context, and variability in study estimates and methodologies, further research and analysis would be required to draw solid conclusions on this.**

5.1.3 Observations on sector-level estimates from the collected studies

Fourteen of the seventeen studies provide rebound estimates at an industrial sector level (i.e. covering some or all of the eight industrial sectors prioritised for this research iron and steel, chemicals, oil refining, food and drink, pulp and paper, cement, glass, and ceramics sectors), and/or at all-industry level. (The other three studies provide only economy-wide rebound estimates from industrial sector efficiency improvements, as seen in the previous section). Figure 7 shows the industrial sector rebound estimates from these fourteen studies. The labels in Figure 7 correspond to the article ID number in Table 12 in Annex 6.

Figure 7: Estimates of rebound by industry sector or all (grouped) industry.



The following high-level observations can be reported:

- **The fourteen studies differ in terms of sectoral coverage and definition.** Seven studies present their results by specific individual sectors, and nine studies aggregate all industry into a single sector and rebound estimate. No studies estimated the rebound effects from energy efficiency measures in the cement and concrete sector. Glass and ceramics are presented as a single sector. Two papers did not present disaggregated sectoral estimates, but split industry into "energy intensive industry" and "other industry". Some studies presented ranges for each individual sector – based on sensitivity analyses for CGE and macroeconometric studies, or heterogeneous firm level data for econometric analyses.

- **Overall, studies show a vast range in estimates, both across and within sectors** (see sector-specific observations below). All-industry rebound estimates varied from around 10% to 134% (backfire).
- **Econometric analyses were focused on more energy-intensive industrial sectors, (i.e. iron and steel, chemicals, pulp and paper) and reported comparatively higher rebound effects.** We can hypothesise that the higher energy efficiency rebound effects in more energy intensive sectors is attributable to energy being a larger proportion of their overall production costs, meaning energy efficiency measures yield bigger cost savings, which could stimulate a larger rebound effect. However, methodological and other factors could also be driving this finding. These hypotheses would need to be tested and validated through further econometric analyses across all industrial sectors.

The wide variation in estimates and differences in study methodologies and contexts make it difficult to determine representative estimates either for specific sectors or across all industries, or to make consistent comparisons between sectors.

5.1.4 Discussion on methodological drivers of variation in estimates

This research has identified the choice of modelling approach as a primary driver of variation in industrial energy efficiency rebound estimates. Three main modelling approaches are commonly used: Computable General Equilibrium (CGE) models, macroeconometric models, and firm-level econometric analyses. Each has unique structures, assumptions, and implications for the scope and scale of rebound effects estimated. This section summarises the main considerations – see Annex 7 for a more detailed discussion of the three methodological approaches.

We have observed that CGE and econometric studies typically estimate larger rebound effects than those using macroeconometric estimation, which may be due in part to the former more effectively capturing supply-side effects, though given other differences this can only be a tentative observation (we also note that econometric studies in the literature have generally been undertaken in more energy-intensive industries, which may be expected to have higher energy efficiency rebound).

Beyond differences in the underlying model structures, the seventeen studies also differ in terms of the scenario assumptions, including across studies that use the same type of model. For example, Turner et al., (2012) show that the size of the rebound effect in their CGE model runs depends on input assumptions about elasticities of substitution between energy and other factors of production (e.g. capital, labour). Higher elasticities, and substitutability, translate to higher rebound effects, as shown in the long-run sensitivity results in Annex 8.

Other methodological differences—including the treatment of capital investment costs, the definition of short- and long-run, and the structure of the economy as represented in the model—further influence rebound estimates. Many studies assume costless capital investment, particularly in CGE modelling, which is likely to exaggerate rebound effects. The assumptions and construction of each modelling approach must therefore be carefully considered when interpreting rebound effect estimates, as they fundamentally shape both the magnitude and policy relevance of the findings.

These methodological differences are layered on top of a range of real-world drivers that can significantly influence the size and nature of energy and resource efficiency rebound effects, such as those discussed in Sections 2 and 3.1. Such drivers include, but are not limited to, the prevailing structure and competitiveness of the sector, the energy intensity of processes, the scale and type of efficiency measures implemented, the responsiveness of market demand, regulatory environments, and the availability of complementary technologies. Additionally, factors such as energy price volatility, input substitution possibilities, and the overall macroeconomic climate can further influence the observed rebound effect in practice.

Given the substantial variation across study methodologies, underlying assumptions, industrial contexts, types of efficiency interventions, and data sources, has not been possible to disentangle the extent to which observed differences in rebound estimates are primarily methodological artefacts or reflective of real-world effects.

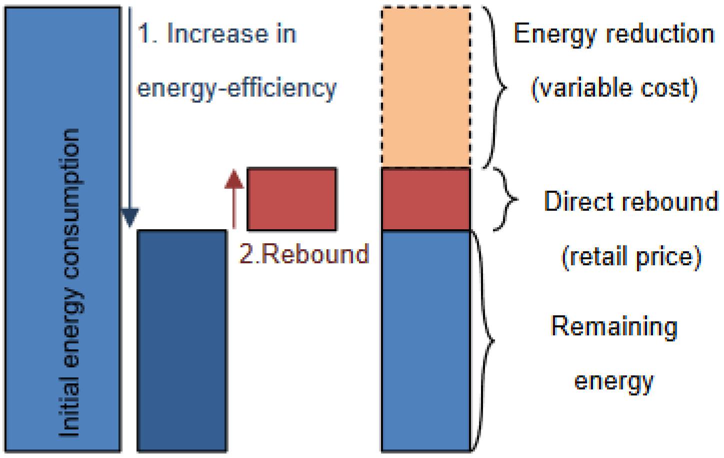
5.2 What methods are used for monetary valuation of industry energy rebound effects?

Social cost-benefit analysis seeks to monetise significant policy impacts so that costs and benefits can be compared on a common metric. Valuing industry energy rebound effects in monetary terms seeks to capture the social welfare benefits of additional industrial output and household consumption arising from rebounded energy use. In this section, we discuss methods used for the valuation of energy efficiency rebound effects in UK Government guidance and the wider literature, and broader evidence on growth and GDP effects.

Existing HMT Green Book guidance on valuing industrial sector energy rebound

DESNZ (2023) supplementary guidance to the HMT Green Book advises valuing the economic benefits of the **direct energy rebound effect in the domestic context** using the value of the retail price of energy, which acts as a proxy for the consumer’s willingness-to pay and a measure of the welfare gain. The Green Book states a default value to quantify the magnitude of energy efficiency rebound of 20%, taken from consumer-sided rebound literature. There is no equivalent UK appraisal guidance for valuing the benefits of energy efficiency rebound in the industrial context.

Figure 8: Current Green Book valuation of changes in energy consumption



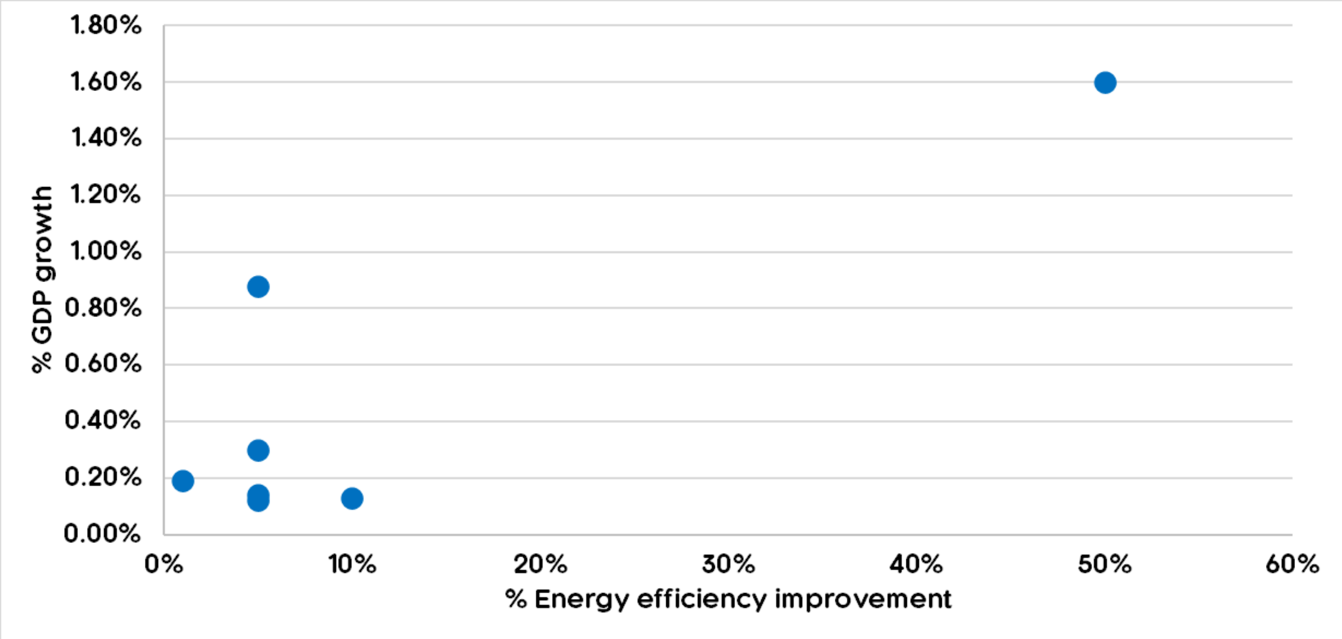
Source: DESNZ (2023). Valuation of energy use and greenhouse gas emissions for appraisal, HMT Green Book supplementary guidance.

Evidence from the literature on valuing the benefits of industrial EE rebound, including growth effects

Of the seventeen studies reviewed and described in section 6.1, **none sought to value directly the economic welfare gains from rebound effects for the purposes of policy appraisal**, or assessed methodological approaches for doing so. However, ten studies estimated the macroeconomic impacts of industrial energy efficiency (including rebound effects) on output, which is discussed below.

Ten studies estimated overall GDP impacts (all CGE models), while six studies estimated impacts on industrial sector output. **All the reported studies observed positive overall long-run GDP and industry sector output growth from an improvement in industry energy efficiency.** These are shown in 6. For example, Allan et al. (2007) central case modelling finds GDP increases of 0.11% in the short run and 0.17% in the long run following a 5% efficiency improvement in UK production sectors. Similarly, Broberg et al. (2015) report a 0.3% GDP increase from a 5% efficiency improvement in Sweden. Garau and Mandras (2015) estimate a 0.06-0.14% short-run and 0.19-0.23% long-run GDP increase for Italy (depending on model specification). The largest result from the reviewed studies is Koesler et al. (2016), which finds 1.6% GDP growth from their simulation of a sustained 10% increase in energy efficiency across all German production sectors. Ahmann et al. (2022), using the PANTA RHEI model for Germany, finds that energy efficiency programmes slightly increased GDP, but when combined with carbon pricing and EEG levy reductions, the net GDP effect turned negative (−0.4%), highlighting the sensitivity of outcomes to policy design.

Figure 9: Sector energy efficiency improvement plotted against long-run GDP growth



Gross Value Added (GVA) output changes are less well reported, with only six studies (5 CGE, 1 macroeconometric model) reporting any impacts versus baseline in terms of annual sectoral output. Some studies were reported the industry impact at an aggregated level. Zimmerman et al. (2021) estimated long term increases in response to an all-industry 50% efficiency increase, for two industry classifications in Switzerland: “energy intensive manufacturing industry” (+22.5%) and “rest of industry” (-6%). Hanley et al. (2009) give long run output growth for “manufacturing” (+0.5%) as a single sector, from a 10% efficiency improvement. CREDS (2021) report estimated an “overall industry” long-run growth of +0.05% in 2040, though the % efficiency improvement is unknown. Other studies were more detailed. Koesler et al. (2016) gave changes in GVA output for 3 industrial classes: “primary industry” (-0.67%), “food drink and tobacco” (-0.55%) and “manufacturing” (+0.43%), though their study for Germany analysed the impacts of a 10% increase in “manufacturing” (not all industry) energy efficiency. Garau and Mandras (2015) obtained GVA output changes for 6 Italian industrial sub-sectors in response to a 1% improvement in industrial energy efficiency: “food drink and tobacco” (+0.24%), “textile and clothing” (+0.23%), “chemicals” (+0.23%), “metals and non-metals” (+0.25%), “transport equipment” (+0.20%) and “other manufacturing” (+0.20%). Allan et al (2007) report long run sectoral output growth from a 5% industrial efficiency improvement for “iron and steel” (+0.67%) and “pulp and paper” (+ 0.46%), with other industrial sectors shown visually, with lower, but still positive, GVA growth.

