Dimensions of systems and transformations: Towards an integrated framework for system transformations

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1 Introduction

The forward looking analysis of pathways of transformation of sociotechnical systems to sustainability has become a key concern of innovation studies (Geels 2002; Grin, Rotmans, and Schot 2010; Köhler et al. 2019; Rogge, Pfluger, and Geels 2020). This is driven by broad concerns about the major challenges we face as societies and the need for thorough and fast change of systems - as opposed to diffusion of individual innovations to fix small-scale problems. The normative claim is that through intelligent, coordinated activity, mankind can cope with existing challenges. To do so, however, it takes an ambition to voluntarily shape and alter the direction of change of socio-technical systems that provide energy, transportation, health and so on.

Against this background, the role of the state and public policy has come under new scrutiny, with some arguing that so-called mission-oriented policies can correct market failures in those markets that shape socio-technical systems (Mazzucato 2018). Others arguing that the role of the state is more modest and depends on specific system constellations which change over time and differ between different regional contexts (Borrás and Edler 2020; Kuhlmann and Rip 2018). Indeed, there is now a plethora of scholarly studies on the new, ambitious role of the state to shape systems transitions (e.g. Fagerberg 2018; Grillitsch et al. 2019; Diercks, Larsen, and Steward 2019; Kern and Rogge 2018; Frenken 2017; Matthes 2017).

These studies have different roots. As early as 2012, Steward has recognised and analysed a shift in international climate policy towards a narrative of systems change and the importance of socio-technical actor networks to radically shift their practices (Steward 2012). Based on this recognition, he claimed that there is a need for "transformative innovation policy". He noted that the incrementalism of policy driven changes, with its traditional instrumentation and analysis, is not sufficient to accelerate system transition - as a result of behavioural and technological change - in the desired directions. At the same time, a highly influential conceptualisation of innovation policy has claimed that the rationale for policy intervention needs to go beyond the traditional rationales of market and structural systems failure and include a number of "transformational" failures (Weber and Rohracher 2012), i.e. directionality, demand articulation, policy coordination and reflexivity failures. Finally, a challenge driven justification for innovation policy intervention has been emerging, in particular at EU level, since the mid-2000s (Aho et al. 2006). This culminated in the explicit claim to devise mission oriented innovation policies that, in truth, are nothing but a claim to shift socio-technical systems in desired directions through the generation and diffusion of innovative solutions and appropriate change of actor practices (Geels et al. 2019). Since then, we see a broadening of the claims as to the ability of analysts and state actors to comprehend the need for systems change, to imagine desired pathways or future scenarios and to design and implement policy interventions and their mix to contribute to desired systems transitions (Wanzenböck et al. 2019; Rogge, Pfluger, and Geels 2020).

Some very recent literature has highlighted the fundamental difference between supporting the generation and diffusion of innovation on the one hand - the traditional role of innovation policy - and the shaping of directionality of entire socio-technical systems (Schot and Steinmueller 2018; Borrás and Edler 2020; Kuhlmann and Rip 2018; Frenken 2017; Wanzenböck et al. 2019). The fluid, highly complex, highly idiosyncratic character of socio-technical systems renders the identification of "failures" or policy levers itself into a real challenge. All studies analysing - ex post - systems change and the role of the state recognise the need to identify, in great detail, the components of systems and their interplay. This need to understand socio-technical systems is even more pertinent when it comes to envisage future scenarios of systems change and what it is policy could do to help systems to transform in the societally desired direction. Especially because the dynamic change of systems is non-linear (Grin, Rotmans, and Schot 2010) and extremely hard to model for policy intervention purposes, we need a conceptual framework that reduces the complexity of systems and systems change down to those key dimensions that have shown to be of major influence for systems change.

The transitions literature has begun to develop a structure for the analysis of transitions processes. Geels and Schot (2007) and Geels et al. (2016) have used the structure of the MLP to develop a typology of transitions 'pathways'. The pathways are derived from various combinations and timings of landscape pressures, niche development, regime responses and the interactions between the levels. However, the application of this typology remains relatively ad-hoc and descriptive. Turnheim et al. (2015) propose a 'bridging' approach to combine qualitative and quantitative methods for the development of transitions scenarios, applied in Köhler, Turnheim, and Hodson (2020).

However, there are few/no studies/meta-analyses comparing the properties of different socio-technical systems generally recognised methods for systematically assessing and comparing future transitions pathways. Köhler et al. (2019) identify a need to more systematically develop explanations of transitions processes.

With this article, we seek to support the future oriented thinking and influencing of systems change by providing a systematic concept to characterise the nature of socio-technical systems as well as the nature of system transitions. We provide and discuss a limited selection of dimensions and criteria for this characterisation of systems and transitions. This is intended to tackle the idiosyncratic nature of any socio-technical system.

