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Notes

Abstract

There is a need for concepts and methods to develop generic insights across cases in transitions studies based on thorough and systematic empirical analysis. Based on the major strands of transition literature, this paper develops dimensions for a socio-technical system level analysis, differentiating between dimensions of the system under study and its dynamic dimensions of change and illustrates their application to compare cases and identify possible entry points for analysis. System dimensions are grouped into the function and sectors of the system, its characteristics, including context, actors and power structures. Transformation dimensions address the societal need (the wicked problem) drivers and barriers, politics and dynamics of the system. We suggest questions to help in starting an analysis of the dimensions. An illustration for the German bioeconomy gives an example of how to draw general conclusions as to the value of a structured systems and transformation analysis to support policy understanding and practice.

Keywords: System dimensions, transformation dimensions, analytical framework, transitions case study

Contents

1 Introduction

The objective of this paper is to further develop a framework for the structured analysis of transformation (or transition) processes and to illustrate how it can be applied to assess and support policy for supporting transformation processes. It updates and extends an earlier version of (Edler et al. 2021). Köhler et al. (2019) propose that there is a need for concepts and methods to develop generic insights across cases in transitions studies. This requires a system level analysis, both of the socio-technical system itself and of the transformation process. However, the 'what' and 'how' of socio-technical systems and transformational changes, while well-outlined by academics, may be difficult to grasp by the people needing to understand systems and make changes, e. g. policymakers. Addressing these issues, this paper identifies dimensions for such an analysis and illustrates how these dimensions can be applied to transitions cases where the dimensions used can be a basis for comparison across studies.

The transitions literature has begun to develop a structure for the analysis of transitions processes. Geels und 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. 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 paper, we seek to support the future oriented thinking and policy-driven influencing of systems change by providing a systematic framework to characterise and analyse the nature of socio-technical systems as well as the nature of system transformations. Based on the sustainability transitions literature, dimensions and criteria for this characterisation of systems and their transformations are deductively derived and described. A brief illustration of the application of the framework is given for the example of the bioeconomy in Germany.

In comparison to the first version of this concept (Edler et al. 2021) we provide the links of such a framework compared to main theoretical transitions frameworks by either using important elements or stressing certain gaps. Moreover, we added several key emerging dimensions, such as financing, in the concept. Finally, the empirical illustration is updated regarding dimensions as well as current developments. This paper thus offers a theoretically grounded and updated conceptualisation to enable and support the analysis of socio-technical systems and their transition, in particular in a policy supporting context.

The article is structured as follows. Section 2 reviews the main theoretical frameworks used in the transitions literature and identifies dimensions used for analysis. The main frameworks are the MLP, TIS (technological innovation systems), TM (transitions management) and strategic niche management (SNM). Using the results of section 2, section 3 describes the choice and structure of the dimensions used to characterise systems in transformations. These extend the dimensions found in the literature review to consider issues of power relationships and contestation. The organisation of a typology is discussed. Then, the dimensions found are combined into a simple typology of transition system dimensions and transition dynamics. Section 4 summarises how we suggest this typology could be used to structure a transitions case study. Section 4 includes the illustration for the bioeconomy. Section 5 summarises the key points with suggestions for future research directions and future applications of the framework.

2 Dimensions in the transitions literature

The main theoretical frameworks are reviewed to identify dimensions of analysis. These are ***highlighted*** in the text.

2.1 MLP

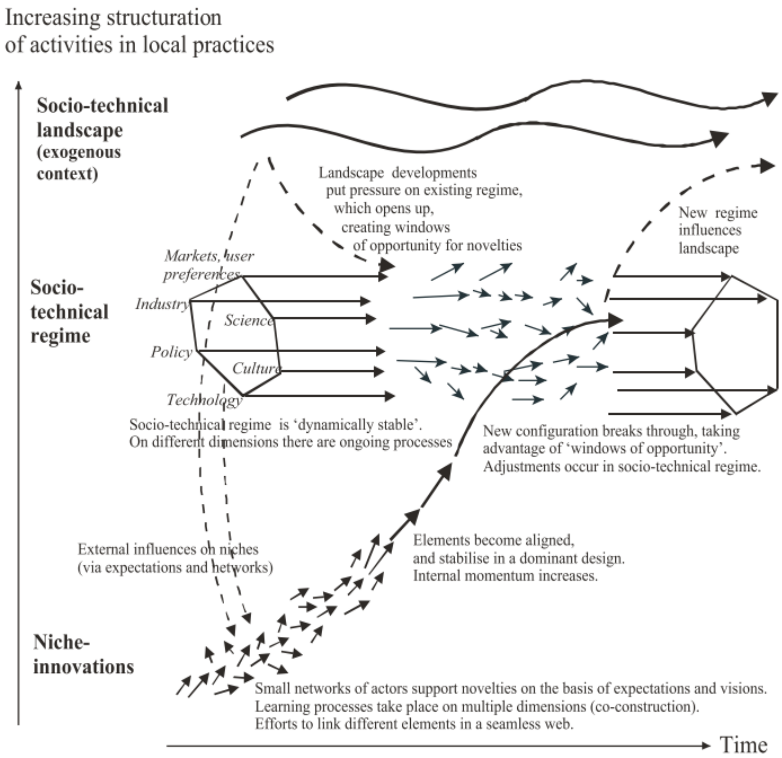

Figure 1: The Multi-Level Perspective (Geels, 2011)

