

# Rebound effect and sustainability science: A review

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**Conflict of Interest Statement:** The authors declare no conflict of interest.

**Keywords:** rebound effect, sustainability science, literature review, circular economy, sustainable development goals, industrial ecology

**Abstract:** Rebound effects have been historically studied through narrow framings which may overlook the complexity of sustainability challenges, sometimes leading to badly informed conclusions and policy recommendations. Here we present a critical literature review of rebound effects in the context of sustainability science in order to (1) map existing rebound research which goes beyond mainstream approaches, (2) unveil and classify current knowledge gaps in relation to sustainability science, (3) outline a research agenda, and (4) provide a knowledge base to support the design of effective policies towards sustainable development. We analysed the literature in accordance with seven criteria for sustainable assessment: boundary-orientedness, comprehensiveness, integratedness, stakeholder involvement, scalability, strategicness, and transparency. Our review identified three main issues: (1) the failure to address the multidimensionality of rebound effects, whereby both negative and positive outcomes may arise simultaneously, (2) the shift towards absolute rebound metrics which allow to contextualise its effect with respect to science and policy goals, and (3) a general lack of attention to behavioural effects. We conclude that addressing these issues will help rebound research gain explanatory power and relevance for key decision makers. We envision that with better alignment with sustainability science, future rebound research could help elucidate trade-offs in policies, including why certain strategies such as those based on the circular economy might fall short of expectations, and why achieving key goals and targets such as the Sustainable Development Goals is so challenging. This knowledge is crucial to promote a prioritisation of actions and a concrete transition towards sustainability.

## 1. INTRODUCTION

The rebound effect has long been the object of interest and debate in academia. The resulting rich body of evidence has even sparked concern among policymakers, who fear that such an effect may render laboriously designed environmental and broader sustainability-oriented policy largely ineffective (Font Vivanco et al. 2016a). While definitions of the rebound effect are diverse in their breadth and depth, their essence is the contrast between the potential and the actual energy benefits and broader environmental benefits delivered by a given efficiency improvement (Greening et al. 2000; Sorrell 2007; Jenkins et al. 2011). The rebound effect (RE) is thus generally defined as the absolute or relative difference between the “ceteris paribus” potential environmental benefits (PEB) (e.g., the expected energy savings from replacing incandescent light bulbs with more energy efficient LED lights, all else being equal) and the “actual” environmental benefits (AEB) (e.g., the energy savings given the effects of cheaper lighting costs, moral licensing, etc.) (Font Vivanco et al. 2016b). Using absolute metrics,  $RE = PEB - AEB$ , while, in relative terms,  $\%RE = \left( \frac{PEB - AEB}{|PEB|} \right) * 100$  (Font Vivanco et al. 2014).

Building on this basic idea, definitions and related research on rebound effects have focused on a panoply of specific issues, such as energy savings from energy efficiency policies (Gillingham et al. 2016), water savings from crop irrigation practices (Berbel et al. 2015), and induced transport demand from fuel efficiency improvements (Hymel et al. 2010; Galvin 2020). Moreover, rebound research tends to focus on specific economic effects, generally direct, indirect, and macro-economic effects (Greening et al. 2000) as well as behavioural effects, namely increased/diffusion of responsibility, moral licensing, attenuated consequences, and frugality (Santarius and Soland 2018). In the context of multifaceted and inherently complex sustainability issues (TWI2050 2018), however, such overly-specific framings can lead to overlooking key aspects, such as (1) the trade-offs between life-cycle stages and environmental impacts, (2) macroeconomic effects, (3) social impacts, and (4) behavioural insights, in turn leading to badly informed conclusions and policy recommendations (Font Vivanco et al. 2018). For example, additional energy demand by low-income groups may contribute to eradicating energy poverty (Ürge-Vorsatz and Tirado Herrero 2012) or indicate that poverty is being overcome (Galvin 2015a). The usefulness of rebound effect analyses to tackle complex sustainability challenges across “areas of protection”, for instance human health, prosperity, and natural resources, and within the domains of society, the environment, and the economy (Finnveden et al. 2009), thus relies on framings that integrate as many aspects of sustainability as possible.

From its inception within energy economics, rebound effect research has progressively absorbed, albeit generally but not explicitly, aspects from industrial ecology and the broader field of sustainability science. Broadly speaking, sustainability science deals with the interactions between biophysical and sociotechnical systems and how such interactions relate to the challenge of sustainable development (Kates et al. 2001). Sustainability science can be operationalised through sustainability assessment to support policy and decision-making in a broad environmental, economic, and social context (Sala et al. 2015). Sustainability science has been defined as a metadiscipline where key disciplines such as industrial ecology, environmental assessment modelling, risk assessment, and others are integrated (Mihelcic et al. 2003). In relation to industrial ecology, this field has been regarded as the science of sustainability (Ehrenfeld 2004), and research further points to a growing unification between

both fields based on their shared principles (Brent et al. 2008). Various works have analysed the rebound literature according to broader framings related to industrial ecology (Hertwich 2005), life cycle assessment (LCA) (Font Vivanco and van der Voet 2014), psychology and sociology (Santarius and Soland 2018; Santarius et al. 2018), non-energy rebound (Font Vivanco et al. 2018), power relations in industry and politics (Galvin 2020) and thermodynamic-evolutionary theory (Ruzzenenti and Basosi 2008). The explicit links between rebound effect research and sustainability science have not, however, been drawn, and current state-of-the-art approaches are scattered across different disciplinary niches.

In this article, we carry out a critical literature review of rebound effect research under the framing of sustainability science. It merits noting that we do not aim to carry out an exhaustive literature review to inventory all rebound effect research. Rather, we aim to identify key literature to discuss how a better alignment of current goals and scopes of rebound research with sustainability science may enable a range of stakeholders, from academics to policymakers, to draw attention to a fuller array of sustainability impacts and trade-offs mediated by rebound effects. We therefore do not negate the value of studies with narrow goals and/or scopes focusing on particular issues but we imply that assessing these studies against a sustainability assessment framework may help in unveiling hidden barriers towards the ultimate goal of sustainable development. Illustratively, typical energy or water rebound studies at local scales may ignore broader macro-scale effects (e.g., global market prices), the social implications of additional demand (e.g., energy poverty and malnutrition), the trade-offs between life cycle stages and/or environmental impacts (e.g., mining-related emissions into water stocks), and the positive impact of stakeholder involvement (e.g., to enhance communication of results). While such broadening of the goal and scope may not be relevant and/or feasible in all cases, the proposed exercise is critical to reconcile the study of specific issues with broader global goals.

This review is structured using, as criteria for evaluation of rebound effect studies, the criteria proposed in Sala et al. (2015) to compare different approaches to sustainability assessment. Despite the fact that several other frameworks for sustainability have been published, none had been translated into operational dimensions to be assessed. To overcome this limitation, Sala et al. (2015) proposed a pragmatic approach to evaluation addressing seven aspects: boundary-orientedness, comprehensiveness, integratedness, stakeholder involvement, scalability, strategicness, and transparency (see section 3 for definitions).

The objectives of this review are to (1) produce a comprehensive map of existing rebound research beyond mainstream energy economics, including existing ontologies and methods, (2) unveil and classify current knowledge gaps in relation to sustainability science, (3) outline a research agenda for future rebound research, and (4) aid the design of effective policies help transition towards sustainability. This review is structured as follows: section 1.2 introduces the rebound effect concept from the perspective of energy economics, section 2 reviews relevant literature through the lenses of sustainability science, section 3 outlines a research agenda from current knowledge gaps, and section 4 concludes.

