Multi-system dynamics in sustainability transitions: Introduction and outlook

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Abstract

Although it is well-known that major technological change can impact multiple socio-technical systems and their patterns of interaction, the issue of multi-system dynamics in transitions has until recently not attracted much attention. For new sustainability transition phenomena such as decarbonization efforts across various systems or circular economy initiatives that involve entire value chains, it is vital to better understand the ways, in which multiple systems interact and shape each other's transitions. The goal of this chapter is to provide overview and orientation for a rapidly emerging topic by taking stock of the current state of knowledge. We review contributions from three main conceptual frameworks in transition studies: the technological innovation systems approach, the multi-level perspective, and deep transitions. On that basis, we discuss similarities, differences, and open issues to identify a future research agenda for the emerging area of multi-system dynamics in transitions.

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1 Introduction

For many years, scholarship in transition studies has primarily focused on the emergence of innovations and the associated transformation of a socio-technical system such as electricity, transport, or agri-food. This is reflected in key conceptual frameworks such as the multi-level perspective (Geels, 2019) and technological innovation systems (Markard, 2020) that typically portray transitions as unfolding around a specific set of technologies in a focal socio-technical system. Influences from outside the focal system were treated as landscape developments, or context factors.

However, many real-world transitions are increasingly characterized by change processes that span across multiple systems. The net-zero energy transition, for example, involves transitions in heating, industry, and transport, which again rely on low-carbon electricity and the transition of the electricity system (Andersen, Geels, Coenen, et al., 2023; Markard & Rosenbloom, 2022). Similarly, multi-purpose technologies such as ICT, batteries, or carbon capture affect many different socio-technical systems (creating new interdependencies), and the circular economy transition could transform entire value chains across different sectors (Decourt, 2019; Finstad & Andersen, 2023; John et al., 2022; Kern et al., 2020).

Transition scholars have worked on multi-system interactions in the past (Konrad et al., 2008; Papachristos et al., 2013; Raven & Verbong, 2007; Sutherland et al., 2015). This early wave of multi-system interaction analysis generated first ideas about how to approach the topic but also left many questions open (Andersen & Geels, 2023; Bakhuis et al., 2024; Rosenbloom, 2020). Our existing knowledge about multi-system phenomena[1] thus needs to be widened in a new wave of conceptual developments and empirical studies to meaningfully grasp currently unfolding multi-system dynamics (Andersen et al., 2020; Kanger et al., 2021; Rosenbloom, 2020).

To provide an overview and orientation, we review existing work on multi-system interactions in transition studies. We look into three strands of the transitions literature: technological innovation systems (TIS), multi-level perspective (MLP), and deep transitions (DT). We discuss phenomena of interest, types of systems and interactions analyzed, and main insights from each framework, see Table 1. Subsequently, we discuss differences, similarities, and open issues across the frameworks to articulate a research agenda, see Table 2.

We focus on interactions between socio-technical systems in different domains (e.g., energy, transport), whereas we mention interactions between systems in different places (e.g., national, global), or between socio-technical and e.g., political, financial, or educational systems only in passing. Socio-technical systems include interrelated actors, institutions, and technologies (Rip & Kemp, 1998) and they typically provide key societal functions such as energy, transport or food (Konrad et al., 2008). Note that readers should have a good understanding of transition studies, and the individual frameworks discussed in this chapter to fully comprehend the text. An obvious starting point would be chapters on MLP, DT, and innovation systems in this book (Davies & Schot, 2024; Geels, 2024; van der Loos, 2024). Also note that multi-system dynamics as a research topic and

[1] With phenomenon we simply mean empirically observable socio-technical changes in the real world. For example, transition phenomena can vary across systems (e.g., electricity and agri-food), places (global north and south), and according to how advanced they are. We can use theory to conceptualize phenomena to try to achieve general insights about conditions, impacts, processes, and mechanisms of change. In this chapter we are interested in multi-system dynamics phenomena related to transitions in sociotechnical systems.