The objective of this paper is thus twofold: it first develops a systematic characterisation of socio-technical systems, which enables, second, a systematic characterisation of pathways of transformation to sustainability that capture generalisable features of such pathways. This should provide a foundation for comparing different examples of transformation processes and possibly developing a typology of these processes. It shall also support policymaking and policy design as it allows forward looking analysis.

This article is structured as follows. Section 2 provides an overview of the structure of the dimensions. The dimensions are explained in detail in Section 3. Section 4 suggests how to use the structure to analyse system transformations and develop insights for governance measures and policy insights. Section 5 concludes the article with future research directions.

2 Deriving System Dimensions and Transformation Dimensions

The structure of dimensions is shown in Table 1. We differentiate between dimensions that describe the elements of the socio-technical system under consideration and the aspects of change that (may) result in a system transformation. In this section, we structure the dimensions and explain the logic of how the set of dimensions was chosen. To develop this structure, it is useful to think in terms of categories of dimensions. For the system, these are the *function* of the socio-technical system, its *characteristics,* the *context* in which the socio-technical system functions and its specific *agency*. These can be described at different points in time to show the state of the system.

In order to undertake an empirical analysis it is necessary to delineate the object to be studied. In the case of system transformations, the object of study is defined to be a socio-technical system - a co-evolving set of social subsystems. Following Freeman and Louçã (2001), these are science, technology, economy, politics, and culture. Debates about the need for the transformation of a socio-technical system have started from the assessment that there are ‘wicked’ problems (Grin, Rotmans, and Schot 2010) associated with the activities of a particular socio-technical system, especially with the sustainability of the system and its impacts. These can be framed in terms of services to society or in the language of Fine and Leopold (1993) ‘systems of provision’. Therefore, the system should be delineated through its *function*: energy, food, mobility, health etc.

The *characteristics* that describe the system include the features of the technology and the practices and cultural expectations involved in the technology, the economic sectors involved and the geographical scope of production and consumption. Interactions with other socio-technical systems need to be considered (Papachristos, Sofianos, and Adamides 2013). The *context* is defined as including infrastructures supporting the system. These can be the physical infrastructure of the technology, but also knowledge and financial infrastructures as emphasised in the TIS (Hekkert et al. 2007; Bergek et al. 2008). Regulation and other institutional structures have been identified as being a critical aspect in maintaining the stability of regimes (Köhler et al. 2019). Recent research is also placing a new emphasis on ethical issues in transitions (Köhler et al. 2019, section 9). Social and cultural factors are also a fundamental element, determining the expectations of users reproducing the practices and attitudes towards the socio-technical system. A final meta-category is *agency*. On the one hand, the TIS literature has emphasised the identification of actors and their roles in socio-technical systems. On the other, a vital contribution to the analysis of transformations is the decisive influence of power relations and power structures (Köhler et al. 2019, section 3).

The categories of factors influencing the dynamics of socio-technical systems can be summarised as the *drivers and barriers*, *politics* (and governance), together with the description of the *dynamics* of the system.

An important aspect of *drivers and barriers* is the directionality of change which describes whether change arises from scientific and technological discoveries and developments opening up new economic and functional opportunities (Freeman and Soete 1997) or whether society identifies a required direction of change (such as sustainability e.g. reduced greenhouse gas emissions). A further differentiation is whether change is producer/supply side driven or user requirement/demand side driven. Barriers to change are also a fundamental part of the narrative of ‘wicked’ problems, where society has difficulty in making changes that effectively address the problem (Grin, Rotmans, and Schot 2010). Beside the fundamental drivers and barriers described by directionality and demand, also specific hampering or promoting factors can play a decisive role in the development of a socio-technical system. This can be e.g. related to agency as incumbents can inhibit change or to context factors as infrastructure is missing,

We also wish to emphasise the role of *politics* in influencing change processes. Grin, Rotmans, and Schot (2010) and Köhler et al. (2019) both consider governance issues and power and politics as major fields of research. The transitions management approach has tried to develop practical governance and policy strategies for sustainability transitions (Grin, Rotmans, and Schot 2010).

The need for comparative analysis of these factors is identified in Köhler et al. (2019) as an area for further research. As part of this, the level of contestation should be taken into account. Important considerations in policy analysis of transformation of socio-technical systems are the degree of national autonomy and the degree of governability of transformation processes. Whereas the degree of coordination required between different actors depends particularly on complexity in the agency structure. The governability of socio-technical systems in terms of the ability of policy processes to generate and/or influence change is called into question by the emergent nature of transitions in the co-evolutionary structure of socio-technical systems (Loorbach 2010).

