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ORIGINAL ARTICLE

Building on and contributing to sustainability transitions research with qualitative system dynamics

Vincent de Gooyert[1] · Attabik Awan[2] · Cem Gürsan[1] · Floris Swennenhuis[1,3] · Zahra Janipour[1,3] · Sara Gonella[1]

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Abstract

This paper explores the novel connection between qualitative system dynamics and sustainability transitions research. As the urgency for sustainable solutions intensifies, this interdisciplinary combination offers a promising avenue for addressing complex sustainability challenges. We reflect on recent research projects to establish the value of combining the two fields. We delve into the methodological and theoretical synergies, using examples to illustrate how the two fields can mutually benefit from each other. We find that qualitative system dynamics complements other sustainability transitions research approaches by encouraging (a) more inductive research that results in a broader system boundary than traditional sustainability transitions research frameworks and (b) higher endogeneity, which leads to a better appreciation of the feedback mechanisms that determine whether transitions succeed or not. This leads to an explicit reflection on assumptions that otherwise might remain hidden, and more explicit conceptualizations of the feedback mechanisms driving and hindering sustainability transitions and recommendations on navigating seemingly opposing interests that diminish when seeing the whole system. We also propose how future research can contribute to further cross-fertilization between the two fields, including the need for explicit positioning in terms of starting points, considering different philosophical paradigms, exploring combinations with other analytical approaches to foster change, and increasing reflection on the part of researchers, particularly in participative modes. We argue that the fusion of qualitative system dynamics with sustainability transitions research can significantly enhance our understanding and ability to manage complex sustainability issues, substantially contributing to both academic discourse and practical applications in sustainability transitions.

Keywords Sustainability transitions · Qualitative system dynamics · Systems approaches · Feedback mechanisms · Endogenous view

Abbreviations

CLD Causal loop diagram
MLP Multilevel perspective
TIS Technological innovation system
QSD Qualitative system dynamics

Introduction

Addressing current challenges, such as climate change, biodiversity loss, and poverty, requires a substantial change in all facets of our society and economy. All our systems need to change, from industry, housing, and mobility to electricity and agriculture. With the increasing urgency of these challenges, a new field of research has emerged that is now known under the label "sustainability transitions research" (Loorbach et al. 2017; Köhler et al. 2019). Although the field is very diverse, a main commonality shared by all scholars is that they consider sustainability to be a matter not just of individual technologies and innovation but also of how those

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✉ Vincent de Gooyert
vincent.degooyert@ru.nl

[1] Institute for Management Research, Radboud University, Heyendaalseweg 141, 6525 AJ Nijmegen, The Netherlands

[2] School of Industrial Engineering & Innovation Sciences, Eindhoven University of Technology, Groene Loper 3, 5612 AE Eindhoven, The Netherlands

[3] Radboud Institute for Biological and Environmental Sciences, Radboud University, Heyendaalseweg 135, 6525 AJ Nijmegen, The Netherlands

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technologies co-evolve with cultural, behavioral and other social aspects in broader socio-technical systems (Markard et al. 2012). Scholars in this field argue that the required system-level changes are to be achieved through fundamental transformation processes or transitions (Markard et al. 2012; van den Bergh et al. 2011). They strive to make sense of the dynamics of these transitions by starting from describing empirical cases, treating human behavior as a complex object of study, and going beyond traditional models of humans as rational actors (Geels et al. 2016), often ending with policy recommendations to augment transitional processes. According to the field of sustainability transitions research, the required transitions are complex because they involve various interdependent actors and are influenced by nonlinear interactions between technical and social elements at multiple levels. The conceptual models and frameworks to understand sustainability transitions acknowledge this dynamic complexity and have been considerably developed (Bergek et al. 2007; Geels 2002; Kemp et al. 2007; Rotmans et al. 2001).

System dynamics is a methodology developed to understand and manage complex systems through the modelling and simulation of causal structures and feedback mechanisms (Sterman 2000), and qualitative system dynamics uses the same feedback thinking and diagrams but then without computer simulation. System dynamics is suitable for understanding the multiple and interacting dynamic processes in sustainability transitions research (Moallemi et al. 2017a, b; Papachristos 2018, 2019). However, the combination of qualitative system dynamics and sustainability transitions research is still nascent. Several studies have connected system dynamics to the field of transitions modeling (e.g., Halbe et al. 2020; Holtz et al. 2015; Köhler et al. 2018; Leventon et al. 2021; Moallemi and de Haan 2019; Papachristos 2018, 2019; Purvis et al. 2022), and transition frameworks (e.g., Papachristos 2011; Walrave and Raven 2016; Yücel and Chiong Meza 2008). However, these studies often either focus on quantitative system dynamics that revolves around computer simulation or they do not distinguish between qualitative and quantitative system dynamics, resulting in an underappreciation of links between sustainability transitions research and qualitative system dynamics. There is a vast debate on the value and limitations of computer simulation modelling for sustainability transitions research, including system dynamics simulation, and how it complements, integrates, and interacts with other approaches (Geels et al. 2016; Holtz 2011; Köhler et al. 2018; McDowall et al. 2017; Moallemi et al. 2017a, b, 2021; Moallemi and Malekpour 2018; Papachristos 2011, 2014, 2018, 2019; Trutnevyte et al. 2014; Turnheim et al. 2015). Our study is different in that we strictly focus on qualitative applications of system dynamics, which hitherto has remained a gap in the literature. Through filling this gap, we contribute to a closer connection between qualitative system dynamics and sustainability transitions research to help future qualitative system dynamicists studying sustainability transitions navigate challenges and opportunities. We build on experiences of several cases where we applied qualitative system dynamics in the context of sustainability transitions (Awan 2020; de Gooyert et al. 2024; Janipour et al. 2022; Gonella 2021; Gonella and de Gooyert 2024; Gürsan and de Gooyert 2021; Gürsan et al. 2024; Janipour et al. 2021; Swennenhuis et al. 2024).