## 1.2. The origins: Jevons' paradox and energy rebound effect

The origin of the awareness of rebound effects can be traced to the seminal works of William Stanley Jevons (1865), who suggested that efficiency gains in the use of coal would lead to a net increase in coal demand. Such an argument would be later branded the “Jevons’ paradox” (Wirl 1997; Giampietro and Mayumi 1998). Jevons’ ideas were however largely dismissed due to the lack of empirical evidence by contemporaneous colleagues such as Mundella (1878). It was not until a century later that Leonard Brookes (1979) and Daniel Khazzoom (1980; 1987; 1989) first proposed and formalized, from a macroeconomic and microeconomic perspective respectively, that energy efficiency could increase energy demand rather than decrease it. The term “rebound effect” was coined for the first time by Khazzoom (1980) in reference to the increase in demand for energy services due to the decrease in the unit price of energy from an energy efficiency improvement in household appliances (Khazzoom 1980). More generally, the rebound effect was defined as the additional consumption of energy services from overall changes in demand as a result of behavioural and other systemic responses to energy efficiency improvements (Binswanger 2001; Brookes 1990; Saunders 1992). The newly named rebound effect became a central topic in an intense debate among energy economists in the aftermath of the 1970s energy crisis and the subsequent needs of policy to reduce energy use and dependence (Herring 2008). Later, Saunders (1992) labelled as the “Khazzoom-Brookes Postulate” the case where energy use ends up increasing after an energy efficiency improvement, which is also called “backfire”, and he suggested it occurs in accordance with a particular implementation of a neoclassical growth model. The first empirical studies on the rebound effect took shape after these early contributions, framed mostly in terms of neoclassical economic theory, and focused on energy uses.

During the 1980s and 1990s, further contributions to the ongoing debate were proposed, fuelled by climate change concerns and a new social and policy awareness on energy scarcity, consolidated during the energy crisis (Herring 2008). These studies directed the debate not toward the existence of the rebound effect, but rather toward its impact on the viability of energy efficiency policies. Some scholars argued that energy efficiency leads to an increase in energy use (following Brookes (1979) and Saunders (1992), among others), while others argued that, while rebound effects offset some of the potential energy savings, energy efficiency nonetheless reduces energy use (Schipper and Grubb (2000), among others). Notable contributions to the debate in this second wave were made by Lovins (1988), Schipper and Meyers (1992), Howarth (1997), Wirl (1997), Greene et al. (1999), Saunders (2000), and Binswanger (2001).

Greening et al. (2000) made the first comprehensive review covering 75 estimates of the rebound in the energy rebound literature of the 1980s and 1990s. They found that estimates of rebound effect size ranged between very low and moderate. Later, Sorrell (2007) provided another extensive literature review of over 500 studies and reports. These documents include both empirical estimates of rebound effects and qualitative discussions. The review showed the impressive growth in rebound literature over these three decades, even though the larger growth in rebound effects literature occurred after 2007. Sorrell concluded that while backfire effects (i.e., rebound effects higher than 100%) were unlikely to follow most energy efficiency improvements, they could emerge during early diffusion stages of improved “general purpose

technologies”, such as electricity and mechanization. Additional reviews, including reports from ‘grey’ and policy-oriented literature, have arrived at similar results (Jenkins et al. 2011; Maxwell et al. 2011; Madlener and Turner 2016).

## **2. REVIEW RESULTS: THE REBOUND EFFECT IN THE CONTEXT OF SUSTAINABILITY SCIENCE**

This section reviews the rebound effect literature through the lenses of sustainability science by organising the relevant literature according to the seven key aspects, noted above, which Sala et al. (2015) proposed as criteria to be considered when comparing sustainability assessment approaches:

- **Comprehensiveness:** the inclusion of sustainability dimensions (environmental, social, and economic), and the principles related to these, in the scope of analysis.<sup>1</sup>
- **Strategicness:** the level to which an approach to assess sustainability is solution-oriented, and so is focusing on transitions and changes towards sustainability.
- **Integratedness:** the level of integration between different sustainability dimensions. This includes the ability to consider the interplay among multiple sustainability dimensions as well as the use of transdisciplinary, inter-sectoral, and participatory approaches.
- **Boundary-orientedness:** the adoption of science and/or policy-based thresholds, such as specific emission limits or broader planetary boundaries.
- **Scalability:** the inclusion of spatial (local, regional, and multi-regional) and temporal (short, medium, and long-term) scales of analysis.
- **Stakeholders’ involvement:** the involvement of relevant stakeholders in the assessment process, namely their interaction, promoting consensus building, access to information, and clear communication.
- **Transparency:** the openness regarding the data, data sources, models, indicators, results, and public accessibility thereof.

The literature review method used is based on the six generic steps described in Paré and Kitsiou (2016) - formulating the research question(s) and objective(s), searching the extant literature, screening for inclusion, assessing the quality of primary studies, extracting data, and analysing data. The review can be categorised as a “critical review” as our goal is to offer an interpretative analysis of existing literature on a particular topic -the rebound effect- to reveal relevant issues, such as strengths and weaknesses, with respect to a particular theory -sustainability assessment and broader sustainability science - (Paré and Kitsiou 2016). Given the significant volume of extant literature on the topic of the rebound effect, assessing the representativeness and quality of primary studies deserves special attention in order to ensure the validity of this exercise. First, we ensure that the selected literature is representative of this topic by applying an exhaustive coverage, thereby ensuring that all relevant studies are

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<sup>1</sup> Alternative definitions describe more dimensions, such as the institutional (O’Connor 2006), cultural (Nurse 2006) and technological (Vos 2007) dimensions of sustainability.

included in the review. The exhaustive coverage is validated through the literature review method and the comprehensive knowledge of the review team on this topic. Even so, some relevant studies may still have been unintentionally omitted, and this constitutes a limitation of this approach (see section 3.7). Second, we have assessed the scientific quality of a selection of studies purely based on the rigour of their research design and methods. Such an assessment will be explicit whenever relevant to the main discussion. This approach can generate a bias towards recent literature due to the iterative nature of the scientific process (see Figure 1). We have prevented the overrepresentation of studies on the same topic by generally avoiding duplication of goals and scopes, namely a single study will be selected from a selection with similar goal and scope. The reviewed literature contains both peer-reviewed academic articles and grey literature. It was conducted using a variety of approaches, such as keyword search (e.g., “rebound effect” and “water efficiency” for the case of water rebound literature) and cross-reference analysis. A total of 138 documents have been included in this critical review. From all documents, 65% are academic papers published in peer-reviewed journals, 28% are books or book chapters, while the remaining 7% are reports, conference papers, or white papers. A summary of the reviewed literature (by type of article, year, journal subject area, and case study region) is presented in Figure 1. Full statistics and individual scores for each reviewed document using the systemic framework for sustainability assessment from Sala et al. (2015) are shown in the supplementary information. Also note that scores do not relate to the scientific quality of the research but to the extent to which the research fulfils the framework’s dimensions. Studies were classified as “case study”, “theoretical” or “literature review” according to their primary goal, and only documents containing case studies will have a case study region and a score for scalability. Documents containing literature reviews were not scored as these do not contain original research.