Different patterns in the *dynamics* of transformation processes can be observed (Geels and Schot 2007; Geels et al. 2016). The ‘maturity’ and ‘phase of development’ of socio-technical systems have been used in the Neo-Schumpeterian literature on Kondratiev or Long Waves as well as in the MLP to describe the development over time (Freeman and Louçã 2001; Perez 2003; Köhler 2012). The idea of learning or experience curves in the innovation literature has been expanded to a broader set of questions of sources and processes of social learning.

Table 1: System and transformation dimensions for analysing sustainability transitions

SYSTEM DIMENSIONS		**TRANSFORMATION DIMENSIONS**	
Meta-category	**Dimension**	**Meta-category**	**Dimension**
General	Function	*Drivers and barriers*	Drivers
Characteristics	Relevant sectors		Barriers
	Interactions with other systems		Directionality
	Characteristics of relevant technologies and practices		Demand
	Geographical scope	*Politics*	Contestation
Context factors	Infrastructures: Physical, knowledge, financial		Degree of national autonomy
	Regulation and its importance		Degree of governability
	Socio-cultural factors		Degree of coordination
Agency	Actor constellations and their capacities	*Dynamics*	Development over time
	Power structures		Learning processes

The interplay of meta-characteristics and dimensions is sufficient to identify and distinguish change processes. In the next section, we go to the literature to describe the individual dimensions in greater detail. This is necessary to draw the broader conceptual conclusions that close the paper.

3 Explaining the dimensions: of systems and of transformations

This section first describes the dimensions of systems, followed by the dimensions of transformations.

3.1 System dimensions

Function

The function of a system relates to the services it provides to society. Examples of functions are e.g. clean water, food, heat, or public mobility. Many of these functions are characterised by unsustainable production and consumption patterns that exacerbate environmental problems such as resource depletion, loss of biodiversity, and climate change (Köhler et al. 2019). Socio-technical transitions research recognises that addressing these grand societal challenges and changing such unsustainable patterns necessitates radical changes in the way these functions are fulfilled.

Relevant sectors

While the MLP conceptualization transition refers to a ‘fundamental’ socio-technical reconfiguration in a focal sector, this single-sector focus has been more and more challenged (Andersen and Markard 2020; Andersen et al. 2020). The respective relevant systems are often characterized by intensive linkages between upstream and downstream sectors or functions are fulfilled in different (sub-)sectors (e.g. wind, solar, bio for energy). Hence, a distinction between single and multiple sector systems, as well as the heterogeneity of sectors in the latter case is important, as certain interdependencies and dynamics may arise in multiple sector systems. E.g. knowledge bases, actors, regulations, demands as well as resources may highly differ between sectors (Malerba 2002). Therefore, first innovation and evolution patterns differ between sectors and related systems. Second, multiple systems may be characterized by high complexity and certain variety of framework conditions that have to be taken into account for certain analysis.

Characteristics of relevant technologies and practices

The characteristics of a technology inform how the technology is put into practice by users, as well as its geographical spread (Köhler et al. 2019). Central questions include what the actual innovation is: is it generally useful or locally specific? The relevant characteristics also inform up- and down-river innovations, e.g. in the creation of input and output value chains.

Geographical scope

The geography of transitions literature explores why and how transitions in different areas are similar or different (Köhler et al. 2019). Transitions are place-specific: different spatial scales, differing natural resource and industrial endowments, and place-specific norms and values shape transitions differently (Binz, Truffer, and Coenen 2014; Hansen and Coenen 2015). Space may be seen as a physical territory or as a set of relations between actors (Raven, Schott, and Berkhout 2012; Bernhard Truffer and Coenen 2012; Calvert et al. 2017). As such, space may be both a product (in terms of socio-cultural elements) and a process (in terms of socio-economic elements) (Levin-Keitel et al. 2018). While initially, much research focused on urban and regional transitions, investigations into national and international aspects of space and scale have increased (Hansen and Coenen 2015). Regimes or innovation systems may be global in manner, cutting across national regimes and innovation systems (Binz and Truffer 2017). In these global regimes, socio-technical transitions follow similar trajectories in different parts of the world, even though resources and contexts vary greatly (Fuenfschilling and Binz 2018). Transnational actors may impact transitions differently in different countries (Gosens, Lu, and Coenen 2015; Wieczorek, Raven, and Berkhout 2015). An underexplored question is how this impact differs or is similar in industrialized and non-industrialized countries.

