Unveiling the dynamic complexity of rebound effects in sustainability transitions

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Review

Unveiling the dynamic complexity of rebound effects in sustainability transitions: Towards a system's perspective

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A R T I C L E I N F O

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A B S T R A C T

Rebound effects (RE) are systemic responses to sustainability-oriented actions that have relentlessly offset the anticipated effects, hindering sustainability transitions. Limitations to account for feedback, delays, and non-linearities hinder a deep understanding of RE, leading to divergent magnitude estimates and management recommendations. Therefore, a better understanding of the dynamic complexity surrounding RE occurrence is needed. Dynamic complexity manifests from the feedback relationships between system elements and how they change over time. This work aims to enhance the understanding of RE's causal and dynamic traits, following system dynamics (SD) as the investigation frame. Based on a literature review, 24 RE-specific dynamic complexities were identified and further categorised following the Iceberg model, which deepens into the causes of RE occurrence, providing additional leverage to prevent or mitigate them. The RE-specific dynamic complexities are then explored in case studies investigating RE through SD, which sustains three propositions for moving forward in RE investigations. This work sets the foundation for enabling less deterministic examinations of RE, capable of reaching recommendations that consider the true nature of the phenomenon.

1. Introduction

Driven by the ultimate goal of reaching societal development within the planetary boundaries (Steffen et al., 2015), sustainability transitions are being carried out on a wide range of fronts: from the renewable energy transition to the implementation of a Circular Economy (CE) (Circle Economy, 2022; Markard et al., 2020; UNEP, 2021). From the energy transition side, although improved energy efficiency has been on the agenda of policy-makers and companies, there are no signs that growth in global energy consumption is slowing down or decoupling from economic growth (Brockway et al., 2021). Additionally, the world is still only 7.2% circular, meaning that only 7.2% of the total yearly material inputs in the economy rely on secondary materials cycled back as input (Circle Economy, 2023). Therefore, despite global efforts towards sustainability, the total Greenhouse Gases (GHG) emissions are still rising (UNEP, 2021).

The disarray between sustainability-oriented actions and the expected reduction in resource use (such as energy and material) is partially explained by the so-called Rebound Effects (RE). Following Hertwich (2005), we define RE as systemic responses to measures designed to enhance sustainability outcomes that partially or entirely offset the measure's intended effects. Three main types of mechanisms determine RE: direct, indirect, and macro-economic (Font-Vivanco et al., 2016; Greening et al., 2000). Empirical studies estimate that direct and indirect RE undermine ca. 20–40% of the intended benefits (Gillingham et al., 2016), while economy-wide RE undermine at least 50% of the intended benefits (Brockway et al., 2021). Nevertheless, much of the findings around RE occurrence and estimations are still limited, contradictory and controversial (Madlener and Turner, 2016). Researchers tend to follow simplistic views based on the relation between the output and input of a system (Giampietro and Mayumi, 2018), as opposed to seeking the underlying causes of RE (e.g., structural resistance to change, behavioural responses) (Font-Vivanco et al., 2018; Polizzi di Sorrentino et al., 2016; Thiesen et al., 2008; Weidema, 2008). In addition, the existing tools are usually biased toward addressing a specific perspective (Madlener and Turner, 2016) and fail to account for the feedback, non-linearities and delays among system elements leading to RE (Brockway et al., 2021; Colmenares et al., 2020). Thus, there is a need for a systemic perspective towards understanding the complexity surrounding RE (Madlener and Turner, 2016).

Abbreviations: CE, Circular Economy; CLD, Causal Loop Diagram; RE, Rebound Effect; SFD, Stock and Flow Diagram; SD, System Dynamics.

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Increased dynamic complexity is a recurrent argument for the persistence of problems over time, as the incapacity to account for the feedback, non-linearities and delays in systems leads to systemic responses that offset the measures' pursued effects (Sterman, 2000, 2001). By failing to understand the role of dynamic complexities giving rise to RE, one might find different RE magnitudes depending on the moment of measurement or even fail to encounter the effects of specific mechanisms altogether. Furthermore, stand-alone percentages of RE are not enough to draw meaningful understanding and make recommendations (Colmenares et al., 2020). Thus, a more thorough understanding of the reasons for RE persistence encompasses dealing with causality and the sources of complexity.

Therefore, this work aims to enhance the understanding of RE's causal and dynamic traits. System Dynamics (SD) is set as the investigation frame because it holds philosophical and methodological lenses that allow for a better understanding of the dynamic complexity of systems (Sterman, 2001). Furthermore, SD enables learning about the causal structure of systems and potential behaviour over time through conceptual modelling and differential equation simulation models (Sterman, 2000). The research applies a systematic literature review combining deductive and inductive content analyses and is built upon three research questions (RQ) to achieve its goal.

- RQ1 – What dynamic complexities manifest in systems leading to RE?
- RQ2 – How have SD investigations tackled the complexity of the RE phenomenon so far?
- RQ3 – How can SD be further used to address the dynamic complexities in RE investigations?

This work is positioned alongside a few recent review studies that contribute to RE understanding and mitigation in different ways. For instance, some studies have consolidated findings from empirical estimates of RE to assert modelling choices from an energy economics perspective (Brockway et al., 2021; Colmenares et al., 2020). Others have provided more comprehensive typologies of RE to help their identification(Lange et al., 2021; Metic et al., 2022). Moreover, a few reviews aimed at integrating areas such as CE (Castro et al., 2022; Metic et al., 2022) and industrial ecology (Reimers et al., 2021), expanding an energy-oriented perspective on the RE phenomenon. Finally, some reviews investigated behavioural and social aspects in decision-making that can lead to RE (Exadaktylos & van den Bergh, 2021; Reimers et al., 2021). These review studies show a substantial intensification of the importance of understanding and resolving RE. Although the reviews investigated and contributed to the phenomenon from multiple angles, there are still critical open angles — specifically related to the strong indications of the limitations of the dominating approaches in accounting for the dynamic complexity that arises from feedback, delays, and non-linearities in RE investigations.

This work sets the foundation for more systemic approaches to investigating RE in several ways. First, this work systematically identifies the dynamic complexities (i.e., factors that increase interrelationships or alter the temporal interaction of system elements (Grösser, 2017; Senge, 1990)) surrounding the RE phenomenon by eliciting and organising 24 specific dynamic complexities. Second, it deepens the understanding of the phenomena from events and patterns of behaviour to the structures and mental models, by organising the RE-specific dynamic complexities according to the Iceberg model (Davelaar, 2021; Kim, 2000). Third, this work explores six documented cases to enhance the awareness of the specific sources of complexity and how they have been addressed, which will enable designing investigations that consider those factors and reach more meaningful insights into tackling RE. Finally, three avenues for moving forward in RE investigations through SD are proposed. Overall, this work makes tangible how a system perspective can address the complexity surrounding RE.

2. Research methodology

In response to the first research question (RQ1), we draw on a Systematic Literature Review (SLR) (Thomé et al., 2016) using the following search string: TITLE ("rebound*" OR "Jevons paradox" OR "unintended consequence*" OR "unanticipated consequence*" OR "unexpected consequence*" OR "policy resistance" OR "second-order effect*" OR "boomerang effect*" OR "ripple effect* OR backfire) AND TITLE, ABSTRACT AND KEYWORDS (sustain* OR circular OR energy OR resource* OR environment* OR emission* OR ecolog*). This string ensured a broad consideration of the RE phenomenon by including keywords often used interchangeably as rebound, Jevons' paradox and backfire. At the same time, it helped narrow down to sustainability-related phenomena, as unintended and unanticipated consequences are also employed in other research areas such as medicine and political sciences. To keep the research manageable, we opt to include only review studies in the systematic literature identification.

In total, 66 review studies were identified through the search in Scopus and Web of Science (carried out in July 2022). Only review studies explicitly addressing RE as the primary unit of analysis (i.e., within sustainability and related areas) were considered, resulting in the selection of 17 studies for further analysis. Co-citation analysis (Boyack and Klavans, 2010; Eck and Waltman, 2014) and snowballing (Wohlin, 2014) enabled the identification of 17 additional influential studies in the RE discourse, resulting in the analysis of 34 studies in total.

The research followed a deductive-inductive content analysis procedure to analyse the dynamic complexity in RE (RQ1) (Elo and Kyngäs, 2008; Hsieh and Shannon, 2005). More specifically, the following steps were deployed.

- Step 1 - Deductive analysis: identification of dynamic complexity factors described in the RE literature (based on Grösser, 2017; Senge, 1990) and further categorisation according to the characteristics of complex systems as proposed by Sterman (2000) – see Table 1.
- Step 2 - Inductive analysis: categorising and clustering similar sources of complexity, resulting in a consolidated understanding of the dynamic complexities of RE.
- Step 3 - Deductive content analysis: categorising sources of complexity according to the iceberg model (Davelaar, 2021; Kim, 2000), which, by analogy, connects the different levels of thinking from the observable events on the surface to the patterns of

Table 1
The dynamic complexities of systems.

Dynamic complexities of systems	Definition following Sterman (2000)
Policy resistant	Many obvious solutions fail or worsen the situation.
Constantly changing	All is changing. System change occurs at many scales, and these different scales sometimes interact.
Tightly coupled	Everything is connected. The actors in the system actively interact with one another and the natural world.
Governed by feedback	One's decisions alter the situation, triggering change and action, giving rise to a new situation which then influences one's subsequent decisions.
Non-linear	The effect is rarely proportional to the cause. Non-linearities often arise due to internal delays and multiple influencing factors.
Counter-intuitive	Causes and effects are distant in time and space, hindering learning. As a result, we commonly focus on the events rather than the underlying causes.
Adaptive	The capabilities and decision rules of agents change over time. Agents evolve and learn over time.
Self-organising	The dynamics of a system arise from its internal structure. Small perturbations are amplified, generating patterns of behaviour.
History-dependent	Previous decisions define the set of decisions available now. Doing and undoing have fundamentally different dynamics.

behaviour, underlying structures and mental models which are often out of sight of the human mind (see Fig. 1).

In response to the second research question (RQ2), six documented case studies that employed SD to tackle the dynamic complexities of RE were analysed. The following criteria determined the inclusion of a study: (1) an explicit sustainability purpose; (2) it must account for a RE. Studies that did not depart from an action holding sustainability purpose

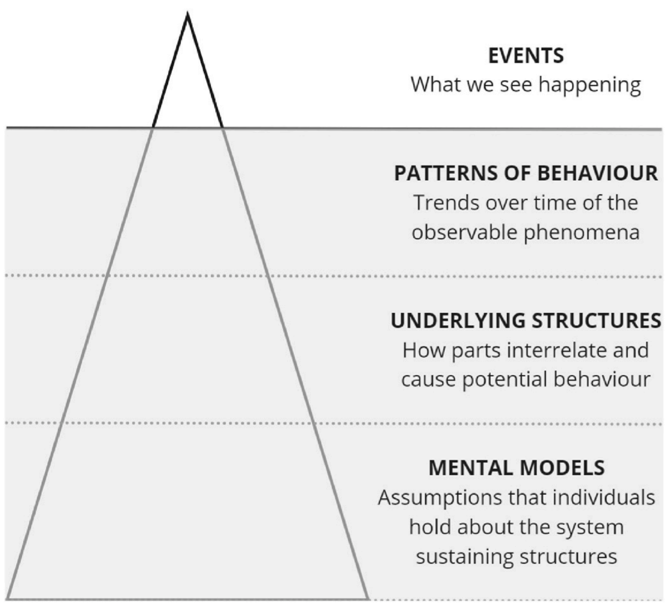

Fig. 1. The Iceberg model making explicit four different levels of understanding – adapted from (Davelaar, 2021; Kim, 2000).

or that dealt with only other "side effects" were disregarded. First, the studies were described as to the framing of the investigation and the explanation, assessment, and recommendations about RE. Then, a deductive content analysis (Elo and Kyngäs, 2008; Hsieh and Shannon, 2005) using the RE-specific dynamic complexities (RQ2) enabled the identification of the dynamic complexities that have been tackled in the studies.

