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Integrating industrial transformation and sustainability transitions research through a multi-sectoral perspective

Allan Dahl Andersen^{1,2*}, Tuukka Mäkitie^{3,1}, Markus Steen³, Iris Wanzenböck⁴

Affiliations and postal addresses

¹TIK Centre for Technology, Innovation and Culture, University of Oslo, Norway | Postal address: P.o. box 1108 Blindern, N-0317 Oslo, Norway

²Department of Food and Resource Economics, University of Copenhagen, Denmark | Postal address: Rolighedsvej 23, DK-1958 Frederiksberg C, Denmark

³Department of Technology Management, SINTEF Digital, Trondheim, Norway | Postal address: P.o. box 4760 Torgarden, NO-7465 Trondheim, Norway

⁴Copernicus Institute of Sustainable Development, Utrecht University, The Netherlands | Postal address: Postbus 80.115, 3508TC Utrecht, The Netherlands

*Corresponding author

Email addresses

Allan Dahl Andersen: ada@ifro.ku.dk

Tuukka Mäkitie: tuukka.makitie@sintef.no

Markus Steen: markus.steen@sintef.no

Iris Wanzenböck: i.wanzenbock@uu.nl

Abstract

Transition studies is a rapidly growing field within innovation studies. It aims to account for system transitions especially in relation to sustainability challenges. The field has however paid limited attention to the economic structural change associated with transitions. This suggests that despite common origins via the concept of technological regimes, evolutionary economics and transition studies have seen limited mutual engagement and cross-fertilization. Since the extension of technological regimes to sociotechnical regimes with the articulation of the multilevel perspective, the transitions field has focused more on institutional and end-user aspects of transitions (e.g. culture, practices, regulations) than the supply-side of regimes. In this paper we attempt to recalibrate the balance between supply- and demand-side analyses by articulating a novel multi-sectoral perspective on transitions which provides a systematic view on the interplay between industrial transformation and system transitions.

1 Introduction

Even though greenhouse gas (GHG) emissions continue to grow (IPCC, 2022), the global energy transition has entered a new phase that increasingly is characterized by large-scale and rapid diffusion of maturing low-carbon technologies such as solar PV, wind turbines, electric vehicles, and heat pumps rather than small-scale experimentation with immature innovations (IEA, 2022). The shift is driven by a heightened sense of urgency in relation to the unfolding climate crisis and adoption of more ambitious climate policies (Fankhauser et al., 2022; IPCC, 2019), remarkable innovation and cost declines in core technologies such as solar, wind, and batteries that create economic opportunities (Schmidt & Sewerin, 2017), and an emerging new paradigm for energy security and technology sovereignty which aligns with renewable energy transitions (Edler et al., 2023). In combination these factors fuel an intensifying net-zero technology race among China, the US and the EU to build (regional) value chains, security, and resilience to shocks which is reflected in recent ambitious policy programs such as the EU's Net Zero Industry Act and the US's Inflation Reduction Act (Cheung, 2023; IEA, 2022; McKinsey, 2022). Consequently, the energy transition is increasingly inducing industrial transformation in several countries and across multiple interlinked sectors through rapid diffusion of low-carbon technologies and upscaling of associated value chains.

These developments present novel challenges for both researchers and policymakers. Sustainability transition scholars have started exploring this new acceleration phase of transitions (Markard, 2018) by elaborating phenomena such as rapid niche diffusion (Yang et al., 2020), technology phase-out (Rinscheid et al., 2021), and interactions between multiple large sociotechnical systems (Rosenbloom, 2020). Despite these advances, transition studies remains largely focused on sociotechnical systems of *provision*, such as electricity, transport, food, or water, and pays only limited attention to the *production* of artifacts and materials in sectors such as mining, chemicals, and manufacturing (Røpke, 2016). In other words, transition studies have tended to focus on the downstream rather than the upstream dimensions of value chains (Andersen et al., 2020). Similarly, Lundvall (2022, p. 4) argues that *“emphasis on transformation at the level of socio-technical systems is a useful rectification of innovation policies oriented exclusively toward the business sector and toward the production system...but is an addition and it remains a major task to transform the business sector and the national production system”*. Although some recent studies pay attention to upstream parts of single technology value chains (Andersen & Markard, 2020; Mäkitie et al., 2022; Stephan et al., 2017) and suggest broader whole system reconfiguration frameworks (Geels, 2018; McMeekin et al., 2019), a more systematic and integrated understanding of how sociotechnical system transitions interact with industrial transformation in multiple upstream sectors is warranted. This is necessary for meaningful engagement with questions on economic impacts of transitions in terms of jobs, regional income, and changes in industrial structure that are integral to just transitions as well as to the design of net-zero industrial policies (Andersen et al., 2020; Fagerberg, 2018; Foxon, 2018; Johnstone et al., 2021; Winskel, 2018).

At the same time, evolutionary economics (Nelson & Winter, 1982; Nelson, 2020; Nelson & Winter, 1977) – a central inspiration and building block for transition studies (Rip & Kemp, 1998; Van den Belt & Rip, 1987) – has since long conceptualized and studied how radical innovations are associated with industrial transformation across multiple sectors (Dahmén, 1989; Perez, 2009a) including changes in the sectoral composition of the economy (Carlsson, 2016; Saviotti & Pyka, 2004). This indicates that despite common origins via the concept of technological regimes, evolutionary economics and

transition studies are rather disconnected (Schot & Steinmueller, 2018).¹ Indeed, evolutionary economics remains focused on technological regimes and supply-side perspectives (Nelson, 2012, 2020) while transition studies embraces the notion of sociotechnical regimes to further explore the demand-side and societal embedding of technological change (Markard et al., 2012; Rip & Kemp, 1998). As the real-world global energy transition is entering an acceleration phase, this disconnect becomes increasingly problematic for transition studies because core frameworks in the literature—such as the technological innovation systems (TIS) framework (e.g. Bergek, Hekkert, et al., 2008) and the multilevel perspective (MLP) (e.g. Geels, 2002)—offer limited explanatory power for new phenomena such as low-carbon technology value chain upscaling and industrial transformation across multiple upstream sectors (Andersen et al., 2020; Marin & van Zwanenberg, 2023). The supply-side focus of evolutionary economics alone is similarly insufficient for making sense of transition processes including the role of cultural, institutional, political and social changes (Geels, 2004).

Against this background, the research objective of this paper is to further integrate insights from evolutionary economics about innovation and multi-sectoral dynamics, on the one hand, and transition studies, on the other, to develop a better understanding of the relationship between sustainability transitions and the dynamics of multiple, linked upstream sectors, i.e., industrial transformation.

We pursue this objective with a three-pronged research design: 1) through a *narrative literature review* (Sovacool et al., 2018; Torraco, 2005) we integrate conceptual insights about industrial transformation from evolutionary economics with transition studies frameworks focusing on MLP and TIS by proposing a novel multi-sectoral framework to understand transitions; 2) guided by the latter, we perform a *systematic literature review* of 80 empirical transition analyses to take stock of the latent empirical knowledge base to test the usefulness of the proposed framework; 3) through *synthesis and analytical reasoning* we refine and extend the framework (see section 2 for more details).

The paper proceeds as follows. In section 2 we explain our methods and describe our data and analysis. In section 3 we perform our narrative literature review. Chapter 4 presents the results of the systematic literature review while chapter 5 presents a synthesis and discusses main insights. Chapter 6 concludes.

¹ Note that we see evolutionary economics and transition studies as two subfields of innovation studies which, according to Research Policy, is a field including studies analyzing, understanding, and effectively responding to economic, policy, management, organizational, environmental, and other challenges posed by innovation, technology, R&D and science. Innovation Studies is dominated by evolutionary economics of technological change which pivots around core ideas as technological regimes, the resource-based view of the firm, and a systemic understanding of innovation that are principally used to explain economic change or performance (Fagerberg et al., 2012; Martin, 2012). Transition Studies is a smaller but rapidly growing subfield of Innovation Studies (Köhler et al., 2019; Rakas & Hain, 2019).

2 Research design and methods

In this section we outline in more detail the three pillars of our research design.

2.1 Narrative literature review

Narrative literature reviews rely on expert domain knowledge of experienced authors (Sovacool et al., 2018; Torraco, 2005) and are suitable for exploratory evaluations of literature and synthesizing insights from different theoretical perspectives such that new frameworks or perspectives can be created. We proceed in three steps. First, we consult evolutionary economics—principally the work of Carlota Perez—about the nature of multi-sectoral industrial transformation related to major innovations to identify categories of different sectors and types of sectoral interaction, cf. section 3.1. Second, holding the sector concept central, we provide an in-depth review of MLP and TIS frameworks regarding how they relate to the notion of sectors and wider industrial change in the economy, cf. section 3.2. We focus on these two frameworks because they are the most prominent in the transition field and devote most attention to the role of multiple sectors among transition studies frameworks (for overviews see Köhler et al., 2019; Markard et al., 2012). In a third step, we synthesize insights from the reviewed material to suggest a novel framework, cf. section 3.3.

2.2 Systematic literature review

In the second pillar of our research design, we perform a *systematic literature review* of empirical analyses within transition studies to take stock of the current knowledge base and extract latent insights from the literature about the relationship between industrial transformation and multi-sectoral dynamics, on the one hand, and sustainability transitions, on the other. A systematic review is a replicable and transparent process for summarizing knowledge and identifying future research priorities building on clear review questions and a repeatable search protocol with defined inclusion and exclusion criteria (Denyer & Tranfield, 2009; Petticrew & Roberts, 2006). Despite the under-conceptualization of industrial transformation in MLP and TIS, the phenomenon of interest is so pervasive that it does appear in transition scholarship. A review of empirical insights is therefore meaningful.