Infrastructures

Infrastructures provide framework conditions for systemic change - they represent sunk costs on the part of the regime, and as such may be barriers ('lock-in') or supports to sustainability transitions (Geels 2004). Socio-technical systems theory refers to three kinds of infrastructures: knowledge, financial, and physical. Coming from innovation systems thinking, knowledge infrastructures refer to places in which knowledge is transferred, including e.g. national university systems (Weber and Rohracher 2012). Generating knowledge on systemic processes may require a reorientation of research priorities along with other, more far-reaching changes in knowledge systems (Geels et al. 2019, 144). Financial infrastructures include the technical systems through which money flows from one place to another. Physical infrastructures include buildings, roads, bridges, factories, etc.

Importance of rules and regulation

Relevant rules and routines determine the requirement for socio-technical systems to operate in markets and in society. They may consist of laws, regulations (e.g. competition regulation, environmental regulations etc.) and technology standards (formal rules). But they also involve cognitive rules, such as problem-solving routines and dominant visions and expectations or normative rules, such as social and organisational networks are stabilised by mutual role perceptions and expectations of proper behaviour (Geels 2004). Hence, rules and regulations frame the conditions under which transitions may take place. An increasingly reflected questions is socio-technical analysis is how rules and institutional processes shape the regime of a system (Fuenfschilling and Truffer 2014). But rules could play also central role in shaping the directionality of transitions in a system, e.g. through environmental regulations, standards, quotas, etc. and/or subject to renewal during transition processes (Köhler et al. 2019). While rules and regulation are of importance in every socio-technical, the type of regulation and the operation of freedom for actors may significantly differ between systems.

Interactions with other systems

Transformations of socio-technical systems take place in a wider context. They do not stop at the boundaries of the system, but interactions between different systems arise and in with different forms and intensities of exchange between the components of two or several systems (Bergek, Jacobsson, and Sandén 2008; Rosenbloom 2020). Relevant examples of system interactions are the food-water-energy nexus or smart energy (Hiteva and Watson 2019; Hoolohan et al. 2019). Hence, there is a need to take those interactions into account to understand important changes or developments that (will) take place in a system that are partly beyond the influence of exiting regimes and niches.

The interactions can take place between different level (niches, regimes) of a socio-technical system and between different components of socio-technical systems, e.g. technologies, infrastructures, resources, policies, actors (Rosenbloom 2019). There is either a two-way effect, with several systems influencing each other, or a direct one-way effect that one system depends on others. There have been various mostly independent approaches to describe and classify system interaction and different typologies of type of interactions developed (Raven and Verbong 2007; Konrad, Truffer, and Voß 2008; Papachristos, Sofianos, and Adamides 2013). Most applied is the approach of Raven and Verbong (2007), who point out potential synergies or conflicts with other social-technical system. They propose a typology of four types of interaction and differentiate between competition, symbiosis, integration, and spill over.

Socio-cultural factors

Major changes in culture and behaviour are required for sustainability transitions. Socio-technical transitions theory recognizes that innovations and new knowledge also come from social sources. Yet, socio-cultural factors are not yet well-addressed or well-theorized in socio-technical systems thought, although it is recognized that place-specific norms and values have important influences on sustainability transitions (Hansen and Coenen 2015, 98). Societies' articulations of their sociotechnical imaginaries - how they visualize their future - are important factors informing how transitions unfold (Pfotenhauer and Jasanoff 2017). Issues such as low levels of public trust and a lack of public climate awareness have been identified as constraints to climate policy progress (Lamb and Minx 2020).

Edsand (2019) offers an orientation by including socio-cultural factors as 'landscape factors'. Given the nature of sustainability transitions, he includes as separate factors: a population's environmental awareness; its (un)equal access to education (leading into the capacities discussion); and national corruption. These landscape factors are particularly important in transitions because of their impact on TIS functions - e.g. national corruption may affect the TIS functions entrepreneurial activities and resource mobilization - and on other landscape factors. Oreg and Sverdlik (2018) propose to measure countries' cultural predisposition towards change (how societies feel about change) using social psychology methods. Based on data from population surveys, they extrapolate a country's cultural predisposition to change from three change dimensions: routine seeking, affective reactance, and cultural rigidity.

