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

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Abstract

There is a need for concepts and methods to develop generic insights across cases in transitions studies and to analyse "transformational system failures" in policy. This paper identifies dimensions for a system level analysis and illustrates their application to compare cases and identify possible entry points for policy. System dimensions are grouped into the function of the socio-technical system, its characteristics, the context and its agency. Transformation dimensions address drivers and barriers, politics and dynamics of the system. The illustrations for German bioeconomy and sustainable mobility in the Netherlands both indicate directionality failures and contested policy goals. This results in reflexivity failures in the German bioeconomy, because clear goals are not set, impeding the monitoring of progress. In contrast, mobility initiatives in the Netherlands are constantly adapting to moving targets. Governance structures facilitating system change need to avoid capture by vested interests influencing the routes of change. Both illustrations allow to draw general conclusions as to the value of a structured systems and transformation analysis to support policy analysis and practice.

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1 Introduction

The objective of this paper is to develop a framework for the structured analysis of transformation processes and to illustrate how it can be applied to assess policy for supporting transformation processes. Köhler et al. (2019) propose that there is a need for concepts and methods to develop generic insights across cases in transitions studies. At the same time, Weber and Rohracher (2012) identify a need for analysis of "transformational system failures" in policy for sustainable transformation of socio-technical systems as an entry point for policy development. This requires a system level analysis, both of the socio-technical system itself and of the transformation process. This paper identifies dimensions for such an analysis and illustrates how these dimensions can be applied to compare cases.

The forward looking analysis of pathways of transformation of sociotechnical systems to sustainability has become a key concern of innovation studies (Geels 2002; Grin et al. 2011; Köhler et al. 2019; Rogge et al. 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 for example energy, transportation and health.

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 argue 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 et al. 2019; Kern and Rogge 2018; Frenken 2017; Matthes 2017) .

These studies have different roots. As early as 2012, Steward recognised and analysed a shift in international climate policy towards a narrative of systems change and the importance of socio-technical actor networks radically shifting their practices (Steward 2012). Based on this recognition, he claimed that there is a need for "transformative innovation policy" (see also Daimer et al. 2012).

He also noted that the incrementalism of previous policy driven changes, with their 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 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 (Mazzucato 2018). Those suggestions are *de facto* claims 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. 2020; Rogge et al. 2020).

Some more 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. 2020) on the other. The fluid, highly complex, very idiosyncratic character of socio-technical systems renders the identification of "failures" or policy levers itself into a real challenge. Consequently, 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 and unpick socio-technical systems is even more pertinent when it comes to envisage future scenarios of systems change and what policy could do to help systems to transform in the societally desired direction. In particular, because the dynamic change of systems is non-linear (Grin et al. 2011) and extremely hard to model for policy intervention purposes, we need a conceptual framework reducing the complexity of systems and systems change down to those key dimensions having major influence for systems change.

The transitions literature has begun to develop a structure for the analysis of transitions processes. Geels and Schot (2007), Geels et al. (2016) and many others have used the structure of the MLP to develop a typology of transitions 'pathways'. Those pathways are derived from various combinations and timings of landscape pressures, niche development, regime responses and their interactions. However, the application of this typology remains relatively ad-hoc and descriptive, and it uses only one model of transitions, the MLP, and thereby limits our analytical lens considerably. Finally, Turnheim et al. (2015) propose a 'bridging' approach to combine qualitative and quantitative methods for the development of transitions scenarios, applied in Köhler et al. (2020), although this concentrates on the research methodology for combining analysis approaches rather than identifying the structures underlying transformation processes of socio-technical systems. However, there are few studies or meta-analyses comparing the properties of different socio-technical systems, or generally recognised methods for systematically assessing and comparing future transitions pathways.

With this article, we seek to support the future oriented thinking and policy-driven 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. The objective of this paper is twofold: it first develops a systematic characterisation of socio-technical systems by providing and explaining a limited selection of dimensions and criteria for this characterisation of systems and for their transitions. Second, with this characterisation framework to enable a systematic analysis of systems transitions we seek to support the identification of possible entry points for policy. To identify those entry points for policy we identify dysfunctionalities in the transformation processes, mobilising the idea of system and transformation failures (Weber and Rohracher 2012). This paper therefore provides the conceptual foundation for comparing different cases of highly idiosyncratic socio-technical transition processes for supporting forward-looking analysis and developing contextualised policies to overcome specific transformation failures.

This article is structured as follows. Section 2 provides an overview of the choice and structure of the dimensions used to characterise systems in transitions. 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 provides two brief illustrations of characterisation and comparative analysis for the bioeconomy and mobility, demonstrating the usefulness for two very different system transition analyses. Section 6 summarises the key points with suggestions for future applications and research directions.

2 Deriving dimensions for systems and transformations

In this section, we structure the dimensions and explain the logic of how the set of relevant dimensions was chosen. 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. The structure of dimensions is shown in table 1. To structure the analysis of system transformations, it is useful to think in terms of meta-categories of dimensions. For the system, we identify four categories 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. We begin by discussing these categories, before moving on to those characterising transformations.

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 Louçâ (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 et al. 2011) 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 meta-category *characteristics* that describe the system include the features of the technology, 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 et al. 2013). The meta-category *context* is composed of socio-technical factors, regulation, institutions and 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). Social and cultural factors are also fundamental elements, determining the expectations of users reproducing the practices and attitudes towards the socio-technical system. These include ethical issues which recent research has confirmed to be of critical importance in transformations (Köhler et al. 2019, section 9). 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 system change 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 change* 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 the meta-category *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 2006), 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 driven predominantly by producers and the supply-side more generally or by societal and user requirements and thus demand. 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 et al. 2011). Barriers to transitions may be directly related to the transition itself or to the direction of the transition (in that the transition does not occur or only partly occurs, or that it moves in a different direction than originally intended, respectively). 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).

In particular, because of our focus on policies influencing transformation, we also need to emphasise the role of *politics* as a meta-category in influencing change processes. Grin et al. (2011) 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 et al. 2011). Köhler et al. (2019) identify the need for comparative analysis of these factors as an area for further research. As part of this, the level and nature of contestation should be considered. 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. A further issue is the degree of coordination required between different actors, which depends particularly on the complexity of agency structures. 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 transformations 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 ('Long Waves') as well as in the MLP to describe the development over time (Freeman and Louçã 2001; Freeman and Soete 2006; Perez 2002; 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*	Societal preferences (culture)
Characteristics	Relevant sectors		Technological change/innovation
	Interactions with other systems		External shocks
	Characteristics of relevant technologies and practices		Policy and regulations
			Emergent vs intentional dynamics (market driven or politically/societally driven)
			Demand articulation
	Geographical scope	*Politics*	Nature of contestation
Context factors	Infrastructures: Physical, knowledge, financial		Degree of (national) autonomy
	Regulation and its importance		Governance structures
	Socio-cultural factors		Degree of coordination

SYSTEM DIMENSIONS		TRANSFORMATION DIMENSIONS	
Meta-category	**Dimension**	**Meta-category**	**Dimension**
Agency	Actor constellations and their capacities	*Dynamics*	Development over time
	Power structures		Learning processes

A systematic characterisation of systems and transitions based on those meta-categories and dimensions and their interplay may not identify all idiosyncrasies in all cases, but it is sufficient to identify and distinguish the basic qualities and challenges of system change processes. In the next section, we build on existing literature to characterise the individual dimensions in more detail. This is necessary to then apply the framework for two illustrations and to draw broader conceptual conclusions that close the paper.

