



Understanding inter-system interactions and their impacts

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Notes

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1 Introduction

Changes in technologies, processes, behaviour and relationships are an essential part of transitions of socio-technical systems. They are induced by 'impulses' within and outside the system. There is a large body of literature discussing interactions within socio-technical systems, between niches and regimes and possibly landscapes (e.g. Geels 2007) or between elements of a system oriented towards specific purposes (Borrás and Edler 2015). However, interactions occur not only within a certain system, but between systems and in different forms and intensities of exchange between the components of two or several systems. Some examples of system interactions are the food-water-energy nexus, smart energy as a field resulting from electricity and ICT, functional foods as a nexus between food and pharmaceuticals, or interlinkages between electricity, transport and heating (Hiteva and Watson 2019; Hoolohan et al. 2019, Papachristos et al. 2013, Rosenbloom 2019). The interactions between systems may have significant impacts on related transformations, e.g. by accelerating changing processes, but these interactions could also have hampering and conflicting effects. Hence, multiple relationships and dynamics have to be taken into account in transitions research. In this context, Rosenbloom states that 'interactions taking place between socio-technical systems merit further attention in sustainability transitions research' (Rosenbloom 2018, p. 229). We also think there is still a need to further explore where and how these interactions take place, what characteristics and features of interactions between socio-technical systems exists and what the implications for the systems and their transitions are. Thus, the objective of this paper is to elaborate a typology for analysing interactions between socio-technical systems and identifying their impacts on innovations and transition of systems.

We review how interactions between two or more socio-technical systems are discussed in the transition literature, set up a systematic framework to identify interactions between systems and try to understand how interactions impact socio-technical systems and their transitions. We use the energy transition, in particular, the interaction between the heating and electricity system as an example to illustrate the arguments.

2 Approach and literature review

The paper builds on the understanding of socio-technical systems given by Geels (2004), Kanger and Schot (2019) and Borrás and Edler (2015). The dynamics and changes in and to systems are studied from the perspective of sustainability transitions that can be defined as 'large-scale societal changes, deemed necessary to solve grand societal challenges' (Loorbach et al. 2017, p. 600). The shift in relations between actors, infrastructures, technologies is a main characteristic of the transformation of socio-technical systems (Kivimaa et al. 2019).

First, we review scientific papers with respect to interactions of at least two socio-technical systems, and second, we cluster existing findings on different understandings and features of interactions. On this basis, a framework is developed that aims to classify different types of inter-system interactions. Finally, we use some examples from the energy transition to illustrate the primary interfaces of socio-technical systems, the consecutive interfaces and relations as well as effects or consequences and critically discuss the applicability of the framework.

In the research area of sustainability transitions, Raven and Verbong (2007) were among the first authors that acknowledged that the multi-level perspective lacks understanding for interactions between socio-technical regimes. They define such a regime as 'a set of rules embedded in technological artefacts and social networks, which together fulfil a societal function.' Their understanding of regimes is close to Kanger and Schot (2019)'s, and Borass and Edler (2015)'s definition of socio-technical systems. Further authors, such as Hassink et al. (2018) look at care farming as an example of inter-system links of agricultural and care regimes, and consider these changes as radical innovations started in niches, because they fundamentally change structures of existing regimes. Another study (Rosenbloom 2019) considers the interaction between the electricity, transport and heating sector. The authors point out the role of actors as well as the symbiotic or competitive nature of interactions linked to different disruptive potentials. They consider interactions among energy systems as functional or jurisdictional and stress the importance of understanding interaction patterns for the pace of the energy transition. Hiteva and Watson 2019 analyse evolution of interdependencies between the electricity and information and ICT in the UK and discuss implications for governance approaches for the development of smart grids. Hoolohan et al. (2019) focus on the scenario methodology as a tool to get rich descriptions of a 'dynamic landscape of institutions and practices with which innovations in the water, energy and food nexus interact'. In a recent paper, Andersen and Markard (2020) discuss three types of multi-technology interactions: within a sector, along the value chain and between sectors. Rosenbloom (2020) points out the need to analyse dynamics of multi-system interactions.

Other authors refer to interactions between components of a system, or different levels, or take a look at dynamics of transitions. In context of the discussion on a multi-coalition perspective, Hess (2018) points out that diversity of coalitions facilitates the understanding of the changes in and interactions between coalitions. Coalitions are a group of actors characterised by goals, strategies, organisational compositions and frames. By contrast, Markard (2018) takes a dynamic and global perspective of the energy transition and considers the shift of interactions between single technologies to clusters of complementary technologies. Further, he sees overarching global forces synchronising energy transitions and interacting with local policies, institutions and infrastructures. Although Moallemi and Malekpour (2018) discuss interaction from a methodological perspective, they recognise that interactions take place between different systems, influenced by multi-level determinants such as infrastructures, resources or governmental interventions, and shape transition pathways. Hölscher et al. (2018) differentiate between interactions in societal subsystems such as social, technological and institutional interactions and social-ecological interactions at a large-

scaled change process. In the field of transition experiments, Sengers et al. (2019) see cities as sites where multiple socio-technical systems connect and provide space for potentially radical changes when tensions between systems create such opportunities of change.