The article is organized as follows. We first provide a background on sustainability transitions research and qualitative system dynamics. Then, we present a section discussing the benefits of combining qualitative system dynamics and sustainability transitions research, followed by a conclusion that summarizes the main benefits in Table 1. This is followed by a discussion linking our findings to broader debates, limitations, and future avenues for further cross-fertilization between qualitative system dynamics and sustainability transitions research.

Background sustainability transitions research and qualitative system dynamics

Before we embark on the connection between sustainability transitions research and qualitative system dynamics, we first provide background on both below.

Sustainability transitions research

Over the last half-century, sustainability transitions have become an influential paradigm for describing and studying past transitions, and projecting and examining possible future scenarios (Markard et al. 2012; van den Bergh et al. 2011). Today, the world is facing sustainability challenges in various domains. For example, the current energy system is unsustainable due to increased greenhouse gas emissions, air pollution, energy poverty, shortage of natural resources, and uncertainties over energy security in the short- and long-run. Supply systems, such as the energy sector, can be conceptualized as socio-technical systems consisting of networks of actors, institutions, materials, and knowledge. To supply services to society, different interrelated components of the system interact and co-evolve with institutions (Markard et al. 2012). To deal with sustainability challenges, a fundamental shift in the existing socio-technical systems needs to occur. Such transition requires substantial changes in society's technological, organizational, political, institutional, economic, and socio-cultural dimensions (Geels and Schot 2010). The complexity and versatility of sustainability transitions require the involvement of stakeholders (Leal Filho and Londero Brandli 2016), who may not share the same

Table 1 Contributions from qualitative system dynamics to sustainability transitions research and vice versa

Benefits of combining qualitative system dynamics and sustainability transitions research	
Description	Consequence
Broader system boundary Qualitative system dynamics encourages a more inductive approach, resulting in a broader system boundary than traditional sustainability transitions research frameworks. It starts with the problem at hand and maps all relevant variables	The more inductive and holistic approach allows for including variables from multiple disciplines, avoiding a narrow focus on one or a few theoretical domains. Such a broader perspective allows a more in-depth exploration of the problem space, uncovering interdependencies and feedback loops that may not be immediately apparent. This enables a more comprehensive understanding of the complex and interdisciplinary nature of sustainability transitions. This also helps uncover the interdependencies between stakeholders, which results in a better appreciation of how each stakeholder group is both enabled and restricted by its context, avoiding the pitfall of overemphasizing the agency of certain stakeholders while underestimating others. This balanced perspective helps address conflicting interests and find alignment among stakeholders, facilitating collaboration and consensus-building
Higher degree of endogeneity Qualitative system dynamics encourages a higher degree of endogeneity compared to more traditional sustainability transitions research frameworks	Encouraging endogeneity leads to a better appreciation of feedback mechanisms and related systemic effects of technologies and policies. The focus on explicitly drawing causal relationships helps challenge assumptions that might otherwise remain hidden. This can help researchers and stakeholders comprehend the sources of policy resistance and identify leverage points for interventions that support sustainability transitions
Integration of frameworks and theories Sustainability transitions research has a rich collection of frameworks and theories to which applications of qualitative system dynamics can connect	Building on earlier sustainability transitions research frameworks and theories and iterating between primary qualitative system dynamics data and secondary sustainability transitions research data helps to increase the theoretical generalizability of results and recommendations. Qualitative system dynamics provides visual representations, such as causal loop diagrams, to communicate and visualize such frameworks and theories, enhancing understanding and communication of causal mechanisms responsible for the (non)evolution of the systems, thus enabling stakeholders to identify sources of policy resistance and design effective interventions. Connecting applications of qualitative system dynamics with other sustainability transitions studies helps to contribute to a broader accumulation of knowledge

understanding of the problem definition and subsequent sets of actions to create sustainable socio-technical systems that do not exist yet.

Historically, sustainability transitions research emerged as an interdisciplinary subject both empirically and intellectually. On a pragmatic level, it connects the worlds of science and policy to address grand societal problems that are "unstructured" (Loorbach et al. 2017), "wicked" (Hazard et al. 2020), "tangled" (van Assche et al. 2022) and "messy" (Kivimaa et al. 2021). On an intellectual level, it can be traced back to the two significant clusters of innovation research (including science and technology studies, history of technology, evolutionary economics, and innovation policy) and environmental studies (including environmental assessment, integrated assessment, sustainability governance, and environmental policy (Arthur 2016; Kemp 1994; O'Riordan 2001; Rip and Kemp 1998; Rotmans 1998; van Asselt and Rotmans 1996; van den Bergh and Gowdy 2000). Thus, sustainability transitions research got its footing from the need to study the dynamics of grand societal challenges and to steer the formulation of systemic solutions for them.

Two main approaches to studying sustainability transitions are the Multilevel Perspective (MLP) and the Technological Innovation System (TIS) approach. The MLP analyses reality from three levels: regime, niches, and landscape (Geels 2002, 2006; Geels and Schot 2007). Transitions in the MLP are characterized by the destabilization of the socio-technical regime via interactions at all three levels (Geels and Schot 2007). These could be the innovations happening at the niche level, e.g., new technologies or new ways of working, the pressures applied by events at the landscape level, e.g., war or internal tensions in the regime that create the window of opportunity for the niche to emerge, e.g., changing preferences of actors towards fossil-fuels. Similarly, another dominant approach in transition studies is the Technological Innovation Systems (TIS), where the focus is on the generation, diffusion, and utilization of new technologies or new fields of knowledge (Bergek 2002; Bergek et al.

2007; Hekkert et al. 2007; Suurs and Hekkert 2012). The generation, diffusion, and utilization of emerging technology in a TIS are determined by the existing system structure (static elements) and its innovation functions or 'motors of innovation' (dynamic elements) (Suurs and Hekkert 2012). A TIS might be contained within a sector (where the analysis is focused on a specific innovative technology, e.g., solar PV) or cross-sectoral (where the focus is on an entire technological field, e.g., renewable energy technologies). Transitions are accelerated when the visions and activities of different actor groups align within the system, and they are completed when the existing system (existing TIS) is replaced by the emerging TIS (Bergek et al. 2007).