Actor constellations and their capacities

Socio-technical systems are composed from actors coming from multiple domains, ranging from academia and civil society to industry and politics (Köhler et al. 2019). Systems, and their transformations, are 'agency-full' processes, and how agency plays a role therein has been a topic of recurrent interest (Farla et al. 2012; Wittmayer et al. 2017; Köhler et al. 2019). Sustainability transition literature has studied actors primarily in terms of the networks, groups, or coalitions that they build with similar beliefs about the system (Markard, Suter, and Ingold 2016; de Haan and Rotmans 2018). Actors can be categorized in various ways, including in terms of their sector (civil society, markets, third sectors, or public authorities) and the level on which they operate (e.g. local, regional, national, etc.) (Avelino and Wittmayer 2016; Fischer and Newig 2016; Wittmayer et al. 2017). Actors have different ways to shape a system's development. Following Avelino and Rotmans (2009), this depends on the available resources, strategies, and skills that they have at their disposal. Moreover, the influence of actors in a transformation depends on diverse roles they could take in the process, e.g. developing innovations, advocating in public debates, etc. (Wittmayer et al. 2017; Mossberg et al. 2018). Actors can challenge existing system practices and rules, to address a problem a different way (Schuitmaker 2012). They also engage in different ways, e.g. by political lobbying (Bergek et al. 2015) or via grassroots movements, and they can follow different strategies (de Haan and Rotmans 2018).

Power structures

Socio-technical systems are built upon power structures that reinforce their stability. These structures manifest diversely. For instance, they can be found in the regulative (e.g. rules, laws, sanctions, etc.), normative (e.g. values, norms, etc.), and cognitive rules (e.g. beliefs) that hinder radical changes in systems (Geels 2004). These rules make difficult for system actors to deviate from existing power structures. They also reinforce what is considered legitimate and appropriate for a system, limiting the resources that actors can draw upon to affect its development (cf. Bergek, Jacobsson, and Sandén 2008). Recently, Avelino (2017) suggested that power can also be studied through "*the nature of the power exercise in relation to stability and change*" (p. 508, italics in original). The author suggested distinguishing between three types of power: *Reinforcive* power, allowing the reproduction and continuity of existing systems; *innovative* power, through which actors' create new resources; and *transformative* power, by creating new structures and institutions (Avelino 2017). Power can also take instrumental, discursive, material and institutional forms (Geels 2014). Another approach for looking into the power structures that reinforce a system is through the lenses of policy studies. The policy and political processes in transformative processes more seriously (Kern and Rogge 2018). Similarly, ideas, institutions, and interests are built upon the system reinforcing it (Meadowcroft 2011).

3.2 Transformation dimensions

Drivers

Large-scale transformations of socio-technical systems happen because strong - or powerful - drivers for change exist. The sustainability transitions literature emphasises sustainability transitions as a response to persistent or 'wicked' problems identified by society e.g. climate change, health risks from poor sanitation, loss of biodiversity (Grin, Rotmans, and Schot 2010; Köhler et al. 2019). Historical perspectives on transitions and Kondratiev Waves emphasise large-scale economic change as coming from technological revolutions (Freeman and Soete 1997). These two perspectives therefore identify two types of driver or origin of transformations: market-based or industrial innovation, in the extreme cases leading to industrial revolutions, and social/policy responses to perceived problems (Köhler 2012). These drivers may be endogenous or exogenous to the socio-technical system under consideration in the sense of coming from the socio-cultural landscape or from actors within the socio-economic system. The development of steam engines for pumping water out of mines that started the development of steam power before is an example of an endogenous driver (Thurston 1878). The introduction of feed-in tariffs for renewable energies in Germany can be considered as a response to the exogenous driver of climate change (Reichardt and Rogge 2016).

Barriers

Barriers to transitions may be directly related to the transition itself (in that the transition does not occur, or only partly occurs) or to the direction of the transition (in that the transition moves in a different direction than originally intended). Because transitions are systemic processes, different kinds of single barriers (e.g. technical, social, market-related, political, cultural, economic, etc.) may have causal relationships and interact to form systemic blockages. Wieczorek and Hekkert (2012) identify such blocking mechanisms based on the presence or absence, and the quality/capacity of, the four TIS structures (actors, institutions, interactions, infrastructures). Based on the literature on system failures, Klein Woolthuis, Lankhuizen, and Gilsing (2005) create a framework for analysis of failures of systems in transitions. Weber and Rohracher (2012) identify further system barriers:

- Directionality failures, which refers to the lack of a shared vision and insufficient collective coordination between actors and maybe closely linked to-policy coordination failures, or problems aligning policies at the national level;
- Demand articulation failures, which reflects the lack of consideration for, and involvement of, demand-side (user/consumer) needs in TIS development;
- Policy coordination failure, which are problems aligning activities at different scales, i.e. between national, regional, sectoral, and technological institutions;
- Reflexivity failures, which is the lack of involvement of actors in a process of adaptive management that allows for anticipation of problems and, if necessary, adaptation of strategies (van Mierlo et al. 2010; van Mierlo, Arkesteijn, and Leeuwis 2010).