From the six meso-level modelling studies, we observe **that efficiency-led rebound effects (i.e. increases in energy use) stimulate economic output**. This finding has support in the wider literature, for example Reuter et al. (2020) studied the ODYSSEE-MURE energy efficiency dataset for European countries, and found energy efficiency in industry is associated with a 7% to 10% GVA increase compared to a counterfactual without energy savings.

In fact, the study of energy use and increased economic output (i.e. productivity) has a long history. Schurr and Netschert (1960) suggested that the impact of electrification in US industry had made a significant contribution to economic growth. After the 1970s oil crises, studies of energy and productivity were common (e.g. Berndt, 1978, 1990), exploring the role of energy consumption in technical progress (i.e. energy efficiency improvements) in driving increases to economic output. In the early 2000s, Worrell and colleagues made significant contributions to the study of energy efficiency in industry. Worrell et al. (2001) found in a US case study that energy efficiency investments can provide a significant boost to overall productivity within industry.

McLaughlin et al. (2021) show in another US study, that energy efficiency investment in industry leads to higher economic activity overall – though no evaluation was carried out in terms of GVA and productivity. Shehzadi (2023) found in a study of Asia, energy efficiency measures across the region are positively associated with productivity improvements in manufacturing sectors. Kalantzis and Niczyporuk (2021) conducted a review of firm-level survey data of more 15,000 firms in 27 European Union member states and the UK during 2018-2019 in a study for the European Investment Bank. They found a positive and causal relationship between energy efficiency investment and labour productivity, suggesting “firms can benefit much more from the energy efficiency investment than what is often assumed”.

Overall, identifying a link between industrial energy efficiency measures and increases to firm level productivity is an important finding, because it demonstrates the potential **benefits of energy efficiency investments on output and economic growth**. This is an expected finding, given that productivity is a central mechanism via which rebound effects occur.

5.3 What are the main evidence gaps and how can they be addressed by further research?

From the review of the literature, we can identify several evidence gaps that can be addressed by further research:

There appears a limited evidence base and wide range of industry sector rebound estimates from improvements to industrial energy efficiency. Beyond the tentative observation of higher rebound effects in energy intensive industrial sectors, there appears little agreement on sector-specific rebound effects – quantitative estimates vary greatly both across and within sectors, primarily because the magnitude of rebound effects appears very dependent on model type (e.g. macroeconometric model, CGE model, macroeconometric analysis). This diversity of models and rebound magnitudes inhibits making generalisable, sector-specific or cross-sector rebound estimates from these studies.

Economic assessment of rebound effects from industrial energy efficiency improvements were also lacking. CGE and macroeconometric modelling frameworks mainly reported changes at the national level, i.e. impact on GDP, but less provided sectoral GVA changes. A key omission in nearly all studies was the lack of capital investment of industrial energy efficiency measures – for example investment in R&D and capital expenditure.

There is a modelling gap in terms of UK-specific analysis, with only one UK study published since 2012. Since then, there has also been growth in econometric analyses using firm-level data for e.g. Sweden (Amjadi et al, 2022). Macroeconometric models are also becoming more widespread, such as MEDEAS (Capellan-Perez et al, 2021) and MARCO-UK (Nieto et al, 2024), though their attention has been largely on consumer-sided energy transition questions in housing and transport. However, key questions on the energy transition are becoming increasingly focussed on industrial decarbonisation, and so these new tools can be used to study industry rebound.

Therefore, a future research call for UK-specific industrial energy efficiency rebound could utilise recent improvements to modelling frameworks. For example, firm-level studies of industrial energy efficiency with actual, empirical data are now emerging, founded on the growth of general equilibrium frameworks on energy rebound that are developing such as Borenstein (2015), Lemoine et al (2020), and Fullerton and Ta (2020). Further econometric analyses, in particular, are needed to validate two hypotheses (1) that the rebound effect will vary between firms in the same sector and (2) that the energy efficiency rebound effect is greater in more energy intensive sectors.

5.4 Energy efficiency: Key findings

The key findings from the literature review for energy efficiency (workstream B) are set out below and expanded on in the Executive Summary of this report:

- Reviewed studies provide a vast range of estimates of industrial energy efficiency rebound – with methodology the key driver of variation. Three modelling approaches were identified from the existing literature – CGE models, macroeconometric models and econometric analyses, which all differed in terms of their scope, underlying assumptions and drivers. These produced a wide range of rebound estimates, with all studies finding positive effects: 18-134% - CGE model studies, 1-25% - macroeconometric model studies, 20->200% - econometric analyses. We observe that CGE models and econometric models show bigger rebound estimates than macroeconometric modelling studies, which is due to differences in the scope of rebound assessed by these approaches, the inherent modelling assumptions and the extent to which they account for demand and supply-side effects.
- Seventeen studies were identified which also differed in terms of their methodological approach, scope and definition of rebound, geographical coverage, sectoral focus and classification, and time period under consideration. The limited and diverse evidence base makes it challenging to identify representative, generalisable sector-specific rebound estimates from energy efficiency measures. Instead, evidence should be considered on a case-by-case basis to establish whether the characteristics of a study that has generated the estimate are appropriate for the specific use-case.
- Notwithstanding these limitations, all studies observe positive rebound effects at the macro and meso level which would impact the energy reductions associated with energy efficiency improvements.

- All the reported studies observed positive overall long-run GDP and industry sector output growth from an improvement in industry energy efficiency. This links industrial energy efficiency and firm level productivity.
- Further research is needed to test emerging hypotheses on the magnitude of energy efficiency rebound effects across different industrial sectors in the UK.

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Annex 1: Classification of rebound effects with illustrative examples.

This annex provides examples of rebound effects that correspond to the definitions outlined in Section 2.

Level	Direct	Indirect	Macroeconomic (including growth effects)
Micro (firm/individual)	Example: A firm invests in resource efficiency, but due to reduced production costs, they reinvest some or all savings to increase output.	Example: A firm reduces its operating costs through improved resource efficiency in aluminium production and lowers the price of its products. This price reduction increases demand for aluminium from one of its client firm. As a result, this firm may also ramp up its production, ultimately resulting in higher resource consumption.	Not typically relevant at this level.
Meso (sector/industry)	Example: A sector-wide innovation in terms of lightweighting reduced the amount of resource used in manufacturing, but some or all of the savings are reinvested in additional production capacity, increasing total resource consumption in that sector.	Example: Increased efficiency in one sector (e.g., steel) leads to growth in downstream industries (e.g., construction) that demand more resources.	Example: Increased resource efficiency from one sector (e.g., steel manufacturing) lowers the prices of intermediate goods used in other sectors, leading to changes in demand and production across the economy, including increased output in industries that rely on stee (e.g., construction and automotive manufacturing), thereby stimulating (for instance) employment in that sector.

Macro (economy-wide)	Not typically relevant at this level.	Not typically relevant at this level.	Example: Efficiency improvements across various sectors often lead to cost savings, which can stimulate price and quantity adjustments across economy. As prices decrease due to these cost savings, consumer spending rises, driving increased demand in other areas of the economy. While this can promote for instance economic growth and create employment opportunities, it is likely to generate additional resource consumption which may negate some or all of the potential savings in resource use.

Annex 2: Methodology for resource efficiency literature review

This annex outlines the methodology that was developed and applied to understand the existing literature on resource efficiency rebound effects. The insights from this literature review are presented in section 3. This annex also summarises the body of literature that was identified as relevant – for example, characterising the geography, method, year of study etc.

Identifying sources of literature

To ensure comprehensive coverage of literature, two broad categories of search terms were developed: one for generalizable insights and the other for sector- and measure-specific insights. Generalisable insights were sought using terms such as "*rebound effects*" AND "*industrial resource efficiency*" and "*circular economy*" AND "*resource efficiency*." For measure- and sector-specific insights, more granular keywords were applied to target studies related to particular industries or measures. Examples include "*lightweighting*" AND "*steel*" AND "*rebound*" or "*recycling*" AND "*automotive*" AND "*environmental impact*." These search terms aimed to identify research that focused on prioritised sectors (i.e., steel, cement and concrete, construction and automotive), and particular strategies or interventions, including material recycling or product design changes. The full list of keywords that were used to search for relevant sources of literature are detailed in Table 5.

Table 5: Keywords used to generate a longlist of literature sources for review.

Keyword – Level 1	Keyword – Level 2	Keyword – Level 3	Keyword – Level 4
Industrial resource efficiency	Rebound	Impact	Steel
Circular economy	Backfire	Drivers	Cement
Resource efficiency	Growth	Magnitude	Concrete
Lean design	Productivity growth	Size	Construction
Lightweighting	Output growth	Sectors	New builds
Resource substitution		Output	Automotive

Over design		Income	Vehicles
Reuse		Emissions	Cars
Industrial symbiosis		Costs	Consumption
Resource productivity		Energy use	Supply chain
		Trade	Timber

Using a combination of all levels of these keywords, several databases were searched to acquire a long list of academic literature: Web of Science, Scopus, Science Direct, JSTOR, EconLit and OECD *iLibrary*. Publications referenced in the literature reviewed were also added as a separate category ("*Cited in reviewed publications*"). It was found that searches using keywords of levels 1, 2 and either 3 or 4 yielded the best results, as using all four levels together created search parameters that were too narrow. The long list generated from these searches comprised 295 research publications.

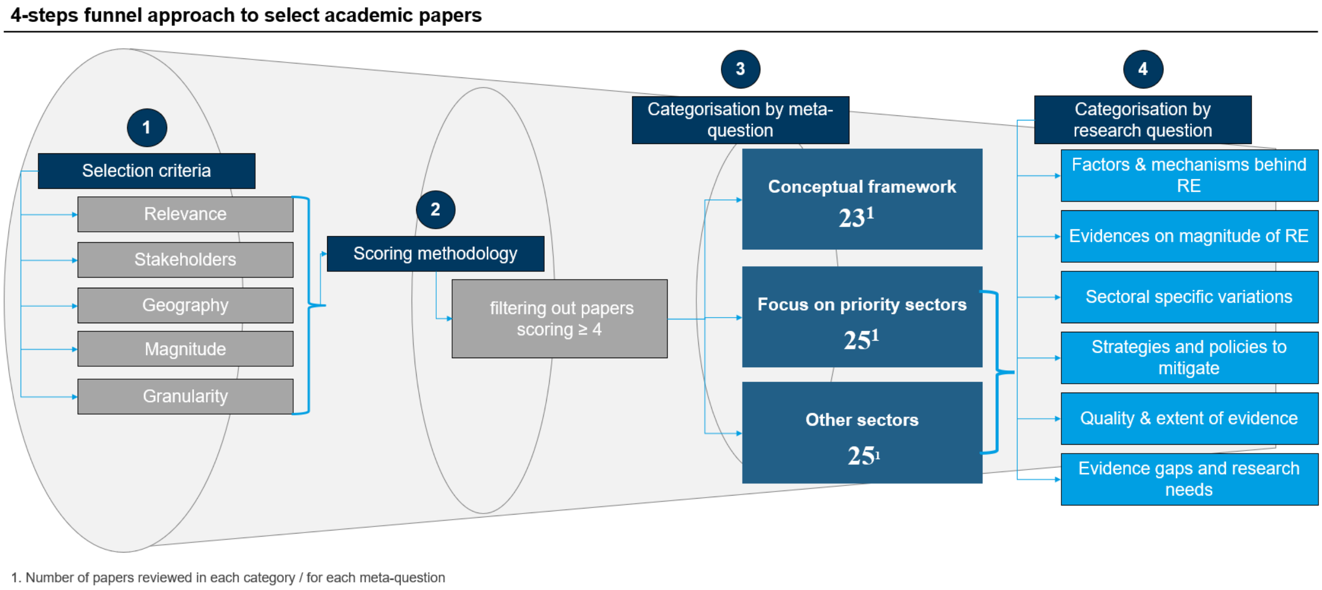
Cambridge Econometrics (CE) and IfM Engage removed duplicates and conducted a quick scan of the abstracts to exclude non-relevant studies. Of the 295 research publications, 165 publications were retained (see methodology below). Key insights from these publications were then systematically extracted across the following dimensions and collated in a spreadsheet database:

- **General information**: Organisation/author, year published, programme/publication name and link.
- **Study scope**: Time coverage (years), geographic scope, sector, methodology (e.g., empirical, theory, survey-based).
- **RE rebound effect specific information**: Resource efficiency indicator (e.g., reduced material use, GHG emissions), resource efficiency measure (e.g., lightweighting), mechanism behind rebound effects (e.g. income or substitution effects), identification strategy, rebound scope (e.g., direct, indirect, macro), resource rebound estimation (e.g., 20-40%), stakeholders / main agents (e.g., consumers, firms, regulators).
- **Assessment of the paper's quality**: Provides a summary of key findings, describing both strengths and limitations of the literature in how effectively the reviewed work addresses the research questions.

