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A systematic literature review

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Frameworks for multi-system innovation analysis from a sociotechnical perspective: A systematic literature review

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ABSTRACT

This paper systematically reviews the literature on sociotechnical multi-system innovation frameworks that broaden the usual focus on one sociotechnical system to encompass influences from multiple systems. The review includes 75 peer-reviewed papers that span a broad range of energy-demanding systems and mainly build upon the core frameworks of the Multi-level Perspective (MLP) and Technological Innovation Systems (TIS). The analysis identifies three key aspects to consider in multi-system frameworks. The first aspect is the importance of considering the overarching directionality of multiple sociotechnical systems and how they influence each other. The second is to explicitly analyse the phase of each transitioning system. The third aspect is a need for explicit system configuration analysis. This includes analysing the value chain and the number and types of sectors linked to it, typifying the distinct characteristics of sectors internally and how they interact, and analysing complementary or competitive technologies. The paper concludes by providing recommendations for future research, with a particular focus on the further development of new multi-system frameworks that include one or more of the prior-mentioned three key takeaways. Firstly, focusing on dynamics within multi-system niches. Secondly, performing actor-level analysis, including demand-side analysis. Finally, applying quantitative methods, such as computer simulation modelling.

1. Introduction

This paper stems from the increased need for multi-system innovations in the current phase of the energy transition, as the ambitious climate goals to limit global warming to well below 2 degrees Celsius (UNFCCC, 2015) require low-carbon transitions across multiple sociotechnical systems. In this context, sociotechnical systems refer to linkages between a large variety of social and physical elements necessary to fulfil societal functions (e.g., electricity, mobility, or heating) (Geels, 2004; Markard, 2011).

In line with the climate goals, the current ‘energy transition’ to decrease fossil-based energy supply to stay within the carbon emissions budget (Rogelj et al., 2019) encompasses transitions of multiple (interacting) sociotechnical systems that need to decrease carbon emissions. As the energy transition progresses, next to transformations of individual sociotechnical systems, the necessity of interactions between sociotechnical systems becomes increasingly critical (Robinius et al., 2017a; Geels et al., 2017a). For instance, in order to efficiently integrate the increasing intermittent renewable electricity sources (such as wind and the sun) into the electricity system, a coupling of the electricity sector to other energy-demanding sectors such as transport, industry and the built environment is needed – generally referred to as ‘sector coupling’ (Fridgen et al., 2020; Brown et al., 2018). Such system linkages can also positively affect the momentum of sociotechnical transitions (Geels, 2018). For example, Vehicle-to-Grid (V2G) configurations, in which electric vehicles can return electricity to the grid when necessary, can promote the adoption of electric vehicles and help mitigate the intermittency problems of wind and solar electricity (Sovacool et al., 2017). The need for such solutions is becoming more pressing as, in the current phase of the energy transition, intermittent renewable electricity is increasingly diffusing in electricity grids (e.g., causing congestion issues) (Markard, 2018; Mitchell, 2016; Turnheim et al., 2018).

Therefore, there is an increasing necessity to study the interplay of multiple systems along with multi-system innovations (e.g., V2G or intelligent heating systems) in the current phase of the energy transition. In this paper, we use the broad term ‘multi-system’ to encompass the

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influence of multiple sectors[1] (multi-sector) and regimes[2] (multi-regime) on each other. The implementation of multi-system innovations adds a layer of complexity since their uptake depends on increasing integration of two or more heterogeneous sociotechnical systems, which can vary substantially, e.g., in terms of historical precedence (norms and standards), knowledge base, actors (types and motivations), technologies, inputs, demands and culture (e.g., Malerba, 2002; Patel and Pavitt, 1994; Dolata, 2009). For example, the success of V2G configurations depends on many social and technical developments across the electricity and road transport systems. A survey of the scientific literature about multi-system innovations such as heat pumps (e.g., Böttger et al., 2014; Lund et al., 2010), synthetic fuels (e.g., biofuels or hydrogen) and electric cars (e.g., Lund and Kempton, 2008; Mwasilu et al., 2014), as well as the emerging sector coupling literature (e.g., Bloess, 2019; Child et al., 2018; Ramsebner et al., 2021), shows that these innovations are mainly studied from a technical or economic perspective. Therefore, there is a need to employ appropriate sociotechnical frameworks to encompass the full range of important aspects of studying multi-system innovations.

The field of (sustainability) 'transition studies' focuses on the study of complex, long-term, fundamental transformations of sociotechnical systems. These studies adopt a systems perspective, considering the mutual influence of social, technical, institutional, political, economic and socio-cultural aspects, and emphasise path-dependency and lock-in (Schot and Geels, 2008; Markard et al., 2012; Markard, 2018). The frameworks used in these studies have predominantly been developed and are mainly used to analyse the emergence of a focal (niche) technology in one specific sector (Geels, 2018; Markard et al., 2016; Raven, 2007), e.g., natural gas replacing a coal-based regime (Correlje and Verbong, 2004) or steamships replacing the sailing ship regime (Geels, 2002). However, within the literature, there have been several recent calls for expansion to consider broader contextual influences, including multi-system interactions (e.g., Markard, 2018; Schot and Kanger, 2018; Geels et al., 2017a). This has been followed by disparate multi-system framework suggestions and adaptations attempting to (partly) address this gap (e.g., Papachristos et al., 2013; Malhotra et al., 2019).

The current work aims to systematically review 'transition studies' literature (also known as transitions literature) to make an inventory of available analytical frameworks and investigate their applicability to study innovations spanning multiple systems (i.e., multi-system innovations) from a sociotechnical perspective. This paper primarily seeks to answer the following research question: "*What insights do papers from the field of transition studies provide for the study of multi-system innovations from a sociotechnical perspective?*"

In this review, we start from a broad perspective to include former research that attempted to extend the usual single-system focus to consider multi-system influences. To narrow the search area, we focus on studies that include two (inter-system) or more (multi-system) of the following energy-demanding sociotechnical systems: electricity, transport, industry, the built environment, and agriculture. Within this scope, e.g., studies that explicitly include the sector coupling concept as described above or that focus on multi-system innovations that anchor in two or more of the abovementioned systems are of particular interest. The purpose is to add value through the exploration of existing transition frameworks to be able to study multi-system innovations from a sociotechnical perspective.

This paper is structured as follows. Section 2 provides a brief theoretical background. Section 3 describes the literature review methodology, including the search strategy and evaluation criteria of the included studies. Section 4 contains the results of this work in the form of a descriptive analysis of the multi-system frameworks used in the reviewed papers. Finally, Section 5 provides conclusions of the research results, discusses the key findings from the reviewed studies and articulates a future research agenda.

2. Theoretical background

Transition studies emerged in response to pressing environmental issues, like climate change, recognising the need for transformative change in the form of a complex non-linear transition process (Rip and Kemp, 1998). At its core, it takes a holistic sociotechnical perspective to conceptualise and explain the profound reconfigurations necessary across technology, actors, and institutions (Geels, 2002). To decipher the intricate dynamics of sociotechnical transitions, the field draws underlying concepts from various other fields, including evolutionary economics, social construction of technology, neo-institutional theory and complex adaptive systems theory (Geels, 2004; Geels and Schot, 2007). Based on these concepts, over the past two decades, core frameworks have been developed for comprehending transition processes. Two widely embraced frameworks include the Multi-Level Perspective (MLP) (Geels, 2002; Geels and Schot, 2007; Smith et al., 2010) and Technological Innovation Systems (TIS) (Hekkert et al., 2007; Bergek et al., 2008, 2015; Markard and Truffer, 2008).

The Multi-Level Perspective (MLP) framework traditionally consists of three interdependent analytical levels that each play a major role in contributing to a particular transition or technological innovation's success (Rip and Kemp, 1998; Smith et al., 2010). Central to this framework is the sociotechnical regime, which encompasses the established systems that impose path-dependent incremental sociotechnical change (Geels, 2002). Niches play an important role in the emergence of radical innovations, providing 'protected spaces' from selection pressure imposed by the regime (Hoogma et al., 2002; Smith and Raven, 2012). Finally, the sociotechnical landscape includes influential developments external to the regime and niche (e.g., political, cultural or macroeconomic), which can form an undercurrent and be relatively slow. Regime-internal or -external tensions exerted by landscape developments can lead to windows of opportunity for niche innovations to gain momentum (Geels et al., 2018). A primary academic focus of this framework is on regime shifts and the factors that lead to the destabilisation of existing regimes and the emergence of new regimes (as illustrated in Fig. 1). Another analytical focus is on gaining deeper understanding of the innovations incubated in niches and evaluating their performance, for example by analysing internal niche dynamics, such as actor expectations, network building and learning processes.[3]

Within the traditional Technological Innovation System (TIS) framework[4] (Carlsson and Stankiewicz, 1991; Hekkert et al., 2007; Bergek et al., 2015; Weber and Truffer, 2017), there is an analytical focus on the development, diffusion, and use of a particular technology

[1] A sector consists of actors, institutions and technologies that generate products (e.g., cars or electronics) or services (e.g., transport or energy) and may use several technologies (e.g., solar or wind). Where to draw the boundaries between sectors depends on the scope of the analysis, e.g., if the competencies needed for a service differ substantially (e.g., in engineering).

[2] A (sociotechnical) regime can be understood as the 'deep-structure' or grammar of sociotechnical systems, including technical and social aspects that account for the stability of sociotechnical configurations. This includes engineering practices, production technologies, skills and procedures, and the institutions and infrastructures they are embedded in (Geels, 2002, 2004).

[3] To understand the internal niche dynamics and evaluate a niche's performance, the Strategic Niche Management (SNM) framework was developed based on similar conceptual grounds (Schot and Geels, 2008; Markard et al., 2012); SNM provides conceptual tools to assess the performance of niche dynamics (e.g., Van der Laak et al., 2007; Hoogma et al., 2002).

[4] The TIS framework has emerged within a broader field of Innovation System (IS) concepts, including national innovation systems (NIS) (Freeman, 1987; Lundvall, 1992), regional innovation systems (RIS) (Asheim and Isaksen, 1997; Cooke et al., 1997) and Sectoral Innovation Systems (SIS) (Breschi and Malerba, 1997; Malerba, 2002).

