Reboundless design: towards the prevention of rebound effects by design

Pigosso, Daniela C. A.

Published in:
Design Science

Link to article, DOI:
10.1017/dsj.2024.32

Publication date:
2024

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Pigosso, D. C. A. (2024). Reboundless design: towards the prevention of rebound effects by design. *Design Science*, *10*, Article e42. https://doi.org/10.1017/dsj.2024.32

Design Science

Reboundless design: towards the prevention of rebound effects by design

Daniela C. A. Pigosso

Department of Civil and Mechanical Engineering, Technical University of Denmark, Kongens Lyngby, Denmark

Abstract

Society's most well-intended efforts to solve sustainability challenges have not yet achieved the expected gains due to rebound effects (i.e., negative consequences of interventions arising from induced changes in system behaviour). Rebound effects offset about 40% of potential sustainability gains, but the understanding of design as a key leverage point for preventing rebound effects is still untapped. In this position paper, three fundamental scientific gaps hampering the prevention of rebound effects are discussed: (1) limited knowledge about the rebound effects triggered by efficiency–effectiveness–sufficiency strategies; (2) the influence of the counterintuitive behaviour of complex socio-technical systems in giving rise to rebound effects is not yet understood and (3) the bounded rationality within design limits the understanding of rebound effects at a broader systemic level. To address the aforementioned gaps, novel methodologies, simulation models and strategies to enable the design of *reboundless* interventions (i.e., products, product/service-systems and socio-technical systems that are resilient to rebound effects) are required. Building on the strong foundation of systems and design theory, this position paper argues for the need to bridge the interdisciplinary gap in the interplay of design and rebound effects, qualitative and quantitative models, engineering and social sciences, and theory and practice.

Keywords: Rebound effects, Design for sustainability, Reboundless design, Circular economy, Sustainable design, Design science, Design theory

Received 03 October 2023
Revised 09 July 2024
Accepted 11 July 2024

Corresponding author
Daniela C. A. Pigosso
danpi@dtu.dk

Des. Sci., vol. 10, e42
journals.cambridge.org/dsj
DOI: 10.1017/dsj.2024.32

1. Rebound effects undermine the potential of design

Never before has there been a stronger global focus on the design of sustainability-oriented interventions (Hauschild *et al.* 2020), but society's most well-intended efforts to solve sustainability challenges (e.g., climate change, loss of biodiversity and resource depletion) have not yet achieved the expected positive societal and environmental impact (Sandberg 2021) due to *rebound effects.*

Rebound effects are negative consequences of interventions that arise due to induced changes in system behaviour, which partially or completely offset their potential sustainability benefits (Hertwich 2005) (Figure 1, adapted from Wolstenholme (2003)).

Literature addressing rebound effects can be traced back to 1865, with the seminal research on the so-called Jevons' Paradox, which proposes that technological efficiency (primarily related to energy efficiency) leads to an associated

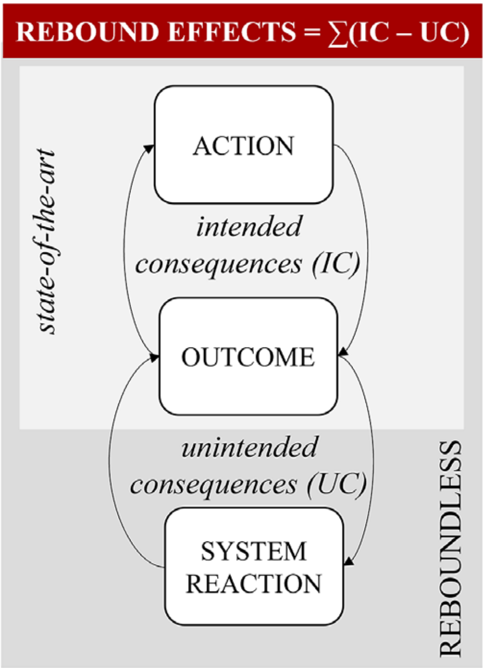

Figure 1. Rebound effects undermine sustainable development. For example, the intended reduction of fuel consumption (IC) by fuel-efficient cars results in lower operational costs and higher disposable income, which leads to re-spending on, for example, more driving (UC), ultimately resulting in increased fuel consumption (rebound effects = $\sum$ (IC – UC)).

growth in resource use (Jevons 1865). After being disregarded for more than 100 years, research on rebound effects re-emerged in the 1980s and can be ordered in four phases (Santarius *et al.* 2016):

(1) 1980s: theoretical exploration at the microeconomic and macroeconomic levels, with research led by Khazzoom and Brookes (Santarius *et al.* 2016), predominantly within energy economics (Font Vivanco *et al.* 2016);
(2) 1990s: empirical investigations, as documented in the meta-analysis by Greening & Greene (1998), and the empirical research carried out by Sorrell et al. (2009);
(3) 2000s: political evaluation with a focus on policymaking support (Ottelin *et al.* 2020), which played an important role in the 'Rio + 20' United Nations conference in 2012;
(4) 2010s: multidisciplinary extension from energy economics to ecological economics, socio-psychology, socio-technology, industrial ecology and sustainability transitions (Metic & Pigosso 2022).

More recently, the so-called transformational rebound (Greening *et al.* 2000) investigates how technology changes consumers' preferences, altering social institutions and rearranging the organisation of production (Greening *et al.* 2000) (e.g., digitalisation and smart products have altered, and will continue to alter, human activity (Bressanelli *et al.* 2022)).

Rebound effects are often classified as direct, indirect and economy-wide effects (Font Vivanco *et al.* 2016; Freire-González 2017):

(i) Direct effects: efficiency gains lead to increased demand and additional consumption of a given product/service (e.g., energy efficient cars lead to higher disposable income and thus increased driving), and/or substitution of other products/services (e.g., car-sharing substitutes public transportation instead of car owning).

(ii) Indirect effects: savings in a given production system drive the consumption of other products/services with higher sustainability impact (e.g., re-spending of disposable income saved via efficient cars with more impactful consumption, such as long-distance flights).