[PLACE FIGURE 1 HERE]

## **2.1 Comprehensiveness: economic, environmental, and social dimensions**

### **2.1.1 Economic dimension**

While rebound effects are generally expressed through indicators of interest such as resource use (e.g., coal and primary energy) or broader environmental issues (e.g., climate change and waste generation), it merits noting that rebound is mediated by changes in consumption and/or production. Following Font Vivanco et al., (2016b), rebound expressed using “pressure” indicators such as resource use can also be characterised using economic indicators such as relative/absolute changes in income, GDP and factor productivity, which then lead to environmental consequences. While not inherently related to a given issue under scrutiny (e.g., whether a given policy led to a net reduction in energy use), such indicators are useful to make explicit the relationship between the driving forces behind changes in resource use. These indicators link resource efficiency with the so-called “core rebound mechanisms”, such as spending and price effects, which are later represented as indicators of interest (Font Vivanco et al. 2016b; Freire-González 2017). Expressing rebound through economic indicators (e.g., changes in income and GDP) was not common in early rebound studies, as these were focused on estimations of direct rebound effects and largely relied on price elasticities as a proxy to

estimate direct energy rebound in relative terms (% of energy savings that are taken back). There was therefore no need to estimate “intermediate results” such as the economic savings associated with fuel improvements, more efficient appliances, etc. The emergence of studies focusing on indirect effects (relating to other products and services, which were not the object of resource improvements), and broader macroeconomic effects made such intermediate results a necessity sometimes worth reporting.

Relating to individual spending, Font Vivanco et al. (2015), Makov and Font Vivanco (2018), and Thiessen et al. (2008), among others, reported rebound effects both in terms of individual economic savings and their associated environmental consequences. Briceno et al. (2004) reported rebound in terms of increases in passenger and vehicle kilometres, where economic savings lead to a rebound in terms of climate change. As for factor productivity, Sorrel (2007) reviewed various examples from the energy efficiency literature, which investigate the link between improved energy efficiency and improved total factor productivity. Regarding macroeconomic effects, a rich body of literature can be found where indicators relating to productivity, GDP, employment, etc. are associated with rebounds (Dimitropoulos 2007; Duarte et al. 2018). For example, Allan et al. (2006) estimated the effects of energy efficiency improvements in terms of changes in long-run GDP, employment and wages. Barker et al. (2007) also estimated the contribution of GDP changes to the total macroeconomic rebound expressed in terms of greenhouse gas (GHG) emissions.

### **2.1.2 Environmental dimension**

Environmental issues have traditionally been the object of interest in rebound studies, from resources use and depletion (e.g. coal and energy use) to more complex pressures and impacts, such as climate change. Environmental indicators used to represent rebound can be classified according to the DPSIR (driving forces, pressures, states, impacts, and responses) modelling framework, as pressures (e.g., CO<sub>2</sub> emissions and water use), states (e.g., global warming and nature occupation), and impacts (e.g., impacts on ecosystems and human well-being) (Smeets and Weterings 1999). Using LCA terminology, pressures, states, and impacts can be defined as elementary flows, midpoint impacts, and endpoint impacts (Weidema et al. 2008). Other than energy rebound, a wide array of environmental issues have been addressed in rebound studies through the so-called “environmental rebound effect” framework (Font Vivanco et al. 2016b) (see Section 3.2.1), and some studies have further addressed so-called cross rebound effects by analysing the effects on other resources different from the resource initially targeted by the efficiency improvement (Freire-González and Font Vivanco 2017). Aside from energy and related GHG emissions (see section 2), water rebound has received special attention.

### **Water rebound effect**

Berbel et al. (2015) performed a literature review on water rebound. They found that, much like traditional energy rebound literature, research into water rebound produces a wide range of sometimes contradictory results. Sears et al. (2018) also performed a brief literature review focused on the Jevons’ Paradox and efficient irrigation technologies, and suggested that existing empirical literature on the effects of incentive-based groundwater conservation

policies on groundwater extraction lent support to the possibility of Jevons' Paradox or backfire.

Recent studies show potentially high rebounds for water use, among which we highlight the most relevant ones. Gutierrez-Martin and Gomez (2011) found that the potential water savings from improved irrigation techniques were compromised by increased water demand due to higher water productivity. In another case study, Pfeiffer and Lin (2014) evaluated the effect of a conversion to higher efficiency irrigation systems and found that the intended reduction in groundwater use did not occur, partly because of shifting crop patterns towards more water-intensive crops. Berbel and Mateos (2014) found high additional water consumption due to the expansion of irrigated land, leading to backfire. Song et al. (2018) and Fang et al. (2020) found water rebound in the order of 60-70% for China following improvements in irrigation technology. Freire-González (2019) found a water economy-wide rebound effect of just over 100% for Spain, meaning that efficiency improvements in water use did not lead to reduced water consumption at the national level.

### **Other environmental rebound effects**

Air emissions have been the focus of many rebound studies, mostly focusing on carbon dioxide and broader GHG emissions. Rebound has been expressed as GHG emissions in a number of such works using LCA, input-output analysis (IOA), or a combination of both, among which we highlight the works of Takahashi et al. (2004), Briceno et al. (2004), Alfredsson (2004), Takase et al (2005), Sanden and Karlstrom (2007), Girod (2008), Ornetzeder et al. (2008), Spielmann et al. (2008), Murray (2009), Rajagopal et al. (2011), Whitefood et al. (2011), Girod et al. (2011), Tukker et al. (2011), Druckman et al. (2011), Cellura et al. (2013), Grabs (2015), Galvin (2020), Makov and Font Vivanco (2018), and Skelton et al. (2020). Among these, we highlight the pioneering work of Takahashi et al. (2004) where LCA was first used to translate demand metrics into life-cycle emissions. Also, Briceno et al. (2004) first described rebound in terms of an impact category (global warming) as well as combining LCA with input-output analysis (IOA) to address the impacts from re-spending. Sanden and Karlstrom (2007) first applied consequential LCA in the context of rebound research, while Murray (2009) first calculated direct and indirect GHG rebound effects using IOA. Multiple air emissions, including nitrogen oxides and sulphur oxides, have been addressed by Thomas and Azevedo (2013) and Font Vivanco et al. (2014, 2015). For additional discussion on environmental metrics used in rebound studies and statistics, we refer to Font Vivanco et al. (2014).

Other environmental issues examined in the rebound literature include metals and minerals (Freire-González and Font Vivanco 2017), abiotic resource depletion (Font Vivanco et al. 2014), land use (Font Vivanco et al. 2015; Larson et al. 2012; Bahn-Walkowiak et al. 2012), and household waste generation (Takase et al. 2005; Salemdeeb et al. 2017; Chitnis et al. 2012). Further, biodiversity rebound has been explored by Maestre Andrés et al. (2012). Rebound for multiple environmental issues has been addressed by Briceno et al. (2004) and Thiesen et al. (2008), while Weidema et al. (2008) further addressed both midpoint and endpoint indicators. The study from Weidema et al. (2008) is of particular relevance as it shows the differences in the relative score across impact categories by adopting different impact assessment metrics. Beyond simply expressing rebound through multiple indicators, the trade-offs across



environmental indicators have been assessed by Freire-González and Font Vivanco (2017) in terms of the economic structure, the consumption patterns, and the own price elasticity of the demand for energy.

### **2.1.3 Social dimension**

The rebound effect has social implications and impacts on several fronts. First, rebound is a social phenomenon because *people* are always involved in causing rebounds. Most micro-level rebound research focuses on types of consumer behaviour which lead to rebound effects. The classic econometric definition of the direct rebound effect as the price elasticity of energy services (Saunders 1992; Berkhout et al. 2000; Sorrell and Dimitropoulos 2008) assumes individuals cause rebounds by increasing their take of energy services. This assumption focuses on individual consumers' response to cost-effective efficiency improvements which reduce the 'effective price' of energy services (Gillingham et al. 2015).