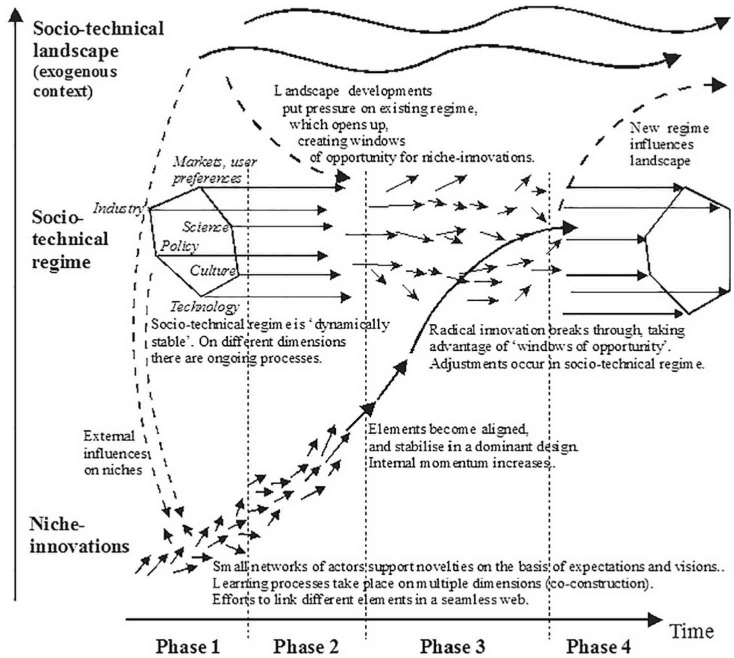

Fig. 1. Multi-Level Perspective (MLP) framework (Geels et al., 2017b).

from a sociotechnical systems perspective, encompassing all components that influence its innovation process (including actors, institutions, and other technologies) (see Fig. 2). A TIS may be a subsystem of a sectoral system or may cut across several sectors (Markard and Truffer, 2008). From this perspective, the development of a new technology results from the positive fulfilment of seven functions: knowledge development and diffusion, entrepreneurial experimentation, influence on the direction of search, market formation, legitimation, resource mobilisation and development of positive externalities (Bergek et al., 2008). Beyond gaining a deeper understanding of internal niche dynamics, a main focus is on uncovering 'system failures' by mapping these key processes to provide a wide range of practical policy recommendations.

As addressed in the introduction, existing conceptual frameworks primarily focused on singular sociotechnical systems (i.e. sectors or regimes). As the energy transition progresses, there is a growing need for framework adaptations that can address transitions spanning multiple sociotechnical systems (Markard, 2018; Köhler et al., 2019). The following section (Section 3) details the research methodology, after which Section 4 synthesises the systematic review results regarding disparate framework adaptations in the literature addressing this gap.

3. Research methodology

The current work systematically reviews the analytical frameworks in transitions literature to synthesise their contributions towards studying multi-system interactions and associated multi-system innovations from a sociotechnical systems perspective. In order to add rigour and thoroughness for conducting such a systematic literature review, we turn to existing guidelines for reviews focussing on framework and conceptual contributions (Wee and Banister, 2016; Snyder, 2019; Xiao and Watson, 2019). Furthermore, we follow the recommendation of various authors to employ transparency and process analysis documentation (Torraco, 2005; MacInnis, 2011; Snyder, 2019).

Considering the breadth of the research question, the choice was made to focus on one broad, emerging body of literature (i.e., transition studies). This review does not consider literature outside of this field, which could grant insights into the study of multi-system innovations from a sociotechnical perspective (e.g., governance studies). Additionally, due to the broad range of concepts and fast-growing database of case studies, the selection criteria were strict to identify only the key and most relevant papers. Only studies written in English from the transitions literature were considered within this scope. Furthermore, both conceptual and empirical (case) studies were included when there was evidence of a multi-system focus (including multi-sector and multi-regime). Moreover, prior to the systematic search, since the literature contains many technical terms, an initial search was done to identify relevant search terms concerning both the theoretical concepts within the literature and the specific terms encompassing multi-system aspects. See Table A.1 in the appendix for a list of the search terms. Considering this, the systematic search was conducted in four separate steps (identification, screening, eligibility and inclusion), as visualised in Fig. 3.

In the first step (identification), a search was done by combining each of the 'transitions literature terms' with the specific 'multi-system terms' found in the initial search and by using quotation marks and the BOOLEAN operators AND/OR. More specifically, the following search string was employed, incorporating every possible combination of the terms listed in Table A.1: ("Transitions Literature Term" OR "Transitions Literature Term Synonym") AND ("Multi-System Term" OR "Multi-System Term Synonym"). Synonyms were considered to encompass variations or alternative notations of the same term or concept. For instance, the search query might appear as follows: ("Multi-Level Perspective" OR "Multilevel Perspective" OR "MLP") AND ("Multi-Regime" OR "Multiple Regimes"). The databases used to identify this research were Google Scholar, Scopus, and Web of Science. These databases were also found to be the most frequently used by other researchers (Norris et al., 2008; Xiao and Watson, 2019). Google Scholar was used initially by searching the first five pages for all identified search-word combinations and adding all relevant papers based on the title and the abstract. After this, Scopus and Web-of-Science were used with the same keyword combinations to add additional relevant literature. In the first step, the general rationale was to include all seemingly relevant papers. After the first step, a total of 621 papers were added to the database. In the second step (screening), the duplicates were removed, and each paper was re-evaluated, mainly based on the abstract and introduction, after which 341 papers remained for further consideration.

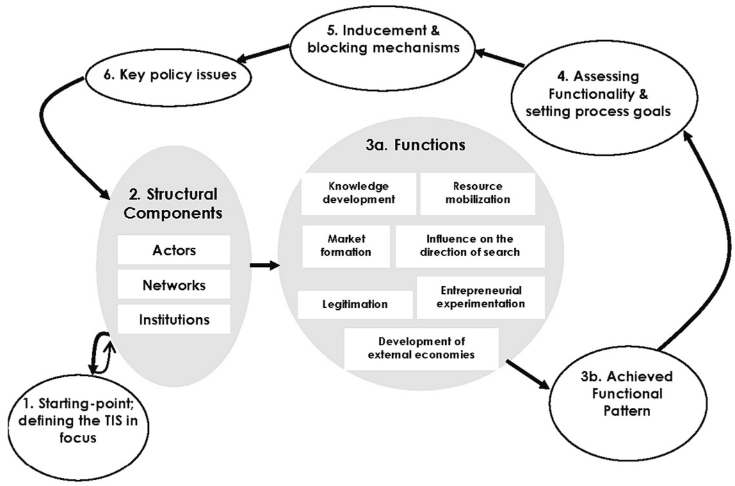

Fig. 2. Technological Innovation System (TIS) framework (Bergek et al., 2015).

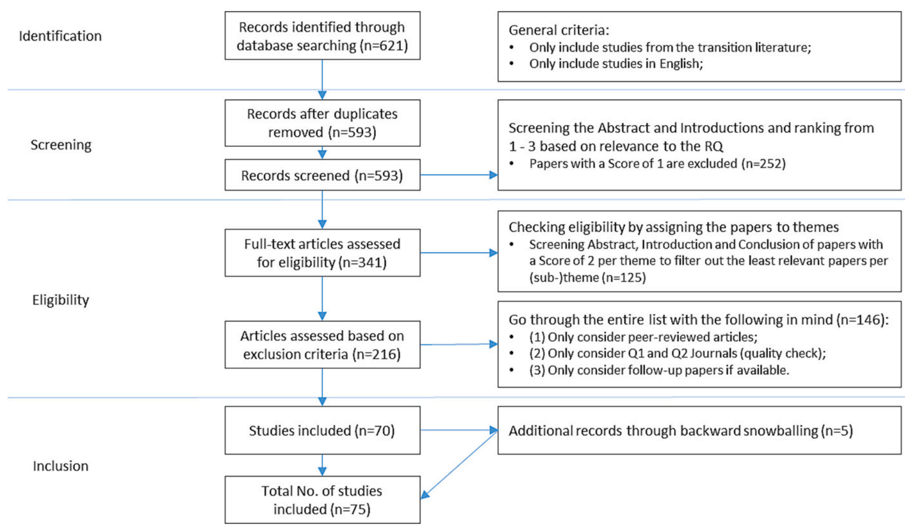

Fig. 3. Literature search and evaluation for inclusion.

The third step (eligibility) was divided into two parts. In the first part, we identified themes and sub-themes to assign the papers, allowing us to uncover the most relevant papers per theme. The two main themes were 'conceptual grounds' (further subdivided into main theoretical concepts) and 'multi-system transition (case) studies' (further subdivided per focal sector under study). The remaining papers' abstracts, introductions and conclusions were more carefully reviewed to decide their relevance to the research topic. A total of 216 papers remained and were distributed over both identified themes. In the second part, the entire list was sifted through once more, with the following criteria in mind: (i) only peer-reviewed articles were considered, and (ii) the quality and reliability of the journal were assessed by predominantly considering papers published in Q1 journals (at the time of the search between May 2022 – July 2022), with some exceptions of papers published in Q2 journals if deemed very relevant. Based on this quality check, the multi-system framework contributions of each of the papers were assumed to be relevant and were therefore considered in the current manuscript. A total of 70 papers remained. In the fourth and final step (inclusion), five studies were added by tracking down references within key documents found in an earlier stage (i.e., Backward snowballing). Therefore, after a careful review covering four steps, a total of 75 papers remained over the two main themes (67 in Q1 and 8 in Q2 journals).

To provide some details about the included papers, the 'conceptual grounds' theme consists of 35 papers. The first set of papers (23 out of 35) covers the main concepts within the sociotechnical transitions literature, including the Multi-Level Perspective (MLP), Strategic Niche Management (SNM) and Innovation Systems (IS). These papers were screened[5] to form the first conceptualisation of the following aspects: (i) core concepts within the literature, (ii) specific definitions of core terms and (iii) conceptualisation of sectors and regimes. The other set of the papers within this theme (12 out of 35) covers conceptual grounds of multi-system analysis in sociotechnical transitions (focusing on the theory of economic sectors and the concept of sector coupling). These papers were screened to deepen the understanding of definitions and characteristics of multiple systems and sectors and how they transform. The papers in this theme serve as a background for the review presented in the current paper, and form the basis for the theoretical background described in Section 2. See Table B.1 in the appendix for a list of the papers within this theme.

Core to our literature review are the remaining 40 papers from the

[5] Screening in this context implies thoroughly reading the abstract, introduction, theoretical background and conclusions and skimming other chapters to find the above information (e.g., by searching for specific terms in the papers).

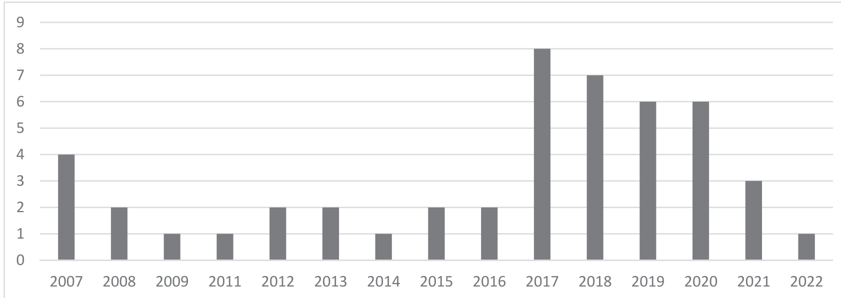

Fig. 4. Depiction of the publication dates of the reviewed papers. This shows that the number of papers has surged around 2017 onwards.

