Sustainability transitions and economic structural change: Towards a multi-sectoral perspective on transitions

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 only paid limited attention to the economic structural change associated with transitions. This suggests that despite common origins via the concept of technological regimes, Economics of Innovation 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 seemingly paid more attention to 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 perspective on transitions which provides a systematic view on the interplay between multi-sectoral dynamics and system transitions.

1 Introduction

Sustainability issues such as climate change, degradation of ecosystems, poverty, depletion of natural resources or lack of clean water and sanitation pose extraordinary challenges for societies (UNEP, 2016). To address these grand challenges, fundamental changes are needed in the way current production and consumption patterns are organized in systems providing key societal services such as electricity, mobility, food, housing, and sanitation. Even though sustainability problems have cumulatively aggravated in recent decades to breach various planetary boundaries (Persson et al., 2022), progress has due to a range of systemic lock-in mechanisms been limited (Editorial, 2018).

Some innovation scholars have approached the analysis of such challenges through the lenses of sociotechnical or sustainability transitions (Köhler et al., 2019). This approach contemplates that a series of sustainability transitions in several systems are needed to stay within planetary boundaries. Transitions are understood as fundamental changes in sociotechnical systems including consumption practices, lifestyles, technologies, infrastructures, and business models. The process typically pivots around radical innovation that disrupts existing systems in different ways (Geels, 2002; Geels & Schot, 2007).

Due to the nature of sustainability challenges, public policy is expected to be a central driver of change (Kern & Markard, 2016; Weber & Rohracher, 2012), and increasingly so as the time left for climate mitigation action dwindles by the day (IEA, 2021). Ambitious policy action, however, can run into conflict with other policy goals such as economic growth, employment, and trade, and implementation requires significant social legitimacy. At the same time, transition policies have led to social backlashes when particular social groups feel unfairly treated and fear for livelihoods and jobs (Pel, 2021).

A major barrier to a series of rapid sustainability transitions therefore is lacking 'political will' rather than technological opportunities (Roberts et al., 2018). A closer alignment of economic and environmental goals can thus possibly increase the political feasibility of transitions (Turnheim & Nykvist, 2019; Vona, 2019). Such alignment is furthermore central for devising new transitions strategies as the "green new deals" that aim to make transitions socially just and inclusive, i.e. transitions where workers, communities, and businesses are protected and included.

To understand how such alignment might take place, careful analysis of the relationship between transitions and structural change in the broader economy is needed. It is well-known that radical technological innovation through cascades of structural imbalances across multiple sectors can induce major economic transformation (Dahmén, 1989; Perez, 2009b). Surprisingly, these insights are not accounted for in main transition studies frameworks such as Technological Innovation Systems (TIS) and the Multi-level Perspective (MLP). Instead, focus has been on emergence and diffusion of new technologies—so-called point source innovations—within single sectors rather than with transformations in the wider economy (Foxon, 2018; Geels, 2018; Winskel, 2018).

For example, the broad canvas of the MLP tends to compress and black-box the economic sectors involved in providing capital goods and services, advanced materials, and natural resources in value chains (Andersen & Gulbrandsen, 2020; Andersen et al., 2020; Steen & Weaver, 2017). The TIS approach has in recent years broadened its scope by articulation of a technology value chain approach accounting for various sectors involved in producing and using a particular artefact (Andersen & Markard, 2020; Stephan et al., 2017), and by directing more and more attention to contextual elements as adjacent sectors, technologies, and geography (Bergek et al., 2015). Even so, analytical focus remains on single technologies rather than wider system transitions. Such approaches therefore have limited reach for analyzing not least explaining economic transformation—changes in the sectoral composition of the economy in a specific place—related to transitions.

The starting point for this paper is thus the paradox that, even though it is well-known that major innovations can induce economic transformation, this phenomenon is not accounted for in main transition studies frameworks. As a consequence, some transition scholars have called for more systematic attention to the innovation and industry dynamics of sustainability transitions (Andersen et al., 2020; Busch et al., 2018; Foxon, 2018; Giuliani, 2018; Johnstone et al., 2021).

Motivated by this knowledge gap, we pose two research questions. First, *how have transition scholars empirically studied multi-sectoral dynamics?* Based on knowledge of the literature, we assert that despite the under-conceptualization of multi-sectoral dynamics in frameworks, the phenomenon of interest is so pervasive that it does appear in transition scholarship. Second, *What are the mechanisms and processes of multi-sectoral interactions in transitions, i.e. how and why do they happen?*

Methodologically we answer these questions in three steps. First, we provide an in-depth review of TIS and MLP frameworks which leads us to suggest a novel typology of nested sociotechnical systems that explicates the role of sectors in transitions. Second, guided by this typology, we perform a systematic literature review focused on our research questions. Third, with our results we explicate accumulated insights about multi-sectoral dynamics to provide both an overview and propose a new multi-sectoral perspective on transitions. This framework, we suggest, can help us think more systematically about the relationships between transitions and economic structural change.

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

2 Multi-sectoral dynamics in socio-technical transitions

In this section, we first present a brief overview of research on the multi-sectoral interactions for innovation. Based on those insights we inquire about how the two main sustainability transitions' frameworks—the Multi-Level Perspective (MLP) and the Technological Innovation System (TIS)—have engaged with inter-sectoral dynamics. We chose these two because they devote most attention to the role of multiple sectors among transition studies frameworks (for overview see Markard et al., 2012). Finally, we propose a new typology that establishes the differences and relationships between systems, sectors and technologies.

Note that we delineate a sector according to a specific set of products (e.g. chemicals, cars or electronics) or services (e.g. electricity supply or finance) whose provision involves and require competing actors (typically firms) with a specific set of core competencies (Malerba, 2002).[1] We see input providers and users as external to the sector. This implies that every sector is a user of inputs from other sectors and is a producer of services or products consumed in other sectors resulting in ubiquitous inter-sectoral user-producer relationships.

[1] 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.

Any sector may apply several individual technologies as part of the 'production function'. It has a sector-specific regime that reflects the dominant configuration of actors, technologies, and institutions including the overall mode of innovation (Malerba, 2005; Markard & Truffer, 2008; Pavitt, 1984). The fact that sectors have particular characteristics is indeed a main reason to pursue a multi-sectoral perspective on transitions.

2.1 Innovation and multi-sectoral interactions

Historical studies have shown that innovations have ripple effects across the economy affecting multiple sectors (Perez, 2002, 2009a). While some radical innovations may influence a specific sector only, others may affect a whole range of sectors or, in rare cases, the entire economy. 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 held back or propelled forward by another 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, for example, requires innovation in complementary technologies as energy storage to deliver a stable provision of power. At the same time, these different, interdependent technologies are typically 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 interactions are important for understanding technological change.

Perez (2009b) identifies four types of sectors involved in major technological shifts (Perez, 2009b). 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 artefact and innovation that other sectors react to—such as automobiles, steel steam ships or iron steam engines. Third, *infrastructure sectors* that enable the other sectors' progress 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 the core innovation (e.g. logistics). They often existed from before but are modernized in the technological shift and take on a different role from before.

Interactions across sectors are typically viewed as linkages between actors (e.g. firms). Linkages can be channels for exchange of goods, services, knowledge or other resources (Ciccone, 2008). Linkages lead to interdependency between sectors in terms of inter alia investment and growth (Hirschman, 1958; Richardson, 1990), input-output-demand relations, and innovation (Dahmén, 1989; Perez, 2009a). 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 importance of interactive learning—and thus the number of sectors involved—varies across products and technologies but generally rises with technological complexity. Such user-producer linkages exist across the economy organized under a division of labour between sectors.

For example, sectors have different modes of innovation, knowledge bases, and core competencies that can complement each other via inter-sectoral linkages (Malerba, 2005; Pavitt, 1984).[2]

From this short review, we conclude that many innovations rely on changes in multiple sectors to emerge and diffuse, and can transform numerous sectors in the process creating ripple effects across the economy. We also saw that, inter-sectoral linkages often are based on technology because every technology requires a particular set of sectors for its production, operation and use.

2.2 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.

2.2.1 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 et al., 2008). The framework provides a systemic view on the evolution of a focal technology (Markard & Truffer, 2008). TIS has been extensively applied for studying emergence of new energy technologies. The focus on emergence has arguably implied limited focus on how TIS dynamics interplay with broader economic transformation (Bergek et al., 2015).

From the outset it was acknowledged that a TIS necessarily crosses or involves multiple sectors (Carlsson & Stankiewicz, 1991; Edquist, 1997; Markard & Truffer, 2008).[3] This insight has more recently been developed into an explicit technology value chain approach to TIS (Andersen & Markard, 2020; Sandén & Hillman, 2011; Stephan et al., 2017). In this approach, technology is seen as a complex system consisting of interacting subsystems, components and materials[4] (Arthur, 2009; Murmann & Frenken, 2006) that are applied in and produced by different sectors (Sandén & Hillman, 2011; Stephan et al., 2017).[5] 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. These are other 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 et al., 2015; Malhotra et al., 2019; Mäkitie et al., 2018), and

---

[2] Note that in this perspective transaction and interactive innovation are intertwined in linkages. Innovation is typically a systematic problem-solving activity emerging within existing production structures. As such, this view blurs the distinction between production and innovation processes and systems (Andersen, 1992; Lundvall et al., 2002).