The focus on individual consumers is also evident in research examining how consumers' attitudes and adoption of social norms cause these economically-motivated rebound effects (Peters and Dütschke 2016; Santarius and Soland 2018). Some research goes beyond the economic framework to investigate broader psychological concepts such as "moral licensing" – where consumers feel free to consume more energy services because they have and done their bit for the environment by increasing the energy efficiency of their appliances or home (see section 2.2.3) – again putting the focus squarely on the individual consumer. Moral licensing has also been documented in field experiments investigating consumers' behaviour in response to circular economy strategies such as recycling (Sun and Trudel 2017; Ma et al. 2019), or sharing (Briceno et al. 2004; Cheng et al. 2020; Warmington-Lundström and Laurenti 2020).

The sole focus on the individual consumer has been critiqued by authors such as Labanca and Bertoldi (2018) and Ruzzenenti and Wagner (2018), who point out that it ignores the social structural constraints which tend to lock people into rebound behaviours. People who heat more rooms in their house after a thermal retrofit often do so because society has changed: for example, their children have to do their individual homework on their own computers in the privacy and quiet of their own space. Women tend to buy high fuel-consumption Sports Utility Vehicles because these vehicles merge the traditional role of women as shoppers and transporters of children, with the feminist image of a powerful woman enhanced by symbols of prestige and competence (Jain 2002; Sheller 2004).

The theme of social and political power in driving rebound effects has begun to be explored in relation to the social structural constraints on individual consumers that lead them and sometimes lock them into rebound behaviour. An example is Galvin's (2020) study of rebound effects in the US automotive industry. These rebounds statistically correlate with increases in average engine power, which are driven by specific, politically powerful actors and groups of actors in the industry. Taking this into account would require rebound scholars to consider theories of (social-political-economic) power (e.g., Giddens (1984), Winters (2011), and Geels (2014)). By incorporating well-developed theories of power such as that of Sovacool and

Brisbois (2019) into rebound studies, researchers would be better equipped to trace the lines of causation from energy efficiency upgrades to increases in energy services consumption.

Another important social aspect of micro-level rebound effects is that they are often welfare-enhancing for people who would otherwise be deprived of life's basic necessities. Roy (2000) and Chakravarty et al. (2013) explored this in the context of emerging economies. Where there is unmet demand, energy efficiency increases can bring the price of essential energy services within the reach of low-income people. Similarly in the UK context, Chitnis et al. (2014) found a tendency toward higher rebounds among lower socioeconomic groups. The welfare-enhancing aspect of rebound effects began to be evidenced in a striking way in the early 21st Century in a stream of studies of heating behaviour in homes in European countries including England (e.g. Kelly (2011)), Germany (e.g. Sunikka-Blank and Galvin (2012)); Belgium (e.g. Hens et al. (2010)), Austria (e.g. Haas and Biermayer (2000)), France (e.g. Cayre et al. (2011)), the Netherlands (e.g. Tigchelaar et al. (2011)), and Switzerland (e.g. Jakob (2007)). In all of these countries, households in thermally-poor dwellings used far less heating energy, on average, than was required to achieve a healthy indoor environment, whereas in dwellings of high thermal quality or after a dwelling was retrofitted to high thermal quality, occupants used about the same as or slightly more than the required amount. After homes were thermally retrofitted, rebound effects often averaged around 40%, but much of this was welfare enhancing: people were now living in warmer, healthier indoor climates. More generally regarding thermal retrofits, some households need large rebounds to escape from fuel poverty because of structural deficiencies such as inadequate housing policies (Bouzarovski et al. 2016), regressive tax systems, and inadequate welfare systems (Galvin 2019).

To some extent, then, rebound effects may be necessary to mitigate energy poverty. But there are caveats. As Bouzarovski et al. (2016) point out, for many low-income households the problem is not (only) thermally-poor dwellings but (also) high fuel prices, often due to regressive fuel price policies (cf. Haar (2019)). Also, there are clear cases where poorer households still have cold homes after retrofitting because they see this as an opportunity to save money by keeping the thermostat set on low (Chen et al. (2018)).

Rebounds can also bring welfare-enhancing effects in relation to gender. We draw attention to this because scholarship overwhelmingly supports the notion that women on average frequently have less access than men to energy services in certain domains. Galvin's (2015b) study of commuting to work in the German state of North Rhine-Westphalia revealed that in the 14 years from 1999 to 2013, females' commuting distances increased proportionately more than males' and therefore, using the standard rebound formula based on elasticities, females' rebound effects were 16.5 percentage points higher than those of males. When the increase in the number of female workers was factored in alongside the decrease in male workers, females' rebound effects were more than twice as high as males'. Looking at absolute values, however, females' commuting distances had been far shorter than males' in 1999 and were still shorter in 2013, so the rebound effect could be seen as welfare enhancing in that through it, females were beginning to catch up. The discussion above on social structural factors is also relevant here. Women commuters have high rebounds in part because social structural factors long kept them from having the same range of jobs and commute choices as men (Blanke et al. (1996); and see reviews in Crane (2007) and Hanson (2010)).

Finally, welfare-enhancing effects from rebounds can also be accounted for at the macro-economic level. Although welfare is correlated with GDP, we find evidence that it also correlates with the level of energy services consumed (and not necessarily the level of energy consumed). In the so-called “least developed” countries significant shares of the population still do not have access to electricity and so do not enjoy the energy services that electricity brings. As such, efficiency improvements are welcome avenues to make electricity more available and affordable so that more people can enjoy their benefits. In these cases, rebound effects may not be considered as “unintended side effects of intended energy efficiency improvements” (Santarius 2012), but rather as a straight means to reduce (energy) poverty and improve economic wealth. But even from a bare (macro-) economic point of view, in both poor and rich countries, some researchers point out that rebound effects always imply increased utility for users and nations, and hence conclude that “where there is rebound, it’s a damn good thing!” (Grubb 2014) since “It’s economic value creation” (Borenstein 2012).

## 2.2 Strategicness and integratedness

On strategicness, sustainability principles are increasingly considered in rebound studies, albeit such considerations are still scarce. As shown in the previous section, the conflict between positive welfare-enhancing effects and negative environmental impacts from energy efficiency improvements has been addressed in a number of studies from a social science perspective. Similarly, macro-economic studies such as that of Barker et al. (2007) describe a related conflict between increased energy demand and increased GDP and employment.

On integratedness, rebound research has greatly evolved from its origins within energy economics to an increasingly transdisciplinary line of work (Santarius et al. 2016), allowing research to capture complex cause-effect interactions. Transdisciplinary research on rebound is gaining momentum and it has recently been the object of the book “Rethinking climate and energy policies: new perspectives on the rebound phenomenon” (Santarius et al. 2016) and the special issue “The Rebound Effect and the Jevons' Paradox: Beyond the Conventional Wisdom” (Ruzzenenti et al. 2019). Among the various disciplinary understandings, those from industrial ecology and ecological economics deserve special attention in the context of sustainability science. These and other disciplines combine their own theories and metrics with those from energy and neoclassical economics, such as the use of price elasticities and household demand models, to address various dimensions of rebound.