Prioritising and evaluating sources of literature

Figure 10 below outlines the approach that was used to prioritise and review publications identified:

Figure 10: Overview of the prioritisation approach for the 'in-depth' review



Note: Of the 165 papers identified during the light-touch review, 23 were retained for in-depth analysis for the conceptual framework and 50 for the sectoral analysis.

Step 1: Selection criteria to determine the inclusion or exclusion of a publication

To prioritise publications for in-depth review, we developed inclusion and exclusion categories with a structured scoring system. This approach ensures the systematic selection of the most relevant literature for further analysis. The criteria for inclusion were based on several key dimensions. First, publications were assessed for relevance, with priority given to those that specifically discussed rebound effects. Only those providing meaningful insights on this concept were considered (i.e., addressed one or several of the research questions listed in Table 1). The second criterion focused on the stakeholders or actors involved, with preference given to publications focused on the supply side i.e., actors critical in shaping production processes and resource use. This included industrial actors such as manufacturers, construction companies or miners. Publications focused solely on consumer behaviour or demand-side dynamics (e.g. effects of shifts to shared mobility or household behavioural analysis) were deprioritised. Geography was another important factor, with studies aiming at the UK, EU, or other developed economies given preference over papers focusing on developing regions due to the lack of similarity with the UK economy and political context (e.g., less prevalence of decarbonisation efforts). The magnitude of rebound effects was also a key criterion. Publications were assessed on whether they included any quantitative estimates of rebound effects or if they discussed rebound effects at either the direct (i.e., resource efficiency leads to increased demand for resources or products within the same consumption area), indirect (i.e., resource efficiency leads to increased demand for resources or products in a different consumption area), or macroeconomic levels (i.e., resource efficiency improvements lead to a reduction in the real price of resources, which has ripple effects throughout the economy). The magnitude of rebound effects are explained in greater detail in the scoring methodology outlined in Table 7. Finally, granularity was assessed, specifically examining whether the paper addresses the mechanisms underlying rebound effects, the strategies for achieving resource efficiency, and the indicators for evaluating resource efficiency and rebound effects. Publications were given additional weight if they explained the mechanisms driving rebound effects, presented measures aimed at improving resource efficiency, or utilised specific indicators to evaluate resource efficiency or rebound effects. No papers were de facto excluded solely based on lacking relevant information for one or more criteria.

Table 6: Inclusion and exclusion parameters for scanning results

Criteria	Positive	Negative
Relevance	RE rebound effects are specifically discussed in the paper	RE rebound effects are addressed as a secondary aspect in the paper The focus of the paper is on a type of RE that is not relevant (e.g., focus on psychological or behavioural aspects) The paper focuses on EE rebound
Agents considered	Focus on firms, and more broadly on industrial / supply side (e.g., manufacturer, farmers, mines, policymakers)	Focus on final demand / use (e.g., consumer, household behaviours and any psychological elements)
Geography	Research or evidence focusing on UK / EU or any other developed economies prioritised	Developing or least developed economies
Magnitude	Research provides (i) estimates of the rebound effects or (ii) insights of rebound effects at either direct, indirect and/or macro level	Research does not include any quantitative estimates or qualitative descriptions of magnitudes
Granularity	Research discusses (i) mechanisms behind rebound effects, (ii) measures to achieve resource efficiency, (iii) indicators to evaluate resource efficiency / rebound effects	Research does not discuss mechanisms, measures or indicators.

Step 2: Scoring methodology

Following the rules explained in Table 7, a scoring system was then applied. Each paper was given a ‘Positive’ or ‘Negative’ assessment depending on whether the criteria was satisfied or not. For instance, on the ‘Agents considered’ criterion, a ‘Positive’ would be given to a paper which would focus on assessing industrial rebound effects, while a paper that would focus solely on consumer behaviour or more generally demand-side dynamics would be given a ‘Negative’. However, publications would not be marked as 'Positive' or 'Negative' for the criteria of ' Agents considered' or 'Geographies', if they discussed these topics in general terms instead of specific terms, to prevent the criteria from being overly restrictive.

Once the publications were assessed against all criteria, a couple of grading rules would then be applied to get the score. First, the lowest score (i.e., 1) was given to publications where either the 'Relevance' or ' Agents considered' criterion was marked as 'Negative' (irrespective of the numbers of ‘Positive’ on the other criteria, as priority was given to these criteria over the rest). Secondly, publications that would be marked as ‘Positive’ over 3 or more criteria, without being given any negative, would receive a score of ‘5’, publications with 2 ‘Positive’ with no ‘Negative’, would be given a score of ‘4’ and publications with ‘1’ Positive with again no ‘Negative’ would be given a score of ‘3’. This was drafted this way such as to avoid excluding theoretical or conceptual publications. For publications with criteria marked as ‘Negative’, a similar inverse rule would apply. Finally, only the publications with a score ≥ 4 were reviewed in depth.

Table 7: Scoring methodology

Number of ‘Positive’ criteria	Number of ‘Negative’ criteria	Final score
Indifferent	3 or more	1
≤ 1	2	2
≥ 2	2	3
≤ 2	1	3
≥ 3	1	4
≤ 1	None	3
2	None	4
≥ 3	None	5
If ‘Negative’ marked for ‘Relevance’ criterion		1

If ‘Negative’ marked for ‘Agents considered’ criterion	1

Step 3: Categorisation by meta question

The publications were subsequently categorised based on their relevance for developing a conceptual framework (see Annex 4) vs addressing the research questions (listed in Table 1). Each paper was uniquely assigned to one category, depending on whether it primarily presented empirical or theoretical findings relevant to the research questions or if it offered methodological insights that could inform the conceptual framework and maps (see Section 4). While each paper was distinctly attributed to one of the two categories, there was flexibility in reviewing publications that offered insights relevant to both categories. For example, a paper primarily classified as useful to answer the set of research questions might still provide valuable empirical examples that could enrich the conceptual mapping rebound effects at the sectoral level.

Step 4: Categorisation by research question

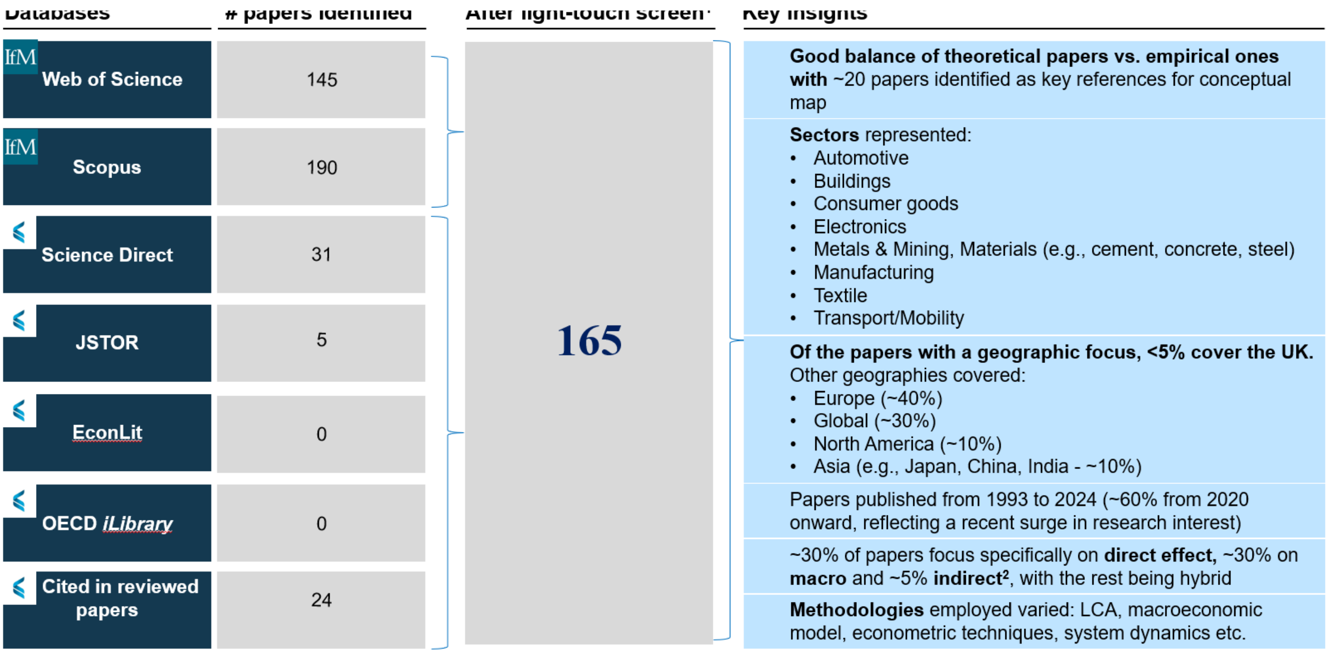
The 50 selected publications were thoroughly reviewed to extract relevant information addressing key research questions (listed in Table 1) related to rebound effects in industrial RE measures.

Summary of relevant literature

The search results detailed in this section are for the 165 studies that underwent a light touch screening (see Steps 1 and 2 above,) to give a broad overview of the search results, rather than the 50 shortlisted papers that underwent detailed review and are synthesised in section 2. As the 50 papers were disparate in their scope, method and research questions a larger sample size was viewed as better suited to general trends in academic and grey literature on resource efficiency rebound effects. Figure 11 summarises some general insights about the 165 studies (115 light touch review + 50 deep dive review). Figure 12 shows trends in the geographies covered and year of publication. Figure 13 shows the level of analysis and the methodological approached covered while Figure 14 outlines the sectoral coverage and the type of economic agents the studies tend to focus on.

The literature that was reviewed in-depth constituted a good balance of empirical vs. theoretical publications, with around 20 publications identified as directly relevant to the development of a conceptual framework. Regarding databases, although no relevant publications were found in the OECD iLibrary and EconLit, the majority of the evidence base was sourced from Web of Science and Scopus. This was supplemented by publications from JSTOR and a review of the references cited in the identified literature (snowballing).

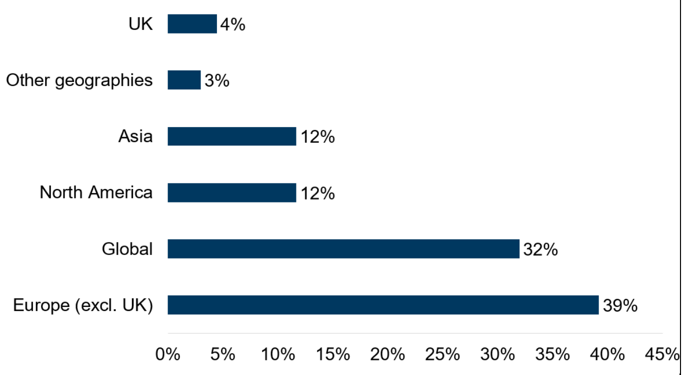
Figure 11: Search results and insights from literature review



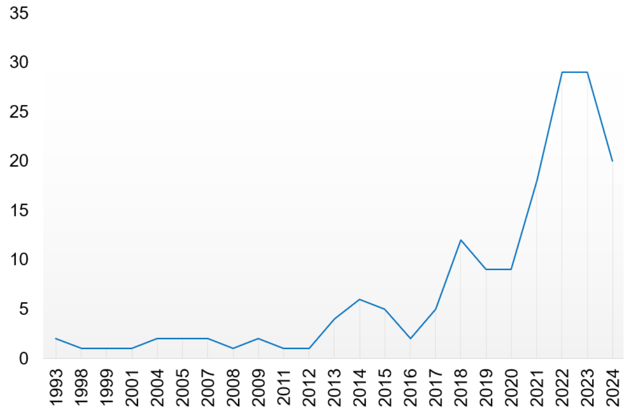
1. Merged / removed duplicates and non-relevant papers by reviewing abstract; 2. Direct rebound refers to increased use of a product as it becomes more resource-efficient; indirect rebound occurs when savings are spent on other goods or services; and macro rebound involves economy-wide effects, including market expansion and sectoral shifts that offset overall resource savings.

In terms of geographic focus, less than 5% of the reviewed publications were focused on the UK context. The remaining studies covered a range of other regions, with approximately 40% focusing on Europe and another 30% examining global implications. North America accounted for around 10% of the studies, while Asia, including countries such as Japan, China, and India, represented about 10% of the geographic focus. This distribution highlights a greater interest for resource efficiency rebound effect in Europe vs the rest of the world. The temporal aspect of the literature was notable, with publications published from 1993 to 2024. Interestingly, around 60% of these studies emerged from 2020 onward, reflecting a recent surge in research interest in this field.