[3] 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.

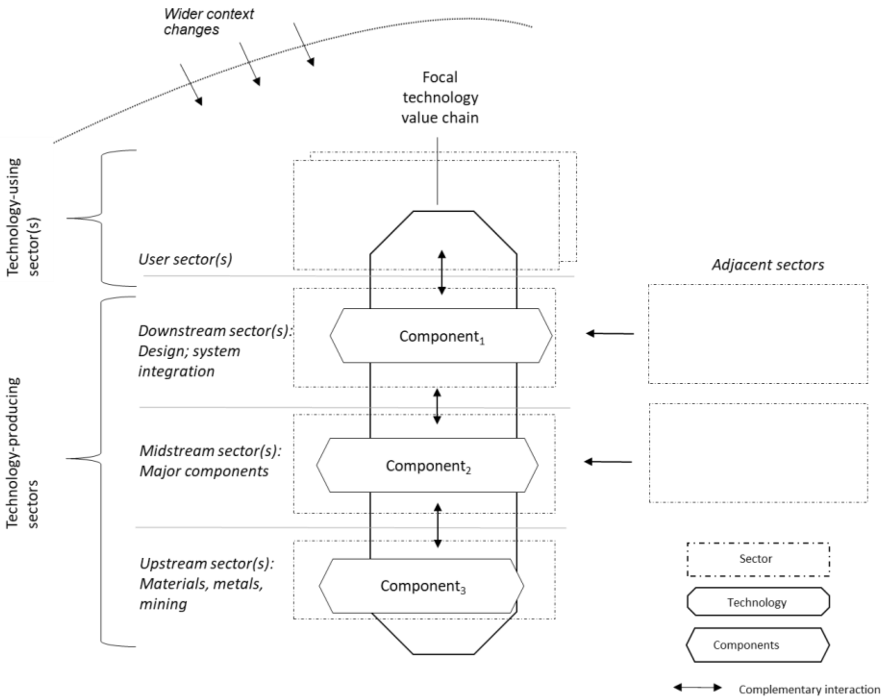
[4] For simplicity we only use the notion of components and not subsystems and materials.

[5] 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.

can be considered as the industrial context for a focal technology (Andersen & Gulbrandsen, 2020; Fontes et al., 2021).

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 TIS that may be important for transitions.

Figure 1: Sectoral configuration of a TIS

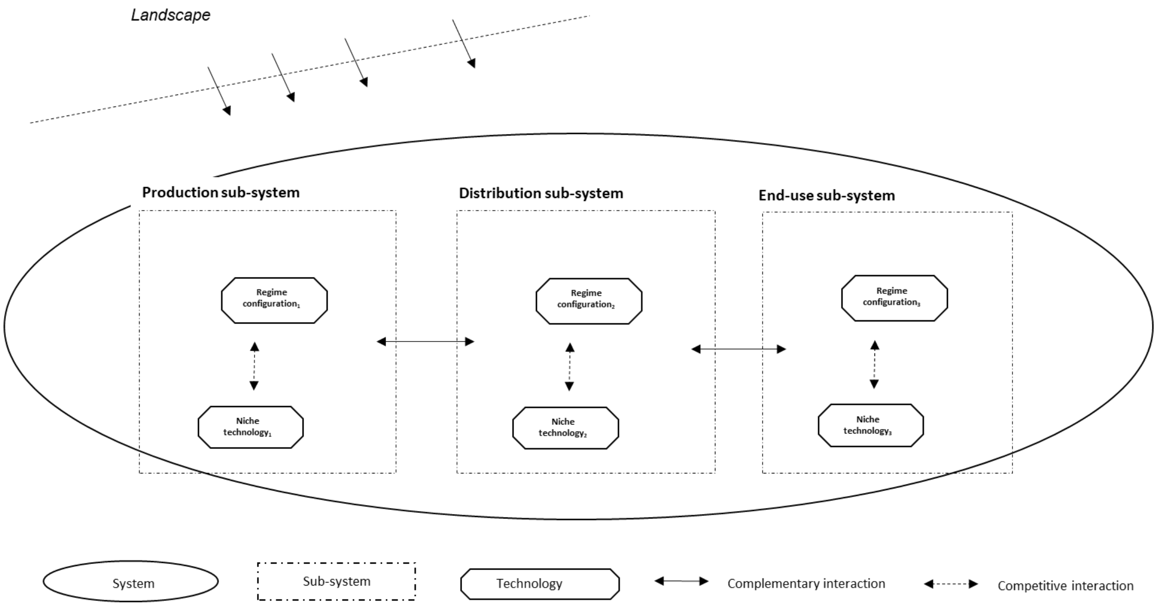


2.2.2 Multi-level Perspective and multi-sectoral dynamics

The MLP is a foundational framework for conceptualizing sociotechnical transitions. Transitions happen in sociotechnical systems that produce, distribute, and consume societal services such as electricity, food, or transportation. Sociotechnical systems 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 contain immature, niche technologies with limited actor support, market share, and weak institutional support. Regimes induce mainly incremental change in systems and therefore often works 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 in the system. Transitions occur when external pressures for change weakens the regime to create opportunities for alternative niche technologies emerging to transform the regime (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 2: The sociotechnical system and sub-systems in the Multi-Level Perspective (McMeekin et al., 2019)



The notion of a sector (as defined in this paper) is not conceptualized within the MLP. Still, 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) while foundational studies clearly 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 2 (Geels, 2018; McMeekin et al., 2019). They divide large systems 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 (McMeekin et al., 2019).

Even so, interactions between sectors in transitions are not articulated. This is however visible in similar concepts as large technical systems and techno-economic complexes (Hughes, 1983; Unruh, 2000). Unruh (2000, p. 822), for example, shows that large technical systems (e.g. electricity) 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 acknowledged as elements of sociotechnical systems in form of technological artefacts, tools and machines, or natural resources and parts (Geels, 2004).

However, the sectoral manifestations of these elements remain latent and compressed in current conceptualizations of sociotechnical systems.

In conclusion, even though the notion of a sector is not conceptualized in relation to sociotechnical systems, they arguably involve multiple sectors (Coenen & Díaz López, 2010).

2.3 Systems, sectors, and technologies: A typology

From the discussion above, we see that existing frameworks do not adequately account for multi-sectoral dynamics in transitions. We note that the literature is not clear on how sectors and sociotechnical systems relate. To impose a systematic and coherent structure on the reviewed concepts we propose a novel typology for distinguishing between systems, sectors, and technologies in transitions. The typology is based on a nested sociotechnical systems view, i.e. we see sociotechnical systems as a nested hierarchy of systems, subsystems, and components, see Table 1 (Geels, 2005; McMeekin et al., 2019; Sandén & Hillman, 2011; Stephan et al., 2017). We do so in three steps.

First, we observe that subsystems of whole systems (Holtz et al., 2008; McMeekin et al., 2019) correspond to our definition of sectors and sub-regimes correspond to sectoral regimes (cf. Malerba, 2005).[6] 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 actors apply conversion technologies as electric devices and motors (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 2.2.1, regime and niche configurations around particular technological artefacts involves multiple sectors that produce (e.g. components and materials) and use it.

Table 1: Systems, sectors, and technologies

Concept	Description	System hierarchy	Sector dimension	Example
System	System providing high-level societal function 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 all technologies, and actors in a sector that share a common set of rules and produce similar outputs	Subsystem	One focal sector within system	Electricity supply; automotive production; chemical sector; mining sector
Technology	Sociotechnical system delineated by a technological field or artefact.	Component	Several sectors producing and using focal technology	Nuclear, coal, wind, solar PV, Li-batteries,

[6] Indeed, electricity generation and distribution have different NACE codes for this reason.

The typology demonstrates how multiple sectors are involved in transitions via the production and use of technological artefacts for the provision of societal services in systems. It follows that different types of sectors can influence transition dynamics in important ways. However, we do not know to what extent multi-sectoral dynamics has been empirically studied, what types of sectors are included, or what the causal mechanisms involved in multi-sectoral dynamics are. This sector-oriented typology will next support our review of the transition studies literature aiming to answer these questions.

3 Methodology

3.1 Research approach

To improve our understanding of multi-sectoral dynamics in transitions we perform a theory-guided, systematic literature review. 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). A systematic review is retrospective and therefore encounters the challenge that the papers reviewed may not have been originally intended to answer the questions that the researcher wants to address. As our phenomenon of interest—although partly visible in the literature—was not labelled and conceptualized according to our perspective, we needed to first pre-define analytical categories and relationships involved in multi-sectoral dynamics to be able to systematically identify them later on the in empirical review. For this reason we divided our research process into three steps.

First, we assessed two central analytical frameworks in the transition studies literature to understand how multi-sectoral dynamics are conceptualized. Based on this we proposed a new typology to establish the concept of a sector in system transitions.

Against this background we formulated two overarching research questions for the empirical review:

1. How has multi-sectoral dynamics been empirically studied in the literature? We divide this question into three sub-questions:
    a. To what extent multi-sectoral dynamics been studied?
    b. What type of sectors are studied?
    c. How important are multi-sectoral dynamics for transitions?
2. What are the mechanisms and processes of multi-sectoral interactions in transitions, i.e. how and why do they happen?