### 2.2.1 Industrial ecology

The early 2000s witnessed an emergence of rebound studies inspired by theories and methods from industrial ecology and specifically the application of LCA and/or input-output analysis (Font Vivanco and van der Voet 2014; Hertwich 2005). Those studies have been framed within the so-called “environmental rebound effect” (Font Vivanco et al. 2016b), given their focus on environmental and broader sustainability issues. Yet rather than simply translating economic to environmental indicators via coefficients, the application of industrial ecology theory brought many valuable insights, from which we highlight the following:

- *Multidimensional indicators.* One of the main contributions of industrial ecology theory to rebound analysis is the ability to express rebound effects using multiple environmental indicators which go beyond energy and related emissions (see Section 3.1.2) at different levels of the society-environment interaction (mostly pressures and impacts). This extension allowed research to identify trade-offs between indicators or cross-rebound effects (Freire-González and Font Vivanco 2017), with some analyses showing great disparity across indicators (Font Vivanco et al. 2014, 2015). Further, by expressing rebound at the impact level, the biophysical context could be considered, for example where emissions are produced (e.g., in a city or close to a fragile ecosystem).
- *Environmental efficiency.* Classical rebound definitions from energy economics focused on “engineering” type definitions of efficiency, specifically the ratio between inputs (e.g., use of energy or other resources) and outputs (economic services). This “input/output efficiency” was expanded under the “environmental rebound effect” by the concept of “environmental efficiency”, defined as the ratio between the fulfilment of a function (e.g., moving from A to B with a certain performance) and its associated environmental damage (e.g., kg of GHG emissions) (Font Vivanco et al. 2016b). Under such definition, studies could address the environmental consequences of changes in the characteristics of products, such as the content of recycled materials (Dace et al. 2014) and changes between functionally-comparable products, such as shifts between vehicle powertrains (Font Vivanco et al. 2016c).
- *Technology detail.* The use of LCA to estimate rebound greatly increased the technology detail of rebound analysis, which allowed researchers to focus on specific products rather than technologies and sectors more broadly. Some examples include the analysis of cheese (Thiesen et al. 2008), electric cars (Font Vivanco et al. 2016c), and smartphones (Makov and Font Vivanco 2018).
- *Life cycle perspective.* Aside from technology detail, LCA applications also innately integrate a life cycle perspective, with the power to unveil determining environmental consequences taking place along the entire supply chain (e.g., impacts from mineral extraction and land use (Font Vivanco et al. 2015)). This perspective integrates embodied-type effects which some authors treat separately (Sorrell 2009; van den Bergh 2011). Other advantages of looking at the life cycle of products are the identification of actors along the supply chain, which can help assessing the process of knowledge generation and technological learning (Sandén and Karlstrom 2007), and the tracing of external costs, which can lead to rebound estimates that are better aligned with sustainability principles (Hertwich 2005; Roth and Ambs 2004).

### 2.2.2 Ecological economics

Some fundamental assumptions associated with ecological economics have a profound impact on the ecological economics view on rebound effects and on its view on achieving ecological sustainability. In his book "The Entropy Law and the Economic Process", Nicholas Georgescu-Roegen (1971) develops the basis for understanding society's economic system not as a closed circular system but as an entropic process closely integrated with natural sources of exergy (low entropy). This idea expanded the application of thermodynamic principles from traditional areas of engineering (energy systems, industrial processes, etc.) to include the overall economic system.

With its point of departure in the entropy law, ecological economics is fundamentally different from mainstream neo-classical economics, which does not include the physical dependence of the economy, especially with regards to the possibilities for decoupling energy use (which could come from energy-efficiency improvements) from economic growth. According to neo-classical economics, energy productivity makes relatively small contributions to economic growth as energy inputs constitute a small share of total costs (Jones 1975). Decoupling energy consumption from economic growth is thus considered both feasible and cheap. The ecological economics perspective states that capital, labour, and energy are interdependent inputs and have synergistic effects on economic output and that energy quality is a crucial but neglected causal variable in explaining economic growth (Ayres and Warr 2005; Cleveland et al. 1986, 2000). A contribution from ecological economics has been to emphasize the dependency of modern societies on high-quality fossil fuels and that this is a driver for other input factors (for instance, on labour productivity) (Sorrell and Dimitropoulos 2007). This dependency implies that rebound effects can be potentially larger, and improvements in energy productivity make an important contribution to economic growth (Røpke 2009; Sorrell 2010; Sorrell and Dimitropoulos 2007; Jenkins et al. 2011).

Georgescu-Roegen's thinking also inspired research on degrowth, which focuses on the decrease in the amount of natural resources consumed by means of structural changes based on principles of sufficiency (Princen 2005; Alcott 2008). This perspective implies that the most effective measure for curbing rebound effects is absolute physical caps on natural resources such as keeping oil and gas in the ground (Alcott 2010); if society first caps its resources, people will automatically live more efficiently and sufficiently (Alcott 2014). The effectiveness of sufficiency measures is, however, not straightforward, as some degree of rebound can take place when the decrease in demand for some products lowers their price which subsequently induces extra demand (Alcott 2008).

Other contributions under the umbrella of ecological economics include those from an evolutionary perspective, which are grounded in the idea that social and ecological systems are "metabolic systems which are organised in nested hierarchical levels and have the ability to evolve simultaneously across different scales to learn" (Giampietro and Mayumi 2008, 91). Such an interpretation challenges neoclassical views on rebound in two important ways (Giampietro and Mayumi 2008, 79–80): (1) energy efficiency becomes harder to define and measure "when dealing with complex adaptive systems operating on multiple tasks across different hierarchical levels and scales", and (2) changes in energy efficiency can arise from either "a change in technological coefficients (when the system performs 'the same set of transformations' but 'better')" or "a change in the profile of tasks to be performed (when the system finds more convenient methods to perform 'something else' instead of the original set of transformations)". Some authors argue that the application of evolutionary principles could capture the dynamic adaptation of markets to new attributes, such as an improved carbon footprint, of existing products (Benedetto et al. 2014).

Time as a consumption factor, rather than income, has been addressed within neo-classical and orthodox economics through the so-called time rebound effect (e.g., by Becker (1965)). The aspect of 'time' was introduced to micro-economic rebound research by Binswanger (2001) and Jalas (2002). More recently, time rebound research has been more in line with ecological economics thinking, since research on time rebound has been concerned with the macro level and how energy efficiency has led to time efficiency gains that have accelerated both

production and consumption. Brenčić and Young (2009), Druckmann et al. (2012), Buhl and Acosta (2016) and Buhl (2016) analyzed how time-saving technical innovations impact on energy service demand, while Santarius (2016a) discussed the implications of social acceleration and energy demand at the macro-level. Time rebound was largely applied to analyse transport systems (Hymel et al. 2010; Small and Van Dender 2007; Spielmann et al. 2008; Girod et al. 2011). Building on Becker (1965) and Spreng (2013), time can be considered an input factor in (household) production functions that is interlinked, if not substitutable, with other inputs such as capital, energy, and information/knowledge. Hence, time efficiency improvements as well as changes in overall time use – e.g., a faster pace of life that entails more activities performed per unit of time (day) – can have direct effects on the use of energy, environmental resources, as well as on social factors such as feelings of time stress or time wealth.

Historically, the relationship between technical energy efficiency, time efficiency and changing time use patterns, and energy demand can be studied from the history of transportation. There is plenty of evidence on how improvements in the technical efficiencies of locomotives, motors, automotive engineering, and transport infrastructures enabled faster and long-distance journeys, particularly during the 19<sup>th</sup> and 20<sup>th</sup> centuries (e.g., Schivelbusch (2014) and Fouquet (2008)). From the invention of the railway in the 19<sup>th</sup> century until about the 1980s, energy efficiency improvements effectively translated into higher travel speed at less costs (Obermayer and Maier 1994). Vice versa, the extensive literature on social acceleration shows that, as people tend to travel faster and further and the pace of life increases, this may result in more energy demand as well as in more time stress and a reduction in the quality of life (Linder 1970; Schor 1991; Rosa 2013; Wajcman 2015).

