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Review

Methods to estimate the circular economy rebound effect: A review

Benjamin H. Lowe [a,*], Meletios Bimpizas-Pinis [a], Pierluigi Zerbino [b], Andrea Genovese [a]

[a] Sheffield University Management School, Conduit Road, Sheffield, S10 1FL, UK
[b] Department of Energy, Systems, Territory and Construction Engineering, University of Pisa, Largo Lucio Lazzarino, 56122, Pisa, Italy

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ABSTRACT

The transition to a circular economy can be undermined by rebound effects, which could mean secondary production does not fully displace virgin raw materials. So called 'circular economy rebound' is under examined in the academic literature and thus requires greater attention if it is to be successfully estimated and mitigated by decision and policy makers. Accordingly, this paper undertakes a systematic review of the methods that have been deployed to measure rebound effects *of all types* and identifies those quantitative tools that have yet to be utilised in the nascent area of circular economy rebound but which could have application in this context. In so doing, the paper also reflects on the data needs of different methods, as well as the magnitude of the different rebounds identified and potential mitigating strategies. Findings suggest clear research gaps within the rebound literature and identify areas in which estimation of the circular economy rebound specifically could benefit from this wider body of work on rebound assessment.

1. Introduction

Circular economy (CE) has emerged as a concept that is anticipated to radically reshape the relationship between ecological systems and economic activities in such a way as to reduce the latter's reliance on non-renewable energy and carbon-intensive material flows (Korhonen et al., 2018). However, CE has been developed and shaped within the context of a market economy that inherently prioritises economic growth (Corvellec et al., 2022). As a result, this dominant conceptualisation of the CE does not challenge the prevailing assumption that the accumulation of surplus resources is the main driver of business and economic prosperity. Moreover, the resistance of established institutions to alternative economic value creation methods in a circular future has led to a linear lock-in of circular practices (Lowe and Genovese, 2022). This resistance highlights the contrast between the intention of CE to address environmental pressure and the widespread perception of the circular transition as an opportunity to create value through arbitrage of virgin materials and end-of-life goods (World Economic Forum, 2014).

Within this context, the circular transition may generate unanticipated consequences falling under the umbrella term 'rebound effects' (REs) (Figge and Thorpe, 2019). As originally understood in the context of energy economics, REs refer to the behavioral or systemic response of consumers to an energy efficiency improvement, which means that the intended energy savings are not fully realized (Greening et al., 2000). In the context of the CE, this behavioral or systemic response is triggered not by an energy efficiency improvement, but through material efficiency improvements achieved by bringing end-of-life goods back to production (*closing resource loops*), extending and/or intensifying the utilization period of goods (*slowing resource loops*), and improving resource efficiency in production (*narrowing resource loops*).

Indeed, REs are generally initiated by circular innovations in products, business models, and strategies, which are both economically justifiable and environmentally beneficial at the micro level of analysis (Castro et al., 2022). However, owing to a failure to displace primary production, REs could lead a CE to drift from its objectives, e.g., by generating more waste (Niero et al., 2021), embodied energy (Ottelin et al., 2020), and emissions and energy consumption (Skelton et al., 2020). Accordingly, neglecting to account for REs could result in environmental assessments overestimating the benefits of CE measures and failing to recognize scenarios in which a CE might yield limited advantages or even increase the overall environmental burden (André and Björklund, 2023).

Despite their relevance in the CE context, REs remain a little-explored phenomenon that demands immediate and thorough attention (Metic and Pigosso, 2022). Scholars have emphasized the necessity of comprehending how to cope with REs to mitigate their detrimental impact (e.g., Genovese et al., 2023). Nevertheless, the range of proposed

* Corresponding author.
E-mail address: Benjamin.Lowe@sheffield.ac.uk (B.H. Lowe).

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solutions to address this need is currently limited, and they have not fully captured the heterogeneity and multiplicity characterizing REs (Zerbino, 2022).

One of the reasons for this may be linked to the widely known quote "You can't manage what you don't measure", variably attributed to the world-renowned economist Peter Drucker or the father of the Total Quality Management movement, Edward Deming. Indeed, the management of REs may be hindered by the well known and inherent difficulties associated with their identification and measurement (Sorrell, 2007). The challenge of modelling and estimating REs has been addressed in various research streams, such as Energy Efficiency and Industrial Ecology, using a variety of approaches. Prominent examples include the use of macroeconomic models such as Computable General Equilibrium (Wei and Liu, 2017), Life Cycle Assessment and Material Flow Analyses (Wiprächtiger et al., 2022), along with advancements like Consequential LCA (Palazzo et al., 2020), econometric models and techniques (Galvin et al., 2021), System Dynamics (Dace et al., 2014), or the combined use of different approaches (Albizzati et al., 2022).

Nevertheless, within the CE context, awareness of REs remains low, and the issue of effectively estimating them remains strongly unchallenged (Siderius and Poldner, 2021). Therefore, this paper aims to answer the following Research Question: *"What methods could be used to estimate rebound effects associated with the implementation of circular economy measures?"*

To address this Research Question, this work takes a broad view of REs and seeks relevant material *within and beyond* CE applications as a way of informing the methods that might be relevant in the transition towards a CE. From a scientific standpoint, this helps fill the gap, as identified by Castro et al. (2022), concerning the need to understand which methods and metrics should be used to estimate the REs within the transition towards a CE, presenting this evidence in an organized and structured manner and singling out the limitations of the methods that are currently available. This can improve the understanding of the REs and inform academics who are willing to engage with the characterization and management of this phenomenon.

From a managerial point of view, answering the Research Question can provide policymakers and decision makers with an overview of the quantitative tools that can be employed in order to accurately evaluate the REs of a CE and the data necessary for this purpose. This can enable the development of courses of action to mitigate REs and direct firms, supply chains, ecosystems, and governing bodies towards sustainability in circular settings.

To answer the above-mentioned Research Question, a systematic review of the methods to measure REs was carried out at the intersection between the management, engineering, economics, energy, and the environmental sciences research fields. The review, the arrangement of its outcomes, and the discussion of the findings were conducted in line with the multi-level typology of REs by Lange et al. (2021). By following this research design, the paper contributes in the following ways.

- It addresses the research gaps identified within the scientific literature at the intersection of the CE and RE research fields by presenting an overview of RE assessment methods and introducing a novel research agenda. The agenda encompasses twelve research questions derived from six gaps related to the estimation, characterization, and management of REs within a CE context.
- It proposes an extension of the adoption and scope of the typology introduced by Lange et al. (2021), originally focused on REs associated with energy efficiency, to REs related to material efficiency in circular settings. This emphasizes the importance of considering the propagation of REs in both depth (different levels of economic aggregation) and breadth (variation in their magnitude) over time. Furthermore, this enhances the theoretical soundness when comparing REs estimated using different assessment methods.
- It provides insights for managers and policymakers by summarizing the primary data needs and possible sources useful to quantifying REs within a CE and suggesting hints for managing the risks associated with REs along a longitudinal perspective.

The remainder of this work proceeds as follows: Section 2 introduces the concepts of REs, also positioning these within the context of a CE. Section 3 provides a summary of the literature review protocol used; Section 4 summarizes the different methods for the assessment of REs; Section 5 discusses the findings, highlights research gaps and avenues for future research, and presents the theoretical and managerial contributions. Finally, Section 6 concludes.

2. The transition to a circular economy and rebound effects

The stage for the awareness of REs was set by the seminal works of William Stanley Jevons (1865), who, during a phase of intense technological development, suggested that the more efficient use of coal in engines could result in an increased overall consumption of coal itself. However, his arguments were largely dismissed at the time, mainly due to the lack of empirical evidence (Alcott, 2005). Despite the criticism, Jevon's ideas still resonated and were brought to the surface a century later by Brookes (1979, 2000) and Khazzoom (1980, 1987, 1989) who formalized the idea that efficiency gains due to technological improvements could lead to an increase in energy demand. Specifically, the idea of the RE re-emerged in the aftermath of the 1970s energy crisis, becoming a central area of intense debate among energy economists concerning the need for policies to reduce energy use and dependence in absolute terms (Font Vivanco et al., 2022). Further contributions to the topic were made, driven by growing climate change concerns and increased awareness on environmental issues (Sorrell and Dimitropoulos, 2008; Lange et al., 2021).

The CE constitutes an environmentally promising concept, which is based on the idea that waste streams from one production process can be used as an input to another. However, the crucial issue remains the extent to which secondary production can displace primary production. The extent to which this displacement can occur is dependent on market forces, which involve the response of buyers and suppliers to prices, as well as the willingness of buyers to switch to secondary products (Zink et al., 2016; Freeman, 2018; Lange et al., 2021). Therefore, the tendency to view the CE solely as an engineering system focused on closing loops, while ignoring the market dynamics of primary and secondary product interactions, is problematic (Zink and Geyer, 2017). In reality, market forces, resulting from market exchanges among individual economic agents, play a significant role in determining investment and disinvestment decisions related to the CE.

Adopting just such an economic view of the CE, Zink and Geyer's (2017) insights were instrumental in stimulating the emergence of a body of research on circular economy REs. Zink and Geyer (2017) conceptualized the CE as a system of interconnected markets, attributing the occurrence of REs to two general mechanisms, namely the effect of secondary goods on prices and their insufficient substitutability for primary goods. Insufficient substitutability is linked to the perception of secondary goods being of inferior quality, making them less desirable to the end customer. Consequently, secondary goods are produced in addition to, rather than instead of primary goods, thus reducing (and potentially nullifying) the benefits of CE practices. According to the law of supply and demand, the increase in supply of (cheaper) secondary goods will also result in a decrease in the price of substitutes (primary goods), since suppliers are competing to attract more buyers. The decrease in prices stimulates the demand (and production) for both goods (price effect) since consumers perceive themselves to have a comparatively higher income than before (income effect).