3 Explaining the dimensions of systems and of transformations

This section first describes the system dimensions, followed by the transformations dimensions.

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. In-depth analysis of the functions is thus a major analytical step.

Relevant sectors

While the MLP conceptualization of transition refers to a 'fundamental' socio-technical reconfiguration in a focal sector, this single-sector focus has been challenged more and more (Andersen and Markard 2020). The relevant systems are often characterized by intensive linkages between upstream and downstream sectors or functions that 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. For example, knowledge bases, actors, regulations, demand as well as resources may differ considerably between sectors (Malerba 2002). Therefore, first, innovation and evolution patterns differ between sectors and related systems. Secondly, multiple systems may be characterized by high complexity and a variety of framework conditions that have to be taken into account in the analysis. Any analysis of systems change needs to understand which sectors are involved in or affected by systems change.

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: rather, interactions between different systems arise with different forms and intensities of exchange between the components of two or several systems (Bergek et al. 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).

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, and actors (Rosenbloom 2020). 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 interactions, and different typologies of type of interactions have been developed (Raven and Verbong 2007; Konrad et al. 2008; Papachristos et al. 2013). Most applied is the approach of Raven and Verbong (2007), who point out potential synergies or conflicts with other social-technical systems. They propose a typology of four types of interactions and differentiate between competition, symbiosis, integration, and spill over. Consequently, to understand and influence system transformation, one needs to understand how the targeted system interacts with other systems, and how the changes and dynamics elsewhere interfere with the targeted transformation. Supporting policies may therefore reach out beyond the system for which transition is sought.

Characteristics of relevant technologies and practices

Technological change has historically had a decisive influence on transformations of society. Historically, some new technologies have led to the development of socio-technological paradigms which have strong influence on production and organization of industries and economies (Perez 2010).

The characteristics of a new socio-technical system determine how the technology is put into practice by users and the transitions literature also emphasises the cultural meanings of a technology that influence the practices of the technology (Köhler et al. 2019). The characteristics of new socio-technical systems feed back into the other subsystems of the socio-economic system: market institutions and new economic demand as well as policy processes (Freeman and Louçã 2001).The physical infrastructure are a component of the practices and may also determine the interactions with other sectors (Berggren et al. 2015; Köhler et al. 2019; Hess 2013). The relevant characteristics also inform innovations in the creation of input and output value chains.

Geographical scope

The geography of transitions literature explores the similarities and differences of transitions in different regions (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 et al. 2014; Hansen and Coenen 2015). Space may be seen as a physical territory or as a set of relations between actors (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 et al. 2015; Wieczorek et al. 2015). An underexplored question is how this impact differs or is similar in industrialized and non-industrialized countries. A major requirement for the analysis of systems and their change is thus the identification of socio-technical systems level and its geographical contextualisation.

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 support for 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). Financial infrastructures include the technical systems through which money flows from one place to another. Physical infrastructures include buildings, roads, bridges, factories, etc. Because existing infrastructures have been developed to support the status quo, a detailed analysis of infrastructure adaptation needs is necessary in all dimensions.

Regulation and its importance

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 question in socio-technical analysis is how rules and institutional processes shape the regime of a system (Fuenfschilling and Truffer 2014). But rules also play central roles in shaping the directionality of transitions in a system, e.g. through environmental regulations, standards, quotas, etc., which may be subject to renewal during transition processes (Köhler et al. 2019). While rules and regulation are of importance in every socio-technical system, the type of regulation and the operation of freedom for actors may significantly differ between systems. It is essential to understand how existing rules and regulations may support or impede system transformation and how a change of rules and regulation may catalyse transformation in certain directions.

Socio-cultural factors

Major changes in culture and behaviour are required for sustainability transitions and are identified as fundamental component (or subsystem) of socio-technical systems (Freeman and Louçã 2001). 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 f. Societies' articulations of their sociotechnical imaginaries - how they visualize their future - are important factors informing how transitions unfold (Pfotenhauer and Jasanoff 2017). Societal 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 the functions of innovation systems – 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. Köhler et al. (2019) identify the impact of civil society organisations on institutional logics and discourses on the development of cultural logics and their influence on the development of policy mixes, as well as their impact on practices and values as an area for further analysis.

Actor constellations and their capacities

Socio-technical systems are composed of 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 et al. 2016; 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; Wittmayer et al. 2017). Actors have different ways to shape a system's development, for example by applying new lenses on existing issues and challenging existing system practices and rules (Schuitmaker 2012). They may engage in a variety of ways, e.g. by political lobbying (Bergek et al. 2015) or via grassroots movements, and they follow many different strategies to achieve their goals (Haan and Rotmans 2018). Following Avelino and Rotmans (2009), engagement 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., which may also change over time (Wittmayer et al. 2017; Mossberg et al. 2018).

Power structures

Mature socio-technical systems are built upon power structures that in general reinforce their stability. These structures are manifest in different ways. 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 it 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 et al. 2008)). Avelino (2017) claims 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) as ideas, institutions, and interests are built upon the system reinforcing them (Meadowcroft 2011). Another approach for looking into the power structures that reinforce a system is through the lenses of policy studies, which calls for a much more explicit consideration of policy processes in addition to policy content (Kern and Rogge 2018). It is necessary to analyse power constellations as a potential barrier to change, in particular as transformational policies will have to deal with existing power structures and the tendency of powerful actors to cling to privileges that are often provided for by the status quo.

After this basic characterisation of the dimensions that allow the qualification of systems, we now turn to the dimensions that characterise transformation of systems.

3.2 Transformation dimensions

Societal preferences (culture)

The sustainability transitions literature emphasises transformations as a response to persistent or 'wicked' problems identified by society, e.g. climate change, health risks from poor sanitation, or loss of biodiversity (Grin et al. 2011; Köhler et al. 2019). Changes of societal preferences regarding e.g. methods of energy or food production and consumption may impulse changes in policies and markets. An example is the changing global mindset regarding methods of food production and the growth of the organic food industry (Willer et al. 2021). A converse example, also from the agri-food system, is the continued entrenchment (and even growth of) demand for meat on a global scale, even though meat production is a major contributor to climate change (Revell 2015). Societal preferences are not inherently sustainability-oriented, but may rather also seek to continue the status quo and deter transformations from happening (EEA 2017; Runhaar et al. 2020)

In particular in recent years the consideration of societal preferences has been broadened to reflect the importance of culture for the dynamics and direction of transitions, in particular in the energy field (Sovacool and Griffiths 2020a, 2020b; Stephenson 2018). Culture as the interplay of "ideas, customs, and social behaviour or a particular population or people"[1] manifests itself in in the basic attitudes and everyday practices of people (Hui et al. 2017; Coutard and Shove 2019). Changes in culture are long-term processes involving changing social processes and the anchoring of new knowledge in society, discussed in greater detail below.