The Multi-Level Perspective on transitions (MLP, see Figure 1 from Geels, 2011) conceptualizes systems as operating on three levels: that of the regime, or the way things are done in a specific socio-technical system that fulfills a societal function; the landscape level, which represents the social context, out of actors' daily control; and the niche level, in which innovations that address challenges (e. g. the 'wicked problem' of sustainability (Grin et al. 2010)), of the regime are nurtured. Regime change is seen to happen due to a combination of pressures from the landscape level and the niche level, which force adjustments in the six sub-systems of the regime (markets & user preferences, industry, policy, technology, culture, science). The MLP proposes a framework of changes that, through its multi-level structure and the conception of change as a co-evolutionary process between the different levels, includes many dimensions of change.

In terms of dimensions for analysis the MLP includes the descriptive dimensions ***societal function***, ***relevant sectors and their technology***, ***policy and regulations***, and ***infrastructures*** (as part of technology). In the framework of Figure 1, the important dimension of ***geography*** is not explicitly included, but is included in Köhler et al (2019). Societal function is a starting point of MLP analysis, identifying the socio-technical system itself. Relevant sectors are analysed as an element of industry structure. Infrastructures are covered by several MLP elements: industrial infrastructures under industry, financial infrastructures under markets, and knowledge infrastructures under science. The MLP addresses both ***policy and regulations*** in its policy sub-system. The MLP as shown in Figure 1 does not explicitly consider ***interactions with other systems,*** but this is addressed in recent literature (Köhler et al. 2019). Although Geels argues that the MLP is shot through with agency (Geels 2011), ***actor constellations and their capacities*** are considered through the lens of niches and regimes, including households, firms and governance actors. Köhler et al. (2019) also emphasise ***power structures*** as a fundamental area.

The MLP is intended to provide a framework for understanding the dynamics of transitions (or transformation) processes. Considering transformation dimensions, ***societal need*** is included as influences from the landscape for e. g. climate stabilization. While ***policy and regulations*** are covered by the MLP's policy element, ***governance structures*** are not explicitly addressed by this element. However, Köhler et al (2019) does include governance as one of the areas explicitly considered. Financing is a question that has been left out of most MLP analyses, which focus more on market structures. The MLP views transitions as contested, in particular as part of niche-regime interactions; the ***nature of contestation*** is also considered in Köhler (2019) as part of politics and power in transitions. ***External shocks*** are conceptualized through the landscape level of the MLP. ***Development over time*** is a fundamental feature of the MLP theory of change in the socio-technical systems; Figure 1 has a time axis. The MLP has been applied to both historical, ***emergent*** transitions (e. g. horses to railways see Geels & Schot, 2007) and ***intentional*** transitions (deliberately started by society to meet a perceived need e. g. climate stabilization). ***Innovations*** relates to the MLP's niche development of technology, as well as potential innovations in the regime technology (Geels & Schot, 2007). ***Demand articulation and market development*** is an important dimension, covered by the market element of the MLP.

2.2 TIS

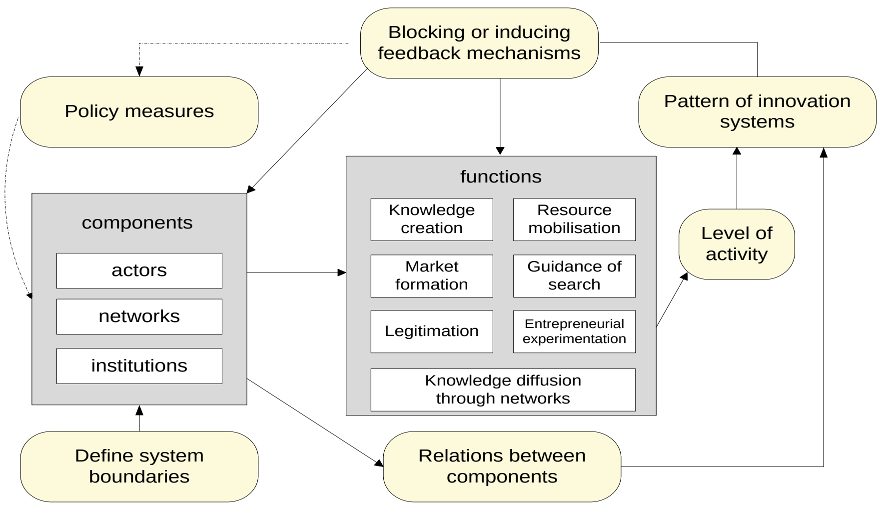

Figure 2: TISSource: own interpretation based on (Bergek et al. 2008) Figure 1

The TIS framework addresses Technological Innovation Systems (Bergek et al. 2008). In the proposed system structure, it includes the ***sector*** and technologies, ***actor networks*** (or constellations) and institutions (culture, norms, laws, regulations and routines) as part of a ***policy*** and governance structure. The framework is conceived in terms of a case (of barriers to uptake of a sustainable technology) to be analysed. The case technology then also includes ***geographical scope*** and the ***physical infrastructure***. The functions to be enacted by the TIS in order for the technology to develop include knowledge formation or ***innovation*** and ***financial institutions***.