### **2.2.3 Other relevant disciplines**

The use of models based on orthodox macroeconomics, such as computable general equilibrium and macro-econometric models (Dimitropoulos 2007; Duarte et al. 2018), allowed researchers to quantify macro-economic rebound effects that were previously only theorised, such as price, market, and growth effects (Jenkins et al. 2011). Theories from behavioural economics have also been used to study rebound, putting attention on the drivers behind consumer choices, such as product substitutability (Makov and Font Vivanco 2018) and discount rates (Ceolotto 2016). Consumer choices in rebound studies have also been explored with the use of agent-based modelling (ABM). For example, Hicks and Theis (2014) and Hicks et al. (2015) combined ABM with LCA to simulate emergent behaviour related to the adoption of energy-efficient lighting technologies by households.

Several other studies were conducted with a psychological and behavioural science perspective (e.g., Girod and de Haan (2009); Santarius (2012); Peters et al. (2012); Peters and Dütschke (2016); Suffolk and Poortinga (2016); Santarius and Soland (2018)), while other approaches were built on sociological theories (e.g., Galvin and Gubernat (2016); Galvin (2015b); Santarius (2016a); Sonnberger and Gross (2018)). In addition, several chapters in the volume by Santarius, et al. (2016) addressed the issue from transdisciplinary and real life-oriented perspectives (e.g., Aall et al. (2016), Naess (2016), and Walnum and Aall (2016)). Moreover, extensive literature in environmental psychology investigates mechanisms that are highly

analogous to rebound effects, but do not necessarily use that term. For example, a wide range of studies show evidence for moral licensing effects (e.g., Eskine (2012), Kaklamanou (2013), Khan and Dhar (2006), Kivetz and Simonson (2002), Mazar and Zhong (2010), Merritt et al. (2010), and Tiefenbeck et al. (2013)). Similar to rebound research, such literature explains why individuals tend to consume more energy services after they have invested in energy efficient technologies. However, a meta-analysis suggests that moral-licensing effects may generally be rather small (Blanken et al. 2015), and several moral licensing studies have been criticized for poor methodological grounds (Gneezy et al. 2011). A second strain of psychological research investigates spill-over effects (e.g., Thøgersen (1999); Thøgersen & Ölander (2003); Klöckner et al. (2013); Dolan & Galizzi (2015); Lauren et al. (2016); Kuhn et al. (2021)). Such literature can elucidate secondary effects of energy efficiency improvements in one domain to behaviours in other domains. At the same time, it shows evidence that runs against rebound argumentations, e.g., by showing that efficiency improvements in one domain may incentivize individuals to achieve additional improvements in other domains, hence leading to beneficial environmental effects that countervail rebounds (Santarius and Soland 2018).

### 2.3 Boundary-orientedness

Using the classic microeconomic definition of the rebound effect as an elasticity, namely the ratio between two proportions, rebound estimates become a weak tool because they give figures for proportions rather than amounts of resources saved. With the emergence of quantitative methods from industrial ecology, macroeconomics, etc., rebounds have been increasingly measured in absolute values, thus allowing these to be compared against any given reference.

#### **2.3.1 Rebounds compared to absolute levels of lost energy savings**

In the context of energy rebound, a recurrent question is to what extent rebound estimates can indicate how much absolute reduction in energy consumption and CO<sub>2</sub> emissions is being achieved. Galvin (2014) touches on this issue as part of a wider discussion of how different definitions of rebound effects can mislead as to which energy retrofit gives the biggest absolute reductions in energy consumption. This issue is also mentioned in Section 3.1.3 in relation to increases in male and female commuting distances in North Rhine-Westphalia. The confusion it sows is evident in a European Commission report on the rebound effect (Maxwell et al. 2011), where it is often not clear whether the authors are speaking of absolute or merely proportionate reductions in energy use in specific spheres.

This point is concretely illustrated in examples given by Galvin (2014), who considers three identical apartment buildings each thermally retrofitted to different standards. The building with the least ambitious retrofit saved the least energy, as expected, but it also had the lowest rebound effect. This was because, after the retrofit, the occupants of this building consumed close to the level the engineers were aiming for, while the occupants of the buildings with the more ambitious retrofits found it difficult to bring their consumption down to the extremely low levels in the retrofit design. We can also see this in private car transport, as Frondel et al. (2012) found that households who do low mileage exhibited higher rebound effects, on

average, than households who do higher mileage. The level of rebound effects was therefore not in proportion to the absolute amounts of lost energy savings.

Part of the reason for these findings is built into definitions of the rebound effect. For example, if the expected energy reduction which engineers calculate on the basis of the planned energy efficiency increase is very large but the actual energy reduction is only moderate, the rebound effect will be high – even though in absolute terms a large amount of energy has been saved. On the other hand, if the expected energy reduction is very small and the actual energy reduction almost matches this, the rebound effect will be small but so will the absolute amount of saved energy.

### **2.3.2 Absolute rebound and policy goals**

Estimating rebound effects in absolute terms can be a powerful way to assess progress towards policy goals. For example, Font Vivanco et al. (2021) calculated a macroeconomic rebound in absolute terms for climate change from the introduction of governmental subsidy on electric cars in the UK, which offered a clearer idea of its impact towards broader goals such as achieving carbon neutrality in the UK by 2050 (CCC 2019). Similarly, Font Vivanco et al. (2015) calculated the absolute change in GHG emissions for various transport eco-innovations in Europe considering the environmental rebound effect. By comparing the results of various innovations against each other, this study highlights that high rebound in relative terms may be negligible when the diffusion of certain innovations is low. In other words, expressing rebound as a ratio as traditionally done may not be very informative for policy. Lastly, the rebound framework has been used by Font Vivanco and Makov (2020) to examine linkages between different SDG targets and strategies, which are sometimes formulated in absolute terms. While SDGs are generally conceptualized as separate, isolated elements within a broader framework, many of the goals are inherently linked, such that progress towards one goal could affect progress towards other goals (Miola et al. 2019). Font Vivanco and Makov demonstrated that, since technology and technological change are central components to many SDG strategies, the rebound effect framework can be utilized to identify hidden barriers for achieving SDGs as well as the underlying mechanisms driving environmental-economic-social trade-offs. Being able to calculate absolute rebounds offers a better understanding of such trade-offs, which is key for formulating informed management strategies to improve the overall cohesiveness of the SDG framework.

## **2.4 Scalability, stakeholders' involvement, and transparency**

Regarding scalability, most studies focus on short-term rebound analysis by calibrating models using historical and/or average data, such as input-output relationships and survey data. Medium-term analyses can be found in those studies applying consequential LCA (e.g., Thiesen et al. (2008) and Whitefoot et al. (2011)) and macro-economic forecasting (e.g., Barker et al. (2007) and Font Vivanco et al. (2021)). Long-term analyses deal with the so-called transformational effects (Greening et al. 2000; Polimeni et al. 2008), namely the consequences



beyond cause-effect relationships between supply and demand, by describing changes in actors' preferences and the availability and cost of technologies from the cumulative build-up of stocks and structures. Such effects were addressed by Sandén and Karlstrom (2007) by combining consequential LCA with theories of technical change, such as scenarios and learning curves. On spatial scales, rebound effects at the micro, meso, and macro scales are well researched, while rebound studies focus largely on developed economies (Sorrell 2007; Chakravarty et al. 2013).

Regarding stakeholders' involvement, rebound research has been progressively involving stakeholders outside of academic circles. For example, the project "Addressing the rebound effect" (Maxwell et al. 2011), commissioned by the European Commission, gathered the viewpoints of policymakers, businesses, and NGOs. Similarly, the project "Capping Macro Rebounds - ReCap" (Lange et al. 2019), commissioned by the German government, brought together different stakeholders to develop proposals to limit economy-wide rebound. Stakeholder consultations have even led to tangible policy action such as the UK government acceptance and inclusion of direct rebound in energy policies after consulting relevant stakeholders (Maxwell et al. 2011).