In the realm of energy research and the implementation of energy transition, sector coupling has been identified as crucial to meet requirements for a sustainable, efficient and secure energy supply (Wietschel et al. 2018; Weiss et al. 2021). From a technical perspective, coupling between the different sectors, such as electricity and mobility or heat relies on the energy flows between these sectors, while from a policy or political science perspective, the interactions take place through policies affecting different sectors, for example between renewable energy support and the emission trading system or infrastructure regulations (del Río and Cerdá 2017, Huang et al. 2013).

3 Analysis and findings

Our literature research finds few papers that put interactions between two or more socio-technical systems at the centre of their analysis, e.g. Hassink et al. (2018), Rosenbloom (2019), Hoolahan et al. (2019). Other authors refer to interactions between systems in many different contexts, e.g. Hess (2018), Markard (2018), Moallemi and Malekpour (2018), Hölscher et al. (2018), Sengers et al. (2019), but they neither apply this term in a consistent way, nor do they put it in a coherent transition framework.

One of our findings is that authors approach inter-system interactions from different perspectives. We call these perspectives dimensions of interaction and they form our basis for characterising inter-system interactions. We have identified the following dimensions: interfaces, relationships, impacts, and intensity, which are outlined in the following sections.

3.1 Dimension: interfaces

To identify interfaces, we consider a socio-technical system as a system that encompasses production, diffusion and use of technologies to meet a certain function, and main components such as resources, material aspects (intermediate goods, materials, resources, infrastructure), actors and organisations, and institutions guiding perceptions and activities and knowledge (Geels 2004). We identify interfaces between two or more systems, when the systems share one of the named elements. In the following we present interfaces for main elements of socio-technical systems.

Actors

Wieczorek and Hekkert (2012) define actors as individuals, organisations or networks such as civil society, companies, knowledge institutions, parties, etc. that can fulfil different functions and roles, and interact through individual contacts or networks. Depending on their role(s), actors fulfil a broad variety of functions and may be active in different system, which may lead to synergies (using resources, knowledge's in other fields). However, decisions and strategies of these 'shared' actors are influenced not only by their membership in systems (Bergek et al. 2015), but also by many other internal and external factors. Actors may simultaneously belong to different categories (Fischer et al. 2016), among others to intermediaries that have a crucial role in transition processes (Wittmayer et al 2017). Actors connect sectors, e.g. agricultural and care sector when they are embedded in both (Hassink et al. 2018). Kivimaa et al. (2019) outline different notions applied in literature that also address the role of actors as intermediaries, and note that they are often identified through the functions they perform within a system. Canzler et al. (2017) look into the interactions between actors in different sectors and call them border crossers between established areas that are colliding in collaborative settings. Similarly, Hess (2018) elaborate a typology for coalitions where actors form a coalition characterised by goals, strategies, organisational compositions and frames, and integration across coalitions occurs through bridge brokers¹ and new frames. According to Schot and Kanger (2018, p 1052), interactions between systems occur through structural couplings "of shared infrastructures, actors and rules". We conclude that actors can perform these outlined function if the actors are part of both systems.

¹ Hess 2018, p 179: „bridge brokers are people or organisations that bring disparate groups together and adjust goal and frames in the process“

Infrastructure

Infrastructure is one of the four I's² – the interacting political domains of sustainable energy transition (Rosenbloom 2018). Rosenbloom (2019) refers to points of contacts of systems that involve actors, infrastructure and policy direction, however it remains unclear whether they are part of both systems or not. Innovation systems theory refers to three kinds of infrastructures: knowledge, financial, and physical (Wieczorek and Hekkert 2012). Knowledge infrastructures refer to places in which knowledge is transferred, including e.g. national university systems (Weber and Rohracher 2012), or places where knowledge is generated and shared, for example, in the case of functional food, where the food industry benefited from the R&D infrastructure of the pharmaceutical industry, and the pharmaceutical industry from the logistics of the food industry (Papachristos et al. 2013). Beyond these physical knowledge structures, Wieczorek and Hekkert (2012) include know-how, expertise and strategic information as well. Similarly, in their view, financial infrastructure encompasses subsidies and financial programmes. We focus on the physical aspect of infrastructure and include any material structures, including financial technical systems through which money is transferred from one place to another as well as locations where knowledge is generated or diffused. Further, physical infrastructures include buildings, roads, bridges, grids, pipelines, etc. Hiteva and Watson (2019a) refer to infrastructure interdependencies as the way how different elements within infrastructure systems influence each other. In our understanding, infrastructure qualifies as an interface if the interdependencies rely on using the same infrastructure in both systems.

Intermediates, materials and resources

Rosenbloom (2019) finds that literature outlines competitive or symbiotic forms of interactions that are interlinked for example through increasing demand for services, which are provided by one sector and demanded by another. He mentions the example of agricultural products as feedstock or intermediates for bio-methane in the energy system. Raven and Verbong (2007) refer to natural gas as the linking 'input' element between the gas and electricity sector, and to electricity as 'output' element of the heat sector linking to the electricity system. Hoolahan et al. (2019) look at the energy, water and food nexus' components such as water and electricity that couple the different sectors. Technology interaction is a key issue of sector coupling e.g. mobility and electricity (Andersen and Markard 2020) that are coupled through the intermediate good electricity. Similarly, the water sector is linked through its electricity input to the energy sector (Watson and Rai 2013). Summarising, all goods and services that are refined or produced or exploited in one system and used in another system represent interfaces that couple different sectors or systems.