1 Oxford dictionary, quoted in Sovacool and Griffiths (2020b)

Technological change / innovation

Changes in science and technology lead to the emergence of powerful framings that strongly influence societal development. Technological change may lead to the emergence of new markets and cause profound changes in socio-technical systems (Geels et al. 2008). On its own, technological change and innovation may be a main driver of transformation, but it needs associated social, political and market-related changes in order to fully transform socio-technical systems. Technological change may also hamper transformations, e.g. through presenting technology-based answers that aggravate (instead of alleviate) socio-environmental problems. An example is the current use of 'sustainable intensification' technologies in agricultural production (Struik and Kuyper 2017).

External shocks

Shocks occur externally to the system under question and are usually theorized as part of the landscape level of the multi-level perspective (Geels and Schot 2007). External shocks may be e.g. market-related or of environmental, political or social origin. Shocks put pressure on socio-technical systems and favour system reconfiguration. Although they may be perceived negatively, shocks may cause recalibrations in various aspects of systems, or even in multiple systems, and hence may also create space for innovations to emerge and transformations to unfold (Roberts and Geels 2019a). A current example is the Covid-19 pandemic, which besides causing tremendous economic, political and social challenges also offers opportunities to strengthen action on the climate agenda and accelerate the decline of carbon-intensive industries, technologies, and practices (Bodenheimer and Leidenberger 2020; Markard and Rosenbloom 2020; Rosenbloom and Markard 2020).

Policy and regulations

As outlined above, rules and regulations are linked to both political and social aspects of societies, and may support or hamper systems in transformations. Regulations and policies can provide directions to systemic change by indicating expected developments (Blind et al. 2017). Regulations may also favour the creation, amongst others, of standards that accelerate the diffusion of new technologies (Blind 2012). Regulations can favour innovations for sociotechnical change such as regulatory sandboxes (Rosemberg et al. 2020). Policies may enable the creation of markets for early adopters: through incentives given by policy, people can decide to benefit and adopt the technology. One example of a public policy is green public procurement, which tends to induce green innovation in supplier companies through purchasing power of the state (Hasanbeigi et al. 2019; Zipperer 2019). Another example is public subsidies to accelerate the adoption of electric vehicles (Kotilainen et al. 2019). Other policies may seek to phase out or reconfigure existing systems: an example is the German Energiewende (Kivimaa and Kern 2016), which seeks to phase out atomic power and coal and replace them with renewables through a stable 'feed-in tariff' providing price support for electricity from renewables. Transformative policy mixes attempt to take into account multiple systems and feedbacks between policies and systems (Schot and Steinmueller 2018; Edmondson et al. 2019; Rogge et al. 2020).

Emergent vs intentional dynamics

Transformations can either emerge through societal and market dynamics or they result from political intervention as a result of a political and discursive processes. Most often, both dynamics will interplay, re-enforce or counteract each other. Markets provide directions to system transformations by working as selection environments for radical innovations (Grin et al. 2011) and by providing responses to changes in societal preferences. This contrasts with state-led directions, which are purposefully set by public authorities together with societal actors to achieve desired outcomes (Weber and Rohracher 2012).

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, even in societally and market driven transformations, interventions from public actors are required to bring the direction of transformation in line with societal preferences and provide political legitimacy, i.e. to overcome '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). 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 and 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. Finally, Wanzenböck et al. (2020) suggested that directions can also be found through the coupling of problems and solutions.

Demand articulation

System transformations imply changes both on the production and consumption sides (Martin and Upham 2016) and demand a collaboration between the production and demand side, which can be 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 sourcing 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 et al. 2019). Following Shove et al. (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 - beyond being users of goods and services themselves - can enable such transformations through policy intervention. Comprehensive research has shown that bottlenecks on the demand side can severely hamper the diffusion of innovation and thus transformation (Edler 2016). Different kinds of demand side policy tools such as public procurement, demand subsidies or training and awareness measures can overcome those bottlenecks (Fagerberg 2018; Edler and Georghiou 2007; Borrás and Edquist 2019) and in particular accelerate the adoption of transformative innovations (Weber and Rohracher 2012).

Nature of contestation

Transformations are subject to contestation as they are political and normative processes, which will ultimately redefine 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, contestation is not just 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). As highlighted already above when characterising power structures in existing systems, transformations challenge powerful incumbent actors. Challengers of the system are required to contest it in other to radically modify its socio-technical trajectory (Voß et al. 2009; Turnheim and Nykvist 2019). A number of transition analysists (Rosenbloom et al. 2016; Rosenbloom 2018) have indicated how the analysis of discursive processes is 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 processes of determining institutions where system actors refuse change (Geels 2014). To understand and influence transformation, understanding the dynamics of contestation based on pre-existing power constellations is a condition sine qua non.

Degree of (national) autonomy

To influence transformations politically, political systems need a sufficient degree of autonomy to act i.e. they need agency. While it is true that many transformations are local or regional (Hansen and Coenen 2015), and influenced at those levels (see Truffer and Coenen 2012) and despite a number of major international efforts to support the governance of transformation, in most political systems, it is the nation state where major public discourses and political decisions for major transformations tend to be taken.

However, 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 being dependent on transnational economic, financial or political forces (Edsand 2019). Some countries are bound 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 may be subject to the influence of international developments and institutions e.g. in setting standards (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 et al. 2016). Therefore, to understand the scope of political intervention into a transformation process means to understand which political level has which responsibility with what degree of autonomy.

Governance structures

What determines the nature of governability of transformation? How can we understand if and how state and non state actors can actually make a difference? In system transformations, neither the state nor non-state actors are expected to change a system alone. In contrast, governance practices are required that allow the inclusion of non-state actors into 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 be supported by experimental governance approaches, facilitating the evaluation and selection of alternatives (Manning and Reinecke 2016). In addition, transformations can be influenced through the establishment of organizations working as intermediary actors, facilitating interactions between different actors (Kivimaa 2014). Political structures facilitating the governability of transitions 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 et al. 2011) to tools for the destruction of existing systems 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, which refers to the capacity of governance to critically reflect and anticipate upon the process and goals that a transformation entails. Reflexivity is a critical capacity for governance for transformations in case a re-orientation of the process is needed (Voß et al. 2006; Voß et al. 2009; Weber and Rohracher 2012).

Degree of coordination

As a multi-actor processes, to govern transformations necessitates coordinated actions of players coming from different domains. In order to achieve such coordination, interests, visions, goals, and expectations need to be aligned (Kemp et al. 2007; Truffer et al. 2008). 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 - and coordinate - resources (Smith et al. 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. Therefore, the role of policy intervention cannot be isolated from the structure of the political system and the coordination needs deriving form it in any given transformation.