In a second step, we did a systematic review of transition studies guided by our typology with focus on empirical insights (see below for detailed explanation of process). This step did involve some subjective interpretation by the researchers as we assessed and connected the deduced typology with empirical observations to answer the posted questions.

In the third step, we synthesized insights from previous steps to propose a novel framework. The latter goes beyond summarizing insights in the literature. Instead, we combined our proposed typology and empirical insights with analytical reasoning to see and outline something which is not already in the literature (Kanger et al., 2020).

3.2 Data selection

The article population was identified in two steps.

First, we made three steps in delineating our sample to focus on core transition studies articles. 1) We focused our search to peer-reviewed articles in the most important international academic journals in the field of sustainability transition studies, by searching papers in the seven most cited journals of the recent agenda for sustainability transitions research (Köhler et al., 2019). 2) To further zoom in on transition scholarship published in these journals we further limited our search to applications of the key frameworks of the field, see Table 2 (Kivimaa et al., 2019; Markard et al., 2012). 3) Within this corpus we searched in title, abstract and article keywords for the following keywords that reflect our interest in upstream sectors: sector, industry, and (value/supply) chain. This first sample included a total of 202 papers.

Table 2: Description of main corpus

Category	Number
Articles (peer-reviewed):	67
Time period:	2002 - 2020
Sources (Journals)	7
Energy Policy	9
Energy Research and Social Science	4
Environmental Innovation and Societal Transitions	16
Journal of Cleaner Production	16
Research Policy	11
Technological Forecasting and Social Change	9
Technology Analysis and Strategic Management	1
Key framework	
MLP	23
TIS	31
TIS – MLP	2
TIS – SIS	1
SNM	8
TEF	1

Notes: 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.

Second, we determined the relevance of papers in several iterative steps. Our criterium for inclusion was that articles must 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 89 papers. Through the process of reading and coding full papers, the sample was further reduced to 67papers. An overview of our final collection of articles is given in Table 2.

3.3 Coding process

Based on our theory assessment in section 2, we developed a coding scheme which reflected our key review questions but was also kept open to allow for new inductive insights. Based on a first coding scheme, we performed a pilot study including 20 papers to test its usefulness and common understanding in the author team. Each paper was coded by two persons, and misalignments discussed in personal meetings. In these meetings, only minor differences between coders were identified. Subsequently, the coding scheme was slightly adapted and a new pilot study of 15 papers was carried out which 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 researcher.

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) adjacent sectors, and (d) lastly, we included a category of other sectors to allow for inductive insights. The latter will also capture infrastructure/distribution sectors. This code addresses research question 1.b.

Second, we assessed the importance of multi-sectoral dynamics for transition processes via a 3-level code: (i) we used the code "central" if a specific multi-sectoral interaction was very important for understanding the phenomenon studied, (ii) we used the code "peripheral" if a specific multi-sectoral interaction was included in the analysis but not dedicated much attention or explanatory power, (iii) we coded "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 they are. This code addresses research question 1.c.

Third, we coded for the mechanisms and processes of multi-sectoral interactions by asking what the driving factors, characteristics, and main barriers to cross-sector interactions were. This code was quite open to allow us to source accumulated insights from the data. This code address research question 2.

For all codes we had two entries in the database. One for the coder's assessment of the particular code, and one for direct excerpts from the paper supporting the assessment.

3.4 Results and synthesis

We present the results for research question 1 in section 4.1 and results for question 2 in section 4.2. Our synthesis of results is presented in section 5. Note that we predominantly base our results on multi-sectoral interactions that were coded "central". We take into account results for the papers coded "peripheral" but only mention this if additional insights are added.

In section 4 we will refer to the papers included in our sample with ID numbers in brackets. For example we refer to paper 3 and paper 5 in our sample as follows [3, 5]. The full overview of papers and IDs can be found in the appendix (not included in this version due to word limit).

4 Results

4.1 How has multi-sectoral dynamics been empirically studied in the literature

In relation to research *question 1.a* we found that the interplay of multiple sectors was relevant in 67 articles. This is by all accounts a relatively low number of papers within a research field that has grown rapidly the last two decades. It indicates that our phenomenon of interest although acknowledged has not received much attention in transition scholarship to date.

In relation to research *question 1.b* we found that there was attention to all sector types that we identified in section 2 in addition to some other sectors such as waste management and recycling, see Table 3. However, all sector types rarely appear together.

Regarding research *question 1.c* we found that multi-sectoral dynamics were important (central) to the transition phenomenon studied in 15 papers looking at input sectors and for 20 papers looking at technology-producing sectors. This indicates that in the papers acknowledging multi-sectoral dynamics, it was important for transitions.

Table 3: Main coding categories and results

	Count	Importance	
		Central	Peripheral
Input sectors (fuels, materials),	34	15	19
Technology-producing sectors	46	20	26
Adjacent sectors	23	-	-
Other sectors	5	-	-

Regarding *research question 1* more broadly, we found that transition researchers largely operate with two different understandings of value chains. These we label as horizontal and vertical chains, and we elaborate on this result in the following.

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 23 papers where horizontal value chain interactions were central, see Table 4.

Several papers focus on the linkages between input sectors and focal sectors for the operation of key technologies in the latter. One example involves interactions between gas and electricity sectors where gas is an input to the production of electricity via gas turbines [1]. Also, new interactions between agricultural and electricity sectors formed with the advent of biogas for electricity [18].

The type of input sectors in the horizontal chain papers is exclusively raw material and primarily fuel inputs (including a few cases of electricity as energy carrier). A majority of papers analyze production and conversion of biomass into fuels or electricity [3, 4, 6, 12, 14, 15, 16, 18, 44, 50, 51]. Other examples include transitions from coal to gas input for both electricity and chemistry sectors [11, 48], electrification of steel production via hydrogen [66] and materials shift in the concrete sector [61].

Distribution or infrastructure sectors are also emphasized in the horizontal chain. In electricity, for example, growth of variable renewables requires major changes in the electricity grid to avoid bottlenecks [21; 37].

Some papers emphasize the role of end-use sectors such as individual consumers of electricity [5] or of aviation services [6]. Horizontal chains can moreover contain multiple end-user sectors. For electricity, for example, users can be distinguished into household consumption and commercial consumption sectors. The latter may again be divided into all kinds of manufacturing and service sectors consuming electricity [7]. Moreover, each of these end-user sectors deploy their own end-use technologies. For example, innovation in electric appliances in washing machines and freezers as well as electric motors for transport and factory work have been crucial for past electrification [7].

Table 4: Attention to different multi-sector chains

	Count	Central	Peripheral
Horizontal chain	36	23	13
Vertical chain	*46*	*20*	*26*

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, cf. section 2.2. In the latter, 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 (46) than to horizontal ones (36), cf. Table 4. This is likely a result of our search interest in upstream sectors and value/supply chains.

We found 20 papers where vertical technology value chains play a central role. The papers typically focus on one particular technology. Several papers also consider important interactions with the broader context in which technologies emerge including other technologies, natural resource endowments, and socio-political issues.

Most papers emphasize the interdependencies between technology-producing and –using sectors in technology value chain dynamics. For example, some papers show that new value chain formation often depends on major changes in the technology-using sector that opens a window of opportunity against the otherwise dominant technological solutions [9, 10, 11, 5, 27].

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) technologies. Ten vertical chain papers deal with raw material input sectors although they are central in only two of them.

Several papers highlight the importance of adjacent sectors that can provide resources to emerging vertical chains.

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).

We find that these two value chain perspectives are rarely combined. Indeed, there is only one article where both vertical and horizontal chains are central for the study [25]. We identified 10 articles where the horizontal chain view is central and where the vertical chain view is peripheral. However, these papers provide limited depth on understanding the development of technological innovations that are transforming how the horizontal chain works (and vice versa). This result indicates 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 5: Attention to interactions between types of chains

		Horizontal chain paper score	
		Central	**Peripheral**
Vertical chain paper score	**Central**	*1*	*1*
	Peripheral	*10*	*7*

4.2 How do multi-sectoral dynamics in transitions unfold?

This section presents our results regarding the processes and mechanisms of inter-sectoral interactions in transitions (research question 2).

The overarching pattern we observe is that growing problems and pressures on the established technologies and practices in a focal sector either leads to emergence of or calls for a set of new technological solutions, i.e. a transition. The new niche technologies disturb existing configuration of inter-sectoral relationships and creates tensions or imbalances across sectors. How much change in these relationships and in sectors is needed differs across cases but it typically involves changes in technology, institutions, or/and actors and networks. Most papers identify such imbalances, and some papers go further to describe how actors try to deal with imbalances or suggest how this could be done.

Below we provide further details of different aspects and variants of this general pattern. We structure the presentation according to the main dimensions of sociotechnical systems (technology, actors and networks, and institutions).

4.2.1 Technology and knowledge

One mechanism of change in inter-sectoral relations is technological change in a focal sector undergoing transition. We observed three variants of this change process. First, the most frequent one concerns how the emergence of a niche technology drives or requires changes in the linkages to other sectors or/and changes inside other sectors. For example, widespread use of biofuels in aviation (a niche) depends on establishing new linkages to biomass provision sectors and stimulating up-scaling of production via investment or/and use of novel niche technologies there (e.g. 2nd and 3rd generation biofuel technology) [6, 12]. Other examples include e.g. biogas power plants, windmills or zero emission houses [3, 4, 5, 12, 14]. The cross-sectoral imbalances arising from new niche technologies often grow as its moves from innovation to diffusion phase because then it starts to threaten other businesses [18] or requires larger changes in related sectors [21; 22, 37].