Technology

While some technological knowledge is specific, general-purpose technologies (e.g. ICT) with many applications in different sectors are relevant for different socio-technical systems. Subsequently, learnings or spill-overs between systems may occur. Although Andersen and Markard (2020) explicitly focus on technology interactions, neither of their definitions identifies technology as part of both systems, but rather as input or throughput of a sector. In contrast, the increasing use of CHP (combined heat and power) technology in the industrial sector as well as its application in the heat supply sector (Raven and Verbong 2007) makes for example the CHP technology an interface that links these two sectors. We acknowledge the potential intermediate nature of a technology i.e. it could be seen as a part of the supply chain. However, we take it as a separate interface (not as part of the previous interface "intermediates, materials and resources" as a technology is applied to fulfil

² Interests, ideas, infrastructure, institutions

certain functions, and, thus, is key to the socio-technical system delineation. Furthermore, technology incorporates technical knowledge constituting a significant element of socio-technical systems (Markard et al. 2012).

Knowledge

Although Wieczorek and Hekkert (2012) consider knowledge as an infrastructure, we take it as a separate interface, subsuming in this term know-how, expertise and strategic information. Actors are knowledge carriers and their ties into their social and business environment give access to knowledge, contacts, support, etc. (Hassink et al. 2018). Subsequently, it might be difficult to separate knowledge interfaces from actor interfaces, but because knowledge is not bound to actors only, but is for example incorporated as technical knowledge in technologies, and because of its significant functions in innovation systems (Bergek et al. 2015) we include it as separate interface as well.

Institutions, culture and policies

Institutions are a set of rules that coordinate and structure activities (Geels 2004). Market structures and institutions such as agreements on responsibilities and control regarding supply of services link sectors that share the same structural characteristics and institutional agreements. For example, changes on market rules in the UK have entailed significant changes in the IT and energy sector (Hiteva and Watson 2019a), both are characterised as natural monopoly. In the case of the Netherlands, interactions occurred through institutional (re)designs, where the government used the gas regime as a model for the electricity sector (Raven and Verbong 2007). As part of user practices and habits and norms, rules are closely related to culture, and are distinguished into formal rules such as laws and directives and informal rules such as informal agreements, and societal models, and governance structures are organisational means to make rules effective (Bock und Polach et al. 2015). Subsequently, shared rules or institutions are important elements of two systems' configuration.

Transitions of socio-technical systems involve co-evolution processes in technologies, with changes in markets, user practices, regulations, infrastructure, culture, etc. (Geels 2006). In the context of energy transitions, Stephenson et al. (2021) interpret energy *culture* as a multi-scalar concept applicable to an ethnic group, workplace, generation, consumption, or nation including nationally specific normative, material, institutional and policy-related attributes, affected by the past and influencing the future. Energy cultures can be characterised, for example, by frugal practices, homogeneous material culture and norms based on traditional values of stewardship and conservation (Klaniecki et al. 2020). According to Skjølvold and Ryghaug (2019), a country's mobility culture is part of the 'overall' culture and self-image, e.g., as an energy nation. A region's culture can be part of two different socio-technical systems delineated by national borders.

Finally, policies comprise roadmaps, strategies and targets as well as governance and policy instruments. Because systems rely on rules that are of regulative, normative or cognitive nature (Geels 2004), *policies* are part of this rule set and shape a system's configuration and transition. Interactions through policies, for example, between the energy system and industrial sector occur through the climate policy instrument (ETS). The support of renewable energies affects prices of CO₂ (del Río and Cerdá 2017) and thus emissions of those actors that fall under the emission trading system.

Summarising our findings, we see that the dimension 'interface' relates to the components of a socio-technical regime that can be linked via functions, including also jurisdictional aspects of interactions (Rosenbloom 2019). The affiliation of systems' components to at least two different systems opens the room for interactions. Components that are part of at least two different systems

are considered to be 'interfaces'. Their key criteria are that they are part of both systems. Based on this literature review, we have identified the interfaces depicted in Table 1.