(iii) Economy-wide effects: often referred to as "macroeconomic rebound effects" describe broader economic responses that alter patterns of consumption and production on a larger scale (e.g., new energy technologies can stimulate additional economic activity, expanding or increasing production).

On average, it is estimated that direct rebound effects undermine between 10 and 30% and indirect effects between 5 and 10% (Binswanger 2001) of the potential sustainability gains, depending on the considered timeframe and system boundaries (Sorell 2010; Sorrell 2009). Thus far, the primary focus of research within rebound effects has been on direct and indirect effects (Font Vivanco *et al.* 2016; Freire-González 2017) within an energy efficiency paradigm targeted at a policy-making support (Shove 2018).

Due to the prevalence in energy economics literature, empirical research has been mostly devoted to energy rebound on the basis of a single unit at the consumer level, whereas the investigation of the producer perspective is still very limited (Van der Loo & Pigosso 2024; Metic & Pigosso 2022; Turner 2013).

Moreover, recent findings from behavioural studies challenge mainstream economic principles (which assumes that individuals make rational decisions striving to maximise utility), by showing that decisions are also shaped by psychological and social influences (Santarius & Soland 2018). To fully understand rebound effects, it is crucial to integrate a behavioural perspective (Exadaktylos & van den Bergh 2021).

Yet, research into the behavioural mechanisms that drive rebound effects is still emerging (Sorrell *et al.* 2020). A recent systematic literature review (Van der Loo & Pigosso 2024) identified 15 distinct behavioural mechanisms that drive the occurrence of rebound effects, clustered into four main types:

(i) Moral licensing: prior moral behaviour leading to subsequent immoral behaviour or inaction (e.g., contribution ethics, single-action bias and social moral licensing).

(ii) Reappraisal of consequences: reflect how actors re-evaluate the (relative) personal or environmental consequences of their pro-environmental behaviour (e.g., need satisfaction, response efficacy, negative associations, negative stereotypes, perceived behavioural control and diffusion of responsibility).

(iii) Motivational crowding: reflect how influencing intrinsic and extrinsic motivations can alter the pro-environmental behaviour (e.g., motivational crowding).

(iv) Cognitive biases: reflect systematic errors in thinking that may lead people to deviate from rationality, make inaccurate judgements, or interpret information illogically (e.g., information overload, time discounting, mental accounting and cognitive dissonance).

Furthermore, there is an increasing recognition that rebound effects occur when an intervention liberates or binds not only money, but any scarce production or consumption factor (e.g., time, convenience, space and technology) (Guzzo *et al.* 2024; Weidema 2008).

In summary, recent developments suggest the need for moving beyond economic mechanisms to also fully embrace the role of behavioural mechanisms in giving rise to rebound effects, towards a broader definition and understanding of rebound effects that expands the focus from energy efficiency to a comprehensive view of environmental impacts triggered by systemic changes driven by a wide range of production and consumption factors, beyond monetary terms.

2. Design fails to prevent rebound effects

Although rebound effects have been widely acknowledged, actual research into rebound effects has had very limited ramifications on design, thus far. Three fundamental scientific gaps hinder the prevention of rebound effects within design, as described in the following subsections.

2.1 GAP 1: limited knowledge about the rebound effects triggered by efficiency–effectiveness–sufficiency strategies

Two major paradigms drive the sustainability discussion: (i) green growth, promoting efficiency and effectiveness measures at the production side (Lorek and Spangenberg 2014) and (ii) degrowth, built upon sufficiency measures at the consumption side (Sekulova *et al.* 2013).

Efficiency measures have traditionally targeted the minimisation of sustainability impacts (primarily environmental), by means of reduced resource consumption across the product life cycle (Pigosso *et al.* 2014; Vilochani *et al.* 2024). Nevertheless, *efficiency* gains have repeatedly been cancelled out or even surpassed by increased consumption (Laurenti *et al.* 2015), due to rebound effects. Higher efficiency generates a greater demand, which in turn leads to unintended higher resource use (Figge & Thorpe 2019). It is now widely recognised that *efficiency* measures alone (e.g., developing products with lower material and energy consumption through ecodesign (Maccioni *et al.* 2019)) will never be sufficient to achieve sustainable development (Figge *et al.* 2014).

Effectiveness has thus gained increased recognition, particularly in a circular economy context (Ellen MacArthur Foundation 2015), as an alternative approach to decouple value creation from resource consumption (Pieroni *et al.* 2021), by maintaining resource productivity through subsequent life cycles (e.g., extending the lifetime of products and materials) (Pigosso & McAloone 2017). *Effectiveness* strategies have focused on, for example: (i) the redesign of material flows (through end-of-use strategies such as remanufacturing, reuse and refurbishment); (ii) a long-term perspective on the economic drivers for sustainability and (iii) the elimination of toxicity through enhanced materials health. *Effectiveness*, however, is also subject to rebound effects and not a sufficient strategy to achieve enhanced sustainability (Kjaer *et al.* 2019; Metic *et al.* 2024). Refurbished phones, for example, rarely compete in the same primary market and are likely to be produced in addition to, rather than instead of, new phones (Zink and Geyer 2017) – the same happens with second-hand clothes (Metic *et al.* 2024). Similarly, biodegradable materials may shorten product longevity and consequently create more production (Chen 2021).