Second, another type of process concerns transformation of existing technologies during a transition. For example, HVDC transmission technology was transformed towards a novel dominant design because of new needs in the electricity distribution sector [37]. The process involved new linkages with chemicals and ICT sectors. Third, the decline of existing technologies implies weakening or dissolving linkages between the focal sector and the sectors in the vertical technology chain [67, 33]. For example, a transition to biofuel aviation would involve breaking up linkages to the Oil and Gas sector.

Another mechanism of in inter-sectoral interaction is knowledge spillovers from existing, adjacent sectors to emerging technology value chains. For example, looking at Solar PV technology in 14 countries (2001-2009) researchers find that 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]. Instead, import of knowledge can be used to build up own manufacturing capacity [28]. Countries do therefore not need to build entire low-carbon value chains to capture economic activity from transitions but can focus where adjacent sectors' specialization can provide useful knowledge inputs [54, 30, 28, 29, 35, 36]. For example, even though Germany's solar PV manufacturing capacity dwindled in competition with China, its machine tool sector continued to develop and export specialized equipment for PV producing-sectors globally [54, 30]. Also, firms in Norway entered the manufacturing segment of offshore wind value chain by building on knowledge from the Oil and Gas sector and without any domestic deployment of offshore wind [33, 35].

4.2.2 Actors and networks

Actors' behavior and strategies are central to all inter-sectoral interactions. The main insight from our result is that actors located in different value chain 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 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 inputs [61]. Cement producers then have to develop alternative supply chains in a very concentrated market dominated by a few suppliers. 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 found three mechanism through which actors seek to mitigate 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 [66, 18, 3, 6]. 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 product **diversification** across sectors is a crucial carrier of resources [33, 35, 67].

4.2.3 Institutions

Institutional change is a central aspect of multi-system interactions because institutions shape the incentive structures and worldviews of actors located in distinct sectors. Institutional alignment is therefore important for obtaining compatible actor strategies and coordination across sectors. Several papers conceptualized the institutional particularities of sectors as sectoral sociotechnical regimes. [1, 3, 4, 51].

Many papers showed the need for institutional alignment across sectors to support growth of an emerging technology [3, 4, 14]. This includes both formal institutions as regulations and policies, and informal institutions as culture, norms, and worldviews.

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 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 cultures. For example, the ministry of energy finds energy efficiency weird, and ministry of housing is not used to think about energy issues [5].

Value chain sectors can also enjoy different levels of legitimacy which can create imbalances.[7] For instance, using biofuels in the aviation sector is per se unproblematic but consumers are critical of the scale of its production in input sectors due to 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].

5 Discussion: Towards a multi-sectoral perspective on transitions

In this section, apply analytical reasoning to synthesize and extend the insights from our literature review and propose a new heuristic framework that explicates multi-sectoral dynamics in transitions. Subsequently we discuss implications for existing frameworks and further research.

5.1 The sectoral configuration of system transitions

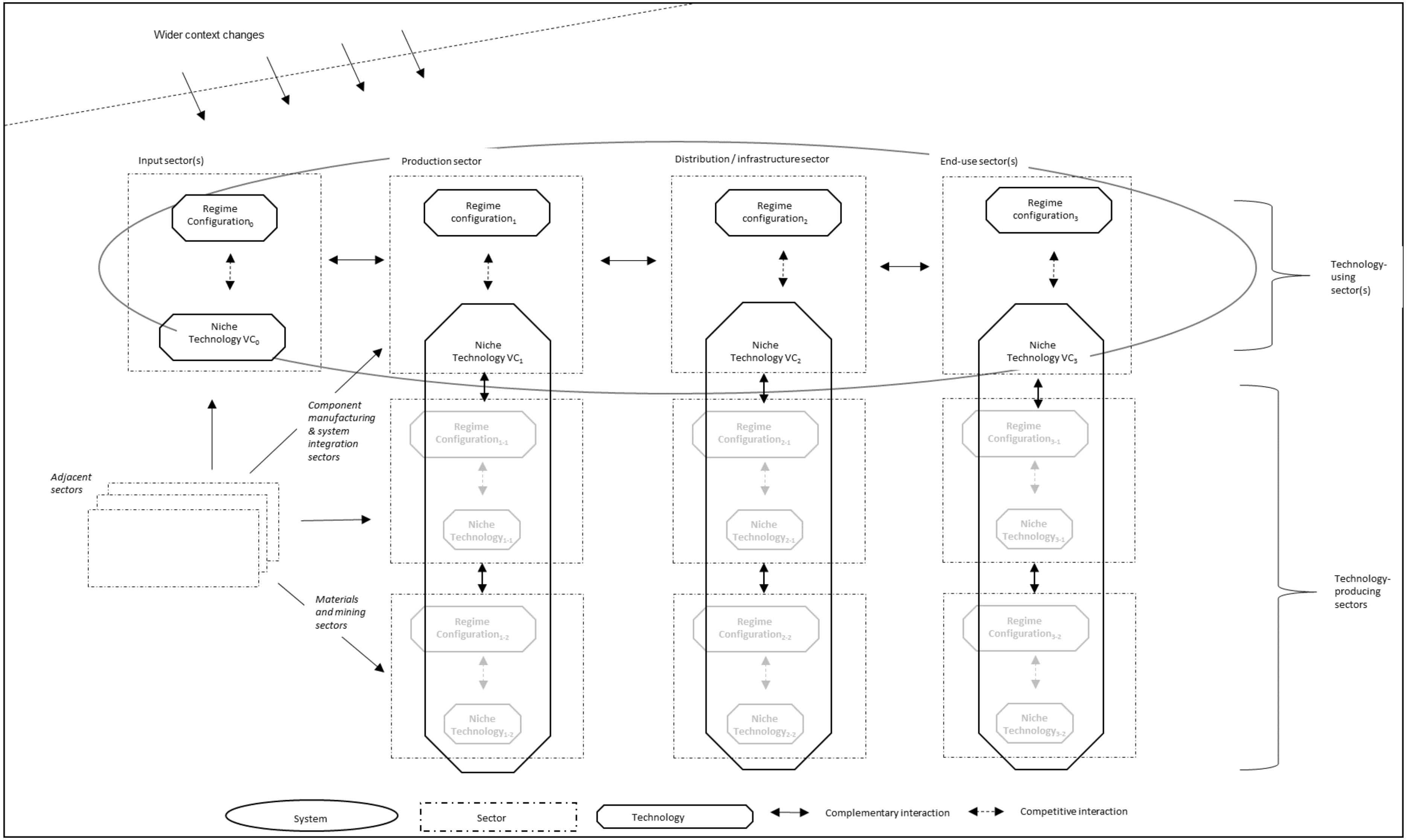
Although horizontal and vertical chains are typically not analyzed together, their dynamics are in fact interdependent. The different perspectives come together in two main ways when analyzing transition processes in a focal sector which involves emergence of new technology. First, whether a new technology breaks through in the focal sector depends on its cost and performance vis-à-vis existing options. Innovation, coordination, and collaboration in the vertical chain as well as resource flows to it from adjacent sectors are important determinants of cost and performance of a new technology. Similarly, change (e.g. policy or user preferences) in technology-using / focal sectors stimulate changes in the vertical chain as actors mobilize to serve new needs. Second, in order for new technology to diffuse widely and the vertical chain to develop further, a reconfiguration of inter-sectoral linkages in the horizontal chain is often required. In this way, what happens in the vertical chain is critical for what happens in the horizontal chain and vice versa. Indeed, the sectors in the horizontal chain are the selection and user environments for technological artefacts developed and produced in vertical chains. For this reason an integrated perspective is needed.

In Figure 3 we integrate the two chain perspectives to portray the sectoral configuration of systems. The framework contains all three levels of our typology—system, sector, and technology—and shows the full scope of sector types involved in transitions and how they relate to each other.[8] The illustrated heuristic framework constitutes a novel combination of recent elaborations of TIS and MLP frameworks, cf. section 2, because it integrates the TIS value chain perspective (vertical) with the MLP 'whole systems' approach (horizontal).

As seen in our review, sectors contain both regime configurations and niche technologies that typically compete. This is arguably true for both technology-producing and -using sectors. 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, cf. section 2.3 (Meadowcroft, 2009), e.g. at levels of system, sector, and technology. It follows, that the notion of a transition as a regime-shift (however gradual or disruptive) can take place both in sectors and in systems. Moreover, inter-sectoral linkage configurations are tied to specific technologies (regime vs niche) used in sectors rather than the sector functionality per se which illustrates the interdependencies across sectors in transition processes as well as why such change can be challenging. Indeed, the perspective suggests that both vertical and horizontal chains consist of a string of interconnected regime-niche constellations.

[7] Here we understand legitimacy as degree of institutional alignment between a sector and its context (Markard et al., 2016).
[8] Note we did not include the waste sector although it would be central for understanding circular economy transitions. It could be added at the end of both vertical and horizontal chains.