Similarly to the case of the energy rebound, the circular economy RE largely focuses on consumer-producer relationships driven by consumer demand (Barkemeyer et al., 2023). According to this conceptual interpretation, improvements in operational efficiency (including, in the case of circular economy rebound, increased focus on secondary production) generate a greater demand, which in turn leads to a higher-than-expected levels of resource consumption. Demand-side REs such as these, which as suggested are mainly driven by income, substitution and price effects, have traditionally been characterized in terms of *direct*, *indirect* and *economy-wide* rebounds. A direct rebound effect, for example, could involve a technical improvement that makes energy services cheaper, thereby increasing the demand for those services. By contrast, an example of the indirect rebound effect would be if the consumer used “the cost savings from both technical improvements and behavioral changes to purchase other goods and services” (Sorrell, 2012, p.6). Economy wide rebound is usually understood as the combination of direct and indirect rebound.

In contrast, Figge and Thorpe (2019) argue that REs can also originate from the supply-side, emphasizing the need to consider producer-producer relationships. Adopting a circular economy perspective where the extraction, collection and re-use of resources transcends the boundaries of a single firm, the authors demonstrated a “symbiotic rebound effect.” Unlike the usual mediating variable of demand, in the case of symbiotic rebound, the driver is represented by opportunity costs, which lead to a higher than expected usage of resources in a circular context. As a result, this counteracts the desired increase in eco-efficiency i.e. the production of goods and services using less materials and energy (Figge and Thorpe, 2023).

Diverging from the eco-efficiency agenda, recent years have also seen the emergence of “eco-sufficiency”, namely the voluntary reduction of resource use at an individual level (Alcott, 2008). However, the supposition that a reduction of resource use at a micro level could achieve a one-to-one overall reduction of economic activity on the macro level, is questioned by the occurrence of sufficiency-based REs. Having as a starting point the variability of income across different consumer groups, the sufficiency rebound stems from the passive transfer of purchasing power from wealthier to marginal consumers (Figge et al., 2014).

3. Review protocol

To investigate the different methods used for the assessment of REs a systematic literature review was conducted. The review process involved four distinct stages, namely research question formulation, identification of studies, analysis and synthesis of findings (Tranfield et al., 2003).

Regarding the identification of studies for the review, Fig. 1 presents the process followed, which is also elaborated on below.

(1) In order to capture relevant studies, both in the context of measuring REs in general and specifically in the context of CE, two search strings were developed. The first string aimed to identify papers that had applied a method for measuring REs, irrespective of discipline or field. Results revealed a lack of studies focusing directly on the interaction between CE and REs. As such, a second string was developed to narrow down the scope to the CE only.

Search string *i* was comprised of the following search terms: “rebound effect” along with “assessment” and “measurement.” Search string *ii* included a range of terms synonymous with “rebound effect” and “circular economy”. More specifically, “rebound effect” was paired with “backfire effect”, a term that was identified during an initial scoping exercise. In addition, “circular rebound” was combined with related concepts and terms, namely “industrial symbiosis”, “eco-industrial park”, “industrial ecology”, “closed-loop”, “reuse”, “recycle*“, “refurbish*“, “sharing”, “refus*“, “eco-efficiency” and “eco-sufficiency.”

(2) The second stage of the review process involved the removal of papers that did not adhere to the first level of selection criteria. In detail, the search was restricted to peer-reviewed journals in English on Elsevier’s Scopus database, and further restricted to title, abstract, and keyword fields. Indexed results were limited to articles, reviews and in press document types. Search string i generated 488 results while search string ii generated 214 results. Following the exclusion criteria with respect to language and document type, the total number of articles for each string was reduced to 412 and 179 respectively. Table 1 provides a summary of the search strings used along with the respective number of articles before and after exclusion criteria were applied. Following the removal of 68 duplicates, the number of total articles was reduced from 591 to 523.
(3) At this stage, the abstracts of the 523 articles from Stage Two were read carefully and only those that were focused on an assessment of REs and belonged to the domain of management, engineering, economics, energy, or environmental sciences were selected. This process returned a total of 209 articles.
(4) The 209 articles from Stage Three were screened in detail in order to determine which ones explicitly focused on the empirical assessment of REs in an applied setting *and* provided information on the method they employed. This screening process was conducted by two members of the research team independently and

Table 1
Search terms used to select papers for review.

	Search terms			Number of articles	Number of articles following exclusion criteria
i.	“rebound effect"	AND	“assessment” OR “measurement"	488	412
ii	“rebound effect” OR “backfire effect”	AND	“circular economy” OR “industrial symbiosis” OR “eco-industrial park” OR “industrial ecology” OR “closed-loop” OR“reuse” OR “recycl*” OR “refurbish*” OR “sharing” OR “refus*” OR “eco-efficiency” OR “eco-sufficiency”	214	179

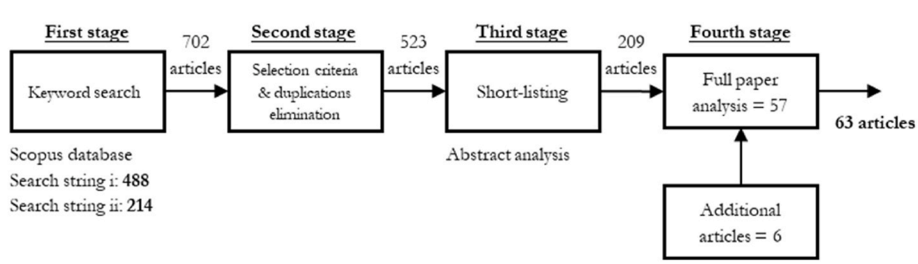

Fig. 1. Overview of systematic literature review stages.

there was a mechanism involving a third senior member of the team that was used to resolve any disagreements. At this stage of the review, 57 articles were selected for analysis. Finally, the sources in Metic and Pigosso (2022) were screened given that their paper on the rebound literature is both up-to-date and one of the few to encompass REs of the CE. In total, 63 articles (henceforth “sources”) were included in the scope of this review.

(5) Each source was classified according to the principal scale at which the impact of the RE occurred. In detail, the micro level refers to the case of a single firm or household; the meso level refers to a single market, sector or supply chain; the macro level refers to a national economy; and the global level refers to the world economy (specifically “interactions between at least two economies”, Lange et al., 2021, p.7). Again, this classification process was conducted by two members of the research team independently and there was a mechanism involving a third senior member of the team that was used to resolve any disagreements thus ensuring the reliability and consistency of classifications. Structuring the typology using these levels of economic aggregation is particularly useful since they are related to economic theories, empirical research, and policies that may alleviate REs (Lange et al., 2021). In addition, sources were also classified according to the RE Type (i.e. direct, indirect etc.) and RE Category (i.e. environmental, energy etc.) Only when sources assessed the displacement of primary production by secondary manufacture within a context that referred to core CE principles (Kirchherr et al., 2023) was their category and type classified as *circular economy rebound.* Finally, the assessment methods identified were grouped into the following seven distinct categories:

- *Life Cycle Analysis (LCA)/Materials Flow Analysis (MFA).* Papers in this category employ traditional environmental assessment approaches in order to produce estimates of the RE.
- *Macroeconomic models.* This category includes sources that develop a wide range of modelling approaches, including but not limited to Computable General Equilibrium (CGE), Input-Output Analysis (I–O), and Stock-Flow Consistent (SFC) frameworks.
- *Elasticity parameter estimates.* Contributions which belong to this category are mainly focused on the determination of elasticity parameters (which play a pivotal role in mechanisms enacting REs), through empirical approaches.
- *Econometric techniques and models.* This category mainly involves studies based on advanced statistical methods applied to the formulation and testing of hypotheses on the determinants of the RE.
- *System Dynamics (SD) and simulation.* Approaches in this area also include simulation models based on economic frameworks.
- *Hybrid approaches.* This set includes sources which employ approaches combining methods from at least two of the different categories listed above.
- *Miscellaneous.* This category is concerned with sources that are not immediately classifiable in any of the categories above.

4. Methods for estimating rebound effects

Table 2 presents the correspondence between assessment methods and economic levels. As shown, the micro level of aggregation (38 %) accounted for the largest share of sources in the review; econometric techniques/models were the most common RE assessment method selected (30 % of sources).

Figs. 2 and 3 show the composition of the 63 sources included in the review by publication and year of publication. As shown, over 60 % of the sources were concentrated in five journals, the most common being the *Journal of Industrial Ecology* (10 sources). Across the 63 sources, which were published between 2000 and 2023, the median publication year was 2019 (modal year 2015) suggesting that the estimation of REs remains an active area of academic enquiry.

Table 2
Papers reviewed by method and economic level of aggregation.

Assessment method	Economic level of aggregation				
	Micro	Meso	Macro	Global	TOTAL (% of total)***
Life Cycle Analysis (LCA)/Materials Flow Analysis (MFA)	4	4	–	–	**8 (13 %)**
Macroeconomic models[a]	–	3	9	2	**14 (22 %)**
Elasticity parameter estimate	2	–	–	–	**2 (3 %)**
Econometric techniques/ models	7	3	8	1	**19 (30 %)**
System dynamics/ simulation	–	1	2	–	**3 (5 %)**
Hybrid approaches[b]	10	4	2	–	**16 (25 %)**
Miscellaneous	1	–	–	–	**1 (2 %)**
TOTAL (% of total)* **	**24 (38 %)**	**15 (24 %)**	**21 (33 %)**	**3 (5 %)**	**63 (100 %)**

[a] Including Input-Output, Computable General Equilibrium and post-Keynesian Stock Flow Consistent models.
[b] Including System-Dynamics Stock Flow Consistent, Agent Based Stock Flow Consistent and Input-Output Stock Flow Consistent models. *** Errors due to rounding.

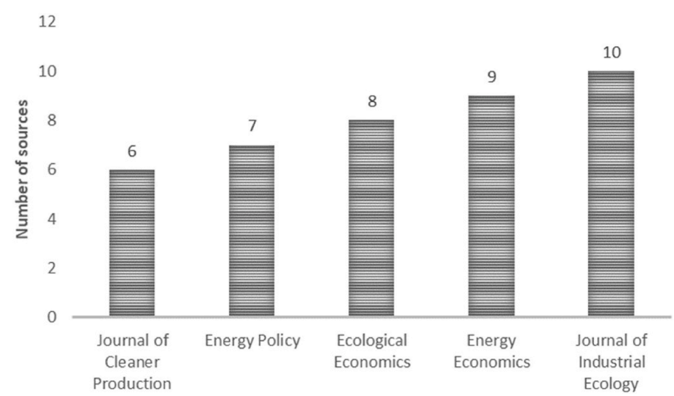

Fig. 2. Composition of sources included in the review by publication (>5 sources).