'multi-system transition (case) studies' theme, which cover both conceptual/theoretical and empirical (case) study papers and were subdivided based on the focal sector of study. These papers can be considered highly relevant according to the inclusion criteria. They are mainly built upon – and quite evenly distributed across – the above-described two prominent (founding) theoretical frameworks within the field (van den Bergh et al., 2011; Markard et al., 2012), namely the Multi-Level Perspective (MLP) and Technological Innovation Systems (TIS), counting 19 MLP papers and 21 TIS papers. This distribution occurred despite our explicit search for papers that cover multiple frameworks within the transitions literature. The selected papers were read thoroughly and consequently were core to the results described in Section 4, reflecting the main research question discussed in the introduction. See Table B.2 within the appendix for a list of the papers in this theme.

4. Results

Within this section, we seek to answer the research question established in the introduction: "*What insights do papers from the field of transition studies provide for the study of multi-system innovations from a sociotechnical perspective?*" This will be done through a descriptive analysis of the reviewed papers, focusing on the Multi-Level Perspective (MLP) and the Technological Innovation Systems (TIS) papers from the 'multi-system transition (case) studies' theme as described in Section 3. These papers fit within the scope of this review since they attempt to extend the usual single-system focus to consider multi-system influences, either with a focus on two (inter-system) or more (multi-system) of the following energy-demanding sociotechnical systems: electricity, transport, industry, the built environment, and agriculture. For this, the papers usually adapt established frameworks (i.e., MLP and TIS) to include multi-system dynamics. As depicted in Fig. 4, based on our inclusion criteria, the selected papers explore multi-system interactions from around 2007 onwards (Geels, 2007; Raven and Verbong, 2007). Notably, in 2017, we observe a steep increase in the number of relevant multi-system papers.

While the papers have overlapping topics and results, we have subdivided them according to each study's core idea to structure the forthcoming analysis. The title of each sub-category is derived either from much-used terms in the clustered papers or the main concept that the papers jointly contribute. Each subsection will summarise the core concepts presented by its respective cluster of papers. Within these subsections, we focus the descriptive analysis on each cluster's main insights and contribution towards studying multiple systems (i.e., sectors or regimes) that moves away from the traditional focus on a single system. Moreover, the core concepts of each cluster are summarised in figures (see Figs. 5–12). The focus of this paper is on conceptual and analytical contributions and not on methodological suggestions.

4.1. Multi-Level Perspective (MLP) papers

We subdivided the MLP papers addressing multi-system transitions across four main sub-categories; (i) Multi-regime Interactions, (ii) Coupled Value Chains, (iii) Transition Phases and (iv) Connected Transitions. Table B.2 in the appendix provides a list of papers per cluster. In the following, we will describe their contributions to the body of knowledge regarding multi-system interactions. Refer to Figs. 5–8 for a graphical summary of the core concepts of each cluster, respectively.

4.1.1. Multi-regime interactions

The sub-category comprising the 'multi-regime interactions' papers contain the biggest number of the reviewed MLP papers (9 out of 21). The papers generally focus on cases where more than one regime and the interplay between these regimes plays a role. These papers span back to 2007; between 2007 and 2008, five multi-regime papers were published, directly addressing the focus of MLP studies on single-regime interactions (e.g., Raven, 2007 or Verbong and Geels, 2007). Each paper included a multi-regime case study design, for example, by exploring the co-evolution of natural gas and electricity systems in the Netherlands (Raven and Verbong, 2007) or interaction patterns among different German utilities providing telecom, electricity, gas, and water (Konrad et al., 2008).

These early papers made two main contributions to multi-system studies. Firstly, they identified common interactions between regimes. For example, Raven and Verbong (2007) identified four types of interactions between regimes: (i) competition occurs when regimes start

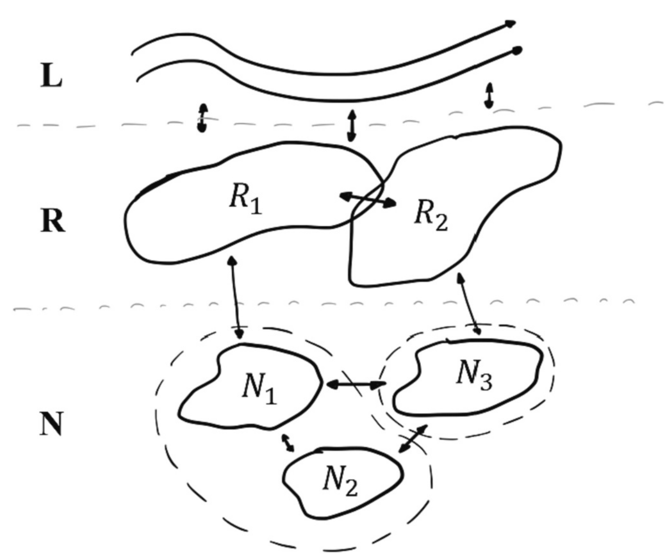

Fig. 5. Aggregated depiction of the main frameworks used by the 'Multi-Regime Interactions' papers. The image is adapted from Sutherland et al. (2015) and graphically depicts two interacting regimes (i.e., cross-regime dynamics) with multiple niches in development. Niches can also be clustered per sociotechnical system, as depicted by the dashed lines around the niches (e.g., Niche 1 and 2 are part of the Electricity system, and Niche 3 is part of the Agriculture system).

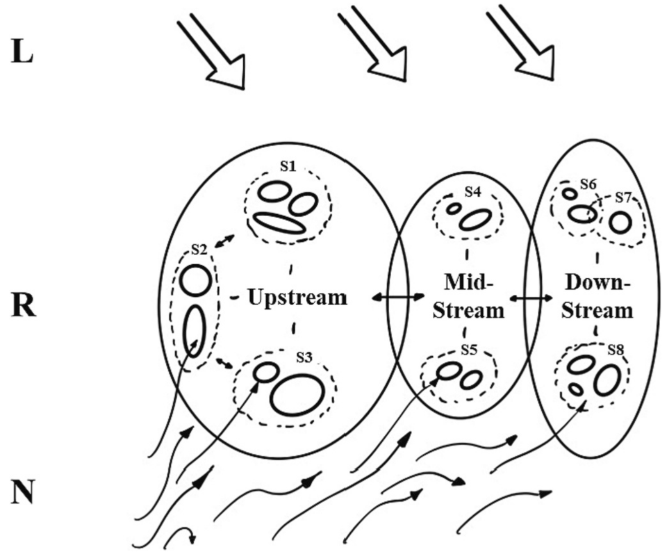

Fig. 6. Aggregated depiction of the main frameworks used by the 'Coupled Value Chains' papers. This is a schematic representation of a sociotechnical system's value chain. The image is adapted from McMeekin et al. (2019) while adding a schematic representation of different systems per part of the value chain as advocated in Meynard et al. (2017). Each part of the value chain consists of sub-systems that perform a different function within the socio-technical system. Each sub-system is part of a bigger (overlapping) socio-technical system. Therefore, across each value chain level, the sociotechnical system interacts with multiple other sociotechnical systems. Multiple niche innovations can influence systems differently, and the niche can have knock-on effects on other sub-systems and parts of the value chain. Researchers can take different scopes in their study of sociotechnical complexity (Geels, 2018).

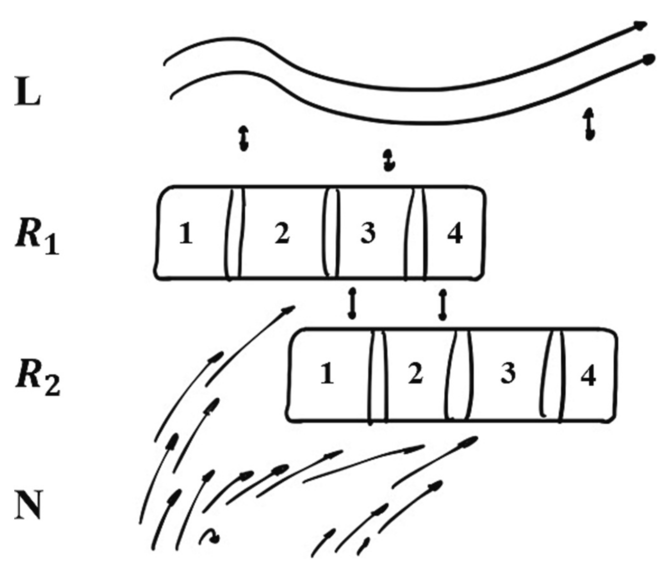

Fig. 7. Aggregated depiction of the main frameworks used by the 'Transition Phases' papers. The image merges the life-cycle model from Kanger (2021) with the MLP conceptualisation from Geels et al. (2017a) to depict transitions as interactions of regimes in different phases of their lifecycle (e.g., emergence, upscaling, consolidation, reorganisation, destabilisation and stagnation, and decline).

fulfilling similar functions; (ii) integration occurs when previously separated regimes overlap (e.g., through actor mergers); (iii) spill-over occurs when practices from one regime become adopted in another, and (iv) symbiosis occurs when the two regimes reap mutual benefits from each other's existence. Secondly, the papers highlight that these interactions evolve over time. For example, in Geels' (2007) exploration

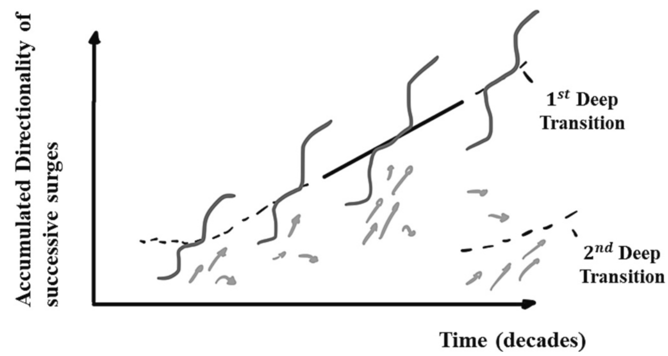

Fig. 8. Aggregated depiction of the main frameworks used by the 'Connected Transitions' papers. The image is a schematic representation of the theoretical framework depicted in Schot and Kanger (2018). Each (S-)curve represents a decades-long technology surge from the installation to the deployment phase. One overarching (path-dependent) Deep Transition may encompass multiple technology surges.

of the breakthrough of rock 'n' roll in the US, the relationship between the radio and recording regimes evolved from competition to symbiosis. Each paper concludes with a call for more explicit multi-regime analysis. Erlinghagen and Markard (2012) answer this call and reinforce these findings by showing that entrants from another sector (i.e., 'adjacents') can be important catalysts for sectoral transformation and should thus be analysed more systematically in transition studies.

Following up, Papachristos et al. (2013) performed a meta-analysis drawing on the cases from the previously discussed multi-regime studies. The paper contributes to multi-system analysis by introducing generalisable system interaction types. Some of the common patterns introduced: (i) the importance of old regimes for the development of a new system, (ii) the influence of specialised applications on new technologies, and (iii) the development and utilisation of complementary technologies and new skills. This paper reveals that interactions between systems may take on a reinforcing or disruptive pattern. A follow-up study by Sutherland et al. (2015) focusing on renewable electricity in the agriculture sector makes two main contributions to multi-system analysis. Firstly, it confirms that working across system boundaries (e.g., agriculture and electricity) is an important source of innovation and that anchoring into multiple regimes can increase the stability of niche development. Secondly, the study advocates researchers to specify the location of niches (e.g., the agriculture regime) instead of simply labelling niches 'outside' of the focal regime (e.g., the electricity regime). In their study, such approach allowed for clearer consideration of the effects of renewable energy transitions on the agriculture regime.