More recently, *sufficiency* (Bocken and Short 2016) emerged as an approach to moderate consumption (Tanneurs and Vezzoli 2008) through substantial changes in consumption patterns (e.g., shift from private car ownership to sharing systems). Complementing *efficiency* and *effectiveness* approaches (which are targeted at the supply side), *sufficiency* turns its attention to the demand side, enabling a complete coverage basis for the sustainable consumption and production framework (Tanneurs & Vezzoli 2008). *Sufficiency* operates through innovative sustainable business models (Blok *et al.* 2015) by influencing and mitigating consumption behaviour to a socially sustainable level that enables a good quality of life for all (Fernandes Aguiar *et al.* 2023; Sandberg 2021). *Sufficiency* (Sorrell 2010) can be achieved through, for example, modal shifts and sharing models intended to reduce individual consumption, extension of product life through reuse, avoidance of planned obsolescence and so forth. Nevertheless, rebound effects triggered by *sufficiency* strategies also start to emerge (Andrew *et al.* 2024; Figge *et al.* 2014). Service-based business models often lead to rebound effects (Sarancic *et al.* 2023) by, for example, inspiring more frequent product replacement (Von Weiszäcker & Ayres 2013), careless behaviour (Ackermann & Tunn 2024) and higher re-spending (Guzzo & Pigosso 2024).

It is believed that *efficiency–effectiveness–sufficiency* can indeed lead to successfully enhanced sustainability performance (Bocken & Short 2016; Figge *et al.* 2014), capable of addressing the current pressing sustainability challenges. Nevertheless, *efficiency–effectiveness–sufficiency*, individually or in combination, are also prone to rebound effects (Buhl *et al.* 2017). The early identification and prevention of rebound effects during the design phase is therefore key to ensure that the designed solutions will have a net positive sustainability impact.

While rebound effect research thus far has focused on *efficiency* measures (and particularly energy efficiency), there is a lack of understanding on how to also account for rebound effects originated from *efficiency–effectiveness–sufficiency* as key strategies for design for sustainability (Sorrell 2010), (Buhl & Acosta 2016).

The fundamental scientific gap is the lack of theoretical foundation to understand the underlying systemic mechanisms giving rise to rebound effects triggered by *efficiency, effectiveness* and *sufficiency* strategies (or, in other words, by the green growth and the degrowth paradigms) in a broader sustainability context (where economy is an integral element of society, within the environmental boundaries) (Griggs *et al.* 2013; Thatcher & Yeow 2016).

2.2 GAP 2: the influence of the counterintuitive behaviour of complex socio-technical systems in giving rise to rebound effects is not yet understood

More than 40 years of academic research and debate on rebound effects resulted on an array of conflicting views regarding the rebound effects' magnitude, causes, mechanisms, indicators and taxonomy (Font Vivanco *et al.* 2016; Madlener & Turner 2016; Sorrell *et al.* 2009).

Although the existence of rebound effects is widely acknowledged, studies that measure the magnitude of rebound effects are diverse with respect to definitions, boundaries, methodologies and data sources (Font Vivanco *et al.* 2016; Freire-González 2017; Sorrell *et al.* 2009). Furthermore, the majority of studies in the current literature are based on measuring realised rebound effects (ex-post) rather than on estimating potential rebound effects (ex-ante), pre-emptively (Giampietro & Mayumi 2018).

The existing methodological approaches for estimating the magnitude of rebound effects (e.g., quasi-experiments at the micro-level and econometrics at the macro-level) are limited and prone to bias, providing insufficient basis to draw general conclusions (Sorrell 2007). Quasi-experiments are often used to measure demand before and after the implementation of an efficiency measure (Sorrell *et al.* 2009), based on primary data often subjected to selection bias, small sample sizes, errors associated with estimates and too short monitoring periods to capture long-term effects. On the other extreme, econometric models are often employed with the use of secondary data (e.g., cross-sectional, panel data) and at different levels of aggregation (e.g., household, region and country). In many cases, nevertheless, data are either unavailable or inaccurate (Sorrell *et al.* 2009). Similar limitations are observed within other attempts to estimate the magnitude of rebound effects related to the use of consequential life cycle assessment (LCA) (Polizzi di Sorrentino *et al.* 2016) due to LCA's limitations in considering the dynamics of socio-technical systems within and across different life cycle phases (Niero *et al.* 2021).

The lack of a strong theoretical background results in up to 87% variation in the estimated magnitude of rebound effects (Sorrell *et al.* 2009). For example, in studies connected to personal car mobility, the estimated rebound effects range from 0 to 87% (Greening *et al.* 2000; Sorrell *et al.* 2009). Furthermore, the major gaps in qualitative and quantitative rebound effect research indicate that existing calculations reflect only a small fraction of the sum of rebound effects that actually occur (Santarius 2012).

Rebound effects are a complex phenomenon that needs to be tackled at the micro-, meso- and macro-levels (Madlener & Turner 2016). The size and impact of rebound effects are affected by changes in the system within which they arise (Freeman 2018). Nevertheless, current research focus is primarily on the micro- and macro-levels (Santarius 2016), targeted at identifying symptoms/events instead of identifying and managing underlying systemic causes (e.g., structural resistance to change, behavioural responses) (Polizzi di Sorrentino *et al.* 2016).

Currently, theoretical and empirical research mostly disregard that rebound effects are the result of complex mechanisms at play within different levels in the system, subject to dynamic interactions with causal links and responses (feedback loops) from socio-technical, behavioural and economic aspects over time (Laurenti *et al.* 2016; Saey-Volckrick 2020). The existing theoretical foundation is limited in understanding the range of systemic mechanisms governing rebound effects, and explaining the dynamics of socio-technical systems (Geels 2004) leading to counterintuitive system behaviour (Freeman *et al.* 2016; Madlener & Turner 2016). The narrow boundary of most rebound studies ignores causal processes underlying the wider complex systemic responses to sustainability interventions (Turner 2013), that is, the tendency for interventions to be defeated by the response of the system to the interventions itself (de Gooyert *et al.* 2016).

There is a need to consider the dynamics of rebound effects (Madlener & Turner 2016) by adopting a systemic view on structure and behaviour of the complex socio-technical systems (Van Den Bergh *et al.* 2011) that we are embedded in Achachlouei & Hilty (2014), Chen (2021), Dace *et al.* (2014), and Laurenti *et al.* (2016) – with the inclusion of socio-economic aspects, time and space considerations, as well as system boundaries at the micro-, meso- and macro-levels) (Fiksel *et al.* 2014). The lack of robust theoretical explanations of how and under which conditions rebound effects emerge (Santarius *et al.* 2016), and how different rebound effects affect each other within complex socio-technical systems (e.g., mobility) limits the prevention of rebound effects (Guzzo *et al.* 2023, 2024).