Figure 3: The sectoral configuration of system transitions



5.1.1 Implications for existing transition frameworks

For understanding transitions, the multi-sectoral framework has the following value-added vis-à-vis existing frameworks. Regarding the *TIS value chain* approach, our framework provides a broader understanding of use environment dynamics including the role played by horizontal inter-sectoral relationships in facilitating a window of opportunity for vertical chain actors. Second, by using the notions of regime and niche in the vertical chain sectors, the framework provides a new way of understanding institutional aspects and actor strategies in relation to cross-sector coordination. Third, our framework broadens the view on TIS value chains. It, for example, allows for understanding interactions between different technology value chains including value chain overlaps (i.e. when one sector or actors play a role in multiple chains such as mining or chemical firms) and when actors diversify across multiple chains. Lastly, the framework enables a systematic view on how adjacent sectors in a given place relate to transitions and how they could be mobilized to participate in emerging niche technology value chains.

Regarding the *MLP 'whole systems' approach*, our framework opens up the supply-side—i.e. flows of raw materials, fuels, and capital goods—of systems that is otherwise compressed and not explicitly articulated in the framework. As such, this opening provides a richer understanding of the both the sectoral configuration of systems and how this configuration influences and is influenced by system transitions.

5.1.2 Implications for existing transitions research

The new perspectives our multi-sectoral transition framework provide can aid transition scholars to see new transition phenomena and ask new questions.

First, it helps getting a systematic overview of sectors affected by and affecting transitions which is a central step for understanding the economic structural change associated with transitions. This allows analysts to zoom in and out across system, sectors, and technologies in a transparent and tractable way to e.g. do partial analyses. The framework can in principle be centered around any type of sector undergoing transition and then from there map out inter-sectoral linkages of importance. This also means it can be applied to different systems and parts of systems.

Second, the fact that some sectors are part of more than one system allows for new perspectives on interaction across not just sectors but also across systems. Indeed, we may ask instead how sectors such as chemicals or mining influence transitions in electricity, transport, and food systems, and investigate the transition strategies of the multinational enterprises dominating such sectors. Indeed, the understanding of incumbency has traditionally been related to a focal sector undergoing transitions. Our framework provides a systematic view on how incumbency via inter-sectoral linkages are distributed across multiple sectors, and possibly systems.

Third, the importance of raw material flows for transitions is not explicitly conceptualized in either TIS or MLP (Andersen & Wicken, 2020; Marín & Goya, 2021). Our framework explicates the importance of the raw material foundations of transitions. Our framework identifies two types of raw material flows for transitions. The raw materials needed in the horizontal chain which often concerns fuels, and the raw materials needed for upscaling and maintaining the vertical chains which often include minerals and metals. These two types of raw material classes have very different knowledge bases and investment cycles (Morris et al., 2012) which can influence transition dynamics. The overarching point emerging from the review is that each system has a particular natural resource footprint.

5.2 On the multi-sectoral aspects of transition dynamics

The multi-sectoral framework outlined above provides a new and broader canvas for understanding the dynamics of transitions with respects to both how transitions unfold over distinct phases, and the patterns they exhibit.

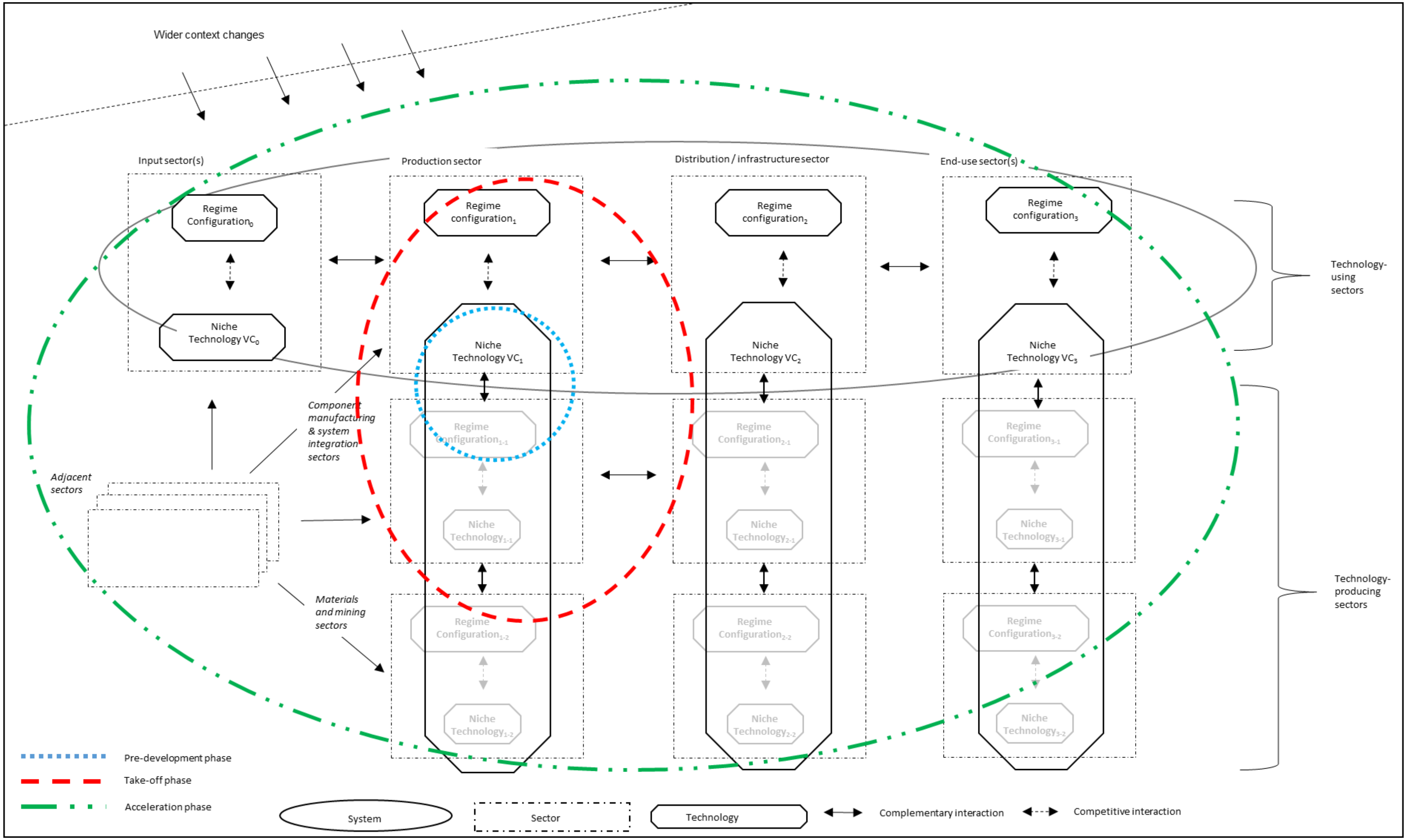
First, scholars divide transitions into distinct phases to portray how central phenomena change over time as transitions progress (Markard, 2018). Rotmans et al. (2001) for instance distinguish four main transition phases: predevelopment, take-off, acceleration, and stabilization. However, these accounts so far do not explicitly consider multi-sectoral dynamics. Including these can enrich our understanding of transition phases.

The pre-formation phase is characterized by small-scale, local experimentation with alternative solutions among pioneers such as lead-users or sustainability entrepreneurs with some involvement of potential lead-producing firms. In this phase, there is no niche technology value chain but rather a loose network of actors, high uncertainty about future development, and wide variety of prototypes that cannot compete with regime solutions. Experimentation is driven by technology users in the focal sector and only involves weak linkage to the manufacturing sector.

In *the take-off phase*, expectations to the niche grows, more actors from distinct sectors enter, and resources flow to the niche. In this phase, there is more and more deployment of the niche technology, the contours of a technology value chain are forming around a few possible dominant designs, and regulatory and policy support emerge. Inter-sectoral linkages now include stronger interaction with lead and professional users, manufacturers, component, and material providers. The growth of the niche also starts to disturb the regime in the focal sector and possibly regimes in input and infrastructure sectors.

The acceleration phase starts with 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 which leads to destabilization of the regime and starts to drive changes in many other sectors (Geels, 2018; Johnstone et al., 2020). As the niche technology grows, it requires new linkages to (new) input sectors and/or dissolving old links, and it can start to transform infrastructure and end-use sectors. In the vertical chain, the upscaling of production of niche technological artefacts will require massive amounts of raw materials which can start to affect mining sectors and possibly result in shortages. The growing number of inter-sectoral linkages across the system that are affected by the transition in the focal sector may or may not lead to transitions in these sectors as well.

Figure 4: System transition phases and multi-sectoral dynamics



Second, scholars have identified different transition patterns—including substitution, transformation, reconfiguration, and dis-alignment re-alignment—that exemplify transitions in particular sectors such as manufacturing or electricity supply (Geels & Schot, 2007). Existing typologies is closely related to the degree of disruption to the regime in a focal sector and make use to the Schumpeterian heuristic of creative destruction (both Mark I and II) where lead-innovators capture market shares and are imitated by others in the course of a transition within a single sector. The imaginary invoked in these accounts is a hierarchical one where established regimes and emerging niches compete for dominance with actors moving across the two.