A systematic review is retrospective and therefore encounters the challenge that reviewed papers may not have been originally intended to answer the questions that the researcher wants to address. We used the outcome of our narrative literature review to pre-define tentative analytical categories and relationships involved in the multi-sectoral dynamics of industrial transformation to be able to systematically identify them in the empirical review. We use the insights gained to further explore, test, and refine the proposed analytical framework.

Two main questions guided our systematic literature review: 1) How have multi-sectoral dynamics been empirically studied in the literature? We divide this question into three sub-questions. 1a) To what extent have multi-sectoral dynamics been studied? 1b) What type of sectors have been studied? and 1c) How important are multi-sectoral dynamics for transitions? 2) How and why do multi-sectoral dynamics happen in practice? We look for drivers and barriers to multi-sectoral interactions to identify explanatory factors and processes that we categorize according to the main dimensions of sociotechnical systems (technology, institutions, and actors and networks).

2.2.1 Data selection

The article population was identified in two steps. First, we delineated our sample to focus on core sustainability transition studies articles published in the seven most prominent journals in the field (Köhler et al., 2019) as listed in Table 2. We performed a Scopus search on all peer-reviewed articles published in these journals within the past 20 years. We limited our search to applications of the key frameworks of the field (Kivimaa et al., 2019; Markard et al., 2012), and searched in title, abstract and article keywords for (variations of) the terms “sector” or “industry”.² This first search strategy resulted in a total of 220 papers.

Table 2: Description of main corpus. Notes: Last data retrieved in June 2022. MLP is Multi-level Perspective; TIS is Technological Innovation System; SIS is Sectoral Innovation System; SNM is Strategic Niche Management; TEF is Triple Embeddedness Framework

Category	Number
Articles (peer-reviewed):	80
Time period:	2002 - 2022
Sources (Journals)	7
Energy Policy	9
Energy Research and Social Science	11
Environmental Innovation and Societal Transitions	20
Journal of Cleaner Production	16
Research Policy	14
Technological Forecasting and Social Change	9
Technology Analysis and Strategic Management	1
Key framework	
MLP	29
TIS	37
TIS – MLP	3
TIS – SIS	1
SNM	8
TEF	1

Second, we determined the relevance of the 220 papers retrieved via Scopus in several iterative steps. Our criterium for inclusion was that articles must empirically analyze and discuss relationships between two or more sectors in transition processes. Every abstract was read by two authors to screen for false positives. In case of disagreement between authors, consensus was achieved via an extra assessment by a third author followed by a discussion in the whole team. With this step, the sample was reduced to 96 papers. Through the process of reading and coding full papers, the sample was further reduced to 80 papers.

2.2.2 Coding process

Based on our framework (cf. section 3.3), we developed a coding scheme which reflected our key review questions while allowing for inductive insights. With this first coding scheme we performed a

² We did not use ‘system’ as a keyword because socio-technical systems fulfil societal functions such as provision of water, electricity or transport services. The notion of a system therefore would not capture insights about upstream sectors and industrial change.

pilot study (20 papers) to test its usefulness and common understanding in the author team. Each paper was coded by two authors, and misalignments discussed in personal meetings. Only minor differences between coders were identified, whereupon the coding scheme was slightly adapted and a new pilot study (15 papers) was conducted. This did not result in further adaptations. Due to consistent coding and clarity of codes across researchers, the rest of the papers were read and coded by a single author.

The final coding scheme had three overall dimensions. We first coded for sector types. Given our primary interest in upstream sectors we coded for (a) input sectors broadly understood, (b) technology-producing / manufacturing sectors, (c) distribution sectors, (d) adjacent sectors, and (e) lastly, we included a category of other sectors to allow for inductive insights. This code addresses research question 1b. Second, we assessed the importance of multi-sectoral dynamics for transition processes by using the code (i) “central” if a specific multi-sectoral interaction was very important for understanding the phenomenon studied, (ii) “peripheral” if a specific multi-sectoral interaction was included in the analysis but not dedicated much attention or explanatory power, and (iii) “absent” if a specific type of multi-sectoral interaction was not mentioned. In this way, papers differ in what type of sectors they analyze and how important multi-sectoral dynamics are. This code addresses research question 1c. Third, we coded for the mechanisms and processes of multi-sectoral interactions by looking at driving factors and main barriers to cross-sector interactions. This code was quite open to allow for inductive reasoning. This code addresses research question 2. For all codes we had two entries in the common database (organized in excel). One for the coder’s assessment of the particular code, and one for direct excerpts from the paper supporting the assessment.

2.2.3 Results

We present the results for research question 1 in section 4.1 and results for question 2 in section 4.2. In section 4 we will refer to the papers included in our sample with ID numbers in brackets, e.g., papers 3 and 5 as [3, 5]. The full overview of papers and IDs can be found in the Appendix.

2.3 Synthesis, refinement, and discussion

In the third pillar we synthesize insights from the narrative and systematic reviews combined with analytical reasoning (Kanger et al., 2020) to further refine the heuristic framework proposed in section 3. Note that in our synthesis we base our results on multi-sectoral interactions that were coded “central”. We take into account results for the papers coded “peripheral” insofar as they provided additional insights.

3 Narrative review: multi-sectoral dynamics in transitions

Drawing on evolutionary economics we delineate a sector according to a specific set of products (e.g. chemicals, cars, steel) or services (e.g. electricity supply, finance) whose provision involves competing actors (typically firms) (Malerba, 2002).³ Input providers and users are thus external to a focal sector. Every sector is thus a user of inputs from other sectors and is a producer of services or products

³ Note that we understand sector and industry as similar. They are flexible and can refer to different levels of industry classification codes. In the broader literature on innovation these concepts are used interchangeably. For simplicity we only use the term sector.

consumed in other sectors (or end-use in households) resulting in ubiquitous inter-sectoral relationships. Any sector may apply several individual technologies as part of the ‘production function’. It has a sector-specific regime reflecting the dominant configuration of actors, technologies and institutions, and an overall mode of innovation (Malerba, 2005; Pavitt, 1984). That sectors differ with regards to configuration and key characteristics is indeed a main reason to pursue a multi-sectoral perspective on transitions.

3.1 Innovation and multi-sectoral dynamics

Historical studies have shown that while some radical innovations only influence a specific sector, others may affect a whole range of sectors or, in rare cases, the entire economy (Perez, 2002, 2009b). Radical innovations or clusters of innovations can thus set in motion “*a series of ever-widening concentric circle*” of change (Rosenberg, 1982) that create a “*sequence of widening imbalances*” in the economy (Dahmén, 1989; Taalbi, 2016).

One mechanism underlying such ripple effects is that technologies tend to be interdependent with other technologies. Sometimes a technology is stifled or propelled forward by innovation in a component (e.g. a material or mechanic device). The compound steam engine, for example, had to wait for availability of cheap high-quality steel to emerge in force (Rosenberg, 1982). Similarly, variable renewable electricity requires innovation in complementary technologies such as energy storage to deliver a stable provision of power. These interdependent technologies are typically developed and produced by different sectors. This implies, as formulated by Rosenberg (1982, p. 73), that “*technological progress in one sector of the economy has become increasingly dependent upon technological change in other sectors*” such that “*technological problems arising in industry A are eventually solved by bringing to bear technical skills and resources from industry B, C, or D*”. Hence, due to technological complementarities, inter-sectoral interaction is important for understanding technological change.

Perez (2009a) identifies four categories of sectors involved in technological revolutions (Perez, 2009a). First, input sectors that provide new and cheap inputs. In previous technological shifts, those included e.g. oil, steel or coal. Second, technology-producing / manufacturing sectors that use the latter inputs to deliver the core technological artefacts and innovations that actors in other sectors react to—such as automobiles, steel steam ships or iron steam engines. Third, distribution (or infrastructure) sectors that enable growth in other sectors such as roads, ports, or national railways. Fourth, a broader category is adjacent sectors. Change in these sectors is induced by the dynamics of the sectors mentioned above. Adjacent sectors are not necessarily fundamentally transformed but are nonetheless important to facilitate development and diffusion of a core innovation (e.g. logistics or machine tools). They often existed from before but are changed in the technological shift and take on a different role. We note the absence of consumption sectors in this approach.

Interactions across sectors are typically viewed as linkages between actors (e.g. firms) that are channels for exchange of various resources such as goods, services, knowledge or energy (Ciccone, 2008). Linkages lead to interdependencies between sectors in terms of inter alia investment and growth (Hirschman, 1958; Richardson, 1990), input-output-demand relations, and innovation (Dahmén, 1989; Perez, 2009b). Inter-sectoral linkages matter for innovation because interactive learning between actors who hold different knowledges is a crucial mechanism in innovation (Lundvall, 1985; Von Hippel, 1994). The number of sectors involved varies across products and technologies but generally increases with technological complexity. Such complementary user-producer linkages exist across the economy organized under a division of labor between sectors, reflecting amongst other different knowledge bases and core competencies (Malerba, 2005; Pavitt, 1984).