2.3 GAP 3: the bounded rationality within design limits the understanding of rebound effects at a broader systemic level

Design science (Broadbent 2004) aims at developing knowledge and scientific methodologies to support the design of interventions capable of solving "real-world" problems and improving conditions for humanity (Denyer *et al.* 2008). Design entails devising courses of action aimed at changing existing situations into preferred ones (Simon 1988), spanning across many disciplines (including, but not limited to engineering, architecture and urban planning) (de Oliveira *et al.* 2024).

Design for sustainability has traditionally focused on developing solutions with enhanced sustainability performance, mostly through the integration of *efficiency* (Pigosso *et al.* 2015) and (more recently) *effectiveness* strategies (Blomsma *et al.* 2019) in the early design stages (Laurenti *et al.* 2015), targeted at the minimisation of sustainability impacts (primarily environmental) across the product life cycle (Pigosso *et al.* 2014).

Over the past decades, the scope of design for sustainability has expanded from: (i) product design (where the focus is on enhancing the sustainability performance of existing products or developing new products which are intrinsically more sustainable) (Pigosso *et al.* 2015); to (ii) product/service-system design (focused on the development of integrated combinations of products and services through new business and ownership models, capable of decoupling value creation from resource consumption) (Kjaer *et al.* 2019). More recently, it is argued for the need to expand the scope of design for sustainability to a more systemic view, based on (iii) socio-technical system design, focused on promoting radical changes on how societal needs, such as mobility or healthcare, are fulfilled (Ceschin & Gaziulusoy 2016) (Figure 2, adapted from Ceschin & Gaziulusoy (2016)).

Currently, design for sustainability strategies (Pigosso *et al.* 2014) are mostly related to the development of products and product/service-systems and solely focused on maximising *efficiency* and *effectiveness*, disregarding the (negative and positive) consequences of design due to induced changes in system behaviour (Figure 1).

State-of-the-art lacks design strategies for systemic sustainability change (Gaziulusoy *et al.* 2013). One exception is the attempt to address economic rebound effects by means of eco-efficient value creation, measured through the eco-costs/value ratio (Hendriks *et al.* 2006). By reducing eco-costs (i.e., environmental impacts across the products' life cycle) and enhancing value (i.e., higher market price), there would be less disposable income to lead to direct, indirect and/or economy-wide rebound effects (Vogtländer *et al.* 2013). The method has been applied to cases such as the design of packaging (Wever & Vogtländer 2013), a smart temperature control for domestic heating (Scheepens & Vogtländer 2018) and a domestic street lighting system (Klaassen *et al.* 2020). Nevertheless, the focus is still on money-related

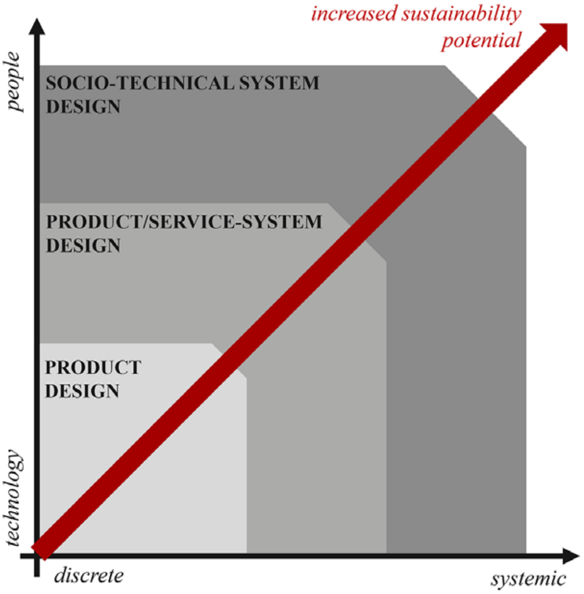

Figure 2. The evolution of design for sustainability, adapted from Ceschin & Gaziulusoy (2016).

rebound effects, and the large set of rebound effects occurring due to systemic behavioural changes are still not addressed.

Sustainability is still considered an abstract ultimate goal and not an inherent dynamic system property (Gaziulusoy & Brezet 2015). Furthermore, there is limited understanding of the role of the design process as a powerful leverage point at which to intervene in production and consumption systems (Randers 2000), despite the increased recognition that wider-scale systemic changes can be addressed by design (Gaziulusoy & Brezet 2015).

To be able to address current sustainability challenges (e.g., climate change and biodiversity loss), there is an urgent need to align design for sustainability practices taking place at micro- and meso-levels to the macro-level of socio-technical systems (Gaziulusoy & Brezet 2015). The boundaries of design for sustainability must be expanded towards a systemic view, in order to enable the influence on high leverage points to lead to significant, sustained and positive effects on sustainability performance (Guzzo *et al.* 2023). In other words, a systems approach for the design of sustainable solutions, capable of managing intrinsic system characteristics to improve its resilience and adaptability, is required (Fiksel 2003).

Despite the increased recognition of the need to drive sustainability change through the design of complex socio-technical systems and the dynamic complexity of rebound effects (Guzzo *et al.* 2023), the prevention of rebound effects (i.e., negative systemic consequences) and the reinforcement of secondary benefits (i.e., positive systemic consequences) is still unexplored due to the lack of a robust theoretical foundation at a systemic level.

This presents, therefore, a large and untapped research potential, which would allow to expand the boundaries of design science towards the design of systems that are resilient to rebound effects.

3. Towards reboundless design

The latest major paradigm shift within design for sustainability occurred in the 1990s, with the ground-breaking view of the need for life cycle thinking (Hauschild *et al.* 2020), as opposed to the dominant focus on cleaner production (1980s) and end-of-pipe-solutions (1970s). To tackle rebound effects and achieve sustainable development, science must further advance to enable the design of *reboundless* interventions (i.e., products, product/service-systems and socio-technical systems that are resilient to rebound effects) at a systemic level, enabling production and consumption systems that are capable to address societal needs within the planetary boundaries.