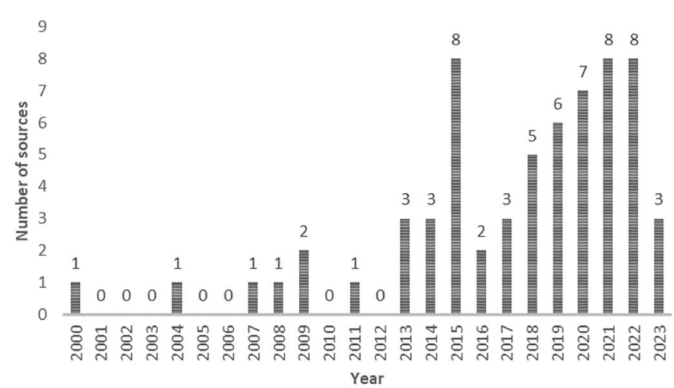

Fig. 3. Composition of sources by year of publication.

In what follows, the sources selected for review are examined according to their level of economic aggregation.

4.1. Micro level

The review returned 24 sources that had examined the RE at the micro level (Table 3). Energy or environmental rebounds, or a combination of the two, were the focus of the sources identified with only four studies on CE rebound (Makov and Font Vivanco, 2018; Warmington--Lundstom and Laurenti, 2020; Meshulam et al., 2022; Wiprächtiger et al., 2022). In terms of methods, three principal categories were represented: hybrid approaches (10), econometric methods/techniques (7) and LCA/MFA (4).

4.1.1. Life-cycle Analysis/Materials Flow Analysis

The Spielmann et al. (2008) study focused on the environmental rebound effect (ERE) associated with high-speed transport technologies. Authors employed an LCA approach to compare the environmental performance of different scenarios corresponding to possible changes in mobility patterns and technological options linked to alternative transport solutions. Analysis showed that, even without accounting for additional transport, energy-efficient technologies that allow high-speed travelling, result in an increase of per capita environmental impacts. These increases were associated with what authors termed the "time rebound effect", arising from increased demand for additional travel distances fostered by innovations in transport technology that enable covering a certain distance in less time.

Salemdeeb et al. (2017) addressed the reduction of greenhouse gas (GhG) emissions associated with household food waste in the UK. To capture the environmental impacts across the global food supply chain, authors used a hybrid LCA model coupled with a multi-regional environmentally extended I–O model. Results suggest that prevention of food waste, especially by avoiding food production overseas, could lead to a substantial reduction in GhG emissions (approximately 706–896 kg CO2-eq. per tonne of food waste). However, associated REs could reduce these savings by 60 %. These reductions were attributed to the re-spending of savings in both major and less GhG-intensive categories, such as wholesale trade, motor gasoline, air transport, communication, and real estate services. The author's findings emphasized the need for adopting a holistic approach when considering the environmental impact of food waste prevention at a global scale given relative implications for developing countries.

Amatuni et al. (2020) assessed the RE associated with the modal shift from ownership to sharing models from a life-cycle perspective. The analysis was based on three geographical cases, namely Netherlands, San Francisco, and Calgary. The life-cycle stages that were considered, covered, in addition to non-operational emissions for major urban transport modes (e.g., car, bus, rail, bicycle), the stages of manufacturing, infrastructure, fuels, and use. The estimation of REs was based on a comparative analysis of distances travelled prior to and after the shift to sharing models. Emphasizing the effectiveness of ride-sharing schemes, findings suggested that the reduction in total mobility-related emissions is significant only if the per-passenger distance demand remains constant. Conversely, an increase in usage intensity, and consequently distance travelled, could unintentionally lead to the sustained or even heightened manufacturing rates of new vehicles.

Wiprächtiger et al. (2022) assessed CE rebound using a sustainable system design framework they previously developed (Wiprächtiger et al., 2020) which combined life-cycle assessment and material flow analysis. Attention was placed on two case studies of clothing and household furniture in Switzerland. Five different waste prevention scenarios were developed, each one corresponding to different R-strategies, namely share, repair, reuse, refuse and sufficiency. The RE was estimated by comparison to a business-as-usual scenario that involved the continuation of current practices. Findings indicated that while a take-back scheme for furniture significantly reduced environmental impacts by 70 %, drastic scenarios for clothes resulted in reductions of only less than 15 %. The latter was linked to the high level of uncertainty characterizing the substitutability rate for textiles, which depends on several socio-economic factors (e.g., income, location) as well as the re-spending of significant savings realized in a scenario of self-sufficiency.

4.1.2. Elasticity parameter estimates

Kawajiri et al. (2015) investigated the ERE in Japan associated with consumption changes due to potential savings. A survey was conducted to derive a "rebound matrix". According to the survey results, while spending reductions could correspond to around 6 % reduction in emissions, these would eventually increase by nearly the same amount after respondents respend their savings.

The purpose of Warmington-Lundström and Laurenti (2020) paper was to investigate the magnitude and likelihood of circular economy REs resulting from resource sharing. Authors used the empirical case of a peer-to-peer boat sharing platform and employed a double spending model. Results indicated that while all lessees experience a RE, only a third of lessors exhibited one. To prevent the likelihood and magnitude of ERE from resource sharing, the authors contend that the focus should be placed on guiding the consumption factors that are released, namely money and time, towards less impactful choices. This can be achieved through increasing awareness and non-economic strategies such as symbolic rewards and information provision.

4.1.3. Econometric techniques/models

Bouhou et al. (2015) investigated the energy RE related to demand-side interventions aimed at residential electricity efficiency gains. Authors developed and applied a mixed regression model of electricity consumption to calculate the increases or decreases in electricity consumption for different sources of marginal technical changes for multiple residential electricity end-uses, including air conditioning, insulation, solar panels, programmable thermostat, multi-pane windows, and energy star certified devices. Based on their findings, it was clear that technological change has a net effect on households based on their baseline technical efficiency as well as their use of existing and new energy services. Their contribution challenged empirical assessments that fail to account for the different technical states of multiple uses of energy.

Orea et al. (2015) utilized the stochastic frontier analysis model introduced by Filippini and Hunt (2011, 2012), to show its relevance in the estimation of REs linked to energy efficiency improvements. Their study showed that the original model implicitly presumed zero REs, which conflicts with most empirical evidence. Developing a new empirical strategy based on the aforementioned stochastic frontier approach, authors relaxed this restrictive assumption by highlighting how improvements in efficiency can mitigate or intensify the effect on energy consumption. Applying this model in the context of the US residential energy demand over the period of 1995–2011, they found average values that placed REs in the range of 56–80 %.

Yin et al. (2018) captured the ERE linked to ride-sharing in Paris, France. As authors pointed out, while ride-sharing is expected to reduce emissions due to the decrease in the number of vehicles on the road, the relative reduction in travel costs and road congestion would make cars more attractive. Despite the expectation that an increase in vehicle occupancy by 50 % could reduce emissions by one third, their analysis showed that mode switching, distance and relocation would actually divide the savings related to emissions by a factor of 2–3 times. A very similar approach, taking Paris as a case study, was also followed by Coulombel et al. (2019). Similarly to Yin et al. (2018), authors found that ride sharing is linked to a substantial RE cancelling out over 70 % of GHG emissions reductions as well as half to three quarters of social benefits, such as congestion, air quality, and noise. Modal shifts were identified as the key source for the occurrence of these REs since with private cars replacing public transit and active modes of transportation,

Table 3
Analysis of micro-level rebound effect literature.

Author(s)	Classification	RE category	Rebound type	Rebound %	Location	Measure	Mitigating strategies
Amatuni et al. (2020)	LCA/MFA	Environmental	Direct, indirect	35–50 %	Netherlands, United States, Canada	GHG emissions	Stimulation of the use of public modes of transport
Baležentis et al. (2021)	Econometric techniques/ models	Energy	Direct	2000-5: 37 %; 2006–10: 12 %; 2011–15: 10 %	European Union	Energy use	Educational campaigns, labelling, smart metering
Barkemeyer et al. (2023)	Econometric techniques/ models	Environmental	Indirect	18–23 %	European Union	GHG emissions	–
Bouhou et al. (2015)	Econometric techniques/ models	Energy	Direct, indirect	–	United States	Energy use	–
Calì et al. (2016)	Miscellaneous	Energy	Direct	6–23 %	Germany	Energy use	Monitoring system
Coulombel et al. (2019)	Econometric techniques/ models	Environmental	Unclear	68–77 %	France	GHG emissions	Improving public transit, reducing road capacity, increasing the cost of car travel
Hicks et al. (2015)	Hybrid	Energy	Direct	Unclear	United States	Energy use	–
Kawajiri et al. (2015)	Elasticity parameter estimate	Environmental	Indirect	50–60 %	Japan	GHG emissions	Changes in lifestyle
Makov and Font Vivanco (2018)	Hybrid	Circular economy	Circular economy	30 %–100 %	United States	GHG emissions	Green design
Meshulam et al. (2022)	Hybrid	Circular economy	Circular economy	20–94 %	United Kingdom	GHG emissions	–
Muñoz et al. (2019)	Hybrid	Environmental; Economic	Direct	Unclear	Italy	GHG emissions, Euros	–
Orea et al. (2015)	Econometric techniques/ models	Energy	Direct	56 %–80 %	United States	Unclear	–
Salemdeeb et al. (2017)	LCA/MFA	Environmental	Direct, indirect	60 %	United Kingdom	GHG emissions	A holistic approach in developing food waste prevention policies
Shinde et al. (2022)	Econometric techniques/ models	Environmental	Possibly indirect	15–30 %	Switzerland	GHG emissions	Awareness campaigns
Spielmann et al. (2008)	LCA/MFA	Environmental	Direct	11 %–114 %	Switzerland	GHG emissions	–
Thomas and Azevedo (2013a)	Hybrid	Energy; Environmental	Direct, indirect	–	United States	GHG emissions, Energy use	–
Thomas and Azevedo (2013b)	Hybrid	Energy; Environmental	Direct, indirect	10 % direct rebound; 5–15 % indirect rebound	United States	GHG emissions, Energy use	Enacting pollution taxes, auctioned permits
Vélez (2023)	Hybrid	Environmental	Direct, indirect	70–85 %	European Union	GHG emissions	–
Vélez-Henao and García-Mazo (2022)	Hybrid	Environmental	Direct, indirect	1.9 %–8.2 %	Colombia	GHG emissions	Subsidy schemes
Vélez-Henao et al. (2020)	Hybrid	Environmental	Direct, indirect	Direct: 41 %–379 %; Indirect: 1 %–58 %	Colombia	GHG emissions	Higher education; wider availability of information
Warmington-Lundstom and Laurenti (2020)	Elasticity parameter estimate	Circular economy	Circular economy	20 % in emissions	France	GHG emissions	Awareness campaigns; non-economic mechanisms (e.g., symbolic rewards, information provision and nudging)
Wen et al. (2018)	Hybrid	Energy	Direct, indirect	74.07 %	China	Unclear	Taxation policy
Wiprächtiger et al. (2022)	LCA/MFA	Circular economy	Circular economy	Clothing: Sufficiency: 39 %; Share: 11 %; Refuse: 4 %; Reuse: 5 % & Furniture: Reduce: 5 %; Reuse: 3 %	Switzerland	GHG emissions	Awareness campaigns
Yin et al. (2018)	Econometric techniques/ models	Environmental	Direct, indirect	11–17 %	France	GHG emissions	Improvement of public transport, curbing urban sprawl and deterring distant residential location choices (e.g. through local taxation)