Directionality

System transformations can take different 'routes' or 'directions'. A central question is how such directions for transformation processes can be set. Market parties alone are not expected to provide societally desirable directions of change. For this reason, interventions from public actors are required, to overcome such 'directionality failure' (Weber and Rohracher 2012). Directionality is an inherently political process, as transformations are normative and political processes in which power and actors come into play (Stirling 2008; Meadowcroft 2011). Recent literature on sustainability transitions has suggested different ways of defining such directions. For instance, Berkhout et al. (2004) proposed that such directions can be defined intentionally, through coordinated mechanisms among system actors, or non-intentionally through inertia of the dynamics of the system. Moreover, Geels und Schot (2007) identified that the direction of a transformation will also depend on the interaction between external pressures of the system, availability of alternatives (within and outside the system), and the interaction between system actors. A third way to look into these directions is through the dichotomy of market and state-led directions. Markets provide directions to system transformations by working as selection environments for radical innovations (Grin 2010). This contrasts with state-led directions, which are purposefully set by public authorities together with societal actors to achieve desired outcomes (Weber und Rohracher 2012). Finally, Wanzenböck et al. (2019) suggested that directions can also we achieved through the coupling of problems and solutions.

Demand

System transformations imply changes in the production and consumption sides to make them more sustainable (Martin and Upham 2016). It demands a closer collaboration between the production and demand side, that can we achieved by arenas of collaboration or through intermediaries (Kivimaa 2014). We can observe two central actors that can influence a system transformation through demand: Users and state authorities. Users can led to a change in systems through new patterns of consumption (Martin and Upham 2016) e.g. by getting products from more sustainable, environmentally friendly, and local networks (Randelli and Rocchi 2017). Users can also organize in groups actively transforming a system, e.g. virtual communities (Meelen, Truffer, and Schwanen 2019). Transformations should have a user-centered approach in order to be successful (Hippel 2006). Following Shove, Pantzar, and Watson (2012), attention should also be given to the practices that should be changed to enable a system transformation, e.g. in energy consumption or daily community. In contrast, state authorities can enable such transformations by policy tools. Not all innovations are good enough to generate their own demand, leaving room for state intervention (Fagerberg 2018). This argument, which primarily comes from innovation policy, suggests that authorities can accelerate the adoption of transformative innovations (Weber and Rohracher 2012), particularly through demand-side instruments such as public procurement (Edler and Georghiou 2007; Borrás and Edquist 2019, Ch. 6).

Contestation

Transformations are subject to contestation. This is so, as transformations are political and normative processes, which will ultimately redefine the societal interests and how a system fulfils a particular function (Meadowcroft 2011). For this reason, we expect to see contestation and disagreements, not only between system actors and challengers, but also within the advocates of transformation -because transformations can take multiple pathways (Köhler et al. 2019). Thus, it is not only a contestation about the system, but also about the directions in which a transformation process unfolds. Conflict emerges as part of what a transformation entails, including the change of production, consumption, norms, and values of a system. Moreover, as a transformation evolves, the power relations, contestation, and potential conflict move accordingly (Avelino and Wittmayer 2016). For socio-technical transformations, contestation is not only intrinsic, but also necessary and perhaps desirable. This is so, as challengers of the system require to contest it, in other to radically modify its socio-technical trajectory (Voß, Smith, and Grin 2009; Turnheim and Nykvist 2019). Rosenbloom et al. (2016) and Rosenbloom (2018) Rosenbloom, Berton, and Meadowcroft (2016) and Rosenbloom (2018) have indicated how discursive processes are central for understanding contestation and conflict, as they are the tools used to legitimize system transformations and the directions they take. Moreover, contestation can occur in the institutional venues where system actors refuse change (Geels 2014).

Degree of (national) autonomy

Despite recent globalization and regionalization trends, the nation-state remains the main unit of analysis for studying transformations. Countries have different capacities to influence a system transformation depending on multiple factors. Some countries have less autonomy to influence a transformation due to landscape factors, such as weak institutions, corruption, or transnational forces (Edsand 2019). In contrast, some countries are bounded to supranational bodies (e.g. in the European Union), which affects their autonomy in a different way, particularly as under contexts of multi-level governance transformations require to be aligned with supranational directives (cf. Ehnert et al. 2018). Moreover, some nation-states are particularly prone to the influence of actors defining policy objectives and pathways of transformations from abroad (Manning and Reinecke 2016). Some states, particularly in the global south, have limited capacity to transform systems due to the trade-off of modernization and economic growth vs. sustainability goals (Swilling, Musango, and Wakeford 2016). Even though we have taken the nation-state as a spatial unit, the reader should consider that for certain transformations (e.g. urban transport) the degree of autonomy should be understood in a different level (e.g. regional, local) (see Truffer and Coenen 2012; Hansen and Coenen 2015).