Development over time

Development over time addresses questions of the duration of transformations (how long they take), expressed in the Multi-Level Perspective as the duration 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 et al. 2009). Policies can affect the rate and direction of transitions through e.g. resource effects. Exogenous conditions can also influence the rate and direction of change of a transition (Edmondson et al. 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 et al. 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 2019b). The analysis of transformation processes needs to consider the time dimension in order to achieve a realistic understanding of the leverage of policy to accelerate, or to let time and learning run its course.

Learning processes

Due to the systemic nature of transition processes, learning processes - and linked to this, capacity development - by actors and institutions throughout the system and over time are necessary. To overcome systemic barriers, stakeholders need to reflect on structural, cultural, and practical domains (Schölvinck et al. 2019). Learning is key so that stakeholders are able to adapt to new circumstances and innovations, and technological innovations may 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; 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. 2010b)). Social learning - the peer-to-peer exchange of knowledge between innovators, involving learning processes across multiple dimensions (van Mierlo and Beers 2020) - 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). Transformative learning processes play a key role in increasing firms' strategic innovation (Gebauer et al. 2012). Policy learning and capacities are important for state guidance of transition processes (Wu et al. 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. The analysis of transformation processes therefore has to try to identify the nature of learning processes and learning bottlenecks in order to identify possible policy entry points to support complex societal and policy learning.

4 Mobilising the framework to analyse and design policy for transformations

The idea of this paper is to propose a structure for the analysis of societal transformations and the analysis of possible future systems transitions for the purpose of learning and policy development. How does our conceptualisation support the ambitious claim to influence and orient transition in desired directions through deliberate policy intervention? The concept we develop to characterise systems and systems transitions is to be understood as a heuristic that can be used for a variety of research questions and practical implications. It can be amended as needed for specific questions and using specific theories.

The concept introduces a critical distinction that is important for analysis and policy design, i.e. dimensions of socio-technical systems and dimensions of transformations. It helps to detect critical attributes of systems that may determine the speed or direction of transformation but are lost if one focuses on the on-going process of transformation and its drivers and barriers in the process. 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. The concept provides a structure to cope with complexity, which has been postulated as the main challenge in analysing system transitions, without simplifying system transition down to a meaningless caricature.

The framework allows a comprehensive analysis of the role of policy and the role of politics to design and implement policy in existing systems and in system transformation. This is not limited to an analysis about which policies we find in a given system or sector - which is also part of our framework. There are meanwhile a large number of sophisticated analyses of the role of policies and even their interplay (Reichardt and Rogge 2016; Kivimaa and Kern 2016; Matschoss and Repo 2020). Those analyses, even if broad, tend to focus on policies that are deliberately designed to support a certain transformation, most often limited to the key actors of a sector and the corresponding ministries and agencies. However, starting with the system and transformation properties (including the role of different kinds of infrastructures, properties of core and supportive innovations etc.) and assessing all dimensions of the heuristic with a policy perspective helps to construct a more complete picture of the role of policy. For example, the framework requires the identification of interdependencies with "neighbouring" systems and their constituencies. A holistic analysis of policy for a specific system transformation then requests the identification of the most relevant context factors in those systems and how they are influenced by existing policy. Another example is our inclusion of dimensions of politics and governance. Our heuristic takes into account the scope and reach of policy. It supports analysis about the locus of political intervention, about where the ability to act politically actually lies, and about the limits of governability of a system transformation. Importantly, this analysis will go beyond the deliberate polices and policy mixes and include all those that affect a system or its transformation even if not designed to do so, as well as the political actor constellations and coordination.

A major purpose of the framework as it relates to policy analysis is to identify policy leverages. In policy analysis, in particular in economic or innovation policy, policy entry points, or levers, are often defined as failures, i.e. structural features in a system that - without deliberate intervention - lead to stubborn, permanent underperformance of the system and, in particular, inertia instead of dynamic transformation.

The analysis of potential needs for policy intervention to support system transitions has been structured through the conceptualisation that there are barriers through:

1. Market failures, i.e. mainly the failure of markets to provide for the necessary knowledge production due to externalities;
2. Innovation system failures, i.e. the inherent limits of systems in providing the necessary competencies and capabilities as well as the productive interactions to exploit complementarities in the system (Edler and Fagerberg 2017); as well as
3. Four transformational system failures (Weber and Rohracher 2012):
   - *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. 2010a; van Mierlo and Beers 2020).

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, beyond allowing the analysis of system transformation at the same time 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).

Demand articulation failures are addressed through an assessment of the dynamics of societal preferences, users' demand articulation and the nature of the transition as emergent or policy/society driven. Demand articulation is an aspect of market failure in innovation systems. Private firms invest only reluctantly in basic, long term, non-directed research because of high uncertainty as to its outcome, and because given the nature of basic research they cannot appropriate the results of this investment fully. As a result, without publicly funded research there is not sufficient investment in long-term basic knowledge generation. Similarly, innovation system "failures" are shortcomings in the competencies and in particular, in the interconnectivity within an innovation system, which is essential for knowledge generation and flows and the development and diffusion of innovation. State intervention in innovation policy thus has a strong focus in nurturing a variety of different actors and competencies and supporting their interaction (Edler et al 2016). This aids in avoiding reflexivity failures stemming from the lack of involvement of actors in processes of adaptive management allowing for the anticipation of problems and, if necessary, adaptation of strategies (van Mierlo et al. 2010a; van Mierlo et al. 2010b).

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. Therefore, any 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 Applying the framework: Two illustrations

We now apply the framework to two contrasting examples, bioeconomy in Germany and mobility in the Netherlands. The transformation towards a bioeconomy sector in Germany had seen an upswing following EU legislation, followed by a recent decline in policy support, resulting in the new sector's stagnation. Transport in the Netherlands is a leading example of the development of new sustainable alternatives with consistent policy support, which nevertheless requires a further drive to achieve a real transformation. We interpret the system and transformation dimensions and briefly assess the system and transformation dimensions for each case (the interpretation of the dimensions for each case are shown in the appendix). We then analyse those dimensions to consider policy and market failures as discussed in section 4 above. This analysis is then used to discuss potential for policy interventions.

5.1 Basic characteristics

5.1.1 Bioeconomy in Germany

The concept of the bioeconomy emerged in the early 2000s and has become increasingly important since then. While originally it focused mainly on the substitution of fossil-based resources with bio-based resources, today a more comprehensive transition towards sustainable consumption and production patterns, not only related to renewable raw materials but broadening to biological knowledge, is under debate. Such focus on the whole bioeconomy encompasses a wide variety of products, processes and behavioural changes. We focus on the situation in Germany, which has been an early-mover in approaching the bioeconomy strategically. However, for many dimensions, Germany's situation is comparable to that of many EU member states.