Note: GHG = Greenhouse gases. kWh = Kilowatt hour. LCA = Life Cycle Analysis. MFA = Materials Flow Analysis. RE = Rebound Effect.

it encourages longer distance travel (distance effect), and relocation outside the urban centre (relocation effect).

Baležentis et al. (2021) focused on the advancement of methods for the estimation of energy REs in the European Union. Their proposed approach was based on the ODEX index,[1] to overcome the limitations of the stochastic-frontier-based approach that is bounded to assumptions related to distributions of the error term. Their findings showed a decline in the energy RE, though with significant spatial variations. The countries that exhibited the higher level of REs were Bulgaria, the Czech Republic, Estonia, Hungary, Italy, Romania, Slovenia, and Spain.

Focusing also on the advancement of methods to quantify REs, Shinde et al. (2022) proposed a novel approach that involved a machine-learning model. Due to the versatility of this method, which included households' socio-economic characteristics as independent variables, authors could estimate any income-related rebound at the household level, taking into account particular household characteristics and consumption patterns as a whole. To test this model, they used the case of cooperative housing in Switzerland. According to their findings, generally, households with lower incomes were more likely to spend their extra money on purchases and operations of vehicles, while higher income groups preferred to buy recreation and package holidays. Their study concluded with some recommendations to avoid REs, namely, the development of incentives for shifting the aforementioned expenses to other consumption categories.

Placing their attention on the demand-side RE, Barkemeyer et al. (2023) paper investigated the RE linked to moral licensing, specifically eco-labelling. Employing multi-level modelling, authors showed the occurrence of an indirect behavioral consumer RE associated with eco-labelling. Their findings suggest that, owing to the popularity of eco-labelled products in wealthier countries with higher consumption levels, the willingness to consume these products leads to an indirect RE, resulting in elevated individual carbon, water, and material footprints. Consequently, they argue that eco-labelling in its current form is inevitably associated with increased, rather than decreased, levels of resource consumption.

4.1.4. *Hybrid approaches*

Utilising I–O modelling, Thomas and Azevedo (2013a, 2013b) developed an analytical model for the estimation of the indirect RE. Their model was based on a direct rebound estimate that integrates consumer demand theory with the embodied energy of household spending from environmental-extended I–O analysis. The model is then applied to simulate the direct and indirect rebound for the average U.S. household regarding primary energy and GhG emissions, on the basis of energy efficiency investments in electricity, natural gas, or gasoline services. Developing a two-goods and n-goods case, authors demonstrated that the indirect rebound is dependent on the consumer budget and inversely related to the direct rebound.

Hicks et al. (2015) followed a hybrid approach to investigate the RE stemming from the multifunctionality of LED lighting that could lead to consumers using significantly more light. In detail, authors followed an agent-based model and complex systems approach (also incorporating LCA considerations) to explore how available information and perceptions influence the adoption and use of energy-efficient lighting options at a residential level. Findings revealed that the mitigation of REs could only be achieved if consumers continue to use the same amount or slightly more light, abstaining at the same time from the expansion of lit spaces.

Using the case study of smartphone reuse in the United States, Makov and Font Vivanco (2018) focused on two main circular economy rebound mechanisms, namely the imperfect substitution between "re-circulated" (e.g., reused, refurbished) and new products and re-spending due to economic savings. Given that the re-circulation and reuse of smartphones requires the consideration of broader factors (e.g., behavior responses) that involves more than just changing the ratio of inputs (e.g., energy) to outputs (use), authors combined LCA with sales statistics, environmentally-extended I–O analysis, consumer surveys and demand modelling to express rebound in terms of greenhouse gas emissions. Their results showed that the RE could result in the loss of about one third (even the entirety in some cases) of the emission savings generated by smartphone reuse. A similar approach that involved the estimation of ERE was also employed by other authors, such as Vélez-Henao et al. (2020), Vélez-Henao and García-Mazo (2022) and Vélez (2023).

Vélez-Henao et al. (2020) combined LCA, I–O modelling, energy system modelling, econometrics, and re-spending modelling to assess the ERE in the Colombian household sector linked to the introduction of wind power into the national power grid. Conducting their analysis across six environmental impact categories, their results showed that depending on the impact category, the year, and the modelling choices considered, the ERE can partially, and even completely, offset any environmental savings. Given the risk to render decarbonisation policies ineffective, their findings showed the need to consider REs in the design of environmental policies. Following a similar modelling approach, Vélez-Henao and García-Mazo (2022) extended Vélez-Henao et al. (2020) analysis by considering the combining role of increasing the shares of solar and wind technologies in the Colombian power grid. In a similar way to Vélez-Henao et al. (2020), impacts varied across models (solar or wind) and the approaches used to test it. Given that REs are significantly higher in developing countries due to a higher rate of growth and a higher cost of energy, it is imperative to consider ERE mitigation policies along with their impact on growth.

Following a hybrid approach that combined I–O modelling and elasticity estimation, Vélez (2023) estimated the RE related to business-to-consumer and consumer-to-consumer car sharing. Findings revealed that peer-to-peer and business-to-consumer car sharing had similar carbon footprints. While car-sharing users that have abandoned car ownership could decrease their carbon footprint of transportation by approximately 40 %, the REs of re-spending for the consumption of other goods and services such as clothing, housing, food and others, could offset it by 70–85 %.

The main objective of Wen et al. (2018) was to investigate the direct and indirect energy REs at the household level in China through the use of informative indicators. Their analysis spanned 27 sector energy I–O tables for 25 provinces based on different data sources. Combining I–O analysis with econometric methods, they focused on four indicators, namely, sectorial rebound risk, sectorial rebound intensity, potential rebound intensity, and structural rebound vulnerability. Their findings showed significant variations of REs across different regions. Finally, to avoid the occurrence of such REs, they concluded that it is imperative for the Chinese government and provincial authorities to take into account the regional differences when designing policies.

Muñoz et al. (2019) looked into the potential REs linked to the integration of an off-grid solar-assisted heat pump and a sequencing batch biofilter granular reactor (SBBGR) for thermal energy recovery from wastewater. Assessment was conducted by combining LCA and life cycle costing. Based on a comparison of this integrated system with the conventional wastewater treatment plant that uses activated sludge for wastewater treatment without a thermal energy recovery system, the integrated system showed strong environmental benefits in terms of greenhouse gas reductions of 42 % and cost reductions of 53 %. However, it was found that the price RE due to the lower cost of the SBBGR scenario could completely offset its environmental benefits, considering the spending of these economic resources in other products.

Using the dataset of a peer-to-peer food-sharing platform in the United Kingdom with over 750,000 food items, Meshulam et al. (2022) investigated the circular economy RE linked to re-spending scenarios.

[1] ODEX is the index used within the Odyssee-MURE (2016) project for assessing energy efficiency improvements across key sectors and the entire economy.

Combining extended I–O analysis, spatial network analysis and econometric modelling, authors found that when platform users re-spend the money they save from food sharing, REs can offset 59–94 % of expected GHG emission reductions, 20–81 % of water depletion benefits, and 23–90 % of land use benefits. The results of this study highlight the importance of incorporating REs into environmental assessments of the digital sharing economy in order to achieve meaningful reductions in environmental burdens through sharing.

4.1.5. Miscellaneous

Developing a field test, Calì et al. (2016) assessed the energy performance of retrofitted buildings in Germany. By comparing actual energy usage to expected usage, they were able to measure the energy performance gap for each retrofitting solution. The range of this gap varied significantly, starting at 117 % in 2011 and ultimately settling at 60 % in 2014. The researchers found that the energy performance gap was caused by a variety of factors including occupant behavior, mistakes in installation, and system malfunctions, therefore confirming the importance of using a monitoring system for buildings with complex engineering systems. This paper was the only one included in the review that utilized a field test for the assessment of REs.