Qualitative system dynamics

System dynamics is a broad approach that combines various elements, namely feedback thinking, structure, levels and rates, modeling and simulation, and policy design (System Dynamics Society n.d.). However, not all applications of system dynamics haven an equal emphasis on all elements of system dynamics (de Gooyert and Größler 2018). Indeed, some studies focus on the feedback thinking, structure, and policy aspects of system dynamics and do not include computer simulation in any way. In this article, we use the term qualitative system dynamics to refer to system dynamics without simulation: the adoption of all elements typically associated with system dynamics, except for computer simulation. Such studies typically use system dynamics tools like causal loop diagrams and/or stock and flow diagrams but do not provide equations and simulation runs, for example, because the study is more aimed at exploring and mapping the structure of complex issues and causal relationships between main variables and fostering shared problem definitions and a shared language to allow coordinated action across stakeholders, rather than prioritizing policies per se. Some applications of qualitative system dynamics include the participation of groups of stakeholders and/or experts, for example, using group model building (Vennix 1996), but for us, qualitative system dynamics does not necessarily include groups and can also rely for example on other primary qualitative data (interviews), or secondary qualitative data (any text including scientific articles, gray literature, reports, minutes of meetings, and so on).

Other terms can also refer to what we mean by qualitative system dynamics, including labels like “systems thinking” and “soft operational research” (Forrester 1994). However, we prefer using qualitative system dynamics because those other terms are broader and include elements not typically adopted in system dynamics. Hence, using those other terms would dilute the importance of feedback thinking, structure, and policy aspects that we find so important in the studies where we apply qualitative system dynamics. Earlier studies have already discussed how qualitative and quantitative system dynamics complement each other and how each has distinct characteristics and contributions (Coyle 2000; Forrester 1994; Richardson 2011; Richmond 1994; Wolstenholme 1999). In line with those articles, we acknowledge that qualitative system dynamics has limitations, as does quantitative system dynamics or any other research approach. If based on intuition alone, causal loop diagrams and stock and flow diagrams can very well lead to misleading takeaways, and it is clear that system behavior cannot be inferred from any but the simplest qualitative models (Forrester 1994). However, computer simulations can be misleading as well and give a false sense of accuracy, for example, if the quantitative data used in those simulations is not of high quality and the interpretation of those numbers can be misleading if the definitions used when collecting data oversimplify the rich complexity of concepts that constitute the problem at hand. We conclude from those earlier studies that different approaches all have their strengths and weaknesses. Our aim in this article is to discuss the value of adopting qualitative system dynamics in the context of sustainability transitions research.

Benefits of combining qualitative system dynamics and sustainability transitions research

Based on our experiences in recent research projects (Awan 2020; de Gooyert et al. 2024; Janipour et al. 2022; Gonella 2021; Gonella and de Gooyert 2024; Gürsan and de Gooyert 2021; Gürsan et al. 2024; Janipour et al. 2021; Swennenhuis et al. 2024), we see three main benefits of combining qualitative system dynamics and sustainability transitions research: adopting qualitative system dynamics encourages broadening the system boundary compared to more traditional sustainability transitions research, it encourages a higher degree of endogeneity and sustainability transitions research offers a rich collection of frameworks and theories that qualitative system dynamics can draw from. Below, we elaborate on these benefits using illustrations from our research, and we discuss the implications of these differences for research and policy recommendations.

Qualitative system dynamics encourages a broader system boundary

We find that qualitative system dynamics encourages adopting a broader system boundary compared with most sustainability transitions research, leading to more holistic approaches. Sustainability transitions research is typically organized around theoretical domains, including political science, geography, business administration, and so on

(Luederitz et al. 2017; Köhler et al. 2019). Although sustainability transitions research is inherently interdisciplinary, the strong emphasis on theoretical advancements often leads to a focus that is confined to a small number of disciplines or that emphasizes one central discipline with other disciplines playing only a peripheral role, e.g., focusing on politics (Avelino et al. 2016), geography (Truffer et al. 2015), or business administration (Loorbach and Wijsman 2013). Sustainability transitions research strongly emphasizes theoretical contributions, requiring researchers to be very clear on the discipline to which they contribute. This is understandable from the way that academia is organized, with research institutes, journals, and careers primarily organized around disciplines, but this also led to critical reflections that sustainability transitions research should adopt more holistic, integrated perspectives to better fit the messy and interdisciplinary nature of sustainability transitions (Andersen et al. 2020; Luederitz et al. 2017; Rosenbloom 2020).

Qualitative system dynamics typically starts from a central problem variable, a reference mode of behavior of that problem, continued by mapping all relevant variables to understand the behavior of that problem (Vennix 1996). This encourages those applying the method to not confine themselves to variables associated with a certain discipline. This holds for researchers when qualitative system dynamics is applied in a non-participatory mode and for participants when applied in a participative mode (Moallemi et al. 2021; Moallemi and Malekpour 2018). It resembles a best practice amongst system dynamicists that in the community is considered of the highest importance when it comes to system conceptualization: "approach system conceptualization creatively, from different perspectives" (Martinez-Moyano and Richardson 2013, p. 112). This characteristic of qualitative system dynamics makes the approach more inductive: the analysis starts from the problem and works its way up. Although sustainability transitions research often shares the ambition to inductively start from empirical cases to then involve the disciplines that the case requires, the focus on theoretical advancements sometimes leads studies to start from a theoretical body of knowledge, using a problem as a case to further advance knowledge in that theoretical domain. Although qualitative system dynamics can also be applied in a purely deductive fashion (de Gooyert 2019), and sustainability transitions research can also be applied in an inductive or retroductive fashion (McDowall and Geels 2017; Papachristos and Adamides 2016), the way that qualitative system dynamics projects are typically organized in general leads to more holistic and integrated results. We see this back in our research projects, where results typically are not associated with a single or a primary discipline. For example, de Gooyert et al. (2016) study the progress of the Dutch energy transition and connect technological diffusion with financial, social, economic, and policy aspects; Gonella and de Gooyert (2024) study sustainability in the chemical industry and include social, economic, and ecological aspects of sustainability, and Janipour et al. (2021) study the sustainability transition of industrial clusters and cover economic, legal, social, and policy aspects.