Assessing system dimensions

The bioeconomy is a special case of a system as it possesses a cross-cutting character that involves many different products, markets and technologies. Moreover, it intersects with other socio-technical systems, such as energy, as biofuels and bioenergy are potentially part of the solution for transformations towards renewables (Purkus et al. 2018; Böcher et al. 2020; Wydra et al. 2020). Therefore, the characteristics for the system dimensions are rather specific to sub-systems and the relevant regulations, technologies, and infrastructural needs may differ between sub-systems, e.g., they differ profoundly between government-induced large-scale biofuel production versus low-volume applications like food ingredients and special chemicals. Hence, depending on the goal of research, a focus on a certain sub-system and sectors may be needed for in-depth transition analysis. Overall, a variety of different technologies, ranging from biotechnology to chemical or mechanical use of bio-based resources to the use of digital technologies (e.g. precision farming, big data processing in research), is important for the further development of the bioeconomy (Laibach et al. 2019). Many different stakeholder groups are involved in the various value chains, e.g. farmers, universities, companies, municipalities and – partly – end users. While some of the actors are traditional, like incumbent large firms that still dominate large markets, new players (e.g. SMEs) emerge as R&D service providers or suppliers in niche markets. The public and civil society (e.g. NGOs) are involved only to a limited extent.

Assessing transformation dimensions

Key drivers for the transformation to the bioeconomy are the increasing pressure to use natural resources sustainably, by reducing dependence on fossil fuels, and environmental and climate protection. A range of emerging (technological) innovations offer new opportunities to address these challenges. However, the transition process to the bioeconomy is in a rather early phase and hampered by a lack of cost competitiveness of bio-based products and path dependencies towards traditional supply of products (Asada and Stern 2018). Moreover, external societal factors, such as higher environmental awareness, still do not lead to a strong rise in demand for bio-based products. Hence, the transition is very much dependent on political influence. The past decades have seen a policy push, with the EU and member states implementing bioeconomy strategies (European Commission 2018; International Advisory Council on Global Bioeconomy 2020). These strategies have tended more and more towards holistic mission-oriented policies, whereby at least some instruments are designed to include a wider set of stakeholders and a stronger orientation towards sustainability goals (e.g. German and European policies focusing particularly on system failures and market failures). The main measures mobilised and combined are the support of R&D, innovation, network coordination, and infrastructure (e.g. financing of biorefinery demonstration plants). A major challenge for governability concerning markets is the wide range of heterogeneous applications (e.g. in terms of low volume vs. high volume, price competition, environmental performance) in very different sectors. Hence, potential demand-side instruments are very difficult to implement and hardly in place, mainly because of unintended side effects. Demand incentives in one market could affect many other markets via their supply chains, e.g. rising biomass prices as the availability of feedstock is limited. In addition, the high range of sectors and heterogeneity of the system highlights the need for actor coordination. Here, significant improvements in coordination between different policy makers and between policymakers and other actors have been achieved. Still, common agenda setting remains a key issue, along with the coherence concerning other systems and policy areas (e.g. energy policy, trade politics) (Böcher et al. 2020).

5.1.2 Mobility transition in the Netherlands

The historical development of the mobility system in the Netherlands has seen considerable emphasis at the local level on the development of high quality public local transport (train and bus) as well as the development of the cycling subsidiary regime. The defined challenge is to achieve a transformation to a sustainable mobility system (i.e. very low GHG emissions) with a transformation away from the current regime of privately owned, fossil-fuelled automobiles.

Assessing system dimensions

A central characteristic of the mobility system in the Netherlands is that, while automobility forms the dominant regime, there are also stable alternative mobility systems: cycling and highly developed public transport (Bakker 2020). These two alternatives play a significant part in the modal split in the Netherlands and have an established institutional and physical infrastructure (Köhler et al. 2020). They are therefore more developed in terms of their socio-technical structure than niches and thus can be defined as 'subsidiary' regimes (Köhler et al. 2020).

Moreover, the mobility system is very closely connected to other systems, e.g. energy and health. This can be seen in the uptake of more energy efficient and active modes of mobility in recent years. In addition, the demand for mobility is not only private, but largely defined by other economic sector and their (changing) needs. To this complexity, we should add that multiple sectors participate in the functioning of the system (e.g. IT, freight transport, infrastructure, etc.), and that the mobility system's function can only be fulfilled by mobilising a range of diverse technologies, the automobile being the dominant one. The mobility system can have national, regional, or local scope, depending on the type and distance of travel.

Contextual factors indicate that the country has a well-developed infrastructure, not only physical, but also in terms of knowledge and capital (I&M 2018). That is an advantage for the Dutch mobility system. The mobility system is a highly regulated system, e.g. as one needs to get permits to innovate in vehicle automation, motorized vehicles, and/or public transport. In addition, regulation of mobility comes hand-in-hand with regulations in other systems, e.g. urban planning. In the recent past, the Netherlands has attempted to make changes in such regulations and to be innovative in these changes. This has been driven by new mobility concepts and fuelled by niche groups (Vrščaj et al. 2021).

The complex picture of how the system works is also reflected in the type of actors participating. Actors range from traditional players (e.g. infrastructure providers) and public authorities (e.g. municipalities, road agencies, etc.), to new players bringing smart mobility ideas to the system (e.g. IT, high-tech systems companies) and consultants (Salas Gironés et al. 2019). This multiplicity of actors participates in consensual decision-making, so that multiple parties come together to define mobility innovations (Manders et al. 2020).

Assessing transformation dimensions

Regarding drivers and barriers, the Netherlands has a strong societal movement towards sustainability, as well a strong tradition of transition thinking in policymaking. This is complemented by its advantage in having a solid knowledge and technological base to push forward innovations in the field of mobility. External factors, such as climate change, health concerns, and recently the COVID situation, have driven policies towards more active modes of transportation inside the country (Haas et al. 2020). Since the Dutch energy transition in the early 2000s, part of the country's orientation towards sustainability has been in policy circles (see (Kemp and Rotmans 2009). Finally, the Netherlands have focused on becoming early-adopters of diverse mobility innovations (e.g. through behavioural change programs) as well as frontrunners in smart mobility technologies (Salas Gironés and Vrscaj, 2018).

The Dutch 'Polder model', which is a national tradition to involve all relevant all stakeholders for decision-making, has the potential to create common visions for a relatively uncontested mobility transformation. Even though some questions have been raised about the course of mobility policy in the last decade, the direction of existing policies has been shifting. Furthermore, the relatively dense and connected network of professionals working in the mobility field allows for a high degree of governability and coordination. Additionally, the country is characterized by a high level of autonomy concerning mobility solutions at regional and local levels, and an active role of national authorities to keep the country well connected. In the next decades, the system transformation seems to be directed towards more sustainability, favoured by multi-year programs (e.g. I&W 2020).

However, there is still strong resistance to change from the automobility regime. For example, the removal of parking spaces for cars and the reallocation of roads used by cars to make pedestrian zones or cycle ways in residential areas is still contested. Despite the potential of the polder model to work towards consensus, it also gives regime actors the possibility to resist (radical) change. Incumbents can mobilize resources and political capabilities to hinder radical innovations sponsored by niche actors (see Feindt and Weiland, 2018). Therefore, an important challenge for policy is to create a governance structure that enables the 'subsidiary regimes' to develop further, possibly in combination with other alternative mobility practices such as car sharing (e.g. Meurs et al. 2020). This differs from the typical 'niche experiment' proposed in the sustainability transitions literature (Kivimaa et al. 2017; Manders et al. 2018).