Table 1: Interfaces between systems

Interface	Description and elements of this interface	References
actors	<p>individuals: consumer, experts, workers, policy makers, etc.</p> <p>organisations consisting of individuals with different functions within the organisation: firms, associations, etc.</p> <p>a group of actors based on common characteristics or functions at the macro-level: politicians, industry, household, consumer, society</p>	(Canzler et al. 2017; Schot and Kanger 2018; Kivimaa et al. 2019; Wesche et al. 2019; Hess 2018; Wieczorek and Hekkert 2012)
infrastructure	<p>physical: pipelines, networks or grids, roads, logistics, etc.</p> <p>financial: financing infrastructure such as IT network, branches, etc.</p> <p>knowledge: education and research structures</p>	(Papachristos et al. 2013; Hiteva and Watson 2019b; Schot and Kanger 2018; Wieczorek and Hekkert 2012; Weber and Rohracher 2012; Rosenbloom 2019)
intermediate goods	<p>output of an industry and an input of another industry belonging to different systems:</p> <p>Goods and material</p> <p>Services and logistics</p>	(Pel 2014; Rosenbloom 2018; Schot and Kanger 2018; Andersen and Markard 2020)
natural resources	resources such as water, (scarce) minerals, fossil fuels, biomass, that is an input in at least two systems	(Hoolohan et al. 2019)
institutions	<p>rules</p> <p>culture</p> <p>policies</p>	(Skjølvold and Ryghaug 2019; Geels 2004; Papa-christos et al. 2013; Schot and Kanger 2018; Hiteva and Watson 2019a; Bock und Polach et al. 2015; Stephenson et al. 2021; Klaniecki et al. 2020; del Río and Cerdá 2017)
technology	technology or technical parts that are used in both systems, e.g. combined heat and power plant used to provide heat and electricity	(Skjølvold and Ryghaug 2019; Markard 2018; Markard et al. 2012; Raven and Verbong 2007; Andersen and Markard 2020)
knowledge	know-how, expertise, skills, knowledge, experience, information	(Wieczorek and Hekkert 2012)

3.2 Dimension: relationship

The dimension 'relationship' is based on the work of Raven and Verbong (2007), who call it the 'typology of interactions'. They extend existing works of Geels (2007) and Geels (2006) who describe

symbiotic and competitive and cooperative relationships between regimes. Findings from literature on interactions of niche and regime actors within one system also shows cooperative and competitive characteristics of interaction as well (Pant 2016).

Closely related to the term relationship is coupling (Konrad et al. 2008; Bergek et al. 2015; Schot and Kanger 2018). The authors distinguish between functional couplings versus structural couplings: Functional couplings refer to input-output relationships, such as supplier-buyer relationships or global value chains. Structural couplings refer to shared use of infrastructures, actors and rules. For example, telecommunication firms using electricity cables of utilities or both types of companies using the same R&D organization. However, structural couplings may also be spill-overs, such as the co-development of technology in different systems (Hiteva and Watson 2019a), or cooperative if waste management and energy system management actors begin to share a R&D facility (Schot and Kanger 2018). Apart from a one-sided (one system gets something from another system) or two-sided (both system inter-change) relationship, there could be neutral relationships, without any interactions, just coexisting interfaces of systems.

We follow Raven and Verbong (2007)'s terminology of relationships between regimes, which they understand as different non-exclusive types of interactions that could occur simultaneously or sequentially. However, we apply their typology to the relationship that two systems have with respect to their interface and not through the functions they are fulfilling or the way they are transforming. The reason for this is that systems could theoretically have two or more interfaces with different relationships, for example a competing relationship through one interface and spill-overs through another interface. The reference to the interface implies a different understanding of the relationships described by Raven and Verbong (2007). We outline the relationship as: (see also Table 2).

- Competitive: competition between systems refers in our case to the competing use of the interface, which is characterised either by scarcity of inputs, opposing interests of systems regarding a design of the interface (e.g. institutions, infrastructure), and both systems can impact each other.
- Cooperative or symbiotic: cooperation or symbiosis is understood as a relationship in which both systems rely on the same interface and its use is non-rival, mutually affecting both systems; and systems cooperate with respect to this interface. It is an intended exchange or co-operation to use, further explore or exploit or develop the interface, for example the use of CHP in the electricity and heat system. Symbiosis has its origin from biology and implies a beneficial relationship of systems with positive outcomes for each of the systems. Therefore, we prefer using the term co-operative because the outcome could be neutral, or even evolve to a negative outcome for one of the systems in the long-term.
- Functional or integrative: in contrast to Raven and Verbong (2007), who refer integration to the merging of two systems into one, we considered this relationship from a technical perspective as a functional one, where one system supplies inputs, e.g. goods, material, resources to another system. It is an input-relationship along the value chain, where one system depends on the other. The dependency is mainly one-sided, and the 'supplier' system is not (only) part of the system in focus but has functional relations to other systems as well. Thus, which up- or downstream industry is part of the system or not depends on the borders chosen to define a system.
- Spill-over: changes in the interface, for example technological innovations or changes in institutions applied in one system are applied to another system where the same in-situations or technologies are applied or actors are involved. An example is the shift from regulated to liberalised grid-bound markets.

Table 2 summarises our findings and definitions. We added neutrality of interfaces as a fifth relationship in case there is a co-existence without any impact through the interface on one of the

systems. As relationships are triggered by functions of systems and availability of elements, they are of dynamic nature and may change over time.