The inductive nature of qualitative system dynamics is relevant because it has substantial implications for results and recommendations. The more holistic approaches lead to a better appreciation of how stakeholders are enabled and restricted by their context. Starting sustainability transitions research from a primary discipline may assume the perspective of one type of stakeholder. For example, approaching sustainability transition from a business administration perspective leads to recommendations on what businesses can do differently to foster sustainability transitions, and that approach typically treats what other stakeholders do (e.g., governments, citizens) more or less as a given. This has the pitfall of overestimating the agency (the extent to which stakeholders have space to influence sustainability transitions) of the central stakeholder and underestimating the agency of other stakeholders, which led to a critique of sustainability transitions research of suffering from discursive fixation (Pesch 2015). Below, we provide an illustration from our research (Janipour et al. 2022) to elucidate how qualitative system dynamics leads to a more balanced approach where each stakeholder is understood as being both enabled and restricted by its context, i.e., each stakeholder having some but limited space to influence sustainability transitions [see for a positioning of system dynamics in the structure agency continuum Lane (2001a, b) as well as de Gooyert et al. (2016)].

In Fig. 1, we illustrate the above with an example based on Janipour et al. (2022) and Swennenhuis et al. (2024). In those studies, the authors show how sustainability transitions can be hindered by the mutual interdependence of government, industry, and society. Industry is restricted because it can only continue to exist if they commit to investments with a positive business case: investing in sustainable technology must be profitable for the industry to survive. Whether investments in sustainable technology are profitable can be enabled by supportive policies or regulations. This suggests that governments have the potential and agency to facilitate sustainability transitions by imposing the required policies. However, governments are restricted because they can only enforce policies and regulations that require support from society. Without support, policies lack legitimacy, and committing to such policies would mean political suicide, elected officials would not be re-elected, and policies would be reversed in the next election cycle. This puts the agency in the hands of society, which determines whether there is support for policies or not. However, this societal support for policies supporting industry to invest in sustainable technology is, in turn, influenced by industry: past industry behavior

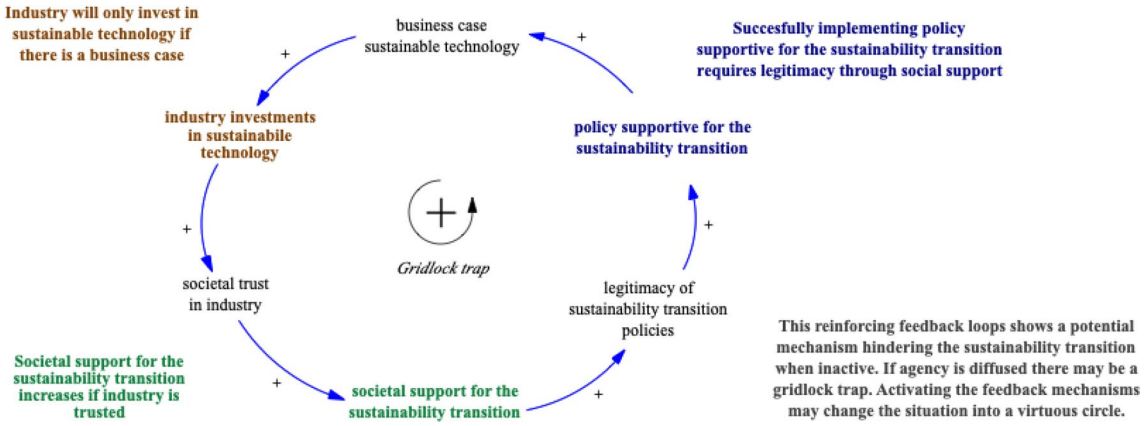

Fig. 1 Example of a stakeholder interdependence in a sustainability transition, based on Janipour et al. (2022) and Swennenhuis et al. (2024)

determines whether society is willing to provide it with the social license to operate. Paradoxically, investing in sustainable technology, which requires societal support, is one crucial way by which industry can foster the societal support necessary for the policies that enable these investments. The interactions between these stakeholder groups form a feedback loop that reinforces the dominant sentiment. This may form a chicken-and-egg situation or a gridlock trap, where the agency is diffused amongst actors. The mutual dependencies make each individual actor both restricted and enabled to act. Qualitative system dynamics encourages research to continue to explore how each actor is enabled and restricted by others, which helps to avoid the pitfall of ascribing too much or too little agency to actors, as is sometimes seen in other approaches in sustainability transitions research (Pesch 2015).

In addition, we find that adopting a more holistic approach with qualitative system dynamics leads to a better appreciation of how stakeholders' interests are not only conflicting but also aligned. Sustainability transitions research typically emphasizes conflicting interests, conceptualizing transitions as a buildup of activities by new actors and a consequent breakdown of activities by actors that used to be dominant (Loorbach et al. 2017). Sustainability transitions research has its roots, amongst others, in evolutionary economics, which emphasizes the struggle for survival between actors and processes of actors replacing each other through creative destruction (Loorbach et al. 2017). In contrast, the inductive nature of qualitative system dynamics, resulting in more holistic analyses, shows how competing actors may have aligned interests. For example, Janipour et al. (2021) describe two contrasting narratives about carbon capture and storage. Opponents argue that carbon is too risky, while proponents plead socio-economic and climate benefits. Using qualitative system dynamics, we find an alternative narrative possible: carefully regulated carbon capture and storage can maximize socio-economic and climate benefits while minimizing carbon lock-in. Qualitative system dynamics helps by making the interactions between stakeholders and the conflicting interests of multiple stakeholder groups explicit and combining them in a holistic perspective beyond that of individual interests. If stakeholder group interests are aligned, their efforts contribute to a common goal of sustainability instead of working against each other and blocking necessary elements of the transition. Qualitative system dynamics, particularly when combined with participative modeling techniques, helps collect and address the different viewpoints of stakeholders around a sustainability challenge and helps acknowledge the interrelated nature of their stakes. This enables finding consensus on the workings of the system, even when opposing stakeholders do not have similar goals. This also translates to an improved shared understanding of the problem, creating a platform for stakeholder collaboration to find longer-term solutions.