Finally, the third research question (RQ3) was addressed by a critical reflection on the gap between the identified dynamic complexities in systems leading to RE (RQ1) and the insofar use of SD to address dynamic complexities in RE studies (RQ2).

Fig. 2 depicts the steps taken to respond to the three RQ posed for the study. The conceptual framework for the dynamic complexities in systems leading to RE (RQ1), the analysis of the use of SD to investigate RE (RQ2), and the research agenda for SD-based RE investigation (RQ3) are respectively described in sections 3, 4, and 5.

3. A conceptual framework for the RE-specific dynamic complexities

This section contains the conceptual framework for the dynamic complexities in systems leading to RE is two formats. First, section 3.1 contains the RE-specific dynamic complexities identified, connected to the evidence found in the literature and following the characteristics of complex systems (Sterman, 2000). Then, section 3.2 contains the categorisation of the RE-specific dynamic complexities following the Iceberg model (Davelaar, 2021; Kim, 2000), making the four different levels of thinking explicit.

3.1. RE-specific dynamic complexities in the literature

Table 2 summarises the 24 specific sources of dynamic complexities leading to RE following the nine characteristics of complex systems. Each specific source of dynamic complexity is described in the following

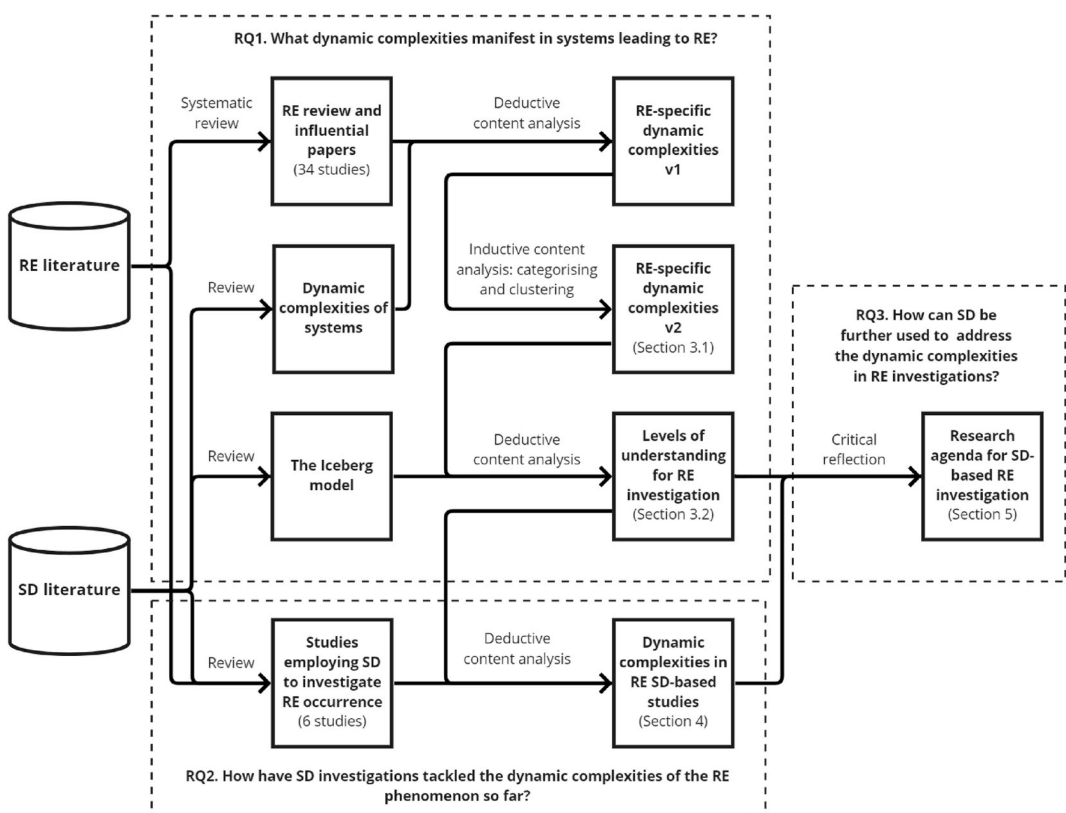

Fig. 2. Research steps to respond to the two research questions.

nine sub-sections.

3.1.1. Policy-resistant systems

Policy-resistant systems are those in which seemingly obvious solutions might fail or worsen the situation (Sterman, 2000). In the first place, economic and behavioural **systemic responses to well-intended sustainability-oriented actions lead to RE (PR1)** (Hertwich, 2005; Lange et al., 2021; van den Bergh, 2011). The collections of RE mechanisms in literature comprehend several economic, behavioural, time-related, and other responses to well-intended actions (Colmenares et al., 2020; Lange et al., 2021; Metic et al., 2022). For example, while a car-sharing solution might decrease the stock of cars required to support the needs of a given user group, RE might occur when users (a) spend additional income on other services (economic response); or (b) take less care of the shared cars (behavioural response). Such responses are why sustainability-oriented action (in this case, a car-sharing system) may not reach its full potential.

As a relative measure, **RE hold different magnitudes and directions (PR2)**. For example, RE might offset or reinforce the expected impact of the action (Binswanger, 2001). Saunders (2008) defined five-point graduation: (1) super-conservation leads to more positive impacts than expected; (2) zero RE leads to no offset; (3) partial RE offsets a portion of the intended impact; (4) full RE offsets the whole intended impact; and (5) backfire leads to a worse situation than before the action. Several studies investigate the magnitude of RE (Brockway et al., 2021; Colmenares et al., 2020; Lange et al., 2021) and show substantial RE magnitudes, even presenting cases that backfired. The magnitudes are, thus, the outcomes of the systemic responses to the expected impacts of the action.

Decision-makers holding a narrow view of the system fail to identify RE ex-ante (PR3) as they often make estimations based on systematic bias and wrong assumptions (Friedrichsmeier and Matthies, 2015). Decision-makers often assume that actions aiming for better resource use will translate straightforwardly into lower energy use and GHG emissions, implicitly assuming RE equals zero and treating essential system elements as exogenous (Madlener and Alcott, 2009; Sorrell et al., 2020). A common assumption is that focusing on the impacts of a single unit (e.g., one car, one phone) will lead to more efficient systems, causing decision-makers to ignore critical feedback, leading to RE (Font-Vivanco et al., 2016; Laurenti et al., 2016). For instance, more efficient heating systems might lead users to leave their windows open to enable air circulation, leading to additional energy usage (Sonnberger and Gross, 2018). In this case, focusing only on the heating system's efficiency can hinder designers from seeing the other potential system responses.

The last policy-resistant characteristic of systems leading to RE addresses the mitigation of RE. **Preventing or mitigating RE requires a deep understanding of their causes (PR4)**. Decision-makers should be educated to understand RE mechanisms to help identify and potentially avoid or mitigate them (Lange et al., 2021; Madlener and Turner, 2016). Although several recommendations are available to address RE in literature (Binswanger, 2001; Castro et al., 2022; Colmenares et al., 2020; Exadaktylos & van den Bergh, 2021; Greening et al., 2000), it is critical to acknowledge that the actions to resolve RE might also cause new ones to occur (Colmenares et al., 2020). Thus, preparing decision-makers to see the potential unintended consequences of actions is very important to prevent or mitigate RE.

3.1.2. Constantly changing systems

Constantly changing systems are those where change occurs at many scales, which sometimes interact (Sterman, 2000). To begin with, RE are outcomes of constantly changing systems as **RE occur in systems at the micro, meso, and macro levels (CC1)**. Sustainability transitions might focus on systems holding different aggregation levels (Castro et al., 2022), such as improving the sustainability potential of a device, an industrial process, the business model of a company, or a socio-technical transformation. Thus, there are different scopes to frame the investigation of a system prone to RE (Greening et al., 2000; Santarius, 2016; Sorrell, 2009; van den Bergh, 2011): micro (e.g., households and firms), meso (e.g., cities, industrial parks and sectors), macro (e.g., nations, cross-national regions and the whole world). The scope set for a given analysis inevitably constrain investigating effects beyond those limits (Santarius, 2015). From one side, micro-level investigations are critical as they can help understand the behaviour of individuals and firms leading to consumption and production patterns (Santarius, 2016; Trincado et al., 2021). On the other side, assessing RE at higher levels may integrate the global markets for resources and account for an extended set of interactions and feedback (Madlener and Alcott, 2009; Santarius, 2016; van den Bergh, 2011). Thus, framing different system levels might enable recognising different dynamics and RE.

In addition, **systems leading to RE are nested and interrelated (CC2).** Giampietro and Mayumi (2018) use the concept of holons (i.e., a whole made of smaller parts and a part of some greater whole simultaneously) to argue that systems on different levels are nested and interrelated and where changes in one level might also result in changes in other levels (Giampietro and Mayumi, 2018). Thus, when aggregating RE at different levels (Gillingham et al., 2013; Santarius, 2016), one must avoid the "fallacy of double counting" (Lange et al., 2021). The different mechanisms for RE interact, leading to combined effects (Brockway et al., 2021; Gillingham et al., 2013, 2016; Lange et al., 2021). For instance, the composition effect (i.e., changes in production factors across the value chain due to efficiency improvements) amplifies the substitution effect (i.e., changes in production factors for each producer) (Santarius, 2016). Also, RE mechanisms in higher aggregation levels might share similar underlying mechanisms with those in lower levels with an adding, subtracting, or multiplying contribution (Lange et al., 2021). Moreover, there might be feedback loops between higher and lower levels (Lange et al., 2021). Therefore, the combined effect in higher levels might be of greater or smaller magnitude than summing its parts (Brockway et al., 2021; Gillingham et al., 2013; Lange et al., 2021).

3.1.3. Tightly coupled systems

Tightly coupled systems manifest dynamic complexity from active interaction between actors and the natural world (Sterman, 2000). First, RE are an outcome of tightly coupled systems as **the interaction of agents holding multiple interests in the system leads to their occurrence (TC1)**. Policymakers (i.e., agents designing public policies), business decision-makers (i.e., agents translating the public policies into business policies or departing from innovation efforts), and consumers (i.e., agents making consumption decisions) perform the actions leading to production, consumption and RE (Colmenares et al., 2020; Greening et al., 2000). Thus, business and public policies must be capable of targeting the multiple objectives of these actors and dealing with the delicate trade-offs emerging from a multi-stakeholder system where the occurrence of RE is one aspect to consider (Castro et al., 2022; Colmenares et al., 2020; Friedrichsmeier and Matthies, 2015; Madlener and Turner, 2016). In addition, some actors may welcome RE (Santarius, 2015). For instance, policymakers may selectively consider the reaction of measures that might lead to RE (e.g., job creation, rural community development, and reduction of energy poverty) to show their potential additional economic benefits, using them as arguments (Hertwich, 2005; Trincado et al., 2021; Weidema, 2008). The indication of selective consideration might mean that decision-makers seek more thoroughly the beneficial higher-order effects of action than the detrimental ones.