Finally, Rosenbloom (2019) emphasises caution towards the energy transition-related policy recommendations, referencing Raven (2007), since policies that target one system may directly or indirectly impact one or more other systems, modulating the course of societal development in unforeseen ways.

4.1.2. Coupled value chains

Three papers fall into the 'coupled value chains' sub-category. These papers generally emphasise the necessity of considering the whole value chain when analysing innovations in multiple sociotechnical systems. The authors usually refer to this as 'whole systems analysis'. For example, Meynard et al. (2017) provide a heuristic 'whole system' framework to organise the design of coupled agrifood innovations. Such a coupled design approach considers the potential synergies or antagonisms between agriculture and food systems involving their value chains (i.e., production, processing, distribution, and consumption). Geels (2018) similarly advocates that the usual analytical focus on 'singular disruption' should be complemented with greater attention to 'multiple innovations and system reconfiguration' (i.e., 'whole system' change focusing on coupled multi-system value chains). The paper points out that addressing system reconfiguration may require some reconceptualisation of the MLP to pay more attention to different kinds of change mechanisms, including (i) interactions between niche innovations, (ii) adoption of niche innovation(s) within existing systems, and (iii) interactions between multiple systems (Geels, 2018). Therefore, the author advocates incorporating insights from other social sciences and moving away from the Schumpeterian dichotomy in which new entrants overthrow locked-in incumbents. This is possible since MLP can be considered a Middle-Range Theory[6] that conceptualises overall dynamic patterns in sociotechnical transitions, which can be adapted and expanded to encompass additional transition dynamics (Geels, 2011).

As a follow-up, in a case study on the UK electricity system, McMeekin et al. (2019) develop an approach for 'whole-system' analysis along with a framework that considers generation, distribution, and consumption, as well as the configuration of systems (e.g., electricity, agrifood, mobility). This study shows that interactions between different system configurations should be studied as an empirical matter since system architecture differs per system and can lead to varying implications for transition dynamics. Furthermore, this study finds that the UK's energy transition consists of multiple co-existing and interacting reconfiguration dynamics, which become more important as cross-system linkages increase (e.g., between electricity and mobility). Therefore, it suggests to characterise the 'whole system transitions' as a (gradual) reconfiguration instead of the traditional conceptualisation of radical niche innovations substituting a prevailing regime, acknowledged as one of Geels and Schot's (2007) four possible transition pathways.[7]

4.1.3. Transition phases

The 'transition phases' papers directly address the phases of the energy transition. They emphasise how developments in multiple sociotechnical domains can bring about 'momentum' that drives upscaling and that linkages between sociotechnical systems may stimulate deep and rapid decarbonisation (Geels et al., 2017a, 2017b; Kanger, 2021). One of the key themes in these papers concerns the timing, duration, and acceleration of transitions. We observe a renewed emphasis on conceptualisations of MLP, which subdivide the decades-long transition processes into four distinguishable phases (Geels, 2005; Geels et al., 2017a, 2017b; Kanger, 2021):

- Phase 1: Radical innovations emerge in (technological) niches;
- Phase 2: Innovations enter small market niches;
- Phase 3: Innovations break through and compete with the established regime;
- Phase 4: Regime substitution with the widespread adoption of new innovations.

Considering multi-system dynamics, Geels et al. (2017b) illuminate the importance of explicitly establishing the status of each sociotechnical system since they tend to be in different phases depending on the geographical location and the timing, which can influence the adoption of specific multi-system innovations like V2G. For example, in most Western countries, the progress of the transition in the electricity system (with wind and solar electricity diffusing rapidly) is greater than low-carbon transitions in passenger transport (where the petroleum-fuelled auto-mobility regime is still mostly deeply entrenched) (Geels et al., 2017b). In line with this, Kanger (2021) seeks to rethink the 'global' model of the MLP to include a more detailed understanding of how, when, and why transitions occur to advance research and stimulate effective interventions for accelerating transitions in energy and mobility systems.

4.1.4. Connected transitions

The papers in the 'connected transitions' sub-category argue that a structural solution to the current pressing global and interconnected (i.e., wicked) environmental problems requires radical transformations towards a sustainable society in the form of a Deep Transition: "*a series of connected transitions in many sociotechnical systems [e.g., energy, mobility, food] towards a similar direction [e.g. sustainability]*" (Schot and Kanger, 2018, p. 1045). These papers move the scope beyond 'system innovations' in a focal sector to resemble a Techno-Economic Paradigm (TEP) shift, which encompasses 40–60 year-long cyclical variations in economic growth (i.e., long waves) (Freeman and Perez, 1988; Mathews, 2013; Perez, 1983, 2003). Each wave evolves from small beginnings in specific sectors or regional areas and ends up encompassing entire economies and societies of certain countries, gradually diffusing to other countries. There have been five such waves since the beginning of the Industrial Revolution (Mathews, 2013). Radical innovations differ with respect to how pervasive their economic effects are (Schumpeter, 1939). While some radical innovations may influence only a specific sector or industry, others may affect a whole range of sectors or, in rare cases, the entire economy. To account for these dynamics in transitions, the papers in this sub-category merge the Techno-Economic Paradigm (TEP) framework with the Multi-Level Perspective (MLP) framework (Mathews, 2013; Schot and Kanger, 2018).

Two sequential papers by Schot and Kanger (2018) and Kanger and Schot (2019) emphasise that Deep Transitions are sociotechnical, transnational, multi-system transitions, which are even more difficult to understand and govern than transitions in individual sociotechnical systems. Techno-economic paradigms (TEPs) provide what they term a meta-regime: A coordinating mechanism generating interconnections between technologies and industries (i.e., a ruleset in multiple systems or regimes) (Schot and Kanger, 2018). They call the build-up of various sociotechnical systems taking place over the 19th and 20th centuries the *First Deep Transition*. According to the authors, the recent sustainability concerns stimulate the emergence of the *Second Deep Transition*. These papers together provide 12 overall propositions that constitute the macro-dynamics of the Deep Transitions framework (Kanger and Schot, 2019). Finally, Van der Vleuten (2019) contrasts these findings by highlighting that 'Deep Transitions' research should be further validated empirically, and assumptions should be submitted to the intersubjectivity of scholarly debate before taking definitions such as the 'First Deep Transition' for granted.

4.2. Technological Innovation System (TIS) papers

We subdivided the TIS papers addressing multi-system transitions into four main sub-categories; (i) Sectoral Change, (ii) Contextual Influence, (iii) Sectoral Configuration and (iv) Structural Tensions. Table B.2 in the appendix provides a list of papers per cluster. In the following, we will describe their contributions to the body of knowledge about multi-system interactions. Refer to Figs. 9–12 for a graphical summary of the core concepts of each cluster, respectively.

4.2.1. Sectoral change

The papers in the 'sectoral change' sub-category generally focus on the sectoral influence on TISs, for example, by introducing concepts from the Sectoral Systems of Innovations (SSI) field. To start, Dolata

[6] Merton (1968:39) defined Middle-Range theories (MRT) as "theories that lie between the minor but necessary working hypotheses that evolve in abundance during day-to-day research and the all-inclusive systematic efforts to develop a unified theory that will explain all the observed uniformities of social behaviour, social organisation and social change". Geels (2011) emphasises that MLP is an MRT since it relates various concepts and uses empirical research to identify recurring patterns and generalisable lessons.

[7] Geels and Schot (2007) develop a typology of four transition pathways: transformation, reconfiguration, technological substitution, and de-alignment and re-alignment. These pathways differ in combinations of timing and nature of Multi-level interactions.

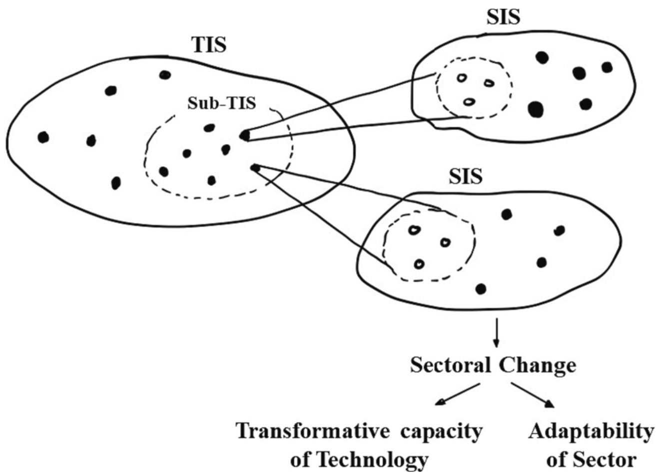

Fig. 9. Aggregated depiction of the main frameworks used by the 'Sectoral Change' papers. The image depicts different TIS levels by adapting the Multi-Level IS framework from Cronin et al. (2022) and combines it with the heuristic framework for analysing distinct patterns of tech-based sectoral change from Dolata (2009). Here a sub-TIS can be a national-level TIS when the TIS is on the European level. The closed dots represent partners consisting of different actors (open circles). These actors can be part of a larger system, e.g., a Sectoral Innovation System (SIS). Key is the observation that technology-based sectoral change is characterised by (i) the transformative capacity of a new technology and (ii) the inherent adaptability of the sector (i.e., structures, institutions and actors). The integrated functional-structural TIS framework presented in Lamprinopoulou et al. (2014) can be used to analyse both micro-level and macro-level aspects.

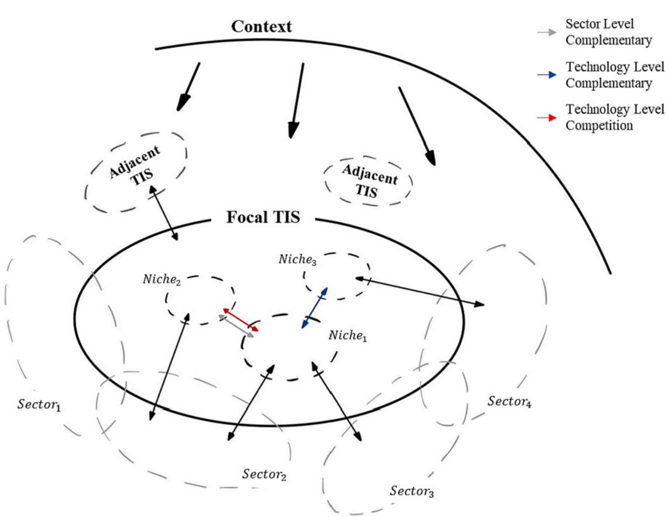

Fig. 10. Aggregated depiction of the main frameworks used by the 'Contextual influence' papers. The image adapts the framework presented in Markard and Truffer (2008) and adds relationship types between niches from Markard and Hoffmann (2016). In essence, it depicts a TIS and key contextual elements, including all systems that it interacts with and different kinds of complementary and competing innovations that emerge within the focal TIS. The black double arrows indicate the sectors that the TIS interacts with, which is specified per niche; While one TIS can interact with multiple sectors, niches can also interact with multiple sectors (i.e., a multi-system niche). Since the TIS has a lifecycle, the configuration of TIS-context interaction can change over time and is distinctly different during expansion (maturation) and decline until the TIS disappears and is replaced by an adjacent (maturing) TIS.