However, the transition imagery outlined above is one that portrays transitions as a process of widening imbalances and tensions with epicenter in a niche innovation(s) in a focal sector whose diffusion produce ripple effects through the web of inter-sectoral linkages associated with the sectoral configuration of systems. Therefore, rather than Schumpeterian creative destruction within sectors, the notion of a development blocks stretching across sectors better describes the nature of transitions. A development block refers to how a set of core innovations generate structural tensions (Dahmén, 1989) across related technologies and sectors that generate pressure for change. These structural tensions can be overcome by complementary innovations—or changes to inter-sectoral linkages—allowing the block to evolve further. As structural tensions occur and are resolved, the boundaries of the block change (Taalbi, 2016).

6 Conclusions

This paper set out to provide a novel way for systematically thinking about the relationship between system transitions and economic structural change in form of transformation of interwoven technologies and sectors.

Via a systematic literature review the paper explored to what extent and how transition scholarship has analyzed interactions between and transformation of multiple economic sectors in the course of transitions. Overall, we find that there is a small stream of work engaging with multi-sectoral dynamics in transitions but that it is limited and disjointed. For example, vertical and horizontal chain perspectives are disconnected, and the types of sectors and causal mechanisms analyzed are case-specific rather than informed by a systematic perspective. There is, in other words, no coherent or systematic approach for dealing with multi-sectoral dynamics in transition studies.

Against that background, the paper proposes a novel multi-sectoral perspective on system transitions. With this framework, the authors draw attention to underappreciated transition phenomena and dynamics as well as suggesting a novel imaginary for how transitions unfold.

Appendix

List of included papers

ID	Authors	Title
1	Konrad K., Truffer B., Voß J.-P.	Multi-regime dynamics in the analysis of sectoral transformation potentials: evidence from German utility sectors
2	Di Lucia L., Ericsson K.	Low-carbon district heating in Sweden - Examining a successful energy transition
3	Sutherland L.-A., Peter S., Zagata L.	Conceptualising multi-regime interactions: The role of the agriculture sector in renewable energy transitions
4	To L.S., Seebaluck V., Leach M.	Future energy transitions for bagasse cogeneration: Lessons from multi-level and policy innovations in Mauritius
5	Kvellheim A.K.	The power of buildings in climate change mitigation: The case of Norway
6	Kim, Y., Lee, J., Ahn, J.	Innovation towards sustainable technologies: A socio-technical perspective on accelerating transition to aviation biofuel.
7	McMeekin, A., Geels, F.W., Hodson, M.	Mapping the winds of whole system reconfiguration: Analysing low-carbon transformations across production, distribution and consumption in the UK electricity system (1990–2016).
8	Arapostathis S., Carlsson-Hyslop A., Pearson P.J.G., Thornton J., Gradillas M., Laczay S., Wallis S.	Governing transitions: Cases and insights from two periods in the history of the UK gas industry
9	Hansen U.E., Nygaard I.	Transnational linkages and sustainable transitions in emerging countries: Exploring the role of donor interventions in niche development
10	Keppler D.	Absorption chillers as a contribution to a climate-friendly refrigeration supply regime: Factors of influence on their further diffusion
11	Bennett S.J.	Using past transitions to inform scenarios for the future of renewable raw materials in the UK

12	Koistinen K., Upham P., Bögel P.	Stakeholder signalling and strategic niche management: The case of aviation biokerosene
13	Mühlemeier S.	Dinosaurs in transition? A conceptual exploration of local incumbents in the swiss and German energy transition
14	Wirth, S., Markard, J.	Context matters: How existing sectors and competing technologies affect the prospects of the Swiss Bio-SNG innovation system.
15	Huttunen S., Kivimaa P., Virkamäki V.	The need for policy coherence to trigger a transition to biogas production
16	Giurca A., Späth P.	A forest-based bioeconomy for Germany? Strengths, weaknesses and policy options for lignocellulosic biorefineries
17	Kushnir D., Hansen T., Vogl V., Åhman M.	Adopting hydrogen direct reduction for the Swedish steel industry: A technological innovation system (TIS) study
18	Markard J., Wirth S., Truffer B.	Institutional dynamics and technology legitimacy - A framework and a case study on biogas technology
19	Tziva M., Negro S.O., Kalfagianni A., Hekkert M.P.	Understanding the protein transition: The rise of plant-based meat substitutes
20	van Welie, M.J., Truffer, B., Yap, X.-S.	Towards sustainable urban basic services in low-income countries: A Technological Innovation System analysis of sanitation value chains in Nairobi.
21	Haley B.	Integrating structural tensions into technological innovation systems analysis: Application to the case of transmission interconnections and renewable electricity in Nova Scotia, Canada
22	Jin J., McKelvey M.	Building a sectoral innovation system for new energy vehicles in Hangzhou, China: Insights from evolutionary economics and strategic niche management
23	Seyfang G., Hielscher S., Hargreaves T., Martiskainen M., Smith A.	A grassroots sustainable energy niche? Reflections on community energy in the UK
24	Leitch A., Haley B., Hastings-Simon S.	Can the oil and gas sector enable geothermal technologies? Socio-technical opportunities and complementarity failures in Alberta, Canada

25	Geels F.W.	Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study
26	Choi, H., Anadón, L.D.	The role of the complementary sector and its relationship with network formation and government policies in emerging sectors: The case of solar photovoltaics between 2001 and 2009.
27	Gosens J., Lu Y.	Prospects for global market expansion of China's wind turbine manufacturing industry
28	Bento N., Fontes M.	Spatial diffusion and the formation of a technological innovation system in the receiving country: The case of wind energy in Portugal
29	Bento, N., Fontes, M.	The construction of a new technological innovation system in a follower country: Wind energy in Portugal.
30	Dewald, U., Fromhold-Eisebith, M.	Trajectories of sustainability transitions in scale-transcending innovation systems: The case of photovoltaics.
31	Mazur C., Contestabile M., Offer G.J., Brandon N.P.	Assessing and comparing German and UK transition policies for electric mobility
32	Wieczorek A.J., Hekkert M.P., Coenen L., Harmsen R.	Broadening the national focus in technological innovation system analysis: The case of offshore wind
33	Steen M., Weaver T.	Incumbents' diversification and cross-sectorial energy industry dynamics
34	Makkonen T., Inkinen T.	Sectoral and technological systems of environmental innovation: The case of marine scrubber systems
35	Mäkitie T., Andersen A.D., Hanson J., Normann H.E., Thune T.M.	Established sectors expediting clean technology industries? The Norwegian oil and gas sector's influence on offshore wind power
36	Hanson J.	Established industries as foundations for emerging technological innovation systems: The case of solar photovoltaics in Norway
37	Andersen, A.D., Markard, J.	Multi-technology interaction in socio-technical transitions: How recent dynamics in HVDC technology can inform transition theories.

38	Caniëls M.C.J., Romijn H.A.	Strategic niche management: Towards a policy tool for sustainable development
39	Jacobsson S., Karltorp K.	Mechanisms blocking the dynamics of the European offshore wind energy innovation system - Challenges for policy intervention
40	Berggren C., Magnusson T., Sushandoyo D.	Transition pathways revisited: Established firms as multi-level actors in the heavy vehicle industry
41	Andersson, J., Hellsmark, H., Sandén, B.A.	Shaping factors in the emergence of technological innovations: The case of tidal kite technology.
42	Gui E.M., MacGill I.	Typology of future clean energy communities: An exploratory structure, opportunities, and challenges
43	Sawulski J., Gałczyński M., Zajdler R.	Technological innovation system analysis in a follower country – The case of offshore wind in Poland
44	Fevolden A.M., Klitkou A.	A fuel too far? Technology, innovation, and transition in failed biofuel development in Norway
45	Sushandoyo D., Magnusson T.	Strategic niche management from a business perspective: Taking cleaner vehicle technologies from prototype to series production
46	Planko J., Cramer J.M., Chappin M.M.H., Hekkert M.P.	Strategic collective system building to commercialize sustainability innovations
47	Hörisch J.	How business actors can contribute to sustainability transitions: A case study on the ongoing animal welfare transition in the German egg industry
48	Arapostathis S., Pearson P.J.G., Foxon T.J.	UK natural gas system integration in the making, 1960-2010: Complexity, transitional uncertainties and uncertain transitions
49	Barrie J., Zawdie G., João E.	Assessing the role of triple helix system intermediaries in nurturing an industrial biotechnology innovation network
50	Browne D., O'Mahony M., Caulfield B.	How should barriers to alternative fuels and vehicles be classified and potential policies to promote innovative technologies be evaluated?