Second, interacting with the natural world unfolds into additional stakes to address. Thus, **RE understanding requires addressing the multidimensionality of sustainability outcomes (TC2)**. Several authors argue that RE is not only an energy phenomenon but a sustainability one, encompassing other environmental (e.g., GHG emissions, air pollution, material resources use, water and energy use) and socioeconomic effects (e.g., quality jobs generation, health risks, accessibility of services) (Azevedo, 2014; Castro et al., 2022; Colmenares et al., 2020;

Table 2
The dynamic complexities in systems leading to RE.

Dynamic complexities of systems	The dynamic complexities in systems leading to RE	References
Policy resistant (PR)	PR1: Systemic responses to well-intended sustainability-oriented actions lead to RE	(Colmenares et al., 2020; Hertwich, 2005; Lange et al., 2021; Metic et al., 2022; van den Bergh, 2011)
	PR2: RE hold different magnitudes and directions	(Binswanger, 2001; Brockway et al., 2021; Colmenares et al., 2020; Lange et al., 2021; Saunders, 2008)
	PR3: Decision-makers holding a narrow view of the system fail to identify RE ex-ante	(Font-Vivanco et al., 2016; Friedrichsmeier and Matthies, 2015; Laurenti et al., 2016; Madlener and Alcott, 2009; Sonnberger and Gross, 2018; Sorrell et al., 2020)
	PR4: Preventing or mitigating RE requires a deep understanding of their causes	(Binswanger, 2001; Castro et al., 2022; Colmenares et al., 2020; Exadaktylos & van den Bergh, 2021; Greening et al., 2000; Lange et al., 2021; Madlener and Turner, 2016)
Constantly changing (CC)	CC1: RE occur in systems at the micro, meso, and macro levels	(Castro et al., 2022; Greening et al., 2000; Madlener and Alcott, 2009; Santarius, 2015, 2016; Sorrell, 2009; Trincado et al., 2021; van den Bergh, 2011)
	CC2: Systems leading to the occurrence of RE are nested and interrelated	(Brockway et al., 2021; Giampietro and Mayumi, 2018; Gillingham et al., 2013, 2016; Lange et al., 2021; Santarius, 2016)
Tightly coupled (TC)	TC1: The interaction of agents holding multiple interests in the system leads to RE	(Castro et al., 2022; Colmenares et al., 2020; Friedrichsmeier and Matthies, 2015; Greening et al., 2000; Hertwich, 2005; Madlener and Turner, 2016; Santarius, 2015; Trincado et al., 2021; Weidema, 2008)
	TC2: RE understanding requires addressing the multidimensionality of sustainability outcomes	(Azevedo, 2014; Castro et al., 2022; Colmenares et al., 2020; Font-Vivanco et al., 2016, 2018; Font-Vivanco and van der Voet, 2014; Friedrichsmeier and Matthies, 2015; Gillingham et al., 2016; Hertwich, 2005)
Governed by feedback (GF)	GF1: RE emerge due to consumer and producer-side reactions	(Castro et al., 2022; Font-Vivanco et al., 2016; Madlener and Alcott, 2009; Madlener and Turner, 2016; Santarius, 2015, 2016; Sorrell et al., 2020; Turner, 2013; van den Bergh, 2011; Weidema, 2008)
	GF2: RE might occur due to seemingly unrelated behaviour	(Azevedo, 2014; Font-Vivanco and van der Voet, 2014; Greening et al., 2000; Sonnberger and Gross, 2018)
Non-linear (NL)	NL1: Multiple causal relationships might moderate and mediate RE	(Azevedo, 2014; Font-Vivanco et al., 2016; Friedrichsmeier and Matthies, 2015; Greening et al., 2000; Ruzzenenti and Basosi, 2008; Santarius, 2015; Sonnberger and Gross, 2018; Sorrell, 2009; Sorrell et al., 2020; van den Bergh, 2011; Weidema, 2008)
	NL2: Causal connections might hold non-linear relationships between factors	(Azevedo, 2014; Binswanger, 2001; Castro et al., 2022; Greening et al., 2000; Hertwich, 2005; Metic et al., 2022; Sorrell, 2009; Sorrell et al., 2020; Trincado et al., 2021; van den Bergh, 2011; Zink and Geyer, 2017)
	NL3: RE present high heterogeneity in occurrence and magnitude	(Azevedo, 2014; Brockway et al., 2021; Castro et al., 2022; Colmenares et al., 2020; Giampietro and Mayumi, 2018; Gillingham et al., 2016; Hertwich, 2005; Madlener and Turner, 2016; Reimers et al., 2021; Sorrell et al., 2020; Trincado et al., 2021; van den Bergh, 2011)
Counter-intuitive (CI)	CI1: There are substantial delays between implementing the sustainability-oriented action and RE emergence	(Castro et al., 2022; Font-Vivanco and van der Voet, 2014; Gillingham et al., 2016; Madlener and Turner, 2016; Metic et al., 2022; Santarius, 2016)
	CI2: Systems present different short-run and long-run responses to changes	(Azevedo, 2014; Colmenares et al., 2020; Font-Vivanco and van der Voet, 2014; Greening et al., 2000; Lange et al., 2021; Madlener and Turner, 2016; Santarius, 2016; Turner, 2013)
	CI3: There are delays between the different types of RE	(Azevedo, 2014; Brockway et al., 2021; Castro et al., 2022; Colmenares et al., 2020; Santarius, 2016; Sorrell, 2009; Trincado et al., 2021; Turner, 2013)
Adaptive (Ad)	Ad1: The purpose of production and consumption systems are subjective and evolutionary	(Font-Vivanco et al., 2016; Font-Vivanco and van der Voet, 2014; Giampietro and Mayumi, 2018; Madlener and Alcott, 2009; Sorrell et al., 2020; van den Bergh, 2011)
	Ad2: Individuals are subjected to bounded rationality	(Azevedo, 2014; Castro et al., 2022; Exadaktylos & van den Bergh, 2021; Friedrichsmeier and Matthies, 2015; Madlener and Alcott, 2009; Reimers et al., 2021; Santarius, 2016; Sonnberger and Gross, 2018; Sorrell et al., 2020; van den Bergh, 2011)
	Ad3: Social systems influence individual behaviour	(Azevedo, 2014; Castro et al., 2022; Exadaktylos & van den Bergh, 2021; Font-Vivanco et al., 2016; Friedrichsmeier and Matthies, 2015; Madlener and Alcott, 2009; Matraeva et al., 2022; Reimers et al.,

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Table 2 (*continued*)

Dynamic complexities of systems	The dynamic complexities in systems leading to RE	References
		2021; Santarius, 2016; Sonnberger and Gross, 2018; Sorrell et al., 2020)
Self-organising (SO)	SO1: Essential reinforcing mechanisms stimulate production and consumption systems	(Castro et al., 2022; Font-Vivanco et al., 2016; Giampietro and Mayumi, 2018; Lange et al., 2021; Laurenti et al., 2016; Santarius, 2016; Sonnberger and Gross, 2018; Sorrell, 2009; Trincado et al., 2021; van den Bergh, 2011)
	SO2: Essential balancing mechanisms regulate production and consumption systems	(Lange et al., 2021; Santarius, 2016; Sorrell et al., 2020)
	SO3: Small changes in production and consumption factors can lead to huge amplifications	(Gillingham et al., 2016; Ruzzenenti and Basosi, 2008)
History-dependent (HD)	HD1: Co-dependence between sustainability actions and transitions influence RE	(Castro et al., 2022; Figge and Thorpe, 2019; Hertwich, 2005)
	HD2: The inertia of systems might influence the timing and magnitude of RE	(Binswanger, 2001; Exadaktylos & van den Bergh, 2021; Hertwich, 2005; Sonnberger and Gross, 2018)

Font-Vivanco and van der Voet, 2014; Friedrichsmeier and Matthies, 2015; Hertwich, 2005). Additionally, there are trade-offs between the dimensions and the potential of identifying co-benefits, including measurements not initially targeted by the action (Font-Vivanco et al., 2016, 2018; Friedrichsmeier and Matthies, 2015; Hertwich, 2005). For example, a critical trade-off in RE studies emerges between the environmental effects of resource consumption and the implications for social welfare. Some researchers suggest combining welfare maximisation and environmental minimisation, as only minimising impacts can hold detrimental social effects (Gillingham et al., 2016; Madlener and Turner, 2016). For instance, from an energy perspective, Gillingham et al. (2016) propose to maximise welfare benefits per energy use, leading to a relative measure to address RE.

3.1.4. *Systems governed by feedback*

Systems leading to RE are governed by feedback, where one's decisions give rise to a new situation influencing follow-up decisions (Sterman, 2000). First, **consumer and producer-side reactions to sustainability-oriented actions lead to RE (GF1)** because of changes in resource use (Castro et al., 2022; Madlener and Turner, 2016; Santarius, 2016; Turner, 2013). For instance, from the consumer side, the substitution effect occurs when a new price relation between two services leads to additional consumption of the cheaper service leading to additional impact. From the producer side, substitution occurs when more efficient resource use for production leads to a new price relation and more output via the cheaper process. Second-order effects also occur, where the reactions of changes in production might lead to changes in consumption, too – and vice-versa (Weidema, 2008). Thus, it is critical to map and distinguish relevant consumer and producer-side actions and reactions (Turner, 2013). In addition, for a complete picture of the occurring RE, it is essential to map the impacts in the complex networks of interconnected firms, production chains, and international transportation (van den Bergh, 2011). Finally, research should integrate embodied energy of goods and services into demand-led RE examinations (Font-Vivanco et al., 2016; Madlener and Alcott, 2009; Madlener and Turner, 2016; Sorrell et al., 2020) when the cause-and-effect chain to the sustainability action is traceable (Santarius, 2015).

Second, **seemingly unrelated behaviour might lead to RE (GF2)**, such as consuming other goods or services. For example, a technical change in a system influences the demand for that good – i.e., direct causality, but it may also affect the demand for other goods – i.e., indirect causality (Font-Vivanco and van der Voet, 2014). From a consumption perspective, it occurs because consumers constantly compare alternative options, considering the availability of money, time, preferences, and other consumption factors (Greening et al., 2000). Also, the needs are co-dependent. For instance, grocery shopping is related to mobility and cooking, and changes in food consumption might lead to changes in those related activities (Sonnberger and Gross, 2018). Although economic frameworks investigate the indirect effects of consumption and production, the relationships between different goods and services are hard to grasp (Azevedo, 2014). Thus, it is critical to accurately account for alternatives by, for instance, setting a functional unit that encompasses different products and services (Font-Vivanco and van der Voet, 2014) while mapping substitute and complementary consumption and production behaviour.