Regarding transparency, rebound models are generally transparent about data sources and assumptions, but with exceptions. For example, some studies using macroeconomic models have been labelled as not being fully transparent, and sensitivity and uncertainty analyses are rarely conducted to test underlying assumptions and data inputs (Sorrell 2007; Dimitropoulos 2007). Multiple modelling approaches are sometimes used simultaneously (e.g., Font Vivanco et al. (2021) and Salemdeeb et al. (2017)), although this feature is relatively rare.

### **3. DISCUSSION: CURRENT KNOWLEDGE GAPS AND RESEARCH AGENDA**

Using the systemic framework for sustainability assessment from Sala et al. (2015), and according to the reviewed literature in this paper, we depict the current state of rebound research in Figure 2 based on the individual scores (on a scale from 1 [no fulfilment] to 3 [full fulfilment] for each sustainability dimension) for each document (see supporting information). On average, the reviewed literature shows the highest values for transparency (score of 2.28), comprehensiveness (2.23), integratedness (2.20), and strategicness (2.11), while stakeholders' involvement (1.03), scalability (1.67), and boundary-orientedness (1.97) show the lowest values. The bottom 10% in terms of total score (summation over single dimension scores) shows no fulfilment of stakeholder's involvement and scalability (1) and a low score for integratedness (1.06). The top 10% show close to full fulfilment for integratedness (2.81), transparency (2.75) and comprehensiveness (2.75). Across studies, stakeholders' involvement and boundary-orientedness show the lowest standard deviation (0.16 and 0.18 respectively) while integratedness and transparency show the highest standard deviation (0.69 and 0.68 respectively). Knowledge gaps in each aspect of the framework are described in the following section and are further used to outline a research agenda. The section concludes with a short discussion on interpretation.

[PLACE FIGURE 2 HERE]

### **3.1 Comprehensiveness**

Addressing at least both the economic and environmental dimensions is widespread in rebound studies (93% of scored studies) given that economic mechanisms, broadly related to consumption and/or production (Font Vivanco et al. 2016b), are generally associated with the consumption of resources, typically energy, and/or associated emissions to the environment. Even so, some articles (7%) focus solely on the consumption of products such as the use of appliances or consumption of automotive fuel without assessing their energy content, thus leaving the environmental dimension on a second plane. On the social dimension, recent literature increasingly focuses to some degree on aspects such as gender, inequality, and social structures on top of the economic and environmental dimensions (30%), thus covering all three dimensions of sustainability.

Additional environmental and social indicators are needed to identify relevant trade-offs. Specifically, while energy and related emissions enjoy great popularity among rebound researchers, other environmental issues are far less prominent. Specifically, the use of resources such as abiotic resources, marine resources, land and soil, water, generation of waste and several environmental impacts including biodiversity are still relatively unexplored (Font Vivanco et al. 2018), and obtaining empirical evidence of such rebound effects should be a focus of future research.

On the social dimension, knowledge gaps exist both at the level of social impacts and at the level of the role of social actors to influence rebound. For the last point, those gaps include how actors with different levels of social and political power influence decisions relevant to resource efficiency, and further research could focus on the relationship between such power relations and changes in social structure, regulations and everyday practices that inhibit reductions in resource-intensive practices. Moreover, much is still unknown about how specific consumer behaviour affects the performance of sustainability-oriented policy.

### **3.2 Integratedness**

Most of the reviewed studies adopt a multidisciplinary approach (49% from the total scored) or transdisciplinary approach (35%), with most monodisciplinary studies published before 2000. Moreover, most monodisciplinary studies were authored by a single researcher, while transdisciplinary studies were generally authored by the largest number of researchers. Transdisciplinary approaches generally tackled more complex problems and involved deeper collaboration to combine theories and methods. Further integration is needed to bring together key disciplines, such as industrial ecology, ecological economics, micro and macro-economics, behavioural sciences and sociology, including theories of social and political power. At the same time, more rebound studies along real-world settings are needed in order to overcome the limited explanatory power of rebound analysis only based on stylized facts, historical demand elasticities, or theoretical assumptions.

### **3.3 Stakeholders' involvement**

Close interaction with relevant stakeholders in all phases of a given rebound study may enhance the credibility and relevance of results (Sala et al. 2015). Relevant stakeholders are however seldom involved in rebound research, and true interaction (see Figure 2), particularly with academics and policymakers, only took place in the context of review rather than research. Such interaction has, however, not yet produced tangible results (Font Vivanco et al. 2016a). Moreover, only 3% of the scored literature resonated the need to involve stakeholders. The involvement of policymakers is particularly key to design policies that effectively mitigate undesired rebound effects, and the experience of past projects (e.g., Maxwell (2011) and Lange et al. (2019)) sets a valuable reference. Among all stakeholder groups, those related to business have not been engaged in rebound research according to our review, and higher involvement would help to better quantify supply-side rebound effects related to improvements in productivity (Santarius 2016b).

Potential outcomes of stakeholders' involvement in rebound studies include redefining goals and scopes to be better aligned with sustainability objectives, access to broader sets of data, and facilitating the communication of results to broader audiences. Moreover, stakeholders' involvement is highly interlinked with other sustainability dimensions such as transparency, strategicness, and boundary-orientedness. For example, some studies claim that transparent models which explicitly reflect the relationship between cause and effect, such as system dynamic models, would facilitate the communication between modellers and relevant stakeholders (Dace et al. 2014). Also, the multidimensionality of results can be communicated through single scores (see section 3.5) which often require the participation of multiple stakeholders to weight conflicting criteria. Lastly, science and policy goals which can be used to contextualise rebound estimates also involve a variety of stakeholders, from business to civil society. To summarise, higher interaction with stakeholders would greatly improve progress towards multiple sustainability dimensions simultaneously.

### **3.4 Scalability**

While only 4% of scored case studies focus on the world economy, the availability of global supply-chain databases has facilitated, at least indirectly, the inclusion of a global spatial scale. There is however a clear bias towards Europe (69% of the total) and the United States (16%) in regional case studies, with only 15% of studies focusing on other regions. Studies focusing on developing economies, where rebound estimates are thought to be largest (Chakravarty et al. 2013; Roy 2000), are lacking, especially for Africa and Latin America, with only a few cases considered (e.g., Semboja (1994), Dufournaud et al. (1994), Vélez-Henao et al. (2020), and Bordón Lesme et al. (2021)). Long-term analyses dealing with transformational effects are also lacking, even though transformational effects can be appraised using theories of technical change, as is done in the pioneering work of Sanden and Karlstrom (2007). The possibility of upscaling site- or context-specific studies to larger scales is also an area in which further research is needed, especially as the transition towards sustainability forces any assessment to link what happen locally to consequences at higher scales, up to global scale. All these gaps in the temporal or regional scales constitute promising areas of future research.

### **3.5 Strategicalness**

Our literature review reveals that few studies (18% of the total) consider the social dimension of rebound simultaneously with the economic and environmental dimensions. Among these studies, none quantify rebound in terms of social impacts (gender and income inequality, forced labour, etc.). Furthermore, the sustainability dimensions are often addressed in isolation. This leads to sometimes contradictory results which can confuse stakeholders and lead to a preference for oversimplistic solutions. For example, the dominating “efficiencyism” doctrine in policy spheres (Schaefer and Wickert 2015) often induces policymakers to favour the positive economic impacts of rebound effects without properly factoring in their negative environmental consequences, which can lead to serious long-term social and economic consequences. Similarly, as described in Section 3.1.3, a focus on relative environmental indicators may obscure social aspects, for example, when backfire effects overshadow poverty alleviation. Further research could tackle all three dimensions - with the help of weighting and single-score metrics as currently done in life cycle sustainability assessment (Finkbeiner et al. 2010; Weidema 2006) - as well as the interplay among dimensions. Such an approach would unveil and quantify trade-offs across sustainability dimensions, offering intuitive results to decision makers about the overall impact of rebound effects.