(2009) produces a heuristic framework for analysing distinct patterns of technology-based sectoral change. The paper points to two key determinants of the likelihood that sectoral change arises through innovation: (i) the sector-specific transformative capacity of new

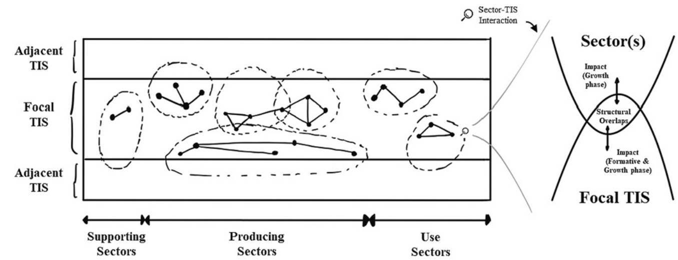

Fig. 11. Aggregated depiction of the main frameworks used by the 'Sectoral Configuration' papers, depicting the sectoral configuration of a TIS. The image adapts the framework presented in Stephan et al. (2017) on the left and adds a zoomed-in perspective on the right to represent sector-TIS interactions with a focus on structural overlaps, as depicted in Mäkitie et al. (2018). Each dashed circle on the left represents a different sector, and each dot is an actor. Each sector encompasses the actors producing similar outputs (e.g., components or sub-systems underlying the focal technology). As represented in the (zoomed-in) image on the right, between a sector and a TIS, there are structural overlaps (e.g., actors, technology, institutions, networks); Actors may share similar institutions and production techniques and are linked through sector-specific networks. One actor might be active in different sectors. The sectors are active in other TISs to varying degrees.

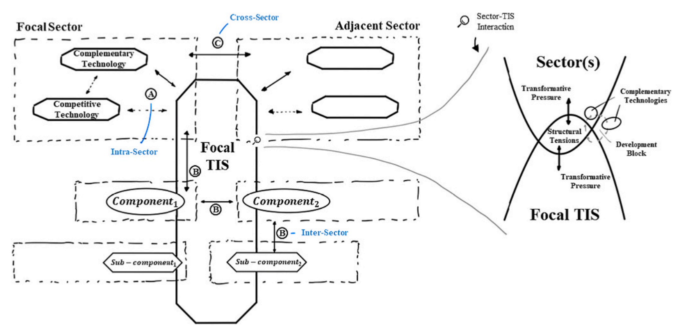

Fig. 12. Aggregated depiction of the main frameworks used by the 'Structural Tensions' papers, depicting a map of multi-technology interaction and associated sectors. The image adapts the framework presented in Andersen and Markard (2020) on the left, adding a zoomed-in perspective into the overlap between a Focal TIS and different sectors on the right (i.e., Sector-TIS interactions). This depicts TIS development cycles with structural tensions and development blocks that are influenced by complementary technologies as depicted in Haley (2018).

technologies themselves and (ii) the sectoral adaptability of socioeconomic systems confronted with the opportunities presented by new technologies. From these insights, the paper makes two main contributions to multi-system analysis. Firstly, it highlights the necessity to typify different sectors more precisely and determine distinct influencing factors that foster their adaptability (e.g., sociotechnical systems must show compatibility). Secondly, the framework highlights the importance of an inter-sectoral TIS view since the transformation of the 'focal' sector can be driven by technology developed 'outside' of that sector. This point was reiterated by Erlinghagen and Markard (2012), which showed that incumbents from adjacent sectors, such as IT or telecommunications, may drive innovation in the energy sector.

Building on this, Lamprinopoulou et al. (2014) draw up a multi-system structural-functional framework that combines the agrifood sectors to assess and compare the Agriculture Innovation Systems of Scotland and the Netherlands. Their framework includes transformational failures in addition to the established concepts of market failures and structural failures that were first introduced by Weber and Rohracher (2012). In this context, transformational failures represent a TIS's overall functioning and capability to renew itself and support major transitions as opposed to incremental improvement of the existing systems. From a multi-systems perspective, this allows for (traditional) 'structural innovation policies' – that address structural deficits in innovation systems – to be complemented by 'transformation-oriented innovation policies' which strategically focus on the transformation of whole systems of innovation, production and consumption (i.e., multi-sectoral). The stepwise framework introduced by Lamprinopoulou et al. (2014) indicates the need first to perform a micro-level failure analysis (i.e., functional analysis and structural-oriented analysis) and then a macro-level failure analysis (i.e., transformation-oriented analysis). Following up, Weber and Schaper-Rinkel (2017) introduce a multi-sector innovation foresight methodology to identify cross-cutting patterns of sectoral change and the effects on innovation policy at the European level. The paper shows that since innovation dynamics differ across sectors, exploring future perspectives on general innovation patterns needs to be rooted in the specific sectoral dynamics while allowing for the identification of (new) cross-sectoral patterns (e.g., to facilitate cross-sectoral 'Key Enabling Technologies'[8]). Based on the insights from five different sectors, the authors find a blurring of sectoral boundaries, along with sectoral and cross-sectoral integration and an increased need for governance of interactions between the sectors.

Finally, in a paper focused on transformative policies for sustainability transitions, Fagerberg (2018) highlights (i) a need to focus on supply and demand factors since both are deemed essential for success (i.e., a 'holistic perspective') and (ii) a need for innovative policy governance and instrumentation to account for policy coordination across different sectors to provide policymakers with tools to consider strategic, long-run societal (sustainability) goals.

4.2.2. *Contextual influence*

The 'contextual influence' sub-category constitutes contributions mainly (co-)authored by Markard. The papers make several key contributions to the multi-system analysis. Markard and Truffer (2008) and Wirth and Markard (2011) develop and use a merged MLP-TIS framework to encompass contextual influences, such as a TISs interaction with one or more sociotechnical regimes and several niches or application contexts. The studies validate that a TIS interacts with and is influenced by the focal sector (the sector it is mainly embedded in) and adjacent sectors (other related sectors); thus, many TISs are part of several sectors. Notably, there is a distinction between negative (competitive) and positive (complementary) sector-TIS interactions, highlighting the relevance of multiple competing vs complementary technologies within a focal sector. These papers point out whether and how an emerging technological field links up with the structures of existing sectors depends on 'complementarities' (i.e., other technologies that affect the focal technology).

Markard and Hoffmann (2016) and Markard et al. (2016) focus on the intricate dynamics of such complementarities. Their work demonstrates that different technologies can both compete and complement each other simultaneously, depending on whether the analytical focus is centred on the performance of the focal technology or the focal sector. For example, from a technology perspective, hydropower and wind power are competing electricity generation technologies, both competing for generation capacity in the electricity mix (i.e., technology-level competition). However, from a sectoral perspective, they are complementary in balancing electricity supply and demand (i.e., sector-level complementary); hydropower can serve as a stable base load to complement the variability of wind energy. Thus, it is important to specify the analytical focus when exploring complementarities. Furthermore, complementarities might change as technologies diffuse more widely or as the technology matures, and they may increase interconnection between different sectors (e.g., electric vehicles connect electricity and transport sectors). In general, they point out that (i) the degree to which contextual elements matter for a focal technology should be determined empirically and (ii) that the relationships with context structures can change over time (e.g., as a technology matures and expands to novel sectors).

Following up, Markard (2018) points out that inter-sectoral relations become denser in the advanced stages of the TIS lifecycle, and Markard (2020) develops a TIS life cycle framework to encompass a TISs configuration evolution over time and distinguishes between four critical stages of TIS development: *formation*, *growth*, *maturity*, and *decline*. For sustainability transitions, such a life cycle perspective highlights two crucial aspects: (i) it requires the TIS to include both technology production and innovation (as opposed to earlier studies' emphasis on innovation), (ii) it also emphasises a TISs ending, considering the necessity of phasing out 'unsustainable' technologies.

4.2.3. *Sectoral configuration*

The 'sectoral configuration' sub-category generally demonstrates the importance of studying the interplay of downstream and upstream segments of focal technology value chains. To begin, Bergek et al. (2015) distinguish two ways in which multi-system interactions are established: (i) 'External links', which refer to one-way influence from a contextual element on a TIS, such as national institutions, politics, or sudden price shifts and (ii) 'structural couplings', which refer to a situation with shared components between a TIS and a sector (e.g., actors, institutions, networks and technology), possibly resulting in a two-way interaction where systems mutually influence each other. For example, a TIS's actors can be categorised under different sectoral subgroups, representing the overlaps between the TIS and various sectors. Mäkitie et al. (2018) focus on these structural couplings to extend and nuance the notion of inter-industry relationships (i.e., between an established sector and a nascent TIS) by considering four types of structural overlaps and by distinguishing between two phases of TIS development. The paper shows that structural overlaps can influence a TIS's functions. For example, structural overlaps can be important for creating positive relationships between sectors and a TIS since they facilitate different forms of resource redeployment from sectors to TISs.

Stephan et al. (2017) propose an explicit delineation of the 'sectoral configuration' of a TIS to classify the number and types of sectors that are linked via its value chain. The paper shows that sectoral configurations are particularly important for modern multi-component technologies (MCTs[9]), such as lithium-ion batteries since their underlying innovation and dynamics involve multiple sectors (e.g., chemical, electronics, and automobile). Furthermore, since the influence of sectors on TISs varies over time, the paper emphasises that the sectoral configuration deserves continued attention in future TIS analyses, especially when TISs centre around the MCTs. Malhotra et al. (2019) further integrate the sectoral configuration into TIS analysis by illustrating the generic sectoral configuration of a TIS's value chain and classifying the value chain segments of a generic MCT into seven categories from production equipment supply to end use. Each of these segments involves one or more sectors, and a single sector can be involved in more than one value chain segment. These papers demonstrate the value of explicitly analysing the sectoral configuration in the TIS analyses. For example, differences in sectoral characteristics (such as complexity and specificity of knowledge) can influence the patterns of inter-sectoral learning (e.g., purposive learning-by-interacting between sectors), which can lead to differences in knowledge development and diffusion.

Finally, Bento et al. (2021) build upon the finding that access to

[8] The authors emphasise that Key Enabling Technologies (KETs) could provide the basis for innovation in a wide range of products and processes across all industrial sectors and could be important in solving Europe's major societal challenges.