3.1.5. *Non-linear systems*

Non-linear systems present disproportionate effects to causes arising from internal delays and the influence of multiple concomitant factors (Sterman, 2000). To begin with, RE are the outcomes of non-linear systems as **multiple causal relationships might moderate and mediate RE (NL1).** First, efficiency changes often unfold into changes in other product attributes, such as safety, comfort, and quality, which also influence the behaviour of consumers and can potentially lead to RE (Azevedo, 2014). Additionally, multiple parameters shape an individual's purchasing decision, such as time, physical space, preferences, skills, and costs (Sonnberger and Gross, 2018; van den Bergh, 2011; Weidema, 2008). Thus, measures might relieve several consumption constraints, leading to interdependent RE occurring concomitantly (Ruzzenenti and Basosi, 2008; Sorrell et al., 2020; van den Bergh, 2011). Thus, factors might moderate and mediate RE, as the different consumption factors might not have autonomous effects (Font-Vivanco et al., 2016). For instance, satiation or time constraints can moderate additional consumption from released income (Greening et al., 2000). That is, consumption power released by a shared mode of transportation may not be consumed entirely due to lack of time. However, it is unclear in RE research what part of the subsequent changes in consumption should be attributed to an efficiency improvement when it is impossible to track the causal linkages (Font-Vivanco et al., 2016; Sorrell, 2009). Also, analyses should disregard other changes co-occurring with the sustainability-oriented action, only accounting for the portion the mechanisms are responsible for (i.e., cause-effect relativity) (Friedrichsmeier and Matthies, 2015; Santarius, 2015).

Additionally, **causal connections might hold non-linear relationships between factors (NL2)**. For instance, the price elasticity of demand will highly influence the RE magnitude (Trincado et al., 2021), which depends on the type of good (Binswanger, 2001). While the demand increases as income increases for normal goods, inferior goods behave oppositely. RE will emerge considering the type of goods and the disparity in sustainability impacts of consuming them. Also, the elasticity of demand is not constant (Azevedo, 2014) and tend to increase as prices increase (Binswanger, 2001; Hertwich, 2005) and according to changes in income, preferences and lifestyles (Greening et al., 2000; Sorrell et al., 2020; Trincado et al., 2021). Also, CE initiatives show many cases where new modes of consumption do not entirely replace primary production (Castro et al., 2022). For instance, second-use and remanufactured products may not completely replace the need for first-use products (Metic et al., 2022; Zink and Geyer, 2017), which could lead to RE. Finally, uncovering the relationship between the gains in economic productivity per resource use and the growth in output not explained by increased inputs might help identify RE (Sorrell, 2009; van den Bergh, 2011).

The multiple causal relationships with potential non-linear effects might cause **RE present high heterogeneity in occurrence and magnitude (NL3)**. A few factors determining RE heterogeneity are the level of economic development of the country, the income group of a household, the local culture, the regional location, and the sector of the industry influenced by the sustainability action (Brockway et al., 2021; Castro et al., 2022; Madlener and Turner, 2016; Sorrell et al., 2020). There is a deep discussion about the magnitude of RE and the level of development of an economy. More specifically, stronger RE are expected in developing economies because (i.) their resource supply is constrained (Azevedo, 2014; van den Bergh, 2011), (ii.) their demand is more constrained by costs (Azevedo, 2014; Hertwich, 2005), (iii.) the consumption is further away from saturation as human needs are not resolved (Azevedo, 2014; Hertwich, 2005; van den Bergh, 2011), and (iv.) relatively more consumption goes to emission-intensive necessities, such as housing and food (Reimers et al., 2021). Some argue for a correlation between welfare increase and emission reduction (Colmenares et al., 2020) by, for instance, using the Kuznets curve as a rule of thumb, which hypothesises an inverted U-shaped relationship between the resource use and per capita income (Trincado et al., 2021). Nevertheless, care is needed in generalising the RE magnitude to the development of the economy as there are significant discrepancies in wealth in developing economies, and the wealth of those influenced by the measure should be considered instead (Gillingham et al., 2016). In addition, Giampietro and Mayumi (2018) argue that it might be more practical to control consumption (and thus RE) when a society has reached a particular welfare threshold.

3.1.6. Counter-intuitive systems

Counter-intuitive systems might lead people to fail to grasp the reasons for the events they see because causes and effects are distant in time (Sterman, 2000). First, RE are an outcome of counter-intuitive systems, as **there are substantial delays between implementing the sustainability-oriented action and RE emergence (CI1)** (Castro et al., 2022; Santarius, 2016). Therefore, it can be very challenging for decision-makers to foresee the consequences of actions before implementation. Such a challenge might explain the disbalance towards ex-post RE investigations, as ex-ante approaches still lack (Metic et al., 2022). Proactive decision-making requires ex-ante scenario-based analyses of potential RE occurrence and magnitudes (Font-Vivanco and van der Voet, 2014; Gillingham et al., 2016; Madlener and Turner, 2016; Metic et al., 2022). Thus, it is essential to address the design-outcome delay consistently.

Second, **systems present different short-run and long-run responses to changes (CI2)**, which influence RE. Different short- and long-run responses to sustainability-oriented action have been widely pointed out (Colmenares et al., 2020; Greening et al., 2000; Santarius, 2016). An important reason is that consumers, producers, supply chains, and social institutions change on different time scales (Font-Vivanco and van der Voet, 2014; Greening et al., 2000; Lange et al., 2021). For instance, prices and incomes adjust through the economy, and complimentary consumption and production decisions change accordingly (Colmenares et al., 2020; Font-Vivanco and van der Voet, 2014; Madlener and Turner, 2016; Turner, 2013). Also, a company might cut costs in the short term and follow an output-maximising behaviour in the long term (Greening et al., 2000). In addition, there might be significant delays between changes in resource use, service demand and the incorporation of capital costs and market saturation (Azevedo, 2014). In synthesis, Lange et al. (2021) argue that short-run changes comprise prices, quantities, and real income, while long-run comprise changes in economic conditions such as preferences, technologies, and capital stock. Short-run and long-run changes interact with each other (Lange et al., 2021), and both can lead to RE.

Finally, **there are delays between the different types of RE (CI3)**. Delays between direct RE (due to rapid system responses), indirect RE (due to slow system responses), and the long-term equilibrium of the economy and resource use have been identified (Castro et al., 2022; Sorrell, 2009; Trincado et al., 2021; Turner, 2013). For instance, long-term RE may be lower than short-term RE if the return on capital investments falls over time and enact 'disinvestment effects' (Santarius, 2016; Turner, 2013). RE, thus, present dynamic behaviour and might diminish or augment over time until reaching stability (Azevedo, 2014; Brockway et al., 2021; Colmenares et al., 2020). Therefore, studies should consider the complete unfolding of markets, technologies and behavioural adjustments in RE investigations (Sorrell, 2009).

3.1.7. Adaptive systems

Adaptive systems are those in which agents' capabilities and decision rules change over time due to evolution and learning (Sterman, 2000). To begin with, RE are outcomes of adaptive systems as **the purpose of production and consumption systems are subjective and evolutionary (Ad1)**. First, the utility of goods is subjective as they differ among individuals (Font-Vivanco et al., 2016; Giampietro and Mayumi, 2018). Also, different goods might solve the same utility (Font-Vivanco et al., 2016), which influences supplementary and complementary consumption. In addition, an action might lead to changes in the purpose and boundaries of systems over time (Giampietro and Mayumi, 2018; van den Bergh, 2011). Some reasons are that consumers and the market adapt to the new attributes (Font-Vivanco et al., 2016; Font-Vivanco and van der Voet, 2014; Madlener and Alcott, 2009) – e.g., an improvement in efficiency aimed at a given function (e.g., a heating system) can lead to a new function at different scales (e.g., now people can install it in the living room) (Giampietro and Mayumi, 2018). Thus, critical challenges emerge in modelling systems prone to RE as new behaviour, additional system elements, or new functions might emerge (Giampietro and Mayumi, 2018). Thus, a thorough appreciation of the potential evolution of the functional unit can enable an adequate reference for comparison (Font-Vivanco et al., 2016; Font-Vivanco and van der Voet, 2014; Giampietro and Mayumi, 2018; Sorrell et al., 2020).

In addition, individuals make sub-optimal decisions for two main reasons. First, **individuals are subjected to bounded rationality (Ad2)** due to biases, "wrong" goals, habits, and lack of information (Exadaktylos & van den Bergh, 2021; van den Bergh, 2011). Individuals are biased by mental representations of the assumed costs leading to time-inconsistent choices as they prioritise immediate costs and benefits (Azevedo, 2014; Exadaktylos & van den Bergh, 2021; Friedrichsmeier and Matthies, 2015). Also, individuals might fail to adequately consider resource use in their decision as they might have incomplete knowledge about the application of devices and incomplete information about their impacts (Azevedo, 2014; Friedrichsmeier and Matthies, 2015; Madlener and Alcott, 2009; Sonnberger and Gross, 2018). Meanwhile, individuals in firms are more prone to maximise profits (Santarius, 2016). However, education and information availability influence their decision-makers, and they might still fail to consider all the potential effects of their decisions (van den Bergh, 2011). Thus, even well-intended individuals might behave inconsistently and prioritise action with low potential sustainability contributions (Sorrell et al., 2020). Therefore, studies following a utility maximisation assumption might neglect important factors driving behaviour.

Sub-optimal decisions are also the result of **social systems' influence on individual behaviour (Ad3)**. People are subject to bounded self-interest (Exadaktylos & van den Bergh, 2021) as social systems (e.g., technological, cultural, religious, political, and economic systems) greatly influence individuals (Sonnberger and Gross, 2018). Specifically, social pressures, prestige, values, norms, and the well-being of others regulate decision-making (Azevedo, 2014; Exadaktylos & van den Bergh, 2021; Font-Vivanco et al., 2016; Madlener and Alcott, 2009; Santarius, 2016). Moral licensing has been consistently used to explain unintended behaviour in resource use. It occurs when past good deeds liberate individuals to subsequently act less environmentally consciously (Friedrichsmeier and Matthies, 2015; Reimers et al., 2021) or if they believe the provider is taking environmental care on their behalf (Castro et al., 2022). Also, informal institutions such as traditions might sustain RE even if formal institutions exist to address them (Matraeva et al., 2022), meaning that well-designed mitigating measures might fail. Conversely, pro-environmental values divert RE by preventing additional consumption (Exadaktylos & van den Bergh, 2021). Finally, social pressure can motivate others to adopt more sustainable behaviour (Sorrell et al., 2020), acting as a self-reinforcing loop and an essential ally to address RE.