From this short review, we see that many innovations rely on interlinked changes in multiple sectors to emerge and diffuse and can transform numerous sectors in the process, creating economy-wide ripple effects. Inter-sectoral linkages are often forged around technology because every technology requires a particular set of sectors for its production, operation and use. This differentiation of sector types and their roles in major innovations is a useful building block for explicating the multi-sectoral dynamics of transitions.

3.2 Transition studies and multi-sectoral dynamics

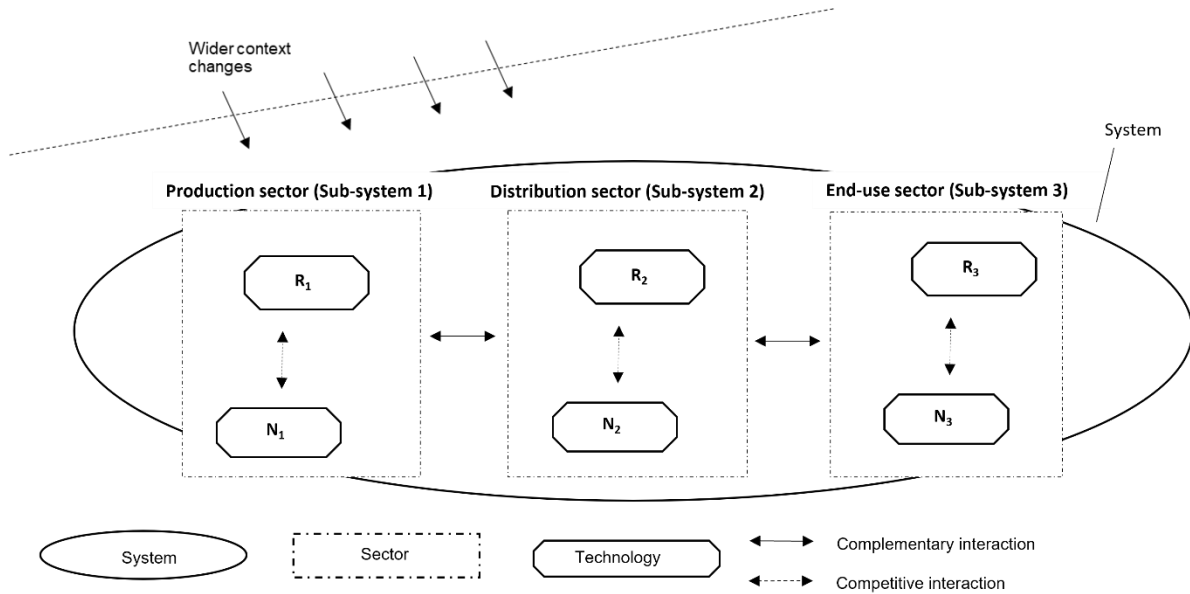
In this section, we review how the two main sustainability transitions' frameworks—the Multi-Level Perspective (MLP) and the Technological Innovation System (TIS)—have engaged with multi-sectoral dynamics as described in the previous section.

3.2.1 Multi-level Perspective and multi-sectoral dynamics

The MLP is a foundational framework for conceptualizing transitions in sociotechnical systems. Sociotechnical systems produce, distribute, and consume societal services such as electricity, food, or transportation, and are comprised of actors, institutions and technologies that can be configured in various ways (Geels, 2004). MLP depicts transitions as sociotechnical regime shifts that take place via interaction between three analytical levels: niche, regime, and landscape (Geels, 2002; Kemp et al., 1998). A sociotechnical regime is *“the ‘deep structure’ that accounts for the stability of an existing socio-technical system. It refers to the semi-coherent set of rules that orient and coordinate the activities of the social groups that reproduce the various elements of socio-technical systems”* (Geels, 2011), including stocks of knowledge, technologies, user practices, expectations, norms, regulations, etc. (Markard & Truffer, 2008; Rip & Kemp, 1998).

Niches are configurations of actors, technologies, and institutions that provide alternative ways of delivering the societal function occupied by the regime. Niche configurations typically comprise immature technologies with limited actor support, market share, and weak institutional support. Regimes induce mainly incremental change in systems and therefore often work as a barrier against new radical niche technologies and thus transitions (see e.g. Geels & Schot, 2007; Geels et al., 2017). The notion of a socio-technical landscape captures the wider exogenous environment that is beyond the direct influence of actors. Transitions are seen to occur when external pressures for change destabilizes regime structures to create opportunities for alternative niche technologies (Geels, 2004; Geels & Schot, 2007). Exactly how lengthy and disruptive a regime shift is depends on the preconditions for and timing of interactions across levels (Geels & Schot, 2007).

Figure 1: The sociotechnical system and sub-systems in the Multi-Level Perspective (adapted from McMeekin et al., 2019)



The notion of a sector (as defined in this paper) is not conceptualized within the MLP, although many studies use the term sector and sociotechnical system interchangeably (see e.g. Berkers & Geels, 2011; Geels, 2004; Geels, 2006; Markard et al., 2012; Verbong & Geels, 2010). Foundational studies however refer to “large” sociotechnical systems (Geels, 2002; Rip & Kemp, 1998), leading to an inconsistent and rather confusing terminology. This reflects that the notion of a sociotechnical system is used at different levels of aggregation in the MLP literature. Recent work on a ‘whole systems’ approach to MLP explicitly reflects distinct levels of sociotechnical systems, see Figure 1 (Geels, 2018; McMeekin et al., 2019), where large systems are divided into three main *sub-systems* of production, distribution, and end-use with each subsystem performing a *sub-function* (Holtz et al., 2008; McMeekin et al., 2019). Furthermore, subsystems can be relatively autonomous, and have sub-regimes and sub-niches. Sub-system interaction is guided by an overarching ‘meta-regime’ (McMeekin et al., 2019).

While sociotechnical systems arguably involve multiple sectors (Coenen & Díaz López, 2010), the role of different sectors and their interactions in transitions nonetheless remains conceptually diffuse in the MLP. This is however visible in similar concepts such as large technical systems (Hughes, 1983) and techno-economic complexes (Unruh, 2000). Unruh (2000, p. 822), for example, shows that large technical systems are characterized by inter-sectoral networks: “*To build cars, for example, whole supply industries including petroleum, glass, rubber, etc. were required, each with their own distinctive core competencies.*” Such types of sectors are admittedly acknowledged in the MLP as elements of sociotechnical systems in the form of technological artefacts, tools and machines, or natural resources (Geels, 2004). However, the sectoral manifestations of these elements remain latent and compressed in current conceptualizations of sociotechnical systems.

In terms of sector interactions, the whole systems approach to MLP suggests that connections between subsystems can be tight (i.e. change in one subsystem requires change in another subsystem) or loose (subsystems can change independently). Distinguishing subsystems allows for identification of institutionalized patterns of interactions which is conceptualized as a meta-regime, i.e. a set of aligned rules that cross and coordinate interactions, e.g. centralization is a meta-rule across electricity sub-systems (McMeekin et al., 2019). More generally, scholars have analyzed interactions between sociotechnical systems (rather than subsystems) as interactions between

niches and regimes located in different socio-technical systems (Geels, 2007; Papachristos et al., 2013; Raven & Verbong, 2007) including regime-regime (Raven, 2007)), regime-niche (Haley, 2015)), and niche-niche interactions. Different patterns and types of system interactions were identified including competitive interactions (i.e. systems compete for resources) and complementary interactions (i.e. systems' development is mutually dependent), (for more details see: Papachristos et al., 2013; Raven & Verbong, 2007). Others distinguish between functional couplings (flows of resources) and structural couplings (technological, institutional, or organizational connections) between systems (Andersen & Geels, 2023; Konrad et al., 2008).

3.2.2 Technological innovation system and multi-sectoral dynamics

A TIS is a sociotechnical system composed of a set of actors, networks, and institutions engaged in developing, diffusing and utilizing a particular technological artefact (Bergek, Jacobsson, et al., 2008). The framework thus provides a systemic view on the evolution of a focal technology (Markard & Truffer, 2008). TIS has been extensively applied for studying emergence of new low-carbon technologies. The focus on emergence has, however, implied limited focus on how TIS dynamics interplay with broader economic transformation (Bergek, Hekkert, Jacobsson, Markard, Sanden, et al., 2015).

From the outset it was acknowledged that most TIS necessarily crosses multiple sectors (Carlsson & Stankiewicz, 1991; Edquist, 1997; Markard & Truffer, 2008).⁴ This insight has more recently been developed into an explicit technology value chain approach to TIS (Andersen & Markard, 2020; Stephan et al., 2017; van Welie et al., 2019a). In this approach, technology is seen as a complex system consisting of interacting subsystems, components and materials⁵ (Arthur, 2009; Murmann & Frenken, 2006) that are applied in and produced by different sectors (Sandén & Hillman, 2011; Stephan et al., 2017).⁶ Each technology value chain thus involves several heterogeneous sectors whose alignment and complementarities influence the evolution of the focal technology (Lundvall, 1985; Pasinetti, 1993; Robertson et al., 2002). How many sectors that are involved depends on characteristics of the focal technology such as degree of complexity and modularity (Tushman & Rosenkopf, 1992) as well as forms of application (Clark, 1985). In addition to up- and downstream sectors, also adjacent sectors play a role. In the TIS literature, the term adjacent sector is (similarly to Perez (2009a)) used in a broad sense to include sectors that provide resources to the focal technology such as energy/material inputs (Wirth & Markard, 2011; Wirth et al., 2013), financial or knowledge resources (Bergek, Hekkert, Jacobsson, Markard, Sanden, et al., 2015; Malhotra et al., 2019; Mäkitie et al., 2018), and can be considered as the industrial context for a focal technology (Andersen & Gulbrandsen, 2020; Fontes et al., 2021).