[9] Multi-Component Technologies (MCTs) and the former-mentioned Key Enabling Technologies (KET) can be categorised under the umbrella-term 'Multi-Purpose Technologies,' which includes technologies with multiple use-sectors that affect different sectors in distinguishable ways.

resources available in the context depends on structural (sectoral) couplings to show that two factors form the basis for attracting different sectors to an emerging TIS (i.e., inter-sectoral relations): 'technological variety' and 'technological relatedness.' In studying the effect of resources on the inter-sectoral relations in TISs, the authors find that high technological capacity and sectoral proximity are not requirements for entry. This indicates opportunities for a greater variety of existing sectors to be mobilised than the literature usually considers (e.g., Boschma, 2017).

4.2.4. *Structural tensions*

The papers in the 'structural tensions' sub-category advocate for incorporating Industrial Dynamics to improve the knowledge about the micro-foundations of TIS growth. They do so in relation to the changing sectoral composition (i.e., emergence, growth, and decline of sectors) associated with the structural transformation of economies (Carlsson, 2016; Kuznets, 1971). Haley (2018) presents a TIS development cycle that combines the TIS framework's ability to illuminate policy failures with the idea that technological diffusion creates 'structural tensions' that introduce transformation pressure (i.e., mismatches between an innovation and its broader sectoral system) (based on Dahmén, 1988). Structural tensions can introduce both positive and negative transformation pressure. 'Positive transformation pressure' occurs when innovations create new opportunities for increasing the performance of the entire sector by combining complementary technologies, institutions, and firms (i.e., development block[10]) (Dahmén, 1988). 'Negative transformation pressure' occurs when innovations make the old ways of doing things obsolete or less effective, which can push economic sectors or actors out of the economy (i.e., *creative destruction*).

Andersen and Markard (2020) introduce a novel multi-technology map to complement existing frameworks as a 'mapping device' for multi-technology interaction. In a nutshell, their framework[11] includes different levels of the technology value chain. It distinguishes three types of multi-technology interaction: (i) technology interaction within the focal sector (i.e., intra-sector technology interaction), (ii) technology interaction between upstream (e.g., involved in sub-component production) and downstream (e.g., use-sectors to create products or services) parts of the value chain (i.e., inter-sector technology interaction), and (iii) technology interaction between focal and adjacent sector(s) (i.e., cross-sector technology interaction). Since inter-, intra- and cross-sector forms of technology interactions often affect each other, they conceptualise these interlinked technologies and sectors as one larger technological system or development block (Hughes, 1983). Tensions can arise both internally and externally, which can be resolved by complementary innovations allowing the block to evolve further. As structural tensions occur and are resolved, the boundaries of the block can change (Taalbi, 2016).

5. Conclusion and discussion

This paper primarily sought to answer the following research question: "*What insights do papers from the field of transition studies provide for the study of multi-system innovations from a sociotechnical perspective?*" To answer this question, we have systematically reviewed transitions literature to identify analytical frameworks used to study multi-system (i.e., multi-sector and multi-regime) innovations from a sociotechnical perspective. After an iterative selection process, 75 papers were selected for this review. Out of these papers, 35 were instrumental in providing background information, while the remaining 40 research manuscripts were directly used to address the research question. These papers were mainly built upon and adapted two prominent (founding) theoretical frameworks within the field; the Multi-Level Perspective (MLP) and Technological Innovation Systems (TIS), counting 19 MLP papers and 21 TIS papers. The current review focused on the contributions of each of the papers in adapting the usual single-sector focus of the above-mentioned frameworks to analyse multi-system influences.

This final Section is structured as follows. First, we provide the conclusions to the research question in Section 5.1 in the form of three key takeaways distilled from the reviewed studies, which constitute generalisable aspects that merit further consideration in future socio-technical multi-system analyses. Subsequently, in Section 5.2, we discuss the implications of these key takeaways to lay the foundation for an integrative framework for multi-system analyses, which is absent in the existing literature. Lastly, in Section 5.3, we discuss the implications for future research and how such a framework can be further developed.

5.1. *Conclusion: key takeaways for multi-system analysis*

In this subsection we reflect on the results of the systematic review and the implications it has on multi-system analysis. In accordance with our research question, the results present a comprehensive overview of how multi-system analysis is conceptualised within transition studies. While all reviewed papers stem from transition studies, they exhibit substantial variations in terms of underlying assumptions, scope of examination, and empirical cases. For instance, in terms of underlying assumptions, there is an evident contrast between the grouped TIS and MLP studies due to their distinct core frameworks. Furthermore, variations also exist between the grouped studies within each conceptual approach. For example, regarding the scope of examination, 'connected transitions' papers seek to identify overarching patterns that transcend various systems, while 'multi-regime' studies adopt a narrower scope to concentrate on bilateral interdependencies between specific systems, such as agriculture and energy. Despite the variability between studies, three key aspects have emerged as pivotal in multi-system analyses, directly addressing our research question.

The first key aspect involves understanding the 'overarching directionality' (common trajectory) of multiple sociotechnical systems (i.e., 'meta-regime'), considering their common trajectory and mutual influence on each other, since the similar trajectories provide the context within which innovations develop (e.g., Schot and Kanger, 2018). For example, in light of the current energy transition, numerous individual systems are concurrently undergoing electrification. This aspect points to an ongoing debate in the literature about the appropriate scope of examination to adopt, such as macro-level (e.g., macro trends), system-level (e.g., systemic effects) or actor-level effects (e.g., cross-sector learning), and the need to explore innovation processes across different levels of analysis since these levels are interconnected, and mechanisms between them can influence each other, enhancing the explanatory power of system concepts (e.g., Cronin et al., 2022; Lamprinopoulou et al., 2014). It indicates the need to explore further how to reconcile and accommodate the study of multi-system innovation processes that cross different levels of analysis.

The second key aspect is the explicit analysis of each system's development phase during a transition. Sociotechnical systems can be in varying phases of development due to factors like timing, duration, location, and acceleration (e.g., Geels et al., 2017b; Markard, 2018; Kanger, 2021). For example, the electricity system transition towards sustainability is further along than the transport system transition in many Western countries. This impacts the implementation of innovations that intersect these two systems, such as V2G. Thus, devising

[10] A development block describes how a set of core innovations generate structural tensions (Dahmén, 1988), 'technical imbalances' (Murmann and Frenken, 2006) or 'reverse salients' (Hughes, 1983) across related technologies and sectors that in turn generate pressure for change in other parts of the system.

[11] Underlying their framework is the presupposition that technologies are both combinatorial and recursive systems, implying that there is no specific scope or level of analysis (e.g., the electric vehicle, its engine or the battery) that is a priori better when studying technological change (Arthur, 2009; Sandén and Hillman, 2011).

interventions for accelerating transitions in two different systems or for supporting multi-system innovations requires explicit analysis of each system's specific phase and how, when, and why transitions occur in each system. In this context, reviewed studies highlight the importance of adopting a life-cycle approach, particularly as we enter a new phase of the energy transition, for example, with the necessity to phase out unsustainable technologies. Such an approach gains increasing significance as transitions progress, with denser multi-system relations (e.g., Bento et al., 2021; Stephan et al., 2017; Markard, 2018) and evolving relationships with complementary technologies in more advanced stages of a transition life-cycle (e.g., Markard and Hoffmann, 2016).

The third key aspect is the necessity of explicit examination of system configuration, which refers to the sociotechnical components and structures that make up the system(s) and how they shape system processes. This aspect can be further subdivided into five primary considerations. First, numerous papers emphasise the importance of considering the value chain associated with an innovation (i.e., whole system analysis) (e.g., Lamprinopoulou et al., 2014; Meynard et al., 2017). Second, they highlight the merit in specifying the 'sectoral configuration' such as the number and types of sectors linked to the value chain. This is especially important for multi-component technologies (e.g., Stephan et al., 2017; Malhotra et al., 2019). Third, the reviewed papers point out a need to perform intra- and inter-sector analysis. Intra-sector analysis helps typify different sectors since each has distinct characteristics, and to understand the differing repercussions that innovations may have on the structural and institutional arrangements of different sectors (e.g., Bento et al., 2021; Erlinghagen and Markard, 2012). Meanwhile, inter-sector analysis helps typify specific relationships and interactions between certain sectors, which can range from positive (complementary or symbiotic) to negative (competitive) patterns (e.g., Markard and Hoffmann, 2016; Mäkitie et al., 2018). Fourth, the analysis of complementarities (i.e., complementary innovations) is critical since transitions involve and depend upon them, for example, to create momentum (e.g., Geels, 2018; Meelen et al., 2021). The analytical focus on 'singular disruption' should be complemented with greater attention for multiple innovations and system reconfiguration (e.g., Geels, 2018). Fifth, the concept of structural tensions (such as the mismatches between an innovation and its wider sectoral system) or structural overlaps (i.e., facilitating flows of resources from sector to TIS, for example, for creating positive relationships) and the creation of development blocks of inter-related technologies can be introduced to understand innovation dynamics better (e.g., Haley, 2018; Andersen and Markard, 2020).

As a general concluding note, each reviewed paper re-iterated the need to consider multi-system aspects in future research, especially as the energy transition progresses and becomes increasingly complex. This point is particularly emphasised in relation to two facets. The first concerns innovation policy, which has the potential to affect a wide range of sociotechnical systems, potentially leading to far-reaching and unintended consequences. The second emphasises the necessity of accounting for multi-system interactions in macro-level transition pathways, beyond the mere influence of interactions within individual sociotechnical systems, such as niche-regime or incumbent-challenger dynamics. Reviewed papers make initial contributions towards conceptualising this added complexity in transition pathways (e.g., Geels, 2007; Papachristos et al., 2013; Rosenbloom, 2019).

5.2. Towards an integrative framework for multi-system analysis

The three key takeaways derived from this review can serve as a first step towards developing an integrative sociotechnical multi-system framework. Such a framework, which may take the form of an adapted MLP or TIS, or a synthesis of both (an MLP-TIS framework), represents a noteworthy gap in the existing literature. It has the potential to either be one comprehensive overarching framework or a collection of frameworks tailored to the specific objectives and emphasis of a multi-system study. While we advocate future studies to take the three key takeaways gleaned from this review into account, we recognise that their relevance depends on the specific focus of each study. In accordance with this perspective, researchers have the flexibility to adopt either a comprehensive approach that encompasses all three key aspects or a more specialised approach that combines and delves deeply into one or more of these aspects. Regardless, it is imperative for multi-system researchers to explicitly acknowledge the aspects they include within their scope and those they exclude, as this choice significantly influences their research outcomes.

As a first attempt, Fig. 13 presents a possible graphical depiction of a multi-system innovation framework, offering a clear and structured way to conduct sociotechnical multi-system analyses. The framework takes inspiration from the MLP to distinguish three distinct levels; The context level to account for the broader landscape-level influences that affect all sociotechnical systems and the associated innovations (depicted by vertical double arrows). The sociotechnical systems level, which entails a broader term to encompass sociotechnical regimes and sectors. And finally, the niche level, where the innovations reside and are protected. At the core of this framework is a hexagon symbolising the central multi-system innovation under study. This innovation resides at the intersection of two or more focal sociotechnical systems, emphasising their interconnectedness and mutual influences. There are inherent interactions between the niche- and sociotechnical system levels (depicted by vertical double arrows), while most of this interaction will take place through the multi-system innovation. Notably, the placement of this hexagon at the intersection of the system and niche levels does not represent an advanced developmental phase of the innovation, rather it indicates its central role in coupling the two systems. Future studies can zoom into the hexagon to distinguish distinct interaction (or coupling) types between the multi-system innovation and the sociotechnical systems.