Degree of governability

In system transformations, the state nor non-sate actors are not expected to change a system alone. In contrast, it requires governance practices that allow the inclusion of non-state actors in the decision-making processes for such transformations. Transition studies have deliberately developed approaches for governing such processes, such as transition management (Voß, Smith, and Grin 2009) and strategic niche management (Schot and Geels 2008). While the former allows the governance of transformation processes through deliberation arenas, the latter enables the explicit empowerment and maturing of radical transformations not aligned with current system rules. Transformation processes should embrace experimental governance approaches, facilitating the evaluation and selection of alternatives (Manning and Reinecke 2016). In addition, transformations can be steered through the establishment of organizations working as intermediary actors, facilitating actors between different actors (Kivimaa 2014). Political structures facilitating the governability of transition go hand in hand with the development of new policy tools (Steward 2012), as well as their combination in policy mixes (Kivimaa and Kern 2016; Kern and Rogge 2018). These tools can range from those protecting radical niches (Grin, Rotmans, and Schot 2010) to tools for destruction of existing system and the creation of new ones (Kivimaa and Kern 2016). Overall, the public sector requires empowering and developing new capabilities to catalyse transformations (Haley 2017; Borrás and Edler 2020). The governability of system transformations requires reflexivity, by which it is referred as the capacity of governance to critically reflect and anticipate upon the process and goals that a transformation entails, for the possibility of re-orientate the process if needed (Voß and Kemp 2006; Voß, Bauknecht, and Kemp 2006; Weber and Rohracher 2012).

Degree of coordination

As a multi-actor processes, transformations are built upon coordinated actors of players coming from different domains. In order to achieve such coordination, interests, visions, goals, and expectations need to be aligned (Kemp, Loorbach, and Rotmans 2007; B. Truffer, Voß, and Konrad 2008). Particularly, approaches to achieve such levels of coordination have been developed under the transition management literature, as transition arenas, in which actors come together to create new coalitions and carry out transformation initiatives (Hölscher et al. 2019). A successful transformation will depend upon the capacity of actors to mobilize resources (Smith, Stirling, and Berkhout 2005). Ehnert et al. (2018) showed how institutions mattered for such coordination, as difference governance settings imply different coordination challenges. Moreover, Weber and Rohracher (2012) expanded on this issue, suggesting that other types of coordination required for transformative processes: coordination among different systems, different governance levels, different state actors (e.g. ministries and implementing agencies), among actors, and in the timing of policy interventions.

Development over time

Development over time addresses questions of the duration of transitions (how long they take), and of the growth and maturation of niches. The question of niche maturity is especially important: Geels and Schot (2007) and Geels et al. (2016) theorize that regime change happens due to interactions between landscape pressures and niche pressures, and that the niche's maturity at the moment of landscape pressure determines which pathway the transition will take. Different stages in a transition's development over time have been theorized in terms of 'deep transitions' (Schot and Kanger 2018; Kanger and Schot 2019). The steering of such long-term change processes has been reflected and enacted in terms of the transition management approach (e.g. Voß, Smith, and Grin 2009). Policies can affect the rate and direction of transitions through e.g. resource effects (Edmonson, Kern and Rogge 2019). Exogenous conditions can also influence the rate and direction of change of a transition (Edmonson, Kern and Rogge 2019). As many empirical transitions studies have taken an ex-post perspective, development over time has been seen retrospectively; an exception are modelling studies that take an ex-ante perspective (e.g. Dumas, Rising, and Urpelainen 2016). A current question of interest is the acceleration of transitions for rapid change (Ehnert et al. 2018; Roberts et al. 2018; Roberts and Geels 2019a; 2019b).