5.2 Analysis of transformation failures

In a final step, based on this characterisation of systems and their transformations, we can now identifying critical transformational failures that can become possible policy entry points. To do so, we follow the basic four failures as outlined above (Weber and Rohracher 2012).

Bioeconomy

The analysis of the dimensions reveals the very high complexity of governance of the bioeconomy transformation and it is clear that there are still important steps ahead. While market and system failures are already addressed to a considerable extent by policy and recent improvements can be identified, challenges remain. Notably, there still is a considerable directionality failure as the direction of the transformation is still debated and contested intensively (Scordato et al. 2017; Hausknost et al. 2017; Bugge et al. 2016). While there is in principal consensus that bioeconomy should contribute to sustainability and food, there are diverging views and debates regarding the prioritization of certain societal goals and desirable paths of the bioeconomy. While some proponents emphasize the potential of technological innovations, others claim to set the planet boundaries as limitation that should be considered fundamental in governance and all bioeconomic activities (Bugge et al. 2016). Potentially related to this problem, a clear shortcoming of the German and other strategies is that concrete operationalizable aims and measurable goals are missing (International Advisory Council on Global Bioeconomy 2020). Together with the absence of relevant demand-side measures it can be concluded that *current policy* *measures address directionality as well demand articulation* failures only to a *limited extent*. Rather, they support incremental changes while production and consumption patterns remain rather stable.

As already stated above, policy *coordination* has improved, but due to the high level of complexity in a multi-layered policy system, further potential and policy needs remain (Lindner et al. 2021). In particular, policy coordination between policymakers has increased with coordination groups between EU member states, between German ministries (e.g. between research, economic, agricultural, environmental ministries) as well as between federal and regional state governments. Still, more coherent action policy action is needed to achieve a successful bioeconomy transition.

Finally, the mobilisation of adequate systemic *reflexivity* is somewhat mixed (Wydra et al. 2020). Some steps have been taken towards increasing the strategies' mission orientation by broadening the scope of what has to be considered to support the transformation towards a bioeconomy and through the inclusion of more and different stakeholder groups in advisory bodies such as the bioeconomy council. However, the lack of operationalisation of concrete goals limits the ability to monitor, assess and reflect on progress.

Mobility

Regarding the *directionality* failure, despite the cultural norm of consensus building in the Polder model, there is still considerable contestation over (sustainable) transport policy at the local/city level. Reduction of GHG emissions has been hampered by the lack of a vision of a truly sustainable mobility system. Even though there is high penetration of low-carbon mobility in the country, the automobility regime seems stable and incumbents are able to determine the speed and direction of transformation. For instance, incumbents were able to tilt the direction of STI policy efforts to favour IT-based solutions, primarily for car technologies (Salas Gironés et al. 2019; Salas-Gironés et al. 2020; see Connekt 2021). Moreover, another difficulty is that transforming the mobility system has been hindered by frequently changing visions and goals (see (I&W 2019; I&M 2016). Thus, the direction of change has not been stable over long periods.

On *demand articulation*, the picture is ambiguous. On the one hand, demand is strong; more sustainable alternatives to the automobility regime are widely available and used for a significant proportion of trips (Köhler et al 2020). Additionally, since the 2010s, authorities have actively generated markets for new mobility services (Manders et al. 2018). However, the question remains of how to enable a change in mobility behaviour among the people who still use a (privately owned or company) car as their main mode of transport. Programs facilitating non-car related daily commuting have tackled this (Salas-Gironés et al. 2018). Graf (2020) argues that a large proportion of people (up to 60%), do not regularly use a bicycle, but are not inherently opposed to cycling. The problem then is to stimulate this large group to try alternatives to their car. These alternatives have to give a perception of safety, without stressful situations while travelling, with ease of use and a feeling that the route is direct and quick.

Weber and Rohracher (2012, p. 1043) *policy coordination* failure implies that successful coordination requires "coherent policy impulses from different policy areas". In the case of mobility, this can include institutions of town planning and transport planning to increase the capacity of alternative modes and sponsoring projects in this realm. The Netherlands have achieved such coordination through intermediary organizations performing boundary work for actors of different policy areas (Manders et al. 2020). Additionally, the mobility policy has changed away from traditional transport management to comprehensive measures connected to other policy areas and new policy actions. For instance, the current National Climate Agreement focuses also in the creation of zero emission zones and reduction of commuting behaviour (I&W 2021). Overall, these measures are intended to accelerate a transformation in the mobility system, used in parallel to more traditional policy actions, e.g. taxes and subsidies for the electrification of the vehicle fleet (e.g. Berveling et al. 2020; I&W 2020), and uptake of alternative fuels (I&W 2020).

Finally, according to Weber and Rohracher (2012), addressing *reflexivity* failures requires a monitoring and assessment system, a decision making process that allows for decentralised governance structures, and an adaptive policy approach that accepts uncertain outcomes and that can change policy directions. Following recent developments, the diagnosis of the problems in the mobility system has remained stable, but long-lasting consensus has not been achieved. Policy directions have fluctuated dramatically, e.g. from transitions in mobility in the energy domain in the late 2000s, to smart mobility during the period 2010-2018, to a hybrid model of sustainable and smart mobility since 2018 (Mooij et al. 2012; I&M 2018; I&W 2019).

Overall, the Netherlands can be argued to have the knowledge and policy capacity to move towards a transition away from automobility. Coherent policy approaches have been developed and the barriers to system transformation have been tackled through measures beyond traditional mobility planning. Remaining challenges are further restrictions on private car usage and long-lasting commitments on how to transform the system.

5.3 Interpreting and comparing policy consequences

After presenting the characteristics of systems and transformation in each illustrative cases, we now turn towards the analysis of policy consequences.

As for supporting *directionality* and *demand articulation* in the case of the bioeconomy transition it appears that despite a strong sense of urgency as for the need for transformation, further steps need to be taken to agree on some broad pathway for the transformation, with goals that are supported by major stakeholder groups. This support allows mobilisation of resources that can accelerate a system transformation (Schot and Kanger 2018). The system analysis has demonstrated how the bioeconomy transformation spans a whole range of sectors, with strong incumbents and innovation for change coming from a limited number of smaller firms. The multiplicity of sectors involved is potentially a very strong lever for real change should all systems move in the same direction. However, this potential is apparently hard to mobilise as key dynamics and practices in those systems differ. A clarity of vision and more convergent expectation management across the main systems involved would then also allow producers and consumers to shift their practices. Any policy measure that deals with individual aspects in different systems in isolation will have very limited effects on the broader transformation necessary.