3.1.8. Self-organising systems

Self-organising systems are those where the internal structure generates behaviour patterns, and small perturbations might be vastly amplified (Sterman, 2000). In the first place, RE are outcomes of self-organising systems as **essential reinforcing mechanisms stimulate production and consumption systems (SO1)**. Although there is a debate about the causality between resource consumption and economic growth, evidence suggests critical reinforcing feedback loops (Sorrell, 2009; Trincado et al., 2021). For example, in cases where enhancements in the production efficiency of a system lead to a decrease in price, demand might rise, and additional profits might feedback into production factors in that system (Castro et al., 2022; Lange et al., 2021; Santarius, 2016). There is, therefore, a positive feedback loop between industrial investment, lower unit costs, lower prices for consumers, and subsequent demand (Trincado et al., 2021). Furthermore, higher efficiency stimulates the diffusion of innovation using that resource, which can introduce long-range and persistent societal changes (Font-Vivanco et al., 2016; Sorrell, 2009; van den Bergh, 2011). In addition, higher efficiency can sustain fundamental social logic as the acceleration of everyday life through time-efficiency measures (Sonnberger and Gross, 2018) and the social reliance on accelerating product obsolescence (Laurenti et al., 2016). Overall, expanding the ability to produce more to consume more (i.e., maximising the energy flux) is a common attractor for socioeconomic systems (Giampietro and Mayumi, 2018).

Concomitantly, **essential balancing mechanisms regulate production and consumption systems (SO2)**. Economies present redundancies like demand for the same resource in different sectors and price linkages of different resources, causing a general system reaction that can (partially) counteract the effects of a sustainability-oriented action (Santarius, 2016). For example, price reduction by a given supply-chain actor due to efficiency gains can enact efficiency investment by another actor aiming to keep relative prices even and avoid market losses. In addition, the choice of some people to pursue sufficiency measures may lead to energy price drops that will encourage other people to increase their consumption (Sorrell et al., 2020). The same applies to efficiency measures (Lange et al., 2021). Thus, critical stabilising mechanisms maintain resource use at high levels.

The interplay of reinforcing and balancing mechanisms can result in **small changes in production and consumption factors leading to huge amplifications (SO3)**. Local efficiency improvements can unfold in significant market changes, leading to substantial resource use (Gillingham et al., 2016; Ruzzenenti and Basosi, 2008). For instance, some argue that the effects of fuel efficiency might have been the critical driver of production outsourcing by shifting the relative costs out of local production and storage to global production and transportation (Ruzzenenti and Basosi, 2008). A similar argument could apply to connecting the improvement of Watt's steam engine and the first industrial revolution, which led to the acknowledgement of Jevons paradox (Sorrell, 2009). Such amplifications can be more evident through macro-level RE mechanisms such as the composition effect, where changes in the relative return of investment in the sector will lead that sector to grow relative to others, reinforced by growth effects through innovation (Gillingham et al., 2016).

3.1.9. History-dependent systems

In history-dependent systems, previous decisions define the decisions available now, leading to fundamentally different dynamics between doing and undoing (Sterman, 2000). To begin with, RE are outcomes of history-dependent systems as **co-dependence between sustainability actions and transition dynamics influence RE (HD1)**. RE occurrence and magnitude might vary due to different timings in transitions and the sustainability action at hand, as the sustainability transition pathway of a given system influences the effects in other systems (Hertwich, 2005). For instance, car electrification might unfold differently according to the region's energy transition status, affecting potential RE magnitude. Also, choosing a CE strategy (e.g., recycling) might lead to adverse effects in adopting another CE strategy (e.g., remanufacturing) in the future due to higher opportunity costs, leading to a less-than-ideal resource use (Castro et al., 2022; Figge and Thorpe, 2019). On the other hand, technological innovation can also contribute to other emission-reducing activities (Hertwich, 2005). For instance, improvements in batteries for car electrification could enable aircraft electrification.

Finally, **the inertia of systems might influence the timing and magnitude of RE (HD2)**. Some actions, such as infrastructure and investment, are hard to revert and frequently necessary to sustain a given good's consumption and production (Sonnberger and Gross, 2018). In addition, investments made when energy prices are high continue when prices go down (Hertwich, 2005). In addition, defaults and habits are sources of inertia as people tend to keep their decision patterns (Exadaktylos & van den Bergh, 2021). Thus, choices might not be flexible and seemingly good sustainability actions that might lead to substantial RE need time to be reverted (Binswanger, 2001). Also, consumption practices and production systems co-evolve, which enhances the inertia of technological and institutional development (Sonnberger and Gross, 2018). For instance, more effective air-conditioning systems can make it possible to wear a suit and tie at the workplace regardless of the outside temperature – a clear example of an efficiency-oriented action enabling a resource-consuming social norm. Although the co-dependence in transitions and the influence of systems' inertia can influence RE, a clear line to separate RE and other similar phenomena (e.g., path dependence and lock-in) is needed.

3.2. The multiple levels of understanding for RE examination

Fig. 3 depicts the 24 dynamic complexities following the Iceberg model. The model clarifies RE-specific dynamic complexity in four levels of understanding, from events to mental models. It helps position the RE-specific dynamic complexities that: (i.) become evident through RE descriptions (i.e., events); (ii.) associate with the behaviour over time of systems (i.e., patterns of behaviour); (iii.) associate with how parts interrelate and cause potential RE (i.e., underlying structures); and (iv.) indicate individuals' assumptions sustaining systems' structure (i.e., mental models). Connections, proximity, and the clusters in the figure indicate relationships identified between RE-specific dynamic complexities enabled by the Iceberg model.

When investigating RE, the tip of the iceberg is to acknowledge that the *occurrence and magnitude of RE* are a snapshot of the RE phenomenon as they represent the observable events or symptoms of the system structure. RE can reach different magnitudes under different contexts and conditions for examination.

The next level of thinking entails acknowledging that the *continuous behaviour of RE* can help understand the reasons for RE occurrence and magnitude. It considers RE timing and magnitude depending on the sources of inertia in the system and the various timings between actions and responses to change. Also, there are potential disproportional amplifications in the system. In the case of multiple RE occurring, potential delays between them should be considered.

Addressing the underlying structures can clarify the relationships, information flows, and physical structures critical to understanding RE occurrence. Three clusters of dynamic complexity leading to RE are associated with structures that determine potential behaviour. First, it is essential to acknowledge that multiple *interrelated systems* under

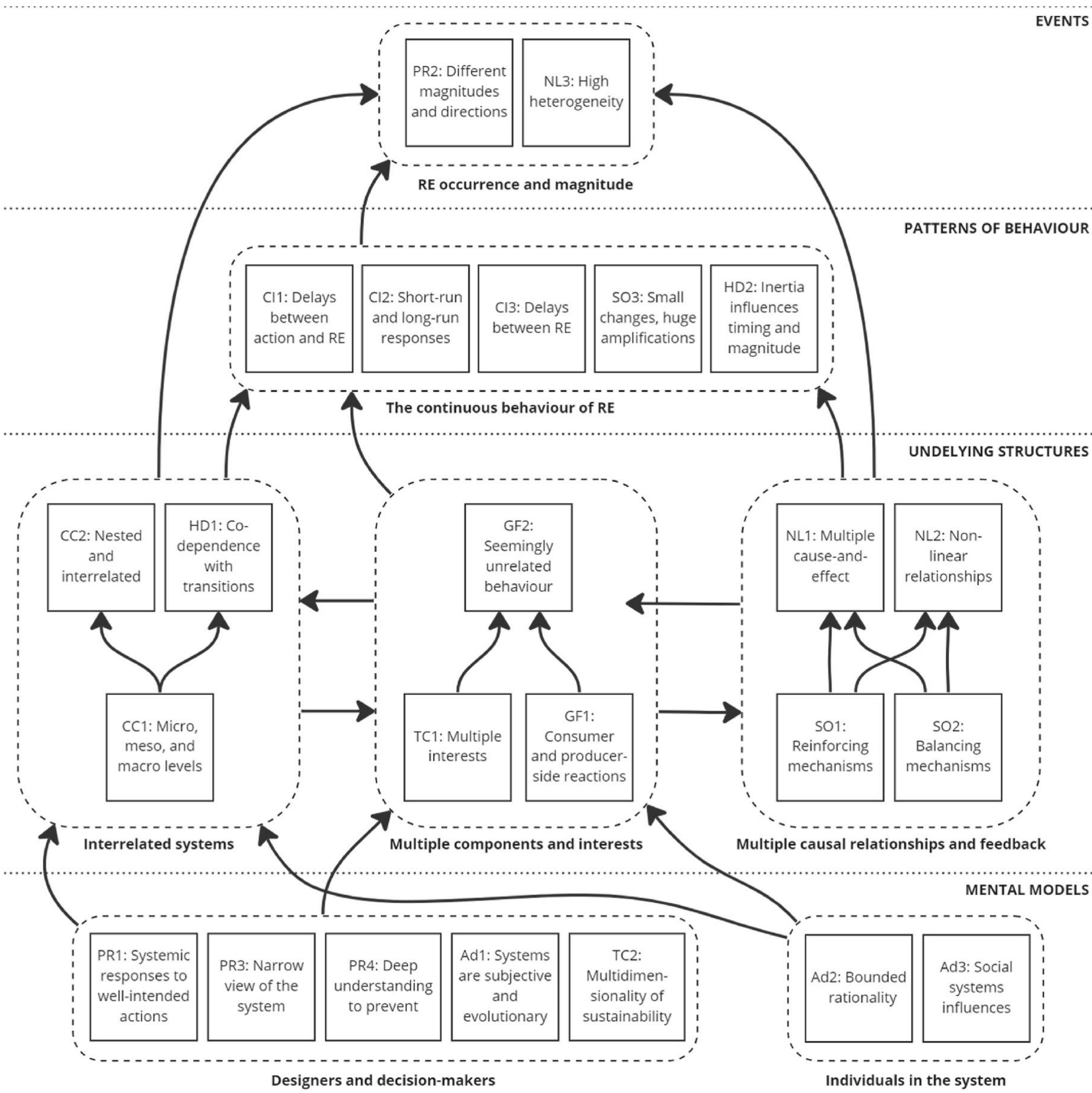

Fig. 3. The Iceberg model of RE-specific dynamic complexities, making explicit the four levels of understanding for RE examination.

transition at different paces can lead to RE. Those systems are composed of *multiple components and interests*, e.g., consumers and producers, whose interactions will set the structures under examination. The structures will be composed of reinforcing and balancing feedback loops stimulating and regulating the system under investigation, where *multiple causal relationships and feedback* between factors with potential non-linear relationships determine behaviour. Framing and scoping the systems, their components, and the feedback relationships of interest will determine the identification of RE.

Finally, helping expand the mental models of *designers and decision-makers* while deeply accounting for the mental models of other individuals acting in the system is fundamental to understanding the RE occurrence. For example, from one side, designers and decision-makers might depart from good intentions and a narrow and subjective view of the system they influence. Addressing RE requires a broader system understanding, including addressing the multidimensionality of sustainability to preventing or mitigating RE. On the other side, *individuals in the system* are influenced by bounded rationality and social pressures in their decisions, which will determine their choices and RE occurrence.

In summary, the Iceberg model's four levels of understanding help frame RE examinations. First, it makes the symptoms of the system structure explicit by demonstrating potential RE occurrence and their magnitude. It also supports examinations to go deeper into unveiling the dynamic complexity of RE in sustainability transitions. Additional insight might be achieved by acknowledging RE as the outcome of continuous systems that may reach stability at different times and conditions. Finally, deepening into the multiple systems and stakeholders holding causal relationships and feedback mechanisms sustained by the mental models of actors enables grasping the reasons for RE occurrence and the places to position high-leverage interventions to address them.