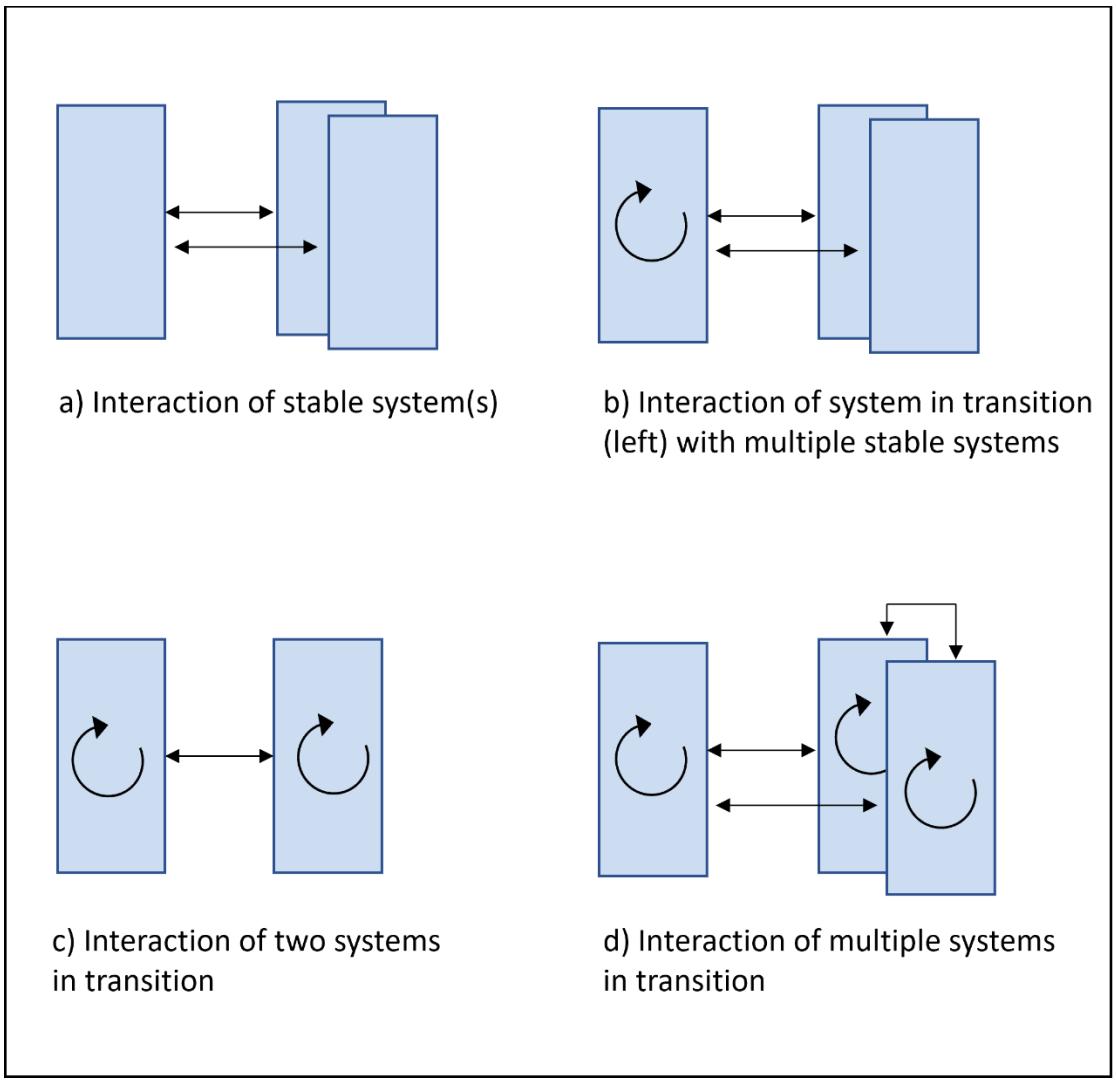
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related concepts are rapidly evolving which implies that our review and discussions merely reflect how we currently perceive the topic.

2 Brief literature review

We distinguish four generic settings of increasing complexity for multi-system interactions to occur, see Figure 1. The first (Figure 1a) is about interactions between two or more stable systems, e.g., through the exchange of resources (input-output relations). For instance, the supply of gasoline (oil and gas system) and conventional cars (vehicle manufacturing system) in the past to the transport system (focal system on the left). This reminds us that multi-system interactions are ubiquitous in modern economies because systems exchange resources all the time. Second (Figure 1b), a focal system is in transition (circular arrow) with interactions to one or more stable systems. For example, the electrification of car-based personal transport in Norway (left) by connecting to an electricity system that was already fully renewable.

Figure 1: Different settings for multi-system interactions



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Third (Figure 1c), interactions of two systems in transition. An example is the electrification of road transport in places where both the electricity and the transport system were originally based on fossil fuels. Fourth (Figure 1d), interactions of several socio-technical systems in transition that together make up a complex of systems. For example, net-zero, digital, or circular economy transitions affecting multiple systems through a shared directionality and interdependent resource exchanges. While multi-system analysis in the second and third setting typically has a focal system as the main unit of analysis , the fourth setting may also come with a shift in the unit of analysis from a focal system towards sets or complexes of interdependent systems (Andersen & Geels, 2023; Kanger & Schot, 2019; Markard & Rosenbloom, 2022).