Table 2: Relationships between systems through their interface

Relationship	Direction	Description and characteristics	References
Competing or structural coupling	Two-way interaction	Systems relying on the same inputs, structures or institutions, characterised by scarcity, opposing interests or needs	(Geels 2007; Pant 2016; Schot and Kanger 2018; Raven and Verbong 2007)
Cooperative or symbiotic	Two-way interaction	systems mutually affecting each other through relying on the same non-rivalries interface, e.g. knowledge, inputs, infrastructures	(Schot and Kanger 2018; Geels 2007; Geels 2006; Pant 2016)
Functional coupling or integrative	One-way interaction	systems where the output of one system feeds into another system, i.e. one system depends on the other system's output or performance	(Schot and Kanger 2018; Konrad et al. 2008; Raven and Verbong 2007)
Spill-over	One-way interaction	System is affected by new insights or adjustments in another system transferred through the interface, e.g. technologies that unintendedly support or affect the other systems	(Schot and Kanger 2018; Hiteva and Watson 2019a; Raven and Verbong 2007)
neutral	No direction	co-existence of systems in which interfaces do not have impacts on the other system (no dependence, rivalry or scarcity, etc.)	

3.3 Dimension: impacts

From the multi-level perspective, a transition is an outcome of alignments between developments at multiple (i.e. three) levels (Geels and Schot 2007) as a result of interactions. It does not explicitly include nor exclude inter-system interactions. In the realm of energy policy, the energy transition to sustainability is understood as a shift in energy generation from fossil fuels to renewable energies (material artefacts in production) and a decline of energy consumption through technological innovations and behavioural changes. Subsequently, in terms of the MLP framework the energy transition entails changes in the landscape, regime and niche. Depending on how we set the borders of a socio-technical systems in the energy transition, we have different numbers of interacting systems such as the heating supply system interacting with e.g. electricity system or mobility system.

Looking into the literature, we find different notions of impacts resulting from interactions – on the system components or on the transition pathway of systems. These notions are not clearly delineated and a clear definition or taxonomy of impacts is lacking. In general, transition involves changes of a system's components or elements and entails the emergence of new structures, e.g. new business models or organisations, products, rules (Markard et al. 2012). Consequently, any impact on a system's component affects the transition of the system. The transition of a system is not only the

result of interactions between the niche, regime and/or landscape within one system (Geels and Schot 2007), but between systems (Papachristos et al. 2013).

In the following, we structure the impacts discussed in literature by the focus on

- i) what is impacted (the subject of impact) through inter-system interactions, and
- ii) how does the system or regime change (mechanism or pathways of transition)?

Subject of impacts of inter-system interactions

The interaction of two regimes is a source of change (Hiteva and Watson 2019a) that could be beneficial as in the case of the UK water and electricity sectors (Watson and Rai 2013). These two authors explore the interaction between the two systems from a governance perspective. According to them, the system becomes more integrated in terms of actors supplying water and energy at the same time and environmental regulations that were aligned to both systems. Further, the number of interacting actors and interfaces between both systems have increased. Hiteva and Watson (2019a) say that developments in technology or infrastructure in one system often involve the development of new interfaces between sectors and testing of new technologies and processes. Andersen and Markard (2020) agree that technological changes in one sector have repercussions on other sectors through interfaces along the value chain. For example, improved automation technology leads to mass production and price declines of goods and, hence, to increased competition. In the case of energy policy, negative impacts arising from unintended interactions of policies lead to price changes (del Río and Cerdá 2017), impeding the transformation of the sectors towards sustainability.

Kanger and Schot (2019) outline in their literature overview several inter-system interactions that pave the way to the emergence of new rules and rule-sets shared between systems (meta-rules, meta-regimes) or create new types of linkages between systems (e.g. food and mobility systems), and creates new or enforces existing patterns at the landscape level.

In his study on the interaction of two regimes – radio and recording systems – Geels (2007) identified a shift in the relationship between the radio and recording regime due to the interaction. Similarly, in his analysis of clashing socio-technical systems, Rosenbloom (2019) finds that emerging interactions affect the relationship between systems, as it leads to greater alignments or deeper tensions between systems. Pant (2016) finds that cooperative and competitive interactions lead to a paradox of incremental and transformational adaptations, respectively. With cooperation, niche practices continue and regimes incrementally adapt while under a competitive relation the regime may shift through transformational adaptations.

Impacts on the pathways or mechanisms of transition

Depending on the type and timing of interactions between regimes or systems, they might slow down or accelerate transitions (Papachristos 2019), and they also may shape the transition pathways (Moallemi and Malekpour 2018). An example for an inter-system transition pathway is the interaction between the health and farming sectors that has led to a new sector, care farming. The transition to care farming has not been the result of niche-regime relationships but of changes in landscapes and entrepreneurial and institutional behaviour (Hassink et al. 2018). Similar, the emergence of the functional food sector has been the result of an interplay between the pharmaceutical and food industry, while the interaction of the water and energy system (Watson and Rai 2013) led to the (partial) merging of systems. Thus, the interaction of two systems could lead to merging of systems, emergence of new systems or their disappearance, or coexistence with small adaptions within the system. Finally, interactions could lead towards a more sustainable system and society

or reverse the transition to a less sustainable system, e.g. interactions between fossil fuel based auto-mobility and the oil industry.

A different approach to regarding actions driving transitions or accelerate dynamics in transitions is outlined by Gorissen et al. (2018). It includes replication, partnering, upscaling, instrumentalisation and embedding.