4. The insofar use of SD to address dynamic complexities in RE studies

Table 3 provides an overview of the dynamic complexities encountered in the six SD-based studies of RE following the investigation framing, the explanation, assessment, and recommendations about RE provided in the studies organised according to the levels of understanding in the Iceberg model (Table A1 in the Appendix provides a detailed description of the encountered dynamic complexities).

The framing of the investigation varies according to the initial assumptions for RE occurrence **(PR1)**. Some studies start from the premise

Table 3
Overview of dynamic complexities encountered in SD-based studies of RE. [1] refers to Dace et al. (2014), [2] refers to de Gooyert et al. (2016), [3] refers to Laurenti et al. (2016), [4] refers to Cavicchi (2016), [5] refers to Freeman et al. (2016), and [6] refers to Freeman (2018).

Level of understanding	The dynamic complexities in systems leading to RE	Investigation	Explanation	Assessment	Recommendations
1. Events	PR2: Different magnitudes and directions			[1],[5],[6]	
	NL3: High heterogeneity			[1],[6]	
2. Patterns of behaviour	CI1: Delays between action and RE			[1]	
	CI2: Short-run and long-run responses		[5]	[5],[6]	
	CI3: Delays between RE				
	SO3: Small changes, huge amplifications			[3],[5]	
	HD2: Inertia influences timing and magnitude		[4]		
3. Underlying structures	CC1: Micro, meso, and macro levels	All	[4],[6]	[4]	
	CC2: Nested and interrelated		[2],[4]	[1]	
	TC1: Multiple interests	[2],[4]	[2]	[5]	[4]
	GF1: Consumer and producer-side reactions		[2],[3],[5],[6]	[1]	
	GF2: Seemingly unrelated behaviour		[4],[5]	[4]	
	NL1: Multiple cause-and-effect		[All]	[6]	
	NL2: Non-linear relationships			[5]	
	SO1: Reinforcing mechanisms		All	[2]	[2],[3]
	SO2: Balancing mechanisms		[1],[2],[4], [5],[6]	[2]	[3]
	HD1: Co-dependence with transitions			[2]	
4. Mental models	PR1: Systemic responses to well-intended actions	All	All	[6]	
	PR3: Narrow view of the system				[4]
	PR4: Deep understanding to prevent				All
	TC2: Multidimensionality of sustainability		[2],[4],[6]	[1],[5]	
	Ad1: Systems are subjective and evolutionary		[5]	[2],[3],[6]	[6]
	Ad2: Bounded rationality				
	Ad3: Social systems influences		[5]	[1]	

of RE occurrence, presenting it as the central phenomenon of analysis (Freeman, 2018; Freeman et al., 2016). Others encounter RE while investigating a sustainability-oriented action (Cavicchi, 2016; Dace et al., 2014). Finally, there are also studies that categorise RE as a kind of "side effect" of sustainability-oriented action while investigating a similar phenomenon – e.g., setting it as a type of policy resistance (de Gooyert et al., 2016) or an unintended consequence of environmental action (Laurenti et al., 2016). The recommendations **(PR4)** tend to follow the focus of the study by, for instance, (i) addressing policy resistance by focusing on incentives reinforcing overlapping interests (de Gooyert et al., 2016) or (ii) indicating ways to address RE to reach a desired decrease in emissions (Freeman et al., 2016). It means that even though RE might not be the central focus of the investigation, it is crucial to support their identification and consider ways of weakening their occurrence.

There are multiple potential sources of information to sustain modelling and simulation studies. Literature reviews considering academic research (Dace et al., 2014; Freeman, 2018; Laurenti et al., 2016), policy documents (Cavicchi, 2016; Dace et al., 2014; Freeman, 2018), and a described existing case (Freeman et al., 2016) have been employed. Thus, secondary data can be a valuable source for RE investigation, not only by providing data for running the models but also for model conceptualisation. When stakeholders were involved in the modelling process, it happened through semi-structured interviews (Cavicchi, 2016) and participatory modelling (de Gooyert et al., 2016), which helped to address the multiple interests that are towards the system **(TC1)**.

As to the level of analysis **(CC1)**, studies show a strong tendency to macro-level investigations, as all six studies deal with macro level-systems: the status of solid waste management system in Latvia (Dace et al., 2014), Dutch energy transition (de Gooyert et al., 2016), theory for consumer goods consumption (Laurenti et al., 2016), regional implementation of bioenergy in Italy (Cavicchi, 2016), regional road transport in the UK (Freeman et al., 2016) and a general theory for macro-level RE (Freeman, 2018). This tendency might indicate opportunities for meso and micro-level RE investigations as they might occur at all levels. Also, there is extended evidence of SD-based investigations of transitions happening at all three levels (Guzzo et al., 2022).

Feedback mechanisms **(SO1 and SO2)** play an essential role to explain the resource dynamics in the system in all studies. However, there is no consensus on setting reinforcing or balancing feedback loops as inherently good or bad in sustainability terms. In some cases, reinforcing loops are desired as they sustain sustainability transitions (de Gooyert et al., 2016); in other cases, reinforcing loops might drive consumption and be undesired (Cavicchi, 2016; Laurenti et al., 2016). RE are mainly identified as feedback mechanisms, too. Studies pictured RE as reinforcing loops that acted against the intentions of well-intended balancing actions (Dace et al., 2014; Freeman, 2018). One study characterised it as a balancing loop that counteracted the effects of reinforcing sustainability investments (de Gooyert et al., 2016). Meanwhile, one study characterised it as a reinforcing loop that reinforced another reinforcing – but undesirable – engine of consumption growth (Laurenti et al., 2016). Thus, the kind of feedback loop to address RE seems to depend on the conceptualisation of resource use in the system. Nevertheless, identifying the feedback mechanisms driving resource use and modelling RE in terms of feedback seems helpful in explaining the system dynamics.

Studies generally considered consumer- and producer-side reactions **(GF1)** to investigate the system and make explicit multiple causal relationships **(NL1)** activating them. Also, there is a tendency to include economic-oriented decisions resulting in RE as price or cost-led additional demand (Dace et al., 2014; de Gooyert et al., 2016; Freeman et al., 2016; Laurenti et al., 2016) and operational efficiency leading to additional production (Freeman, 2018). Meanwhile, social norms **(Ad3)** were identified as sustaining detrimental behaviour and leading to RE in one case (Freeman et al., 2016). In another case, RE occurs due to a local effect disparate to the global intentions **(GF2)** – i.e., local warming in contrast to intentions in decreasing GHG emissions (Cavicchi, 2016). Although economic-oriented decisions still dominate SD-based studies, the inclusion of the role of social norms and seemingly unrelated behaviour showcase the potential to help identify and consider other types of feedback effects. Nevertheless, no explicit consideration of the effects of bounded rationality in decision-making **(Ad3)** in RE occurrence is remarkable because SD constantly challenges the idea of perfect rationality and can integrate degrees of limitation in human decision-making in its simulation models (Sterman, 2000). Also, there is space to further addressing the unfolding of different RE mechanisms as no study was capable to show the potential delays between them **(CI3)**.

As to the modelling approach, most studies used only qualitative modelling to make assertions about the systems under investigation (Cavicchi, 2016; de Gooyert et al., 2016; Laurenti et al., 2016), while two of them combined qualitative and quantitative modelling.[1] For instance, in the packaging waste management case (Dace et al., 2014) and the regional road transport in the UK (Freeman et al., 2016), the RE magnitude is quantified in simulation and explained through the CLD model. Qualitative models are often used to represent the subjectivity in systems' understanding **(Ad1)** by representing different models for different assumptions of RE occurrence (Freeman et al., 2016). The modes of behaviour emerging from the model structure may help investigate potential system evolutions **(Ad1)** to draw policy recommendations **(PR4)** (de Gooyert et al., 2016; Freeman et al., 2016; Laurenti et al., 2016)**.** Quantitative scenarios show that RE magnitude varies through time **(PR2)** (Dace et al., 2014). Also, different policies can lead to entirely different behaviours for key variables, indicating potential amplifications from small changes **(SO3)** and non-linear relationships between system elements **(NL2)** (Freeman et al., 2016). Thus, combining qualitative and quantitative SD in investigations seems to be a strong approach to address RE complexities more thoroughly.

Studies show a tendency to recommend combinations of policies based on the increased understanding of the systems **(PR4)**, sustained by the argument that focusing on one part of the system might lead to resistance in another. Authors are very vocal in recommending policies that "simultaneously" address (Dace et al., 2014), "combinations of policies" (de Gooyert et al., 2016), a "policy portfolio" (Cavicchi, 2016), and "a system of interventions" (Freeman et al., 2016). Qualitative SD demonstrates its usefulness as it provides a comprehensive map that can help see where to position the multiple policies as the leverage points become apparent from the structure and expected behaviour emerging from it. In turn, simulation enables investigating the recommendations to help understand how they could play out in practice. Freeman et al. (2016) provide an interesting reference for multi-policy investigation, as it shows the combined effect of four interventions, including the potential for RE.

In general, the studies present evidence of investigating the dynamic complexities of RE within all the four levels depicted in the Iceberg model beyond the level of events. Some studies acknowledged RE as the outcome of continuous systems, in some cases demonstrating the RE magnitudes over time (**PR2**) with different behaviours, eventually reaching system stabilizations (e.g., magnitudes rising or decreasing before stabilising – **CI2)**. Simulation (Dace et al., 2014) and CLD investigations (Freeman, 2018) sustained the discussions on the continuous trait of systems leading to RE occurrence. The studies consistently made explicit the underlying structures sustaining the RE occurrence. Most of the studies recognize that RE are the outcome of consumer and producer-side reactions (**GF1**), involving multiple cause-and-effect relationships (**NL1**) and emerging from the interplay of reinforcing and balancing feedback loops (**SO1** and **SO2**). Finally, there is evidence of making explicit the mental models of decision-makers by considering studies with varying assumptions for RE occurrence (**PR1**) and making recommendations that match the insights gained from modelling and simulation (**PR4**). Also, the subjectivity of the decision-makers' mental models (**Ad1**) was made explicit by using concurrent models to explain a system's behaviour in multiple studies. Meanwhile, there is plenty of space to clarify the mental models of individuals acting in the system (**Ad2** and **Ad3**).

A combined view of the set of RE-specific dynamic complexities, the levels of understanding of the phenomenon, and the modelling stages enable an actionable approach to investigating RE. When setting the examination, a researcher or practitioner can identify and prioritise which sources of dynamic complexity will play a role in their case. Then, the Iceberg model will help position which level of thinking is necessary to understand the reasons for RE occurrence while considering the prioritised RE-specific dynamic complexities. Finally, the modelling steps for setting the investigation will help set the modelling strategies to adequately frame, explain, assess and make recommendations about the system so that one can avoid or address RE occurrence. Qualitative and quantitative SD modelling and simulation can help unveil the dynamic complexity of RE in sustainability transitions and lead researchers and practitioners closer to addressing RE occurrence.