4.1.6. Summary

Hybrid methods were the most commonly used approach at the micro-level. These methods primarily involved combining macroeconomic methods, principally I–O analysis with econometric modelling (Wen et al., 2018; Vélez-Henao et al., 2020; Meshulam et al., 2022). In other cases, I–O analysis was combined with elasticity estimation (Vélez, 2023), or LCA was integrated with agent-based estimation (Hicks et al., 2015). EREs were the category that received the most attention (14 sources), followed by energy rebound (8 sources) and circular economy (4 sources). A notable exception was Muñoz et al. (2019), who did not confine their analysis solely to the assessment of EREs but extended it to life-cycle costing.

4.2. Meso level

The literature search returned 15 sources that had examined the RE at the meso level (Table 4). Whilst energy and environmental rebounds have been the focus of this literature, five sources examined circular economy rebound (Chan et al., 2020; Levänen et al., 2021; Morimoto et al., 2021; Ryter et al., 2022; Zhang et al., 2023). In terms of methodological approaches, four principal categories have been utilized: econometric techniques (3), macroeconomic models (3), LCA/MFA (4) and hybrid methods (4).

In five of the 15 sources, the RE was tangential to the focus of the study or dealt with in a limited way (Chan et al., 2020; Zhang et al., 2020; Levänen et al., 2021; Prest and Krupnick, 2021; Zhang et al., 2023). As such, these sources have been excluded in the discussion that follows. The remaining sources (10) reflect the paucity of literature on rebounds at the meso level and together with their median and modal year of publication (2021), suggest that the meso level has only started to be examined in the academic literature to date.

4.2.1. Econometric techniques/models

Galvin et al. (2021) and Llorca and Jamasb (2017) both examined the energy RE in the road freight transport sector. In the case of the former, the authors employed a simple regression model to examine why energy efficiency improvements in the European truck industry have not translated to lower fuel intensity. The authors find that improvements in vehicle power is the most relevant exogenous variable determining the direct RE, which ranged from 6.13 % to 20.21 %.

Similarly, using stochastic frontier analysis models, Llorca and Jamasb (2017) examine energy efficiency improvements and corresponding REs in the road freight transport industry of 15 European countries between 1992 and 2012. They report an average direct rebound across the countries studied of 3.8 %, with larger REs for more fuel-efficient countries and lower REs for less fuel-efficient countries.

4.2.2. Macroeconomic models

Continuing the emphasis on transport, Skelton et al. (2020) employ a CGE model to investigate the economy-wide environmental RE in the automotive sector supply chain, focusing on GhG emissions as the key environmental impact. Specifically, the authors examine three scenarios that allow REs associated with energy efficiency (7 %), material efficiency (77 %) and product-service efficiency (85 %) to be compared using the global and EU specific GEM-E3 CGE model. Overall, they conclude that "downstream efficiency improvements that save embodied emissions involve greater potential monetary savings per unit GhG avoided, spurring rebound effects" (Skelton et al. (2020), p.1).

Li et al. (2022) also applied a static CGE model to examine the energy RE in the transportation sector in China. In particular, they discuss the role for carbon taxes in reducing the direct RE (level unspecified) associated with simulated improvements in energy efficiency spurred by technological innovation.

4.2.3. Life-cycle Analysis/Materials Flow Analysis

Deng and Williams (2011) utilise a "dynamic" LCA approach to explore the direct energy rebound using what they call a "typical product approach," which allows the functional unit (and its use) to evolve through time. Specifically, the authors estimate the electricity use per typical desktop microprocessor of a given year and conclude that these microprocessors exhibit a particular type of rebound: "the additional functionality built into the next product generation roughly cancels the improvement in energy use per functionality" (p.118).

Liu et al. (2016) also deploy an LCA approach, this time to analyze the direct RE associated with the energy used by household room air conditioners (RACs) in China. The authors focus on the carbon footprint as the environmental indicator and how these emissions have changed following the introduction of the *Air Conditioner Energy Efficiency Standard*. Specifically, they model RACs produced in 2008 and 2012, and supplement LCA data with a questionnaire survey to analyze how consumption behavior might vary given higher energy efficiency and lower energy costs between these dates. Ultimately, the authors conclude that greater energy efficiency has led to longer usage periods with a life cycle RE estimated at 67 %.

4.2.4. Hybrid approaches

The four sources that employed hybrid approaches combined a wide range of methods to estimate RE. Font Vivanco et al. (2014) combined LCA with the IPAT equation and decomposition analysis to estimate the direct RE associated with a shift from gasoline to diesel engines in European passenger cars between 1990 and 2005.[2] They find that despite lower CO2 and NOx emissions associated with diesel engines, total emissions nonetheless increase because of an increase in demand for travel triggered by fuel savings and fuel price differences. Specifically, the authors estimate a RE of 9 % for CO2 emissions and 50 % for NOx emissions.

Albizzati et al. (2022) investigate the RE associated with food waste prevention activities across the food supply chain in the EU. Employing a global general equilibrium model (Fidelio 3) to estimate (what appear to be) direct, indirect and economy-wide REs, the authors couple this with environmentally extended I–O analysis to convert REs into environmental impacts (in this case, GhG emissions). The study finds a 38 % RE associated with food waste prevention that targets households.

With a specific focus on the circular economy RE, Ryter et al. (2022)

[2] The IPAT equation tries to explain the impact that humans have on the environment. I=PxAxT = impacts on the environment (I) are the product of the population size (P), affluence (A), and level of technology (T) of the human population in question.

Table 4
Analysis of meso level rebound effect literature.

Author(s)	Classification	RE category	RE type	RE %	Location	Measure	Mitigation
Albizzati et al. (2022)	Hybrid	Environmental	Direct, indirect and economy-wide	38 %	EU	GHG emissions	Incentives to direct consumption expenditure.
Chan et al. (2020)	Macroeconomic model	Circular economy	Circular economy	–	Ontario, Canada	Energy use	–
Deng and Williams (2011)	LCA/MFA	Energy	Direct	–	USA	Energy use per typical microprocessor	–
Font Vivanco et al. (2014)	Hybrid	Environmental	Direct	Variety of scenarios and accompanying REs	Europe	Carbon dioxide and nitrogen oxides	Fuel taxes, urban planning, and the promotion of public transport and car sharing.
Galvin et al. (2021)	Econometric techniques/ models	Energy	Direct	6.13 %–20.21 %	Europe	Fuel intensity	–
Levänen et al., 2021	LCA/MFA	Circular economy	Circular economy	–	EU	GWP	–
Li et al. (2022)	Macroeconomic model	Energy	Direct	–	China	Carbon emissions	Carbon tax
Liu et al. (2016)	LCA/MFA	Environmental	Direct	67 %	China	Carbon footprint	–
Llorca and Jamasb (2017)	Econometric techniques/ models	Energy	Unclear - possibly direct and indirect	Average across 15 European countries 3.8 %	15 European countries	Aggregate fuel consumption	Taxes, fuel efficiency improvements, cap-and trade schemes, alternative transport options
Morimoto et al. (2021)	Hybrid	Circular economy	Circular economy	–	Japan	CO2 reductions	–
Prest and Krupnick (2021)	Econometric techniques/ models	Environmental	Economy wide, transformational	–	USA	–	–
Ryter et al. (2022)	Hybrid	Circular economy	Circular economy	50 %		CO2 equivalent emissions	Mine taxes and royalties. Increasing reclamation costs and exploration costs. Including scrap prices on major futures exchanges.
Skelton et al. (2020)	Macroeconomic model	Environmental	Economy wide	7 % (energy efficiency scenario); 77 % (material efficiency scenario); 85 % (demand reduction scenario).	UK	GhG emissions	–
Zhang et al. (2020)	System dynamics/ simulation	Environmental	Unclear	–	Tokyo	CO2 emissions	–
Zhang et al. (2023)	LCA/MFA	Circular economy	Circular economy	–	Not specified	Engineering Material Footprint and Fossil Fuel Material Footprint	–

Note: CO2 = Carbon dioxide. GHG = Greenhouse gases. GWP = Global Warming Potential. LCA = Life Cycle Analysis. MFA = Materials Flow Analysis. RE = Rebound effect.

combine four different components - econometric time series analysis, inventory-driven price formation, dynamic material flow analysis, and LCA – in their copper supply chain simulation model. The authors assess the potential for recycling to displace copper mine production and thus reduce GhG emissions in the transition toward a more circular economy. The study discusses a range of policy options for minimizing rebound and maximizing displacement, however, on average, permanent increases of one tonne in recycling are found to displace ~0.5 kilotons of mine production per kiloton increase in scrap supply (i.e. 50 % RE). Also in a circular context, Morimoto et al. (2021) examine the material recycling of neodymium (a rare earth element used in high-efficiency motors) from final product waste in Japan. Employing substance flow analysis as well as various multivariate analysis methods to forecast demand and waste of neodymium, the authors suggest that recycling leads to a circular economy RE thus minimizing the potential for reductions in CO2.

4.2.5. *Summary*

Whilst the meso level represented the fewest sources in the review (the global level notwithstanding), it contained the highest number of sources that directly referred to the circular economy rebound RE (five). From a methodological standpoint, the meso level has drawn most on LCA/MFA and hybrid approaches (the latter including general equilibrium models, I–O analysis and LCA/MFA). As elsewhere in this review, given the predominance of energy and environmental REs, the metrics with which the RE is calculated at the meso level tend to favour carbon, energy and GHG.

4.3. *Macro level*

The literature review found 21 sources that had studied the RE at the macro level (Table 5). As with the meso level, studies had focused predominantly on environmental and energy rebounds. However, at the macro level the material efficiency RE was also evident, as was the CE rebound even if only in three studies (Dace et al., 2014; Ottelin et al.,

Table 5
Analysis of macro level rebound effect literature.