Geels and Schot (2007) use the term pathways to describe how changes at the regime level take place under the MLP: i) under the *transformation* pathway the regime actors adapt to moderate changes at the landscape and to not yet fully developed innovations in the niche; ii) under large changes of landscapes the regime erodes while multiple non-dominating niche innovations emerge and a *de-alignment* takes place; iii) under large landscape pressure and well developed niche innovations, the regime will be replaced by the niche actors (*technical substitution*); iv) in case symbiotic niche innovations are adopted by the regime, a *reconfiguration* of the system takes place. Gorissen et al. (2018) depict different mechanisms how to accelerate dynamics in transition, among others they address pooling of resources or competences and aligning to new patterns, but without explicitly accounting for interactions.

Summing up, we suggest the following typology for impacts resulting from inter-system interaction (see also Table 3):

- **subject of impact:** we differentiate between two 'subject categories' that are impacted:
 - within systems: all components of a system can be affected by inter-system interactions e.g. actors, networks and relations within a system and at different levels, whereas transition is the outcome of these changes within a system
 - between systems: changes in relationship, interfaces, intensity of interactions between systems, and transition of one or both (or none) system(s) is the outcome of these changes
- **impacts on mechanism or pathways of transition:**
 - within systems: adaptions such as de-alignments, replacements, reconfiguration and transformation between regime and niche, according to Geels and Schot (2007)
 - between systems: moving closer or (partial) merging of systems, emerging of new system, disappearing of system(s) or coexisting of (un)changed systems
- **impact on direction** of change: transition towards or away from a sustainable society or way of life
- **impact on speed** of transformation: this includes a time component, at which we look in qualitative terms, and cluster it into stagnation, slow-down, or acceleration of the transition

Table 3: Impacts of inter-system interactions – typology

	Within systems	Between systems
<i>Subject of impact</i>	changes of components: actors, institutions, infrastructure, resources, intermediates, etc.	interfaces, relationships
<i>Mechanism or pathway of transition</i>	transformation, replacements, de-alignments, reconfiguration	(partial) merging, emerging, disappearing, coexisting
<i>Direction of transition</i>	contributing to or moving away from sustainability transition	
<i>Speed of transition</i>	stagnation, slow-down, acceleration	

3.4 Dimension: Dynamics of interaction

Interactions are dynamic and thus they are not only a structural element (Wieczorek and Hekkert 2012). This points to another dimension that has not yet been discussed in literature, the intensity of interactions resulting from the dynamics of the interactions. When speaking about dynamics we always refer to "something" evolving over time and, thus, implying an intensity. This "something" could be of abstract or intangible nature such as relationships, or of tangible, material nature such as technologies.

We illustrate this using the example of heat pumps. The heat pump is a device that takes ambient heat from one source e.g. from the air or soil and transports it into another location through electric and mechanical means. Heat pumps are mainly used in buildings for heating and cooling of space and supply of hot water. They are considered as part of a functional system providing space heat and hot water. In Europe, heat pumps have been in use in the 1950s, experienced a boom after the oil price crisis in 1973, but sales declined again in the 1980s (Sanner 2017). Due to the low number of installed heat pumps, the interaction with the electricity system was not an issue during this time, although an interface with an integrative/functional relationship existed. Due to changes in the market and regulatory landscape (i.e. European directives, market and prices of energy, climate change and emissions concerns) heat pumps became an alternative heating technology for buildings (Lauttamäki and Hyysalo 2019). With increasing ambitions to combat climate change and decarbonise the heating sector, the significance of heat pumps and sector coupling between the electricity and heat sector rose, and the number of applications grew in detached houses as well as in district heating networks. Heat pumps are recognised as a technology that provides heat and cold in buildings (and industry) and flexibility in the electricity sector as well (Bernath et al. 2019). The interfaces have widened and encompass now 'the intermediate good electricity' and 'technology' providing heat and flexibility in the electricity sector, on a functional and symbiotic basis, respectively. Further, the impact of this interaction materialises through potential changes in the niche and regime. These changes encompass the number and size of heat pump providers, and potentially new actors in the heat and also in the electricity market, due to the flexibility potential that heat pump offers to users. In the course of a potentially growing flexibility market, new market rules and regulations and further interactions with the 'digital' sector are likely to emerge.

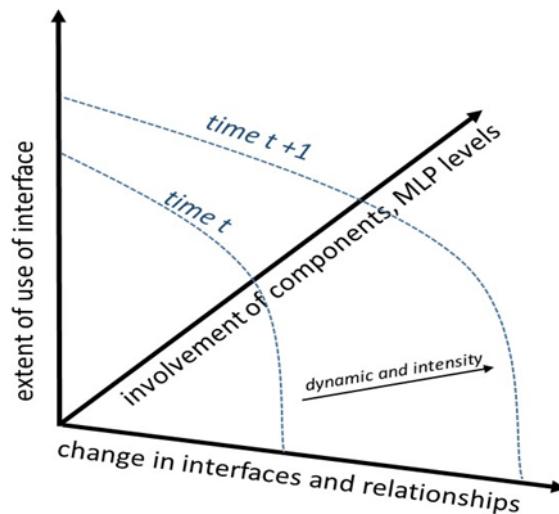
From this example, we consider the increase in frequency of use (number of heat pumps), expansion of interfaces (e.g. electricity, technology) and relationships (functional, symbiotic), and potential impacts on further components of the system (i.e. actors, institutions) as aspects embodying an increase in intensity and dynamics of the interaction. At this includes a time dimension, we suggest

taking into account the time period/space over which the development expands. In case the increase in interfaces or extent of use expands slowly over time, the changes only evolve in a slow mode, thus the dynamics and, hence, intensity is low.