51	van Eijck J., Romijn H.	Prospects for Jatropha biofuels in Tanzania: An analysis with Strategic Niche Management
52	Musiolik, J., Markard, J.	Creating and shaping innovation systems: Formal networks in the innovation system for stationary fuel cells in Germany.
53	Sandén, B.A., Hillman, K.M.	A framework for analysis of multi-mode interaction among technologies with examples from the history of alternative transport fuels in Sweden.
54	Quitzow R.	Dynamics of a policy-driven market: The co-evolution of technological innovation systems for solar photovoltaics in China and Germany
55	Randelli F., Rocchi B.	Analysing the role of consumers within technological innovation systems: The case of alternative food networks
56	Stephan A., Schmidt T.S., Bening C.R., Hoffmann V.H.	The sectoral configuration of technological innovation systems: Patterns of knowledge development and diffusion in the lithium-ion battery technology in Japan
57	Andersson M., Ljunggren Söderman M., Sandén B.A.	Lessons from a century of innovating car recycling value chains
58	Malhotra, A., Schmidt, T.S., Huenteler, J.	The role of inter-sectoral learning in knowledge development and diffusion: Case studies on three clean energy technologies.
59	Geels F.W.	From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory
60	Elzen B., Geels F.W., Leeuwis C., Van Mierlo B.	Normative contestation in transitions 'in the making': Animal welfare concerns and system innovation in pig husbandry
61	Wesseling J.H., Van der Vooren A.	Lock-in of mature innovation systems: the transformation toward clean concrete in the Netherlands
62	Dijk, M., Orsato, R.J., Kemp, R.	Towards a regime-based typology of market evolution.
63	Wicki S., Hansen E.G.	Clean energy storage technology in the making: An innovation systems perspective on flywheel energy storage

64	Markard, J.	The life cycle of technological innovation systems.
65	Carstens D.D.D.S., Cunha S.K.D.	Challenges and opportunities for the growth of solar photovoltaic energy in Brazil
66	Karakaya E., Nuur C., Assbring L.	Potential transitions in the iron and steel industry in Sweden: Towards a hydrogen-based future?
67	Allan Dahl Andersen, Magnus Gulbrandsen	The innovation and industry dynamics of technology phase-out in sustainability transitions: Insights from diversifying petroleum technology suppliers in Norway

References

Andersen, A. D., & Gulbrandsen, M. (2020). The innovation and industry dynamics of technology phase-out in sustainability transitions: Insights from diversifying petroleum technology suppliers in Norway. *Energy Research & Social Science, 64*(June). doi:https://doi.org/10.1016/j.erss.2020.101447

Andersen, A. D., & Markard, J. (2020). Multi-technology interaction in socio-technical transitions: How recent dynamics in HVDC technology can inform transition theories. *Technological Forecasting & Social Change, 151*.

Andersen, A. D., Steen, M., Mäkitie, T., Hanson, J., Thune, T. M., & Soppe, B. (2020). The role of inter-sectoral dynamics in sustainability transitions: A comment on the transitions research agenda. *Environmental Innovation and Societal Transitions, 34*, 348-351. doi:https://doi.org/10.1016/j.eist.2019.11.009

Andersen, A. D., & Wicken, O. (2020). Making sense of how the natural environment shapes innovation and industry dynamics: Implications for policy, sustainability challenges, and research. *Innovation and Development*. doi:10.1080/2157930X.2020.1770975

Andersen, E. S. (1992). Approaching National Systems of Innovation from the Production and Linkage Structure. In B. Å. Lundvall (Ed.), *National systems of innovation : toward a theory of innovation and interactive learning*: London: Pinter.

Arthur, W. B. (2009). *The Nature of Technology: What It Is and How It Evolves*: Free Press.

Bergek, A., Hekkert, M. P., Jacobsson, S., Markard, J., Sanden, B. A., & Truffer, B. (2015). Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics. *Environmental Innovation and Societal Transitions, 16*, 51-64. doi:doi:10.1016/j.eist.2015.07.003

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., & Rickne, A. (2008). Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Research Policy, 37*.

Berkers, E., & Geels, F. W. (2011). System innovation through stepwise reconfiguration: the case of technological transitions in Dutch greenhouse horticulture (1930–1980). *Technology Analysis & Strategic Management, 23*(3), 227-247. doi:10.1080/09537325.2011.550392

Busch, J., Foxon, T. J., & Taylor, P. G. (2018). Designing industrial strategy for a low carbon transformation. *Environmental Innovation and Societal Transitions, 29*, 114-125. doi:https://doi.org/10.1016/j.eist.2018.07.005

Carlsson, B., & Stankiewicz, R. (1991). On the nature, function and composition of technological systems. *Journal of Evolutionary Economics, 1*(2), 93-118. doi:10.1007/bf01224915

Ciccone, A. (Ed.) (2008) The New Palgrave Dictionary of Economics Online (2nd ed.). Palgrave Macmillan.
Clark, K. B. (1985). The interaction of design hierarchies and market concepts in technological evolution. *Research Policy, 14*(5), 235-251. doi:https://doi.org/10.1016/0048-7333(85)90007-1
Coenen, L., & Díaz López, F. J. (2010). Comparing systems approaches to innovation and technological change for sustainable and competitive economies: an explorative study into conceptual commonalities, differences and complementarities. *Journal of Cleaner Production, 18*, 1149-1160.
Dahmén, E. (1989). "Development Blocks" in Industrial Economics. In B. Carlsson & R. G. H. Henriksson (Eds.), *Developments blocks and industrial transformation : the Dahménian approach to economic development*. Stockholm: The Industrial Institute for Economic and Social Research.
Denyer, D., & Tranfield, D. (2009). Producing a systematic review. In *The Sage handbook of organizational research methods.* (pp. 671-689). Thousand Oaks, CA: Sage Publications Ltd.
Editorial. (2018). Tracking progress on the SDGs. *Nature Sustainability, 1*(8), 377-377. doi:10.1038/s41893-018-0131-z
Edquist, C. (1997). Systems of Innovation Approaches - Their Emergence and

Characteristics. In C. Edquist (Ed.), *Systems of Innovation: Technologies, Institutions and Organizations*. London: Routledge.
Fontes, M., Bento, N., & Andersen, A. D. (2021). Unleashing the industrial transformative capacity of innovations. *Environmental Innovation and Societal Transitions, 40*, 207-221. doi:https://doi.org/10.1016/j.eist.2021.07.004
Foxon, T. J. (2018). *Energy and Economic Growth: Why we need a new pathway to prosperity*. London: Routledge.
Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy, 31*, 1257-1274.
Geels, F. W. (2004). From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. *Research Policy, 33*(6-7), 897-920.
Geels, F. W. (2005). *Technological Transitions and System Innovations. A Co-Evolutionary and Socio-Technical Analysis*: Edward Elgar.
Geels, F. W. (2006). Co-evolutionary and multi-level dynamics in transitions: The transformation of aviation systems and the shift from propeller to turbojet (1930–1970). *Technovation, 26*(9), 999-1016. doi:https://doi.org/10.1016/j.technovation.2005.08.010
Geels, F. W. (2011). The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions, 1*, 24-40.
Geels, F. W. (2018). Low-carbon transition via system reconfiguration? A socio-technical whole system analysis of passenger mobility in Great Britain (1990–2016). *Energy Research & Social Science, 46*, 86-102. doi:https://doi.org/10.1016/j.erss.2018.07.008
Geels, F. W., & Schot, J. (2007). Typology of sociotechnical transition pathways. *Research Policy, 36*(3), 399-417.
Geels, F. W., Sovacool, B. K., Schwanen, T., & Sorrell, S. (2017). Sociotechnical transitions for deep decarbonization. *Science, 357*(6357), 1242-1244. doi:10.1126/science.aao3760
Giuliani, E. (2018). Regulating global capitalism amid rampant corporate wrongdoing—Reply to “Three frames for innovation policy”. *Research Policy, 47*(9), 1577-1582. doi:https://doi.org/10.1016/j.respol.2018.08.013
Hirschman, A. (1958). *The Strategy of Economic Development*. New Haven, Conn.: Yale University press.
Holtz, G., Brugnach, M., & Pahl-Wostl, C. (2008). Specifying “regime” — A framework for defining and describing regimes in transition research. *Technological forecasting and social change, 75*(5), 623-643. doi:https://doi.org/10.1016/j.techfore.2007.02.010