Author(s)	Classification	RE category	RE type	RE %	Location	Measure	Mitigation
Ahmadova et al. (2022)	Econometric techniques/ models	Environmental	Not specified	–	Multiple countries	Environmental performance scores of ESG criteria	–
Allan et al. (2007)	Macroeconomic model	Energy	Indirect, economy wide	30–50 %	UK	% change in energy demand	–
Broberg et al. (2015)	Macroeconomic model	Energy	Economy wide	40–70 %	Sweden	% change in energy demand	Carbon and energy taxes
Dace et al. (2014)	SD/Simulation	Circular economy	Circular economy	–	Latvia	Consumption of packaging materials	Packaging tax
Font Vivanco et al. (2015)	Hybrid	Environmental	Direct and indirect	Catalytic converters 0 % Diesel engines 7000 % Direct fuel injection 63 % High speed rail 91 %–227 % Park and ride facilities −1224 % Car sharing 135 % Bicycle sharing 900 %	Europe	GhG emissions	Carbon pricing
Grepperud and Rasmussen (2004)	Macroeconomic model	Energy, environmental	Economy wide	Manufacture of metals: electricity consumption 17.8 %; oil consumption 87.5 %; gross production 31.9 %; CO2 (sectoral) 39.7 %; CO2 (national) 3.7 % [a]	Norway	Energy use and GhG emissions	–
Jaccard and Bataille (2000)	SD/Simulation	Energy	Direct and possibly indirect and economy wide	N/A - Elasticity of substitution for Canadian economy 0.24	Canada	–	–
Kulmer and Seebauer (2019)	Macroeconomic model	Energy	Direct, indirect and economy wide	Economy wide rebound effect 65 %; direct rebound in household consumption 8–12 %	Austria	Household fossil fuel consumption	Fossil fuel tax
Li and Lin (2018)	Econometric techniques/ models	Energy	Economy wide	–	China	Energy use	–
Li et al. (2020)	Econometric techniques/ models	Environmental	Economy wide	Carbon 30 %–41 %; energy 38 %–42 %	China	Carbon emissions	Carbon tax
Ottelin et al. (2020)	Econometric techniques/ models	Circular economy	Circular economy	–	EU	Material footprints	Environmental taxes, green product labels, and nudging (to guide consumers).
Pfaff and Sartorius (2015)	Macroeconomic model	Material efficiency	Economy wide	Rocks and minerals 2.5 %; chemical products 7.76 %; ceramics 3.39 %; steel 10.54 %; nonferrous metals 4.25 %; secondary raw materials 2.78 %	Germany	Raw material demand	–
Saunders (2013)	Econometric techniques/ models	Energy	Direct	Simulation 1: short term 126 %; long term 62 %. Simulation 2: short term 649 %; long term 172 %.	USA	Energy consumption	–
Schandl and Turner (2009)	Hybrid	Environmental	Possibly economy wide	–	Australia	–	–
Solaymani et al. (2015)	Macroeconomic model	Environmental	Unclear - possibly direct and economy-wide	–	Malaysia	Carbon emissions	Carbon tax and energy tax
Van Fan et al. (2021)	Econometric techniques/ models	Circular economy	Circular economy	–	EU 27	–	Environmental taxes
Vita et al. (2019)	Macroeconomic model	Environmental	Unclear - possibly direct and economy wide	Rebound effect of flying 3 % [b]	Europe	Carbon footprint, water footprint, human toxicity and land footprint	–
Wang et al. (2019)	Econometric techniques/ models	Environmental	Economy wide	–	China	CO2 emissions	–

(continued on next page)

Table 5 (*continued*)

Author(s)	Classification	RE category	RE type	RE %	Location	Measure	Mitigation
Wood et al. (2018)	Macroeconomic model	Environmental	Economy wide and indirect	Clothing sector 75 %; food and diets 25 % and 5 %	Global	CO2 equivalent emissions	–
Yan et al. (2019)	Econometric techniques/ models	Energy	Economy wide	Average across all provinces 88.5 % (short run) and 77.5 % in the long run	China	Energy use	Energy price reform; fiscal and taxation policies
Zimmermann et al. (2021)	Macroeconomic model	Energy	Economy wide	Average economy wide 38 %	Switzerland	–	Energy and carbon taxes

Note: CO2 = Carbon dioxide. GhG = Greenhouse gases. RE = Rebound effect. SD = System Dynamics. [a] Manufacture of pulp and paper, chemical and mineral products, finance and insurance, fisheries and road transport all exhibit negative rebound effects or small positive rebound effects (all but one <5 %). [b] Based on a scenario whereby the saving from commuting by walking, cycling and public transport are spent on flying.

2020; Van Fan et al., 2021).

Regarding methodology, macroeconomic modelling and econometric approaches predominate (9 and 8 studies respectively), followed by SD/simulation (2), and hybrid approaches (2).

4.3.1. Econometric techniques/models

Several authors have used econometric techniques to investigate the economy-wide RE in China. Yan et al. (2019) and Li and Lin (2018) both examined the energy RE induced by technological change, with the former suggesting an average RE across all provinces of 88.5 % in the short run and 77.5 % in the long run.

Similarly, Wang et al. (2019) and Li et al. (2020) examined the ERE in China. Focusing on carbon emissions, the former examined new types of urbanization pathways, whilst the latter focused on carbon REs prompted by technological progress or energy efficiency. Li et al. (2020) report average carbon REs of 36 %, 38 %, 41 %, and 30 % for national, eastern, central, and western China respectively.

Outside China, Saunders (2013) used a translog unit cost function to look at historical energy efficiency rebound in the USA, both in aggregate and by sector. Ahmadova et al. (2022) and Van Fan et al. (2021) both utilised regression models to estimate ERE and circular economy RE respectively. In the case of Ahmadova et al. (2022), the authors investigated whether there is a RE associated with an excess of digitalization and how this impacts the environment as measured by ESG criteria. Van Fan et al. (2021), estimated the relationship between waste generation and socio-economic and sustainability related variables including Circular Material Use Rate.

On the subject of CE, Ottelin et al. (2020) looked into the CE rebound by studying households, their consumption habits and how these habits are reflected in material footprints. They conclude that because of REs, circular consumption habits only have a weak connection to material footprints.

4.3.2. Macroeconomic models

Of those studies that employed macroeconomic models to examine macro REs, six drew on CGE modelling and three on a version of I–O analysis.

Five of the sources using CGE - Grepperud and Rasmussen (2004), Allan et al. (2007), Broberg et al. (2015), Kulmer and Seebauer (2019) and Zimmermann et al. (2021) - applied this approach to estimate the energy RE, mainly at the economy-wide level, in Norway, the UK, Sweden, Austria and Switzerland respectively. Utilising different assumptions regarding the scale and scope of energy efficiency improvements ranging from 5 % to 10 %, energy REs were estimated at 30–50 % (Allan et al., 2007), 40–70 % (Broberg et al., 2015) and 65 % (Kulmer and Seebauer, 2019). Similarly, Zimmermann et al. (2021), estimate an economy-wide energy RE or 38 % in Switzerland.

Solaymani et al. (2015) used a CGE model to examine the imposition of carbon and energy taxes on the Malaysian economy and transport sector and how these could mitigate the ERE in terms of volumes of carbon emissions.

Vita et al. (2019) and Wood et al. (2018) both used Environmentally Extended Multiregional I–O analysis to estimate the consumer-orientated ERE. In the case of Vita et al. (2019), the authors looked at different sustainable lifestyle options and the associated carbon footprints, water footprints, human toxicity and land footprints. Wood et al. (2018) focused on consumer diets and clothing and the resulting CO2 emissions.

4.3.3. Hybrid approaches

Font Vivanco et al. (2015) applied their Dynamic IPAT-Life cycle assessment with Environmental Rebound effect or DILER model to estimate the direct and indirect ERE associated with transport eco-innovations in Europe. The DILER model is made up of two components: the first part attempts to scale up product-level LCA data to the macro level using the IPAT equation, and it introduces dynamic technological change to an otherwise static model. The second component draws on econometric approaches to "[describe] how the consumption patterns of innovation users will change as a result of the cost changes resulting from the use of the new product" (Font Vivanco et al. (2015), p.73). Measuring the ERE in terms of GhG emissions, the authors conclude that the majority of ecoinnovations increase environmental burdens owing to a RE, the size of which is "highly correlated with two variables: the total change in effective income resulting from the use of the innovation and the difference between the environmental pressures per monetary unit of the studied innovations and that of the rest of consumption" (Font Vivanco et al. (2015), p.71).

Schandl and Turner (2009) utilized a stock-flow model based on a simulation framework to examine the long-term dematerialisation potential of Australia in terms of materials, energy, water use, and CO2 emissions. In particular, the authors sought to understand the impact of substantial changes in technology, infrastructure, and lifestyle and how these might contribute to decoupling the economy from the environment. Unspecified macroeconomic REs are discussed, albeit to a limited degree. It is important to note that the model does not explicitly deal with macroeconomic accounting conditions, rather being based on physical accounts.

4.3.4. System Dynamics/simulation

Jaccard and Bataille (2000) used a technology simulation model to estimate long-run, future ESUB (elasticity of substitution) values for capital and energy for the Canadian economy.[3] The authors conclude that the capital-energy ESUB is lower than reported by other studies owing to the inclusion of a behavioral component in their model i.e. that there is only weak substitution between capital and energy. Therefore, they suggest that energy efficiency measures will be less effective than

[3] ESUB represents "(1) the extent to which the effective costs of energy services (capital and operating) actually decrease from efficiency improvements, (2) the technical and economic ease with which energy and other inputs to production and consumption (capital, labor, materials) can be substituted when the efective cost of using energy does in fact decrease" (Jaccard and Bataille, 2000, p.451).

predicted but that the RE will also be less prominent.

Dace et al. (2014) applied a SD model to study packaging waste management in Latvia and how the consumption of packaging materials per product unit is impacted by eco-design and economic policy instruments. In the course of their analysis, the authors identify a circular economy rebound akin to that described by Zink and Geyer (2017). Specifically, some of the eco-design scenarios examined present a situation whereby "the supply of cheaper recycled materials in the market and the opportunity to replace virgin materials with recycled materials results in increased total use of packaging materials" (Zink and Geyer (2017), p.182). A packaging tax is discussed as a way of counteracting this.

4.3.5. Summary

Perhaps as expected, the macro level was dominated by the presence of econometric approaches and macroeconomic models (although it did also see the use of SD/simulation, which was a rarity in this review). Nonetheless, the macro level witnessed the widest range of RE categories including energy, environment, CE and material efficiency rebounds. In addition, and as discussed in what follows, the macro level also provided the most in-depth discussion of rebound mitigation options identified in this work, primarily centred on tax and pricing policy.