To conduct a comprehensive multi-system analysis, the framework incorporates the key takeaways in the following ways. First, concerning system configuration, researchers can explicitly define and delineate the sociotechnical systems central to their study. This provides a clear focus on each system's role in the multi-system innovation, including their necessary interactions (depicted by the horizontal double arrow). Furthermore, within the niche level, complementary innovations impacting the central multi-system innovation can be depicted, which are sorted according to their respective systems, while acknowledging that some innovations may transcend multiple systems. Second, to consider distinct system phases, the entire system-specific boxes within the niche level can be placed at different heights, depending on each system's transition phase. Furthermore, a scale is integrated into the niche level of the framework to represent the developmental phase of innovations within the context of each system (denoted by the vertical dashed double arrow); denoting the furthest developed innovations at the top, near the system level and less-developed innovations at the bottom. Third, the framework takes into account the overarching directionality that can impact each focal system in similar ways, providing a broader context for understanding the multi-system innovation (denoted by the dashed box around the focal systems). This perspective helps researchers identify the conditions and influences shaping the multi-system innovation.

Fig 14 offers a practical illustration of the framework applied to the analysis of the multi-system Vehicle-to-Grid (V2G) innovation, which enables electric vehicles to not only be used for mobility but also to direct electricity back into the grid when needed. With regards to the system configuration, the framework indicates the two focal sociotechnical systems between which V2G anchors: electricity and transport. Furthermore, it depicts complementary and competing technologies, such as shared mobility services (pertaining to the transportation system) and distributed energy resources that are relevant to the electricity system. Regarding the overarching directionality, both systems align with the trend of electrification in response to the ongoing energy

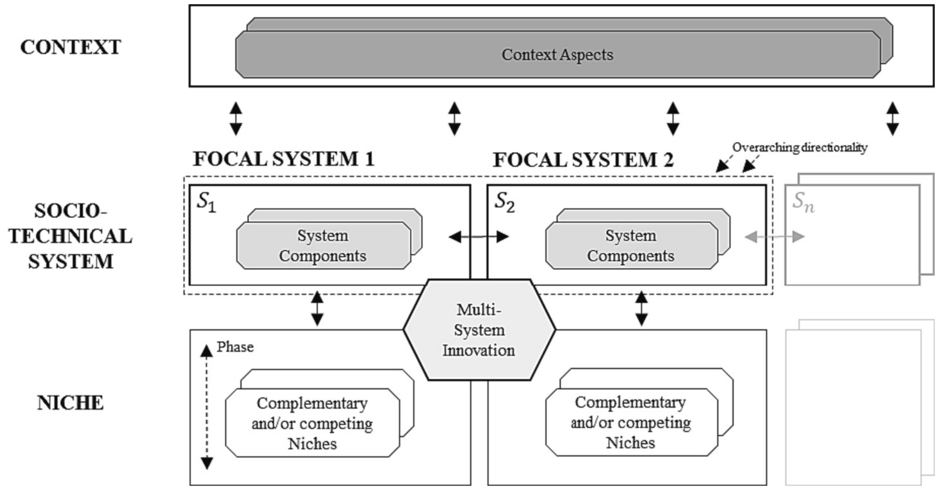

Fig. 13. Possible graphical representation of a multi-system innovation framework.

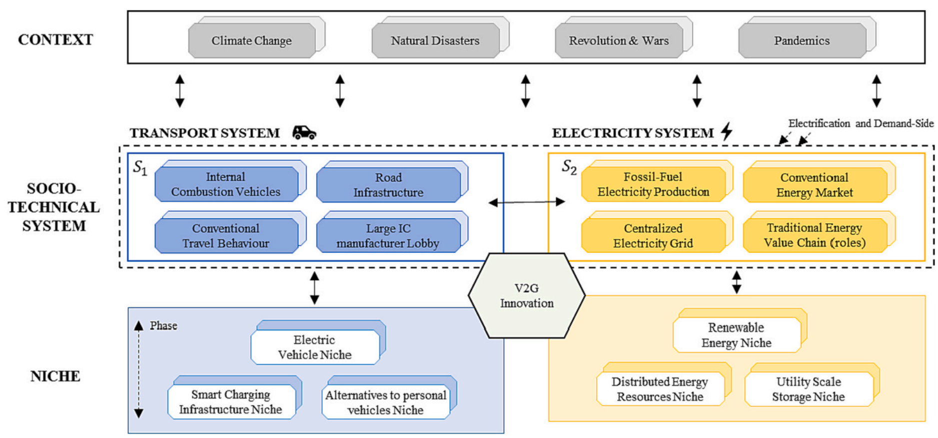

Fig. 14. Possible graphical representation of a multi-system innovation framework applied to the Vehicle-to-Grid (V2G) innovation.

transition, as well as a shift towards increased demand-side engagement. Regarding the phase of each transition, there exists a discrepancy in the advancement of these systems; in many Western countries, the low-carbon transition in the electricity system is further along than in the transport system. This is denoted by placing the system-specific box encompassing the electricity niches slightly higher than the box encompassing transport system niches. Furthermore, the niches within each box have been placed at different heights depending on their developmental phase.

5.3. Implications for future work

Within this subsection, we explore the implications for future work concerning both the further development of an integrative socio-technical multi-system framework and the broader field of multi-system research. Here, we address three aspects that stand out as important in this context.

The first aspect pertains to the analytical focus and underscores the importance of niche analysis in multi-system research. Transitions literature highlights the central significance of multi-system innovations within niches, that anchor in multiple systems (e.g., V2G), in socio-technical transitions; they can, for example, increase developmental stability and innovation resilience (Sutherland et al., 2015) or even accelerate transitions (Geels et al., 2017a). Given that multi-system innovations often lead to greater complexity and thus to new and difficult-to-estimate in-practice risks, niche protection becomes arguably more pivotal (Büscher et al., 2020; Ornetzeder and Sinozic, 2020). This review shows that, while the results are focused on multi-system interactions, the (internal) niche dynamics, such as actor expectations, network building and learning processes, and how multi-system innovations influence and are influenced by multiple systems is understudied. Therefore, we recommend more in-depth focus on innovation analysis and internal niche dynamics in future multi-system studies. This could be done by using an adapted multi-system framework mentioned in Section 5.2, potentially serving as a validation of this new multi-system framework.

The second aspect relates to the discussion on the scope of examination mentioned in Section 5.1. Along with the typical focus of transition studies, the reviewed multi-system papers mainly focus on identifying macro-trends or systemic effects. Next to a need to explore further how to reconcile and accommodate the study of innovation processes that cross different levels of analysis, we argue that there is a lack of focus on actor-level effects, such as inter-sectoral actor relationships and cross-sector learning. Within this actor-level focus, we highlight the importance of including demand-side characteristics since those are pivotal for the success of low-carbon transitions involving millions of citizens with unique characteristics (e.g., user practices, beliefs, culture, and skills). Incorporating insights from social sciences (such as sociology and psychology) and introducing new methods (such as discrete choice modelling) into transition studies can help shed light on societal attitudes and consumer behaviour. Notably, the introduction of multi-system innovations can make the demand-side perspective more complex since various users, stemming from different sectors, may have different perspectives and interests regarding a certain innovation (which can serve distinct purposes depending on the focal sector) (Bettin, 2020; Bergek, 2019). Therefore, we recommend that future multi-system transition research and the associated multi-system framework further integrate demand-side characteristics.

The third aspect relates to a need to explore multiple methods used in future multi-system research. Aligned with the broader field, the reviewed multi-system papers are dominated by qualitative case-based research methods, aiming for more generic insights and explanations (Geels, 2007, 2010; Köhler et al., 2019). Considering the complex nature of multi-system analysis, it can be useful to explore complementary methodological approaches. Two promising, under-utilised methodological approaches for such complex analysis include process-methodological methods and simulation models.[12] Firstly, ontologically process-methodological methods (Garud and Gehman, 2012) fit well since transitions research is understood as a process of change with complex chains of causation, multiple actors, and dynamic framework conditions (Geels and Schot, 2007). Among others, specific approaches such as Event Sequence Analysis (ESA) allow for comparing multiple cases using pattern matching, where patterns constitute distinct transition pathways (Spekkink, 2013; Spekkink and Boons, 2016; Boons et al., 2014). Secondly, simulation models can be used to reduce complexity and identify essential factors and processes through various degrees of abstraction. 'Transition modelling' has recently become a growing research area (Timmermans and de Haan, 2008; Halbe et al., 2015; Köhler et al., 2018; Holtz et al., 2015). Köhler et al. (2018) provide a guideline towards choosing an appropriate modelling approach based on an analysis of six model types[13] (Köhler et al., 2018). Notably, agent-based models (ABM) and system dynamics (SD) models or a combination of the two seem well-suited (Köhler et al., 2009, 2018; Walrave and Raven, 2016). In addition, proposals have been made to combine qualitative and quantitative approaches, in which models serve to check the internal consistency of narratives, which in turn inform models (Köhler et al., 2020; Turnheim et al., 2015; Trutnevyte et al., 2014; McDowall, 2014). Previously, there has been a lack of multi-system modelling research, which could be related to the associated complexity (Ramsebner et al., 2021). Thus, we recommend that future multi-system transition research implements these complementary methods, such as ESA and ABM, to capture the complexity of multi-system interactions.

The findings of this systematic literature review underscore the critical relevance of adopting a sociotechnical multi-system perspective in transition studies. The results not only shed light on the complexities of multi-system innovations but also offer invaluable insights on aspects to consider in future studies.

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CRediT authorship contribution statement

Jerico Bakhuis: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. **Linda Manon Kamp:** Conceptualization, Supervision, Validation, Writing – review & editing. **Natalia Barbour:** Supervision, Writing – review & editing. **Émile Jean Louis Chappin:** Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

Appendix A. Search strategy

Table A.1
Search terms.

Transitions Literature Terms	Multi-System Terms
Socio Technical Transition	Multi-System
Transition Theory	Multiple Sectors
Transition Management	Multiple Regimes
Transition Studies	Multi-Regimes
Sustainability Transition	Multi-Technology
Multi-level perspective	Multi-Purpose
Niche Development	Sector Coupling
Strategic Niche Management	Infrastructure
Innovation Theory	Converging Infrastructures
Innovation System	Convergence
Sectoral Innovation Systems	Vehicle to Grid
Regional Innovation System	Vehicle-to-X
Technical Innovation Systems	Car as a powerplant
System Dynamics	Sector
- Combination of MLP and Policy	- Inter-sector
- MLP and Quality	- Cross-sector
- MLP and Complexity	- Multi-Sector
	Coupled Transition
	- Food, Water, Energy Nexus

(*continued on next page*)

[12] See Köhler et al. (2019) for more details on state-of-the-art methodologies in Transition Studies.
[13] The six models include: Eco-innovation (energy-economy models and Integrated Assessment Models); Evolutionary economics; Complex systems; Agent-Based Models (ABM); System Dynamics (SD); Socio-ecological systems (SES).