Table 1: Overview of literature review

Multi-system dynamics phenomena of interest	
TIS	• Emergence, growth, and decline of a TIS involve interactions with different kinds of context systems
MLP	• Niche emergence and transition of focal socio-technical system can involve major/minor changes in other systems
DT	• Landscape changes because of multi-system dynamics
Main types of systems considered in multi-system dynamics	
TIS	• Other TIS, socio-technical systems, other types of systems (e.g., policy, education) and systems at different spatial scales
MLP	• Socio-technical systems • Production, distribution, consumption systems • Niches and regimes
DT	• Socio-technical systems • Complex of systems / multi-system complex
Types of interactions studied	
TIS	• Links and structural couplings • Uni- and bilateral • TIS and context systems • Sector-Sector in technology value chain
MLP	• Functional and structural couplings • Interaction modes: Competition, symbiosis, integration, spillover, niche interference
DT	• Meta-rules and -regimes • Functional and structural couplings • Rhetorical couplings
Main insights	
TIS	• Emerging system must be embedded and connected to context systems • Interactions change as systems change potentially creating conflicts • Multi-system interactions in TIS value chain crucial to TIS dynamics
MLP	• Transitions can be constrained by inertia in other systems • Systems may have incompatible logics • Asymmetric power relations can lead to tensions and conflicts
DT	• Landscape changes can be explained by multi-system dynamics • Similarities emerge across multiple systems, e.g., due to changes in technology or values • Importance of directionality in multi-system dynamics

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We further distinguish between *multi-system interactions,* referring to different types of couplings and resource flows between systems, and *multi-system dynamics*, which refer to sociotechnical change processes (of varying depth) significantly influenced by other systems (i.e., figures 1b, 1c, and 1d). Although interactions and dynamics obviously are closely related, we make the distinction to emphasize that zooming in on the interactions and couplings (e.g., how to design or create them) is only one part of the broader research topic of multi-system dynamics. The distinction also highlights that that different multi-system dynamics phenomena may involve similar types of multi-system interactions.

2.1 Technological Innovation System perspective

The technological innovation system (TIS) perspective places a selected technology center stage with the idea to analyze its prospects, often including drivers and barriers (Bergek et al., 2008; Hekkert et al., 2007). The focus is typically on early stages of innovation, but also diffusion of innovations from small to mass-markets as well as mature technologies and those in decline have been studied (Andersen & Gulbrandsen, 2020; Carlsson & Jacobsson, 1994; Markard et al., 2020).

Types of systems: From the outset it was acknowledged that TIS necessarily interact with other systems in its context (Carlsson & Stankiewicz, 1991; Edquist, 1997; Markard & Truffer, 2008). These systems include other technological innovation systems (Bergek, Hekkert, Jacobsson, Markard, Sanden, & Truffer, 2015), established socio-technical systems (Markard et al., 2016) different systems in a technology value chain (Andersen & Markard, 2020; Mäkitie et al., 2022; Stephan et al., 2017), and systems at other spatial scales (Binz & Truffer, 2017). This shows that there is a broad range of systems whose interactions we can study. We will get back to this in section 3.

Types of interactions: Bergek et al. (2015) distinguished two types of interactions between a focal TIS with systems in its context: *links* and *structural couplings* (Bergek, Hekkert, Jacobsson, Markard, Sanden, & Truffer, 2015). The former capture uni-lateral influences (i.e., context systems affecting the TIS but not vice versa), whereas the latter capture bi-lateral interdependencies. Structural couplings are understood as elements (e.g., actors, networks, institutions, technologies) shared by the focal TIS and context systems. The same actors, for instance, may operate in multiple systems, technologies may be used in multiple systems, and systems may also have similar institutions (e.g., mass production logic) (Bergek, Hekkert, Jacobsson, Markard, Sandén, & Truffer, 2015). For example, some oil companies diversified into offshore wind creating new structural couplings between the oil and gas system and the offshore wind TIS (Mäkitie et al., 2018). Scholars have also referred to functional couplings (see below) between the systems involved in a TIS value chain to describe the flows of material resources between them (Gong & Andersen, 2024). A TIS may also have linkages to context systems as finance, education, or science (Fontes et al., 2021; Malhotra et al., 2019).

Main insights: In our reading, TIS studies have made at least three contributions to multi-system dynamics. First, novel technologies need to be embedded into a wider context of existing systems and structures: to obtain resources, to benefit from complementary innovations, to attract firms, to receive policy support, or to create legitimacy (Binz et al., 2016; Binz & Truffer, 2017; Karltorp et al., 2017; Wirth & Markard, 2011). For this embedding, an emerging TIS must adapt (to a certain extent) to the structures of existing systems in its context, e.g., by addressing context problems. For our review, it is important to note that there can be a wide range of different systems to interact with, plus a wide range of interactions.

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Second, the interactions between systems change over time. As a technology matures and the associated TIS grows, it starts to increasingly influence context systems, potentially also creating conflicts (Markard, 2020; Markard et al., 2016). The result is a shift from dependence to interdependence (or integration) between focal TIS and context systems. Also, resource flows change. While knowledge flows across systems might dominate in early stages of TIS development (Malhotra et al., 2019), later stages increasingly demand additional flows of resources such as materials (e.g., minerals for batteries), skilled labor, and capital for upscaling (Jacobsson & Karltorp, 2013). The new demand for resources might be a source of competition and conflict with other systems (Wirth & Markard, 2011). For our review, we note that system interactions and interdependencies may change as systems transform.