4.4. Global level

As noted earlier, in line with Lange et al. (2021), the global level is distinguished from the macro level by focusing on sources that have examine the *interactions* between *at least two* economies. In keeping with this definition, the review of the literature identified only three sources that examined the RE at the global level (Table 6). Each of these sources has addressed the energy RE, and in two of the three cases, associated GhG emissions.

Wei and Liu (2017) adopted a CGE model to estimate the economy-wide RE, ultimately finding a rebound of 70 % for energy use and 90 % for related emissions in 2040, albeit with sectoral and local disparities. Similarly, Barker et al. (2009) utilised a Post Keynesian non-equilibrium model to again study the economy-wide RE arising from the IEA WEO 2006 energy-efficiency policies for final energy users. The authors arrive at a total RE of 31 % by 2020, rising to 52 % by 2030.

Finally, Antal and Van den Bergh (2014) employed an econometric approach that they labelled a *re-spending model* to estimate what appears to be, in effect, the direct RE across multiple geographies. They conclude that the RE is larger in emerging economies than OECD countries, and that it is also larger for gasoline than for natural gas and electricity. In addition, and as the authors themselves note, somewhat paradoxically they suggest that "stronger financial incentives to conserve energy tend to increase the rebound … suggest[ing] that with climate regulation and peak oil the re-spending rebound may become more important" (Antal and Van den Bergh (2014), p.585).

5. Discussion

The aim of this paper was to take a broad view and seek relevant sources that had looked to estimate the RE across multiple contexts, not just the CE. In doing so, this review particularly wanted to reflect on those methods and approaches that had been utilized in other disciplines and fields that might be relevant to the assessment of circular economy REs, but which had not yet been used in a CE context.

In light of this exercise several observations can be made. First, it is clear that the study of REs, whilst increasingly researched, has not received uniform empirical attention from the academic community. Most obviously, the literature continues to be skewed in favour of the energy and environmental REs (c.79 % of reviewed sources). Indeed, this review only found 12 sources (c.19 %) that had examined circular economy rebound (i.e. they had examined displacement of primary production within a context encompassing core CE principles) (Kirchherr et al., 2023) (see Tables 3–6). This focus on energy and environmental REs also feeds through into the metrics with which the RE is calculated: as Tables 3–6 show, the RE is most commonly measured in terms of energy use and CO2 (or GhG) emissions. There are notable exceptions to this, for example, displacement rate (Makov and Font Vivanco, 2018), fuel intensity (Galvin et al., 2021), engineering material footprints (Zhang et al., 2023), fossil fuel material footprints (Zhang et al., 2023), ESG scores (Ahmadova et al., 2022), raw material demand (Pfaff and Sartorius, 2015), and consumption of packaging materials (Dace et al., 2014). Also, Deng and Williams (2011) took what they called a "typical product" approach and charted energy use in the production of successive iterations of the same product. However, these examples remain exceptions. Therefore, this work identifies a shortage of research focusing on the circular economy rebound and its relationship with product displacement, and relatedly, a shortage of alternative RE measures other than energy use and CO2 equivalent emissions.

Second, when viewed through the lens of the levels of economic aggregation, which was the main organizing device used to structure this review, contrary to Metic and Pigosso (2022), this review did not discover that the meso level was a *clear* research gap even if this level is underrepresented when compared to the micro and macro levels (representing 24 % of sources, albeit only 16 % when those sources that had only employed very limited empirical measurement were excluded). However, this may well be because of the definition of the meso level that was deployed here, following Lange et al. (2021), that understood this level as a *single sector or market*. This framing may have been considered as part of the macro level by other authors. On the contrary, the main research gap that this review points to is the global level (i.e. the *interaction* between multiple economies) as this appears to have been almost entirely ignored in the empirical work to date (representing only

Table 6
Analysis of global level rebound effect literature.

Author(s)	Classification	RE category	RE type	RE %	Location	Measure	Mitigation
Antal and Van den Bergh (2014)	Econometric techniques/models	Energy, environmental	Unclear	Gasoline: energy (1 %–157 %); carbon (1 %–114 %) Natural gas: energy (4 %–31 %); carbon (5 %–35 %) Electricity: energy (7 %–22 %); carbon (7–240 %)	Multiple	Energy and CO2 emissions	Carbon pricing, appliance standards, smart technology, and behavioural incentives
Barker et al. (2009)	Macroeconomic model	Energy	Indirect and economy wide	c. 30 % 2020 c. 50 % 2030	Global	Energy use	–
Wei and Liu (2017)	Macroeconomic model	Energy, environmental	Economy wide	68–76 % energy use 73–90 % related emissions	Global	Energy use and related emissions	–

Note: CO2 = Carbon dioxide. GHG = Green-house gases. RE = Rebound effect.

5 % of sources). This omission perhaps stems from the preponderance of material on the energy rebound, which has traditionally fed into a discourse of 'independence' and 'self-sufficiency' rather than one that crosses borders. Indeed, on this point, with the exception of China, the literature on REs is heavily slanted in favour of a handful of mainly western countries. Emerging economies are virtually absent from view, the three global levels studies (particularly that by Antal and Van den Bergh, 2014) and the micro level case studies on Colombia developed by Vélez-Henao et al. (2020) and Vélez-Henao and García-Mazo (2022), being the exceptions. Accordingly, this review identifies a shortage of analyses at the global level, and a lack of consideration of emerging economies.

The levels of economic aggregation also influence methodological choices: for example, in broad terms, LCA/MFA and elasticity estimates tend to be more evident at lower levels of aggregation, whereas econometric techniques and macro modelling are more present at higher levels of aggregation. However, certain techniques are largely absent: for example, agent-based modelling, despite the appeal from Hicks (2022) to incorporate this in RE studies. In addition, pure SD/simulation is barely covered and SFC modelling approaches were not present. As one would expect, the level of economic aggregation also influences the type of RE addressed with macro level studies focusing more on economy-wide and, to a lesser extent, indirect REs, whereas lower levels of aggregation sought to focus on the direct RE.

Third, specifically thinking about REs in a circular context, it is noticeable that these were mainly estimated using basic approaches in the literature reviewed. For instance, two sources use simple linear regression (Ottelin et al., 2020; Van Fan et al., 2021) and one source discussed REs drawing on simple scenario based LCA (Levänen et al., 2021). Only seven sources use (or discuss the use of) more sophisticated approaches such as I–O modelling, SD, or sophisticated hybrid approaches (Dace et al., 2014; Makov and Font Vivanco, 2018; Chan et al., 2020; Morimoto et al., 2021; Meshulam et al., 2022; Ryter et al., 2022). Therefore, there is clearly scope to learn from the more complex methods that have been employed in other parts of the rebound literature to provide a more accurate and encompassing understanding of REs in a circular economy context. In particular, a promising avenue is the use of modelling frameworks of a dynamic and multi-period nature such as, for instance, Stock-Flow Consistent models, which can offer a multi-period view of the phenomenon while also being integrated with Input-Output Analysis for capturing cross-sectoral flows. As mentioned, SFC models were entirely absent from the literature reviewed. As such, this review has identified the limited adoption of advanced approaches to circular economy RE assessment as a further research gap.

Fourth, whilst there is scope for the study of CE rebounds to draw on the wider RE literature, this review exercise also suggests that the wider field is still in search of an agreed set of guiding principles for the reporting of REs. For instance, Lange et al. (2021) recently tried to codify a systematic approach in this regard, however, key parts of this framework such as the level of economic aggregation and the time frame (short-run or long-run) are largely absent from the sources reviewed, and thus represents a further research gap. Indeed, because of this, it is very difficult to directly compare different RE estimates. That being said, the unusually large estimates from Saunders (2013), Antal and Van den Bergh (2014) and Font Vivanco et al. (2015) aside (which appear to be driven by particular methodological choices), Tables 3–6 suggest that most *energy* and *environmental* REs lie in the 30–90 % range. This largely accords with Sorrell (2007), Azevedo et al. (2013) and Kulmer and Seebauer (2019) who find similar results in the context of economy wide energy REs. However, again, this should be treated with caution given the complexity of comparing different RE estimates.

Finally, based on the empirically-focused literature reviewed in this work, discussion of how REs could be avoided or mitigated appears to be rather shallow, focusing as it does primarily on tax and pricing policy. Objects of fiscal and taxation policy include carbon (e.g. Broberg et al., 2015), energy (e.g. Solaymani et al., 2015), fossil fuels (e.g. Kulmer and Seebauer, 2019), packaging (e.g. Dace et al., 2014) and mines (e.g. Ryter et al., 2022). Thinking beyond this to include, for instance, behavioural mechanisms, is almost entirely absent, the work of Antal and Van den Bergh (2014), Ottelin et al. (2020) and Albizzati et al. (2022) being exceptions. Also absent is a focus on which CE practices could lead to optimal displacement of production. While there are several sources that address the occurrence of potential REs in the context of the 'sharing economy' (Yin et al., 2018; Coulombel et al., 2019; Amatuni et al., 2020; Warmington-Lundström and Laurenti, 2020; Meshulam et al., 2022; Vélez, 2023), these are preoccupied with comparing the environmental performance between baseline and sharing scenarios using standardized metrics. This is another indication of the reductionist perspective that is dominating the CE discourse, hence the sole focus on metrics rather than suggestions on how behavior changes could actually be achieved in terms of production and consumption. Therefore, based on the literature reviewed, this work identifies the limited coverage of empirical research that focuses on devising solutions to avoid or mitigate REs as the final research gap of note.