The TIS framework also explicitly addresses the issue of change - as the (innovation) system developing a new technology. The technology addresses a given ***societal need***. The scheme of analysis proposed by Bergek et al derives policy measures i. e. ***policy and regulations*** to overcome blocking mechanisms and enable a positive ***development over time*** of the technology. Suurs (2009) introduced the idea of motors of innovation to show how these functions can form a dynamic system to also shape development over time. The resource mobilisation function includes personnel, knowledge development over time and ***financing***. The innovations are assessed and the market formation function addresses market development.

The TIS framework was introduced as a framework for assessing how barriers to the development of sustainability technologies can be overcome and therefore has an intentional aspect.

While issues of governance and power structures were not commonly addressed in the earlier TIS literature, (Lindner et al. 2016) and (Wesseling und Meijerhof 2023) have discussed how the TIS framework can be extended to consider governance issues. In summary, the TIS literature indicates how the system and transformation dimensions address important factors determining the process of development of systems of innovation.

2.3 Dimensions derived from the transitions management and strategic technology management frameworks for transitions research

These two frameworks are closely related to each other and to the MLP. Strategic niche management identifies niches (in juxtaposition to a regime) of radical innovation to develop sustainable socio-technical systems and theories that such niches can be supported by ***policy*** acting at a niche or local level and can then develop to challenge and possibly replace a regime. Transitions management is a ***governance*** concept based on local action to identify issues or ***societal needs***, develop a vision and scenarios with measures or policies to enable and support and niches, implement the measures and then adapt the measures in the light of experience.

Given the case being considered, the ***sector and technology*** are defined. The ***geographical scope*** is included in the definition of the system to be analyzed. Both frameworks emphasize decentralized, local action, but can be applied to niches that act over national or international systems. Both emphasize ***policy and regulations***, tailored to a local niche. The objective is to develop a niche consisting of the ***constellation*** of ***actors***. TM has the concept of 'transitions arenas', a form of ***governance*** structure in which actors work together in a co-development process to drive transition processes.

The frameworks have an explicit view of ***power structures and contestation***: they theorize that local actors need to isolate/protect themselves from the actions of the regime and that this can be possible through organized, coordinated action at the niche level.

The dynamics of change to a sustainable system arise in these theories from the identification of a ***social need*** for a more sustainable system to provide a ***societal function***. SNM and TM include policy to support the niches, and they also include a new, decentralized governance approach. ***Financial requirements*** are addressed in terms of niche development and are often problematic at the local/niche level, which is emphasized by these frameworks. TM and SNM both posit a high level of ***coordination*** between the actors constituting and supporting the niche.

Both frameworks are explicitly co-evolutionary with the objective of developing a social change process. ***Development over time*** and adaption are explicitly incorporated in the frameworks. These frameworks are applied as ***intentional*** system change processes - with the goal of achieving sustainability. In case study analyses, niche(s) may arise in response to ***external shocks*** which change the social and political context in which the niches are being developed. Niches are by definition ***radical innovations***. They explicitly include both social and technical components encapsulated in the concept of a socio-technical system.

The measures developed in these two frameworks have the goal of understanding and communicating with users (or sometimes prosumers) how the innovation can address the societal need that users wish to address. This involves technology development and/or a new service which may initially be uncompetitive or not be recognized as a significant benefit to users. The objective is to support market development of the niche by either creating a new market or eventually to make the niche competitive in the market with the regime technology/system.

3 Deriving Dimensions for Systems and Transformations

In this section, we explain the logic of how the set of relevant dimensions was chosen and structure the dimensions. The overall approach is to start with the aspects or dimensions identified in the transitions literature as outlined in section 2 above. We also adopt dimensions from the recent innovation and innovation policy literature where these consider aspects where the 'basic' theories of the transitions literature can be argued to be insufficient.

We differentiate between ***system dimensions*** that describe the elements of the socio-technical system under consideration and the ***transformation dimensions*** of change. The structure of dimensions is shown in Table 1. A further discussion of the individual dimensions is to be found in Edler et al. (2021).

3.1 The reasoning used to identify the dimensions

The proposed framework is intended for the analysis of socio-technical systems fulfilling a ***societal function*** and how they can change, a central aim of transitions research (Köhler et al. 2019). The scope of the socio-technical system under examination can include ***geographical/political*** units or functions across several sectors (e. g. the bioeconomy), but the starting point is the delivery of a function (e. g. food, mobility or energy) through a system that has the sub-systems identified in the MLP (science, technology, culture, industry, policy, markets). Transformations can either be ***emergent***, through societal and market dynamics (see the discussion of the MLP above) or ***intentional,*** addressing a 'wicked problem' (Grin et al., 2010), resulting from political and social intervention as a result of a political and discursive processes, as with the idea of a need to transform society to ensure sustainability (Club of Rome limits to growth).