Figure 12: Deep-dive geographies covered and year of publication



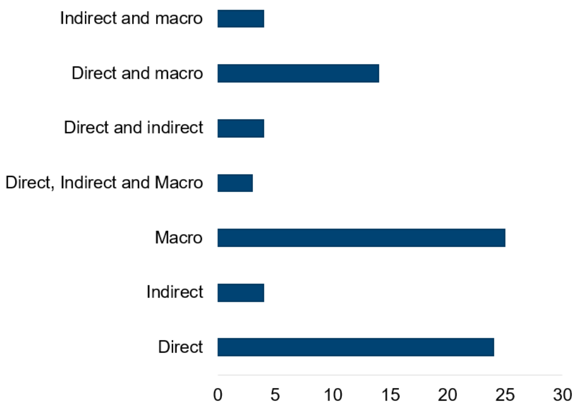
Note: Share over total number of publications mentioning a geographical focus. Sample size = 69 publications. No specific geographic focus for the rest of the publications (e.g., simulated data, theoretical models, or literature reviews that draw from a broad range of studies across different regions).

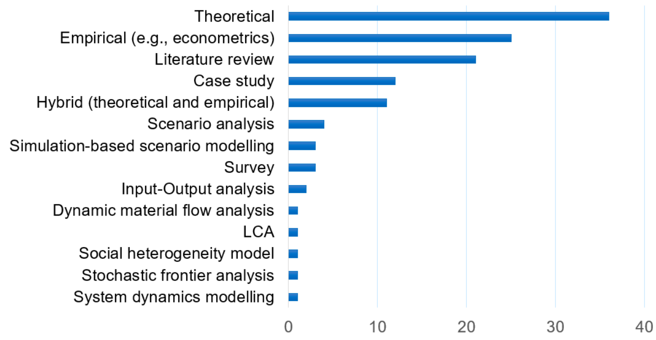


Note: Total count of paper published per year. Sample size = 165

The methodological approaches applied within the publications varied widely, encompassing macroeconomic models like Computable General Equilibrium (CGE) and macroeconometric models, econometric techniques, and system dynamics depending on the type and level at which the rebound effect was studied. Regarding the specific focus of the studies, approximately 30% concentrated on direct rebound effects, another 30% on macro-level impacts, and about 5% on indirect effects, with the remainder categorised as hybrid studies that combined various perspectives.

Figure 13: Deep-dive on RE rebound level and estimation method



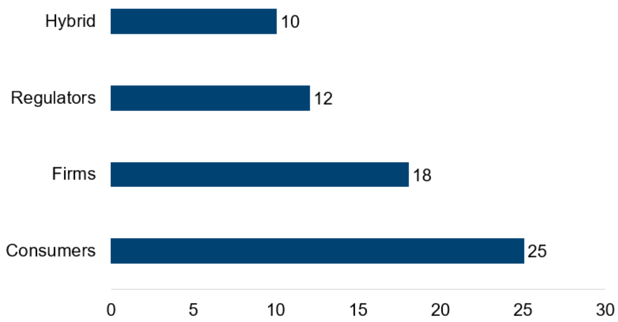


Note: Total count of number of publications per category. Sample size = 78 publications. The discussion for the remaining publications is conducted at a more general level.

Note: Categories are not mutually exclusive. Total count of number of publications per category. Sample size = 122 publications. The methodology for the remaining publications was not clearly defined (e.g., discussion publications, no reference to economic analysis).

The studies that concentrated on specific economic agents show a pronounced emphasis on consumer-level rebound effects. These studies account for approximately 25% of the reviewed literature, while those examining firm-level impacts represent less than 20%. Additionally, a subset of research, about 10%, focuses on regulators as the primary agents in addressing rebound effects, particularly in examining how such effects can be managed effectively. This distribution highlights the significant emphasis given to consumers in the rebound effect landscape compared to firms and governments, most likely due to the difficulty of gathering sufficient data at sectoral level or firm-level to draw generalisable conclusions.

Figure 14: Deep-dive on stakeholders/agents focus on sectors



Note: Share of number of publications per category. Sample size = 65 publications. The remaining literature does not focus on any specific economic agents. Hybrid refers to

Total count of number of publications per sector. Sample size = 78 publications. Other publications are either theoretical or sector-agnostic. “Consumer goods” include clothing, furniture, consumer electronics and home appliances.

publications focusing on at least two different categories.	*"Manufacturing and Industry" focus on other sectors than the four priority industrial sectors and/or combine multiple manufacturing and industry sectors. "Multiple sectors" refer to combinations manufacturing, industry and other sectors, this categorisation is often found in publications using macro models.*

Annex 3: Quantitative estimates of resource efficiency rebound effects from the existing literature.

This annex describes the limited existing literature that quantifies the rebound effects arising from resource efficiency measures. It is spare and more disparate than the literature discussed in Section 6 on industrial energy efficiency rebound effects.

Table 8: Quantitative estimates of resource efficiency rebound effects from the existing literature.

Source	Type of rebound effect and sector (if any)	Sector(s)	Estimates	Estimation method
Sourabh et al. (2024)	Direct	Metals	The rebound is found to be elastic in the range of − 2.16 to 2. 57	Econometric circular economy model based on the co-flow structure in a multivariate framework for metal industries.
Greene et al. (1999)	Direct	Car	20%	Econometrics
Greene (1993)	Direct	Car	5-15%	Econometrics
Buyle et al. (2023)	Direct and indirect	Steel	From 10.5% for VAR to 19.8% for SVAR; 4.6% increase in total stainless steel demand in the long term.	Vector autoregression (VAR) and Structural vector autoregression (SVAR): dynamic models where lagged values of all included variables estimate current state of the system.
Ryter et al. (2021)	Direct and macro	Mining	Permanent increases in recycling displace ~0.5 kilotonnes mine production per kilotonne increase in scrap supply on average	Dynamic supply chain simulation model for copper through 2040 incorporating inventory-driven price evolution, dynamic resource flow analysis, and life

				cycle-assessment alongside mine-level economic evaluation of opening, closing, and production decisions.
Lu and Schandl (2021)	Direct and macro	Metals & Construction	8.6% at sector level and 65% at economy level by 2060	Global Trade and Environment Model (GTEM-C)
Di Domenico et al. (2023)	Macro		Depending on the scenario (one or multiple shocks on the energy efficiency of recycling sector), rebound varies from 0.5% to 3.1%	Agent-Based Stock-Flow Consistent model with a simplified Input-Output (IO) structure of production
Skelton et al. (2020)	Macro	Steel & Automotive	77% of emissions in the resource efficiency scenario are offset by macro rebound effects.	GEM-E3 model
Pfaff and Sartorius (2015)	Macro		The specific values range from 2.5% to 10.5%, with an average of 3.8%.	Static input-output model in Germany. Bottom-up analysis that scales up findings from 16 resource efficiency projects across a range of non-energetic raw resources to the national level.
Distelkamp and Meyer (2014) using Skelton et al. (2020) calculations	Macro		24%	GINFORS (Dynamic multi-regional input output model with imperfect markets and bounded rationality). Identified the 30 most important input coefficients that determine resource demand in the EU27.
Saunders (2004)	Macro		68%	Neoclassical macroeconomic framework

Zink and Geyer (2017)	Macro		Potentially cause a negative net environmental impact	Econometrics
Karakaya et al. (2024)	Macro		52%, among EU member countries and their trading partners, the UK has the seventh-highest resource rebound effect after Switzerland, Sweden, Norway, France, Denmark, and Luxembourg.	Stochastic Frontier Analysis (SFA)
Pfaff and Sartorius (2015)	Macro	Rocks and minerals Chemical products Ceramics Steel Nonferrous metals Secondary raw resources	3.1% in economy-wide 2.5% for rocks and minerals 7.8% for chemical products 3.4% for ceramics 10.6% for steel 4.3% for nonferrous metals 2.8% for secondary raw resources	Input-output approach
Ellen MacArthur Foundation (2015)	Macro	Mobility; food; built environment	5%-20%	Scenario analysis by summing up the primary resource cost (e.g., virgin resources), other cash-out costs (e.g., maintenance), and externalities (e.g., CO_2)

Annex 4: Conceptual Framework for mapping Resource Efficiency Rebound Impacts

This annex shows the conceptual framework that was developed, through a literature review, and informed the development of the sector maps outlined in section 4.

Figure 15: Conceptual framework with illustrative examples

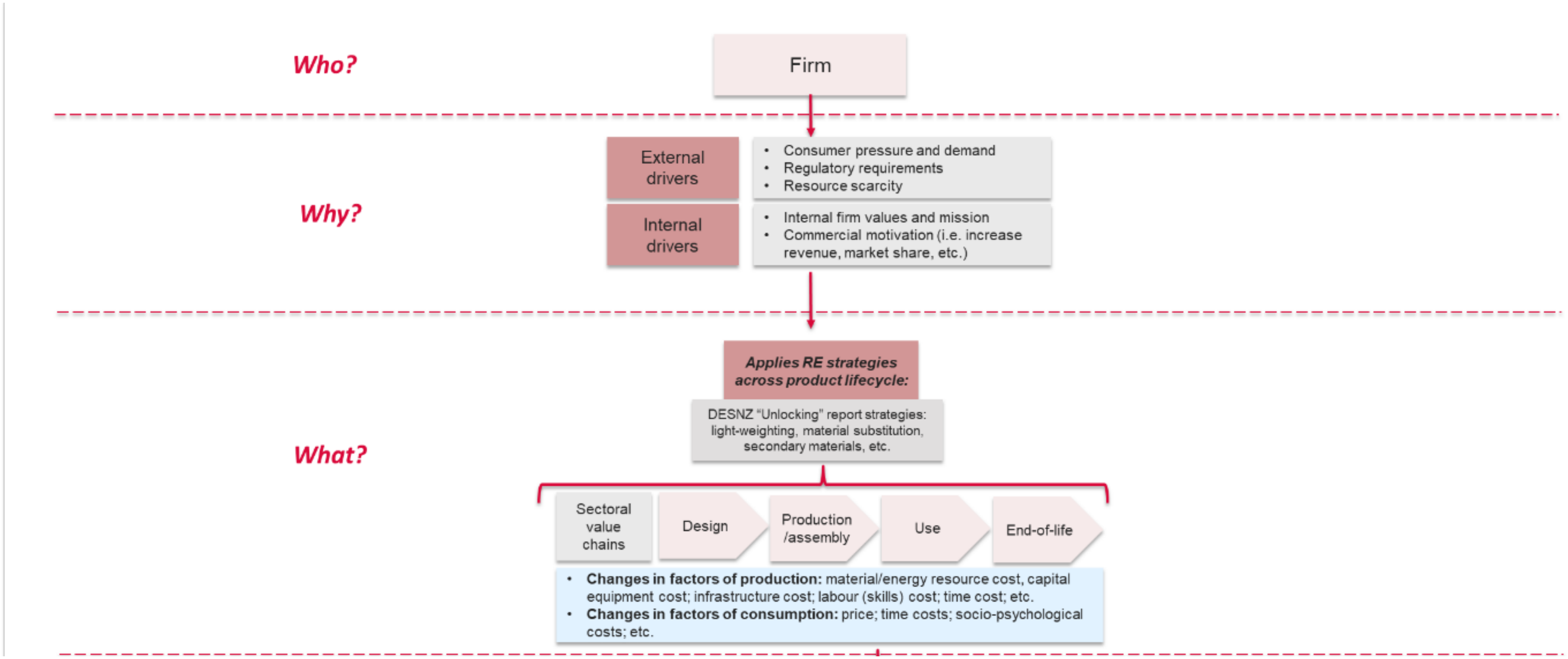
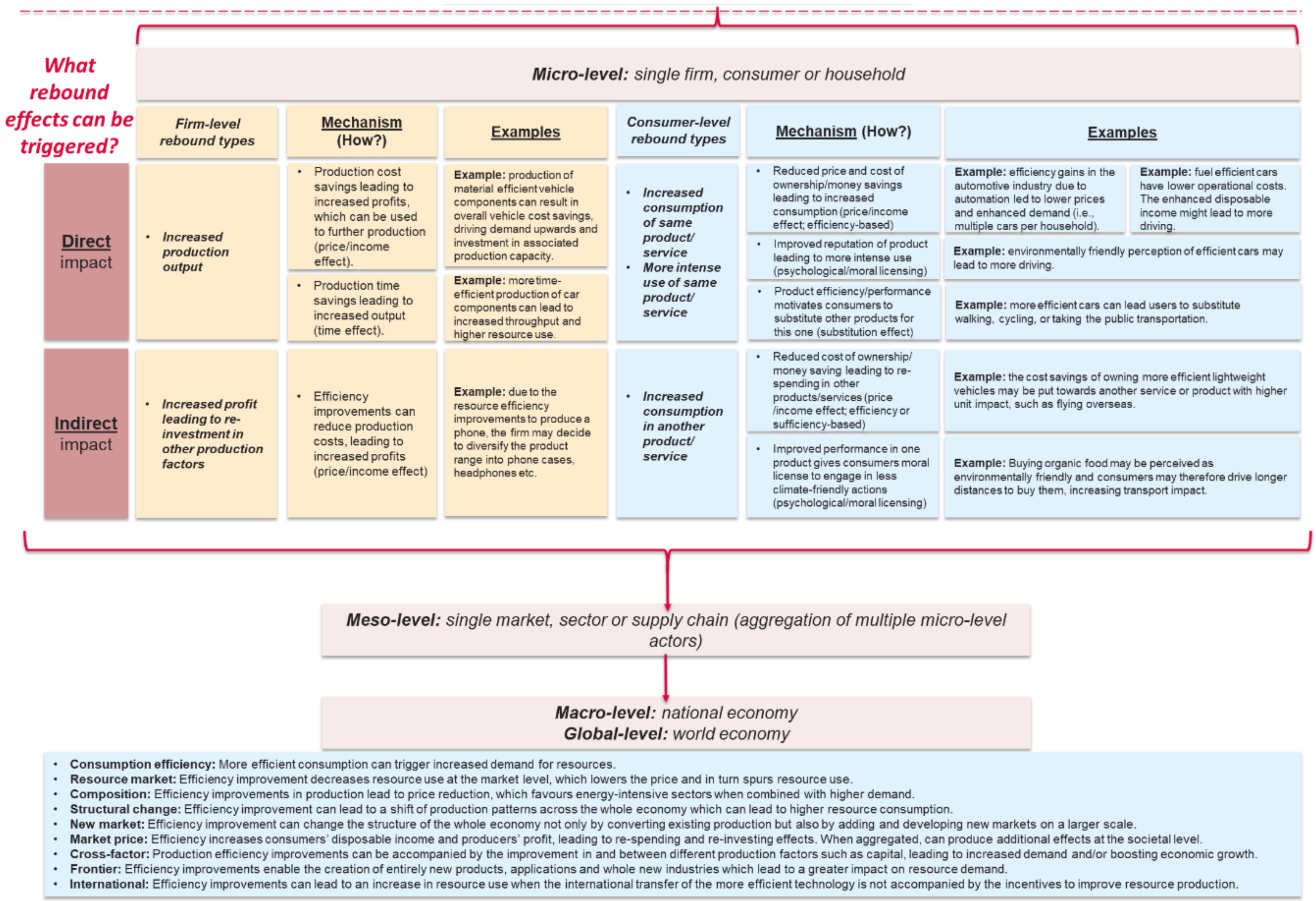