5.1. Theoretical implications

The literature review conducted provides a summary of methods for estimating different types of REs, and investigates the actual and potential application of these methods in the CE related literature. In this endeavor, it helps respond to the call made by Siderius and Poldner (2021) to better understand the effective estimation of REs within the CE context and to clarify, in line with the recommendations of Castro et al. (2022), the primary methods and metrics suitable for this purpose. In tackling these gaps, it enriches the scientific literature at the intersection of the CE and REs research fields in two ways. Firstly, it comprehensively presents the state of the art in the assessment methods of REs and highlights areas where research in this regard has limitations. These limitations not only provide useful insights for further research but also reflect a limited characterization of REs within the context of the CE. For instance, the limited capability of the assessment methods used so far to effectively incorporate a short or long-term temporal perspective in assessing REs in circular settings is presumably due to the fact that the characterization of REs generally overlooks their longitudinal evolution, e.g., their potential for propagation in depth (i.e., across different levels of economic aggregation) and breadth (i.e., the increase in their magnitude) over time. Based on this, Table 7 presents a non-exhaustive research agenda containing potential research questions related to the identified research gaps. These questions suggest possible unexplored research avenues concerning the assessment of REs in a circular context, and scope for more advanced characterization of REs and their effective management.

Secondly, the authors propose the adoption of the multilevel typology developed by Lange et al. (2021), originally designed for the analysis of energy efficiency-related REs, to also be applied to REs associated with material flows within a CE. Indeed, REs within circular contexts are generally induced by market forces that evolve over time (Zink and Geyer, 2017). Since the multilevel typology developed by Lange et al. (2021) is based on various levels of economic aggregation and temporal perspectives, the authors believe it can serve as a suitable theoretical framework for categorizing REs in circular settings. This not only adds greater theoretical robustness to the research agenda outlined above but also addresses the inconsistency in classification that characterizes current research on REs within the CE and more generally. This advancement could, therefore, promote the accumulation of knowledge in this research area and facilitate a more objective comparison of RE assessments conducted using different methods within diverse CE contexts.

5.2. Practical implications

While REs can stifle the intended benefits of a CE and may pose a

Table 7
The proposed research agenda regarding circular economy rebound effects.

Scope	Research gaps (RGs)	Research questions
Object of estimation	**RG1.** Shortage of research focusing on the circular economy rebound and its relationship with materials and product displacement	● What are the most effective and objective methods for estimating materials and product displacement in circular settings? ● What are the primary forces driving product displacement, and how can they be effectively directed towards low-rebound strategies?
	RG2. Shortage of alternative RE measures other than energy use and CO2 equivalent emissions	● How can REs be estimated in economic and social terms?
Scope of estimation	**RG3.** Shortage of analyses at the global level	● How may inter-economy import and export affect REs in a global CE?
Method of estimation	**RG4.** Low adoption of advanced approaches to circular economy REs estimate	● How can advanced modelling techniques, e.g., agent-based modelling and Stock Flow modelling, and simulation approaches, e.g., Systems Dynamics simulation, support the estimation of circular economy rebound? ● How can hybrid approaches improve the estimation of REs? ● What role can Information Technology play in supporting and enhancing REs estimation? ● How can simulations forecast REs in the design phase of circular strategies and policies?
Characterisation	**RG5.** Lack of the longitudinal dimension in reporting and estimating REs	● How does the occurrence and magnitude of REs vary over time? ● How could REs propagate over time across different levels of economic aggregation?
Mitigation and avoidance	**RG6.** Limited efforts in devising solutions to avoid or mitigate REs	● What behavioural mechanisms should be incentivised or discouraged to mitigate or prevent REs? ● What CE practices may lead to optimal displacement?

genuine threat to the effectiveness of the circular transition, awareness of them remains somewhat limited (Levänen et al., 2021). Yet, the limited quantification of REs can instil in decision-makers a sense of scepticism regarding the potential negative impact of these effects on the outcome of a circular strategy.

Having actionable and sound methods to provide reliable quantitative estimates of REs and a framework for their classification can address this issue by adding concreteness and objectivity to these effects. This not only increases decision-makers' awareness of potential obstacles that a CE may encounter in pursuing sustainability but also clarifies that, to create sustainability through circularity, closing material loops is not sufficient and could even be counterproductive from an environmental perspective.

More importantly, quantitative estimates of REs can enable decision-makers to potentially alter circular trajectories to steer them towards more effective displacement. In this context, REs can be considered a risk in circular strategies (Zerbino, 2022). Therefore, their estimation can support the formulation of risk profiles related to different strategies and the development of appropriate risk management solutions. For instance, circular strategies with low REs may simply involve accepting the RE itself, without the need to view it as a reason to discontinue a specific circular trajectory. Conversely, strategies characterized by medium or high REs may require the adoption of more sustainable production and consumption patterns that lead to more effective displacement.

Furthermore, adopting the multidimensional typology proposed by Lange et al. (2021) can be beneficial for decision-making for two reasons. Firstly, considering a temporal dimension when assessing REs enables the identification of circular strategies that may worsen environmental performance in the short term in favour of improved environmental sustainability in the long term — an outcome generally deemed acceptable in transitional phases (Siderius and Poldner, 2021). An example is causing additional emissions in the short run necessary to build infrastructure for establishing reverse logistics channels to bring end-of-life goods back into the economic system, enabling greater emissions savings in the long run. Conversely, a longitudinal perspective in evaluating REs in CE also allows for the identification of circular strategies in which low short-term REs are amplified over time by market forces and consumption behaviors. In such cases, a decision-maker could intervene to select circular courses of action that are more effective in promoting displacement.

The second reason for the utility of adopting the typology by Lange et al. (2021) is that it also considers levels of national and cross-national economic aggregation. Therefore, the tools identified through this review may be used to quantitatively assess the effectiveness of CE policies in achieving environmental impact reduction.

To support decision-making processes in circular contexts through RE estimation, Table 8 specifies, for each assessment method, the general data requirements that the scientific literature has complied with for RE estimation.

5.3. Limitations

The principal limitation of this review is that it has focused on sources that have looked to assess REs empirically in an applied and 'real-world' setting. As such, there are no doubt prominent papers on REs that have not been captured because, for example, they were primarily conceptual analyses or because they lacked an empirical assessment method that was both applied and readily discernible. For example, Palazzo and Geyer (2019) who examined the environmental consequences of material substitution in the automotive sector, van den Bergh (2011) who discussed the policy implications of energy REs, and van den Bergh (2020) who examined material-energy rebound in the transition to a semi-circular economy. However, this focus has been by design - as a way of examining only those sources that have empirically assessed REs so that the relevance of any methods used can be gauged for application in 'real world' CE scenarios.

6. Conclusions

In conclusion, this paper has sought to review the academic literature on the empirical assessment of REs across multiple fields. The wide scope has been deliberate as a way of reflecting on the 'state of the art' and how this might influence and improve the future assessment of the circular economy RE (Zink and Geyer, 2017).

The 63 sources that were ultimately the focus of the review suggest that research into the RE is both expanding rapidly but also that this research is currently uneven with some areas that are mature (i.e., energy), and some that are still taking root (e.g., CE). Perhaps because of this, a widely accepted set of definitions and reporting criteria that move beyond those associated with the initial energy-based idea of the RE and reflect the concept more broadly, are still to be agreed.

One result of this uneven development is that the methods used to estimate REs associated with the CE appear at present to be quite simple. As highlighted, the level of sophistication used to estimate REs outside

Table 8
Examples of data needs for estimating rebound effects.

Estimate method		Examples of data needs	Example data sources
LCA/MFA		Inventory data; impact assessment data; geographical data; sensitivity analysis data.	Ecoinvent, GaBi
Macro models	I–O	Input-output tables – SNA data (Supply-Use tables). Socio-economic extensions – SNA data (Generation of income account, Allocation of income account).	National accounting systems of each country (e.g. ONS in the UK) and multilateral institutions (e.g., OECD, Eurostat); GTAP 7; Exiobase.
	CGE	Social Accounting Matrix – SNA data (multiple SNA accounts) coupled with detailed information on taxes, labour market, income and consumption.	As above. In addition, for example, business and household surveys.
	Post-Keynesian SFC	Balance sheet matrix – SNA data encompassing sectoral financial and non-financial assets. Transactions flow matrix – SNA data encompassing sectoral financial and non-financial transactions.	As per I–O modelling (will not use disaggregated data by sector of activity). In addition, may also use, for example, business and household surveys.
Elasticity parameter estimate		Price and quantity data on goods and services; control variables.	Consumer surveys; market research.
Systems dynamics/ simulation		Stock and flow data; time series data; parameter values.	Various, depending on the level of investigation, including material flow data, surveys and interviews with experts.

the CE has not yet been mirrored within the CE literature itself. This includes the use of modelling frameworks of a dynamic and multi-period nature such as, for instance, Stock-Flow Consistent models, which hold potential in a circular context. More broadly, there are also glaring omissions in the empirical literature regarding the assessment of REs where two or more economies interact (i.e., at the global level), where emerging economies are concerened, and where REs may propagate through time.

Addressing these issues - together with those developed in the indicative research agenda developed - would help provide decision makers with relevant and reliable estimates of circular economy REs thus also helping to ensure that those circular sustainability strategies pursued and the cleaner production technology that they employ, maximize displacement of primary production and associated environmental benefits. In doing so, this would also facilitate the achievement of an ambitious CE that moves beyond the predominant ecomodernism framing with its focus on prosperity through the continual accumulation of resources. However, in this vein it was also noted that aside from a discussion on the use of tax and pricing policy to remedy REs, the discussion of remedial action also appears to be limited, certainly in a circular context. In particular, this includes the potential use of *ex ante* methods to address resource allocation decisions and thus the role that planning and coordination might play, for example, at the supply chain level in tackling the RE 'at source.' Indeed, the preoccupation of selected sources with measuring *ex post* REs rather than questioning the systemic and behavioral mechanisms that cause them, points towards the need for a wider discussion on market-based allocation and the logic that drives the wider economic system to truly establish an ambitious version of the CE.

CRediT authorship contribution statement

Benjamin H. Lowe: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **Meletios Bimpizas-Pinis:** Data curation, Formal analysis, Investigation, Writing – original draft, Methodology. **Pierluigi Zerbino:** Investigation, Writing – original draft, Writing – review & editing. **Andrea Genovese:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing, Methodology.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

Data will be made available on request.

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