Summarising this outline, we define intensity of an interaction along three axes and include a time component as well (see also Figure 1):

- **extent of use of the interface:** how often is an interface applied, what is the volume of application, the overlapping e.g. of rules, share of actors involved, etc. over time. In the case of heat pumps: capacity and volume of electricity needed for heat pumps
- induced **change in interfaces and relationships:** how many interfaces and relationships exist between systems (number) over time and how does this change due to interactions. In case of heat pumps: first interface: electricity needed to produce heat; second interface: technology providing flexibility for the electricity sector
- **involvement of system's components** in the change process: how many components or levels (MLP) of the system are or will possibly be affected over time. In the case of heat pumps: new technology providers, changes in actors participating in electricity (flexibility) market, adjustment of market rules.
- **dynamics:** are defined by the time period over which intensity of the three aspects above evolves and includes: accelerating effect on transition of one system, contribution to transition, emergence or disappearance of at least two systems.

Figure 1: Illustration of intensity and dynamics of an interaction



4 Example and discussion

Coming back to our work and research focus – the interaction between systems in the energy transition – we apply this framework using the example of the heating and electricity system.

In a first step, we outline components of the heating and electricity systems that could represent potential interfaces of inter-system interactions (based on Table 1). These are:

- actors: suppliers or generators of heat, suppliers or generators of electricity, heat consumers, electricity consumers, technology and service suppliers, network suppliers (including district heating (DH) networks), fuel suppliers, flexibility providers
- institutions: local DH markets, technology and service markets, fuel markets, local (virtual) power and electricity markets, and electricity markets with flexible loads and generation; European (and national) directives and regulations related to energy and emissions (e.g. EU ETS), national heating costs, various ordinances or acts such as energy efficiency and renewable energy directive; energy culture (sub-culture: heating culture encompassing habits and routines, based on attitudes, beliefs and norms)
- infrastructure: networks for heating (gas and district heat), electricity grid, digital communication networks
- technologies: fossil fuel based thermal power stations or boilers, waste heat incinerations, combined heat and electricity generation (CHP) using different fuels, geothermal heat and electricity generation, heat pump using ambient and/or (industrial) waste heat (HP), solar thermal heat (and electricity) generation with storage
- natural (key) resources: fossil resources, biomass resources, geothermal heat, ambient (and excess) heat, solar thermal resources, water, atmosphere

In a second step, we assign a relationship to each interface. We use Table 2 for this and, as a result, we obtain a matrix with the dimensions interface and relationship. We look at two cases:

- i) interaction between heating and electricity without flexibility options (green shaded cells in Table 4) and,
- ii) interaction between both systems with flexibility options of heating technologies (green and yellow shaded cells in Table 4).

Table 4: Heating system, its interfaces and relationships with the electricity system

		Relationships				
Interfaces		Competing: bi-directional	Cooperative: bi-directional	Functional: one-directional	Spill-over: unin-tended, bi- or one-directional	Neutral: no direc-tion
	Actors	Heat consumer HP = flexibility provider DHC = flexibility provider				Heat consumer = electricity consumer
	Institutions		Flexibility markets Flexibility regulations'		ETS: heat (large fuel suppliers, CHP), electricity, industry	
					Energy culture	
	Energy-related directives, ordinances, acts					
	Infrastructure		Digital grid: flexibility service			
	Technology	CHP (i.e. focus on heat or electricity), (GT, ST&storage)	HP, CHP, GT, SG: flexibility service			
	Knowledge					
Natural resources	B: electricity, food, feedstock, nature F: electricity, feedstock, W: water supply, food, nature AT: all CO ₂ emitting systems					ST, GT, AM: heat and electricity
Intermediate goods and services	Electricity: (if electricity is scarce) any other system using electricity as input			Electricity: for GT, HP (heating and electricity system)		

Note: *cursive letters* refer to other systems than electricity or heating; GT: geothermal plant, CHP: combined heat and power; HP: heat Pump; SG: solar energy generation and storage; F: fossil fuels; W: water; AT: atmosphere; GT: geothermal; ST: solar thermal; AM: ambient&waste heat; yellow shades: primary interface; green shades: second interface.

As illustrated in Table 4, the primary interface (all green shaded cells) between the heating and electricity system has been electricity as intermediate good when using HP technology (electricity as input), or CHP as technology generating heat and electricity at the same time. A further interface is the ETS (policy) that applies to both systems and has spill-overs through CO₂ prices. Biomass and the atmosphere as well as to a certain degree fossil fuels and water represent interfaces in terms of natural resources. Directive and regulations related to the energy system address issues in heating and electricity, but we have not yet analysed the specific links to both systems. The same applies to the energy culture. Both are realms that could be further researched. This is why the cells are shaded grey.