Our logic is therefore to consider the ***general*** description of the ***system*** to be studied. This defines the object of study i. e. the function and socio-technical system to provide that function, including the characteristics of the system. Given that we are considering radical change towards a new system, the processes of change, i. e. the dynamics of the transformation, are the other main area of consideration. Thus, ***systems*** and ***transformation*** dimensions are the two main categories of the framework.

The system can then be delineated by its function and its sectors and technologies. In addition, the ***characteristics*** of the system include: ***geographical scope***, the ***policy, regulative and institutional*** context, ***infrastructures, interactions with other sectors*** and ***actors.*** The narrative of the main transitions theories (SNM, MLP, TIS, and TM) is one of ***contestation*** between the regime and niche(s) responding to changes in the landscape environment. Therefore, it is necessary to understand the ***power relationships*** between the niche and regime actors. Both agency and the roles taken by actors are dynamic and may change during the transformation process.

When it comes to understanding the dynamics of transformations, processes of change are often analysed by identifying drivers and barriers (internal or external to the system). Grin et al. (2010) identify problems of sustainability that drive change while the innovation system/TIS approach supports the identification of how to overcome barriers (Bergek et al. 2008). Those drivers are either bottom-up changes in societal preferences and demand as well as technological development, or they are politically constituted through policy and regulation. Given that major transformations produce winners and losers, they are, in general, highly political. We thus also pay particular attention to the properties and dynamics of political structures, ***contestation*** and ***coordination of policy*** extending the discussion of policy following (Mazzucato 2018).

Finally, the transformation ***dynamics*** will have to be analysed, to assess the progress of the transformation and how those drivers and barriers as well as context may change through time (Freeman und Louçâ 2001; Geels 2002; Geels und Schot 2007).

Table 1: System and transformation dimensions for analyzing sustainability transformations

SYSTEM DIMENSIONS

Meta-category	Dimension	Questions for analysis
General	Societal function	Which societal function does the system address?
	Relevant sectors and technologies	Which sectors and technologies are involved?
Characteristics	Geographical scope	What is the geographical scope of the system? Are system phenomena globally similar or locally specific?
	Policy, regulations, institutions	Which policies, regulations and institutions are relevant – in the focal sector and in other involved sectors?
	Infrastructures: Physical, knowledge, financial	Which physical, financial, and knowledge infrastuctures are involved?
	Interactions with other systems	With which other socio-technical systems can interactions be observed? Which levels and/or components of the focal system are interacting with other systems? What types of interactions can be observed (competitive, cooperative, functional, spill-over, neutral)?
	Actor constellations and their capacities	Which actor groups are involved to what extent? What networks are relevant? What are actors' and networks' capacities (resources, strategies, skills?)
	Power structures	What are existing power constellations (e.g. politically, financially, industrially, in civil society) that hinder greater sustainability of the system?

TRANSFORMATION DIMENSIONS

Meta-category	Dimension	Questions for analysis
General	Societal need	Which societal need does the transformation address? How strong is societal support for the transformation?
Coordination & contestation	Policy and regulations	Which policies and regulations need to change (in terms of both new policy formulation and phase-out of old policies)?
	Governance structures	Do governance structures alllow for the inclusion of non-state actors into decision-making processes?
	Financing	What financing is needed? What investment opportunities exist? What are risks?
	Degree of coordination	Is a high or low degree of coordination amongst actors necessary for the transformation? How successful are actors in mobilizing and coordinating resources?
	Nature of contestation	What is the potential for social conflict (distribution, ethics, etc.)?
	Degree of (national) autonomy	To what extent is there a national degree of freedom to act on the technological, economic, and political sides?
Dynamics	Development over time	Which transformative learning processes are needed by which actors? Which future windows of opportunity are possible and what is needed to take advantage of them?
	Emergent vs intentional	Is the transformation driven by market forces or politically/societally?
	External shocks	How can the transformation be resilient to and/or take advantage of external shocks?
	Innovations	Which innovations (e.g. technological, organisational, social) are necessary for the transformation?
	Demand articulation & market development	To what extent is demand articulated by users? How is market development progressing (who is involved, what is happening)?

3.2 System dimensions (see Table 1)

General description of the socio-technical system

In order to undertake an empirical analysis, it is necessary to delineate the object to be studied. In the case of system transformations, the object of study is defined to be a socio-technical system - a co-evolving set of social subsystems. Following Freeman and Louçã (2001), these are science, technology, economy (markets and industry in Figure 1), politics and culture. Debates about the need for the transformation of a socio-technical system have started from the assessment that there are 'wicked' problems (Grin, Rotmans, and Schot 2010) associated with the activities of a particular socio-technical system, especially with the sustainability of the system and its impacts. Therefore, the system should be delineated through its ***function***: energy, food, mobility, health etc. The technology, the practices and cultural expectations involved in the ***technology***, and the economic ***sectors*** involved are part of the general description.

Characteristics of the socio-technical system

Transitions are place-specific: different spatial scales, differing natural resource and industrial endowments, and place-specific norms and values shape transitions differently (Binz, Truffer, and Coenen 2014; Hansen and Coenen 2015). Space may be seen as a physical territory or as a set of relations between actors (Raven, Schott, and Berkhout 2012; Bernhard Truffer and Coenen 2012; Calvert et al. 2017). A requirement for the analysis of systems and their change is thus the identification of socio-technical systems level and its ***geographical scope***.