In terms of sector interactions, TIS scholars distinguish between linkages, which refer to market-based, input-output transactions between sectors, and structural couplings which refer to shared structural elements. The same actors, for instance, may operate in multiple sectors, technologies may be used in multiple sectors, and sectors may also have similar institutions (e.g., organized

⁴ Note that while a TIS involves actors, institutions, and networks from multiple sectors, these sectors are not proprietary to the TIS. Indeed, sectors typically participate in the production and use of multiple technological artefacts. However, particular firms may focus exclusively on producing one technology (component) only.

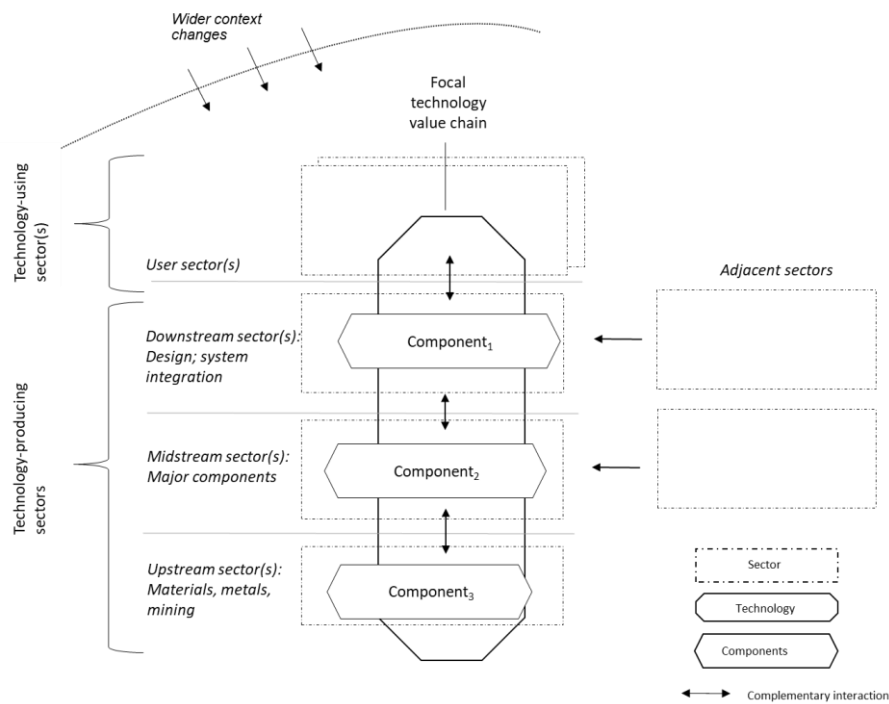
⁵ For simplicity we only use the notion of components and not subsystems and materials.

⁶ Upstream and downstream sectors are delineated in relation to a focal technology value chain. The focal sector is where the technology is applied, while upstream sectors are those that produce important subsystems and components of the technology.

monopolies or mass production logic) (Bergek, Hekkert, Jacobsson, Markard, Sandén, et al., 2015; Mäkitie et al., 2018).

Although, in its traditional form the TIS framework does not pay explicit attention to multi-sectoral dynamics, the more recent technology value chain approach does start to systematically emphasize this. At this level of analysis, however, scholars do not study transitions but rather the evolution of a particular focal technology that may be important for transitions.

Figure 2: Sectoral configuration of a TIS



3.3 Systems, sectors, and technologies: A multi-sectoral perspective on transitions

An outcome from our narrative review above is that existing transition studies frameworks do not adequately account for multi-sectoral dynamics. We note that the literature is not clear on how sectors and sociotechnical systems relate. To impose a coherent understanding of the notion of sectors onto the reviewed frameworks and concepts, we propose a novel typology and heuristic framework that distinguish between systems, sectors, and technologies and systematically integrates these concepts to clarify how we can think of sectors in transition studies. The typology reflects an understanding of sociotechnical systems as a nested hierarchy of systems, subsystems, and components, see Table 1 (Geels, 2005; McMeekin et al., 2019; Murmann & Frenken, 2006; Sandén & Hillman, 2011; Stephan et al., 2017). We elaborate the framework in three steps.

First, we observe that sub-systems of whole systems (Holtz et al., 2008; McMeekin et al., 2019) correspond to our definition of sectors, and that sub-regimes therefore can be seen as sectoral regimes (cf. Malerba, 2005). This allows us to identify production, distribution / infrastructure, and user sectors within large sociotechnical systems. *Second*, each sector can contain regime and niche configurations of technological artefacts, actors, and institutions. For example, the electricity production sector deploys several different electricity generation technologies such as coal plants or

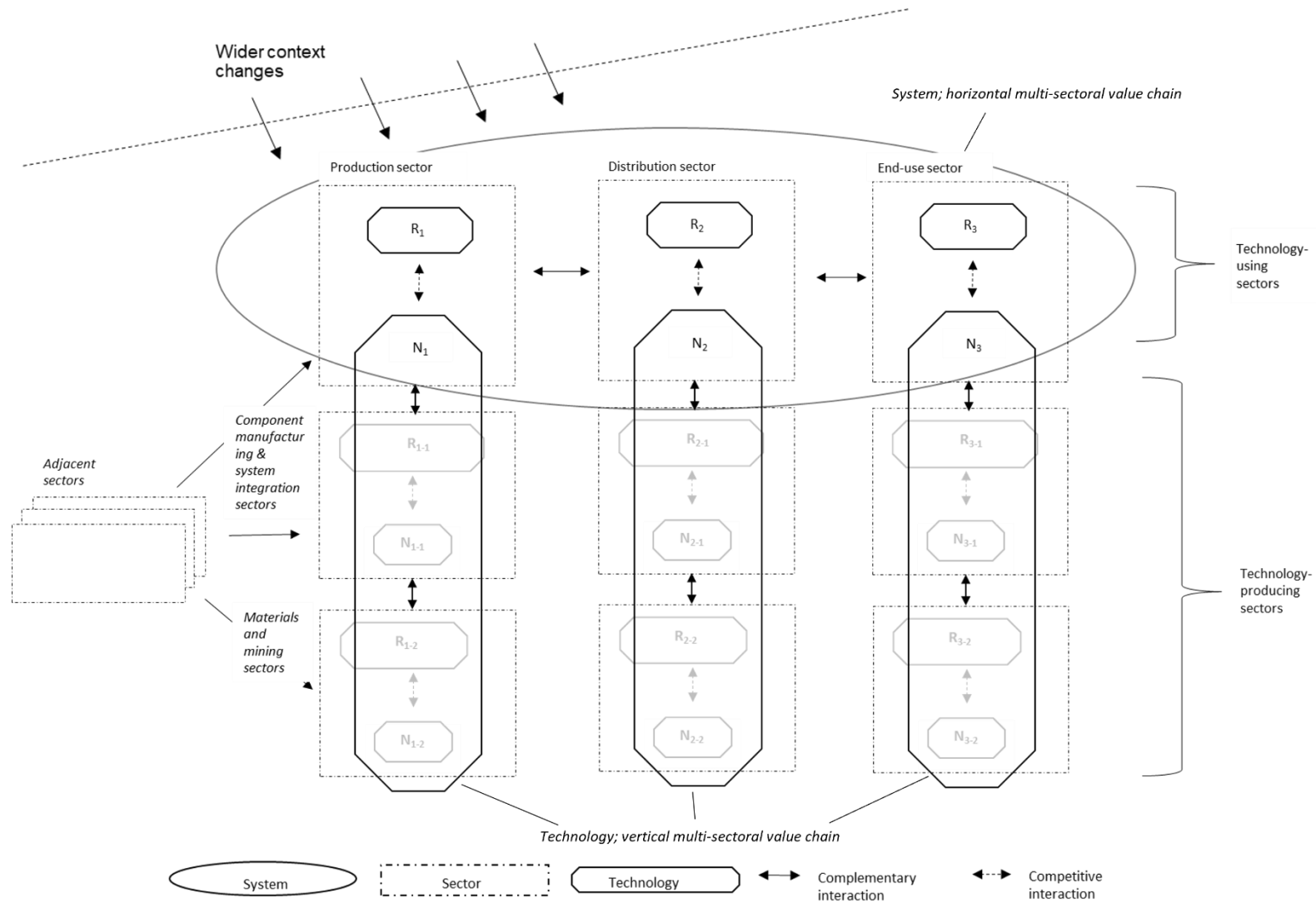
wind turbines, the electricity distribution sector use transformers or storage technologies, and in end-use sectors different conversion technologies such as electric devices and motors are applied (McMeekin et al., 2019; Sovacool & Geels, 2016). In this view, regime and niche configurations are components within sectors that make up the (whole) system. *Third*, building on insights from section 3.2.2, regime and niche configurations involve multiple sectors in the production and use of technological artefacts. Our application of concepts reflects an inherent flexibility in the notions of sociotechnical systems, regimes, and niches such that they can be defined at different levels of aggregation (Meadowcroft, 2009), e.g., at levels of system, sector, and technology.