Learning processes

Due to the systemic nature of transition processes, learning processes - and linked to this, capacity development - are necessary by actors (and organizations) throughout the system and over time. To overcome systemic barriers, stakeholders need to reflect on structural, cultural, and practical domains (Schölvinck, Schuitmaker, and Broerse 2019). Learning is key so that stakeholders are able to adapt to new circumstances and innovations - technological innovations can also create new problems demanding innovative answers. Moving towards a knowledge economy, different forms of learning such as collaborative learning, organizational learning, and interactive learning have taken greater importance (Borrás 2011; Lundvall 2016; Frantzeskaki and Rok 2018). Authors differentiate between first-order learning processes, in which actors accumulate information, and second-order learning processes, in which this information is used to question and change previously held assumptions (these are also known as first-loop and second-loop; see van Mierlo et al. (2010)). Social learning - the peer-to-peer exchange of knowledge between innovators, involving learning processes across multiple dimensions (van Mierlo and Beers 2018) - and social innovation are essential parts of niche development (Raven 2005; Geels and Raven 2006; van Mierlo et al. 2020). Collective actors engage in learning processes through their networks, and different types of networks use different types of learning processes (Goyal and Howlett 2020). For firms, innovation-focused management forms are necessary to foster and maintain innovative activities and outputs (Dougherty 2009). Policy learning and capacities are important for state guidance of transition processes (Wu, Ramesh, and Howlett 2015). Borrás (2011) identifies three levels of policy learning and associated organizational capacities: 1) government learning by government institutions and state officials, learning about very concrete processes and generating specific organizational change; 2) lesson-drawing by policy networks, who learn about policy instruments and mixes, for specific program/instrument/policy mix change; 3) social learning by broad social and policy communities, who learn general ideas supporting policy paradigm shifts.

4 Reflections on analysing and designing transitions

The idea of this paper is to enable the analysis of systems transitions and the design of possible future systems transitions for the purpose of learning and policy development. How does our conceptualisation support these the ambitious claim to influence and orient transition in desired directions through deliberate policy intervention?

First, the concept introduces a critical distinction that is important for analysis and policy design, i.e. dimensions of systems and dimensions of system transitions. While those dimensions are by default strongly intertwined, this distinction allows and forces analysts and policy makers to open up to forces and variables that influence transitions but are not essential part of the initial systems analysis in the first place. It also supports the analysis of system transitions that results from the transitions of interdependent systems

Second, the concept reduces complexity, which has been postulated as the main challenge in analysing system transitions, without simplifying system transition down to a meaningless caricature. As each transition in each context is idiosyncratic, policy learning and scenario building must find a middle ground between specific situations and generalizable dynamics. Thus, a concept like the one proposed helps to tackle two of the main directionality failures. It supports reflexivity in the system by providing this middle ground in ways that are accessible to policy makers (reflexivity failure) and it supports the understanding of what directionality means, what components of the system interfere with the desire to orient a system in a certain direction (directionality failure).

Third, being forced to reflect on those dimensions in a systematic way, highlights the need for a multi-faceted policy approach. Many of the dimensions discussed will go beyond the usual policy areas (e.g. energy, mobility, health) and highlight the need for a combination of policy areas and instrumentation to target those variables that need support. Policy discourse will inevitably be confronted with developments that cut across established policy areas and will thus lay the basis for the third transformational failure, i.e. coordination.

5 Conclusions

In this paper, we presented a framework that enables the characterization of socio-technical systems and their pathways of transformations. Drawing from the literature on sustainability transitions, we identified twenty dimensions spanning seven categories of analysis. We briefly elaborate on each of the dimensions in section 3, and we recommend how this framework could be used in policy analysis and for the study of contemporary transformations in section 4.

A central rationale for developing this framework is that so far, there are few/no studies/meta-analyses comparing the properties of different socio-technical systems generally recognised methods for systematically assessing and comparing future transformation pathways. Moreover, there is no agreed(Wanzenböck et al. 2019; Rogge, Pfluger, and Geels 2020) method for performing analysis in them. Köhler et al 2019 identify a need to more systematically develop explanations of transitions processes. Thus, this framework intends to be use for analysing the complex ways in which pathways of socio-technical systems unfold. It shall also support policymaking and policy design as it allows forward looking analysis.

The framework provides a foundation for comparing different forms of transformation processes and possibly developing a typology of these processes. We differentiate between dimensions that describe the elements of the socio-technical system under consideration and the aspects of change that (may) result in a system transformation. Regarding the system dimensions, we identified the following categories: *functions* of the socio-technical system, its *characteristics*, the *context* in which the socio-technical system functions and its specific *agency*. In contrast, our transformation dimensions consist of factors influencing the dynamics of socio-technical systems can be summarised as the *drivers and barriers*, *politics* (and governance), together with the description of the *dynamics* of the system. By structuring the search for significant factors (through dimensions) and indicating central points of interest, the complexity of the analysis can be reduced. Change processes can be distinguished and major principles can be elaborated. This makes possible to search for patterns and ideally even leads to a typology.

Regarding the next steps and improvements of this work, we identify the following. First, the dimensions could be further operationalized and serve as input for modelling approaches. Second, the dimensions could be refined, adapted, or reconsidered. Third, the relationships between the dimensions could be further refined. So far, we have suggested that these dimensions are interconnected. However, this work could benefit from a more rigorous analysis of how these dimensions are interconnected. Finally, case studies should be carried out using this framework, to show its usefulness in analysing system transformations.

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