Relevant rules and routines determine the requirement for socio-technical systems to operate in markets and in society. An important question in socio-technical analysis is how rules and institutional processes shape the regime of a system (Fuenfschilling and Truffer 2014). They may consist of ***policies*** enacted through laws or ***regulations*** (e. g. competition regulation, environmental regulations etc., technology standards and institutions (formal rules). They also involve cognitive rules, such as problem-solving routines, visions and expectations, as well as normative rules. Social and organisational networks are stabilised by mutual role perceptions and expectations of proper behaviour (Geels, 2004).

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). 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).

While the MLP conceptualization of transition refers to a 'fundamental' socio-technical reconfiguration in a focal sector, this single-sector focus has been challenged (Andersen and Markard 2020; Andersen et al. 2020). Thus, ***interactions with other socio-technical systems*** need to be considered (Papachristos, Sofianos, and Adamides 2013). 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).

Agency is a central area of debate in the transitions literature (Grin 2010; Farla et al. 2012; Wittmayer et al. 2017). Sustainability transition literature has studied ***actor constellations*** primarily in terms of the networks, groups, or coalitions that they build with similar beliefs about the system (Markard, Suter, and Ingold 2016; de Haan and Rotmans 2018). Actors can be categorized in various ways, including in terms of their sector (civil society, markets, third sectors, or public authorities) and the level on which they operate (e. g. local, regional, national, etc.) (Avelino and Wittmayer 2016; Fischer and Newig 2016; Wittmayer et al. 2017).

Major changes in culture and behaviour are required for sustainability transformations and are identified as fundamental components (or subsystems) of socio-technical systems (Freeman and Louçã, 2001). Societies' articulations of their sociotechnical imaginaries - how they visualize their future - are important factors informing how transformations 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). 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. Ethical issues are also of critical importance in transformations (Köhler et al. 2019, section 9). Edsand (2019) offers an orientation by including socio-cultural factors as 'landscape factors'. Given the nature of sustainability transformations, he includes as separate factors: a population's environmental awareness; its (un-)equal access to education; and national corruption. (Oreg und Sverdlik 2018) discuss countries' cultural predisposition towards change. These considerations are included as the ***capacities for change*** of the actor constellations identified.

Mature socio-technical systems are built upon ***power relations*** and power structures that in general reinforce their stability (Avelino, 2017; Köhler et al. 2019). Such structures develop regulative (e. g. rules, laws, sanctions, etc.), normative (e. g. values, norms, etc.), and cognitive rules to reinforce what is considered legitimate and appropriate for a system. This limits the resources that actors can draw upon to affect its development (cf. Bergek, Jacobsson, and Sandén 2008). 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 an explicit consideration of policy processes in addition to policy content (Kern and Rogge 2018).

3.3 Transformation dimensions (see Table 1)

General

A transformation is driven by a perceived ***societal need*** e. g. climate stabilisation. The perceived urgency of such a need is often different between different groups in society and perceptions usually change over time, leading to changing landscape pressures on the regime. These differing perceptions and their dynamics lead to a consideration of contestation between different groups of society and coordination in actions.

Coordination and contestation

Policy and regulations can provide directions to systemic change by structuring incentives and indicating expected developments (Blind et al. 2017). Regulations may create standards that accelerate the diffusion of new technologies (Blind 2012). Policy may enable the creation of markets for early adopters or seek to phase out or reconfigure existing systems (Kivimaa und Kern 2016; Rogge und Johnstone 2017). Policies supporting the current system are a barrier to change (Köhler et al. 2019).

As well as specific policy measures, the transitions management approach has tried to develop practical ***governance structures*** and policy strategies such as transition management (Voß, Smith, and Grin 2009) and strategic niche management (Schot and Geels 2008). These can complement existing governance structures that support the regime. Transformation processes should be supported by experimental governance approaches, facilitating the evaluation and selection of alternatives (Manning and Reinecke 2016). Overall, the public sector requires the empowerment and development of new capabilities to catalyse transformations (Haley 2017; Borrás and Edler 2020). Reflexivity is a critical capacity for governance for open-ended transformation processes (Voß and Kemp 2006; Voß, Bauknecht, and Kemp 2006; Weber and Rohracher 2012).

In addition to policy and regulations, ***finance*** is also fundamental to change. Bergek et al. (2008) discuss finance as a part of the TIS function Resource Mobilisation. Steffen und Schmidt (2021) highlight the need to strengthen the analysis of finance for sustainability transitions.

Transformations necessitate ***coordination*** of interests, visions, goals, and expectations (Kemp, Loorbach, and Rotmans 2007; B. Truffer, Voß, and Konrad 2008). A successful transformation will also depend upon the capacity of actors to mobilize and coordinate resources (Smith, Stirling, and Berkhout 2005).