Hughes, T. (1983). *Networks of Power. Electrification in Western Society 1880-1930*: Johns Hopkins University Press.
IEA. (2021). *Net Zero by 2050*. Retrieved from Paris: https://www.iea.org/reports/net-zero-by-2050
Johnstone, P., Rogge, K. S., Kivimaa, P., Farné Fratini, C., & Primmer, E. (2021). Exploring the re-emergence of industrial policy: Perceptions regarding low-carbon energy transitions in Germany, the United Kingdom and Denmark. *Energy Research & Social Science, 74*, 101889. doi:https://doi.org/10.1016/j.erss.2020.101889
Johnstone, P., Rogge, K. S., Kivimaa, P., Fratini, C. F., Primmer, E., & Stirling, A. (2020). Waves of disruption in clean energy transitions: Sociotechnical dimensions of system disruption in Germany and the United Kingdom. *Energy Research & Social Science, 59*, 101287. doi:https://doi.org/10.1016/j.erss.2019.101287
Kanger, L., Sovacool, B. K., & Noorkõiv, M. (2020). Six policy intervention points for sustainability transitions: A conceptual framework and a systematic literature review. *Research Policy, 49*(7), 104072. doi:https://doi.org/10.1016/j.respol.2020.104072
Kemp, R., Schot, J., & Hoogma, R. (1998). Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. *Technology Analysis & Strategic Management, 10*, 175-198.
Kern, F., & Markard, J. (2016). Analysing Energy Transitions: Combining Insights from Transition Studies and International Political Economy. In T. Van de Graaf, B. K. Sovacool, A. Ghosh, F. Kern, & M. T. Klare (Eds.), *The Palgrave Handbook of the International Political Economy of Energy* (pp. 291-318). London: Palgrave Macmillan UK.
Kivimaa, P., Boon, W., Hyysalo, S., & Klerkx, L. (2019). Towards a typology of intermediaries in sustainability transitions: A systematic review and a research agenda. *Research Policy, 48*(4), 1062-1075. doi:https://doi.org/10.1016/j.respol.2018.10.006
Köhler, J., Geels, F. W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., . . . Wells, P. (2019). An agenda for sustainability transitions research: State of the art and future directions. *Environmental Innovation and Societal Transitions, 31*, 1-32. doi:https://doi.org/10.1016/j.eist.2019.01.004
Lundvall, B.-Å. (1985). Product Innovation and User-Producer Interaction. *Industrial Development Research Series, Aalborg University Press*.
Lundvall, B.-Å., Johnson, B., Andersen, E. S., & Dalum, B. (2002). National systems of production, innovation and competence building. *Research Policy, 31*, 213-231.
Malerba, F. (2002). Sectoral systems of innovation and production. *Research Policy, 31*(2), 247-264.
Malerba, F. (2005). Sectoral systems: how and why innovation differes across sectors. In J. Fagerberg, D. Mowery, & R. Nelson (Eds.), *The Oxford handbook of innovation*: Oxford University Press, USA.
Malhotra, A., Schmidt, T. S., & Huenteler, J. (2019). The role of inter-sectoral learning in knowledge development and diffusion: Case studies on three clean energy technologies. *Technological forecasting and social change, 146*, 464-487. doi:https://doi.org/10.1016/j.techfore.2019.04.018
Marín, A., & Goya, D. (2021). Mining—The dark side of the energy transition. *Environmental Innovation and Societal Transitions*. doi:https://doi.org/10.1016/j.eist.2021.09.011
Markard, J. (2018). The next phase of the energy transition and its implications for research and policy. *Nature Energy, 3*(8), 628-633. doi:10.1038/s41560-018-0171-7
Markard, J., Raven, R., & Truffer, B. (2012). Sustainability transitions: An emerging field of research and its prospects. *Research Policy, 41*, 955-967.
Markard, J., & Truffer, B. (2008). Technological innovation systems and the multi-level perspective: Towards an integrated framework. *Research Policy, 37*, 596-615.
Markard, J., Wirth, S., & Truffer, B. (2016). Institutional dynamics and technology legitimacy: A framework and a case study on biogas technology. *Research Policy, 45*, 330-344.
McMeekin, A., Geels, F. W., & Hodson, M. (2019). Mapping the winds of whole system reconfiguration: Analysing low-carbon transformations across production, distribution and

consumption in the UK electricity system (1990–2016). *Research Policy*. doi:https://doi.org/10.1016/j.respol.2018.12.007
Meadowcroft, J. (2009). What about the politics? Sustainable development, transition management, and long term energy transitions. *Policy Sciences, 42*(4), 323-340. doi:10.1007/s11077-009-9097-z
Morris, M., Kaplinsky, R., & Kaplan, D. (2012). *One Thing Leads To Another: Promoting Industrialisation by Making the Most of the Commodity Boom in Sub-Saharan Africa*: Open access.
Murmann, J. P., & Frenken, K. (2006). Toward a systematic framework for research on dominant designs, technological innovations, and industrial change. *Research Policy, 35*(7), 925-952. doi:http://doi.org/10.1016/j.respol.2006.04.011
Mäkitie, T., Andersen, A. D., Hanson, J., Normann, H. E., & Thune, T. M. (2018). Established sectors expediting clean technology industries? The Norwegian oil and gas sector's influence on offshore wind power. *Journal of Cleaner Production, 177*, 813-823.
Pasinetti, L. (1993). *Structural economic dynamics: a theory of the economic consequences of human learning*: Cambridge University Press.
Pavitt, K. (1984). Sectoral patterns of technical change: Towards a taxonomy and a theory. *Research Policy, 13*, 343-373. doi:10.1016/0048-7333(84)90018-0
Pel, B. (2021). Transition 'backlash': Towards explanation, governance and critical understanding. *Environmental Innovation and Societal Transitions, 41*, 32-34. doi:https://doi.org/10.1016/j.eist.2021.10.016
Perez, C. (2002). *Technological Revolutions and Financial Capital. The Dynamics of Bubbles and Golden Ages*. Cheltenham (UK) and Northampton (USA): Edward Elgar.
Perez, C. (2009a). *Technological revolutions and techno-economic paradigms*. Working Papers in Technology Governance and Economic Dynamics. Tallinn University of Technology. Tallinn.
Perez, C. (2009b). Technological revolutions and techno-economic paradigms. *Cambridge Journal of Economics, 34*(1), 185-202. doi:10.1093/cje/bep051
Persson, L., Carney Almroth, B. M., Collins, C. D., Cornell, S., de Wit, C. A., Diamond, M. L., . . . Hauschild, M. Z. (2022). Outside the Safe Operating Space of the Planetary Boundary for Novel Entities. *Environmental Science & Technology, 56*(3), 1510-1521. doi:10.1021/acs.est.1c04158
Petticrew, M., & Roberts, H. (2006). *Systematic Reviews in the Social Sciences: A Practical Guide*. Malden, MA, USA: Blackwell Publishing.
Richardson, G. B. (1990). *Information and investment*. Oxford: Clarendon Press, Oxford Clarendon.
Rip, A., & Kemp, R. (1998). Technological Change. In S. Rayner & E. L. Malone (Eds.), *Human Choice and Climate Change – Resources and Technology* (pp. 327-399): Battelle Press, Columbus.
Roberts, C., Geels, F. W., Lockwood, M., Newell, P., Schmitz, H., Turnheim, B., & Jordan, A. (2018). The politics of accelerating low-carbon transitions: Towards a new research agenda. *Energy Research & Social Science, 44*, 304-311. doi:https://doi.org/10.1016/j.erss.2018.06.001
Robertson, P. L., Pol, E., & Carroll, P. (2002). A new typology for economic sectors with a view to policy implications. *Economics of Innovation and New Technology, 11*(1).
Rosenberg, N. (1982). *Inside the black box : technology and economics*. Cambridge Cambridgeshire ; New York: Cambridge University Press.
Rotmans, J., Kemp, R., & van Asselt, M. (2001). More evolution than revolution: transition management in public policy. *Foresight, 3*(1), 15-31. doi:doi:10.1108/14636680110803003
Sandén, B. A., & Hillman, K. M. (2011). A framework for analysis of multi-mode interaction among technologies with examples from the history of alternative transport fuels in Sweden. *Research Policy, 40*(3), 403-414.
Sovacool, B. K., & Geels, F. W. (2016). Further reflections on the temporality of energy transitions: A response to critics. *Energy Research & Social Science, 22*(Supplement C), 232-237. doi:https://doi.org/10.1016/j.erss.2016.08.013
Steen, M., & Weaver, T. (2017). Incumbents' diversification and cross-sectorial energy industry dynamics. *Research Policy, 46*(6), 1071-1086. doi:https://doi.org/10.1016/j.respol.2017.04.001

Stephan, A., Schmidt, T. S., Bening, C. R., & Hoffmann, V. H. (2017). The sectoral configuration of technological innovation systems: Patterns of knowledge development and diffusion in the lithium-ion battery technology in Japan. *Research Policy, 46*(4), 709-723. doi:https://doi.org/10.1016/j.respol.2017.01.009

Turnheim, B., & Nykvist, B. (2019). Opening up the feasibility of sustainability transitions pathways (STPs): Representations, potentials, and conditions. *Research Policy, 48*(3), 775-788. doi:https://doi.org/10.1016/j.respol.2018.12.002

Tushman, M. L., & Rosenkopf, L. (1992). Organizational determinants of technological-change-toward a sociology of technological evolution. *Research in organizational behavior, 14*, 311-347.

Taalbi, J. (2016). Development blocks and structural analysis. In J. Ljungberg (Ed.), *Structural Analysis and the Process of Economic Development* (pp. 22). London: Routledge.

Unruh, G. C. (2000). Understanding carbon lock-in. *Energy Policy*.

Verbong, G. P. J., & Geels, F. W. (2010). Exploring sustainability transitions in the electricity sector with socio-technical pathways. *Technological forecasting and social change, 77*, 1214-1221.

Von Hippel, E. (1994). "Sticky information" and the locus of problem solving: implications for innovation. *Management Science, 40*, 429-439. doi:10.1287/mnsc.40.4.429

Vona, F. (2019). Job losses and political acceptability of climate policies: why the 'job-killing' argument is so persistent and how to overturn it. *Climate Policy, 19*(4), 524-532. doi:10.1080/14693062.2018.1532871

Weber, K. M., & Rohracher, H. (2012). Legitimizing research, technology and innovation policies for transformative change: Combining insights from innovation systems and multi-level perspective in a comprehensive 'failures' framework. *Research Policy, 41*(6), 1037-1047. doi:https://doi.org/10.1016/j.respol.2011.10.015

Winskel, M. (2018). Beyond the disruption narrative: Varieties and ambiguities of energy system change. *Energy Research & Social Science, 37*, 232-237. doi:https://doi.org/10.1016/j.erss.2017.10.046

Wirth, S., & Markard, J. (2011). Context matters: How existing sectors and competing technologies affect the prospects of the Swiss Bio-SNG innovation system. *Technological forecasting and social change, 78*, 635-649.

Wirth, S., Markard, J., Truffer, B., & Rohracher, H. (2013). Informal institutions matter: Professional culture and the development of biogas technology. *Environmental Innovation and Societal Transitions*.