Figure 16: Conceptual framework with illustrative examples (cont.)



As shown in Figure 16, the most tangible and commonly studied rebound effects in literature are those direct and indirect effects happening at the micro level, in both individual firms and consumers. In this regard, micro-level direct effects occur when improvements in resource efficiency lead to increased demand for resources or products within the same consumption area (by both firms and consumers), whereas indirect effects arise when benefits from resource efficiency lead firms and consumers towards increased investment in other production areas and/or consumption in other final or intermediate goods and services.

At the micro-level, direct effects can be triggered by production cost and time savings that lead to increased production output by firms. Similarly, indirect effects observed in firms can be triggered by efficiency improvements that reduce production costs, leading to increased profits that can be re-invested in other production factors. On the consumer side, three main mechanisms are observed for direct effects:

- reduced market prices and cost of ownership lead to increased consumption in the same product/service area;
- resource efficiency results in improved reputation of products leading to more intense use; and
- product efficiency/performance motivates consumers to substitute other products for this one. Indirect effects observed on the consumer side can be triggered by either reduced cost of ownership that leads to consumer re-spending in other products/services, or when improved performance in one product gives consumers moral license to engage in less climate-friendly actions.

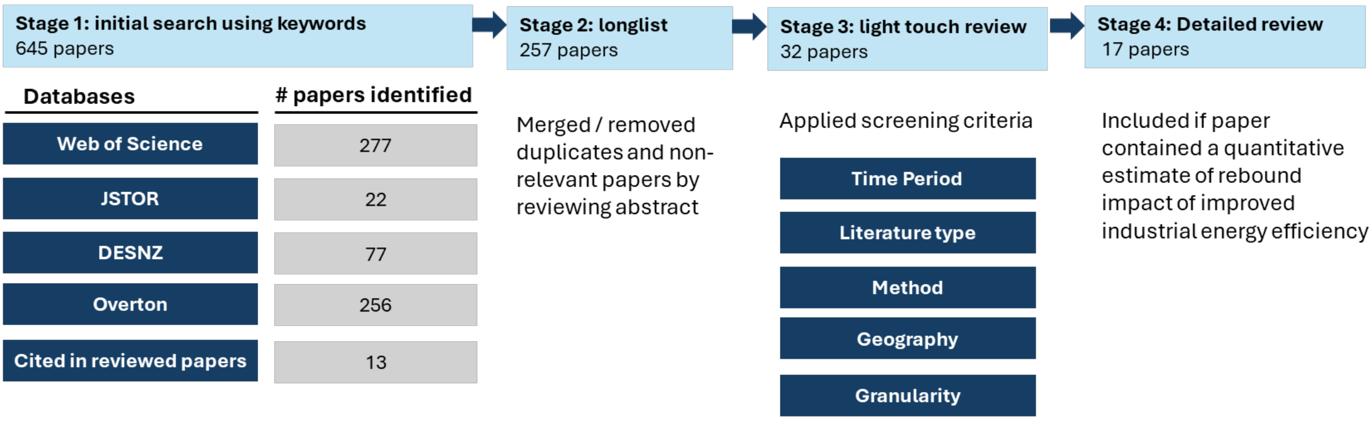
Annex 5: Methodology for literature review on industrial energy efficiency

This annex outlines the methodology that was developed and applied to understand the existing literature on energy efficiency rebound effects. The insights from this literature review are presented in section 6. This annex also summarises the body of literature that was identified as relevant – for example, characterising the geography, method, year of study.

Literature review method

A four-stage screening approach was used to identify the final section of 17 documents for detailed review on industrial energy efficiency rebound effects from an initial search of 645 potential literature sources, as shown in Figure 17.

Figure 17: Four stage literature screening process



Identifying sources of literature

Stages 1 and 2: Initial search and long listing

Following consultation with DESNZ, a hierarchy of search keywords were established, as set out in Table 9. Using a combination of all levels of these keywords, several databases were searched to acquire a long list of both academic and grey literature. For academic literature, Web of Science was the primary database used, with searches on JSTOR and expert elicitation from both DESNZ and other peer experts supplementing the findings. For grey literature, searches were primarily made using Google and Overton to identify potentially relevant sources. In both cases, it was found that searches using keywords of levels 1, 2, and either 3 or 4 yielded the best results, as using all four levels together created search parameters that were too narrow. The initial search generated over 600 documents, nearly equally split between academic journal papers and grey literature documents. Duplicate sources were removed and the title and abstract of each study were reviewed for relevance. This approach resulted in a longlist of 244 publications.

Table 9: Keywords used to generate a longlist of literature sources for review.

Keyword - Level 1	Keyword - Level 2	Keyword - Level 3	Keyword - Level 4
Industrial energy efficiency	Rebound	Impact	Iron
Industrial efficiency	Backfire	Drivers	Steel
	Growth	Magnitude	Chemicals
	Productivity growth	Size	Oil refining
	Output growth	Sectors	Food and drink
		Output	Pulp and paper
		Income	cement
		Emissions	glass
		Costs	ceramics
		Energy use	
		Trade	

Prioritising and evaluating sources of literature

Stage 3: Light touch review

The 244 publications were then further reviewed using six categories of assessment criteria to determine their relevance for this study. The keywords in Table 9 were informed by the research questions detailed in Table 1. The guidance to assess the relevance of a publication was iterated during the light touch review. For example, for the "geographical relevance" category, only UK studies were identified as relevant initially. However, when only five UK studies were identified, it was agreed with DESNZ that studies that focused on countries with a similar economic structure to the UK would also be relevant. During the light touch review, 13 more papers were identified through snowballing – searching the references and citations of the 244 longlist of publications.

Table 10: Categories and guidance to assess the relevance of the existing literature

Category	Guidance to assess relevance
Time period	Favouring more recent studies
Type of literature and organisations	Favouring academic publication - including those that are peer-reviewed, official government documents and reports. For other grey literature, favouring independent studies, conducted by reputable research organisations.
Method	Favouring those publications that outline, in sufficient detail, a robust and replicable method.
Geographical relevance	Favouring publications that were focused on the UK or are demonstrably applicable to the UK context (e.g. a country that is a key UK trading partner for steel products or has a similar economic structure). For example, other European countries, the USA, Canada, and Australia.
Sectoral relevance	Favouring publications that are focused on the eight priority DESNZ industrial sectors.
Rebound estimation	Including only studies that estimated quantitative rebound effects

Stage 4: Detailed review

There were 32 relevant publications identified following the light touch stage 3 review. These publications were then reviewed in-depth, applying the final criteria to select 17 remaining studies that specifically estimated quantitative energy rebound effects from industrial energy efficiency improvements. Thus, excluded studies (from stage 3 to 4) included

- National-level studies – with industrial sector rebound not isolated/quantified, e.g. Adetutu et al. (2016) and Karakaya et al. (2024).
- One study that exclusively looked at carbon emission rebound rather than energy - Skelton et al. (2020).

- Energy intensity analyses - where rebound was not estimated, e.g. Dahmus (2011).
- Sector analyses that were outside the industry-specific remit, and focussed on other sectors such as personal transport. e.g. Anson and Turner (2009).
- Theoretical/conceptual rebound papers, but with no estimation of rebound, e.g. Blackburn and Moreno-Cruz (2019) and Guzzo et al. (2024).

Overall, the academic literature was more relevant for this study than the grey literature. The CREDS report (publication no.17 in Table 11) was the only source of grey literature included in the final list of 17 studies. Even so, the Centre for Research into Energy Demand Solutions (CREDS) was a research consortium led by UK academics. The main limitation of the grey literature was the lack of quantitative analysis on potential rebound impacts.

Summary of relevant literature

A summary table of the collected documents is given in Table 11, which shows key aspects of the study modelling framework, coverage of industry sectors, rebound estimations and economic indicators:

Table 11: Summary table of 17 collected studies

ID	Author, year	Region, time coverage	Modelling approach	Industry coverage	Sector rebound estimate	Total rebound estimate	Economic indicators
1	Ahmann et al., 2022	Germany, 2020-2030	Macro-econometric model. (PANTA RHEI)	15 industrial sectors	Y	Y	Y
2	Allan et al., 2007	UK, calibrated to year 2000. 25 year model horizon	Dynamic CGE modelling (UKENVI)	All production sectors.	-	Y	Y
3	Amjadi et al., 2018	Sweden, 2000-2008	Econometric Analysis, using Stochastic frontier analysis.	Mining, Pulp and paper, Chemicals, Iron and steel	Y	-	-
4	Amjadi et al., 2022	Sweden, 1997-2008	Econometric Analysis, using	14 manufacturing sectors	Y	-	-

			Factor Demand model				
5	Barker et al., 2007	UK, 2000-2010	Macroeconometric model. (MDM-E3)	50 industrial sectors	Y	-	Y
6	Bohringer and Rivers, 2021	USA Calibrated to year 2010	General equilibrium (CGE) model	Manufacturing sector.	Y	Y	-
7	Broberg et al. 2015	Sweden, 2009-2035	Dynamic CGE modelling (EMEC)	All productive industries	Y	Y	Y
8	Dahlqvist et al. 2021	Sweden, 2001-2012	Econometric Analysis, using Factor Demand model	Pulp and paper, Iron and steel, Chemicals, Mining	Y	-	-
9	Garau and Mandras, 2015	Italy, Calibrated to year 2010. 30 year model horizon	Dynamic CGE model	All production sectors	-	Y	Y
10	Hanley et al. 2009	Scotland, Calibrated to year 1999. 25 year model horizon	Dynamic CGE modelling (AMO-SENVI)	All 25 Scottish production sectors	Y	Y	Y
11	Kahouli and Pautrel, 2023	USA, calibrated to 2018. 20 year model horizon	Dynamic CGE model.	All industry as single sector	Y	Y	-