Qualitative system dynamics encourages a higher degree of endogeneity

We find that qualitative system dynamics encourages adopting an endogenous point of view. As discussed above, sustainability transitions research is typically organized around theoretical domains, including political science, geography, business administration, and so on (Köhler et al. 2019). This typically leads to distinctions between independent and dependent variables: factor A influences factor B, with A being the independent variable and B being the dependent variable. For example, how do other factors influence political factors, or how do political factors shape other factors. This has led to the critique that sustainability transitions research does not always appreciate the complexity inherent in transitions (Alkemade and de Coninck 2021). Qualitative system dynamics puts a central focus on feedback

mechanisms; for each situation where factor A influences factor B, the system mapping procedure urges you to also consider whether there is also a path through which factor B influences factor A again. Especially building causal loop diagrams is known to encourage an endogenous perspective, with feedback mechanisms as the unit of focus (Martinez-Moyano and Richardson 2013, p. 118). More generally, mapping variables in diagrams makes it visually very clear when a variable has only arrows going out of the variable and no variables coming in, raising the question: are we omitting any factors influencing this variable that has yet no arrows coming in? This process typically leads to "endogenizing" to a higher degree compared with sustainability transitions research and is seen as the foundation of system dynamics (Richardson 2011, p. 219).

The higher degree of endogeneity is relevant because it shifts the focus to feedback mechanisms, and understanding these feedback mechanisms is crucial for understanding and influencing the behavior of sustainability transitions. The appreciation of feedback loops results from the endogenous point of view of system dynamics (Richardson 2011, p. 221). Also, in our research, we have seen how sustainability transitions are substantially shaped by a myriad of feedback mechanisms, including carbon lock-in, learning effects, crowd-out, and carbon leakage (Gürsan and de Gooyert 2021; Janipour et al. 2021, 2022; Gonella and de Gooyert 2024). Below, we briefly elaborate on some such mechanisms with illustrations from our past and ongoing research projects. By addressing these feedback mechanisms and putting them center stage, qualitative system dynamics can contribute to sustainability transitions research (Alkemade and de Coninck 2021). Qualitative system dynamics can help sustainability transitions research by explicitly mapping the reinforcing and balancing feedback mechanisms that drive or hinder a sustainability transition. Sustainability transitions are characterized by path dependencies and lock-ins: path dependency is the inclination of socio-technical systems to continue and develop along existing paths, influenced by their historical evolution, previous investments, and institutional structures that provide barriers to change (Geels and Schot 2007). Because existing socio-technical pathways benefit from economies of scale, a lock-in effect emerges, which means that technologies and institutions reinforce the existing socio-technical pathways both through technological and institutional developments that favor the existing direction (Unruh 2000). Qualitative system dynamics helps elucidate the specific feedback structure of the system that is causing the path dependencies and lock-ins in the current system, thereby enabling researchers and stakeholders alike to understand the sources of policy resistance and identify leverage points for interventions that support sustainability transitions (Hjorth and Bagheri 2006). Comparably, qualitative system dynamic modeling in participatory settings involves stakeholders in the modeling process. This results in a more robust and widely accepted model, especially where shared understanding and consensus support policy development (Moallemi et al. 2021). This is illustrated by de Gooyert et al. (2016), a study on the Dutch energy transition, where policies are historically made using transition frameworks, as an example to show how qualitative system dynamics in a participatory setting can be used to conceptualize the energy system as a superset of various subsystems where technological, ecological, social, economic, and political factors dynamically influence each other. The resulting feedback loops not only assisted in achieving consensus among stakeholders on the sources of policy resistance plaguing the Dutch energy transition but also enabled them to identify leverage points for policy interventions, e.g., heavy governmental investments in renewable energy can lead to "crowding-out" of community-based renewable energy initiatives, and instead a policy mix that supports both governmental and grassroots renewable energy projects would counter the effect of a potential policy resistance.

Another illustration is given in Fig. 2, which shows a causal loop diagram (CLD) adaptation from Gürsan and de Gooyert (2021) of a policy resistance example using natural gas as a transition fuel. Lower natural gas prices in the USA were expected to crowd-out coal usage and thus reduce carbon emissions. The USA was able to reduce its emissions with an ample supply of shale gas; however, the increasing competition in the US fossil market had also pushed the US coal export prices to drop remarkably (Ahmed and Cameron 2014). The affordable coal had been exported to Europe, enabling the coal plants in Europe to stay open and keep running (Baron 2013). This is an example of a fossil spill-over where the offset carbon in the USA had been carried or spilled over to Europe because of the competing coal export prices. The CLD in Fig. 2 shows this unexpected influence of affordable gas prices in the USA on the European energy markets. Affordable gas prices support coal investments because of the balancing loop that connects gas and coal costs. If this balancing loop is overlooked, the rest of the model structure looks highly similar to the 'success to the successful' system archetype (Meadows 2008) (with a causal link between both loops which leads to the spill-over), where we could assume that natural gas would crowd-out coal investments since gas is relatively cleaner and more affordable than coal. In reality, cheap gas prices could offset the emission reduction benefits by allowing more affordable coal prices due to the competition in the energy market. In this example, long-term market effects (economies of scale) and the interconnectedness between global energy markets (competition in US markets' influence on European markets) led to this specific policy resistance mechanism.