Table A.1 (*continued*)

Transitions Literature Terms	Multi-System Terms
	- Food, water, Materials - Water-nexus - Agro-food

Appendix B. List of papers

Table B.1
Conceptual grounds of sociotechnical transitions.

Main part	Cluster	Authors	Title	Journal Rank (Quartile)[a]
Main concepts within the transitions literature	General Studies	Markard et al. (2012)	Sustainability transitions: An emerging field of research and its prospects	Q1
		Köhler et al. (2019)	An agenda for sustainability transitions research: State of the art and future directions	Q1
		Loorbach et al. (2017)	Sustainability transitions research: transforming science and practice for societal change	Q1
	Multi-level Perspective	Geels (2002)	Technological transitions as evolutionary reconfiguration processes: a Multi-level perspective and a case-study	Q1
		Geels and Schot (2007)	Typology of sociotechnical transition pathways	Q1
		Geels (2011)	The Multi-level perspective on sustainability transitions: Responses to seven criticisms	Q1
		Geels (2010)	Ontologies, socio-technical transitions (to sustainability), and the Multi-level perspective	Q1
		Smith et al. (2010)	Innovation studies and sustainability transitions: The allure of the Multi-level perspective and its challenges	Q1
		Raven (2007)	Niche accumulation and hybridisation strategies in transition processes towards a sustainable energy system: An assessment of differences and pitfalls	Q1
	Strategic Niche Management	Kemp et al. (1998)	Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management	Q2
		Schot and Geels (2008)	Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy	Q2
		Turnheim and Geels (2019)	Incumbent actors, guided search paths, and landmark projects in infra-system transitions: Re-thinking Strategic Niche Management with a case study of French tramway diffusion (1971–2016).	Q1
		Van Eijck and Romijn (2009)	Prospects for Jatropha biofuels in Tanzania: An analysis with Strategic Niche Management	Q2
		Susur et al. (2019)	The emergence of regional industrial ecosystem niches: A conceptual framework and a case study.	Q1
	Transition Management	Rotmans et al. (2001)	More evolution than revolution: transition management in public policy	Q2
	Innovation Systems	Jacobsson and Bergek (2011)	Innovation system analyses and sustainability transitions: Contributions and suggestions for research	Q1
		Malerba (2002)	Sectoral systems of innovation and production	Q1
		Bergek et al. (2008b)	Analyzing the functional dynamics of technological innovation systems: A scheme of analysis	Q1
		Suurs and Hekkert (2009)	Cumulative causation in the formation of a technological innovation system: The case of biofuels in the Netherlands	Q1
		Weber and Rohracher (2012)	Legitimizing research, technology and innovation policies for transformative change: Combining insights from innovation systems and Multi-level perspective in a comprehensive 'failures' framework.	Q1
		Pigford et al. (2018)	Beyond AIS? Exploring an agricultural innovation ecosystems approach for niche design and development	Q1
	Combined Frameworks	Geels (2004)	From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory	Q1
		Coenen and López (2010)	Comparing systems approaches to innovation and technological change for sustainable and competitive economies: an explorative study into conceptual …	Q1
Multi-system analysis in sociotechnical transitions	Theory on (Economic) Sectors	Pavitt (1984)	Sectoral patterns of technical change: towards a taxonomy and a theory	Q1
		Dosi (1988)	Sources, procedures, and microeconomic effects of innovation	Q1
		Carlsson and Stankiewicz (1991)	On the nature, function and composition of technological systems	Q1
		Castellacci (2008)	Innovation and the competitiveness of industries: Comparing the mainstream and the evolutionary approaches	Q1
	The concept of Sector Coupling	Robinius et al. (2017a).	Linking the power and transport sectors—Part 1: The principle of sector coupling	Q2
		Robinius et al. (2017b)	Linking the power and transport sectors—Part 2: Modelling a sector coupling scenario for Germany	Q2
		Thellufsen and Lund (2017).	Cross-border versus cross-sector interconnectivity in renewable energy systems	Q1
		Brown et al. (2018)	Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system	Q1

(continued on next page)

Table B.1 (*continued*)

Main part	Cluster	Authors	Title	Journal Rank (Quartile)[a]
		Arabzadeh et al. (2020)	Deep decarbonization of urban energy systems through renewable energy and sector-coupling flexibility strategies	Q1
		Fridgen et al. (2020)	A holistic view on sector coupling	Q1
		Ramsebner et al. (2021)	The sector coupling concept: A critical review	Q1
		Brear et al. (2020)	Sector coupling: supporting decarbonisation of the global energy system	Q2

[a] Q: Defines the rank/quartile of the Journal (Q1 is occupied by the top 25 % of journals in the list; Q2 is occupied by journals in the 25 to 50 % group); C1: Total Citation in Scopus (date: between April 15 and May 1, 2022); C2 is total citation on Google Scholar (date: between April 15 and May 1, 2022), References are according to APA-style.

Table B.2
Multi-system transition (case) studies.

Main theory	Cluster	Authors	Title	Journal Rank (Quartile)
Multi-level Perspective	Multi-Regime Interactions	Geels (2007)	Analysing the breakthrough of rock 'n'roll (1930–1970) Multi-regime interaction and reconfiguration in the Multi-level perspective	Q1
		Raven (2007)	Co-evolution of waste and electricity regimes: multi-regime dynamics in the Netherlands (1969–2003)	Q1
		Verbong and Geels (2007)	The ongoing energy transition: lessons from a socio-technical, Multi-level analysis of the Dutch electricity system (1960–2004)	Q1
		Raven and Verbong (2007)	Multi-regime interactions in the Dutch energy sector: the case of combined heat and power technologies in the Netherlands 1970–2000	Q2
		Konrad et al. (2008)	Multi-regime dynamics in the analysis of sectoral transformation potentials: evidence from German utility sectors	Q1
		Erlinghagen and Markard (2012)	Smart grids and the transformation of the electricity sector: ICT firms as potential catalysts for sectoral change	Q1
		Papachristos et al. (2013)	System interactions in socio-technical transitions: Extending the Multi-level perspective	Q1
		Sutherland et al. (2015)	Conceptualising multi-regime interactions: The role of the agriculture sector in renewable energy transitions	Q1
		Rosenbloom (2019)	A clash of socio-technical systems: Exploring actor interactions around electrification and electricity trade in unfolding low-carbon pathways for Ontario	Q1
	Coupled Value Chains	Meynard et al. (2017)	Designing coupled innovations for the sustainability transition of agrifood systems	Q1
		Geels (2018)	Disruption and low-carbon system transformation: Progress and new challenges in socio-technical transitions research and the Multi-level Perspective	Q1
		McMeekin et al. (2019)	Mapping the winds of whole system reconfiguration: Analysing low-carbon transformations across production, distribution and consumption in the UK electricity system (1990–2016)	Q1
	Transition Phases	Geels et al. (2017a)	Sociotechnical transitions for deep decarbonization	Q1
		Geels et al. (2017b)	The Sociotechnical Dynamics of Low-Carbon Transitions	Q1
		Kanger (2021)	Rethinking the Multi-level Perspective for energy transitions: From regime life-cycle to explanatory typology of transition pathways	Q1
	Connected Transitions	Mathews (2013)	The renewable energies technology surge: A new techno-economic paradigm in the making?	Q2
		Schot and Kanger (2018)	Deep transitions: Emergence, acceleration, stabilization and directionality	Q1
		Kanger and Schot (2019)	Deep transitions: Theorizing the long-term patterns of socio-technical change	Q1
		Van der Vleuten (2019)	Radical change and deep transitions: Lessons from Europe's infrastructure transition 1815–2015	Q1
Technological Innovation Systems	Sectoral Change	Dolata (2009)	Technological innovations and sectoral change: Transformative capacity, adaptability, patterns of change: An analytical framework	Q1
		Lamprinopoulou et al. (2014)	Application of an integrated systemic framework for analysing agricultural innovation systems and informing innovation policies: Comparing the Dutch and Scottish agrifood sectors	Q1
		Weber and Schaper-Rinkel (2017)	European sectoral innovation foresight: Identifying emerging cross-sectoral patterns and policy issues	Q1
		Fagerberg (2018)	Mobilizing innovation for sustainability transitions: A comment on transformative innovation policy	Q1
		Cronin et al. (2022)	Multi-actor Horizon 2020 projects in agriculture, forestry and related sectors: A Multi-level Innovation System framework (MINOS) for identifying Multi-level system failures	Q1
	Contextual Influence	Markard and Truffer (2008)	Technological innovation systems and the Multi-level perspective: Towards an integrated framework	Q1
		Wirth and Markard (2011)	Context matters: How existing sectors and competing technologies affect the Swiss Bio-SNG innovation system.	Q1
		Markard and Hoffman (2016)	Analysis of complementarities: Framework and examples from the energy transition	Q1
		Markard et al. (2016)	Institutional dynamics and technology legitimacy–A framework and a case study on biogas technology	Q1
		Markard (2018)	The next phase of the energy transition and its implications for research and policy	Q1

(continued on next page)

Table B.2 (*continued*)

Main theory	Cluster	Authors	Title	Journal Rank (Quartile)
		Markard (2020)	The life cycle of technological innovation systems	Q1
	Sectoral Configuration	Bergek et al. (2015)	Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics	Q1
		Stephan et al. (2017)	The sectoral configuration of technological innovation systems: Patterns of knowledge development and diffusion in the lithium-ion battery technology in Japan	Q1
		Mäkitie et al. (2018)	Established sectors expediting clean technology industries? The Norwegian oil and gas sector's influence on offshore wind power	Q1
		Malhotra et al. (2019)	The role of inter-sectoral learning in knowledge development and diffusion: Case studies on three clean energy technologies	Q1
		Decourt (2019)	Weaknesses and drivers for power-to-X diffusion in Europe. Insights from technological innovation system analysis	Q1
		Bettin (2020)	Electricity infrastructure and innovation in the next phase of energy transition—amendments to the technology innovation system framework	Q1
		Bento et al. (2021)	Inter-sectoral relations to accelerate the formation of technological innovation systems: Determinants of actors' entry into marine renewable energy technologies	Q1
	Structural Tensions	Haley (2018)	Integrating structural tensions into technological innovation systems analysis: Application to the case of transmission interconnections and renewable electricity in Nova Scotia, Canada	Q1
		Andersen et al. (2020)	The role of inter-sectoral dynamics in sustainability transitions: A comment on the transitions research agenda	Q1
		Andersen and Markard (2020)	Multi-technology interaction in socio-technical transitions: How recent dynamics in HVDC technology can inform transition theories	Q1

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