5. Discussion: Research paths for further addressing the dynamic complexities of RE

The accumulated knowledge from the awareness of the dynamic complexities surrounding RE research and the insofar use of SD to address them lead to the proposition of three research paths to further address RE's dynamic complexities. Each path is detailed in such a way that we make explicit the dynamic complexities that could be resolved by following each path.

- Research path 1: Help decision-makers understand the reasons for RE and identify effective leverage points.

RE examination approaches should help expand decision-makers' mindset to acknowledge not only the expected and intended consequences of actions as to appreciate the potential unexpected and unintended consequences **(PR1 and PR3)**. Investigations show that qualitative modelling can help identify (Cavicchi, 2016; de Gooyert et al., 2016) and draw recommendations (Laurenti et al., 2016) to deal with RE, alongside the use of simulation results to derive (Dace et al., 2014) and even test (Freeman et al., 2016) them.

Investigation approaches should help integrate the concept of RE into sustainability thinking accounting for the long-term, system-wide effects of policies and strategies before implementation (van den Bergh, 2011). Therefore, qualitative SD can provide insight into helping decision-makers and scholars understand the reasons for RE and identify leverage points that can weaken or prevent them. Quantitative SD can help clarify the determinants for RE occurrence and the most effective prevention or mitigation mechanisms.

When addressing RE, the focus must expand from the events (e.g., RE is likely to occur, and the magnitude of RE is x%) to patterns of behaviour (e.g., how the occurrence and magnitude of RE behave through time). Also, it should make decision-makers aware of the occurrence, magnitude, and direction of potential RE through time **(PR2)** and make sense of the reasons **(PR4)**. Furthermore, making the dynamic behaviour of system elements explicit will help deal with the different short-run and long-run responses to change **(CI2)** and the delays between different types of RE **(CI3)** to avoid inaccurate snapshots of RE occurrence and magnitude. Finally, the investigations should translate an increased understanding of the system into recommendations to prevent or mitigate RE.

- Research path 2: Reach generalisable cause-and-effect structures that explain the systemic responses leading to RE.

The consistent use of feedback loops acting against well-intended

[1] SD studies can use qualitative modelling through causal loop diagrams (CLD) to articulate the endogenous causal understanding of a system and challenge individuals' assumptions about a given system's structure and its potential behaviours (Grösser and Schaffernicht, 2012; Lane, 2008). Qualitative modelling aims to identify feedback loops, i.e., successions of cause-effect relations that start and end in the same system element, and which interplay can lead to specific patterns of behaviour (Barlas, 2002). Quantitative simulation uses stock and flow diagrams (SFD) to reach scenario-based analyses of potential behaviour emerging from system structure (Sterman, 2000). Both approaches can contribute to knowledge about RE and can be combined.

desirable actions (Cavicchi, 2016; Dace et al., 2014; de Gooyert et al., 2016; Freeman, 2018; Freeman et al., 2016) or reinforcing undesirable behaviour (Laurenti et al., 2016) to represent RE provides evidence that RE are sustained by feedback structures and hold dynamic behaviour. A catalogue of cause-and-effect structures, potentially based on CLD, could help decision-makers make sense of RE occurring in the micro, meso, and macro levels **(CC1)**, helping them to clarify the interconnections and consider the different RE concomitantly at play **(CC2)**.

The causal explanations for RE make clear multiple triggers, including economic (Dace et al., 2014; de Gooyert et al., 2016; Freeman et al., 2016; Laurenti et al., 2016) and behavioural (Freeman et al., 2016) reasons for RE. The catalogue of cause-and-effect structures must be capable of making explicit the structures giving rise to consumer and producer-side reactions **(GF1)** within similar and different consumption needs **(GF2)**. Meanwhile, it is critical to thoroughly address the bounded rationality of individuals **(Ad2)** and the social influences on behaviour **(Ad3)**.

The cause-and-effect structures should help make sense of the potential multiple causes-and-effect relationships leading to RE while clarifying the factors holding a moderating and mediating effect on its occurrence **(NL1)** and appreciating potential positive effects **(PR2)**. The structures should easily connect to the reinforcing and balancing mechanisms that sustain resource usage **(SO1 and SO2)**, so that they can be instantiated into specific examinations**.**

Finally, the capacity to derive recommendations (Dace et al., 2014; de Gooyert et al., 2016; Laurenti et al., 2016) and discuss potential pathways (Freeman, 2018) for RE from the structures in different cases indicates the structure-behaviour relation enabled by CLD can provide essential insights in understanding RE. Generalisable cause-and-effect structures and their complimentary behaviour could assist in addressing the need for a rigorous codification of the mechanisms through which RE emerge (Brockway et al., 2021; Madlener and Turner, 2016; Ruzzenenti et al., 2019; Sonnberger and Gross, 2018).

- Research path 3: Employ modelling and simulation as agile and engaging tools that enable proactive decision-making.

Different levels of engagement might occur in RE investigations, from using existing long-term case studies (Freeman et al., 2016) to participatory modelling based on the SD group model-building approach (de Gooyert et al., 2016; Vennix, 1999). On the one side, existing sources of information (such as reports and literature) can help identify reasoning for modelling and datasets for simulation calibration. On the other side, involving decision-makers in the process can help reach more valid models and recommendations as they are specialists in the subject with a further potential of being applied in practice.

Qualitative modelling and quantitative simulation can be essential allies in making sense of how the multiple agents are causing (and could help resolve) RE **(TC1)** while contributing to the multidimensionality of sustainability outcomes in RE **(TC2)**. The tools should enable including the critical factors determining RE in the context under investigation **(NL3)** and the essential co-dependent sustainability transitions **(HD1)**.

Furthermore, it is critical to consider the significant delays between designing actions, their implementation, and RE occurrence **(CI1)** to enable proactive decision-making to avoid RE. If the intention is to make ex-ante investigations and inform decision-making before RE occur, one should take stock of how much uncertainty and little time there is to consider all the potential outcomes of actions. The fact that only one study simulated policies' effects (Freeman et al., 2016) indicates that going through the entire process of investigation, model building and testing, and policy analysis can be challenging and time-consuming. Thus, it is critical to develop structured and agile forms of engaging with decision-makers and deploy the cause-and-effect structures into simulation models so that the investigation process integrates seamlessly into practical decision-making.

6. Final remarks

This work aimed to enhance the understanding of RE's causal and dynamic traits, following SD as the investigation frame. The systematic literature review, employing inductive and deductive content analysis, resulted in 24 specific sources of dynamic complexities (RQ1), providing a comprehensive overview of the factors that increase interrelationships or alter the temporal interaction of system elements to explain RE. Furthermore, it evidences RE as a complex phenomenon. The Iceberg model connected the RE-specific dynamic complexities to the multiple levels of thinking: from events and patterns of behaviour of observable phenomena to more fundamental underlying structures and mental models causing that behaviour. Going deeper into the iceberg enhances the potential for understanding the causes of RE occurrence, providing additional leverage to prevent or mitigate them. In addition, it makes explicit the limitations of getting snapshots of RE magnitudes and that investigators must approach RE with the appropriate mindset and tools to address inherent uncertainty in understanding and managing them. Therefore, the dynamic complexities should be integrated into every kind of investigation and is an invitation to additional lenses to engage in RE studies.

This research also shows how SD has been employed to address dynamic complexities in six documented RE cases (RQ2). It makes explicit that SD-based studies have addressed the sources of dynamic complexity in different ways. Addressing the dynamic complexities depend on the modelling approach (i.e., qualitative or quantitative), the centrality and assumptions about the RE phenomenon in the study, the choices about how to represent the intended and unintended consequences using feedback loops, and other aspects of the investigation made explicit in Section 4. The applicability of the set of dynamic complexities to analyse existing RE cases demonstrates its potential as an instrument to help identify and manage them in further analyses. Thus, it could also be used proactively by assisting investigators in mapping how the dynamic complexities might unfold in the systems of interest to guide how to design the investigation to tackle them. Here, case studies that depart from using the conceptual framework are welcome, making explicit the scope decision and modelling strategies to deal with the RE-specific dynamic complexities of those cases.

The foundation for taking a system's approach to investigating RE is completed by drawing research paths to further address the dynamic complexities in RE through SD (RQ3). RE research should strive to help decision-makers understand the reasons for RE occurrence and identify effective leverage points, reach generalisable cause-and-effect structures that explain the systemic responses leading to RE, and employ modelling and simulation as agile and engaging decision-making that enable proactive decision-making. The research paths demonstrate a less deterministic approach for RE examination, capable of reaching recommendations that consider the nature of the phenomenon – i.e., capable of dealing with the uncertainty surrounding RE occurrence and magnitude.

Within the SD realm, a few state-of-the-art modelling and simulation techniques can help address the RE-specific dynamic complexities. For instance, automated loop dominance analysis (Schoenberg et al., 2020) can connect the RE behaviour patterns identified in models to the actual structures at play through time. Also, simulation-based role-playing games (Rooney-Varga et al., 2020) have the potential to enable participants to play with the model and learn about the causes of RE. Finally, algorithmic tools (Kwakkel and Pruyt, 2013; Schoenenberger et al., 2021) can be coupled to simulation models to generate automated policy recommendations, assisting in identifying leverage points to addressing RE.

The choice of building upon the SD approach was an attempt to make tangible how a system perspective can address the complexity surrounding RE. Moreover, the SD community is deeply involved in addressing sustainability-related issues (Honti et al., 2019; Moon, 2017) and fundamentally deals with unintended consequences (Forrester, 1971; Sterman, 2001). Thus, further understanding why and how it occurs can spill over in helping to understand other "side-effects" such as policy resistance (de Gooyert et al., 2016) and externalities (Laurenti et al., 2016).

Nevertheless, SD modelling and simulation presents several limitations. First, it is a common criticism that SD models can be highly abstract as they rely on the aggregated behaviour of average types of actors – this could be addressed by combination with Agent-based modelling (ABM), for example. Additionally, as with any other modelling approach, SD models rely on the modellers' assumptions and modelling choices, which influences the models' validity and requires strong model validation and calibration, which can be made by following rigid processes for model validation (e.g., Schwaninger and Groesser, 2016). Also, a significant challenge is connecting with existing models already used to investigate RE and related phenomena, such as general equilibrium models from economics and impact assessment models from engineering backgrounds. Regardless of the modelling approach to assess RE, researchers and decision-makers must be aware of the dynamic complexities, how they might influence choices in understanding the system, and to what extent they address the inherent uncertainty in RE investigations. Unrestricted engagement is needed to address such a complex issue and facilitate timely sustainability transitions that reach their intended outcomes.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A1
Dynamic complexities encountered in SD investigations of RE.