The mobility case has a similar gap, i.e. a lack of a shared vision. However, here the problem is less complex and much more concrete: as the analysis above has shown, the alternative pathways and the respective innovations are known, policy now needs to debate around those known alternatives and experiment in localities and regions. Such alternatives can be further developed into pathways for system transformation. For the Dutch mobility transition, the policy challenge in terms of *directionality* is to further develop and maintain governance structures enabling proper consensus building. Such structures can enable common visions and objectives that benefit system transformation (Grillitsch et al. 2019). A key challenge therein is to incorporate all relevant stakeholders, and not only incumbent actors. Incumbent actors will likely reinforce the automobility system rather than support the desired transformation. Further, *demand articulation* requires policies to encourage car owners to experiment with the alternative modes, while adapting public transport and active modes to meet the needs of car owners and making private cars less attractive (Beirão and Sarsfield Cabral 2007). Such decisions heavily rely on user acceptance and promoting changes in user routines and behaviours (Schippl and Truffer, 2020). Demand has been partially articulated (as stated in section 5.2) and seems to be less of a policy issue in comparison to the bioeconomy case.

As for *coordination failures*, the bioeconomy case again has specific challenges. The systems and the transition analysis have shown the need for very broad horizontal (cross sectors and policy domains) and vertical (local, regional, national, EU) coordination. While progress in setting up coordination mechanisms has been made, the nature of the transformation, with societal pressures as main drivers in very different national systems across Europe, is not susceptible to meaningful coordination at European level as long as there is no shared vision that is institutionalized at EU level. It is telling that the policy at EU level focuses on market and system failures, side-stepping important normative decisions. Against this background, it appears more promising to focus on bottom up coordination, of building the bioeconomy from local to national level and in doing so creating transformative pressure at EU level.

For the mobility system in the Netherlands, there is already a high level of coordination in governance structures. However, despite this high level of coordination, there is still a *coordination failure* between mobility policy actions and other policy sectors. Cross-sectoral coordination is considered as a prerequisite for achieving societal transformations, as they require changes of multiple domains (Fagerberg 2018). Even though this has been substantially addressed in the last decade, connecting mobility and other sectors could be further improved. This suggests that the organisational structure of mobility policy needs to be changed. The traditional mobility policy measures, e.g. taxes and infrastructure, need to be complemented by measures that place a higher weight on sustainability through modal shift, including measures to support changed travel behaviour and patterns of daily commuters.

Finally, the *reflexivity* challenge in the bioeconomy case is considerable. The lack of clear goals and operationalisation of those goals or interim milestones is a consequence of the lack of overall agreement on a desirable direction. Under these circumstances the attempts to include more diverse actor groups in consultation is still far from a genuine involvement in "adaptive management" (Weber and Rohracher 2012). Given the lack of a clear vision and a breakdown of that vision to different sectors, the next policy step would have to be to improve the transparency in the various sectors, provide analysis about the consequences of different pathways and the opportunities of innovations and change of practice in cooperation with stakeholders. This then could be the basis for sufficiently robust consensus regarding the pathways or goals to prioritize that would support to define strategies and to set up instruments accordingly.

In contrast, the mobility case in the Netherlands indicates that sustainability goals and problems have been correctly diagnosed. For this reason, mobility initiatives are constantly adapting to shifting moving targets. This could be the result of how transformations create their own politics, generating incentives for actors to participate in such reflexive processes and aim to direct such processes towards their own aims (see Feindt and Weiland 2018). Therefore, the policy challenge here is not reflexivity as such, but making sure that the governance structures that enable long-term plans and policies facilitating system change are not captured by vested interests having a strong influence in selecting routes of change.

6 Conclusions

The objective of this paper is to develop a framework for the structured analysis of transformation processes and to illustrate how the framework can be applied to assess and inform policy for supporting transformation processes. This requires a system level analysis, both of the socio-technical system itself and of the transformation process.

We present a framework that enables the characterization of socio-technical systems and their pathways of transformations. This paper identifies dimensions for such an analysis and illustrates how these dimensions can be applied to compare cases. Drawing from the literature on sustainability transitions, we identified twenty dimensions spanning seven categories of analysis.

A central rationale for developing this framework is that so far, there are very few studies or 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. 2020; Rogge et al. 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 is intended to be used for analysing the complex ways in which pathways of socio-technical systems unfold. It should 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 potentially identifying common features across cases. This might provide a basis for 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.

We identify the following aspects for future research. 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 only suggested that these dimensions are interconnected. This work could benefit from a more rigorous analysis of how these dimensions interact. Finally, the framework should be applied to case studies for policy proposals, to show its usefulness in analysing idiosyncratic system transformations and at the same time to identify patterns of causalities and dynamics in different types of transformations.

7 References

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Appendix: Interpretation of the dimensions for the bioeconomy and mobility illustrations

Bioeconomy transition in Germany

System dimensions

Meta-category	Dimensions	Analysis
General	*Function*	Securing the long-term and more ecologic-friendly supply of energy, food and various materials through the sustainable production and use of renewable resources
Characteristics	*Relevant sectors*	Many sectors belong totally or partially to the bioeconomy (agriculture, forestry, fisheries, food and feed, paper, chemicals, pharma, energy, fuels, plastics, furniture, R&D services, municipal waste collectors)
	Interactions with other systems	The bioeconomy is either partly integrated or interacting with energy and mobility transitions via the applications bioenergy and biofuels and respective cascade uses. In addition, mobility and energy policy may set high incentives and demand for the use of biomass and therefore has a high influence on the whole bioeconomy
	Characteristics of relevant technologies and sectors	The relevant technologies are quite diverse ranging e.g. from feedstock production/breeding chemical conversion to biotechnology or mechanic use. Many science and technologies have to be adapted very specifically for the processes, application and the used feedstock
	Geographical scope	Rather global, but this depends on raw material and application sector. The value chain for the use of biomass for fuel/chemicals/plastics is rather international, as well as the trade for various crops. However, some feedstocks and value chains are rather local (e.g. certain plants, wood supply, algae)
Context factors	*Infrastructures: Physical, knowledge, financial*	No specific large infrastructure is required (e.g. such as power grids), but there are high investment and knowledge needs to build up specific plants (e.g. biorefineries) and logistics. This is a key bottleneck for the commercialization of bio-based products.
	Regulation and its importance	The importance of regulatory framework conditions depends on technology (genetic engineering / genome editing), sectors, feedstock (e.g. waste regulation). For many applications regulatory changes would be needed for high market adoption.
	Socio-cultural factors	Environmental awareness, perspective on food security as well as agricultural systems (industrial, agro-ecologic) are of high relevance

Meta-category	Dimensions	Analysis
Agency	*Actors constellations and their capacities*	Basically, many groups of actors are relevant and affected by consequences. These range from farmers, SME, large companies, municipalities, services providers R&D institutes, users.. New actor constellations emerge in particular in cross-sectoral collaborations, e.g. biomass providers with different application sectors.
	Power relations	Rather high market and political power of incumbent large companies. The concept of bioeconomy is rather determined by a few expert circles / community, with some increasing efforts to integrate society increasingly.