To be achieved, the design of *reboundless* solutions requires three major scientific advancements in the state-of-the-art:

(1) explanation of the systemic behavioural mechanisms giving rise to rebound effects triggered by *efficiency–effectiveness–sufficiency* design strategies;
(2) quantification of rebound effects emerging from the counterintuitive behaviour of complex socio-technical systems in the early design stages;
(3) prevention of rebound effects through the expansion of design science towards the avoidance of negative systemic consequences of design targeted at addressing system behaviour.

The expansion of the mental models within design science for the development of *reboundless* interventions will enable the transition to a new design for sustainability paradigm targeted at the systemic level, enabling the design of sustainable production and consumption systems that are resilient to rebound effects.

Reboundless design has, moreover, a high scientific multiplier potential, enabling, for example, the incorporation of rebound effects in sustainability impact assessment methodologies, such as LCA; the early identification of rebound effects of new technologies and the support for policymaking within sustainability transitions.

Acknowledgements

REBOUNDLESS is co-funded by the European Union (ERC, REBOUNDLESS, 101043931). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them.

References

Achachlouei, M. A. & **Hilty, L. M.** 2014 Modelling rebound effects in system dynamics. *EnviroInfo 2014, Proceedings of the 28th Conference on Informatics for Environmental Protection.*

Ackermann, L. & **Tunn, V. S. C.** 2024 Careless product use in access-based services: A rebound effect and how to address it. *Journal of Business Research* **177**, 114643. doi: 10.1016/j.jbusres.2024.114643.

Andrew, E. M., **van den Bergh, J.** & **Pigosso, D. C. A.** 2024 Uncovering rebound effects of sufficiency-oriented product-service systems: a systematic review. *Proceedings of the Design Society* **4**, 1189–1198. doi:10.1017/pds.2024.121.

Binswanger, M. 2001 Technological progress and sustainable development: what about the rebound effect?. *Ecologial Economics* **36** (1), 119–132. doi:10.1016/S0921-8009(00)00214-7.

Blok, V., **Long, T. B.**, **Gaziulusoy, A. I.**, **Ciliz, N.**, **Lozano, R.**, **Huisingh, D.**, **Csutora, M.** & **Boks, C.** 2015 From best practices to bridges for a more sustainable future: Advances and challenges in the transition to global sustainable production and consumption: Introduction to the ERSCP stream of the Special volume. *Journal of Cleaner Production*. doi:10.1016/j.jclepro.2015.04.119.

Blomsma, F., **Pieroni, M.**, **Kravchenko, M.**, **Pigosso, D. C. A.**, **Hildenbrand, J.**, **Kristinsdottir, A. R.**, **& Kristoffersen, E.** 2019 Developing a circular strategies framework for manufacturing companies to support circular economy-oriented innovation. *Journal of Cleaner Production* **241**, 118271. doi:10.1016/j.jclepro.2019.118271.

Bocken, N. & **Short, S.** 2016 Towards a sufficiency-driven business model: Experiences and opportunities. *Journal of Cleaner Production* **18**, 41–61. doi:10.1016/j.eist.2015.07.010.

Bressanelli, G., **Adrodegari, F.**, **Pigosso, D. C. A.** & **Parida, V.** 2022 Towards the smart circular economy paradigm: A definition, conceptualization, and research agenda. *Sustainability* **14** (9), 4960. doi:10.3390/su14094960.

Broadbent, J. 2004 A future for design science?. *International Symposium on Te Development and Prospects of a PhD Programme in Design Science Education.*, p. 16.

Buhl, J. & **Acosta, J.** 2016 Indirect effects from resource sufficiency behaviour in Germany. In *Rethinking Climate and Energy Policies: New Perspectives on the Rebound Phenomenon*, Springer International Publishing, pp. 37–54. doi:10.1007/978-3-319-38807-6_3.

Buhl, J., **von Geibler, J.**, **Echternacht, L.** & **Linder, M.** 2017 Rebound effects in Living Labs: Opportunities for monitoring and mitigating re-spending and time use effects in user integrated innovation design. *Journal of Cleaner Production* **151**, 592–602. doi:10.1016/j.jclepro.2017.03.001.

Ceschin, F. & **Gaziulusoy, I.** 2016 Evolution of design for sustainability: From product design to design for system innovations and transitions. *Design Studies* **47**, 118–163. doi:10.1016/j.destud.2016.09.002.

Chen, C. W. 2021 Clarifying rebound effects of the circular economy in the context of sustainable cities. *Sustainable Cities and Society*, **66**. doi:10.1016/j.scs.2020.102622.

Dace, E., **Bazbauers, G.**, **Berzina, A.** & **Davidsen, P. I. P. I.** 2014 System dynamics model for analyzing effects of eco-design policy on packaging waste management system. *Resources, Conservation and Recycling* **87**, 175–190. doi:10.1016/j.resconrec.2014.04.004.

de Gooyert, V., **Rouwette, E.**, **van Kranenburg, H.**, **Freeman, E.** & **van Breen, H.** 2016 Sustainability transition dynamics: Towards overcoming policy resistance. *Technological Forecasting and Social Change*. doi:10.1016/j.techfore.2016.06.019.

de Oliveira, I. C., **Guzzo, D.** & **Pigosso, D. C. A.** 2024 Feedback thought at the intersection of systems and design science. *Proceedings of the Design Society* **4**, 13–22. doi:10.1017/pds.2024.4.

Denyer, D., **Tranfield, D.** & **Van Aken, J. E.** 2008 Developing design propositions through research synthesis. *Organization Studies* **29** (3), 393–413. doi:10.1177/0170840607088020.