Transformations are subject to ***contestation*** as they are political and normative processes, which ultimately redefines societal interests, actors' positions and influence (Grin et al.) and how a system fulfils a particular function (Meadowcroft 2011). Challengers of the system are required to contest it in order to radically modify its socio-technical trajectory (Voß, Smith, and Grin 2009; Turnheim and Nykvist 2019). Contestation can occur when developing new institutions where regime actors refuse change (Geels 2014).

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. This level of governance is only implicit in the MLP structure of Figure 1. In a context of international or global financial institutions, trade flows and political power structuring ***national autonomy*** in influencing a transformation may be limited due to landscape factors, such as limited economic resources, weak institutions, corruption, or being dependent on transnational economic, financial or political forces (Swilling et al. 2016; Edsand 2019). In a context of multi-level governance (e. g. the European Union), transformations require to be aligned with supranational directives (cf. Ehnert et al. 2018).

Dynamics

Different patterns in the ***development over time*** 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 Waves as well as in the MLP to describe the development over time (Freeman and Louçã 2001; Köhler 2012). Geels and Schot (2007) and Geels et al. (2016) theorize that the dynamics are determined by interactions between landscape pressures and niche pressures. Different stages in a transformation's development over time have also been theorized in terms of 'deep transitions' (Schot and Kanger 2018; Kanger and Schot 2019). Learning processes are key so that stakeholders are able to adapt to new circumstances and innovations. Moving towards a knowledge economy, different forms of learning such as collaborative learning, organizational learning, and interactive learning have taken greater importance (Borrás 2011; Lundvall 2016; Frantzeskaki and Rok 2018). Social learning - the peer-to-peer exchange of knowledge between innovators, involving learning processes across multiple dimensions (van Mierlo and Beers 2018) - and social innovation are essential parts of niche development (Raven 2005; Geels and Raven 2006; van Mierlo et al. 2020). 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 transformation processes (Wu, Ramesh, and Howlett 2015).

The ***development over time*** may have different rates of change for different factors. In the MLP, the landscape level is often considered to involve broad societal changes that move slowly. In this sense, the consideration of societal preferences has been broadened to reflect the importance of culture for the dynamics and direction of transformations, in particular in the energy field (Stephenson et al. 2015; Stephenson 2018; Sovacool und Griffiths 2020). Changes of societal preferences regarding e. g. methods of energy or food production and consumption may result in changes in policies and markets. Culture as the interplay of ideas, customs, and social behaviour of a particular population or people[1] manifests itself in in the basic attitudes and everyday practices of people (Hui et al. 2016; Coutard und Shove 2019). Therefore, transformation dynamics involve changes in culture, long-term processes involving changing social processes co-evolving with new technologies in society. Technological change may lead to the emergence of new markets and cause profound changes in socio-technical systems (Geels et al. 2008).

A socio-technical regime is also theorised as being relatively slow to respond to landscape changes, with large scale change typically assessed as evolving over decades (Freeman and Louçã 2001). Niches are typically theorised to be relatively agile, responding in a shorter timescale to the dynamics of a transformation (Grin et al., 2010).

Transformations can either be ***emergent***, through societal and market dynamics or ***intentional***, resulting from political intervention as a result of a political and discursive processes (Geels and Schot, 2007). Most often, both dynamics will interplay, reinforce or counteract each other. Markets provide directions to system transformations by working as selection environments for radical innovations (Grin 2010) 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 und Rohracher 2012).

External 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 und Geels 2019). These are included in the Landscape of Figure 1.

The dynamics of a transition are manifest in ***innovations*** that involve changes towards a new socio-technical system. These innovations may be radical ideas realised through incremental steps. They open up new structures of demand and new ways of supplying that demand. The radical change of a transition will bring institutional and cultural change as well. Grin et al. (2010) point to the idea of radical change in incremental steps. This is an important insight, through which radical change is not a single 'leap', but a process of innovations through time.

Comprehensive research has shown that bottlenecks on the demand side as well as the supply side can severely hamper the diffusion of innovation (Edler 2016), and thus transformation. In addition to industrial innovation (Freeman und Louçâ 2001), we can observe two central actors that can influence a system transformation through ***demand articulation*** and the resulting ***market development***: users and state authorities. Users can lead to a change in systems through new patterns of consumption (Martin and Upham 2016). Different kinds of demand side policy tools such as public procurement, demand subsidies or training and awareness measures can overcome bottlenecks in market development or (Fagerberg 2018, Edler and Georghiou 2007; Borrás and Edquist 2019, Ch. 6).

[1] Oxford dictionary, quoted in Sovacool / Griffiths 2020b)

4 How to apply the dimensions (Table 1): An illustration for Bioeconomy in Germany

A systematic characterisation of systems and transformations on the basis of 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 this next section, we give examples the framework by applying it to the case of bioeconomy in Germany

The bioeconomy is a special case of a system as it possesses a cross-cutting character that involves many different products, markets and technologies. The concept of the bioeconomy emerged in the early 2000s and has become increasingly important since then, with increasing and common activities by various stakeholders to replace fossil-based resources with bio-based resources but also applying biological knowledge and technologies. 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. The analysis, developed as answers to the questions in table 1, is shown in the appendix.