Table 1: Systems, sectors, and technologies

Concept	Description	System hierarchy	Sector dimension	Example
System	System providing high-level societal function such as water or electricity, including production, distribution and use subsystems	System	Multiple linked sectors across production, distribution, and use of societal service	Electricity, food, or transportation systems
Sector	Covers technologies, institutions, and actors in a sector that produce similar outputs	Sub-system	Can be a focal sector within system (e.g., distribution sector)	Electricity grid; automotive production; chemical sector; mining sector
Technology	A socio-technical system delineated by a technological field or artefact which is deployed by some sectors and produced by others	Component	Each technology has an associated value chain which crosses multiple sectors	Nuclear, coal, wind, solar PV, Li-batteries,

Based on this typology we integrate the value chain perspective on TIS with the whole system approach to MLP to propose a multi-sectoral perspective on transitions, see framework in Figure 3. It illustrates how multiple sectors are involved in transitions via the production and use of technological artefacts for the provision of societal services in systems. The framework thus contains and connects two types of multi-sectoral dynamics related to i) transitions in systems such as electricity generation, distribution, and consumption which we refer to as horizontal value chains, and ii) the evolution of focal technology value chains such as electric vehicles covering mining, batteries, and car manufacturing sectors which we refer to as vertical technology value chains. This implies that our interest in upstream sectors broadens to include sectors that provide e.g., energy or raw materials, process raw materials, and sectors involved in manufacturing the technology itself. We consider both types of multi-sectoral dynamics inherent to industrial transformation.

Figure 3: The sectoral configuration of systems



This multi-sectoral framework complements the MLP ‘whole systems’ approach by opening up the production or supply-side—i.e. flows of raw materials, fuels, capital goods—of systems that is otherwise compressed and not explicitly articulated in the MLP (Andersen & Markard, 2020; Steen & Weaver, 2017). Our framework also complements the TIS value chain approach by i) broadening the understanding of use environment, and ii) by introducing notions of regime and niche in value chain sectors which provides a new way of understanding institutional aspects and actor strategies in relation to cross-sector coordination. Indeed, for these reasons, the multi-sectoral framework provides a new synthesis of TIS and MLP frameworks (Markard & Truffer, 2008). Note that there are likely multiple niche value chains in any given sector, and that also regimes will be connected to various value chains. Figure 3 is thus a highly stylized representation of multi-sectoral dynamics in sustainability transitions.

In terms of interactions, our typology and framework can integrate the types of interactions discussed above into a more generic perspective on interactions between sociotechnical systems at different levels of analysis, i.e. systems, sectors/subsystems, and technologies (sub-sub systems). We suggest that cross-sector interactions can be understood as a) various types of regime-niche interactions, b) being competitive or complementary, and c) being functional or structural of nature (these can co-exist).⁷ Although extant concepts allow for characterizing interactions, there is still need for better understanding processes of how and why interactions emerge and change (Rosenbloom, 2020). We therefore explore this issue in our systematic review of empirical studies.

Our framework provides a useful starting point for exploring how industrial transformation relates to transitions in systems. In the next section, we use it to identify and analyze empirical transition studies research focused on multi-sectoral upstream dynamics to explore and test its usefulness.

4 Results of systematic literature review

4.1 How have upstream multi-sectoral dynamics been empirically studied in transition studies?

In relation to *RQ1a* we found that the interplay of multiple sectors was relevant in 80 articles on transition studies. This is a relatively low number in a research field that has grown rapidly the last decade (Rakas & Hain, 2019). Work on multi-sectoral dynamics is thus a small but growing research stream in transition studies.

In relation to *RQ1b* we found that there was attention to all sector types that we identified in section 3, in addition to ‘other sectors’ such as waste management and recycling (see Table 3). Note that all papers included a focal sector exhibiting transition dynamics as the starting point. Interestingly, all sector types do not appear together, and studies mainly consider the interaction between a focal sector and one other sector.

Regarding *RQ1c* we found that multi-sectoral dynamics were important (central) to the transition phenomenon studied in 55 and peripheral in 25 papers, which indicates that multi-sectoral dynamics were important for transitions in most reviewed papers.

⁷ Note that we merge linkages and functional couplings. Also, this terminology describes interactions between sociotechnical systems at the same level of analysis (e.g., sector-sector) rather than across levels (e.g., system-sector-technology).

Figure 4: Number of articles on multi-sector interactions. Orange bars show publications per year. Blue bars show cumulative publications.

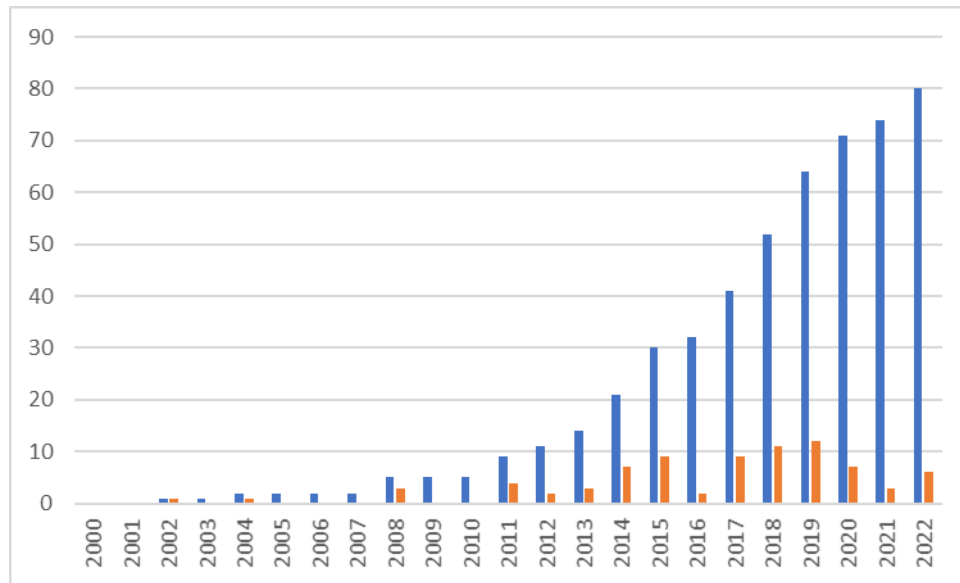


Table 2: Main coding categories and results

	Frequency
Input sectors (fuels, materials)	44
Technology-producing / manufacturing sectors	50
Adjacent sectors	29
Distribution sectors (grids)	8
Other sectors (Waste sector / circular economy)	2

Regarding RQ1 more generally, the reviewed studies cluster into the two types of multi-sectoral dynamics discussed in our framework, i.e., horizontal and vertical value chains. We elaborate this finding below.

4.1.1 Horizontal value chains

Horizontal value chains refer to generation, distribution and end-use of a particular service [7, 13]. In addition to a focal “production” sector (e.g. electricity), the horizontal chain includes input sectors, infrastructure / distribution, and end-use sectors. We found 33 papers where horizontal value chain interactions were of central importance (see Table 4).

Several papers focus on interactions between **input sectors** and focal sectors for the operation or change of technologies in the latter. One example involves interactions between gas and electricity sectors where gas turbines produce electricity [1]. Also, new interactions between agricultural and electricity sectors formed with the advent of biogas for electricity production [18]. The type of input sectors in the horizontal chain papers is exclusively raw material and energy inputs including electricity. A majority of papers analyze production and conversion of biomass into fuels, electricity, or materials [3, 4, 6, 12, 14-16, 18, 44, 50, 51, 68, 71-73, 75, 78, 80]. Other examples include transitions from coal to gas input for both electricity and chemical sectors [11, 48], electrification of

steel production via hydrogen [66] and materials shift in the concrete production sector [61]. While the above refers to the quantity of resources available, also the resource quality matters. For example, renewable and non-fossil based electricity is needed to make electric vehicles diffuse [77].

Distribution sectors are mostly noted in form the importance of the electricity grid for integrating variable renewables [21, 37] and to charge electric transportation [75-77] as well as for electrification of industrial sectors [80]. Distribution sectors are also important for biofuels and hydrogen [75].

User sectors are important for niche development in the focal sector [5, 6, 12, 74, 80]. For instance, the application of block chain for managing electricity systems is pioneered in the building sector (user of electricity) [74]. Pressure from environmental regulation or consumers in user sectors can incentivize actors in the focal sector to pursue sustainable innovation [6, 12, 80]. In five articles where horizontal chain dynamics were important, also **adjacent sectors** were discussed—particularly as additional user sectors [25, 72, 75, 76].

Table 3: Attention to different types of multi-sectoral dynamics

	Count	Central	Peripheral
Horizontal chain	48	33	15
Vertical chain	50	23	27

4.1.2 Vertical value chains

Vertical technology value chains refer to the array of different sectors involved in producing different parts of a particular technology as well as sectors using the technology. The technology-using sector typically coincides with the focal sector (undergoing transition) in the horizontal chain. In our sample, there is slightly more attention to vertical chains (50) than to horizontal ones (48), cf. Table 4.

We found 23 papers where vertical technology value chains play a central role. The papers typically focus on one particular technology produced by different **manufacturing sectors**. Most papers emphasize the interdependencies between technology-producing and **technology-using sectors** in technology value chain dynamics. For example, some papers show that formation of new technology value chains often depends on major changes in the technology-using sector that opens a window of opportunity against the otherwise dominant technological solutions [e.g., 9-11, 5, 27, 77].