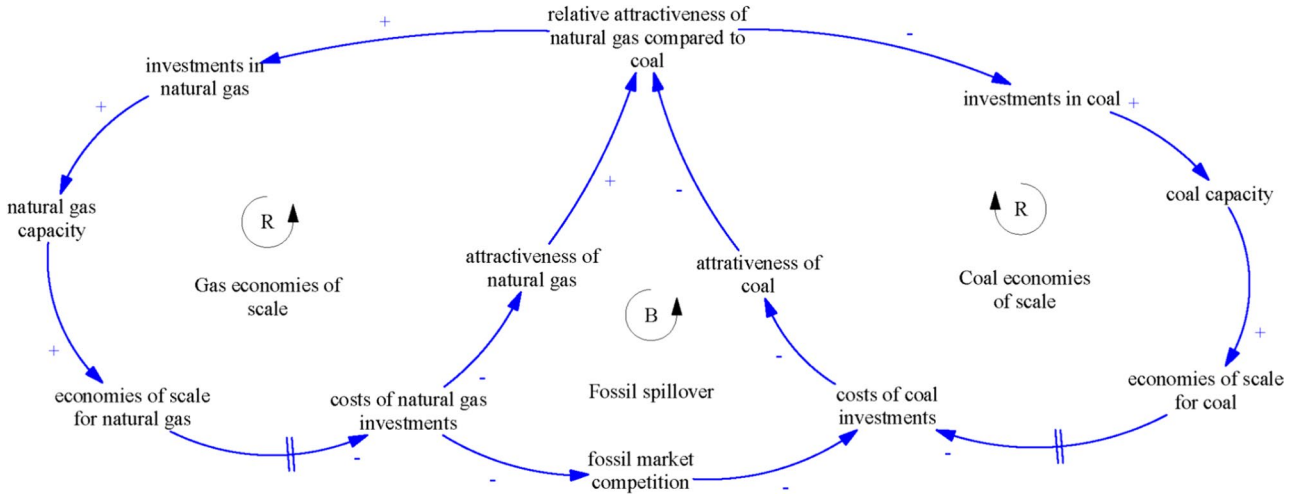

Fig. 2 CLD showing the unexpected influence of affordable gas prices in the USA on the European energy markets (adapted from Gürsan and de Gooyert 2021)

Sustainability transitions research offers a rich collection of frameworks and theories that qualitative system dynamics can build on

Based on our experiences in past and ongoing research projects, we see the main contribution of sustainability transitions research to qualitative system dynamics in offering a rich collection of frameworks and theories to build on when applying qualitative system dynamics to sustainability issues. Below, we elaborate on this point using illustrations. Transitions are large-scale socio-technical changes that are "polycentric, multi-actor, multi-factor, and multilevel with temporal and spatial scales that vary" (Geels and Schot 2007; Köhler et al. 2018; Papachristos 2019, p. 252). They are characterized by dynamic interactions between actors, institutions, technologies, business models, organizations, products, and services. They consist of path-dependent processes that result in specific transition pathways (Geels and Schot 2007). Sustainability transition research studies such pathways and elucidates how different elements of a system, such as technologies, actors, and institutions, cause a "lock-in" and "path-dependency" preventing other (sustainable) pathways from emerging (Geels and Schot 2007), e.g., a strong dependency on fossil-fuel as primary energy source prevents the embedding of renewable energy technologies as their replacement. Applying qualitative system dynamics can draw from this rich ensemble of frameworks and theories to inform the research. System dynamics is fundamentally interdisciplinary. To study and improve complex systems, system dynamics "draws on cognitive and social psychology, economics, and other social sciences" (Sterman 2000, p. 5). Sustainability transitions research can then be seen as another body of knowledge that system dynamics can build on.

At first glance, this observation might seem at odds with our earlier statement above that qualitative system dynamics complements sustainability transition research because qualitative system dynamics is more inductive, less restricted by schools of thought that revolve around one discipline, like political science, geography, business administration, and so on. We argued that qualitative system dynamics helps adopt a more holistic approach because it does not use existing frameworks and theories as a starting point, which seems to conflict with the suggestion that sustainability transitions research complements qualitative system dynamics by offering such frameworks and theories. Therefore, it is good to stress that we do not mean that these frameworks and theories should steer the qualitative system dynamics applications too much, but that they fit in an iterative exploration of a topic through primary qualitative data and secondary qualitative data, with existing scientific publications as one out of multiple sources of data to draw from.

To illustrate this point, we use the research design of one of our studies on a sustainability transition in the chemical industry, see Fig. 3. That study also navigated between inductive and deductive approaches. It used existing documents on the sustainability transition of a chemical cluster and developed a seed model out of that as a starting point for group model-building workshops, as suggested by Richardson (2013). In addition, conversations with stakeholders and a review of earlier sustainability transitions research resulted in a list of topics to discuss in interviews. These interviews then further helped prepare for the group model-building workshops, as also suggested by Vennix (1996). Finally, the results of the group model-building workshops, as well as

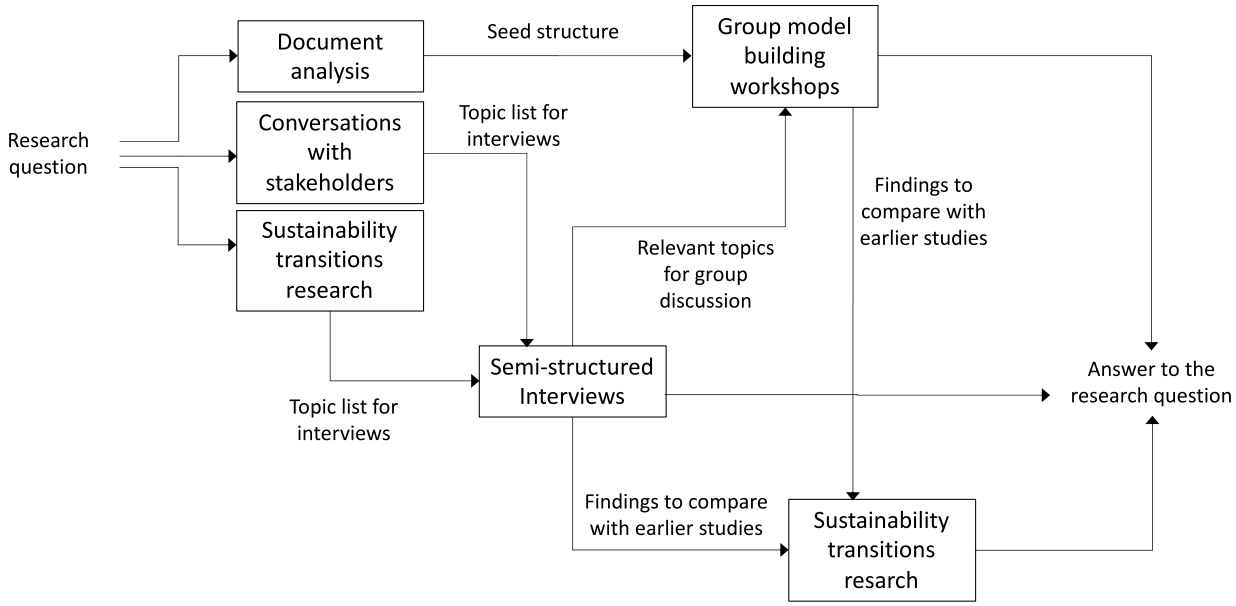

Fig. 3 Qualitative system dynamics drawing from sustainability transitions research (adapted from Janipour et al. 2022)