12	Koesler et al., 2016	Germany Calibrated to 2009. Model horizon not specified.	WIOD CGE model	All German productive industries	Y	Y	Y
13	Lutz et al. 2022	Germany, 2020-2030	Macroeconometric model. (PANTA RHEI)	All German productive industries	Y	-	Y
14	Saunders, 2013	USA, 1980-2000	Econometric Analysis, using Translog cost Function	All USA productive sectors	Y	Y	-
15	Turner et al. 2013	UK, Not specified. Calibrated to 2004	Dynamic CGE (UKENVI)	All production sectors	-	Y	Y
16	Zimmerman et al. 2021	Switzerland, 2020-2050	Dynamic CGE model (SEEM)	Manufacturing sector (split energy and non-energy intensive)	Y	Y	Y
17	CREDS report, 2021	UK, 2020-2040	Macroeconometric model. (E3ME)	70 industry sectors (reported as a single sector)	Y	-	Y
Total number					(14)	(11)	(11)

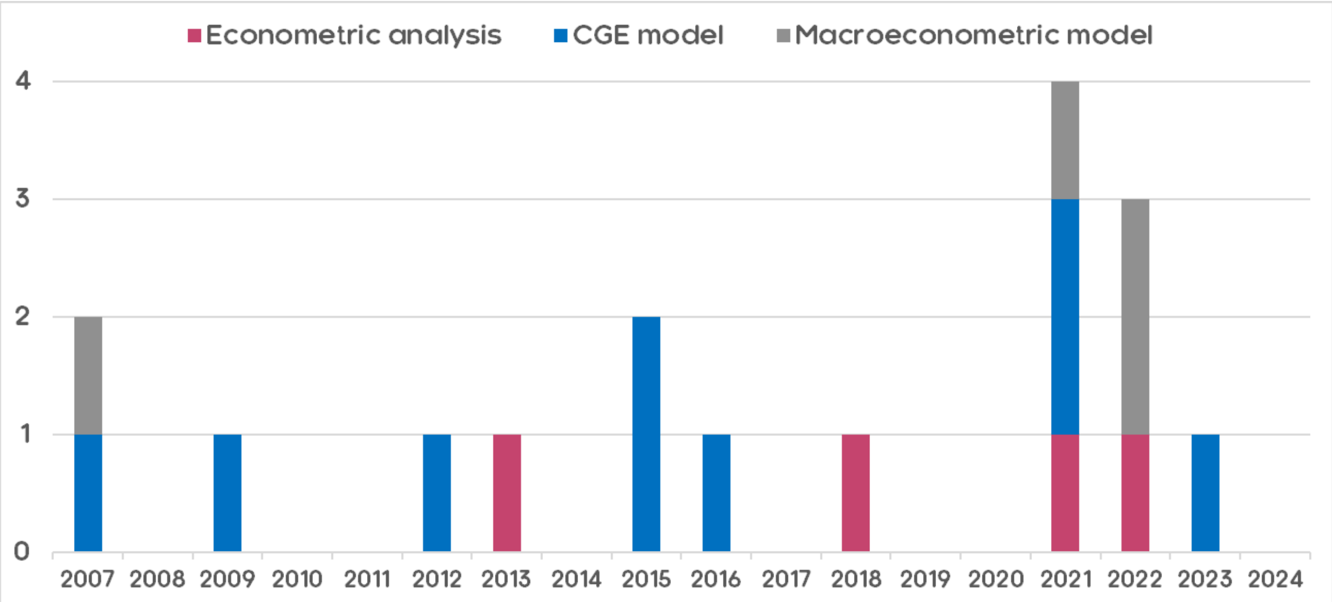
The 17 relevant studies employed three distinct methodological approaches (see Section 5.1.4 and Annex 7 for more detailed discussion):

- CGE models (9 in total.): CGE macroeconomic simulation models explore interactions between energy, the economy and the environment (e.g. Turner et al., 2012). They are based on a system of equations which combine economic theory with real economic data to assess the impacts of policies or economic shocks. Typically calibrated on a single base year, energy efficiency improvements are modelled as an exogenous costless energy reduction to sector/s, assumed as an improvement to energy augmenting technological change. The model then runs through iterative loops until economy-wide (also known as general equilibrium) effects such as adjustments in market prices, labour and capital supply are settled. Rebound is estimated from identifying the difference between expected and scenario energy consumption.

- Macroeconometric models (4 in total): Econometric-based modelling approaches use statistical analysis (e.g. regression) to test or verify economic relationships. Four studies use macroeconometric models, either the German model (PANTA RHEI - Ahmann et al., 2022 and Lutz et al. 2022) or UK models (MDM-E3 - Barker et al. 2007, and E3ME - CREDS, 2021). These models are based on a system of identity and econometrically estimated equations to represent an entire economy. Calibration is based on historical timeseries data. The sample studies were used for scenario analysis of energy efficiency policies, to estimate ex-ante (i.e. future) or ex-post (i.e. historical) energy rebound effects by comparing energy use after energy efficiency improvements, against baseline scenarios.
- Econometric analysis methods (4 in total): Four studies apply econometric techniques (e.g. stochastic frontier analysis) to firm-level empirical data (obtained from national statistical agencies, e.g. of sales, labour, energy expenditure, capital investment data), to estimate ex-post (i.e. historical) rebound directly via calculated own-price energy elasticities.

Figure 18 shows that nearly half of the studies were published after 2021, reflecting perhaps a growth of attention on rebound impacts of industrial energy efficiency, or advances in modelling capabilities and data availability. For example, the three CGE studies since 2021 involve newly created models: Zimmerman et al (2021) includes annual (rather than one off) efficiency improvements, Kahouli and Pautrel (2023) includes residential-industry cross spillover effects, and Bohringer and Rivers (2021) includes more granular general equilibrium effects. In addition, five of the eight econometric-based studies were published since 2021, including three of the four econometric analysis papers – which are a newer type of rebound estimation approach, using firm-level data.

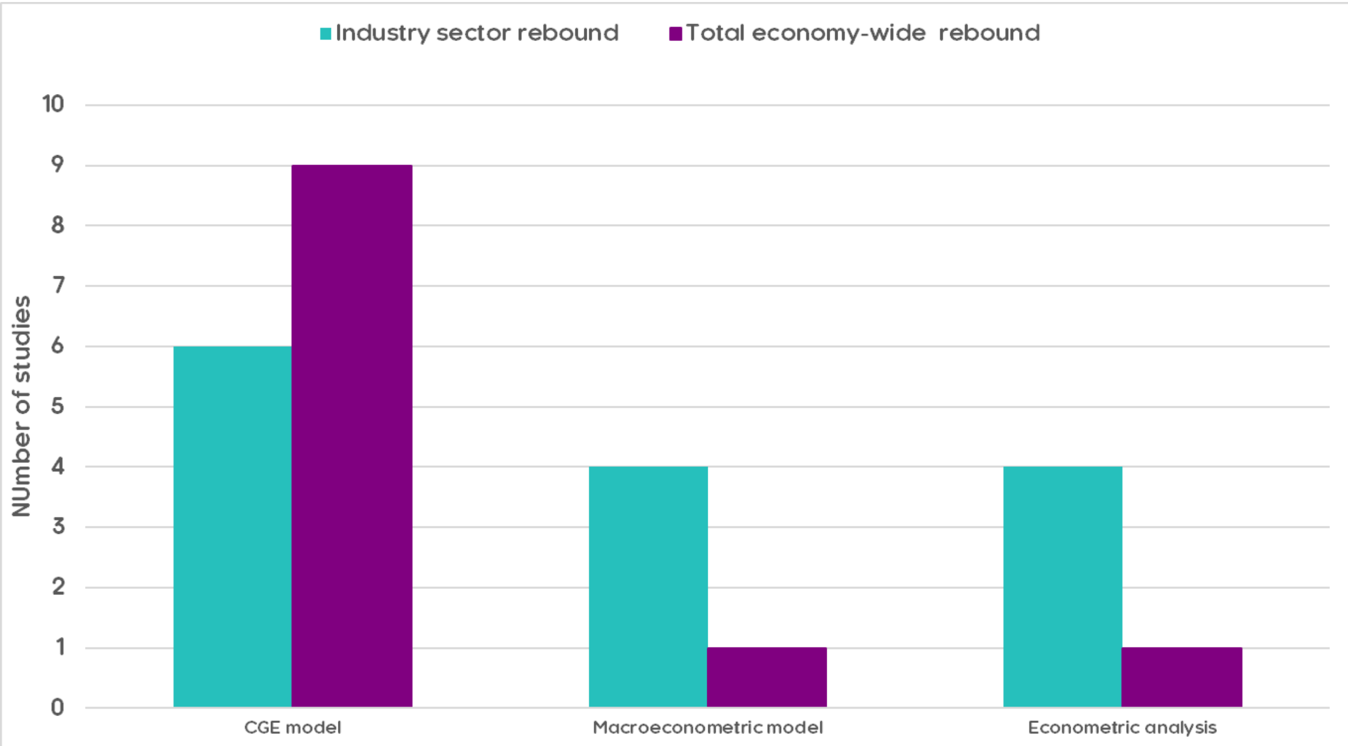
Figure 18: Publication year and modelling framework



As noted in Table 11, the studies differ in terms of sectoral coverage and disaggregation. Eleven studies assessed rebound effects in response to an efficiency improvement applied to a group of all productive (including industry) sectors of an economy (e.g., Allan et al., 2007; Turner et al., 2012). Two studies looked in detail at specific industry sectors (Amjadi et al., 2018; Dahlqvist et al., 2021) whilst three others looked more broadly at manufacturing sectors (Amjadi et al., 2022; Zimmermann et al., 2021, Bohringer and Rivers, 2021). A single study (Kahouli and Pautrel, 2023) modelled and reported on rebound effects for industry which was categorised as a single sector.

Figure 19 shows that of the seventeen studies, nine used CGE and eight used econometric methods to estimate rebound effects from industrial energy efficiency improvements. Fourteen (6 CGE model, 4 macroeconometric model, and 4 econometric analysis) studies estimated rebound of industrial sector/s, whilst eleven (9 CGE model, 1 macroeconometric model, and 1 econometric analysis) studies estimated total, economy-wide rebound magnitudes. Sectoral and total rebound values are set out in more detail in Section 6

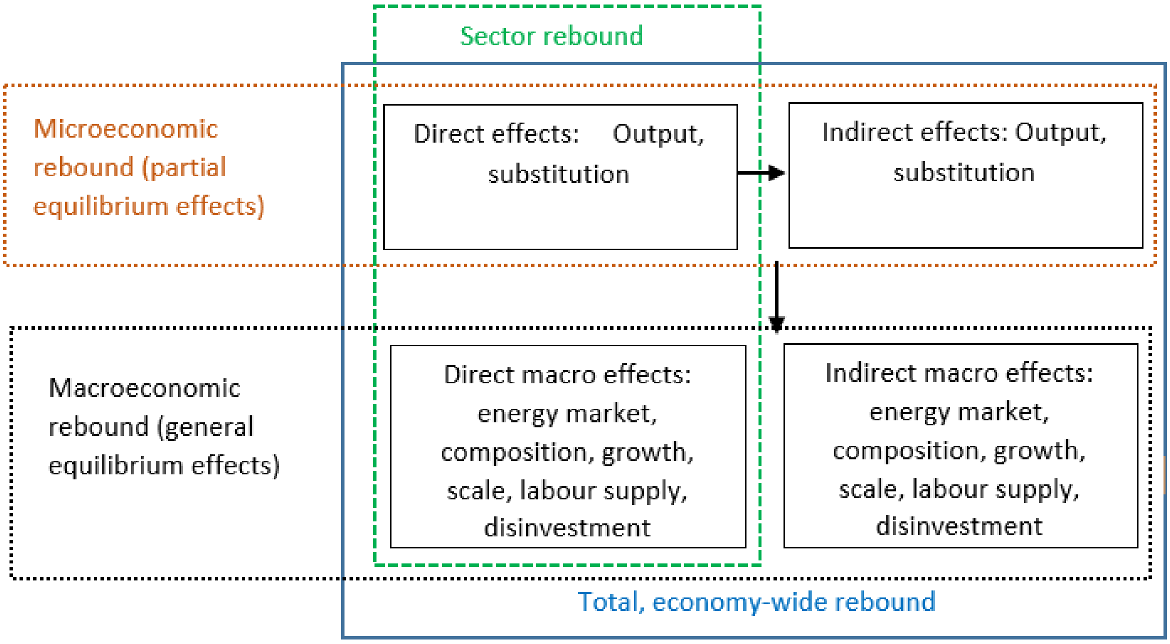
Figure 19: Modelling approaches by rebound scope



Annex 6: Sector-level estimates of industrial energy efficiency rebound effects

Table 12: Summary of sector-level rebound estimates by modelling type (next page) summarises the sector level rebound estimates from seventeen studies that estimate the industrial energy efficiency rebound effects. These estimates cannot be viewed as like-for-like comparisons as they all define the scope of the rebound effect differently. Figure 20 shows a typology of different scopes of rebound effects, building on the information presented in Table 13 in Annex 7.