Transformation dimensions

Meta-category	Dimensions	Analysis
Drivers and barriers	*Societal preferences (culture)*	In Germany, societal preferences have a high influence in certain markets, such as agro food concerning use of technologies, openness for new products (e.g. meat alternatives), valuation of waste-based/recycled products.
	Technological change/innovation	Rather broad range of innovations offer new opportunities, often with the aim to improve the sustainability of the bioeconomy transition, but partly also providing new product with different performance to satisfy consumer needs
	External shocks	Relevant external developments include climate change, reduction of emissions, CO_2, etc. However, the often do not lead directly to sufficient pressure to change production and consumption patterns of the bioeconomy.
	Policy and regulations	While there many relevant policies and regulation, overall the current policy mix has only limited (but increasing) impact in terms of directionality (e.g. sustainability orientation) and diffusion of new products and processes
	Emergent vs intentional (market driven or politically/societally driven)	The transformation is highly politically driven by the expectation that the bioeconomy contributes to address societal needs, such as climate changes. The markets are rather reacting on policy incentives or rules, in particular as bio-based products are often not cost competitive.
	Demand articulation	Industry, consumers and politics (public procurement) are rather reluctant to pay the often higher prices for bio-based products. Early adopters are relevant for some markets (e.g. bio-packaging).
Politics	*Nature of contestation*	The need of transformation is uncontested, but rather different perspectives on future paths of bioeconomy exist (technology-driven, social-ecologic driven, etc.). Connected to that, there are ethical discussion around advanced technologies, such as genetic engineering, gene editing, synthetic biology, as well as social issues in food security and more

Meta-category	Dimensions	Analysis
	Degree of (national) autonomy	The national autonomy of Germany vs. EU competences depends on the type of policy instruments (high autonomy in R&D funding, less for technology regulation) and market (e.g. biofuel policy regulated in RED II, no equivalent for material uses.
	Governance structures	The governance of larger parts of systems is complex as a lot of material flows and markets are interlinked. Moreover, there is high heterogeneity for applications, markets, feed-stocks.
	Degree of coordination	Very high coordination between political actors is necessary for the bioeconomy. It has improved in Germany, but still challenges in particular for coordination with other policies outside the system missing (e.g. energy, trade, climate mobility)
Dynamics	*Development over time*	The transformation to the bioeconomy is assessed to be rather in early phase and a tipping point is not reached yet. High changes in production and consumption are expected for next 2-3 decades, however a high substitution of fossil fuels by biomass even in this time frame rather unlikely.
	Learning process	There are many activities to enable learning processes across markets, innovation, geographical units, policy ac-tors, but these are mostly in an early stage

Mobility transition in the Netherlands

System dimensions

Meta-category	Dimensions	Analysis
General	*Function*	Efficient transport of people in the Netherlands.
Characteristics	*Relevant sectors*	The mobility system is essential for any sector. It allows access to goods, capital, etc. In the mobility system, the sectors that play a role are currently traffic management, and traffic information systems, while other sectors are becoming more important in its transformation (e.g. IT, services, high-tech, navigation) and providing new mobility concepts (e.g. new concepts through user information).
	Interactions with other systems	The mobility system affects and is affected by other systems, including: energy, in terms of fuels and grids; heath, in terms of local pollution, obesity, and wellbeing; materials, as the current mobility system depends on materials such as rubber, glass, steel; tourism; land, because of land use, distances, etc. Overall, the mobility system has a relationship with any economic activity.
	Characteristics of relevant technologies and sectors	Vehicles play an important role: it is a global and mature industry. Other technologies coexist with dominant cars (e.g. bicycles, public transport, etc.). Technologies in the mobility system depend on the different scope and distances in question. Technologies can be combined (multi-modality), thus allowing users to use multiple technologies. It also makes relevant the points of exchange in which this multi-modality occurs.
	Geographical scope	Hybrid. Some technologies have a national scope due to their long-range and infrastructure (e.g. cars) while other innovations are locally specific (e.g. new concepts as sharing, cycling, smart cycling, etc.), depending on local-dependent characteristics (e.g. urban space).
Context factors	*Infrastructures: Physical, knowledge, financial*	Current infrastructure is well developed in the country: physical infrastructure, knowledge is available; multiple finance streams are set in place. Digital infrastructure (that enables smart solutions) has a high degree of penetration and maturity in the country. The country has a strong knowledge infrastructure and at pool of high-tech companies working in areas concerning the mobility system.
	Regulation and its importance	Crucial. Mobility is a highly regulated system, in which innovation within the system requires legal changes. Among the relevant regulation, we can think of: Dutch legislation on urban planning, transition arenas, traffic regulations (e.g. standards, procedures, etc.).
	Socio-cultural factors	Stable but changing. The change is fuelled by market niche groups (e.g. young people, etc.), which are more likely to adopt new mobility concepts.

Meta-category	Dimensions	Analysis
Agency	*Actors constellations and their capacities*	Main established actors include: Infrastructure providers, regional and local authorities, road agencies. Moreover, other actors participate in the development of the system, including academics, industry, service providers, consultants, technology providers, towns, research institutions, users. New actors constellations are emerging as part of the recombination of technological fields (e.g. IT, high-tech systems), that are disrupting the mobility system.
	Power relations	Governance institutions (town planners) Institutions and relationships between actors (industry, local governance, user networks) in transition management arenas. The Netherlands is characterised by consensual, *polder-model* like decision-making.

Transformation dimensions

Meta-category	Dimensions	Analysis
Drivers and barriers	*Societal preferences (culture)*	The Netherlands has a strong movement towards more sustainable ways of mobility, resulting in initiatives in car-sharing etc. There is an emphasis in adopting more active lifestyle habits, favouring cycling, walking, etc. Moreover, cycling is central in the culture of the country.
	Technological change/innovation	The change is driven by new possibilities offer by new technologies, including telecommunications and AI. This new technologies allows a movements towards new concepts of mobility, including MaaS.
	External shocks	External developments influencing include climate change, reduction of emissions, CO_2, etc. Recently Corona has created long terms effects, particularly in the demand side.
	Policy and regulations	General policy guidelines have been set in place to direct the transition in the Dutch mobility system.
	Emergent vs intentional (market driven or politically/ societally driven)	Transformation is driven by political and societal expectations, but some innovations are driven by markets. Transformation is fuelled by the need of sustainability issues and the use of IT. The country conceives transformative innovation as part of its economic development.
	Demand articulation	There are early adopters for mobility innovations. Additionally, demand has been fuelled by behavioural change programs, and through public procurement.
Politics	*Nature of contestation*	The need of transformation of the Dutch mobility system is uncontested. Moreover, there is an agreement (in general terms) on what is the direction that the transformation should take (e.g. automation, IT, sharing, etc.). Question: Why is it not working/ or less ambitious?

Meta-category	Dimensions	Analysis
	Degree of (national) autonomy	The country is largely autonomous in their decisions, mobility is relatively of national (or subnational) competence. However, other regulations come from international level (e.g. freight, driving, etc.). The Netherlands is not restricted by a car-manufacturer, in the way Germany, France.
	Degree of governability	Well-developed set of policy instruments and governance structures set in place to govern a transformation.
	Degree of coordination	Very highly coordination activities in place for the actual system + new coordination mechanisms for directing a transition.
Dynamics	*Development over time*	Mobility system is expected to be transformed in the following decades (e.g. 2030, 2050) with some general routes of action, including multi-year programs and finance, goals or ambitions (e.g. in terms of CO_2).
	Learning process	Open question: Did they have a learning from the energy transition?

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