Ellen MacArthur Foundation. 2015 *Growth Within: A Circular Economy Vision for a Competitive Europe*. p. 100. Ellen MacArthur Foundation.

Exadaktylos, F. & **van den Bergh, J.** 2021 Energy-related behaviour and rebound when rationality, self-interest and willpower are limited. *Nature Energy* **6** (12), 1104–1113. doi:10.1038/s41560-021-00889-4.

Fernandes Aguiar, M., **Costa, J. M. H.** & **A. Pigosso, D. C.** 2023 How are emotional attachment strategies currently employed in product-service system cases? A systematic review underscoring drivers and hindrances. in Otto, K., Eisenbart, B., Eckert, C., Eynard, B., Krause, D. and Oehmen, J. Eds., *Proceedings of the International Conference on Engineering Design ICED23)*, **3**, Cambridge University Press2095–2104. doi:10.1017/pds.2023.210.

Figge, F. & **Thorpe, A. S.** 2019 The symbiotic rebound effect in the circular economy. *Ecological Economics* **163**, 61–69. doi:10.1016/j.ecolecon.2019.04.028.

Figge, F., **Young, W.** & **Barkemeyer, R.** 2014 Sufficiency or efficiency to achieve lower resource consumption and emissions? The role of the rebound effect. *Journal of Cleaner Production*. doi:10.1016/j.jclepro.2014.01.031.

Fiksel, J. 2003 Designing resilient, sustainable systems. *Environmental Science and Technology* **37** (23), 5330–5339. doi:10.1021/es0344819.

Fiksel, J., **Bruins, R.**, **Gatchett, A.**, **Gilliland, A.** & **Ten Brink, M.** 2014 The triple value model: A systems approach to sustainable solutions. *Clean Technologies and Environmental Policy*. doi:10.1007/s10098-013-0696-1.

Font Vivanco, D., **McDowall, W.**, **Freire-González, J.**, **Kemp, R.** & **van der Voet, E.** 2016 The foundations of the environmental rebound effect and its contribution towards a general framework. *Ecological Economics* **125**, 60–69. doi:10.1016/j.ecolecon.2016.02.006.

Freeman, R. 2018 A theory on the future of the rebound effect in a resource-constrained world. *Frontiers in Energy Research* **6** (Aug), 81. doi:10.3389/fenrg.2018.00081.

Freeman, R., **Yearworth, M.** & **Preist, C.** 2016 Revisiting Jevons' Paradox with System Dynamics: Systemic Causes and Potential Cures. *Journal of Industrial Ecology* **20** (2), 341–353. doi:10.1111/jiec.12285.

Freire-González, J. 2017 Evidence of direct and indirect rebound effect in households in EU-27 countries. *Energy Policy* **102**, 270–276. doi:10.1016/J.ENPOL.2016.12.002.

Gaziulusoy, A. I., **Boyle, C.** & **McDowall, R.** 2013 System innovation for sustainability: A systemic double-flow scenario method for companies. *Journal of Cleaner Production*. doi:10.1016/j.jclepro.2012.05.013.

Gaziulusoy, A. I. & **Brezet, H.** 2015 Design for system innovations and transitions: A conceptual framework integrating insights from sustainablity science and theories of system innovations and transitions. *Journal of Cleaner Production*. doi:10.1016/j.jclepro.2015.06.066.

Geels, F. W. 2004 From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. *Research Policy* **33** (6–7), 897–920. doi:10.1016/j.respol.2004.01.015.

Giampietro, M. & **Mayumi, K.** 2018 Unraveling the complexity of the Jevons Paradox: The link between innovation, efficiency, and sustainability. *Frontiers in Energy Research* **6** (April), 1–13. doi:10.3389/fenrg.2018.00026.

Greening, L. a., **Greene, D. L.** & **Difiglio, C.** 2000 Energy effciency and consumption - the rebound effect - a survey. *Energy Policy*, **28** (6–7), 389–401. doi:10.1016/S0301-4215(00)00021-5.

Greening, L. & **Greene, D.** 1998 Energy use, technical efficiency, and the rebound effect: A review of the literature. *Annual Conference of the International-Association-for-Energy-Economics IAEE*, pp. 321–330.

Griggs, D., **Stafford-Smith, M.**, **Gaffney, O.**, **Rockström, J.**, **Öhman, M. C.**, **Shyamsundar, P., & Steffen, W.**2013 Sustainable development goals for people and planet. *Nature* **495** (7441), 305–307. doi:10.1038/495305a.

Guzzo, D. & **Pigosso, D. C. A.** 2024 Identifying rebound effects in product-service systems: actors, mechanisms, triggers and drivers. *Proceedings of the Design Society*,**4**, 1279–1288. doi:10.1017/pds.2024.130.

Guzzo, D., **Walrave, B.** & **Pigosso, D. C. A.** 2023 Unveiling the dynamic complexity of rebound effects in sustainability transitions: Towards a system's perspective. *Journal of Cleaner Production* **405**. doi:10.1016/j.jclepro.2023.137003.

Guzzo, D., **Walrave, B.**, **Videira, N.**, **Oliveira, I. C.** & **Pigosso, D. C. A.** 2024 Towards a systemic view on rebound effects: Modelling the feedback loops of rebound mechanisms. *Ecological Economics* **217**. doi:10.1016/j.ecolecon.2023.108050.

Hauschild, M. Z., **Kara, S.** & **Røpke, I.** 2020 Absolute sustainability: Challenges to life cycle engineering. *CIRP Annals* **69** (2), 533–553. doi:10.1016/j.cirp.2020.05.004.

Hendriks, F., **Vogtländer, J. G.** & **Janssen, G. M. T.** 2006 The eco-costs/value ratio: A tool to determine the long-term strategy for delinking economy and environmental ecology. *International Journal of Ecodynamics* **1** (2), 136–148. doi:10.2495/ECO-V1-N2-136-148.

Hertwich, E. G. 2005 Consumption and the rebound effect: An industrial ecology perspective. *Journal of Industrial Ecology* **9** (1–2), 85–98. doi:10.1162/1088198054084635.