the individual interviews, were compared with earlier sustainability transitions research to provide an answer to the research question. Figure 3 below provides a more generic research design for a study combining, in this case, participatory qualitative system dynamics and sustainability transitions research, iterating between induction through system dynamics and deduction from sustainability transitions research to provide an answer to the research question that is both holistic and well-grounded in earlier research. Such an approach is also possible for qualitative system dynamics applied in a non-participatory setting, for example, as demonstrated in both Gonella and de Gooyert (2024) and Gürsan and de Gooyert (2021), where secondary qualitative data were used to iterate between various studies, including sustainability transitions research.

The above shows that qualitative system dynamics can be coupled with frameworks and theories from sustainability transition research to complement them and support a more comprehensive analysis. The application of these transition frameworks is primarily limited to qualitative case studies. Research employing formal modeling approaches to understand the transformation of socio-technical systems is still emerging, amongst others under the name transitions modeling (Halbe 2015; Holtz 2011; Holtz et al. 2015; Köhler et al. 2018; Lopolito et al. 2013; Moallemi and de Haan 2019; Papachristos 2019; Walrave and Raven 2016). While we acknowledge that modeling sustainability transitions is an arduous task riddled with complexity and interdependencies of the processes involved, we propose that qualitative system dynamics, both in participatory and non-participatory settings, can fruitfully complement other sustainability transition studies, not the least because it forces scholars to explicitly explore causal links between the dynamics of emerging systems (Raven and Walrave 2020; Walrave and Raven 2016). Transition scholars have acknowledged that modeling approaches like qualitative system dynamics can elucidate transition dynamics more precisely and tangibly by providing the value of visualizing (and communicating) the complex interrelations and feedback in socio-technical systems (Holtz et al. 2015). Exposing these dynamics will allow researchers and stakeholders to use qualitative system dynamics to, for example, identify sources of policy resistance in the system (de Gooyert et al. 2016). Transition frameworks are not always able to fully describe the complex causal relations and underlying dynamics that cause these lock-ins and path dependencies. Using the multilevel perspective as an example, we can conceptualize system pathways as an "aggregate balance of reinforcing and disrupting forces from the landscape, regime, niches, and/or other systems" (Papachristos 2019, p. 253). For instance, these reinforcing and disrupting forces could be dynamic feedbacks between elements (such as actors, institutions, and infrastructure) at a socio-technical level (Geels 2002). For a sustainability transition to successfully transpire, the balance between the endogenous reinforcing and balancing mechanisms at niche, landscape, and other system levels must counteract the balance between the endogenous reinforcing and balancing mechanisms at the regime level. Policy interventions should adapt to the exogenous landscape events and reinforce the balance at the niche and other system levels while diminishing the balance at the regime level. A similar analogy could be made with the incumbent

and emerging systems in the TIS framework. In this spirit, system dynamics can also bridge the two dominant transition study frameworks—an underexplored connection that can potentially have significant benefits (Markard and Truffer 2008; Weber and Rohracher 2012).

Sustainability transitions research often acknowledges the complex nature of sustainability challenges. Various frameworks have been developed in the sustainability transition literature. However, these frameworks do not always have an explicit basis for the causal mechanisms responsible for the evolution of the systems they describe. We argue that system dynamicists can benefit from the existing conceptual frameworks and contribute to the literature by using qualitative system dynamics as an explicit causal language that helps cross the boundaries between disciplines and specialists.

Conclusion

In this article, we have reflected on the benefits of combining two fields of research: qualitative system dynamics and sustainability transitions research. Sustainability transitions are required to preserve the needs of future generations (Markard et al. 2012). Sustainability transitions research acknowledges the complex nature of the socio-technical systems that need to change and aims to advance understanding of how human behavior, institutions, and technologies co-evolve over time (van den Bergh et al. 2011). Sustainability transitions succeed or stall because of the underlying feedback dynamics responsible for either progress or inertia (de Gooyert et al. 2016). By providing explicit, tractable conceptualizations of interrelated causal relationships, qualitative system dynamics helps to improve theory building in sustainability transitions research (Carter and Little 2007).

We identified three key benefits of combining qualitative system dynamics and sustainability transitions research and supported these findings using illustrations from earlier studies. We find that qualitative system dynamics helps sustainability transitions research by encouraging a broader system boundary and a higher degree of endogeneity, and we find that sustainability transitions research helps qualitative system dynamics by allowing advancements through the integration of earlier frameworks and theories from the rich literature that sustainability transitions research has to offer. Table 1 summarizes these key findings.

Using qualitative system dynamics for sustainability transitions research fosters a greater appreciation for how the interests of different stakeholders are interrelated. Mapping the causal feedback mechanisms enabling and hindering sustainability transitions leads to recommendations on how to navigate seemingly opposing interests. The balancing feedback underneath inertia and resistance to change can be addressed by aligning stakeholders' interests, for example, by exploring solutions and narratives where both industry and environmentalists benefit (Gürsan and de Gooyert 2021; Janipour et al. 2021). It shows how a just transition is not just a discussion on normative aspects of sustainability but a pragmatic solution for defining a solution space where the actors involved all help push the system in the same, more sustainable direction (Gonella 2021). Sustainability transitions research and qualitative system dynamics have a lot to benefit from the combination of the two, and we encourage future researchers to contribute to this emerging stream of literature.