Figure 20: Typology of scopes of rebound effects.



General equilibrium models estimate rebound in two states. One is in partial equilibrium shown in the brown box), where direct rebound effects in the sector considered can be calculated. These direct effects (caused by e.g. increased output, substitution of energy by labour or capital) lead to changes in other sectors of output and input production factors (i.e. indirect effects). These direct and indirect microeconomic effects induce long run macroeconomic effects (shown in the black box), which are captured in the settled general equilibrium condition (typically after 20-25 modelling cycles i.e. years). The total of direct, indirect and macroeconomic effects sum to total economy-wide rebound (shown in the blue box)

For macroeconometric models, their sector level rebound effects include combined direct microeconomic and macroeconomic components (shown in the green box) in both short and long run analysis. Macroeconometric models also feature other sectors in their modelling frameworks, so can include both indirect (microeconomic) and indirect (macroeconomic) effects in both the short and long run. The sum of all effects is the total economy-wide rebound (shown in the blue box).

Econometric analysis studies only estimate sector level rebound effects from combined direct and macroeconomic components (shown in the green box) in both short and long run analysis.

Table 12: Summary of sector-level rebound estimates by modelling type

ID	Author, year	Region, time coverage	Method /model	Specification of energy efficiency	Method of estimating rebound	Scope and baseline estimate of sector rebound
1	Ahmann et al., 2022	Germany, 2020-2030	Macroeconometric model. (PANTA RHEI)	Policy measures in modelled scenario: includes energy reduction, carbon/energy taxes	Expected versus actual efficiency scenario energy use	Long run Quarrying, other mining 13%, Manufacture of basic metals 21%, Mineral processing 19%, Food and tobacco 8%, Non-ferrous metals, foundries 20%, Paper 9%, Metal processing 21%, Basic chemicals 5%, Other chemical industry 3% Glass and ceramics 16% . Total industry: 13%
2	Allan et al., 2007	UK, calibrated to year 2000. 25 year model horizon	Dynamic CGE modelling (UKENVI)	Improvements made to efficiency of energy inputs (energy augmenting technological change) to all production sectors.	Expected versus efficiency scenario energy use	N/A (only models economy-wide rebound)
3	Amjadi et al., 2018	Sweden, 2000-2008	Econometric Analysis, using Stochastic frontier analysis.	Stochastic frontier analysis (SFA) to give estimation of firm-level	Elasticities of energy demand w.r.t changes in energy efficiency	Short run: Sector: fuel/electricity Iron and steel: 65%/86%

ID	Author, year	Region, time coverage	Method /model	Specification of energy efficiency	Method of estimating rebound	Scope and baseline estimate of sector rebound
				efficiency improvements.		Pulp and paper: 64%/84% Chemicals: 62%/76% Mining: 58%/82%
4	Amjadi et al., 2022	Sweden, 1997-2008	Econometric Analysis, using Factor Demand model	Data envelope analysis (DEA) to give estimation of firm-level efficiency improvements.	Short run and long run elasticities of energy demand w.r.t changes in energy efficiency	Short run: 92-100% across 14 manufacturing sectors (95% confidence intervals 79% to 114%) Long run: 70-100% across 14 manufacturing sectors (95% confidence intervals -367% to 507%)
5	Barker et al., 2007	UK, 2000-2010	Macroeconometric model. (MDM-E3)	Implementation of UK energy efficiency policies 2000-2010 across industry, residential, commercial, transport sectors.	Expected versus actual efficiency scenario energy use	Long run: Energy intensive industry: 25%, Other industry: 16%
6	Bohringer and Rivers, 2021	USA Calibrated to year 2010	General equilibrium (CGE) model	Macroeconometric General equilibrium model	Sum of substitution, Income, Composition, Growth, Labor supply, Energy price effects	Short run: Energy intensive manufacturing 40% Long-run: Energy intensive manufacturing 63%

ID	Author, year	Region, time coverage	Method /model	Specification of energy efficiency	Method of estimating rebound	Scope and baseline estimate of sector rebound
						(elasticity of substitution, σ = 0.4)
7	Broberg et al. 2015	Sweden, 2009-2035	Dynamic CGE modelling (EMEC)	5% improvements made to efficiency of energy inputs to all production sectors.	Expected versus model scenario energy use	Long-run: Mining 47%, Mineral products 92%, Pulp and paper mills 101%, Chemical industries 87%, Iron and steel industries 70%, Non-iron metal industries 50%
8	Dahlqvist et al. 2021	Sweden, 2001-2012	Econometric Analysis, using Factor Demand model	n/a: model uses firm-specific data on sales, labour and energy expenditure to estimate rebound directly	Own-price elasticities of different energy inputs	Short run: Paper and pulp: (electricity 119-132%; fossil fuel 24%, non fossil fuel 27-40%); iron and steel: (electricity 64-141%; fossil fuel 43-45%); chemicals: (electricity 162-179%; fossil fuel 59-241%); mining: (electricity 135-142%; fossil fuel 80%)
9	Garau and Mandras, 2015	Italy, Calibrated to year 2010. 30 year model horizon	Dynamic CGE model	1.014% improvement in energy efficiency of production sectors	Expected versus model scenario energy use	N/A (only models economy-wide rebound)
10	Hanley et al. 2009	Scotland, Calibrated to year 1999. 25	Dynamic CGE modelling (AMO-SENVI)	Improvements made to efficiency of	Expected versus model scenario energy use	Short run:

ID	Author, year	Region, time coverage	Method /model	Specification of energy efficiency	Method of estimating rebound	Scope and baseline estimate of sector rebound
		year model horizon		energy inputs (energy augmenting technological change) to all production sectors.		All industry: 54% (non-electricity) - 63% (electricity) Long-run: All industry: 131% (non-electricity) - 133% (electricity)
11	Kahouli and Pautrel, 2023	USA, calibrated to 2018. 20 year model horizon	Dynamic CGE model.	1% increase to industrial and residential energy efficiency	Expected versus model scenario energy use	Short run: All industry: 54.6% Long-run: All industry: 54.6%
12	Koesler et al., 2016	Germany Calibrated to 2009. Model horizon not specified.	WIOD CGE model	10% increase in energy efficiency of production over 5 years	Expected versus model scenario energy use	Long-run: All industry: 56.4%
13	Lutz et al. 2022	Germany, 2020-2030	Macroeconometric model. (PANTA RHEI)	Targeted 7.4% by 2030 decrease in energy demand (prior to rebound effects) - compared to the reference scenario	Expected versus actual efficiency scenario energy use.	Short run: food drink tobacco 1%, paper 5%, basic chemicals 1%, other chemicals 0%, glass and ceramics 11%, basic metals 14%, non ferrous metals and foundries 14%, all-industry 7% Long-run: food drink tobacco 9%, paper 13%, basic chemicals 7%, other

ID	Author, year	Region, time coverage	Method /model	Specification of energy efficiency	Method of estimating rebound	Scope and baseline estimate of sector rebound
						chemicals 3%, glass and ceramics 13%, basic metals 18%, non ferrous metals and foundries 18%, all-industry 12%
14	Saunders , 2013	USA, 1980-2000	Econometric Analysis, using Translog cost Function	n/a: model uses sector-specific US industry data to estimate of a four-factor (K, L, E, M) Translog unit cost function and estimate rebound directly	Rebound = elasticity of substitution / (1 – energy cost share)	Short run (sector): 31% (construction), 185% (primary metal), 64% (fabricated metal), 25% (motor vehicles), 20% (chemicals), 26% (food and drink), 101% (glass and ceramics), 65% (paper and pulp). Long run (sector): 58% (construction), 66% (primary metal), 40% (fabricated metal), 29% (motor vehicles)), 53% (chemicals), 40% (food and drink), 55% (glass and ceramics), 44% (paper and pulp).
15	Turner et al. 2013	UK, Not specified. Calibrated to 2004	Dynamic CGE (UKENVI)	5% increase in energy efficiency (energy augmenting technological change)	Expected versus model scenario energy use	N/A (only models economy-wide rebound)
16	Zimmerman et al. 2021	Switzerland, 2020-2050	Dynamic CGE model (SEEM)	50% improvement to industrial energy	Expected versus model scenario energy use	Short run: energy-intensive industry 57%; rest of industry 19.4%;

ID	Author, year	Region, time coverage	Method /model	Specification of energy efficiency	Method of estimating rebound	Scope and baseline estimate of sector rebound
				efficiency (2020-2050, 2.2% p.a.)		all industry = 37.5% (KL,E σ = 0.34) Long-run: energy-intensive industry 39.6%; rest of industry 18.3%; all industry: 29.2% (KL,E σ = 0.34)
17	CREDS report, 2021	UK, 2020-2040	Macroeconometric model. (E3ME)	£13.54bn in domestic energy savings, £0.6bn in industrial energy savings	Expected versus model scenario energy use	Long-run: All industry: 7%

Annex 7: Discussion of methodologies used to estimate industrial energy efficiency rebound

Section 5 identified differences in methodological approach as the main driver for the wide variation in published quantitative estimates of industrial EE bound effects (Workstream B). This annex discusses and compares the three main methodological approaches in more detail.

Summary of the main methodological approaches

Table 13 provides a summary of the 3 main approaches identified in the seventeen studies reviewed for Workstream B: computable general equilibrium (CGE), macroeconometric, and econometric modelling.

Table 13: Introduction to modelling approaches to estimate industrial energy efficiency rebound effects.

CGE models	CGE models are widely used for energy-economic analysis and are based upon social accounting matrices for the economies under consideration. They consist of a set of neoclassical equations describing the behaviour of producers, consumers and other economic actors, together with the interdependencies and feedback between different sectors. The model then runs through iterative loops until economy-wide (also known as general equilibrium) effects such as adjustments in market prices, labour and capital supply are settled. The rebound effect is estimated through the differences in energy consumption between the energy efficiency scenario and the counterfactual scenario.	• Direct & indirect • Meso & macro • Short & long-term (defined by partial and general equilibrium states)
Macroeconometric models	Econometric-based modelling approaches use statistical analysis (e.g. regression) to test or verify economic relationships. These models are based on a system of identity and econometrically-estimated equations to represent an entire economy. Calibration is based on historical timeseries data. As with CGE models, the rebound effect is estimated through the differences in	• Direct & indirect • Meso & macro • Short & long term (defined temporally)

	energy consumption between the energy efficiency scenario and the counterfactual scenario.	
Econometric analysis	Purpose built econometric analysis of firm-level empirical data (e.g. of sales, labour, energy expenditure, capital investment data), to estimate energy rebound via the proxy of calculated own-price energy elasticities.	• Direct & indirect • Meso only • Short & long term (defined temporally)

Comparison of the approaches

This section compares some of the key characteristics of the different methodological approaches and highlights where these may drive differences in quantitative estimates of rebound.

Econometric approaches vs CGE and macroeconometric modelling

CGE and macroeconometric models are macroeconomic models capable of estimating both the meso and macro-level rebound effects from industrial energy efficiency measures. In contrast, econometric analyses – by their construction and use of firm-level data - can only examine the rebound effect at the meso level, within the sectors of focus.

Econometric analyses are better able to capture the supply-side (producer) response to industrial energy efficiency, including to the micro (firm) level, where lower energy costs would lead to increased production and associated rebound in energy demand at the producer level.

Unlike CGE and macroeconometric models, econometric analyses do not capture broader linkages with the economy, environment and energy system, which means they cannot capture macro-level rebound impacts.

However, econometric analyses can estimate meso-level impacts in a more detailed way than CGE and macroeconometric models because they show how rebound effects can differ between firms in the same sector (sector heterogeneity).