Third, TIS studies have highlighted the relevance of a technology value chain perspective, which widens the focus from a selected part of an innovation to broader up- and down-stream developments (Andersen & Markard, 2020; Sandén & Hillman, 2011; Stephan et al., 2017). The value chain approach therefore divides a TIS into various subsystems corresponding to different parts of the value chain including upstream (produce important materials and components of the technology), midstream (integration of components and manufacturing of technology units), and downstream (where technology is used). Each subsystem is embedded in different institutional environments and actor-networks. For example, for electric vehicles, the subsystem related to raw materials (e.g. lithium or graphite) is embedded in the mining system, the subsystem related to integration and manufacturing is embedded in the automotive industrial system, the utilization subsystem is embedded in the wider transportation system, and subsystem related to recycling is embedded in the waste management system (Gong & Andersen, 2024). A key issue for TIS value chain performance is to achieve sufficient institutional alignment and actor coordination across the heterogeneous systems involved to avoid bottlenecks (Malhotra et al., 2019; Stephan et al., 2017). This perspective is particularly helpful for grasping widespread diffusion of a focal technology where establishing and upscaling a value chain is important (Markard, 2020). For multi-system dynamics, we note that heterogeneity of sectoral systems in the value chain can complicate actor collaborations and lead to bottlenecks in resource flows in the TIS.

2.2 Multi-level perspective

The multi-level perspective (MLP) was developed to study transitions of socio-technical systems, juxtaposing the emergence of novelty in niches and the persistence of existing structures in regimes, both affected by exogenous developments at the so-called landscape level (Geels, 2002; Geels, 2006, 2024).

Multi-system interactions in the MLP have played some role early on. Examples include niche innovations such as combined heat and power plants or biorefineries: they affect, interact with, and potentially bridge different socio-technical systems (Raven & Verbong, 2007; Sutherland et al., 2015). Similarly, landscape developments such as market liberalization affect multiple socio-technical systems, creating similarities across systems (Konrad et al., 2008).

Types of systems: The MLP literature focuses on socio-technical systems. Recent MLP split up socio-technical systems into production, distribution, and consumption subsystems, which means that also the relationships between these subsystems can be studied as multi-system interactions (Bauknecht et al., 2020; McMeekin et al., 2019). Others differentiate subsystems according to technologies (e.g., car, train, and airplane regimes and car-sharing, mobility as a service, and electric vehicle niches within the whole system of transportation) and study interactions between these (Geels, 2018; van

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Welie et al., 2018). The most common approach is to study regime-regime interaction (e.g., oil and gas with internal combustion engine vehicles), regime-niche interactions (e.g., hydropower regime and electric vehicle niche), and niche-niche interactions (e.g., electric vehicles and roof-top solar), for niches and regimes located in different socio-technical systems (Haley, 2015; Papachristos et al., 2013; Raven & Verbong, 2007).

Types of interactions: Konrad et al. (2008) distinguishes between functional and structural couplings as main types of multi-system interactions. *Functional couplings* refer to flows of resources across systems (e.g., materials, energy, financial resources) that create functional interdependencies. *Structural couplings* refer to overlaps in the elements of two or more socio-technical systems, i.e., actors, technology, or institutions (Konrad et al., 2008; Sutherland et al., 2015; van der Vleuten, 2019). Another distinction is about modes of system interactions where scholars have suggested various types: 1) competition, 2) symbiosis, where systems develop functional relationships (Nykamp et al., 2023), 3) integration, where separate systems become integrated via a new innovation (Bakhuis et al., 2024), 4) spillover, where elements from one systems are taken up within another (Konrad et al., 2008; Mäkitie et al., 2022), and 5) niche interference, in which niche-innovations in different systems interact and co-evolve (Papachristos et al., 2013; Verbong et al., 2007).

Main insights: The MLP holds three main insights for understanding multi-system dynamics. First, transitions in one system can be constrained by inertia in other systems thereby making transition processes more complex (Bakhuis et al., 2024).- Required changes in other systems may be a mix of minor (e.g., expanding biomass production in agriculture) or major changes (e.g., shifting to renewables in electricity supply for low-carbon electric vehicles) that can result in coupled transitions across multiple systems (Nykamp et al., 2023).

A second insight is that inherent differences between socio-technical systems (e.g., system architecture, regulations, culture, business models, user practices) may complicate creating new interactions and halt unfolding multi-system dynamics. Even when new interactions could benefit both systems, we might see disagreements, misunderstanding and conflicts between central actors (Andersen, Geels, Steen, & Bugge, 2023; Ertelt & Kask, 2024; Raven & Verbong, 2007; Sutherland et al., 2015).

Third, multi-system interactions may be uneven or asymmetric. For example, systems may differ in terms of resources and power, or exposure to external pressure to change. Such asymmetries can result in one-sided solutions, or disruptions (e.g., new electrifying sectoral systems critical depend on grid access but grid actors are not dependent on new users reflecting markedly different incentive structures) (Nykamp et al., 2023; Rosenbloom, 2019). The challenges from system differences often surface once a focal innovation starts to diffuse widely and incumbent actors rather than pioneers need to change (Andersen, Geels, Steen, & Bugge, 2023; Geels, 2021). Multi-system interactions are thus also about power and politics.