4.1 System dimensions

General

The underlying ***societal function*** is the long-term and more ecologically friendly supply of energy, food and various materials through the sustainable production and use of renewable resources. The goal is ideally to avoid the use of fossil-resources and the enabling of more sustainable production and consumption patterns. Bioeconomy ***technologies*** address this goal by using biomass as a raw material input for a range of processes The technologies are quite diverse ranging e. g. from feedstock production/breeding chemical conversion to biotechnology or mechanic use of feedstock. Many technologies have to be adapted very specifically for the processes, application, used feedstock in a broad range of ***sectors***. Statistics for the bioeconomy show that the bioeconomy generates significant value added primary sectors as well as various secondary sectors, such as chemicals, pharmaceuticals, plastic and rubber, textiles, furniture and other wood-based products (Ronzon et al. 2022). Moreover, biomass is relevant for the construction and energy and fuel sector. The technologies are quite diverse ranging e. g. from feedstock production/breeding chemical conversion to biotechnology or mechanic use of feedstock. Many technologies have to be adapted very specifically for the processes, application and the used feedstock

Characteristics

Regarding ***geographical scope***, the bioeconomy has strong global and regional features at the same time, depending on the specific 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 more local (e. g. certain plants, wood supply, algae).

Many activities in the bioeconomy are ***highly regulated***, e. g. on the productions side of biomass, use of certain feedstock (e. g. waste) on technology (e. g. gene editing), on product (e. g. market authorization) or market level (e. g. feed-in tariffs). Moreover, many applications regulatory changes would be needed for high market adoption, as they are not currently competitive under current framework conditions. Hence, discussions regarding regulations are broader than current conditions.

No specific large ***infrastructure*** is required (e. g. such as power grids, roads), 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.

Related to the broad use in various sectors, the bioeconomy ***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; Wydra et al. 2021). There are clear dependencies between those transitions. e. g. if bioenergy is supposed to contribute significantly to energy transition the consequent high needs of biomass and potential focus of actors on this application with limited complexity and market uncertainty (if feed-in tariffs are fixed) may impede activities e. g. for biomass - based materials. However, synergistic interactions, e. g. biorefineries with multiple products, are also in development or partly active in the market.

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. There are high policy-driven efforts to include additional actors (e. g. farmers, waste management actors) in value chains and cross-sectoral collaborations. However, the public and civil society (e. g. NGOs) are still involved only to a limited extent, which is highly criticized by these groups. These **current *actor constellation and capacities*** may be partly driven by the ***power structures***. Currently, incumbent companies possess high power due to high entry barriers at least in many mass markets (e. g. chemicals) and limited political pressure for transition to bio-based resources.

4.2 Transformation dimensions

General

As indicated above the goal of the bioeconomy transition is to fulfil ***societal needs*** and to address major economic, societal and ecological challenges like resource depletion, food insecurity or climate change. Therefore, new innovative solutions and more sustainable production and consumption patterns have to be developed. Key drivers for the transformation to the bioeconomy are the increasing pressure to use natural resources sustainably, by reducing dependence on fossil fuels, securing food supply and environmental and climate protection.

Societal support for this transition is mixed. While there is in principle a positive basic attitude towards this green, sustainable pathway and food security, there is some reluctance towards the mostly prevailing technology-driven or bio-resource driven paradigm, instead of a more-socio-ecological vision. Moreover, there is hesitance towards new technologies with partly unknown risk in close-to-human areas such as food, textile and ecosystems.

Contestation and coordination

Still the ***government structures*** can be assessed as rather policy-driven with a strong orientation towards industrial actors. Because of 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. However, common agenda setting remains a key issue, along with the coherence concerning other systems and policy areas (e. g. energy policy, trade politics) as well as between different government levels (EU, national, regional (Böcher et al. 2020). ***Policy and regulations*** have limited directionality efforts and mainly consist of R&D, innovation, network coordination, and infrastructure (e. g. financing of biorefinery demonstration plants) (Dietz et al. 2024; Scordato et al. 2022). A major challenge for governability concerning markets is the wide range of heterogeneous products and applications in very different sectors. Relevant regulations differ significantly across the related sectors. In principle, man different regulations impact technology use and market access of products. Moreover, other 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. Here, also questions of geographical ***national autonomy*** arise as many markets for feedstocks are rather global and global policies and markets having significant influence. In addition, EU policies and regulation are relevant for technology use and many relevant sectors (e. g. biofuels regulation, plastic bans, etc.).

While public ***finance*** instruments especially for earlier stages in the bioeconomy in Germany have evolved, still high needs for alter stages (upscaling, market access) persist. Over the last years more and more private investors got aware and a better understanding of the bioeconomy, however still remaining high-risky, because of market uncertainties.

Contestation arises because of the uncertainty whether the bioeconomy (or certain products and processes) is really more sustainable than the fossil-based systems. While there are promising assessments, the evidence is not clear-cut. Concerns arise especially regarding land-use conflicts.

Dynamics

A range of emerging (technological and social) ***innovations*** offer new opportunities to address these challenges. 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).