Jevons, W. S. 1865 *Coal Question; An Inquiry Concerning the Progress of the Nation, and the Probable Exhaustion of Our Coal Mines*, Macmillan & Co.

Kjaer, L. L., **Pigosso, D. C. A.**, **Niero, M.**, **Bech, N. M.** & **McAloone, T. C.** 2019 Product/service-systems for a circular economy: The route to decoupling economic growth from resource consumption?. *Journal of Industrial Ecology* **23** (1), 22–35. doi:10.1111/jiec.12747.

Klaassen, N., **Scheepens, A.**, **Flipsen, B.** & **Vogtlander, J.** 2020 Eco-efficient value creation of residential street the value, the costs and the eco-costs during the design and engineering phase. *Energies*. doi:10.3390/en13133351.

Laurenti, R., **Singh, J.**, **Sinha, R.**, **Potting, J.** & **Frostell, B.** 2016 Unintended environmental consequences of improvement actions: A qualitative analysis of systems' structure and behavior. *Systems Research and Behavioral Science* **33** (3), 381–399. doi:10.1002/sres.2330.

Laurenti, R., **Sinha, R.**, **Singh, J.** & **Frostell, B.** 2015 Some pervasive challenges to sustainability by design of electronic products - A conceptual discussion. *Journal of Cleaner Production* **108**, 281–288. doi:10.1016/j.jclepro.2015.08.041.

Lorek, S. & **Spangenberg, J. H.** 2014 Sustainable consumption within a sustainable economy - Beyond green growth and green economies. *Journal of Cleaner Production* **63**, 33–44. doi:10.1016/j.jclepro.2013.08.045.

Maccioni, L., **Borgianni, Y.** & **Pigosso, D. C. A.** 2019 Can the choice of eco-design principles affect products' success? *Design Science* **5**. doi:10.1017/dsj.2019.24.

Madlener, R. & **Turner, K.** 2016 After 35 years of rebound research in economics: Where do we stand?. In *Rethinking Climate and Energy Policies: New Perspectives on the Rebound Phenomenon*, Springer International Publishing, pp. 17–36. doi:10.1007/978-3-319-38807-6_2.

Metic, J., **Guzzo, D.**, **Kopainsky, B.**, **McAloone, T. C.** & **Pigosso, D. C. A.** 2024 A simulation-based approach for investigating the dynamics of rebound effects in the circular economy: A case of use-oriented product/service system. *Journal of Environmental Management* **365**, 121627. doi:10.1016/j.jenvman.2024.121627.

Metic, J. & **Pigosso, D.** 2022 Research avenues for uncovering the rebound effects of the circular economy: A systematic literature review. *Journal of Cleaner Production* **368**. doi:10.1016/j.jclepro.2022.133133.

Niero, M., **Jensen, C. L.**, **Fratini, C. F.**, **Dorland, J.**, **Jørgensen, M. S.** & **Georg, S.** 2021 Is life cycle assessment enough to address unintended side effects from circular economy initiatives? *Journal of Industrial Ecology* 13134. doi:10.1111/jiec.13134.

Ottelin, J., **Cetinay, H.** & **Behrens, P.** 2020 Rebound effects may jeopardize the resource savings of circular consumption: evidence from household material footprints. *Environmental Research Letters* **15**, 104044. doi:10.1088/1748-9326/abaa78.

Pieroni, M. P., **McAloone, T. C.**, **Borgianni, Y.**, **Maccioni, L.** & **Pigosso, D. C. A.** 2021 An expert system for circular economy business modelling: advising manufacturing companies in decoupling value creation from resource consumption. *Sustainable Production and Consumption* **27**, 534–550. doi:10.1016/j.spc.2021.01.023.

Pigosso, D. & **McAloone, T.** 2017 How can design science contribute to a circular economy? *Proceedings of the International Conference on Engineering Design, ICED* **5**, 299–307.

Pigosso, D. C. A., **McAloone, T. C.** & **Rozenfeld, H.** 2014 Systematization of best practices for ecodesign implementation. *Proceedings of International Design Conference, DESIGN*, pp. 1651–1662.

Pigosso, D. C. A., **McAloone, T. C.** & **Rozenfeld, H.** 2015 Characterization of the state-of-the-art and identification of main trends for Ecodesign Tools and Methods: classifying three decades of research and implementation. *Journal of the Indian Institute of Science* **95** (4), 405–427.

Polizzi di Sorrentino, E., **Woelbert, E.** & **Sala, S.** 2016 Consumers and their behavior: state of the art in behavioral science supporting use phase modeling in LCA and ecodesign. *International Journal of Life Cycle Assessment* **21** (2), 237–251. doi:10.1007/s11367-015-1016-2.

Randers, J. 2000 From limits to growth to sustainable development or SD sustainable development) in a SD system dynamics) perspective. *System Dynamics Review* **16** (3), 213–224. doi:10.1002/1099-1727(200023)16:3<213::AID-SDR197>3.0.CO;2-E.

Saey-Volckrick, J. 2020 What does the rebound effect tell us? Reflection on its sources and its implication for the sustainability debate. In *Sustainability and Law*, Springer International Publishing, pp. 103–118. doi:10.1007/978-3-030-42630-9_7.

Sandberg, M. 2021 Sufficiency transitions: A review of consumption changes for environmental sustainability. *Journal of Cleaner Production* doi:10.1016/j.jclepro.2021.126097.

Santarius, T. 2012 Green Growth Unravelled: How rebound effects baffle sustainability targets when the economy keeps growing. In *The Handbook of Global Climate and Environment Policy*. Heinrich Böll Foundation, Wuppertal Institute for Climate, Environment and Energy https://www.greenpolicyplatform.org/research/green-growth-unravelled-how-rebound-effects-baffle-sustainability-targets-when-economy

Santarius, T. 2016 Production-side effects and feedback loops between the micro and macro level. In *Rethinking Climate and Energy Policies: New Perspectives on the Rebound Phenomenon*, Springer International Publishing, pp. 73–86. doi:10.1007/978-3-319-38807-6_5.