2.3 Deep transitions perspective

The deep transitions (DT) perspective looks at large-scale, fundamental and long-term socio-economic transformations (Schot & Kanger, 2018). A central concept is surges of development which refers to major transformations such as the age of Steel, Electricity and Heavy Engineering (Perez, 2009). Each surge involves transitions in individual sociotechnical systems and the emergence of a new 'multi-system complex' (i.e., a novel configuration of multiple systems that interact in a coordinated manner).

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DT suggests that surges typically share common directionality because they are guided by a macro-level selection environment creating between-surges continuity (Davies & Schot, 2024).

A deep transition is viewed as a series of connected and fundamental transitions in multiple socio-technical systems in a similar direction that involves discontinuity in the macro-level selection environment (Schot & Kanger, 2018). The DT framework builds on the multi-level perspective and on the techno-economic paradigm framework (Davies & Schot, 2024; Perez, 2009). The idea is to better understand the larger context (or landscape), in which contemporary transitions unfold, and how this context changes. The perspective is particularly interested in the emergence of overarching structures (e.g., production and consumption practices) that guide and affect multiple socio-technical systems (Kanger & Schot, 2019). Key concepts include meta-rules (norms and institutions that span multiple systems) and *meta-regimes* (sets of rules that span multiple systems) (Kanger, 2022).

The process of DT involves several steps. New rules emerge in niches in individual sociotechnical systems in response to (meta-)regime problems. The new rules compete with incumbent rules, and eventually, they replace existing rules and create a new regime. New rules increasingly cross system boundaries, thereby turning into meta-rules. They might lead to cross-system alignments although variety and contestations may still occur. Subsequently, new meta-rules combine in a new meta-regime which spreads across different socio-technical systems. Finally, the new meta-regime acts as a selection environment for new niches and diffuses to more and more systems, ultimately changing the landscape (Kanger & Schot, 2019; Schot & Kanger, 2018). Industrial mass-production, digitalization, or servitization can serve as examples here.

Types of systems: The DT perspective looks at socio-technical systems. Its primary interest is in the diffusion of meta-rules and meta-regimes across different socio-technical systems and how these systems become aligned and connected in a complex of systems as a consequence.

Types of interactions: A key form of interaction in the DT perspective is that socio-technical systems develop common features over time through the presence and workings of meta-rules and meta-regimes - similar to the idea of isomorphism in institutional theory (DiMaggio & Powell, 1983). As underlying mechanisms, DT also mentions functional and structural couplings. They are regarded both as transmission channels of and as means for consolidating meta-rules. DT also discusses the role of organizations (e.g., consultancies, international organizations) in creating and shaping couplings between meta-regimes (Schot & Kanger, 2018; van der Vleuten, 2019). To emphasize flows of ideas or legitimacy, the notion of *rhetorical couplings* is used. It refers to cross-system discourses, i.e., referring to an activity/rule in one system to legitimize an activity in another system (Kanger & Sillak, 2020).

Main Insights: First, the DT perspective broadens the scope of analysis to a broad range of interconnected socio-technical systems. In fact, the framework theorizes the interplay of transition processes at the level of individual socio-technical systems and larger complexes of systems (Kanger & Schot, 2019; Schot & Kanger, 2018). In MLP terms, it can be viewed as a theory of landscape changes, which is mindful about the directionality of multi-system dynamics.

Second, DT is concerned with similarities across systems and how they emerge. It shows how transformations of individual systems may generate new meta-rules (or change existing ones) and how these may combine into meta-regimes and diffuse across multiple systems (Kanger, 2022).

Third, the framework points to agency and the role different kinds of actors play in the creation and diffusion of meta-rules (Kanger et al., 2021; van der Vleuten, 2019). However, this aspect has not been elaborated systematically yet and empirical studies are required here.

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Finally, the DT perspective highlights the importance of directionality (and potential lock-ins) created by meta-rules. As such the perspective enables transition scholars to examine issues around deep-rooted societal values, conventions and practices associated with capitalism, equality, our relationship with nature, or the exploitation of resources (Kanger et al., 2022).

3 Discussion and outlook

A general feature of multi-system perspectives is that elements, which were treated as context or landscape before, are now integrated into the analysis (endogenized). This allows for more encompassing analyses of (new) multi-system phenomena, but it also makes the conceptual frameworks more complex.