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 und Stern 2018; EC Expert Group 2021). Significant ***developments over time*** are still needed to develop efficient bioeconomic solutions and to build up infrastructure and sustainable, circular value chains. While some ***demand is articulated***, usually awareness and willingness-to-pay for bio-based products is limited. External societal factors, such as higher environmental awareness, still do not lead to a strong rise in demand for bio-based products. Hence, willingness-to-pay is limited and hence, the transition is very much dependent on ***intentional*** political influence, such as market pull mechanisms. The past decades have seen a policy push, with the EU and member states implementing bioeconomy strategies (FAO 2024; Dietz et al. 2024)), but mainly on a strategic level and less regarding concrete policy instruments.

In addition, ***external shocks*** may influence the transition process, especially those which have an impact on resource availability and prices, either on biomass or fossil oil. Large disruptions may limit the cost competitiveness and supply of bio-based products or - in case fossil-based resources get scare and expensive - foster the transition efforts.

Bioeconomy as a good example?

The example to characterize the bioeconomy is not easy, because of high heterogeneity of the bioeconomy system and its early phase of development, which limits the manifestation of certain dimension characteristics. For example, the heterogeneity and complexity may impede clear characterization regarding the global character vs. national autonomy, but these dimensions still may help to be aware of issues for further analysis. The description still helps to point out key features of the system and transformation, such as the high level of intentional transition characteristic, but faced by contestation and limited demand articulation.

Another potential implication would be that it might be also meaningful to analyse a part of the bioeconomy transition, e. g. considering its role either in food transition, energy transition or part of sustainability in the context of providing new (bio-)materials. Such more detailed analysis may help to sharpen the characteristics.

5 Conclusions

The objective of this paper is to develop a framework for the structured analysis of systems and system 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.

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, and a dearth of generally recognised methods for systematically assessing and comparing future transformation pathways. Moreover, there is no agreed method for performing analysis on them (Wanzenböck et al. 2020; Rogge et al. 2020). Köhler et al. (2019) identify a need to more systematically develop explanations of transformations 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. 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 environment in which the socio-technical system functions and its specific *agency*. In contrast, our transformation dimensions, consisting of factors influencing the dynamics of socio-technical systems, can be summarised as ***contestation*** and ***coordination*** and ***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 - we believe - can subsequently lead to a typology of systems and system transformations. This would potentially improve the analysis of system transformations without ignoring the idiosyncrasies of systems.

The illustration has shown the potential of the framework to identify bottlenecks that could be tackled through policy. Providing a systematic checklist of critical dimensions for transformations on the basis of a sound understanding of the underlying system can indeed improve diagnosis for policy design purposes.

We emphasise that the typology of dimensions proposed here is not complete. However, the dimensions proposed reflect the aspects or themes found in the transitions literature. For a particular case study, they can be used as a starting point. In Table 1 we have suggested questions that can be used to address the dimensions. The depth to which a case study addresses or includes the dimensions is a decision that the researcher has to make. Equally, it is up to the researcher to identify aspects of their research questions that require analysis not covered by the dimensions in Table 1. However, the benefit of covering the dimensions proposed is that it could help to develop a set of case study analyses that are comparable to the extent that they explicitly identify dimensions that are addressed in terms of Table 1.

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.

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A.1 Appendix: Interpretation of the dimensions for the bioeconomy and mobility illustrations

A.1.1 Bioeconomy transition in Germany

A.1.1.1 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
	relevant technologies and sectors	The relevant technologies are quite diverse ranging e. g. from feedstock production/breeding chemical conversion to biotechnology or mechanic use for various primary (agriculture, forestry, fishery) and secondary sectors (chemicals, fuels, construction, textiles, etc.). Many technologies have to be adapted very specifically for the processes, application and the used feedstock
Characteristics	*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)
	Policy, regulations and institutions	Various regulation influence production side of biomass, use of certain feedstock (e. g. waste) on technology (e. g. gene editing), on product (e. g. market authorization) or market level (e. g. feed-in tariffs). For many applications regulatory changes would be needed for high market adoption.
	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.
	Interactions with other systems	The bioeconomy is either partly integrated or interacting with food, energy and mobility transitions via the applications bioenergy and biofuels and respective cascade uses. E. g. if biomass is allocated (via policy and/or market mechanisms) to a certain use and sector this may limit the opportunities for other transitions
	Actors constellations and their	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.

Meta-category	Dimensions	Analysis
	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.

A.1.1.2 Transformation dimension

Meta-category	Dimensions	Analysis
General	*Societal need*	goal of the bioeconomy transition is to fulfil societal needs and to address major economic, societal and ecological challenges like resource depletion, food insecurity or climate change. However, the societal support is rather mixed, while there is a positive basic attitude, there are concerns…
Coordination and Constellation	*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
	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, feedstocks.
	Financing	instruments for earlier stages in the bioeconomy in Germany have evolved, still high needs for alter stages (upscaling, market access) persist
	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)
	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
	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).
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.
	Emergent vs intentional	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.

Meta-category	Dimensions	Analysis
	External shocks	External shocks may influence the transition process, especially those which have an impact on resource availability and prices, either on biomass or fossil oil.
	Innovations	Rather broad range of innovations (new, product and new processes in primary and secondary sectors) 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
	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).