Discussion, limitations, and suggestions for future research

In this section, we discuss the position of qualitative system dynamics and sustainability transitions research in broader debates, and provide avenues for future research. The first broader debate that our findings relate to is the debate on epistemological and ontological foundations of sustainability transitions research, which is receiving increasing attention, especially in the discussion about how more case-based narrative studies on the one hand and computer simulation studies, on the other hand, compare (Geels et al. 2016; Geels et al. 2020; McDowall and Geels 2017; Turnheim et al. 2015). As described earlier, qualitative system dynamics and sustainability transitions research both deal with problems that are 'messy' and complicated (Kivimaa et al. 2021; Vennix 1996). Studies start from divergent ontological and epistemological assumptions to investigate these problems. While scientists do not fully agree on how to classify these philosophical paradigms (Avenier and Thomas 2015), the spectrum ranges from positivism to interpretivism (Hazard et al. 2020). Positivistic approaches consider reality independent of the observer and aim to produce knowledge that offers an unequivocal explanation of this 'objective' reality that exists independent of us. The philosophical paradigms that do not consider reality independent of the researcher (such as pragmatism, constructivism, constructionism, relativism, etc.) can be grouped under interpretivism (Yanow and Schwartz-Shea 2015). Interpretivist approaches consider reality socially constructed through each individual's experience and aim to produce knowledge that offers a plausible explanation of the 'subjective' realities appropriate for the lived experience (Avenier and Thomas 2015). While computer simulation models are typically characterized on the positivistic side of the spectrum, case-based narrative studies in sustainability transitions are typically characterized on the interpretivist side of the spectrum. The interesting position of qualitative system dynamics here is that it falls somewhere in between and that it, to some extent, is flexible enough to be applied in different philosophical paradigms,

ranging from positivistic to interpretivist [see for a discussion Lane (2001a, b), as well as de Gooyert et al. (2019)]. In the positivist research tradition, rigor is established using methods that bring models as close as possible to an 'objective' reality. This is primarily achieved by collecting observations dispassionately, quantifying qualitative data, and (predominantly) using deductive logic. In other words, models are "micro-hypotheses or minor content theories" (Lane 2000, p. 12) to be verified, authenticated, or contested. On the other hand, in the constructivist tradition, multiple realities exist that are socially constructed as a cause and consequence of peoples' behaviors towards their environment. Thus, 'systems' do not need to exist in reality, and models describe "how things might be from a particular viewpoint" (Mingers and Rosenhead 2001, p. 299). Such approaches primarily rely on collecting qualitative data through extended discourses with research subjects and (primarily) using inductive logic. Therefore, models are considered rigorous if they reach a certain confidence level and incentivize consensus. While positivistic system dynamicists triangulate to decrease subjectivity [see Homer (1996) for examples], constructivist system dynamicists investigate that very subjectivity [an example is Group Model Building (Vennix 1996)]—perceptions are not considered as a distorted image of reality, but as meanings that an entity assigns to different aspects of reality. We argue that qualitative system dynamics is a fruitful approach to advance sustainability transitions research because it falls in between more positivistic simulation approaches and more interpretivist narrative approaches, but this benefit comes with the challenge that epistemological and ontological assumptions remain hidden, which hinders reflection. Hence, we believe that future applications of qualitative system dynamics in sustainability transitions research would benefit from a more explicit and argued positioning of their foundations. This will help avoid confusion and ensure that contributions are assessed against their intended outcomes in light of the original ambitions.

Another suggestion for future research is to explore potential combinations with other approaches that help to foster the necessary change to bring about sustainability transitions. Both qualitative system dynamics and sustainability transitions research share the explicit aim to contribute to not only generating new knowledge but also addressing problems. However, the change necessary to achieve more sustainable modes of production and consumption often requires more than what a research approach like qualitative system dynamics can offer. At its core, qualitative system dynamics is an analytical approach aimed at creating a better understanding of complex issues. However, even if a perfect understanding of all the complexity of a sustainability challenge is achieved, this may still not be enough to bring about change (de Gooyert et al. 2016). Sustainability transitions require analytical approaches that help identify leverage points (Leventon et al. 2021) and engage stakeholders on an emotional level to inspire action. Therefore, we think combining analytical approaches like qualitative system dynamics with other approaches that engage more on a personal level may prove useful. Such approaches could include shared visioning, for example, that helps individuals to believe in alternative futures, to motivate and empower them (Loorbach et al. 2017), or "futuring" approaches employing, for example, multi-media installations for more immersive experiences to bring about shared orientations for action (Hajer and Pelzer 2018).

A limitation of our article is that we presented illustrations revolving around energy transition and climate mitigation. We expect similar considerations for other sustainability transitions like those around biodiversity and poverty. Future researchers could broaden the types of cases on which they apply qualitative system dynamics for sustainability transitions research, so that it contributes to the broad agenda of sustainable development as discussed in, for example, the Global Sustainable Development Report (Miranda and Scholz 2023), the IPCC assessment reports (IPCC 2023), and the IPBES reports (IPBES 2019). While one approach might be to seek cases beyond energy and climate mitigation in future research, another approach would be to broaden the scope of studies so that the transitions around energy and climate are connected to other sustainable development transitions like biodiversity and poverty. This is the topic of an emerging stream of literature on multi-system transitions (Andersen and Geels 2023; Andersen et al. 2023; Papachristos et al. 2013). In this article, we presented the encouragement of adopting broader system boundaries as one of the key benefits of applying qualitative system dynamics to sustainability transitions research. Indeed, contributing to the study of multi-system transitions would be a logical next step.

A final suggestion is to increase the extent to which we reflect on our role as researchers. Sustainability transitions research is inherently value-laden as it involves bringing about a better world, which requires operationalizing what "better" means. Earlier studies in sustainability transitions research showed how researchers combine roles, including process facilitator, knowledge broker, reflective scientist, and change agent (Wittmayer and Schäpke 2014). Especially for participative modes of qualitative system dynamics, we deem it relevant to reflect more on the positions we take as a researcher, for example using an evaluation framework as the one presented by Moallemi et al. (2021). In a context like that of group model building, you interact with stakeholders and influence how they perceive the sustainability challenge at hand. Exploring leverage points with participants from incumbents who have a stake in current systems might be seen as a justification for systems that stand in the way of required radical change. There is a real danger that efforts

to empower new perspectives may reinforce existing power structures (Avelino et al. 2016).

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Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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