Because of the growing use of variable renewable energies in the electricity sector and the associated need for flexible electricity demand, the heating technologies with a link to the electricity

sector got acknowledged as a potential 'flexibility provider' in the electricity sector. Subsequently, the technology (HP and potentially GT and ST in combination with storage facilities), itself becomes an interface – as flexibility and heat supplying technology in the electricity and heating system, respectively. This entails a further change in the role of operators and/or owners of heating technologies providing flexibility, as they are not only heat generators or consumers but also service providers in a new market – the electricity market with flexibility offers. This second interface is visualised in Table 4 by the yellow shaded cells.

Third, the operationalisation of the new service entails further changes between and within systems and on transition pathways as already mentioned above:

- within the system: DHC suppliers or individual HP users as new flexibility providers in the electricity sector, and new or adjusted institutions such as flexibility markets, and new regulations addressing requirements to operationalise the participation of new actors and new flexibility solutions in the electricity market;
- between systems: new interfaces (technology, e.g. HP, and actors e.g. flexibility providers) and relationships (functional and cooperative, eventually even competing); potentially involvement of a third sector – digital sector – providing digital tools enabling market participation;
- impact on the transition of one system: new actors and rules, probably affecting the market structure in the electricity and heat market (e.g. demand shift in heat generating technology from fossil energy to heat pump technology);
- impact on the transition of both systems: co-existing systems while both systems are slightly adjusted or even merging of systems

The direction of change induced by the interaction is towards a sustainable heating and electricity system.

Finally, we look at the intensity. The intensity and dynamic of interaction differs between the different heating technologies. While it is increasing during the last years due to the growing usage of the interfaces and changes between systems for HP, it remains low and slow for SG, GG and (partly) biomass-based CHP as there is hardly an increase in generated electricity volume and number of CHPs or ST and GT, e.g. in Germany. Thus, from a system perspective, the extent of induced changes at the systems and in transition as well as its dynamic is so far limited to HP.

Moreover, Table 4 reveals interfaces with neutral relationships (not shaded cells). This relationship might change, for example, if technological innovations occur, or resources or intermediates become scarce. Based on this outline, we understand an existing interface and neutral relationship and low intensity and dynamic of change not as an interaction.

This conceptual framework proposes potential interfaces and the type of relationships, and helps to identify actual and potential interactions through the identification of interfaces and relationships. It indicates which dimensions between systems could be supported by policies or need further research, such that interactions contribute to a transition towards sustainability.

Second, the characterisation of interactions based on the dimensions may allow the analysis of the interfaces or relationships that have impacts on the transition with respect to direction and speed and changes within and between systems. This new understanding might be applied in the drafting of specific policy measures.

Finally, it could support the identification of requirements with respect to technological development and institutional or regulatory frameworks to further exploit this interaction to support a sustainable transition.

5 Conclusions

The objective of this paper is to elaborate a typology for analysing interactions between socio-technical systems and for identifying their impacts on innovations and transition of systems.

We review how interactions between two or more socio-technical systems are discussed in the transition literature, set up a systematic framework to identify interactions between systems and try to understand how interactions impact socio-technical systems and their transitions. We identify four dimensions of inter-system interactions, interface, relationship, impacts, and intensity & dynamics, which we use to describe and define inter-systems interactions.

We define an interface as an element of a system that is shared by both interacting systems. Interfaces could comprise actors, institutions, infrastructure, intermediate goods and resources, technology and knowledge. Relationships are defined as the way systems interact through the interface, i.e. competing, cooperative, functional, spill-over, and neutral. Impacts outline the effects of the interaction on the system's components, interfaces or relations, and on its transition pathway comprising different degrees of adjustment of one system (transformation, replacement, de-alignment, reconfiguration) and different ways of transformation of at least two systems (disappearing, co-existing, merging, emerging), and direction and speed of change. The dimension intensity refers to the intensity of interactions that comprises several indicators, e.g. extent of use of interfaces, induced change in interfaces and relationships, involvement of system's components and the time perspective.

The dimensions of inter-system interactions are themselves interconnected. We find that the possible 'relationships' can each occur for a variety of 'interfaces' between systems. We show, the possible combinations in a matrix. The application of the new framework on our example of interacting systems (heating and electricity systems) suggests that the interactions between two systems usually span a variety of combinations. However, the focus and number of interactions depend on technological developments, increasing scarcities and political drivers. For the heat and electricity systems the interaction occurs mainly through the interface technology (i.e. heat pumps and combined heat and power systems) that is significant as it provides flexible solutions that are increasingly needed in the course of growing use of renewable energy. Thus, changes within the electricity system (technology regime) and technological (digital) developments supported by changes at societal and political levels (landscape) have driven these new interactions, promoting sector coupling and leading to a further change of the electricity and the heating system.

We suggest that this framework can be applied to bring an improved understanding to the design of policies for transition. It can identify existing or potential interfaces between systems, outline potential relationships, and assess potential areas of impacts in a systematic way. Policy makers can compare the targets to the expected intensity and impacts on transition, and design policies accordingly.

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