Table 2: Main observations, learnings, and research needs

	Observation	***Key learnings***	***Research needs***
Systems	Many types	Different types of systems and boundaries required for different research questions	• How do 'horizontal' and 'vertical' multi-system dynamics unfold, and interact? • How do system properties influence interactions? • Are spatial multi-system dynamics similar to sectoral multi-system dynamics?
Interactions	High diversity of concepts Analysis often descriptive and abstract	Couplings as a shared concept but more synthesis work required Better understanding of coupling processes needed	• How do the politics in multi-system dynamics differ from single-system transitions? • How do organizational strategies and roles (e.g., incumbents and newcomers) play out in multi-system dynamics? • How do interactions differ when we look at the flow of resources vs. the flow of rules, ideas, and values? • What is the role of multi-system dynamics in destabilization and decline of systems (complexes)?
Phenomena	Most focus on 'bilateral' multi-system dynamics	Exploration of processes of change in multi-system settings is central, especially when studying complexes of systems	• How do boundaries of complexes change? • How do multi-purpose technologies affect innovation and transition in different systems? • How do overarching transition pathways and directionality emerge from interdependent transitions of multiple systems? • Do complexes always need meta-rules to ensure coordination or shared directionality? • How to analyze and govern competing demands (e.g., for electricity) from different systems (e.g., as they transition toward net-zero emissions)? • How to coordinate innovation and transition processes across systems in different parts of the value chain for circularity challenges?

Our review shows that there is so far not one dominant approach to study multi-system interaction phenomena. Instead, multi-system dynamics have been analyzed with different frameworks and at different levels of aggregation. Multiple systems are at the core of the DT framework and have also gained more attention recently for TIS and MLP. There are some conceptual overlaps among the frameworks but also many differences. In this section we share reflections and discuss future

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research needs to aid cross-framework synthesis and advance our knowledge about multi-system dynamics. We focus on three topics: i) systems, ii) interactions, and iii) phenomena, see Table 2.

3.1 Systems

Our review revealed that scholars have analyzed interactions between a broad range of different systems. So, a key task for future studies will be to be explicit about the type of systems studied, about which analytical boundaries were set and why, and what multi-system phenomena are in the focus. On this basis, we can start to analyze why, how, when, and where interactions take place or change.

In the review, we observed four ways of delineating a sociotechnical system: a) complexes of systems comprised of various sociotechnical systems that are functionally interdependent, exchange resources, and may be coordinated by shared (meta) rules such as the complex made up by oil and gas, oil-based transport, fossil-based energy, and petrochemical systems emerging in the early 20th century, b) socio-technical systems in the traditional sense, providing societal services such as energy, water, or transport and covering production, distribution, and consumption domains. c) sub-systems of socio-technical systems or sectors (e.g., power supply, distribution systems, chemicals, or mining), and d) systems associated with specific technologies e.g., windmills or electric vehicles which are applied in yet other systems/sectors to generate their key service.[2] Reminiscent of this, we note a tendency to narrow system boundaries for analyzing multi-system dynamics, e.g., focusing on production, distribution, or consumption sub-systems rather than the larger sociotechnical system as one. Splitting up 'whole systems' to better characterize subsystems and technologies as well as how they differ and interact is one way of handling the growing complexity of multi-system dynamics and real-world transitions. Regardless of these different system delineations, it is worthwhile to remember that some flexibility in boundary setting remains and that different research questions require different system boundaries.

We also observe that multi-system dynamics may unfold 'horizontally' or 'vertically' (also see Bergek et al, 2015 for similar observation). Horizontal multi-system dynamics may refer to relationships between production, distribution, and consumption domains in the provision of a societal service or between distinct systems of provision (e.g., water, energy, transport) (McMeekin et al., 2019). Vertical multi-system dynamics may refer to the systems connected via value chains covering mining, materials, manufacturing, and use of a particular technology or product (Andersen et al., 2020; Stephan et al., 2017). These types of multi-system dynamics are rarely considered in an integrated way which arguably obscures some aspects of transitions. Think of how limited critical minerals and underwhelming manufacturing capacity in Europe influence further developments in production (renewable energy diffusion), distribution (power cables, transformers, and battery systems), and consumption (batteries and electric vehicles) (Andersen et al., 2024; Edler et al., 2023).

In addition, there is so far limited attention to describing and analyzing system differences (e.g., structures or business cultures) and how these influence system interactions (Miörner et al., 2021; Nykamp et al., 2023). Indeed, understanding the combination of cross-system (inter)dependencies and system differences is a basic rationale for multi-system analysis.

We also observe that although interacting systems can be spatially delineated (e.g., local vs. global) and multi-system interactions unfold across different places (e.g., electricity systems in Germany and

[2] See Andersen et al (2024) for a very similar distinction.

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Denmark), that area of multi-system analysis merits more attention to connect the geography of transitions (Binz et al., 2020).

3.2 Interactions

In terms of types of interactions, we noted significant variety in the literature (modes and types), but also that the concept of structural couplings has received attention in all three perspectives, and it might be promising to study and develop further.

As also noted by Rosenbloom (2020), interaction concepts are, across the three frameworks, mostly applied descriptively and in an abstract and macroscopic manner which leads to a limited understanding of local, micro-level accounts of *how* system interactions are created and changed in practice (Andersen & Geels, 2023; Breitschopf et al., 2023; Rosenbloom, 2020). This is important because the emergence and scaling of new low-carbon value chains, sustainable transitions of systems, and of complexes of systems all involve the creation of many new interactions.