Another strength of econometric analyses is that key determinants of the rebound effect, such as the price elasticity of supply or demand, are directly estimated from empirical, firm-level datasets. These datasets are very granular at the micro level – for example, Dahlquist et al (2021) study of Sweden's industry includes firm-level data for 2001 to 2012, including firm-specific data on sales, labour and energy expenditure, as well as the number of employees and energy volumes purchased for firms with 10 or more employees. Consequently, econometric analyses can produce a range of meso level rebound estimates, reflecting the fact that firms within the same sector would respond differently to implementing energy efficiency measures (e.g. firms have the option of reduce prices, increase output, substitute energy for other production inputs).

More detailed comparison of CGE and macroeconometric approaches

Despite a common macroeconomic basis for analysis, CGE and macroeconometric models do still show clear divergences in the ranges of rebound that were predicted in the studies reviewed. The points below highlight some key differences and similarities between CGE and macroeconometric approaches that lead to these variations.

- *Modelled structure of the economy*: both CGE and macroeconometric models can be used to capture interactions between the economy, environment and energy system. However, they will differ in the way that they define the linkages between them. As Turner et al. (2012) noted, the most important aspects of the CGE model construction are defined by their production (e.g. KLEM nesting) structures and choices of associated elasticities of substitution between factor inputs. In macroeconometric models, the modelled equations are built on a system of identity and econometric equations based on historical timeseries data. Thus, the way that the economy is structured in a model will be a key determinant of the feedback mechanisms that drive rebound effects. For example, Allan et al.’s (2007) CGE study, the rebound effect was influenced by labour market structure, production elasticities, time-period and government revenue recycling mechanisms. In Lutz et al.'s (2022) macroeconometric PANTA RHEI model study, their rebound estimate was mainly affected by the price effect induced by lower energy inputs (following efficiency improvement), leading to lower costs of production, affecting aspects such as demand for goods, wages, and investment.
- *Demand vs supply side drivers of the rebound effect*: In macroeconometric models, the demand response is a key driver of the rebound effect. In the reviewed studies, energy efficiency improvements lead to lower unit costs for domestic industry, which are passed on to the consumer via lower final prices for industrial products. In turn, that incentivises higher demand and increases consumption of domestically produced products. By comparison, in CGE models, the supply side response is a key driver of the rebound effect. As energy efficiency improvements lower production costs, the firm level response is to increase production output. If a firm increases output, it will need to purchase more inputs to production – i.e. capital, labour, material resources and energy (even if the energy use per unit of product output has decreased through energy efficiency measures). As shown in Figure 6, the supply-driven rebound effects reported in CGE models are, on average, larger than demand driven rebound effects reported in macroeconometric models.
- *Treatment of the long-run and short-run*: While both macroeconomic and CGE models can estimate long and short run rebound effects, they are defined differently between models and are based on different underlying assumptions about the economy. A key feature of CGE models is that, over time, the economy converges to an “equilibrium” state (i.e. demand equals supply for products, labour, capital etc). The short run in a CGE model is the period directly following the introduction of an energy efficiency measure. The economy is temporarily in a “partial equilibrium” state – whereby capital stock and population are fixed but workers (labour) can move between sectors in response to industrial energy efficiency measures. For example, if energy efficiency measures in the steel sector lead to an increase in production output, in a CGE model, the steel sector would offer higher wages to attract workers, who would move from other sectors. In the long run, the partial equilibrium constraints are removed and the population and stock of capital can change

and the economy is back to being in a general equilibrium state. The long-run in a CGE model is typically reported as 25-30 years. This is when the economy returns to a full equilibrium state again, where all factors of production can be deployed flexibly, markets clear and demand equals supply. By comparison, in macroeconometric modelling studies, there is only a temporal distinction between long-run and short run. The short-run refers to the initial year and long-run refers to the last year in the timeseries scenario analysis. For example Lutz et al. (2023) run a 2020-2030 analysis and provide short run (2021) and long run (2030) rebound values.

- *Assumptions on the cost of capital investments*: Most of the CGE modelling studies that were reviewed assumed that energy efficiency improvements were achieved without any capital investment or associated costs. For example, Broberg et al., (2015) describe energy efficiency improvements happening through “a continuous replacement of old machines with new and more energy-efficient ones”. Of the nine CGE studies, only Allan et al. (2007) and Broberg et al. (2015) consider capital investment costs. They showed that when capital investment costs were explicitly considered, the rebound effects were lower than when capital investments were assumed to be “costless”. By comparison, the macroeconometric modelling studies tended to explicitly include additional capital investment associated with energy efficiency improvements as part of their modelling scenarios. This capital investment stimulates growth in the economy, leading to higher consumption investment and overall energy use (e.g. CREDS, 2017).

Annex 8: Quantitative estimates of macroeconomic output effects from industrial energy efficiency measures

This annex summarises the ten studies that estimated the macroeconomic output effects of the rebound effect following the introduction of an energy efficiency measure in industry (see section 6.2)

Table 14: Macroeconomic impacts of industrial energy efficiency

ID	Author, year	Region, time coverage	Method/ model	Specification of energy efficiency	Economic Valuation metric	%/yr change vs baseline / base year
1	Ahmann et al., 2022	Germany, 2020-2030	Macroeconometric model. (PANTA RHEI)	Policy measures in modelled scenario: includes energy reduction, carbon/energy taxes	GDP	GDP Long run (in 2030): (+0.05%)
2	Allan et al., 2007	UK, calibrated to year 2000. 25 year model horizon	Dynamic CGE modelling (UKENVI)	5% improvements made to efficiency of energy inputs (energy augmenting technological change) to all production sectors.	GDP, GVA	GDP Short-run (+0.11%), Long run (+0.17%) GVA: Long run: largest sectors: Iron + Steel (+0.67%), pulp and paper (+ 0.46%) Short run: values not stated but shown as lower than long run.
7	Broberg et al. 2015	Sweden, 2009-2035	Dynamic CGE modelling (EMEC)	5% improvements made to efficiency of energy inputs to all production sectors.	GDP	GDP Long run (in 2035): (+0.1%)

ID	Author, year	Region, time coverage	Method/ model	Specification of energy efficiency	Economic Valuation metric	%/yr change vs baseline / base year
9	Garau and Mandras, 2015	Italy, Calibrated to year 2010. 30 year model horizon	Dynamic CGE model	1.014% improvement in energy efficiency of production sectors	GDP, GVA	GDP: Short run: +0.06%, Long run +0.19% GVA: Short run: food, drink tobacco (+0.08%); textiles (+0.09%); chemicals (+0.10%); metal and non-metal goods (+0.13%); transport equipment (+0.10%); other manufacturing (+0.08%) Long run: food, drink tobacco (+0.24%); textiles (+0.23%); chemicals (+0.23%); metal and non-metal goods (+0.25%); transport equipment (+0.20%); other manufacturing (+0.20%)
10	Hanley et al. 2009	Scotland, Calibrated to year 1999. 25 year model horizon	Dynamic CGE modelling (AMO-SENVI)	10% improvements made to efficiency of energy inputs (energy augmenting technological change) to all production sectors.	GDP, GVA	GDP: Short run: (+0.06%), Long run (+0.88%) GVA: Short run: Manufacturing (<0.1%) Long run: Manufacturing (~0.5%)

ID	Author, year	Region, time coverage	Method/ model	Specification of energy efficiency	Economic Valuation metric	%/yr change vs baseline / base year
12	Koesler et al., 2016	Germany Calibrated to 2009. Model horizon not specified.	WIOD CGE model	10% increase in energy efficiency of production over 5 years	GDP, GVA	GDP (DEU): Long run (+0.133%) GVA: Long run: Manufacturing (+0.43%) primary industry (-0.67%), food drink and tobacco (-0.55%)
13	Lutz et al. 2022	Germany, 2020-2030	Macroeconometric model. (PANTA RHEI)	Targeted 7.4% by 2030 decrease in energy demand (prior to rebound effects) -compared to the reference scenario	GDP	GDP: Long run (in 2030): (+0.20%)
15	Turner et al. 2012	UK, Not specified. Calibrated to 2004	Dynamic CGE (UKENVI)	5% increase in energy efficiency (energy augmenting technological change)	GDP	GDP: Short run (central case 1a): (+0.13%) Long run (central case 1a): (+0.18%)
16	Zimmerman et al. 2021	Switzerland, 2020-2050	Dynamic CGE model (SEEM)	50% improvement to industrial energy efficiency (2020-2050, 2.2% p.a.)	GDP, GVA	GDP: Long run (in 2050): (+0.64%), GVA: Long run (in 2050): Energy intensive industry output (+22.58%); Rest of industry (+5.98%)

ID	Author, year	Region, time coverage	Method/ model	Specification of energy efficiency	Economic Valuation metric	%/yr change vs baseline / base year
17	CREDS report, 2021	UK, 2020-2040	Macroeconometric model. (E3ME)	£13.54bn in domestic energy savings, £0.6bn in industrial energy savings	GDP, GVA	GDP: Long run (in 2040): (+0.50%), GVA: Long run (in 2040): Industry (+0.05%),

Annex 9: Glossary of terms

Technical terms are used and explained throughout this report, with a selection included here for ease of reference.

Backfire effect: In the context of rebound effects, the backfire effect occurs when improvements in energy or resource efficiency lead to total energy or resource consumption that is higher than it was before the efficiency measure was implemented. Unlike a standard rebound effect, where some of the expected savings are offset by increased demand, the backfire effect exceeds 100% of the efficiency savings, resulting in a *net* increase in energy or resource use.

Jevons paradox: precursor to the modern concept of the rebound effect. William Stanley Jevons introduced the idea in his 1865 book *The Coal Question*, where he noted that improvements in the efficiency of steam engines led to an increase in coal consumption rather than a decrease. His observation was specific to energy use in the context of the Industrial Revolution. It underscores that while efficiency can reduce per-unit resource use, the systemic effects on production, consumption, and market dynamics can drive total resource use higher.

Life cycle assessment (LCA): is a systematic method for evaluating the environmental impacts of a product, process, or service throughout its entire life cycle, from raw material extraction (cradle) to disposal or recycling (grave). This approach involves compiling an inventory of relevant energy and material inputs and environmental releases, assessing the potential environmental impacts associated with these inputs and releases, and interpreting the results to inform more sustainable decision-making.

Material footprint assessment: Material footprint assessment quantifies the total amount of raw materials extracted globally to meet a nation's domestic final demand, encompassing biomass, fossil fuels, metal ores, and non-metal ores. This metric provides insight into the material standard of living and resource efficiency of an economy.

Price elasticity: in the context of energy and resource efficiency rebound effects, refers to the degree to which the quantity supplied or demanded of a resource responds to changes in its price due to efficiency improvements. In the context of rebound effects, if the demand for a resource is highly elastic, a reduction in price due to efficiency gains can lead to a significant increase in consumption. Elasticity of supply on the other hand measures how the quantity of a resource supplied changes in response to a change in its price.

Income effect: The income effect in the context of the rebound effect refers to the phenomenon where cost savings from efficiency improvements increase the disposable income of consumers or firms, which is then used to purchase additional goods and services. In the context of energy and resource efficiency, this additional consumption can offset some or all of the resource savings achieved through the initial efficiency improvement.

Substitution effect: refers to the change in consumption patterns that occurs when the price of a good or service changes, making it relatively more or less expensive compared to alternatives. In the context of energy and resource efficiency rebound effects, the substitution effect occurs when efficiency improvements lower the price of a resource or product, encouraging consumers or producers to shift their consumption toward that cheaper, more efficient option. For example, if resource efficiency reduces the cost of using recycled materials compared to virgin materials, firms may substitute recycled materials for primary ones.

Output effect: refers to the overall increase in production. When efficiency measures lower production costs, firms often respond by producing more goods or offering products at lower prices.

Primary and secondary production: Primary production refers to the extraction and initial processing of raw materials directly from natural resources, such as mining metals, harvesting timber, or extracting oil. It involves obtaining materials in their original, unprocessed form for use in manufacturing or other industrial activities. Secondary production involves the recovery, reuse, or recycling of materials from waste or previously used products. This includes processes like melting down scrap metal, reprocessing plastics, or repurposing materials from demolished buildings to create new products, reducing reliance on virgin resources.

Lightweighting: Lightweighting is the process of removing weight from a component or assembly during the design and manufacturing stages. This can involve material substitution, optimising designs, or eliminating materials entirely. For example, in the cement/concrete sector, lightweighting can reduce the overall need for cement, raw material extraction, and energy consumption in cement manufacturing. It is considered a key resource efficiency measure.

Material substitution: Material substitution in the context of resource efficiency refers to the practice of replacing traditional materials with alternative materials that offer similar or improved performance while reducing environmental impact. For example, this can involve using biobased materials in vehicle manufacturing or substituting cement with lighter materials in construction to enhance sustainability and reduce raw material use.

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