Raw material **input sectors** are also important in vertical chains but as input for the technology producing sectors that use these to build (new and incumbent) technological artefacts. 10 vertical chain papers deal with raw material input sectors although they are central in only two of them [25, 27, 30, 36, 43, 56, 57, 59, 62, 65]. We found 15 papers where multi-sector interactions were central to evolution of vertical technology chains that also included the role of **adjacent sectors** [25-29, 31-37, 44, 67, 70]. These can both hinder niche technology growth in a focal sector by competing for and absorbing critical resources [31, 44] or support the niche by providing resources leading to growth in adjacent sectors [25, 26, 28, 29, 32-37, 67].

4.1.3 Interplays between value chain types

The relationship between vertical and horizontal chains is that while the sectors in the horizontal chain are largely technology-users (e.g. agriculture, electricity, transport), the sectors involved in the vertical chains are technology-producing (e.g. materials, component designs, and complex products such as power plants or automobiles).

Even so, we only identified one article where both vertical and horizontal chains are of central importance for the study [25]. We identified 12 articles where the horizontal chain view is central and where the vertical chain view is peripheral. However, these papers have limited depth regarding the dynamics of the vertical technology value chain that influences the horizontal chain (and vice versa). This result shows a remarkable disconnect in the literature between interlinked phenomena that seem crucial for understanding transitions. We will return to this issue in section 5.

Table 4: Attention to interactions between types of chains

Vertical chain paper score	Horizontal chain paper score		
		Central	Peripheral
Central		1	2
Peripheral		12	7

4.2 How and why do multi-sectoral dynamics in transitions unfold?

The overarching pattern observed in the reviewed papers is that growing problems and pressures on the established technologies and practices (i.e. regime) in a focal sector leads to the emergence of a new niche technology which often disturbs existing configuration of inter-sectoral relationships and creates tensions across sectors. Below we present results according to the main dimensions of sociotechnical systems (technology, institutions, and actors and networks).

4.2.1 Technology

One typical change process in inter-sectoral interactions is the emergence of a niche technology in a focal sector which requires changes in the relations to or/and changes in other sectors. For example, widespread use of biofuels in aviation (a niche) depends on establishing new relations to biomass provision sectors and stimulating production via investment or/and use of novel niche technologies there (e.g. 2nd/3rd generation biofuel technology) [6, 12]. Other examples include e.g. biogas power plants, windmills or zero emission houses [3-5, 12, 14].

Adjacent sectors with resources relevant for the emerging niche can be highly influential for its development. For example, the existence of a knowledge-related adjacent sector (in this case semiconductor production) is the strongest explanatory factor for whether countries develop PV manufacturing sectors [26]. However, when related knowledge is not readily available, the process of value chain formation is slower and costlier [27]. Countries are therefore more likely to succeed with entry to low-carbon technology value chains if they can build on knowledge from adjacent sectors [30, 28, 29, 35, 36, 54].

A second pattern of change concerns the wider diffusion of niche technologies in a focal sector which impact multi-sector interactions. For example, increasing diffusion of variable renewables or electrification of transport requires corresponding changes in electricity grids (distribution sector) [21, 22, 37, 75, 80] and expansion of the electricity supply sector [75, 80]. Such changes in related sectors also impacts the vertical technology chains. For example, the need to integrate large shares of variable renewables stimulated transformation in HVDC transmission technology towards a novel dominant design requiring new linkages with chemicals and ICT sectors [37]. In addition, expansion of vertical technology value chains is critical for sufficient production capacity to facilitate niche diffusion [39].

A third type of change process is technology decline which implies weakening or dissolving patterns of interaction between the focal sector and the sectors in the vertical technology chain [33, 67] as well as the sectors in the horizontal chain. For example, a transition to biofuels in the aviation sector

would involve breaking up linkages to the petroleum sector. In this case, adjacent sectors become receivers of outgoing resources [67].

We furthermore found that studies differed in how many sectors were involved. In terms of *vertical chains*, a focal technology can have multiple user sectors such as electricity generation and defense for nuclear [70], and electricity, road, and maritime transport for batteries [75]. Also, some upstream sectors such as the chemical sector serves many different technological producing sectors further downstream and thus has a central role in multiple overlapping technology value chains [37]. For *horizontal chains*, sector outputs can have many user sectors. For electricity, user sectors include many types manufacturing and service sectors that can compete for electricity [72]. Multiple and shifting user sectors can also support each other's' transition dynamics via opportunities for innovation [25, 75, 76]. An extreme case is the financial sector which arguably has all other sectors as its user sectors [72]. Moreover, in the case of biomass, there are multiple input sectors such as agriculture, waste, and forestry that deliver to multiple user sectors such as electricity, food, transport, furniture, or chemical sectors [71]. Several distinct horizontal value chains interact in such cases whereby they utilize the same input and distribution sectors [75]. This varied complexity of the sectoral configuration influences multi-sectoral dynamics in emergence, diffusion, and decline.

Lastly, we note that the multi-sectoral dynamics identified are predominantly revolving around flows of tangible (technology components, materials, fuels, etc.) and intangible resources (knowledge, financial capital, legitimacy, etc.) across sectors.

4.2.2 Institutions

We found that institutional change is an important process in multi-sector interactions for enabling or blocking the change processes discussed above, such as supporting the growth of an emerging technology [3, 4, 14, 75]. This includes both formal institutions (regulations, policies), and informal institutions (culture, norms, worldviews). Institutional alignment is important for obtaining compatible actor strategies and coordination across related sectors. Several papers conceptualized the institutional particularities of sectors as sectoral sociotechnical regimes [1, 3, 4, 51].

In terms of formal institutions, for example, when the sugarcane production sector became a significant supplier of biomass-based electricity, changes to regulations were needed to generate electricity on a stable rather than intermittent basis following harvest cycles. At the same time, the electricity supply sector developed new forms of contracts tailored to the characteristics of sugarcane production [4]. In some cases, niche actors' access to resource inputs was restricted by existing regulation in terms of long-term contracts that reserved resources for other purposes [14, 68, 71]

In terms of policy, different sectors often fall under different policy domains. Coordination across ministries of energy and agriculture, for example, can create barriers for diffusion of new technology [3]. Some new technologies like smart houses require alignment across ministries of energy and of housing but this is difficult due to distinct policymaking cultures. For example, the ministry of energy has limited understanding of energy efficiency, while ministry of housing is not used to considering energy transition issues [5].

In terms of informal institutions, interacting sectors can have different levels of legitimacy which can create imbalances.⁸ For instance, using biofuels in the aviation sector is relatively unproblematic in technical terms, but consumers are critical of the scale of biofuel production in input sectors due to

⁸ Here we understand legitimacy as degree of institutional alignment between a sector and its context (Markard et al., 2016).

concerns over fuel-vs-food. Low legitimacy for fuel production holds back deployment of and investment in biofuel technology and thereby a biofuel transition in the aviation sector [6, 12]. Actors in input and focal sectors can also have diverging expectations and worldviews that limit institutional alignment and flows of resources [35, 69].

4.2.3 Actors and networks

Actors enact transitions as well as inter-sectoral interactions. Their behavior, expectations, and strategies are thus crucial. The main insight from our results is that actors located in interacting sectors depend on each other to enable a transition in a focal sector [26, 34, 37, 44, 53].

When actor strategies are incompatible, inter-sectoral resource imbalances occur. For example, in the case of the cement sector, producers are locked-in when the suppliers on which they depend have no incentive to deliver the necessary new inputs. Cement producers must then nurture new suppliers in a very concentrated market [61]. Also, the absence of competent and proactive actors in the technology-using sector inhibited further innovation in the windmill technology-producing sectors in China [27, 37]. Moreover, investment by firms in innovation in bio-refineries in Germany was held back by uncertainty about whether producers in wood, forestry, and agricultural sectors could provide sufficient biomass [16].

We identified four processes through which actors seek to mitigate cross-sectoral imbalances. First, in response to uncertainty over inputs, firms pursue vertical integration to secure access [30, 2]. Another way to address imbalances, is to build cross-sectoral networks that function as coordination mechanisms [3, 6, 18, 66]. For instance, hydrogen-based steel created a new coalition between electric supply utilities and green hydrogen actors [66]. Furthermore, aviation firms created networks with biofuel producers to make pilot projects, experiment with new technology as well as developing certificates and standards [6]. Third, when there is opportunity to strengthen emerging value chains with resources from adjacent sectors, firm diversification across sectors is a crucial enabler of resource flows [33, 35, 67]. Fourth, firms work to change institutions in support of new multi-sectoral interactions. Some seek to develop new institutions such as cross-sectoral standards [6], policies [43, 80], or R&D programs [52]. Others work to defend and maintain institutions supporting existing multi-sector configurations [31].

5 Discussion

In this section, we assess the usefulness of our analytical framework in making sense of the findings from the systematic review and, on that basis, suggest refinements and extensions through analytical reasoning. We proceed in three steps: 1) we discuss our framework's ability to account for the comprehensive diversity of observed multi-sectoral phenomena (relates to section 4.1), 2) we discuss how the identified change processes can inform us about *how* multi-sectoral dynamics unfold (relates to section 4.2), and 3) implications for policy and future research.

5.1 The scope of industrial transformation revisited

Overall, our heuristic framework was useful for guiding the analysis of identified scientific articles and interpreting the results of the review. Unsurprisingly, the reviewed studies individually only addressed a small part of the framework but offer important insights when seen as an accumulated stock of knowledge about multi-sectoral dynamics.