We acknowledged that transition scholars have recently made efforts to address this issue by identifying structural coupling mechanisms related to the dimensions of technology (technological complementarities such as the need for particular inputs or complementary innovations), actors (e.g., company diversification across systems creates organizational couplings, and capability or value changes in multi-system consumers can transmit these across systems), and institutions (e.g., actors can build cross-system institutional couplings to overcome system differences, and similar changes in cultural conventions in distinct systems can lead to new institutional couplings) (Andersen & Geels, 2023; Andersen, Geels, Steen, & Bugge, 2023; Ertelt & Kask, 2024; Käsbohrer et al., 2024; Löhr & Chlebna, 2023; van der Vleuten, 2019).[3] A related proposal is to shift analytical focus from individual couplings to multi-system sites or interfaces that encompass multiple different couplings and their interrelations (Andersen, Geels, Steen, & Bugge, 2023; Löhr & Chlebna, 2023; Rosenbloom, 2020). An interface approach draws attention to how inter-system domains are created and associated tensions and conflicts. Despite these suggestions, the analysis of multi-system interactions and multi-system dynamics more broadly would benefit from more attention to the role of actor strategies and of politics, i.e., how actors and coalitions work to influence the pace and directionality of multi-system dynamics (see Löhr et al., 2024; Ohlendorf et al., 2023).

In terms of the content of interactions, we note that for TIS and MLP, multi-system interactions are often about flows of (tangible and intangible) resources across system boundaries (e.g., electricity, fuels, data, materials, finances). DT, however, focus on diffusion of rules, ideas, and principles which often is a precursor to tangible resource flows that, in turn, require new structural couplings to consolidate. While resource flows are facilitated by specific structural couplings (Andersen & Geels, 2023), our understanding of how meta-rules travel across systems is less clear. DT suggests rhetorical couplings as transmission mechanism, but this concept remains rather unexplored, e.g., how are they created and how do they relate to structural couplings.

[3] Note that Andersen and Geels (2023) distinguish overlaps and couplings. *Structural overlaps* refer to structural similarities (i.e. shared elements that do not facilitate resource flows per se but reflect a shared socio-material context, e.g., private ownership). *Structural couplings* refer to direct connections between systems in three dimensions (actors, institutions, and technology) whose purpose is to facilitate resource flows. They argue that shared elements may be quite different from the need to create new couplings that advance transitions.

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Lastly, we note that multi-system interactions are almost exclusively studied in relation to the emergence or diffusion of new technologies or practices. However, as highlighted by DT, existing, unsustainable systems are already connected via bundles of functional and structural couplings. Such couplings may imply greater resilience to external pressures for change and suggest that incumbency is inherently a multi-system phenomenon (Andersen & Gulbrandsen, 2020; Johnstone et al., 2017). It is therefore important for future studies to explore the role of multi-system interactions in destabilization and decline of systems or complexes of systems.

3.3 Phenomena

From our review, we note that TIS and MLP studies largely focus on 'bilateral' multi-system dynamics, i.e., between a focal technology or system, and context systems (Figure 1b or 1c). DT, however, considers deep transitions across most if not all sociotechnical systems in the economy (Figure 1d). DT does apply the notion of a complex of systems which is used to describe clusters of co-evolving systems (or surges) around particular impactful technologies or energy carriers which is seen as a mechanism for bringing about deep transitions. However, from a sustainability transitions perspective, the emergence of complexes is an important phenomenon in its own right. While DT does provide an abstract account of how such complexes emerge and transform, it remains quite 'broad-brushed' and insufficient with respect to e.g. diffusion and coupling mechanisms, actor strategies, system properties, tensions, and conflicts as well as governance issues (Kemp et al., 2022).

Many currently unfolding multi-system transition processes such as net-zero, circular economy or digitalization resemble multi-system complexes 'in the making'. To better grasp such multi-system dynamics, we need more conceptual exploration of the emergence and transformation of system complexes as this currently escapes existing frameworks.

Contemplating the example of low-carbon electrification reveals some of the limitation of existing frameworks. While there are several studies of low-carbon electrification, these tend to focus on a focal innovation and/or bi-lateral multi-system dynamics (see e.g., Andersen, Geels, Steen, & Bugge, 2023; Käsbohrer et al., 2024; Löhr & Chlebna, 2023). However, low-carbon electrification as phenomenon exhibits dynamics that merit a multi-system complex approach (see e.g., Markard & Rosenbloom, 2022; Nykamp et al., 2023; Ryghaug & Skjølsvold, 2023), see Text Box 1.

Our general understanding of the processual aspects of how multi-system complexes change (emerge, contract / expand, or decline) is still limited. More knowledge is needed e.g., about how new systems become included, whether and how complexes can build momentum (e.g., successful electrification in one system creates resources and support for electrification in other systems), the relation between horizontal and vertical multi-system dynamics within complexes, to what extent new meta-rules and -regimes are critical to complex development (in the electrification example it was not immediate clear), or which strategies actors pursue to navigate or expand complexes.