Santarius, T. & **Soland, M.** 2018 How technological efficiency improvements change consumer preferences: Towards a psychological theory of rebound effects. *Ecological Economics* **146**, 414–424. doi:10.1016/J.ECOLECON.2017.12.009.

Santarius, T., **Walnum, H. J.** & **Aall, C.** 2016 Introduction: Rebound research in a warming world. In *Rethinking Climate and Energy Policies: New Perspectives on the Rebound Phenomenon*, Springer International Publishing, 1–14. doi:10.1007/978-3-319-38807-6_1.

Sarancic, D., **Metic, J.**, **Pigosso, D. C. A.** & **McAloone, T. C.** 2023 Impacts, synergies, and rebound effects arising in combinations of Product-Service Systems PSS) and circularity strategies. *Procedia CIRP* **116**, 546–551. doi:10.1016/j.procir.2023.02.092.

Scheepens, A. E. & **Vogtländer, J. G.** 2018 Insulation or smart temperature control for domestic heating: A combined analysis of the costs, the eco-costs, the customer perceived value, and the rebound effect of energy saving. *Sustainability* **10** (9), 1–24. doi:10.3390/su10093231.

Sekulova, F., **Kallis, G.**, **Rodríguez-Labajos, B.** & **Schneider, F.** 2013 Degrowth: From theory to practice. *Journal of Cleaner Production* **38**, 1–6. doi:10.1016/j.jclepro.2012.06.022.

Shove, E. 2018 What is wrong with energy efficiency?. *Building Research and Information* **46** (7), 779–789. doi:10.1080/09613218.2017.1361746.

Simon, H. A. 1988 The science of design: Creating the artificial. *Design Issues* **4** (1/2), 67. doi: 10.2307/1511391.

Sorell, S. 2010 *Mapping Rebound Effects from Sustainable Behaviours: Key Concepts and Literature Review*, Brighton, Sussex.

Sorrell, S. 2007 *The rebound effect: An assessment of the evidence for economy-wide energy savings from improved energy efficiency*. UK Research Centre ISBN 1-903144-0-35 https://d2e1qxpsswcpgz.cloudfront.net/uploads/2020/03/the-rebound-effect-an-assessment-of-the-evidence-for-economy-wide-energy-savings-from-improved-energy-efficiency.pdf

Sorrell, S. 2009 Jevons' Paradox revisited: The evidence for backfire from improved energy efficiency. *Energy Policy* **37** (4), 1456–1469. doi:10.1016/j.enpol.2008.12.003.

Sorrell, S. 2010 Energy, economic growth and environmental sustainability: Five propositions. *Sustainability* **2** (6), 1784–1809. doi:10.3390/su2061784.

Sorrell, S., **Dimitropoulos, J. and Sommerville, M.** 2009 Empirical estimates of the direct rebound effect: A review. *Energy Policy* **37** (4), 1356–1371. doi:10.1016/j.enpol.2008.11.026.

Sorrell, S., **Gatersleben, B.** & **Druckman, A.** 2020 The limits of energy sufficiency: A review of the evidence for rebound effects and negative spillovers from behavioural change. *Energy Research and Social Science* **64**. 10.1016/j.erss.2020.101439.

Tanneurs, H. & **Vezzoli, C.** 2008 Sustainable consumption and production : Framework for action. In *2nd Conference of the Sustainable Consumption Research Exchange SCORE!) Network*.

Thatcher, A. & **Yeow, P. H. P.** 2016 A sustainable system of systems approach: a new HFE paradigm. *Ergonomics*. doi:10.1080/00140139.2015.1066876.

Turner, K. 2013 'Rebound' effects from increased energy efficiency: A time to pause and reflect. *Energy Journal*, **34** (4), 18. doi:10.5547/01956574.34.4.2.

Van Den Bergh, J. C. J. M., **Truffer, B.** & **Kallis, G.** 2011 Environmental innovation and societal transitions: Introduction and overview. *Environmental Innovation and Societal Transitions* **1** (1), 1–23. doi:10.1016/j.eist.2011.04.010.

Van der Loo, I. & **Pigosso, D. C. A.** 2024 Explaining the rebound effects of sustainable design: a behavioural perspective. In *Proceedings of the Design Society*, Cambridge University Press.

Vilochani, S., **Mcaloone, T. C.** & **Pigosso, D. C. A.** 2024 Consolidation of management practices for Sustainable Product Development: A systematic literature review. *Sustainable Production and Consumption* **45**, 115–125. doi:10.1016/j.spc.2024.01.002.

Vogtländer, J. G., **Mestre, A. C. M.**, **van der Helm, R. M.**, **Scheepens, A. E.** & **Wever, R.** 2013. *Eco-Efficient Value Creation, Sustainable Design and Business Strategies*, 1st ed. Delft Academic Press.

Von Weiszäcker, E. U. & **Ayres, R. U.** 2013 Boosting resource productivity: Creating ping-pong dynamics between resource productivity and resource prices. *Environmental Innovation and Societal Transitions*. doi:10.1016/j.eist.2013.09.001.

Weidema, B. P. 2008 Rebound effects of sustainable production. *Bridging the Gap; Responding to Environmental Change – From Words to Deeds*, Portorož, Slovenia, p. 5.

Wever, R. & **Vogtländer, J. G.** 2013 Eco-efficient value creation: An alternative perspective on packaging and sustainability. *Packaging and Technology and Science* **29**, 229–248. doi:10.1002/pts.

Wolstenholme, E. F. 2003 Towards the definition and use of a core set of archetypal structures in system dynamics. *System Dynamics Review* **19** (1), 7–26. doi:10.1002/sdr.259.

Zink, T. and Geyer, R. 2017 Circular economy rebound. *Journal of Industrial Ecology* **21** (3), 593–602. doi:10.1111/jiec.12545.