Several of our propositions (cf. section 3.3) were validated by the review. Our review confirmed that horizontal chain sectors are largely technology-users (e.g. agriculture, electricity, transport) and vertical chain sectors are technology-producing (e.g. materials, components, complex products). The review also showed the interdependency between change processes in vertical and horizontal

chains, thereby demonstrating the need for a more integrated understanding of multi-sectoral dynamics spanning upstream sectoral transformation and transitions in systems. Even so, the review demonstrated a near complete disconnection of research on horizontal chains and vertical value chains cementing the need for an integrated framework. Moreover, many studies applied the concepts of sociotechnical regime and niche at the level of sectors instead of larger systems [1, 3, 4, 51]. Our proposition of extending the use of niche-regime concepts to multi-sectoral vertical value chains was therefore validated.

The review revealed several nuances of multi-sectoral dynamics that require extension of our framework. First, there are two more *sector types* involved than we initially included in the framework. One type concerns the importance of *additional input sectors* to the horizontal chain. For example, to produce electricity actors could need coal inputs from mining sectors or biomass from forestry or agricultural sectors. Another additional sector type is *waste management*. The review showed that change in waste management strongly depends on changes in the waste-generating sectors. Waste management is critical (including re-use, re-manufacturing, recycling, etc.) in material efficiency and circular economy transitions. Another insight is that the *number of sectors* involved in a particular system differs, i.e., each *sector type* can contain multiple *specific empirical sectors*. A hydrogen system, for example, would approximately include two input sectors (gas and electricity), one production sector (hydrogen generation), three distribution sectors that both compete and complement each other (pipelines, road trucks, and shipping), and an array of different user sectors (chemicals, maritime, aviation, steel, electricity, etc.). Explicating the number of heterogeneous sectors involved in delivering system services provides a novel perspective on sociotechnical systems, as visualized in Figure 5.

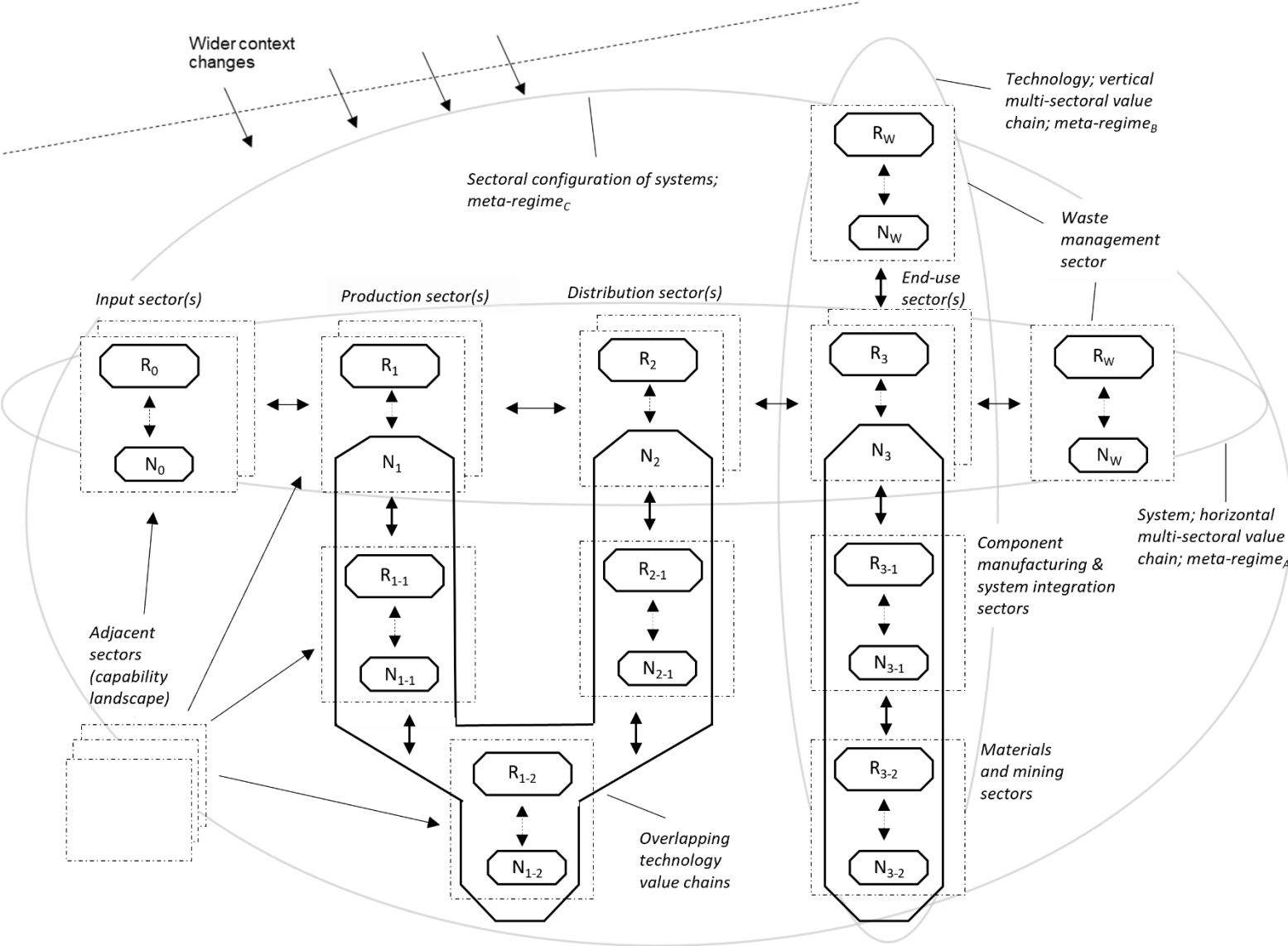
Considering these extensions, our framework enables us to map *the sectoral complexity of systems* across interlinked horizontal and vertical chains. In a next step we discuss four selected transition phenomena that are increasingly relevant but so far overlooked in transitions research, and that our extended framework draws attention to and facilitates analysis of.

First, the framework revision draws more attention to *sector overlaps* in and across value chains. Here we give three relevant examples. For vertical value chains, for example, it facilitates analysis of technologies that are applied in multiple sectors, i.e., *multi-purpose technologies*. A sociotechnical perspective on multi-purpose technologies goes beyond techno-economic factors (price-performance ratios) (Frenken & Nuvolari, 2004) to consider institutional idiosyncrasies and actor strategies for handling multi-sector innovation challenges such as diversity-learning dilemmas (i.e., too high user sector diversity can impede learning (Schot & Geels, 2008)). Such challenges currently occur for energy-dense batteries, carbon capture, and fuel-cell technologies and this topic merits more attention (Finstad & Dahl Andersen, 2023). Another sector overlap type occurs in horizontal chains related to food and energy that receive inputs from the same biomass sectors (forestry, agriculture, fishery, etc.) leading to input sector overlaps. Similarly, there are multiple sectors relying on electricity from the same electricity grid sector leading to overlaps in distribution (Nykamp et al., 2023). Such overlaps can involve important cross-sector resource competition, e.g., think of food versus fuel debates, or complementarities, e.g., scarce electricity leads to cross-user sector co-creation of industrial microgrids in energy hubs. Lastly, important sector overlaps occur in relation to ‘transition minerals’ making the mining sector a critical base for most vertical chains which can influence transitions (IEA, 2021). The speed and scale of diffusion required to reach goals of net-zero emissions by midcentury implies that many low-carbon value chains must upscale in parallel, in many places, and in a short period of time making the challenge unprecedented (Andersen et al., 2023). Even so, this topic has not received much attention (Andersen & Wicken, 2020; Marín & Goya, 2021).

Second, our revised framework, and especially the waste management sector, draws attention to two new uses of the terms *meta-regimes* and -rules that are seen as important for ensuring rule-alignment and avoiding sector interaction bottlenecks in horizontal chains, cf. section 3. This also emerged from the review where unsustainability of input sectors undermined the legitimacy of a sustainable aviation sector. With our framework, however, meta-regimes are also relevant for vertical chains. For any mature vertical chain, a degree of rule-set alignment is needed for its functionality. A shift from linear to *circular value chains* will in this context require a fundamental shift in meta-regime logic (including the waste sector) because change in one sector depends on change in others. When viewing technology value chains as a type of system of subsystems/sectors, a shift in vertical chain meta-regimes constitutes a new type of transition phenomena, which has received limited attention in the literature. Similarly, building a new value chain can be understood as creating a new meta-regime that coordinate inter-sectoral interactions (Gong & Andersen, 2023). Lastly, the meta-regime concept may be extended to the entire sectoral configuration of systems. Indeed, in mature systems (e.g., fossil-fuel based electricity provision in centralized systems with passive consumers), the horizontal chains are largely aligned with an array of relevant technology value chains (coal, gas, and nuclear, HVAC transmission technologies) and various material inputs (no major growth in copper, steel, coal, or gas). Considering the *full sectoral configuration of systems* provides an interesting transition canvas where many inter-sectoral bottlenecks (horizontal and vertical) could occur. As transitions broaden and increasingly cuts across multiple sectors, more attention to meta-rules and regimes, and especially how new ones emerge, is an important research topic.

Third, our broad transition canvas reveals the extent to which transitions depends on aligned action by a large and diverse set of actors from distinct sectors to succeed in coordination and collective action. It shows that innovation hotspots where newcomers present novel innovations and threaten incumbents are probably needed across many sectors to drive a system transition. On the flipside, it also draws attention to the fact that incumbency and its possible negative impact on transitions, is distributed across many sectors and each may exert a unique influence (i.e. “deep incumbency” (Stirling, 2019)). Our framework also draws attention to the role of multi-sector actors, i.e., those that are present in multiple sectors and/or multiple value chains and thereby exert disproportional influence on transitions such as multinational companies, highly diversified technology firms, or labor unions. Such multichain (Navas-Alemán, 2011) or keystone actors (Österblom et al., 2022) have received limited attention in transitions research (Kunl, 2023).