### **3.6 Transparency**

Only 41% of the scored studies are considered fully transparent and 13% are considered a black box. The lack of transparency is largely associated with the lack of public availability of input data and/or model code/software, the availability of which would allow full replicability of results. Transparency is also associated with sensitivity and uncertainty analyses, which are rarely carried out in rebound studies to test key model and modeller assumptions, such as calibration parameters (e.g., elasticities), model closures (e.g., exogenous saving rates), and environmental multipliers (e.g., total emissions per unit of output), leading to untransparent and unreliable results that are less likely to be taken seriously by policymakers and other stakeholders. An option to address modelling uncertainty is to apply multiple modelling approaches simultaneously to test their underlying modelling assumptions: for example, through alternative ways of spending additional income (Font Vivanco et al. 2014; Saleemdeen et al. 2017), background input-output databases (Font Vivanco et al. 2016c), consumer heterogeneity (Kulmer and Seebauer 2019), and substitution elasticities (Allan et al. 2007; Hanley et al. 2009). Such sensitivity analyses would generate more robust results that are transparent and credible to wider audiences.

### **3.7 Boundary-orientedness**

Rebound results generally focus on relative metrics (e.g., percentage of environmental savings that are taken back) and are rarely contextualised with regards to science- and/or policy- based goals. Consequently, and erroneously in our view, most of the current debates focus on the relative magnitudes of rebound effects instead of their absolute impacts (Maxwell et al. 2011). Absolute estimates of rebound offer a much clearer idea of their magnitude and so whether such effects jeopardise science and policy goals. Note that although absolute rebound can be easily calculated given that the absolute initial savings are known, the issue is rather that

absolute rebound is rarely the main focus when interpreting the implications of the results. Future research avenues could quantify the inefficiencies generated by rebound effects in the achievement of goals such as the SDG, climate agreements, or efforts towards keeping production and consumption systems within planetary boundaries.

Moreover, rebound studies generally focus on exogenous and costless technical changes that are disconnected from the policies governing them (Gillingham et al. 2016), such as the governmental incentives to kick-start electric powertrain technologies (2021). By disregarding the policy landscape, rebound estimates may overlook key aspects related to capital costs, finance, and broader macro-economic dynamic adjustments. Some of such aspects can be included in existing macro-economic models (e.g., computable general equilibrium models) by generating appropriate shocks (Font Vivanco et al. 2021), while others, such as modelling financial markets, require approaches which have not been used extensively for rebound analysis, such as post-Keynesian models (Godley and Lavoie 2016; Barker et al. 2009).

### **3.7 Interpretation**

We suggest that future rebound research which is aligned with sustainability goals must address, to the extent possible, the seven dimensions of sustainability assessment. In doing so, however, it is important to differentiate between those dimensions which are dependent on the goal and scope of the rebound research and those which are not. In this sense, transparency, boundary-orientedness, integratedness, and stakeholders' involvement should always be addressed and maximised regardless of the goal and scope. These four dimensions can be seen as quality checks which answer the following questions: how replicable are the results? what are the implications of the results? does the research team have the expertise to address complex problems? and are relevant stakeholders involved in the decision-making within the research? Among these, stakeholders' involvement is currently the most lacking and must be prioritized, for two main reasons: first, to help clarify the parameters and characteristics of the situations in which rebounds are to be investigated, and second, to exploit the many synergies with other dimensions (see section 3.3). On the other hand, strategicness, comprehensiveness, and scalability will be inherently delineated by the definition of the goal and scope of the study, which can be influenced by many external factors such as funding, resources, knowledge, etc. We suggest that these simple recommendations be followed when weighting the importance of each dimension.

A key limitation in interpreting the results above is the fact that the critical review method is not based on a systematic literature review. It thus merits noting that the statistics, scores, and their interpretation relate solely to the selected literature and can only be indirectly attributed to the rebound literature as whole. According to our judgement, however, carrying out a systematic literature review would not yield significantly different conclusions as those which follow.

## **4. CONCLUSIONS**

Our review shows that rebound effect research systematically lacks goals and scopes that fully address the complexity of current sustainability challenges. With the help of key insights from sustainability assessment, we have identified specific areas that future research could address, specifically aspects related to comprehensiveness, scalability, strategicness, transparency, and boundary-orientedness. Among these, key outstanding issues are the need to address the multidimensionality of rebound effects, whereby both negative and positive outcomes across areas of protection may arise simultaneously, and the shift towards absolute rebound metrics that allow contextualising and quantifying its effect with respect to science and policy goals. Addressing such outstanding issues could help reformulate two rather unproductive debates commonly found in rebound research. The first is whether rebound is big or small, which should no longer depend on relative metrics but in relation to absolute references. The second is whether rebound is good or bad, which should no longer focus exclusively on isolated welfare effects but on comprehensive and transparent metrics that account for the divergent effects in different areas of protection, which need to be simultaneously recognised and acknowledged, even if they must then be held in tension.

Another outstanding issue is the lack of interaction between rebound research and behavioural science to address crucial knowledge gaps as to why certain policies fail, such as how the behaviour of key actors generates important barriers to change. For example, research increasingly shows how a flagship policy strategy such as that based on the circular economy concept is greatly affected by detrimental rebound effects (Zink and Geyer 2017; Makov and Font Vivanco 2018). For example, actual displacement rates of primary production from reuse and sharing actions appear lower than expected (Cooper and Gutowski 2017; Makov et al. 2019; Guide Jr. and Li 2010; Thomas 2003), yet the specific behavioural rebound mechanisms which might hinder such displacement, including moral licensing, diffusion of responsibility, and attenuated consequences (Santarius and Soland 2018), have not been identified nor quantified. Further research could thus complement existing studies, for instance on car sharing (Gong et al. 2017; Clewlow and Mishra 2017) and house sharing (Sheppard and Udell 2016; Schor 2020). Beyond rebound research, the ability to address behavioural features of key actors acting in the system, including at individual level, is a central aspect of sustainability assessment which is not directly addressed in the framework by Sala et al. (2015) yet merits greater attention.

We propose that better aligning rebound research with sustainability assessment, and placing more attention on behavioural aspects, will help rebound research gain explanatory power and increase its relevance to key decision makers. In this sense, we envision that future rebound research could help understand why certain strategies such as those based on the circular economy are not as effective as expected, and why key goals and targets such as the SDGs are at high risk of not being achieved as a whole. This critical literature review offers some ideas on how to make rebound research more relevant, credible, and transparent to finally become a central aspect in policymaking.

## **ACKNOWLEDGMENTS**

The authors would like to thank two anonymous reviewers for their comments.

## FOUNDING INFORMATION

Jaume Freire-González received the support of the Beatriu de Pinós postdoctoral program of the Government of Catalonia's Secretariat for Universities and Research of the Ministry of Business and Knowledge.

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## SUPPORTING INFORMATION

Supporting information is linked to this article on the *JIE* website:

**Supporting Information S1:** This supporting information provides the reviewed rebound literature and associated metadata and sustainability assessment scores, document count by journal, and description of journal subject areas.

## Figure Legends

**Figure 1.** Summary statistics of the reviewed literature by type of article, year, journal subject area, and case study region. SCIE: Science Citation Index Expanded, SSCI: Social Sciences Citation Index, ESCI: Emerging Sources Citation Index. Journal subject areas' description can be found in the supporting information.

**Figure 2.** Current state of rebound research according to sustainability assessment scores. Based on Sala et al. (2015).