Reference	Investigation framing	RE explanation	RE assessment	RE recommendations
Dace et al. (2014)	• **Did not investigate RE directly; encountered RE** by examining how public policies affect waste management systems (PR1). • The investigation applies **qualitative and quantitative modelling** and builds upon **literature review and policy documents.** • The study is about the status of the **solid waste management system in Latvia** (macro-level) (CC1).	• RE occur due to **systemic responses to policies** that replace virgin material with recycled material, decreasing the price/costs of using the material and expanding demand (PR1). • A CLD composed of two balancing loops and a reinforcing loop explains the reason for RE occurrence. The **two balancing loops are two economic mechanisms** (SO2), where the first is a packaging tax that controls the demand for material, and the second is the landfill costs driving more sorters and recycling. **Multiple factors determine the demand for material**, such as the price of recycled and virgin material, a tax for packaging, and the fraction capacity (NL1). • **The RE is characterised by a reinforcing economic mechanism** (PR1 and SO1), where more recycling drives the demand for material and thus more waste, which drives recycling.	• The simulation model comprises **three sub-models** (market, waste management, and sorting), which have their **interrelations defined** (CC2). • **Consumer-side reactions** are modelled in the market sub-model, which considers change of attitude in sorting through time (GF1). **Individuals** are driven by **environmental concerns** and **influenced by the positive example** of those who sort their waste (Ad3). **Producer-side reactions** include the waste management dynamics and supply of recycled material (GF1). • **Scenarios** consider **introducing taxes and different elasticities of demand and material substitution** (PR2 and NL3). In addition, RE assessment considers the **amount of material used per product** and the **filled fraction of landfills** (TC2). • The behaviour over time shows **different points of stabilisation** concerning policy implementation in the scenarios (CI1). Also, the scenarios show that **RE magnitude varies through time** (PR2). In one case, the **magnitude reaches a plateau and decreases** until stabilisation (CI2).	• As a general recommendation, authors argue that **policies should simultaneously** replace virgin with recycled material and increase sorted waste but ensure the material price does not decrease. Different scenarios demonstrate **different instruments.** Authors Argue that a combination of the different instruments must be applied **depending on the target** (PR4).
De Gooyert et al. (2016)	• RE is **not the central phenomenon** investigated. Instead, RE **leads to policy resistance in sustainability transitions** (PR1). • The investigation applies **qualitative modelling** and builds upon **participatory modelling** involving 96 participants in 8 workshops (TC1). • Focuses on the **national Dutch energy transition** (Macro-level) (CC1).	• The argument is centred on **finding leverage points in feedback loops** that sustain (reinforce) or hinder (balance) sustainability transitions (SO1 and SO2). **Multiple factors influence the investment** in renewables: energy market price, civil engagement, and the cost of energy production (NL1). • Includes both **consumption and production side reactions** (GF1) – e.g., the feedback in energy sufficiency by consumer-side production in lowering the market price that will	• The **modes of behaviour that emerge** from analysing the model (Ad1) show that **several mechanisms play against the investment in renewable energy** (SO2), leading space to encounter **reinforcing mechanisms that might unlock the transition** (SO1). The argument for the energy transition relies on **phasing out fossil fuels**, as the economies of scale and vested interest in the incumbent energy system play against the transition (HD1).	• Policy recommendations are designed **based on leverage points identified in the model** to address policy resistance: releasing the power of vested interest through creative destruction, which will release the government to focus on overturning policies (SO1 and PR4). Argues that interventions should be combined, as focusing in only one part of the system will result in resistance in another part (PR4). The study **does not address the RE specifically.**

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Table A1 (*continued*)

Reference	Investigation framing	RE explanation	RE assessment	RE recommendations
		bring fewer investments. Also, **explicitly consider societal interests** via the calming effect of sustainable energy production in civil unrest (TC1). The study considers technological, ecological, social, economic, and political factors, identifying them as **sub-systems** that influence each other (CC2). • In the model, **RE occurs as a balancing loop to energy system sustainability**, activated by a decrease in price and costs (PR1 and SO2). **Investment in renewable energy is the proxy variable** for the energy transition (TC2).		
Laurenti et al. (2016)	• RE is **not the central phenomenon** investigated. Instead, RE is **an unintended consequence of environmental action** (PR1). • The investigation applies **qualitative modelling** and builds upon **literature review**. • The study takes broad system boundaries to illustrate the dynamics of **physical consumer goods** (Macro-level) (CC1).	• The argument centres on the **reinforcing loop between innovation, product obsolescence, consumption, and economic growth** (SO1). **Multiple factors determine consumption** as the lifespan of products and the consumer costs (NL1). • It includes both **consumption and production-side reactions** – e.g., innovation and efficiency measures by producers and increased consumption responding to those measures (GF1). • RE occurs as a **reinforcing loop for consumption, activated by consumer costs decreases due to increased efficiency** (PR1 and S12)**. Negative externalities are also mapped as reinforcing loops** that drive consumption due to non-internalised consumption costs (SO1). Meanwhile, several other negative environmental and social impacts are named ripple effects. • **Waste pollution** is the proxy variable for **environmental impacts,** while **economic inequalities** for **social impacts** (TC2).	• The **modes of behaviour that emerge** from analysing the model (Ad1) show that **incremental efficiency improvements will result in more significant waste generation, reverberating into negative environmental and social impacts** (SO3).	• Policy recommendations are designed **based on leverage points identified in the model**: consumption and incremental innovation (SO1 and PR4), which lead to economic growth without additional resource consumption**.** Recommendations are **included in the model**. For instance, they show that environmental policy instruments could help internalise costs and counterbalance the externalities mechanisms (SO2). In contrast, it **does not address the RE specifically.**
Cavicchi (2016)	• **Did not investigate RE directly; encountered RE by** investigating regional biogas development in a region and its impacts on sustainable development (PR1). • The investigation applies **qualitative modelling** and builds upon **semi-structured interviews and public reports**. **Informants include** bioenergy producers, farmers' union members, governmental actors, and members of local committees (TC1). • Focuses on **regional bioenergy adoption in northern Italy** (Macro-level) (CC1).	• The model encompasses **economic, environmental, social, and technological processes** (CC1). In addition, the **use of colours in the model makes explicit the interrelations** of the different sub-systems (CC2). • **Multiple factors determine biogas production** as reinvestments from profits, which are reinforced by governmental incentives (NL1). • The argument is based on **several reinforcing and balancing loops** that emerge in the economic, environmental, and social spheres (SO1, SO2, and TC2). For instance, from an economic perspective, **reinforcing loops** enhance producers' profit by lowering costs or increasing revenues (SO1). From an environmental perspective, **balancing loops** show the intended consequences in controlling GHG emissions while **reinforcing loops** communicate the unintended ones (PR1, SO1, and SO2). **GHG emission** is adopted to assess sustainability impacts (TC2). • **Local warming** and the **emissions from intensified traffic in the area**	• The modes of behaviour that emerge from analysing the model show the **tensions between the contribution to European targets and the regional environmental and social effects** (CC1 and GF2)	• Based on the idea that the **identified problems emerged from a profit-oriented policy** (PR3), the author argues for a **policy portfolio** that could **influence the different feedback loops at play and align the different interests** (PR4 and TC1). However, the identified **RE are not explicitly addressed** in the policy discussions.

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Table A1 (*continued*)

Reference	Investigation framing	RE explanation	RE assessment	RE recommendations
		are two of the **identified RE** (PR1, CC1 and GF2). From a **social perspective**, farmland rent price raises the odds of conflicts and hampers cooperation (TC2). • There are **delays indicating the time taken** for building infrastructure for biogas production and the time taken between civil society pressure and governmental reactions (HD2).		
Freeman et al. (2016)	• **RE is the central phenomenon**. Examine the causal mechanisms leading to RE and discuss if it is inevitable (PR1). • The investigation applies **qualitative and quantitative modelling** and builds upon a **long-term case study on the RE occurrence**. • Focuses on **regional road transport in the UK** (Macro-level) (CC1).	• Two conceptual models sustain the argument – a no-rebound model and a structural rebound model (Ad1). **A few factors determine how much people drive**, such as costs, congestion, and social norms (NL1) • The models make explicit a few demand mechanisms, such as the **balancing loop** that limits growth in driving due to costs of fuels and vehicles (SO2) and the **reinforcing loop** of fleet efficiency increasing travelling and more supply-side investments (SO1), integrating **consumer and producer-side reaction** (GF1). • RE occur as **feedback loops** that increase distance driven per person, activated by road building through congestion, social norms for travelling more, travel costs, and additional income (SO1, SO2 and PR1). The building of roads to release congestion makes explicit RE occur from changes in **seemingly unrelated behaviour** (GF2). The feedback between **social norms** and consumption rates indicates the influences of social systems in RE (Ad3). • There are **delays indicated in a few of the structures leading to RE** (CI2).	• The **simulation model** comprises **four sub-models** representing the theory: economic growth, social norms, vehicles-in-use, and road network (CC2). • Exogenous uncertainty factors influence such as **political ideology** that could prioritise private or public transportation, **regional policy** and **science development** (TC1). • The model is calibrated against historical data. Then, **four scenarios** show the effect of behavioural change for travelling less, technological investment into fleet efficiency, the inclusion of externalised costs, and investment into public modes of transportation (PR2). **Total emission** is adopted as the variable to assess sustainability impacts and RE (TC2). Several other **indicators relevant to public and private stakeholders** assess the scenarios, such as the cost of road travel per km and the fleet efficiency in km per litre (TC1). • Some **indicators show exponential growth or decline from one policy to another**, indicating potential **amplifications** by small changes in factors (SO3) and **non-linear relationships** between system elements (NL2).	• Authors argue for a **mix of policies to influence the strength and direction of the different feedback loops** at play. The results indicate that reductions in travel by individuals and increased investment by the public sector and industry are needed **to reach the desired decrease in emissions while considering RE occurrence** (PR4). The four scenarios **examine the behaviour of combinations of proposed policies.**
Freeman (2018)	• **RE is the central phenomenon**. Examine the historical role of RE in socio-technical systems and discuss how RE magnitude might change in the future (PR1). • The investigation applies **qualitative modelling** employing hybrid modelling (i.e., CLD that makes explicit critical stocks and flows). It builds upon a **literature review** of concepts of natural capital, global ecological footprint, and the great acceleration. • The author adopts an **"extremely large" system boundary** to support the angle of the investigation (macro-level) (CC1).	• The model comprises two main sub-systems: socio-technical and natural capital systems (CC1). The argument is centred on the **stocks of natural capital, human-created capital, and waste** (TC2), the **flows between them**, and the **causal relationships** that enable them. **Multiple factors determine the production of goods and services** as population size, consumption per person, and availability of resources (NL1). • The model demonstrates **several reinforcing and balancing loops** (SO1 and SO2). For example, increased access to goods and services leads to an increasing population due to longer lives, which increases consumption (SO1). Meanwhile, limited natural stocks will inherently limit the available resources for growth (SO2). The model includes **consumers' responses** to lower costs and **producers'** investments in technology and operations due to increased sales (GF1). • The **core RE dynamics occur due to a reinforcing loop** from increased consumption, driving technology development up and decreasing consumption costs (PR1).	• The **potential system evolution** is discussed for three pathways based on the **interplay of the identified feedback loops** while considering the **potential role of four types of RE**: secondary, transformational, frontier and international (PR1). The analysis suggests that the **RE will play a different role and hold different magnitudes according to the system's evolution** (Ad1 and PR2). This might indicate **heterogeneity in scenarios** (NL3) due to **moderating or mediating factors** (NL3) changes. In some cases, it is suggested that **RE might disappear or even reverse**, indicating differences in short- to long-run responses (CI2).	• Recommendations **lead towards the most desired pathway**. The study concludes that **RE might be less or more important according to the pathway** (Ad1) and only mentions that policies and investment decisions **should be designed** to avoid them (PR4).

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