Figure 5: The sectoral configuration of systems revisited



Fourth, minor and major changes anywhere in the sectoral configuration of systems is part of industrial transformation and constitutes opportunity for *value creation* by actors. This will be conditioned by the 'local capability landscape', reflecting the pre-existence of relevant adjacent sectors (either horizontally or vertically) and the ability to attract and anchor resources. Our framework is helpful for thinking through strategies for 'green growth' that go beyond single green innovations to consider how to connect interlinked value creation opportunities across multiple vertical and horizontal value chains with existing capabilities.

5.2 On the multi-sectoral aspects of transition dynamics

In this section we discuss two points: 1) driving processes and barriers in multi-sectoral dynamics, and 2) extending our findings to account for transition phases and outline the big picture transition dynamics our framework reveals.

5.2.1 Driving processes and barriers in multi-sectoral interactions

Our review focused on how and why multi-sectoral dynamics happen and identified nine driving processes and barriers, see Table 6.

Table 5: Change processes in multi-sectoral dynamics

	Processes	Multi-sector dynamic	Paper examples
Technology	1) <i>Emergence of niche technology</i>	New technology requires linkages to other sectors or/and changes in them.	[3-5, 12, 14]
		Adjacent sector boosts niche emergence	[28-30, 35, 36, 54].
	2) <i>Technology diffusion</i>	Diffusion requires, often rapid, upscaling of both horizontal and vertical chains, and sometimes induce transitions in those sectors	[21, 22, 37, 75, 80]
	3) <i>Technology decline</i>	Dissolving inter-sectoral relations in both horizontal and vertical chains	[67, 33]
Institutions	4) <i>Changing formal institutions</i>	Misaligned regulation and policies in inter-linked sectors can hold back actors and technological change	[3-5, 68, 71]
	5) <i>Changing informal institutions</i>	Value chain sectors enjoying different levels of social legitimacy can block multi-sector synergies	[6, 12, 35, 69]
Actors & networks	6) <i>Vertical integration</i>	Uncertainty over ability/willingness of input sectors to supply what is needed leads to multi-sector actors	[2, 30]
	7) <i>Building cross-sectoral networks and coalitions</i>	Coordinate / orchestrate collective action across value chain sectors	[3, 6, 18, 40, 66]
	8) <i>Diversification from adjacent sectors</i>	Diversifying actors realize resource flows across adjacent sectors and emerging value chains	[33, 35, 40]
	9) <i>Institutional work</i>	Actors work to build new cross-sectoral institutions or defend existing ones.	[6, 31, 52, 80]

In the reviewed papers, the most common driver of change in multi-sectoral interactions in transition is the emergence of a new niche technology value chain which necessitates new couplings to input sectors that provide material and energy inputs as well as resources from adjacent sectors (e.g., knowledge and finance). Interestingly, the need for changing the multi-sectoral interactions typically intensifies as the focal niche technology diffuses widely and needs still more materials and

complementary changes. Multi-sectoral dynamics happen in practice because actors enact them by working to innovate, to change institutions, and to build new structural couplings. Overall, the myriad of different drivers and barriers that can unfold across the sectoral configuration of systems suggests there will be many multi-dimensional inter-sectoral change processes happening in parallel at any one moment of a system transition.

A next step for improving our understanding of how multi-sectoral dynamics happen in practice is to connect systematically with knowledge areas that theorizes actor strategies for cross-sectoral collaboration (Helfat, 2015; Rothaermel, 2001; Teece, 1986) and for building new systems and value chains (Musiolik et al., 2020; Planko et al., 2016) with particular attention to how varying sector properties (e.g., capital intensity, firm types, or exposure to international competition), sectoral complexity and maturity of value chains, as well as transition phases impact such strategies.

5.2.2 Transition phases and industrial transformation

Scholars divide transitions into distinct phases to portray how central phenomena change over time (Markard, 2018; Rotmans et al., 2001) including: pre-development, take-off, acceleration, and stabilization. However, so far these accounts do not explicitly consider multi-sectoral dynamics. We extend our findings on differences in multi-sectoral dynamics across early and acceleration via analytical reasoning to outline how industrial transformation broadens across transition phases.

The pre-formation phase is characterized by small-scale, local experimentation with alternative solutions among pioneers such as lead-users and lead-producing firms. There is no niche technology value chain but rather a loose network of actors, high uncertainty about future development, and high technical variety. In *the take-off phase*, expectations to the niche grows, more actors from distinct sectors enter, and resources flow to the niche. There is early deployment, and the contours of a value chain form around a few possible dominant designs. Inter-sectoral linkages now include stronger interaction with lead and professional users, manufacturers, component, and material providers. The growth may start to disturb the regimes in input and infrastructure sectors.

The acceleration phase is catalyzed by emergence of a dominant design around which actors can specialize and upscale the technology value chain. The phase includes rapid diffusion of the new niche technology in the focal sector requiring new couplings to (new) input sectors and it can start to transform distribution and end-use sectors. In the vertical chain, the upscaling of production will require massive amounts of raw materials which can start to affect mining sectors and possibly result in shortages, leading for instance to interest in circular value chains. The growing number of inter-sectoral linkages across the system that are affected by the transition in the focal sector may or may not cause transitions in these sectors as well.

This adapted account of transition phases illustrates that multi-sectoral dynamics differ across phases and highlights that the sectoral scope of the system transition expands as it progresses, creating cascading effects on still other sectors (Markard, Geels, et al., 2020). This aligns with the whole system reconfiguration approach (Geels & Turnheim, 2022; McMeekin et al., 2019) that goes beyond seeing transitions as driven by singular radical innovations (Geels, 2018) to understand transitions as resulting from interactions between multiple change processes at multiple places over long time spans that together produce larger outcomes (Geels, 2022).

To this perspective we add multi-sectoral lenses that can systematically map sectoral interdependencies in systems and suggest a sequence of imbalances across them as the transition unfolds. The general logic is to see transitions as processes of widening imbalances and tensions with

epicenter in niche innovation(s) in a focal sector whose diffusion produce ripple effects through the web of inter-sectoral couplings mirroring waves of industrial transformation (Carlsson & Henriksson, 1991).

Our multi-sectoral perspective helps comprehend and analyze how renewable energy niche technologies (e.g., solar PV, wind) could shift from being irrelevant in the electricity supply sector to currently transforming multiple other sectors such as transport, industry, and heating through low-carbon electrification (horizontal couplings) and creating entirely new value chains, as well as transforming manufacturing and materials sectors through their upscaling (vertical couplings). It helps us to think across multiple solutions and sectors to understand the scale of the challenges related to scarcity of minerals, skills, land, and manufacturing capacity but it also reveals a nuanced picture of opportunities for new value creation.

6 Conclusion

Transition studies lacks systematic attention to the relationship between sustainability transitions and industrial transformation. As transitions advance and broaden, this deficit increasingly makes transitions studies unable to account for emerging phenomena. Based on a combination of a narrative review of main transition theory frameworks and a systematic review of multi-sectoral dynamics in transitions research, we outline, qualify, and discuss implications of a novel multi-sectoral framework that systematically integrates system transitions and wider economic structural change in the form of transformation of interwoven technologies and sectors. The framework allows analysts to zoom in and out across system, sectors, and technologies as well as their interactions in a transparent and tractable way to e.g. do partial analyses. The framework can in principle be centered around any type of sector and from there map out inter-sectoral couplings of importance for transitions.

Our findings are also relevant for policy debates and policymakers. There is much debate around how policy can support transitions under the overlapping terms as transition policy mix, transformative innovation policy, and mission-oriented innovation policy (Kern et al., 2019; Schot & Steinmueller, 2018; Wanzenböck et al., 2020). However, these approaches typically focus on system transitions without explicit acknowledgement of the multi-sectoral dynamics involved including multiple technology value chains. Schot and Steinmueller (2018) criticize evolutionary economics (what they call the 2nd frame of innovation policy) for being too focused on firms and supply-side innovation dynamics (i.e., technology value chains) calling for more attention to the changes in the selection environments of these technologies (i.e., systems) enabled by users and institutional changes (which they call the 3rd frame of innovation policy). Our framework thus provides a new template for integrating 2nd and 3rd frames and systematically discuss relationships between innovation policy and industrial policy (technology value chain) and energy, climate, and transport policy (systems) across different phases and places.

Our framework integrates ideas from evolutionary economics and transition studies, and, in our view, provides a new bridge between these research areas because it provides transition researchers a frame for talking about industrial transformation and evolutionary economists a frame for connecting to transition studies. We hope that that the paper can inspire new dialogue and collaborations across the research areas to better understand and analyze new phenomena in broadening and accelerating transitions that require our scholarly attention.

Appendix: List of included papers in the systematic literature review

ID	Authors	Title
1	Konrad et al. (2008)	Multi-regime dynamics in the analysis of sectoral transformation potentials: evidence from German utility sectors
2	Di Lucia and Ericsson (2014)	Low-carbon district heating in Sweden - Examining a successful energy transition
3	Sutherland et al. (2015)	Conceptualising multi-regime interactions: The role of the agriculture sector in renewable energy transitions
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