The questions raised above, will also be relevant for related phenomena. One example is about transitions from linear technology value chains to a circular economy, which depends on institutional alignments across interdependent actors and systems that often lead to tensions and conflicts (Kuhlmann et al., 2023), as well as changes in functional and structural couplings (Gong & Andersen, 2024; Magnusson et al., 2022). The complex of systems perspective can also be useful for thinking about the challenges of multi-purpose technologies such as mobile phones, carbon capture, or batteries. Such technologies take part in the transitions of multiple systems at the same time and connect them in a complex (see e.g., Decourt, 2019; Finstad & Andersen, 2023). Next to these,

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phenomena as digitalization (Andersen et al., 2021; John et al., 2022), or the bio-economy (Wirth & Markard, 2011) also seem to exhibit multi-system complex dynamics. Surely each of these evolving complexes have their own particularities that are waiting to be explored.

Text box 1: Low-carbon electrification as an evolving complex of systems

Low-carbon electrification involves interdependent changes in production (decarbonize electricity generation), consumption (use clean electricity where possible), and distribution domains (adapt the grid system to facilitate generation and consumption changes). Some also include the production, distribution, and consumption of green hydrogen in (indirect) low-carbon electrification which further expands the complex of involved systems (BNEF, 2020; ETC, 2021).

Systems: In Norway, for example, low-carbon electrification is established in the electricity production system which is fully decarbonized. In terms of consumption, low-carbon electrification is already well-established in personal car transportation (EVs). Driven by climate policy, direct electrification has in recent years continued to spread to maritime transport, buses, heavy transport, construction, industry, and oil and gas systems. Indirect electrification via green hydrogen, ammonia, and other e-fuels is also receiving increasing interest in systems as chemicals and shipping (Hansen et al., 2024). To stimulate economic development around the electrification efforts, policymakers and companies try to build new upstream sectors within strategic technology value chains including battery manufacturing, low-carbon mining for critical materials, electric vessels, smartgrid systems, and manufacturing electrolyzers (Bugge et al., 2021; Ryghaug & Skjølsvold, 2023). The *scope of the complex* thus covers an array of different systems and sectors, and thus include both horizontal and vertical multi-system dynamics.

Interactions: Key resource flows between these systems include electricity, fuels, materials and technology components. However, the success of electrification in personal transport spurred electrification of other systems – legitimacy around the idea of 'electrify everything' diffused across multiple systems and applications (Mäkitie et al., 2022; Ryghaug & Skjølsvold, 2023). In the process, several new interface actors and roles emerged to connect these new systems and sectors via structural couplings and help mitigate inherent institutional differences and outlooks. For example, electric utilities developed new electrification divisions, startups provided mobile battery systems for temporary use in construction, port organizations did intermediation between maritime and land-based transport as well as energy and industrial systems, and environmental NGOs created new cross-system meeting places (Andersen, Geels, Steen, & Bugge, 2023; Bjerkan et al., 2021) .

Several tensions and bottlenecks in the complex were also observed. For example, growing new consumption requires that generation capacity must expand significantly which, especially for wind power, is challenged by low social acceptance (Korsnes et al., 2023). Also, the speed and scale of planned new electricity production and consumption (e.g., energy-intensive processing sectors, oil and gas, hydrogen, and data centers) overwhelmed actors in the electricity grid system resulting in major interconnection queues (Nykamp et al., 2024). In this context, new tensions emerge about who should get priority access to low-carbon electricity (oil and gas or green hydrogen projects?). Tensions and delays also created new uncertainty about the boundary between electrification versus other options such as carbon capture and storage in industry, blue hydrogen or even bioenergy (Inderberg et al., 2024).

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4 Conclusions

In this chapter we have reviewed how three central transition studies frameworks conceptualize and analyze multi-system interactions and dynamics in transitions and discussed similarities and differences. We also outlined a research agenda for multi-system dynamics in transition studies building on opportunities for synthesizing insights across the reviewed frameworks to better address new and emerging empirical multi-system dynamics phenomena.

An important omission from our chapter is methods for studying multi-system dynamics. It is easy to be fascinated by the interconnectedness a multi-system perspective reveals, but one should always critically ask what value-added to answering a specific question or understanding transition phenomena such a perspective brings. We noted the need to be careful about system boundaries but also the discussion about methods is still immature. Another omission from our review is policy and governance in relation to multi-system dynamics. Despite recent advances (Kanger et al., 2020; Rogge & Goedeking, 2024) the topic is rather novel, and we hope that our discussion of systems, interactions, and phenomena can support future work on policy and governance (Rogge et al., 2024).

Despite its limitations, our review aims to provide a starting point and an introduction to multi-system analysis in transition studies that we hope will inspire more scholars to engage with this rapidly emerging topic.

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